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PETROLOGY OF THE TJÖRN AREA IN WESTERN SWEDEN

BY

LARS BERGSTRÖM

WITH ONE MAP IN SCALE 1:50 000

STOCKHOLM 1963

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PETROLOGY OF THE TJÖRN AREA IN WESTERN SWEDEN

AN INVESTIGATION OF ARCHEAN SEDIMENTS, THEIR TRANSFORMATIONS AND OTHER PETROLOGICAL FEATURES

BY

LARS BERGSTRÖM

WITH ONE MAP IN SCALE 1:50 000

STOCKHOLM 1963

Contents

Preface

My interest in the Tjörn area was first aroused in 1952 by Doctor P. H. Lundegårdh who pointed out how fascinating the geology was there. Since then I have been devoted to the beautiful scenery of southern Bohuslän.

In the summer of 1958 I commenced the field work for this thesis. It would have been impossible for me to carry out this investigation if I had not received the encouragement and help of a number of people, and the support of several institutions.

Professor G. Beskow, Head of the Geological Department of Chalmers University of Technology, Gothenburg, has put the resources of the department at my disposal. He has always given me support and helped me in many ways. I am deeply indebted for this.

My teacher Professor S. Hjelmqvist has visited the area on several occasions and has taken encouraging interest in my work.

I am indebted to Professor N. H. Magnusson, formerly Director of the Geological Survey of Sweden, for his letting my first fieldwork in the Tjörn area ~~be a~~ part of the official survey program. The present Director, Mr K. A. Lindbergson, and the Editorial Board of the Geological Survey have kindly accepted this thesis for publication.

Doctor W. Larsson has read the manuscript with great care and has suggested valuable improvements.

The chemical analyses, performed by Mr A. Aaremäe, and the trace-element analyses, performed by Doctor S. Landergren, have been carried out at the laboratories of the Geological Survey of Sweden.

Fil. mag. L. Samuelsson has most willingly helped me in many ways. He has made the originals for the colour reproduction — a most tedious job. He has assisted in the field for eight days and has mapped the breccia on Stora Buskär. He has also checked the chemical computations.

Mr S. Dahlén has made the thin-sections and has performed the photographical laboratory work with great skill.

Miss U. B. Johansson has typed the first and second editions of the manuscript.

Mrs. M. Jonsson has drawn the maps and sections.

Fil. mag. B. Karlsson and Mr Gordon Evans have together carefully gone through and corrected the English of my manuscript.

Finally I want to thank my wife Irja for her great understanding and her encouraging interest in my work. Without her help this thesis would never have been completed.

Financial support has been received from Anslaget för Ograduerade Forskare, Chalmers Tekniska Högskolas Fältarbetsanslag, and Anna Ahrenbergs Stiftelse.

To all persons who have helped me in my work I want to extend my warmest thanks.

Geological Department,
Chalmers University of Technology,
Gothenburg
January 5th, 1963.

Lars Bergström

Petrology of the Tjörn Area

An investigation of Archean sediments, their transformations and other petrological features

ABSTRACT

A geological map is presented of the area studied. Low-metamorphic plagioclase-dominated gneisses of sedimentary origin, with graded bedding, form together with arkosic beds and amphibolites, the oldest rocks in the investigated area. Where these sediments — due to folding — are vertical or nearly so, they have been subject to regional metamorphism with partial anatexis and a secondary supply of potash feldspar. These processes led to the formation of veined gneisses and migmatite. In an early phase of migmatitization a plagioclase-dominated mobile granitoid was formed. This rock type is now found as conformable beds (*in situ*) or has brecciated the sediments. In a late phase of the orogenesis, there was an intense potash metasomatism, especially where the metasomatizing, ascending solutions were captured. In these positions the metasomatized matter became mobile, and could brecciate adjacent brittle rocks. These processes produced beautiful breccias.

Within the area there is a norite body with anorthositic fragments. The norite is proved to be intrusive and the anorthosite is derived from the same magma as the norite. A secondary origin of the magma which formed these rocks is anticipated.

Fifteen new chemical analyses are published. Twelve mafic specimens have been analysed on some of their trace-element contents. The results are given here.

The petrogenetical problems are emphasized.

Chapter 1

Introduction

The centre of the investigated area is 37 km NNW of Gothenburg (Fig. 1). The bedrocks in this area are extremely well exposed as it is a borderland between land and sea, where overburden, except in the valleys, is absent or extremely scanty. Fig. 2 gives a general impression of the landscape. The high degree of exposition makes the geological surveying very easy. Fig. 3 shows the exposed bedrock which is indicated by a dark shadowing.

The bedrocks are exclusively pre-Cambrian. Schists, gneisses, and granitoids have a wide distribution, while mafic rocks are of minor areal importance. One exception is the norite on the islands of Brattön and Älgön, which is briefly treated in chapter 15. The geological map covers 190 square kilometres of land. Since 1956 the author has spent 175 days mapping within the area. The area covered per day was roughly 1 sq. km except when surveying the big islands of Instön, Koön, and Marstrand and the mainland adjacent to these islands. Here the mapping rate was 4 sq. km per day. These figures are presented in order to

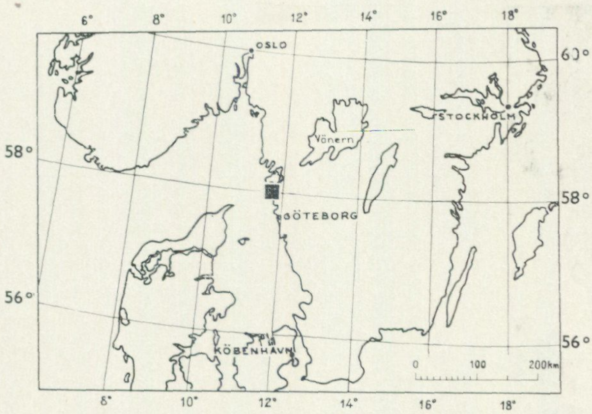

Fig. 1. Geographical position of the Tjörn area.

explain why there are fewer details within the rapidly mapped parts, but also in order to give an idea of the amount of field work involved.

A geological map is one of the results of the field work, and is found at the end of the book. It is referred to as "the map." The names of localities discussed in this paper are only in exceptional cases found on the map. Instead the localities are given a reference number on a simple grid system based on a millimeter scale. The reader will find two scales along the margins of the map. The west—east scale goes from 0 to 375 and the south—north scale goes from 500 to 930. Any point on the map can be located by means of two groups of three figures each. For example the church of Klövedal in the north—western

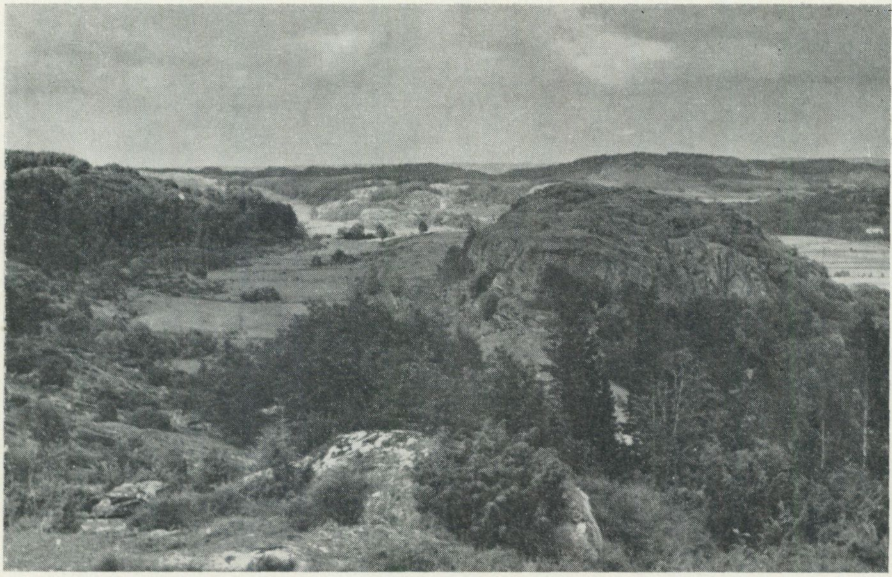

Fig. 2. View, central Tjörn (from 20.82 northeastwards).

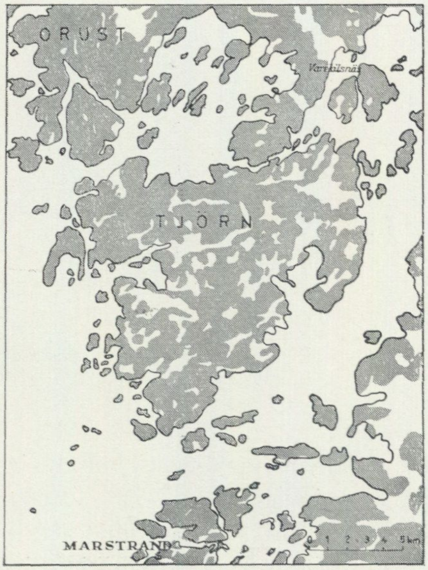

Fig. 3. Map of Tjörn and surroundings. Exposed bedrock shadowed.

part of the map has a map reference of 135.845. All references to localities are given in this way. In some cases, when exactness is not necessary, only four figures are used.

On the map the contacts between different rock types are marked by continuous lines, as they are generally exposed and consequently there is no doubt about their exact positions. A broken line indicates a gradational transition between the two rock types on each side of the line.

The general lithological features can be seen at a glance. The eastern part of the mapped area is built up of low- metamorphic supra-crustal rocks. Veined gneisses and migmatites with amphibolitic inclusions are found on the western side of Tjörn.

The central and the most eastern parts of Tjörn consist of granitoid rocks, striking in direction NNE. The colours are strong when metamorphism and/or mobility is high. For example: The granitoid rock found around point 16.68 is an authigenic rock. More or less the same rock is found around point 15.80 but here the rock is of an allogenic character due to its intrusive behaviour. Thus these rock types are represented by the same colour but distinguished by different intensities of the colour.

The investigated area lies within the Stora Le-Marstrand series. This series mainly consists of sedimentary gneisses of varying composition and metamorphic grade. They extend from south of Gothenburg to central Dalsland west of Lake Vänern (Fig. 1). This series has been briefly described by Magnusson (1960 b). Around Gothenburg the rocks belonging to the Stora Le-Marstrand series have been investigated in detail by Lundegårdh (1953 a, 1958). Previous work within the Tjörn area dates back to 1902, when Blomberg published a map with a short description. Many of Blomberg's observations as read in his field books are excellent, but the map and the printed description hardly do justice to the interesting bedrocks of the area.

South of the investigated area the sedimentary series dips steeply but within the area the fine-grained gneisses together with amphibolite form a bow in which dips are moderate. As seen on the map by the notations of strikes and dips the fine-grained gneisses form an anticline in which there is a core of granitic gneiss near Höviksnäs. Further south the gneisses form an other anticlinal structure as seen from the strikes and dips on the islands of Katten and Lövön, near Rörtången and on the islands of Instön and Koön.

Along the contacts between the fine-grained gneisses and granitic augen-gneiss from Kuballe to Kållekärr and further northwards the fine-grained gneisses dip eastwards, thus lying over the granitic augen-gneiss. The gneisses are, if continued upwards, supposed to form an anticline in which the granitic augen-gneiss is situated. The western limb of the anticlinal fold consists of migmatite which is seen along the line Klövedal—Skärhamn—Koholmen. Here dips are very steep or vertical (cf. Fig. 53).

Two age determinations have been performed on the fine-grained gneisses (mica schists) from the quarry at Tjuvkil 299.538. The determinations were made according to the potassium 40/argon 40 method at the Laboratory for Precambrian Geology in Leningrad, USSR. These age determinations are published by Magnusson (1960 a). The specimens from Tjuvkil gave the ages 1 040 and 1 066 million years (op. cit., pp. 408, 424). The relative ages of the rocks in the investigated area are indicated by the order in which they are placed in the map legend. Further details on the relative ages are found in following chapters. All rock units, however, are younger than the fine-grained gneisses mentioned above. The granitoid rocks in central and eastern Tjörn are younger too. These are found in anticlinal folds in the gneisses and the contacts show that the granitoid rocks in their present state of metamorphism are younger than the gneisses. This is not consistent with the map "Pre-Quaternary rocks of Sweden" compiled by the Geological Survey of Sweden in 1957. On this map these granitoid rocks are classified as pre-Gothian and the Stora Le-Marstrand series as Gothian. On pages 410 and 411 in Magnusson's paper on age determinations of Swedish pre-Cambrian rocks, he says that the pre-Gothian rocks have a slightly lower age than the Gothian rocks. To this remarkable fact Magnusson comments, "The only possible explanation to the crowding of ages into a narrow interval" (around 1 000 m. y.) "seems to be the acceptance of a regeneration in Dalslandian time in connection with the development of the Bohus granites and their accompanying pegmatites" (p. 424).

These intricate problems do not come within the scope of this investigation, but as there is a contradiction between the only modern geological map of this area and the results presented in the following chapters, the problem cannot be completely neglected.

There is a striking petrographical similarity between the pre-Gothian rocks east of Gothenburg (outside the Tjörn area) and the granitoid rocks on Tjörn. This is the obvious reason for labelling the Tjörn granitoids "pre-Gothian". Pre-Gothian rocks from localities outside the investigated area gave ages approximately 1 001 m. y. (op. cit., p. 424). Specimens from the Stora Le-Marstrand series at Tjuvkil 299.538 gave the ages 1 066 and 1 040 m. y. Thus the "pre-Gothian" rocks are, as it would seem, slightly younger than the Stora Le-Marstrand series.

This is in consistency with the results put forward in this paper. For this reason the writer wants to abandon the name "pre-Gothian" when alluding to the granitoid rocks on Tjörn.

The following chapters treat the rock units in the order oldest to youngest. Petrographical and chemical data on the rocks are given. The refractive indices were determined in sodium light. The volumetrical determinations were performed on a Leitz line-integrator. Anorthite contents of the plagioclases were determined on the universal stage. Every chapter concludes, with a few exceptions, with a petrogenetical discussion. Fifteen new analyses as well as a number of trace-element determinations are given. All photographs have been taken by the author.

Chapter 2

Schists and fine-grained gneisses

As mentioned in the introduction schists compose the bedrock from the north—eastern part of Tjörn continuing southwards over Valla, Kållekärr, and Kuballe. Here their strike is turning more easterly with a bow over Lövön, Rörtången, and Tjuvkil 299.539. The dip of the schists is nearly vertical in the southern part of their extension, but nearly horizontal at Tjuvkil and Rörtången and again nearly vertical on Lövön. On Tjörn they show a moderate easterly dip near the central granitoid part of the island. The schists evidently roof the granitoids. At Kuballe 20.68 there is a syncline. The axial plane of the syncline can be traced in a northeastern direction in the central part of the schist area. As seen on the map the schists dip westwards at the contact of the granitic rock extending north and south of Höviksnäs. Sections AA^1, BB^1, and CC^1, in Fig. 53, which are drawn nearly perpendicular to the strike show in their eastern parts the fine-grained gneisses. The pattern of the schists in section BB^1 and CC^1 is thought to be a compressed syncline.

The schists are light gray and fine-grained. They are often rather homogeneous quartzo-feldspathic rocks, but there are parts that show a distinct foliation, due to

Fig. 4. Banded sediments. St. Äggelös 31.61.

a higher percentage of micas. So for instance slabs of mica schists are quarried for pavement purposes at Tjuvkil. The schistose gneisses often contain veinlets of quartz. When surveying the area it became obvious to me that these frequently occurring quartz veinlets should be distinguished from the veinlets with quartz *and* feldspar which are found in the migmatite proper and in certain well defined zones in the gneiss. An accumulation of quartz-feldspar veinlets is

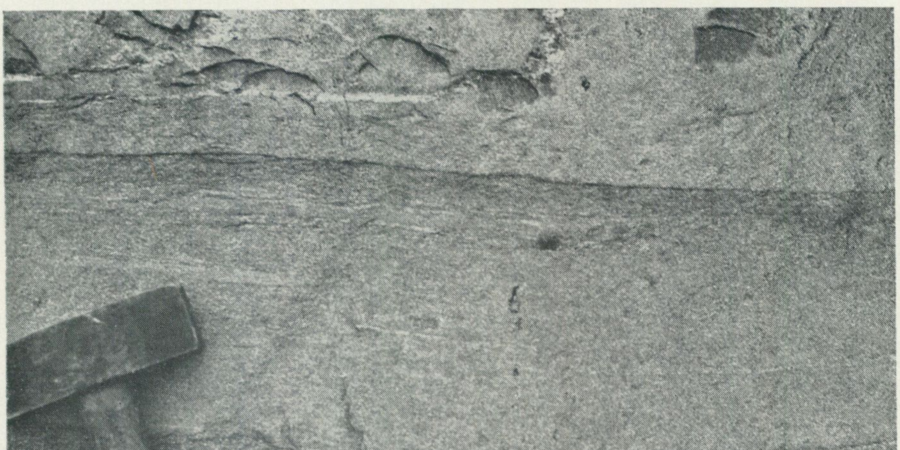

Fig. 5. Graded bedding. St. Äggelös 31.61.

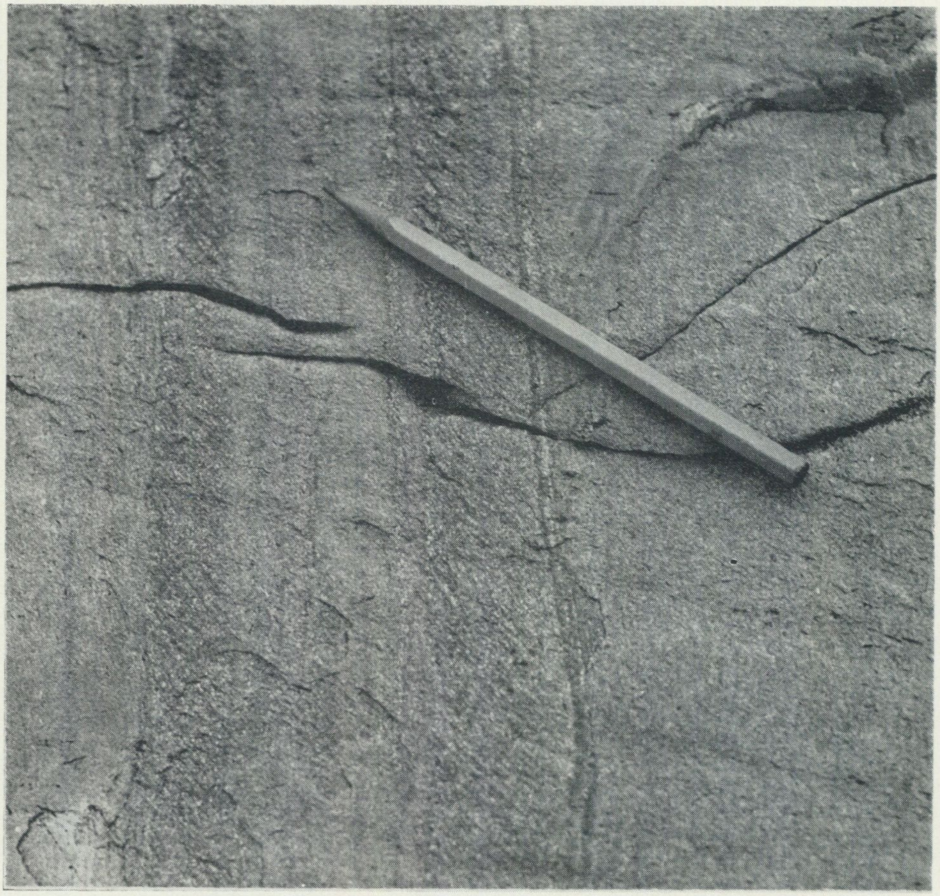

Fig. 6. Shearing in micaceous beds. St. Äggelös 31.61.

to be found in a distinct zone extending in a north-northeastern direction from point 24.78.

The quartz veinlets, that have a width of few millimetres, indicate a lower degree of metamorphism than the veinlets of quartz *and* feldspar, as the former are found in connection with the most fine-grained gneisses where also other primary sedimentary characters are preserved. (See below.) The quartz-feldspar veins on the other hand are only found where the gneisses are coarser.

At many localities in the investigated area there is an obvious parallelism in the gneisses, due either to an alignment of the minerals constituting the gneiss or to a bedding where beds which differ in mineralogical composition alternate. Such a bedding is shown in Fig. 4 from the islet St. Äggelös 31.61. The thickness of the beds varies from 3 to 25 cm. Each unit consists of a quartzitic and a micaceous part with a gradational transition between the two. Each unit of two beds is distinctly separated from the adjacent unit by a sharp mineralogical boundary (Fig. 5).

Thus the banded rock of the island St. Äggelös is interpreted as an example of graded bedding. Another structural feature at first glance reminding of cross-lamination is shown in Fig. 6. A more detailed study proves, however, that the textures depend on differential movements which have been released in the most micaceous layers, while the more quartzitic parts have acted rigidly.

In the quarry at Kuballe 190.675 a bedding was found of identical appearance as was observed on the islet mentioned above (Fig. 5). Here the gneisses are in a nearly horizontal position. The quarry is situated in the right part of section AA^1 (Fig. 53) near the contact to the granitoid rock. In each bipartite layer the basal part is more quartzitic and grades upwards into a more micaceous part. Bedding of this type is regarded as an excellent tool in order to determine the direction of original verticality. Provided no extraordinary conditions controlled the sedimentation, which caused these textures — and there are no indications of this — the gneisses here have their correct position concerning "up and down". This fact is of great importance in the discussion about the granitoid rocks in later chapters.

In the fine-grained schists sporadically white beds a few centimetres wide occur. Under favourable conditions these beds can be followed up to 10 metres. In the centre of the bed there can be some hornblende. These white beds mainly consist of quartz and subordinate feldspar, with an average grain size of 0.1 mm. In connection with the hornblende zone in the bed there is an enrichment of such calciferous minerals as clinozoisite and titanite. The garnet occurring in these beds has $n = 1.782$ and the unit-cell dimension 11.58 Å indicating about 50 % almandine, 25 % grossular and 20 % pyrope (Frietsch 1957, Sastri 1962).

Beds of this mineralogical composition are found in the quarries at Tjuvkil 295.538 and Kuballe 191.675, on the island of St. Äggelös 31.61, and sporadically over the gneiss area on Tjörn. It seems reasonable to assume that they really are beds, since they can hardly have been formed by metasomatism alone, though metasomatism has played an important role in the formation of their present mineralogical composition.

The contacts between schists and medium-grained gneisses are gradational and thus shown by broken lines, e. g. at 32.51. There is an increasing amount of pegmatitic veins and a plastic deformation of the gneiss close to the migmatite proper. The contacts between fine-grained gneisses and granitoids are sharp.

The petrography of the schists is rather simple. The grain size varies between 0.1 and 0.4 mm in parts where metamorphism is low. In the zone of the compressed syncline (for instance at 28.84) the grain size reaches 0.5 to 1 mm. The grain size was determined on micas and quartzes. Table 1 shows the mineralogical composition of the gneisses from different localities.

Table 1. Mineralogical composition of the fine-grained gneisses, % by vol.

Sample	Quartz	Microcline	Plagioclase	Biotite	Muscovite	Epidote	Acc.
1	27	32	16	+	25	+	+
2	48	29	9	13	1	+	+
3	39	10	38	12	+	+	1
4	43	14	8	+	24	10	1
5	37	17	34	9	+	+	3
6	74	8	18	+	+	+	+
7	33	19	29	15	4	+	+
			An: 8—20 %				

1 = Kuballe, 2 = 700 m W of Valla church, 3 = Hakenäset (E of Djupvik), 4 = Varekilsnäs, 5 = 1 km S of Valla church, 6 = Brattön, 7 = Tjuvkil.

Mica schist proper where micas dominate over quartz was not observed within the area investigated. In many cases feldspars dominate over both quartz and micas. The composition varies between feldspathic quartzite and pelitic schist.

Fig. 7 is a microphotograph of the gneiss at Valla 29.82. In the least metamorphosed parts the quartz is subrounded and shows slight to moderate undulatory extinction. In some of the examined specimens the quartz shows complicated sutured boundaries and is strongly undulatory. The extinction is also extremely "wavy" in the lenticles and aggregates of flattened quartz, so characteristic of the gneiss.

Potash feldspar seems in many of the investigated specimens to be of secondary origin. It appears as irregular intergranular fillings or in some specimens as an integral part of the mineral constitution. In the former case none or very few show any perthitic characteristics. This is the case, however, when the potash feldspar forms a major part of the rock. Beautiful cross-hatched microclines are found in the gneiss where the pegmatitic veins occur. Typical vein perthites are common also in the coarser gneisses.

The plagioclase is generally clustered with sericite and subordinate epidote. These secondary minerals make the determination of the anorthite content difficult but it varies between 8 and 20 %. Twinning of the plagioclase is not frequent — when observed it is according to the Albite law.

Muscovite and biotite are found coexisting, but generally biotite seems to dominate. The darkness of the gray colour of the gneiss is due to the amount of biotite. In the light parts muscovite is the only mica. Two distinct types of biotite are found in the low-metamorphic gneiss. One is brown and the other green. Their refractive index, however, differs only slightly. The brown biotite has $n_y = 1.648$ and the green biotite $n_y = 1.646$ indicating that they both are lepidomelanes (Tröger 1959, p. 79).

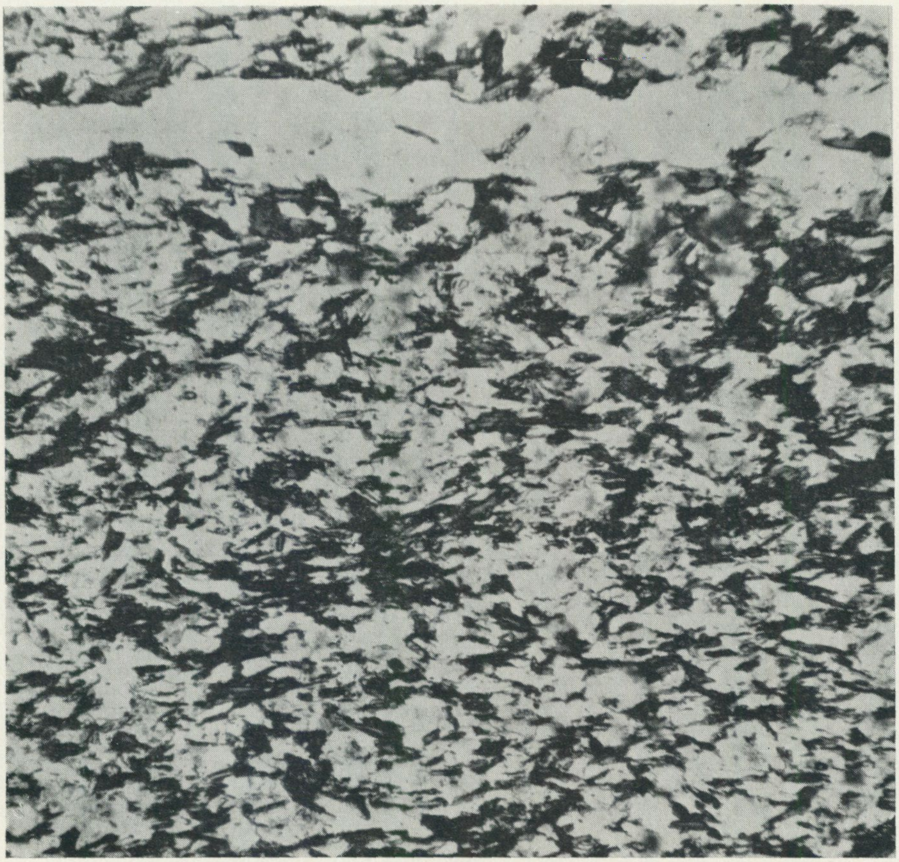

Fig. 7. Fine-grained gneiss. Svanvik 29.82. Ord. light. 25 ×.

Among the minor constituents clinozoisite is the most important. In one of the volumetrically analysed thin - sections clinozoisite constitutes 10 % of the volume. Epidote minerals are found in all investigated specimens of the gneiss.

On Brattön 33.58 and Älgön 27.59 a spotted slate is sporadically found. The spots are accumulations of pinite — in very few cases unaltered cordierite with $2V_x = 64°$ and $n_z = 1.55$, $n_z - n_x = 0.009$. The optical properties indicate that the cordierite contains 25 % of iron-cordierite. Few, very small garnets occur as a minor constituent in the gneiss.

Apatite is found as slender prisms in the gneiss. More interesting from a genetical point of view, however, is the occurrence of tourmaline. The size of the tourmaline grains does not diverge from the predominant grain size of the rock where it occurs. Tourmalines of 0.05 to 0.3 mm may be observed. Tourmaline is found in layers which do not show any other mineralogically or structurally distinctive features. The tourmalines are mostly xenomorphic, but sometimes they form ditrigonal prisms. Pleochroism is strong with O dark green and E brownish. $n_o = 1.659$. The tourmaline is a schorlite. Only the best preserved fine-grained gneisses contain tourmaline, but in connection with the gneisses, lens-shaped pegmatitic exudations are found to contain tourmalines with cross-sections of up to 3 cm. These tourmalines have the same optical data as those in the gneiss, thus indicating the same composition.

Three analyses have been performed on samples consisting of several fragments of the fine-grained gneisses. In Table 2 there are also analyses of arkose, graywacke, and of "delta"-sediment.

Table 2. Chemical composition of fine-grained gneisses in the Tjörn area and as comparison compositions of arkose, graywacke, and "delta"-sediment

Locality	299.538	190.676	288.828	A	B	C
% by weight						
SiO_2	75.93	68.40	66.66	76.37	65.5	64.7
TiO_2	0.51	0.63	0.86	0.41	0.5	0.5
Al_2O_3	12.72	15.82	15.28	10.63	12.0	14.8
Fe_2O_3	1.24	0.73	2.75	2.12	3.1	1.5
FeO	1.95	3.44	2.20	1.22	1.7	3.9
MnO	—	—	—	0.25	—	0.1
MgO	0.93	1.54	1.42	0.32	2.0	2.2
CaO	0.74	0.82	1.76	1.30	4.5	3.1
Na_2O	3.49	2.14	3.04	1.84	1.0	3.1
K_2O	1.15	4.90	4.24	4.99	2.6	1.9
H_2O-	0.12	0.11	0.22	tot.	—	0.7
H_2O+	1.20	1.42	1.40	0.83	2.9	2.4
Niggli values						
al	45.8	44.4	39.8	39.5	33.5	36.4
fm	24.2	26.9	27.1	20.1	31.3	32.2
c	4.8	4.0	8.2	8.7	22.7	13.8
alk	25.3	24.6	24.9	31.6	12.5	17.6
si	463	326	294	483	310	271
k	0.19	0.60	0.48	0.64	0.64	0.29
ti	2.2	2.3	2.9	1.9	1.7	1.5

A = average of 7 arkoses. Pettijohn 1957, P. 324.
B = one part of average sandstone + two parts of average shale. Pettijohn 1949, p. 271.
C = average of 23 graywackes. Pettijohn 1957, p. 307.

The analysed samples from the Tjörn area show compositions between argillitic and arkosic sediments — possibly nearer sediments of graywacke composition.

DISCUSSION ON THE ORIGIN

As already stated the fine-grained gneisses are sedimentary. The occurrence of graded bedding and skarny-quartzitic beds are proofs enough.

The mineralogical composition does not contradict a sedimentary origin. In this connection the occurrence of tourmaline is of great interest.

In V. M. Goldschmidt's Geochemistry (1954) Goldschmidt says (p. 288), "The boron contents of marine argillaceous sediments account excellently for the appearance of tourmaline in metamorphic rocks".

Goldschmidt regards the new-crystallized tourmaline in schists and gneisses as the accumulation of mobilized boron from the primary sediments. This process is, according to the same author, possibly but not necessarily influenced by magmatism. Recently Harder (1959) has shown that boron is markedly enriched in marine argillitic sediments compared to limnic sediments. From the Swedish bedrock Hjelmqvist (1938) described tourmaline in mica schists and mica quartzites from the sedimentary Larsbo series in Central Sweden. The tourmalines there quite well reflect their different mineralogical environment, the tourmalines of the mica schists being more ferruginous than those of the mica quartzite. In the slates of Grythyttan in Central Sweden Sundius (1923) reports sporadically occurring prisms of tourmaline (p. 43) but also rounded fragments of tourmaline of varying optical character, indicating a clastic nature. From the Muruhatten region in Northern Sweden Du Rietz (1938) reports tourmaline in sedimentary mica schists. Lundegårdh (1960) also reports tourmaline, the boron of which is supposed to have originated from synclinal sediments (p. 61).

These examples on the behaviour of boron in sediments and on the occurrence of tourmaline in rocks of sedimentary origin can give a probable key for the explanation of the genesis of the gneisses of the Tjörn area. The occurrence of boron in tourmaline is a strong indication of the sedimentary marine origin of the matter now forming the gneisses.

The chemical composition of the gneisses also points to a sedimentary origin.

The frequently occurring quartz veins in the fine-grained gneisses indicate a low degree of metamorphism. These observations are in close consistency with statements made by other workers in the metamorphic field. Korzhinsky (1950 b) states that "silica is highly mobile in low-temperature processes, when quartz veins and silicified rocks are readily formed" (p. 57). He also states that it seems as if the solubility of silica in the high-temperature solutions is low, but that it is increased with a drop of temperature (p. 57). In a paper on metamorphism in impure feldspathic grits and sandstones Phemister et al. (1960) state that at an early stage of metamorphism "quartz is extremely mobile and recrystallization is active" (p. 357). The observations of De Sitter et al. (1960) concerning metamorphism in mountain chains are most interesting. They remark that on in-

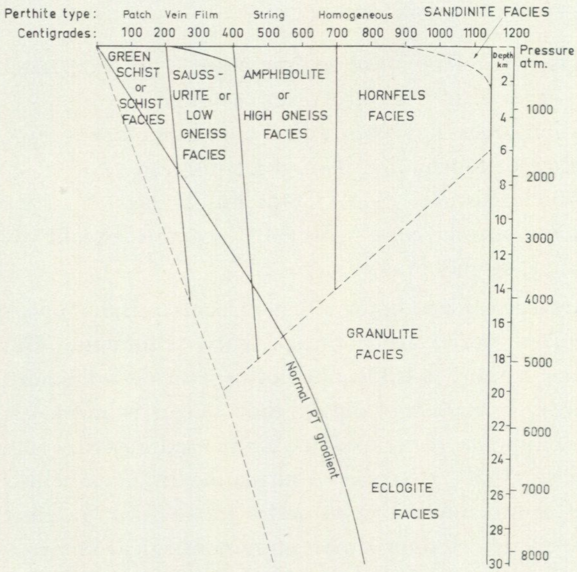

Fig. 8. Mineral facies and perthite types. (After Rosenqvist.)

creasing metamorphism of primary slates the grain size increases and that the exudation bands and lenses of quartz are frequent. According to the cited authors quartz lenses and veinlets are signs of fairly low metamorphism. This is in complete agreement with the observations in the Tjörn area.

According to Eskola's facies rule the gneisses described above fall within the epidote-amphibolite facies or "low-gneiss" facies as Rosenqvist (1952) prefers to call it. The lower limit of this facies is lined up by the occurrence of plagioclase containing anorthite molecules (op. cit., p. 37), whereas the upper limit of that facies is more difficult to define. The upper boundary, however, must have been passed when pyroxene occurs. But Rosenqvist also proposes another basis for a facies system, namely the perthites (p. 85). Fig. 8 gives his different facies correlated to the different types of perthites. Rosenqvist's nomenclature, schist, low-gneiss, and high-gneiss facies, seems more convenient than the classic one when applied to quartzo-feldspathic rocks such as those now dealt with. Observations on differently metamorphosed parts of the gneisses confirm that vein and film perthites occur.

Chapter 3

Pegmatitic-aplitic layers

Blomberg (1902) has previously observed the close genetical connection between the pegmatites and the gray schists occurring near Marstrand (op. cit., p. 26). Pegmatite-aplites of this close connection to the fine-grained gneisses

Fig. 9. Pegmatitic bed. Southern Älgön 283.584.

are found on the islands of Katten 26.64, Lövön 32.63, Älgön 27.59, and on the adjacent mainland. On the map the size of the pegmatites is slightly exaggerated. Fig. 9 shows the pegmatitic-aplitic bed on the central part of Älgön. This bed is 5—8 m thick and generally follows the plane of schistosity although in details it can be cutting. As seen in the same figure it also contains thin conformable schist layers. Similar beds are frequently found in the gneisses in the Lövön—Älgön—Instön area but they are not so large that they have been represented on the map. Such minor conformable pegmatites are found on western Brattön (Fig. 68). There are two petrographical types of layers. Though they have the same way of appearing, they differ in colour and in mineralogy. One of the two types is represented by the figured pegmatite on Älgön and the other by those at e. g. Rörtången and on the island of Katten 26.64. The Älgö type is light gray — the Rörtången type is pinkish white. The differences in colour very well reflect their mineralogical compositions. The Rörtången bed consists of 0.1 mm grains of microcline, porphyroblastic grains of perthite, flattened undulatory quartz, muscovite flakes, and garnets. They have a refractive index n = 1.781 and the unit-cell size a = 11.81 Å corresponding to a grossular-dominated garnet. The porphyroblastic microclines are surrounded by a rim of small clear plagioclases indicating that the porphyroblasts have pushed aside the small grains. But there are also indications of a formation of the porphyroblasts in another way: they contain relicts of plagioclase with the Albite twins orientated parallel to the perthite lamellae in the microclines.

The Älgö type of pegmatitic beds is light gray and dominated by a plagioclase with 10—14 % anorthite. The plagioclases occur as small grains (0.01 mm) and larger porphyroblasts (1—3 mm).

Frequently the twin lamellae of the plagioclases are bent and sometimes broken, thus indicating a post-crystalline deformation. In addition to the small plagioclases quartz and subordinate microcline, biotite and muscovite have been observed. Accessory minerals have not been found.

It is believed that this bed is the less metamorphosed of the two types, and that the first described Rörtången type is derived from the Älgö type mainly by potassium metasomatism. The Älgö type is thus primary, compared to the frequently occurring Rörtången type, which is secondary.

The same type of plagioclase relicts as those found in the Rörtången beds has been studied by Ljunggren (1954). He has treated the formation of albitic lamellae in microclines (p. 62). He regards these lamellae as remnants of the pre-existing plagioclases which were replaced by potash feldspar. The rebuilding of plagioclase into microcline only needed potassium, which was incorporated into the plagioclase lattice at the same time as calcium was removed. Ljunggren's observations are consistent with those of Drescher-Kaden given in his detailed work on myrmekites (1948). In geological writing there are many observations on the replacement of plagioclase by microcline. Seitsaari (1951) repeatedly points to this process in his work on the schists near Tampere in Finland and regards it as an obvious fact (p. 17).

The constituents needed for transforming the anorthite component into microcline are potassium and silica. As pointed out earlier in this paper Korzhinsky (1950 b) stresses the high mobility of silica in early stages of metamorphism, but he also points to the complete mobility of potassium and sodium during any metasomatic process. Like many other authors he regards potassium as more mobile than sodium. During the conditions of metamorphism the following reaction could have taken place in the pegmatitic beds of Rörtången:

$$K + Si + CaAl_2Si_2O_8 \rightarrow KAlSi_3O_8 + Ca + Al \quad (1)$$

But because of the low mobility of calcium and aluminium these elements were very soon captured in new lattices. The calcium expelled from the anorthite component of the plagioclase is now found in the garnets. The excess of aluminium was used in the formation of muscovite. The albite component was easily transformed into potash feldspar by the simple substitution of sodium by potassium according to formula (2).

$$K + NaAlSi_3O_8 \rightarrow KAlSi_3O_8 + Na \quad (2)$$

Generally the beds of both Älgö and Rörtången type are conformable to the schists, but in minor details the material of the beds cuts the foliation of the adjacent schists. This is due to tectonical movements traced in the deformed plagioclase twins mentioned above, and the general increase of the foliation, the latter possibly caused by differential movements mainly parallel to the schistosity. During this phase of tectonization conditions favoured local mobilization, which caused transgressive contacts of the beds. The problem of mobilization in connection with potassium metasomatism is treated in detail in later chapters.

Other pegmatite types are found in the outer rim of the schist zone for instance at the quarry of Tjuvkil 299.538. They are lens-shaped (width 20 cm and length up to 2—3 m) but always conformable to the schists enclosing them. They are medium- to fine-grained but there are also very coarse parts within these pegmatitic lenses. Their mineralogical composition is: albite, quartz, muscovite, garnet, and tourmaline. Beryl and apatite are characteristic components. These lenses are often enveloped by mantles of micas. The lenses show a typical pinch-and-swell structure. Their colour is white with a pinkish tint. As already mentioned in the treatment of the tourmaline occurring in the schists, the tourmaline of the pegmatitic lenses is of the same composition as the tourmalines in the schists. Tourmalines of 3 cm cross-section are found in the lenses.

Ramberg (1956) has treated the pinch-and-swell structures of pegmatites of the same kind as those occurring at Tjuvkil. He regards the structure as being formed by lateral expansion of the schists already containing a layer of solid pegmatite (op. cit., p. 193). The lateral expansion caused a rupture of the formerly continuous layers giving them their present pinch-and-swell structure which thus is a type of boudinage. My opinion is, however, that the lensoids were formed before the complete solidification of the pegmatitic material, because there are no signs of cataclasis among the minerals. Of course later recrystallization could have veiled such a cataclasis.

We have now to consider the sources of the matter forming these pegmatites. The mineralogical composition is very close to the composition of the sediments, but there is a slight enrichment of boron and beryllium and a decrease in mafics in the pegmatites. The enrichment of micas around the lenses and the occurrence of tourmaline give implications on their genesis. About the enveloping micas: Ljunggren (1957) has studied veined gneisses with their enrichment of biotite close to the veins and shows by means of planimetric analyses that part of the vein material was derived by expelling biotite and epidote (pp. 119, 121) from certain layers in which plagioclases were transformed into microcline. Ljunggren regards that there has been a secondary supply of feldspar. In the small lensoid pegmatites of Tjuvkil there is no evidence of a similar potassium metasomatism. Metamorphic differentiation with short-distance migration seems to have been the only force active in their formation. There has been a migration of the most mobile elements of the schists into parts with lower pressure. The locally occurring patches of lower pressure have been caused by a dilatation of the schists, and no doubt the present form of the lenses indicates the primary low-pressure patches. The lenses at Tjuvkil are interpreted as dilatation pegmatites (cf. Ramberg 1952, p. 252) which were synorogenic. Ramberg (1956) shows that the lenses of pegmatites occurring in the regionally metamorphosed areas of West Greenland were formed at PT conditions very similar to those characterizing the metamorphism in the country rocks.

As mentioned above the pressure gradient was the ~~main~~ driving force causing the migration of feldspathic material to the lenses found in the quarry at Tjuvkil. Reitan (1960) points to the possibility of the formation of higher temperatures along certain surfaces (friction heat) during movements in schists containing pegmatitic lenses. Reitan thinks that this heat has played a role in the formation of the pegmatitic lenses. In the present area similar processes are not believed to have had any great importance, and thus the facies of the lenses is the same as that of the country rock.

CONCLUSIONS

From the presented data on the gneiss-schist formation it is clear that it is a sedimentary formation with mainly pelitic-clayey-arkosic material. The sediments on the eastern part of Tjörn are in their correct up-down position. Their metamorphic state lies within the low-gneiss facies.

Occasionally there are plagioclase-dominated beds within the more argillitic sediments. These beds were subject to a potassium metasomatism rebuilding plagioclases into microclines and simultaneously forming muscovite and garnet. On the island of Älgön there is an arkosic bed not influenced by potassium metasomatism.

Within the schists there are pegmatitic lenses carrying mainly quartz, plagioclase, and accessory tourmaline. These lenses are regarded as dilatation pegmatites in the sense that Ramberg uses the term. They have mainly received their matter by short-distance migration.

It should be noticed that no cutting pegmatites of major importance are found within the gneiss area.

Chapter 4

Amphibolitic gneisses

Amphibolitic gneisses are distributed quite evenly over the investigated area. Generally the amphibolite occurs as steeply dipping, thin discs being rather extended in their direction of strike, as may be seen on the map e. g. around Skärhamn 11.74. Vast areas of amphibolite-gneisses are found south of Höviksnäs 32.76 and on the islands of St. Dyrön 18.60 and Kärrsön 22.62. Here, however, the amphibolite-gneisses are rather flat. The fact of their vast extension is thus not explained by thicker beds, it is only a matter of how the strata of amphibolite-gneisses are cut by the present surface. Field observations prove that the amphibolite is folded in the same way as the schists. The amphibolite has a distinct foliation (Fig. 10) which is conformable to the foliation of the schists. That is observed in localities where the two rocks come into contact with each other 212.872 and 30.75. On the southern part of St. Dyrön a beautiful isoclinal fold in the amphibolite may be observed.

Usually the amphibolite is rather homogeneous only containing minute quartz veinlets. One can also find quartzo-feldspathic beds of up to 25 cm thickness in the amphibolite. These beds are folded in the same way as the amphibolite.

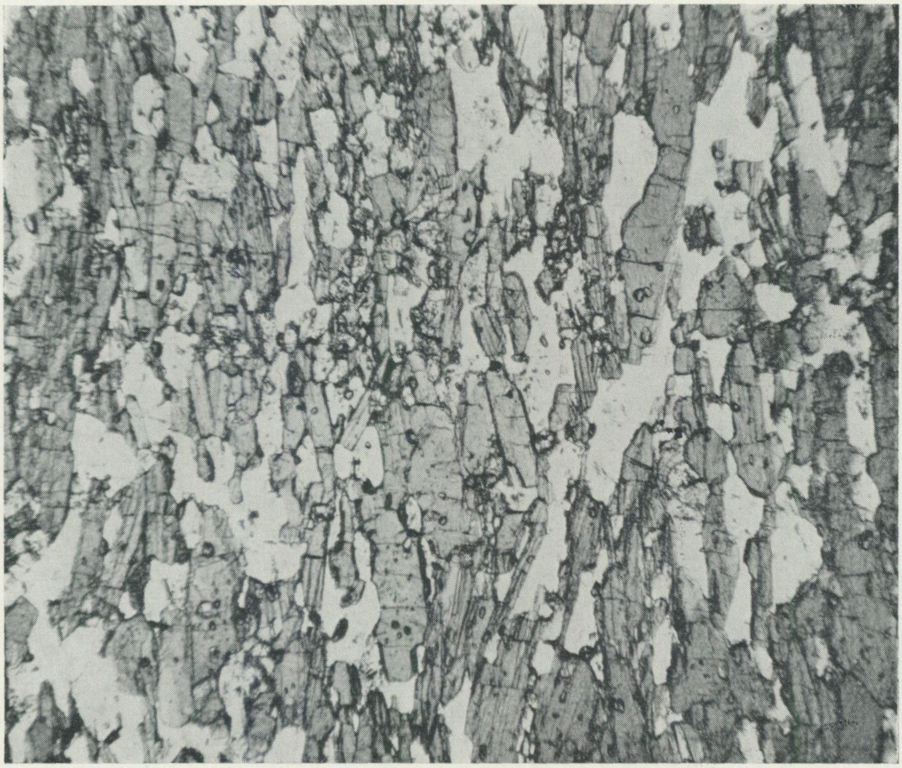

Fig. 10. Amphibolite. St. Dyrön 183.594. Ord. light. 30 ×.

The foliation of the amphibolites is conformable to the planes of stratification. These planes are indicated by quartzo-feldspathic interbeddings and by extensive but thin layers of garnets in the amphibolite. Relict textures have not been found, no doubt due to the intense recrystallization which has hidden the primary textures. The recrystallization has caused a parallel alignment of the small hornblende needles in the main direction of the fold axis. Simultaneously the grain size increased. The amphibolites have a grain size from 0.1 mm in places where the metamorphism is low (e. g. St. Dyrön) up to 2—3 mm in the amphibolite lenses in the migmatite area on western Tjörn. On St. Dyrön where generally the amphibolites are fine-grained, much coarser amphibolite is found in the folds. Even if foliation is characteristic, the distinctness of the schistosity varies considerably. Thus foliation is not so characteristic of the coarser amphibolites.

The amphibolites have a very monotonous petrography. Hornblende is the main mineral — generally more than 50 % of the rock volume is hornblende with the following optical properties: extinction c/z 15—20°, $n_x = 1.657$, $n_z = 1.683$. Pleochroism: X = light greenish; Z = bluish green; $2V_x$ abt. 85°.

Mostly the hornblendes have the same grain size within a limited area, but occasionally some hornblende crystals grow porphyroblastically and then contain small non-undulatory quartz inclusions. There is no sign that hornblende was secondarily formed from pyroxene.

Plagioclase is the most abundant mineral next to hornblende. It has compositions between An_{10} and An_{35}. The more anorthitic plagioclase shows distinct Albite twinning but the more albitic plagioclase is often devoid of twinning. The albitic plagioclase contains minute flakes of sericite. Clinozoisite is also abundant in these amphibolites. The clinozoisite is no doubt secondarily formed.

Quartz is a minor constituent in the amphibolites. It occurs as small xenomorphic to slightly rounded grains. The quartz shows little or no undulatory extinction. Plagioclase and quartz together do not exceed 30—35 % of the rock volume. Quartz, plagioclase, and subordinate biotite also occur as distinct layers within the amphibolite. The layers are regarded as interstratifications. The conformable beds of the same composition and grain size as the surrounding gneisses found *in* the amphibolites, must be syngenetic with the amphibolitic material.

Titanite frequently occurs. Apatite was observed, though not in abundance.

Garnet from an amphibolitic lens near Kyrkesund has been investigated. The garnet has $n = 1.798$ and $a = 11.65$ Å which corresponds to an almandine-spessartine- dominated garnet.

An indication of a retrogressive metamorphism is the change of hornblende into brown biotite which was observed in some of the amphibolite inclusions in the migmatite area.

A low content of potash feldspar penetrating the grain boundaries between the light minerals is in some cases observed. This potassium metasomatism must have taken place after the crystallization of the hornblende.

Ore grains are extremely rare, except in the amphibolites showing the reactions hornblende → biotite. The ore seems to have been released during this reaction. In a few cases a network of rutile was observed in the hornblende. A chemical analysis was made on a representative sample of the amphibolite of Bockholmen 115.645 (Table 3). The contents of V, Cr, Co, Ni, and Ti have been determined on a sample from St. Dyrön (Table 4).

The results of these analyses give meagre hints on the genesis of the amphibolite. As a comparison an analysis of a similar amphibolite from Eastern Sweden is also given as well as an analysis of basalt. It is the average of 198 analyses.

The composition of the Bockholmen amphibolite is in accordance with the analysis of the average basalt (Table 3).

The trace-element content (in p. p. m.) of the amphibolite on St. Dyrön is given in Table 4. As a comparison trace-element analyses are given from other localities in Western Sweden.

Table 3. Chemical composition of amphibolite from the Tjörn area and as comparison that of an amphibolite from Eastern Sweden and the average composition of basalt

	Amphibolite Bockholmen 115.645	Amphibolite[1]	Basalt[2]
	% by weight		
SiO_2	49.12	50.20	49.06
TiO_2	0.96	0.84	1.36
Al_2O_3	14.65	15.02	15.70
Fe_2O_3	2.32	1.54	5.38
FeO	10.20	7.98	6.37
MnO	0.22	0.08	0.31
MgO	7.54	8.22	6.17
CaO	10.35	9.43	8.95
Na_2O	2.12	2.06	3.11
K_2O	0.80	2.12	1.52
H_2O tot.	1.52	2.11	1.62
P_2O_5	0.09	0.16	0.45
	Niggli values		
al	19.7	20.9	22.2
fm	49.3	47.4	45.3
c	25.3	23.9	23.0
alk	5.7	7.8	9.5
si	112	119	118
k	0.19	0.40	0.24
ti	1.6	1.4	2.4

[1]) Sundius 1938, p. 50. [2]) Rankama-Sahama 1950, p. 159.

Table 4. Trace elements in amphibolite from the Tjörn area and from other amphibolites in Western Sweden

Locality	Contents in p.p.m. of				
	V	Cr	Co	Ni	Ti
St. Dyrön 18.60	480	76	63	36	5 400
Gottskär[1]		10	40	50	
Smål. Taberg[2]	400	300	50	60	
Varberg[3]	280, 440	200, 300	30, 40	90, 110	9 000, 14 400

[1]) Lundegårdh 1953, p. 55. [2]) Hjelmqvist 1950, p. 48. [3]) Quensel 1951, p. 331.

In the sample from St. Dyrön no ore grains were observed — thus the analysed trace elements must exist in the mafic minerals of the amphibolite — mainly in the hornblende lattice. The titanium content is rather high, but can be explained by the possible presence of minute submicroscopical rutile needles in the hornblende.

DISCUSSION ON THE ORIGIN

The trace elements can perhaps give us a clue to the origin of the amphibolite, but before discussing them we turn to the geological and petrological indications of the genesis, because these indications seem to be more conclusive of the genesis than the chemical indications.

Lundegårdh (1953 a) describes amphibolitic rocks found south of Gothenburg of similar appearance and mineralogy as those in the Tjörn area. Lundegårdh says that before the orogenesis, which gave the amphibolitic rocks their present features, they "displayed concordant beds of basaltic lava, tuff and tuffite" (p. 14). In a paper on the petrology of the Gothenburg—Kungälv region Lundegårdh later (1958) expresses the same ideas of the genesis of the amphibolites occurring within the Stora Le-Marstrand series. Freely translated Lundegårdh says, "It seems probable that many of the banded metabasitic rocks once were volcanic ash layers interstratified with arenitic and argillitic sediments" (op. cit., p. 33). But before reaching this conclusion Lundegårdh admits that minor parts of these rocks could have had another origin (p. 31). Possibly they formed dolomites and impure limestones before metamorphosis (op. cit., p. 32) though he mainly restricts this genesis for the ultra-basic xenoliths which are found in the migmatite.

From Merrimac, California, Hietanen (1951) describes amphibolites which, in occurrence and general appearance, are very similar to those in the Tjörn area except in one respect: the Merrimac amphibolites contain marble lenticles (p. 576). Hietanen considers that "these amphibolites most likely represent marly layers in the sedimentary strata" (p. 577). A similar mode of origin is proposed by Härme (1954) on a similar carbonate-bearing amphibolite from the Mustio area in Southern Finland. Härme has also described an amphibolite interstratified by quartz-feldspar strata. In this amphibolite carbonatic minerals are absent. Härme regards this rock as being of volcanic origin. They are volcanic ash sediments deposited in water. The quartzo-feldspathic layers represent weathering products deposited contemporaneously with the ashes (p. 37).

According to these examples, amphibolites may originate from calcareous sediments and from tuffaceous beds — the most obvious origin from mafic sills not being mentioned. The presence of carbonatic layers in the amphibolites is conclusive for the origin. Intercalations of marble are not found in the area but carbonatic sediments are not completely unknown in the Stora Le-Marstrand series. Lundegårdh (1958) reports the occurrence of marble within this series in the northern part of its extension (p. 32). As mentioned earlier in this paper the skarny layers on e. g. the island of St. Äggelös containing clinozoisite and garnet, are believed to represent carbonate-rich strata in the generally sandy-clayey sediments.

The amphibolites so frequently encountered within the Tjörn area are, however, not regarded as being primarily marly sediments. In accordance with Härme (1954) and Lundegårdh (1958) the amphibolites in the Tjörn area are believed to represent volcanic ashes deposited in water. If the amphibolites are of volcanogeneous origin the similarity in composition to the basalt is to be expected (cf. Table 3) even if the amphibolites were volcanic ashes. The close similarity between the analyses of the amphibolite and the average basalt shows that if the amphibolites were ashes they have sedimented not far away from the place of the volcanic outburst. Aeolic differentiation (Larsson 1935) has not been active. The conformable quartzo-feldspathic strata observed in the amphibolites represent sediments of the same kind as those described in earlier chapters. The deposition in water is in agreement with the conclusions reached on the origin of the gneisses.

Are these results confirmed by the trace-element determinations?

The amphibolite of Gottskär is of the same type as that of St. Dyrön. Lundegårdh (1953 a) has found that it is of volcanogeneous origin. Hjelmqvist (1950) has found that the amphibolite of Smålands Taberg is a metamorphic intrusive. Quensel (1951) is of the same opinion concerning the analysed amphibolite from Varberg. The analyses can therefore be divided into two groups — those originating from volcanic ashes and those of intrusive-magmatic origin. In the latter group magmatic differentiation has been active — certainly at Smålands Taberg (Hjelmqvist 1950). A high content of chromium is characteristic of these "magmatic" amphibolites as chromium, — according to Goldschmidt, Rankama-Sahama, and others — is enriched in early differentiates. As seen in Table 4 the chromium content of the St. Dyrön amphibolite is a fourth of that in the amphibolites of Varberg and Smålands Taberg regarded as magmatic.

Extremely high chromium contents may possibly prove a magmatic origin, but low or moderate chromium contents are not proofs of a non-magmatic origin. Icelandic basalts are very low in chromium (Lundegårdh 1949) but their magmatic origin is beyond doubt.

CONCLUSIONS

Petrographical and chemical data give little information on the genesis of the rather monotonous amphibolites, but geological data and the interstratifications give indications on their origin. It is regarded as most plausible that the amphibolites are metamorphic derivatives of volcanic ashes of basaltic composition. It is not excluded that some of the amphibolites were true basaltic beds.

CHAPTER 5

Hornblende porphyroblasts

On the islet of Bockholmen 117.645 two amphibolite bodies occur. The northern one is, in parts, well exposed by a roadcutting. In the amphibolites there are lensoid inclusions of a white, fine-grained, feldspar-quartzitic rock.

These inclusions are interstratifications (as mentioned above p. 24) and their lensoid shape is due to deformation. The deformation is a tension parallel to the main planes of foliation (which coincide with the planes of sedimentation). The tension caused boudinage of the more brittle rock units. When amphibolites and felsic rocks are intermingled as here the latter are the more brittle and are thus deformed. One of the felsic boudins is seen in Fig. 11. The dominating grain size of plagioclase and quartz is 0.2—0.4 mm. Plagioclases with a maximum content of 35 % anorthite make up 60 % of the rock volume. Undulatory quartz with subrounded boundaries constitutes the rest except for a small quantity of beautifully wedge-shaped titanite. The plagioclases are partly secondarily altered and they contain sericite and clinozoisite. There seems to be all gradations from extremely altered to completely fresh plagioclases.

The described type of felsic rock is by no means extreme neither in the area nor as interstratifications in amphibolite. But the remarkable fact is the occurrence of up to 20 mm long and 5—8 mm broad laths of black hornblende, Fig. 12. As seen in Fig. 11 there is a significant enrichment of the hornblende crystals along two zones parallel to the borderlines of the felsic boudin. When microscopically examined it becomes evident that the feldspar quartzite is penetrated by zones of crushing following the foliation. The hornblende, which megascopically looks like homogeneous crystals, is under the microscope proved to be very heterogeneous. 50 % of the apparent hornblende volume is, instead, subrounded undulatory quartz and fresh plagioclase.

When hornblende and strongly altered plagioclase are in contact with each other, hornblende seems to attack the plagioclase by using the direction of the small sericite grains orientated parallel to the formerly existing plagioclase lamellae as paths for the solutions carrying the replacing hornblende matter.

The observations related give a clue to the formation of the hornblende porphyroblasts in the feldspar quartzite: dilatational deformation — probably of later age than the tensional deformation forming the felsic boudins — opened cracks and crush zones mainly parallel to the planes of schistosity. These cracks may, in some part, have affected the secondary alteration of the plagioclases. They were also the paths of access for the solutions forming the secondary hornblende. Hornblende could only crystallize where plagioclase was completely altered. Hornblende replaced some of these plagioclases and, as a secondary effect, the quartz grains adjacent to the positions of replacement were enclosed by the growing hornblende "skeleton". It is presumed that the components necessary for the formation of hornblende porphyroblasts were derived mainly from the adjacent amphibolite beds but also from the secondarily altered plagioclases.

From the Mölndal—Styrsö—Vallda region south of Gothenburg Lundegårdh (1953 a) describes quartzite-sandstones with penetrative columns of secondary hornblende (op. cit., p. 22). Here Lundegårdh writes, "... the formation of horn-

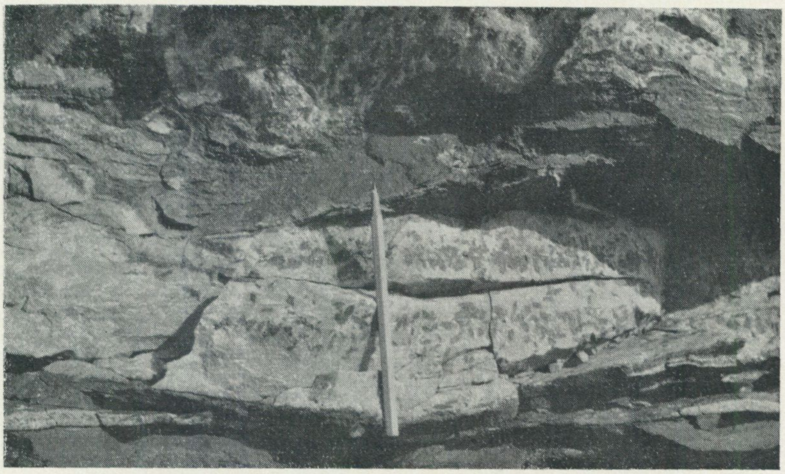

Fig. 11. Feldspar-quartzitic boudin with secondary hornblende porphyroblasts. Bockholmen 116.646.

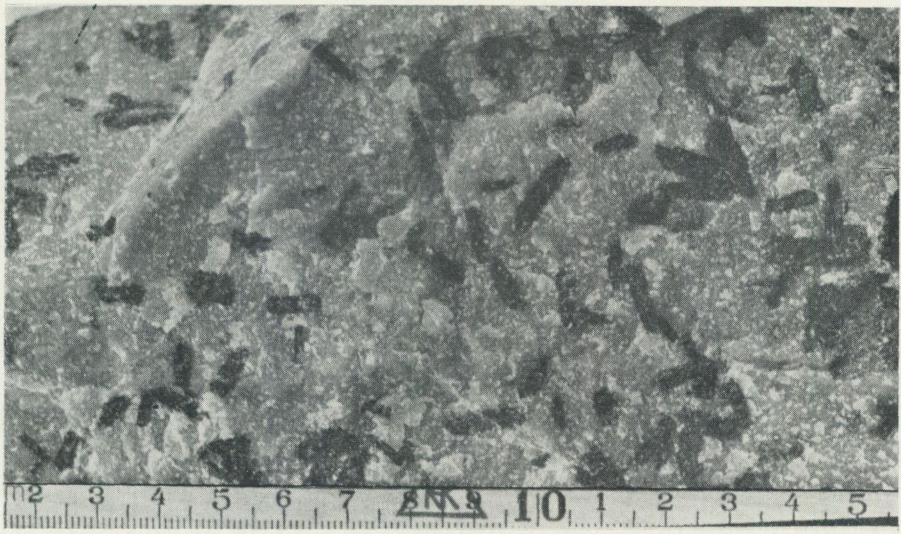

Fig. 12. Detail with hornblende porphyroblasts. Bockholmen 116.646.

blende has started from faces that are at the same time planes of stratification and schistosity. The number of hornblende columns is still highest along these faces. Furthermore, . . . the formation of hornblende is dependent on the presence of basic volcanics in the close vicinity of the quartzite-sandstone rock. From the volcanics, magnesium and iron have been introduced along the mutual planes of stratification and schistosity. Metasomatic reactions have then taken place" (pp. 22—23).

An obvious similarity between the two secondary hornblende occurrences described is that the secondarily introduced matter forming the hornblende lattice is regarded to have used the existing planes of stratification (Lundegårdh) or destruction (as on Bockholmen) as access routes to its present position in the hornblende porphyroblasts.

Chapter 6

Ultra-mafic rocks of peridotitic character

Within the area investigated three smaller bodies of maximum length 100 m and a width of 25—40 m occur. Their composition is meta-peridotitic. Sometimes they have a more or less pronounced soapstone character. They all occur within the eastern gneiss area. On the map they are marked PER. The small meta-peridotitic body near the eastern map boundary at point 367.667 is well exposed. The gneiss softly envelopes the dark green massive ultra-basite. The surrounding gneiss shows evidence of plastic flow. The contacts between the ultra-basite and the gneiss are conformable. At this locality, where contacts can be studied very well, all observations indicate that the ultra-basite occurs as a solitary xenolith in the gneiss. The ultra-basite on the island of Brattön cannot contribute to the contact relationships as overburden makes contact observations impossible. The massive hornblendite at 255.840 contains fragments of the gneiss in its border zone. This hornblendite only consists of grammatite and its alteration products. The ultra-basic rocks show moderate schistosity near the contacts to the gneisses but are devoid of schistosity in their cores. On Brattön the ultra-basite is dark greenish gray on fresh surface — the weathered is rusty brown. Grain size in the non-schistose central parts is 5—10 mm and the main mineral is hornblende. In parts of the outcrop the rock is extremely tough and hard. In other parts it has been used because of its soapstone character. There it is soft and light gray. Grain size is 0.5—1 mm with remnants of 10 mm long dark amphiboles in the light matrix.

The peridotite of Aröd 367.668 is, in places, of a dark greenish colour and contains hornblende. The optical properties are: extinction c/x 21°, $2V_x = 84°$ $n_x = 1.610$, and $n_z = 1.633$. These data agree with the optical characteristics of grammatite — the calcium-magnesium-dominated member of the actinolitic hornblendes. The hornblende crystals are 1—4 mm in diameter. No preferred orientation is observed. In other parts of the small ultra-basic body, strong secondary alterations may be observed. The same type of hornblende as described above is found as relicts in a mass of secondary minerals (Fig. 13). Among these antigorite occurs in equal amounts as optically positive penninite. Calcite and talc are found as minor constituents. Ore grains of magnetite and chromite are scattered over the investigated thin-sections, though a slight tendency to

Fig. 13. Mesh of antigorite, penninite, and talc in peridotite. Aröd 367.668. Nic. +. 25×.

collect in groups is observed. From Brattön Ljungner (1927) reports a coarse-grained hornblende peridotite consisting mainly of colourless hornblende with relicts of olivine. The olivines have $2V_x = 85°$ and thus they correspond to chrysolite with a fayalite content of 20 %. The olivine is considerably altered; the cracks are filled with ore grains and secondary silicates such as serpentine and talc. The core of the peridotite lens on Brattön is monomineralic and of the same hornblenditic composition as the lens at Aröd. The observations on the peridotites indicate that, before the retrogressive metamorphism which is specially observed in the marginal parts of the bodies, they contained olivine and hornblende which in part is uralitic. Retrogressive metamorphism is responsible for the present mineralogical composition. The successions of minerals are:

Olivine + Pyroxene and Hornblende → Serpentine + Chlorite →
→ Talc + Carbonate.

DISCUSSION ON THE ORIGIN

The genesis of this type of rock is a matter of controversy. In his paper on the composition and origin of soapstone, Wiik (1953) gives a review of the different modes of soapstone formation. Though the peridotites in the present area are not soapstones *sensu stricto*, Wiik's investigation is still of great interest and in part applicable to the small peridotites of the Tjörn area. As a first group Wiik mentions soapstones formed by decarbonatization and silicification of sedimentary, mainly dolomitic, rocks. The formation of talc from dolomite necessitates the introduction of silica and water. If the reaction

Dolomite + Water + Silica → Grammatite + Calcite + Carbon dioxide

takes place, there is an increase in volume. According to Wiik the increase amounts to 11.4 % (p. 34). This fact is of great importance in the coming discussion on the contact relationships.

The second main group of soapstones are those formed by secondary alterations of ultra-basic igneous rocks. This reaction also needs silica, but, where ultra-basic rocks are enclosed by schists, gneisses etc., the silica can be provided from these rocks, and be metasomatically introduced into the ultra-basic rocks. Even this reaction could be connected with an increase of volume (op. cit., p. 41).

Leaving the main problem of the genesis of the primary material aside, we turn to the schistosity observed in the marginal zones of the peridotite lenses. This schistosity is explained by the increase of volume which took place when the secondary minerals were formed. As Wiik points out (op. cit., p. 41) the schistose texture "seems to indicate that these soapstone bodies have not been left unaffected by the tectonical events in the area." It is possible that continuous tectonical movements opened access routes for silica and water. Those components caused the serpentinization observed in the marginal zones especially on the lens on northern Brattön. The observations prove the interdependence of metamorphism and deformation.

In recent literature the formation of peridotites and serpentinites with talc is, in several cases, attributed to metasomatic changes of impure calcite-dolomite rocks (Mortensen 1945, Engel 1949, Sörensen 1955). These authors believe that they have found proof for the metasomatic type of formation of peridotites and serpentinites out of dolomites.

Sörensen (1955) suggests that the "the peridotites were formed in calcareous and dolomitic sediments where these rocks were subjected to stress of a high order" (op. cit., p. 103). This seems to coincide with the observations on peridotites along zones of strong dislocation (Hess 1955).

Rosenqvist (1946) was of the same opinion as Sörensen concerning the formation of peridotites (GFF, vol. 68, p. 483). His opinion was strongly opposed by Kolderup, Asklund, and Du Rietz (op. cit., pp. 482—484) who regard the peridotites as magmatic formations.

In connection with the olivine-bearing peridotites it is also important to observe the occurrence of olivine in carbonatic rocks. This is common textbook knowledge (see Hurlbut 1959, p. 401) and is reported, among others, by Sörensen (op. cit., p. 96). The olivine found as relicts in peridotites could be olivine primarily formed in the same way as those observed in the sedimentary carbonatic rocks.

The ideas of Avias (1949) concerning the peridotites and serpentinittes on New Caledonia are briefly reviewed here. The primary rock is an andesitic lava with a high content of glass. This glass, which is readily reacting, was the primary rock out of which the peridotite-serpentinites were formed. The glass-containing volcanite was subject to metasomatic processes (below 500° C) leading to a concentration of mainly metallic ions — among which magnesium dominated. Avias gives the following rather unconvincing scheme:

$$\left.\begin{array}{l}\mathrm{Cr}\\ \mathrm{Mg}\\ \mathrm{Ni}\\ \mathrm{Co}\\ \mathrm{Fe}\end{array}\right\} + \begin{array}{l}\text{Rocks of volcanic}\\ \text{origin interstratified}\\ \text{by geosyncline sediments}\end{array} = \begin{array}{l}\text{Greenstones}\\ \text{Serpentinites}\end{array} + H_2O + SiO_2$$

Before touching upon the possible ways of formation of the ultra-basic rocks investigated at Aröd and on the island of Brattön, the contents of some of the trace elements are given here.

Table 5. Trace elements in peridotites

Locality	Contents in p.p.m. of				
	V	Cr	Co	Ni	Ti
Peridotite, Brattön	130	4 000	130	1 300	1 500
Peridotite, Aröd	110	3 200	140	1 200	1 320
Dunite, Garaball Hill[1]		3 000	300	1 000	

[1]) Nockolds and Mitchell 1948, p. 538.

As a comparison the contents of Cr, Co, and Ni in a dunite from Garaball Hill are given. This dunite is interpreted as an early magmatic differentiation product (Nockolds and Mitchell 1948, p. 533). The similarity in trace-element

3—630230

distribution tempts one to consider the ultra-basites of Aröd and Brattön as similar formations. Disappointingly the author has not found any trace-element analyses of peridotites which are interpreted as metasomatically changed dolomites in previous studies. Concerning the ultra-basic rocks in the Tjörn area the following ways of formation are possible:

1. Metasomatically changed dolomites might possibly give a mineral distribution as that found in the investigated peridotites. The trace-element distribution would then be explained as a metasomatic enrichment of elements which occur in the surrounding sediments. The migration and accumulation of the elements — mainly the ferrides as defined by Landergren 1948, p. 12 — could possibly have been caused by thermal and chemical gradients. Tectonical forces could have influenced the formation, too.

2. Both mineral composition and trace-element content *can* also be explained by orthodox magmatic interpretation, though geological data such as contact relationships and general environment do not favour this interpretation. One exception, however, is the hornblendite on Tjörn at 255.840 which due to the gneiss inclusions is regarded as magmatic, though the "swelling" during retrogressive metamorphism could have contributed to the brecciation, too.

An evaluation of the different data does not give sure indications in any direction as to the genesis of the peridotite lenses. No relict interstratifications indicating a sedimentary origin of the peridotite as carbonatic or other sedimentary rocks are found in the ultra-basites, nor do the contacts provide arguments in favour of a magmatic origin. Possibly the present bodies are boudins of a primary sheet of magmatic origin, but there is no proof of this either. The author is of the opinion that sufficient data, enabling a positive interpretation of the origin of the peridotites in the area. do not yet exist and can hardly be provided from these small and only partly exposed bodies.

However, retrogressive metamorphism is well documented in the peridotites. The present mineralogical composition with mainly phyllosilicates indicates a low facies, lower than the neighbouring gneisses. Differences in metamorphic facies of peridotites and their enclosing bedrock may often be observed. Serpentinites and soapstones often occur in rocks of low-or high-gneiss facies. Foslie (1931) discusses this matter and suggests that this lower facies in the meta-peridotites is due "to the special sensibility of the magnesian silicates to changes of temperature and pressure, and their tendency to hydration. It might be compared with an extended retrogressive metamorphism (diaphtoresis). When diaphtoresis is not a universal phenomenon, the reason is that the velocities of the readjustment reactions decrease very rapidly with the temperature, and are generally induced only by the aid of violent tectonic movements. For the magnesian silicates we must suppose, that this velocity has not decreased so rapidly, but the readjustment could continue to lower temperatures than elsewhere" (op. cit., p. 227).

In the case of the Brattön peridotite the readjustment has not reached the point where olivine has completely disappeared.

CHAPTER 7

The migmatite area on western Tjörn

As already pointed out in the introductory chapter, western Tjörn consists mainly of migmatites. On the map that rock type has the same yellow colour as the sedimentary schists and gneisses on eastern Tjörn. But the colour is more saturated. The author's opinion on the origin of the migmatite is that it is primarily the same type of rock as that occurring in the gneiss area in the eastern part of the mapped area, but more highly metamorphosed. For this reason the colour on the map is the same but of a more intense shade, indicating the higher degree of metamorphism.

FIELD RELATIONS

The migmatite, generally gray of different shades depending on varying contents of mafic minerals, is met with west of a line Klövedal 15.85 — Bleket 12.65 and on the islands of Marstrand, Koön, and Instön near the southern boundary of the map. The strike of the migmatite is mainly N to N 70° E. The general trend of the dip is easterly, thus coinciding with the dip of the fine-grained gneisses at their western boundary at e. g. Kållekärr and Kuballe. The dips in the migmatite area are, however, very steep.

The map shows the main constituents of the western area: Migmatite with pegmatitic veins, amphibolite inclusions, and light gray granite. The two latter groups give the key to the first type of rock. The amphibolite inclusions belong to the paleosome — the gray granitoid rock constitutes part of the neosome, the two together forming the migmatite. The close connection between the migmatite and the sedimentary gneisses is obvious in the southeastern part of the investigated area where the gneisses show a gradational contact against the migmatite. The migmatite on western Tjörn and the migmatite found in the archipelago west of Tjörn have no connection with the eastern gneiss area in the present surface, but observations in the field suggest that the gneisses on the eastern part of Tjörn have had a continuation westwards in an anticline. The western limb of this anticline had an easterly dip and reached the present surface mainly along the line Klövedal—Bleket. The observation of graded bedding in a feldspar-quartzitic paleosome in the migmatite on a small islet 060.633 shows that the present easterly dip in this locality is an inversion of the strata. This observation is not conclusive, but in connection with observations concerning the granitoid rocks in the central parts of Tjörn, it seems probable that the gneisses and the migmatite formed an anticlinal fold (see Fig. 53).

The best preserved paleosome in the migmatite consists of extremely felsic and mafic rocks. The intermediate types seem to offer the least resistance to

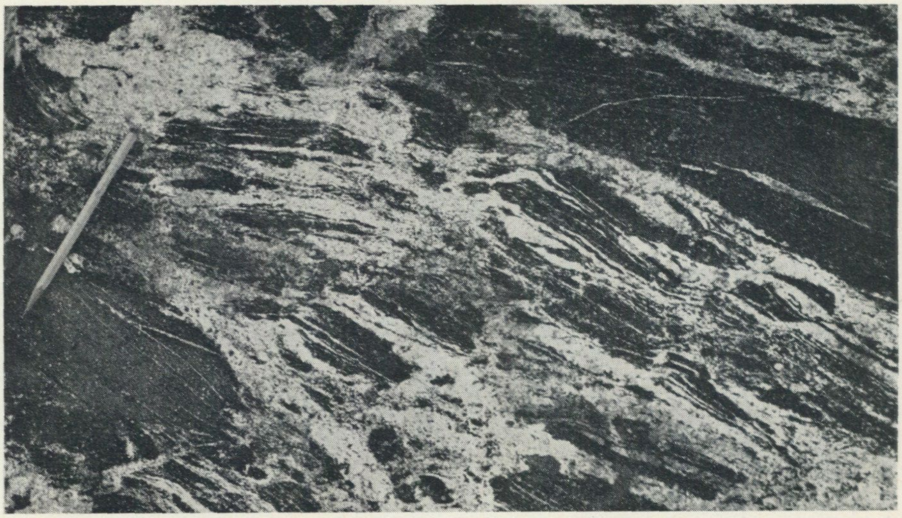

Fig. 14. Amphibolite-gneiss penetrated by granitic matter. Hallsbäck 083.884.

migmatitization. As mentioned above quartzites occur in the migmatite. The feldspar quartzite on Bockholmen is one of the paleosome types frequently encountered. On the islands of Koön and Marstrand there are pure quartzite lenses in the migmatite. The amphibolite, however, is the most spectacular paleosome constituent. The amphibolite within the migmatite does not differ much from the same rock occupying large areas outside the migmatite. Such an area is the island of St. Dyrön. The amphibolite inclusions in the migmatite

Fig. 15. Veined gneiss. Aröd 36.68.

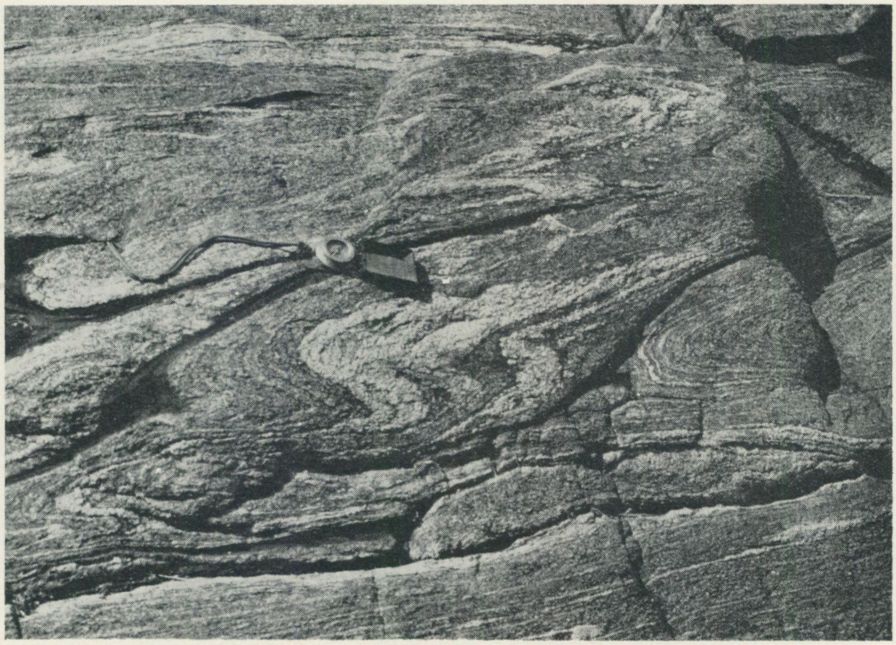

Fig. 16. Veined gneiss. Toften 122.678.

Fig. 17. Migmatite. Nordvik 102.725.

Fig. 18. Pods of neosome in migmatite. Viks Ödegärde 085.845.

are a little coarser than the amphibolites in the eastern part of the mapped area — and very often the inclusions have a biotite-rich border zone. The inclusions of amphibolite vary in size from a few centimetres up to several kilometres as on the islands southwest of Skärhamn. The amphibolite inclusions are often boudinaged or strongly penetrated by felsic neosome, Fig. 14.

The intermediate rock types constitute the main bulk of the migmatite. Figs. 15 and 16 show veined gneisses with felsic neosome accumulating along the S-surfaces of the metamorphic paleosome. Fig. 17 shows a more complex state when the neosome and the paleosome are intermingled. Fig. 18 finally shows pods of neosome without the close connection to the paleosome. In this case the neosome has an augen texture. Around point 12.74 east of Skärhamn the migmatite has a nebulitic character and is, contrary to the rest of the migmatite, pale red. At this locality there is a gradational transition between the nebulitic migmatite and the more ordinary migmatite with easily distinguishable relicts. The migmatite west and northwest of Klövedal shows some interesting deviating features compared to that east of Skärhamn. Here there are often sharp contacts between the neosome and the paleosome. There are also gray, medium- and even-grained, granitic dikes cutting and winding through the migmatite. The amphibolitic inclusions are here extremely brecciated (Fig. 14). This is not the case east of Skärhamn. These conditions are not easily visualized in a map on this scale, but the difference between the two areas is anyhow seen in the presence of granitic beds northwest of Klövedal.

The brecciated amphibolite, the granitic dikes, and the neosome which now occurs in secondary positions — all these features most easily can be explained by postulating an intense tectonization in the northern area causing a re-deposition of the mobile components (neosome, anatexite) and a rupture of such brittle components as the amphibolite. In the southern area conditions were more calm, allowing the mobile and the less mobile components to remain together thus forming the migmatite with nebulit icgneiss schlieren in a granitoid matter. In many cases it is impossible to maintain the distinction between paleosome and neosome because of the feldspar metablasts, which in places constitute 30—40 % of the rock volume. In the early stages of metablastesis it is still easy to recognize the primary gneiss material, but in more advanced stages the paleosome is gradually transformed into neosome, due to mobilization and formation of feldspar metablasts. The early stages of this alteration can especially well be studied between Klövedal and Hallsbäck 09.88. A general observation on the metablasts is that they tend to become idiomorphic and that their long diagonal coincides with the plane of schistosity in the exposed section through the crystal.

PETROGRAPHY OF THE MIGMATITES

The fine-grained relicts in the migmatite of identical appearance as the eastern gneisses have also a mineralogical composition, identical to that of the fine-grained gneisses. Volumetrical analyses of the fine-grained relicts gave: Undulatory quartz 22—54 %, potash feldspar 0—10 %, plagioclase (An_{20-37}) 20—40 %, biotite 10—25 %, muscovite, epidote, garnet a. o. From the volumetrical analyses it is clear that the most fine-grained inclusions (average grain size 0.2 mm) in the migmatite are plagioclase-dominated. Those with the highest plagioclase content are nearly devoid of potash feldspar.

When the grain size increases, the potash-feldspar content also increases. This is still more obvious when the granitic-pegmatitic neosome is considered, because in these rock types with a grain size exceeding 1 mm the potash-feldspar/plagioclase ratio is 5: 1 or higher. The plagioclases hold 25—37 % anorthite; the average value approximately 27—30 % anorthite. As seen by a comparison with the gneisses, the anorthite contents of the plagioclases in the migmatites are less schattered,

During the first stages of metamorphism leading to migmatite, the plagioclases seem to accumulate — first into aggregates of several crystals and as a secondary effect these aggregates recrystallize into larger crystals adopting hypidiomorphic or idiomorphic forms. They are seldom more than 10 mm in cross-section. During this recrystallization some of the adjacent rounded quartz grains have been incorporated in the plagioclases and are now found as rounded, moderately undulatory inclusions. Phemister et. al. (1960) have remarked that during plagioclase metablastesis grains of quartz and mica are incorporated,

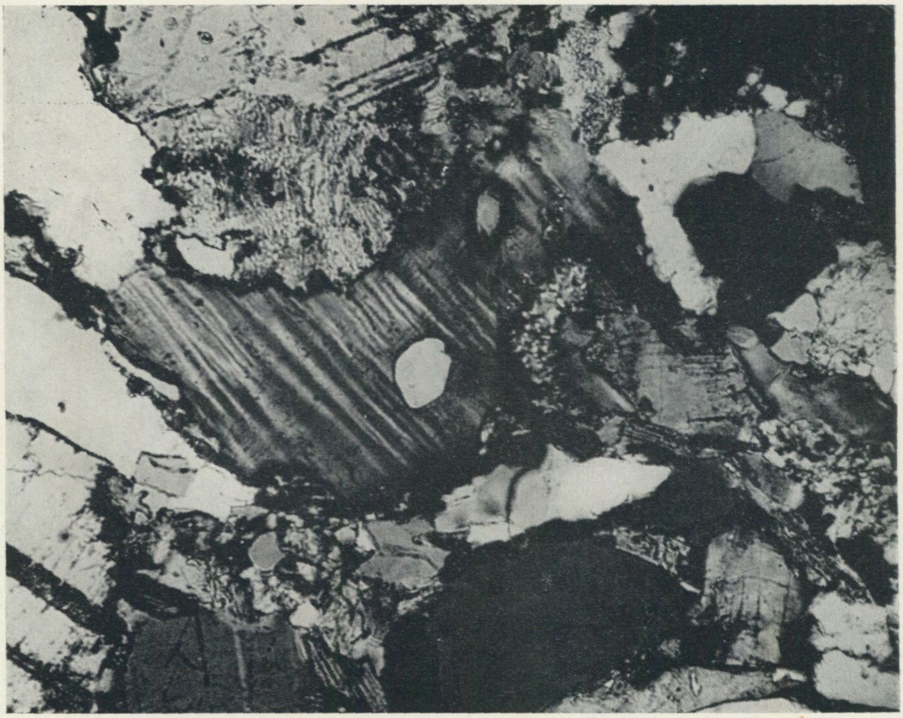

Fig. 19. Quartz relict in new-formed microcline. Klövedal 165.858. Nic. +. 40×.

and thus the plagioclase is poikiloblastic (p. 357). Other quartz grains were forced aside and became strongly undulatory. The anorthite content of the plagioclase metablasts is remarkably constant at 25—28 % No zoning is observed in the plagioclase metablasts. The largest metablasts are found in the biotite-rich strata. They are enveloped by biotite, which is curved around the feldspars. The long axis of the metablasts coincides with the plane of the schistosity. Thin-sections do not give any information on how the transportation of matter necessary for the formation of the metablasts has occurred, but it seems that it has been very short.

The next stage in the evolution of the plagioclases is the formation of minute sericite grains inside the crystals. Only exceptionally one can find sericite grains at the boundaries of the plagioclase. There is a formation of very small amounts of calcite inside the plagioclase as well. No epidote minerals seem to be formed during the sericitization. The anorthite content drops down to 8—15 % in the sericitized plagioclases. The sericitization does not affect all the plagioclases. In thin-sections some plagioclases are observed showing strong secondary alteration, while others are completely unaltered.

Microcline is a minor constituent in the paleosome but in coarser parts of the migmatite the amount of potash feldspar increases. The K-feldspars are, in

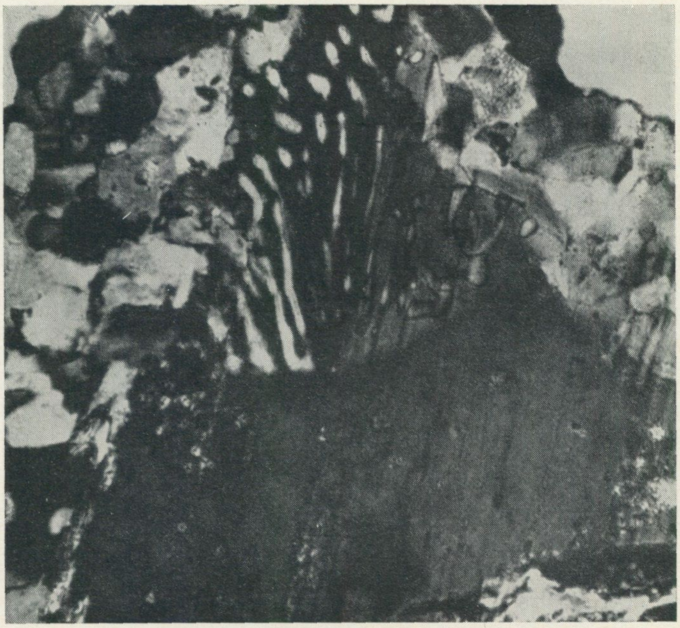

Fig. 20. Myrmekite textures where potash feldspar replaces plagioclase. Klövedal 120.852. Nic. +. 130×.

all the investigated rock types, the last crystallized mineral. They form irregular penetrative blebs, and fill interstices and narrow veinlets. When coming into contact with the plagioclase the aggressive character of the potash feldspar is always evident. The K-feldspar penetrates and replaces the plagioclase. When the process is not completed, remnants of plagioclase are found within the new formed, cross-hatched microclines. An indication of this process is the formation of myrmekite quartz in a border zone between the plagioclase and the potash feldspar (Fig. 20).

The angle 2V has been determined in the interstitial and corrosive microcline in the paleosome, and in the larger cross-hatched microclines in the neosome. There is evidently a peak in the frequency of the 2V-values at about 85° (18 determinations) in the interstitial, corroding microcline. In the neosome, nearly devoid of plagioclase, the 2V-values in the microcline are slightly lower — the medium value being 81° (10 determinations).

Biotite is the most important mafic mineral.

Garnet has n = 1.792 and a = 11.58 Å. These data correspond to an almandine—dominated garnet.

DISCUSSION ON THE ORIGIN

A general survey of the migmatite problem actually touches upon many controversial problems of petrology. It is not the intention to treat all these problems. A brief survey of the questions raised by the migmatites is anyhow necessary. In previous works on the Stora Le-Marstrand series both Lundegårdh (1953 b, p. 18 and 1958, p. 30) and Larsson (1956, p. 13) stress the plagioclase dominance in the veined gneisses (which correspond to the migmatites in the present area). In the areas investigated by Lundegårdh and Larsson, there are no examples of plagioclase metablastesis such as those found on northwestern Tjörn, but still this phenomenon is well known in literature dealing with other areas. In papers on Schwarzwald Mehnert (1940) and Hoenes (1948) described plagioclase metablastesis and considered it to be a recrystallization without an external supply of matter. In a later paper Mehnert (1957) suggests that the transport length of the plagioclase matter which formed the blasts is not more than decimetres or centimetres (op. cit., p. 51). In the same work Mehnert mentions that the plagioclase porphyroblasts are bigger in the biotite-rich layers, an observation identical with the behaviour of the plagioclase porphyroblasts on Tjörn. The fixation of metablasts in the tectonical S-surfaces, with a preferred orientation, is commonly observed. Rosenqvist (1943) deals with the formation of porphyroblasts in gneisses (op. cit., p. 171). He regards the blasts as post-tectonic. When they grew in the tectonized rocks the resistance against crystal growth was higher perpendicular to the schistosity and lower parallel to it.

The plagioclase blastesis is also treated by Misch (1949). Sandy and silty shales and fine-grained sandstones, comprising Mesozoic marine sediments in Yunnan, China, contain closed "socks" of granite. The strata which contain these socks are undisturbed. The metasomatic processes which culminated in the formation of granite were carefully followed by Misch. He found proof of a metasomatic formation of metablasts of plagioclase, potash feldspar, and quartz. The formation of plagioclase porphyroblasts needs an addition of sodium from a source outside the sediments, because the normal, quartzose-argillaceous sediments do not contain the necessary amount of sodium (op. cit.). Misch does not consider trapped saline pore solutions as a possible source for the sodium needed. This simple way of solving the sodium problem is (according to Mehnert 1959, p. 149) proposed by Shand 1943 and Gaertner 1951. Thus far we have been confronted with two main ideas concerning the Na-sources: 1. The sodium required for the plagioclase blastesis was introduced from outside (Misch) and 2. sodium was present in the primary sediments as trapped saline pore solutions (Shand). Luckily our choice between these ideas is very simple due to the important work on experimental rock metamorphism done by Winkler and coworkers (1958—62). They have metamorphosed quartzose-illitic clay together with water under pressure conditions equivalent to a depth of 7—8 km and temperatures up to 800°. By changing minor constituents different types of anatectic melts were obtained. In one of the tests the NaCl-contents were changed systematically between 1.8 and 3.2 %. It is of special interest to observe the excellent correlation between the primary NaCl-content in the test matter and the albite content in the final metamorphic product (Winkler and v. Platen 1958, p. 99). In a recent paper Althaus and Winkler (1962) draw the geological conclusions of the experimentally found data: there can be a change between more or less albitic strata in a mica schist. The less albitic strata have been more dehydrated than the more albitic. The albite content is thus proportional to the captured amount of saline pore solutions in the primary sediment if acidity is low (op. cit., p. 177). According to these authors there is no need for a local supply of sodium from outside to the more albitic layers in the mica schist. The investigations on the salinity of pore solutions performed by von Engelhardt (1961) confirm Winkler's ideas. von Engelhardt shows that sodium is enriched in arenitic beds whereas the argillitic beds are impoverished of it.

We now return to the bedrock of Tjörn. Previous chapters proved the gneisses to be sedimentary (graded bedding) and marine (the boron content). These facts and the experimental data briefly presented above allow us to conclude tentatively that the sodium content in the plagioclases originates from captured saline solutions. During earlier stages of metamorphism the plagioclases accumulate and recrystallize as hypidiomorphic prophyroblasts, preferably in the S-surfaces. The plagioclase metablastesis is regarded as a concentration of the pre-existing plagioclase matter.

After the plagioclase blastesis a period of sericitization followed with a concomitant de-calcification of the plagioclases. Sericitization was caused by a minor introduction of potassium (Marmo 1955). The introduced potassium substitutes the sodium in the albite component of the plagioclase and potash feldspar is formed. Some of the potash feldspar is immediately transformed to sericite. But the new-formed K-feldspar can also react with the anorthite component then forming zoisite and muscovite. If zoisite is not formed, the calcium is expelled and forms calcite *or* it is captured in minerals in the close vicinity of the sericitized plagioclases. Such a new-formed mineral is the garnet frequently met with in the migmatites where potash feldspars dominate.

The sericitization is a first sign of potassium metasomatism. But the most conclusive signs of this metasomatism are the microcline in the interstices and the microcline attacking the plagioclase. Plagioclase remnants are found within the new-formed potash feldspar, indicating the secondary origin of the latter. Similar observations are reported in great amount in recent investigations. Hoenes (1941), in a paper on Schwarzwald, reported observations on how potash feldspars replace plagioclases. He says that the plagioclase "wird randlich angefressen" (op. cit., p. 206). Further, he observes that the plagioclase shows tendencies to be idiomorphic, whereas the potash feldspar, on the other hand, is always xenomorphic. From this he concludes a secondary supply of the microclines. In a paper on the schists of Tampere Seitsaari (1951) repeatedly stresses the mobility of potassium and the metasomatic increase of the potash content during metamorphism. He also observes undeniable cases of potash feldspar mainly replacing plagioclases. Simultaneously there was an increase of K and Si and a decrease of Fe, Mg, and Ca (op. cit., p. 17).

Ljunggren (1954) has observed a similar supply of potassium from outside causing a potash feldspathization (e. g. p. 97). The pre-existing plagioclases are frequently attacked by the secondary K-feldspars. Similar observations on the secondary supply of potash feldspar and its preference to corrode the plagioclases have been made on leptite rocks from Central Sweden by the present author in 1959 (pp. 650, 666).

The examples given enable us to conclude that 1) potash feldspar is extremely mobile, 2) the same feldspar is often replacing plagioclase. This phenomenon seems to be extremely common. Still there remains the question whether the potash feldspar is the result of a supply of matter from outside *or* a mobilization of pre-existing feldspars. Some of the analyses on the fine-grained gneisses (p. 16) from the Tjörn area show that their potassium content is low.

This favours the conclusions of an external source of the potassium. A general field observation is that the mobility of the migmatite increases with the increase of microcline and decrease of plagioclase.

TRANSVERSE GRANITIC DIKES WITHIN THE MIGMATITE

As mentioned above cross-cutting granitic dikes are frequent in the northwestern parts of Tjörn. Fig. 21 shows migmatite traversed by a gray, fine-grained granite dike. These dikes are seldom more than 20 to 50 cm in width. They can be followed up to 50 m in their winding paths through the migmatites. Two petrographically different types of dikes have been discerned. Megascopically they are very similar. One, however, is dominated by plagioclase, as for instance the dike found on Björholmen 06.88. The other type, represented by a specimen from a dike on the islet of Orskär (west of the area), has microcline as a major constituent.

Table 6. Mineralogical composition of granitic dikes

Locality	% by vol.					
	Quartz	Microcline	Plagioclase	Biotite	Muscovite	Accessories
Björholmen .	29	3	51 (An_{27})	11	5	1
Orskär . . .	45	23	20 (An_{15})	3	9	—

In the Björholmen type quartz is strongly undulatory. In the dike from Orskär the quartz only is slightly undulatory or non-undulatory. The potash feldspar fills up the interstices and attacks the plagioclases in the Orskär dike.

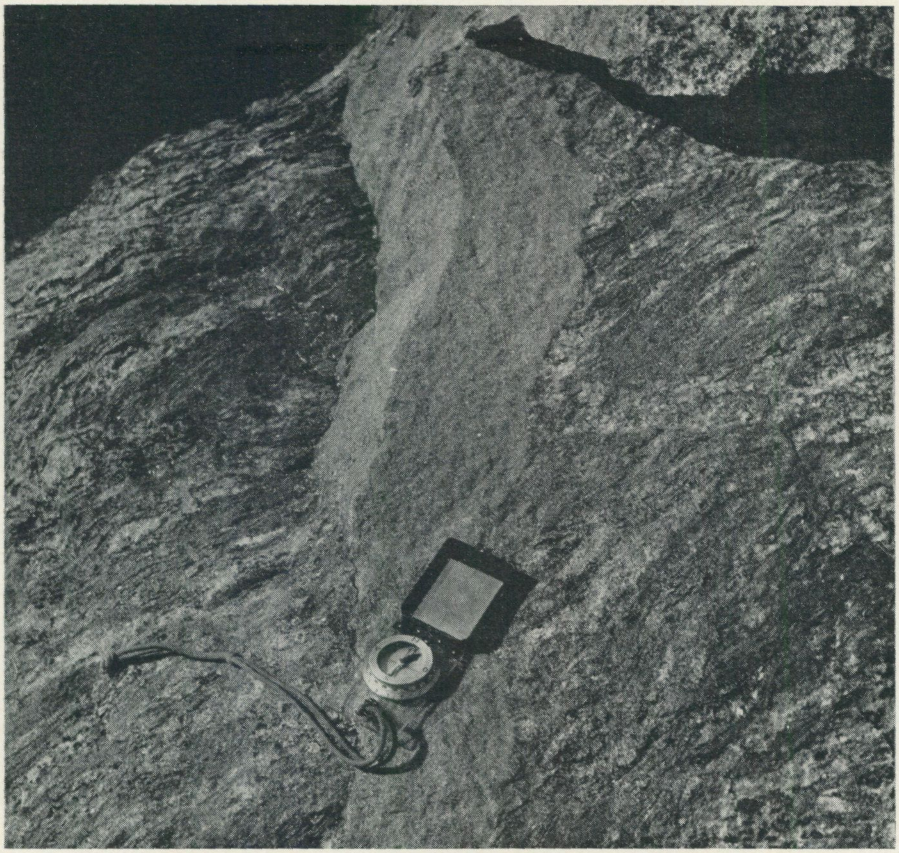

Fig. 21. Granitic dike in migmatite. Orskär.

A characteristic feature is the frequency of myrmekitic textures in this latter dike type, indicating metasomatic reactions. The myrmekite seems to follow the secondary introduction of the potash feldspar. Myrmekite does not occur in the Björholmen type. Another difference is the presence of chlorite secondarily formed from biotites in the Orskär type.

Transverse dikes in similar terrains are described by Lundegårdh (1958), in his paper on the petrology of the Gothenburg—Kungälv region. The dikes reported by Lundegårdh always contain microcline as an essential component, though the potassium-sodium quotient varies. The reason for this is, according to Lundegårdh, that the dikes were formed in an early stage when strong sodium concentrations still could occur locally (p. 69). Lundegårdh distinguishes three types of dikes in the migmatites. They consist of: 1) mobilized gneiss, 2) granite, 3) pegmatite. The two first types are easily separated from each other *inter alia* due to the higher content of microcline in the granite dikes compared to the dikes composed of "mobilized gneiss".

The two types of dikes described from the Tjörn area indicate that the difference in mineralogical composition is secondary. The primary composition of the dikes is very similar to the neighbouring gneisses, which also are plagioclase-dominated. Microcline is secondary both in the transverse dikes and in the gneisses transformed into migmatite.

The present author regards it as most probable that the dike matter is *sensu stricto* an anatectic part of the gneisses. This anatectic part or anatexite is now found in the narrow and irregular dikes in the migmatite. These dikes are found in areas characterized by ruptural deformation. When deformation took place, the most mobile part of the anatexite was squeezed into its present positions now forming the dikes. This premises that the bedrock was brittle and would not yield plastically to deformation. The present features of the bedrock in places where gray granitic dikes are found, support this conclusion. In these areas the bedrock was only subject to a plagioclase metablastesis, which is an initial stage of metamorphism, while the bulk of the rock was still semi-solid (NW Tjörn). Where the migmatite shows convincing features of once having been plastically deformed, as for instance east of Skärhamn, granitic dikes as those described above are absent.

The northwestern part of Tjörn, where plagioclase porphyroblasts and gray granitic dikes characterize the bedrock, possibly presents a metamorphism at lower temperatures than areas where deformation was plastic and consequently no granitic dikes were formed.

Chapter 8

Light gray granite

On the geological map the gray granite is shown brown. This type of "granite" is found in two main types of occurrences. The first type forms conformable beds in the gneisses and in the migmatite, with contacts against the latter indicating a non-intrusive origin. This type is found in the southern part of Hakenäset 30.75 and just outside the map area east of Rörtången and near Aröd 36.68. The second main type is clearly brecciating. It is found in the southern part of Tjörn and in the archipelago south of Kärrsö 21.62. Here it brecciates the amphibolite-gneisses.

Beside these two easily distinguished types there are also other occurrences of gray "granite" for example in the central parts of Tjörn: near Stenkyrka 20.80, east of Kållekärr 27.80, 29.80, on the small islands of Kaurö 01.85 and Skaboholmen 04.85. The gray granite in the migmatite is indicated on the map by the small brown pegs. The granite occurring at these localities cannot be classed as belonging to either of the two main types because here the granite shows features of both. It seems in some places to have been formed as an integral part of the surrounding gneisses, but in other places it has been mobile with minor emplacements. In some cases the rocks show a rather strong foliation. The microscopical investigation proved, in many cases, the rock to be a tonalite, though all transitions from granitic to tonalitic compositions exist. The term "granite" has been used in the map legend because the rocks treated under the present title often show a massive texture, and seem to have a granitic composition.

After this brief presentation of the rocks concerned, we shall study the different types in more detail and begin with the gray conformable beds in the gneisses as they might give a clue to the origin of all the types.

The thickness of the conformable beds varies from a few cm up to an estimated thickness of at least 35 m. Their colour is light gray. The grain size in the thin conformable beds is 1—2 mm. In the thicker beds the grain size increases to 3—5 mm and the texture becomes porphyritic due to the plagioclases which generally are bigger than the other minerals in the rock. Biotite is always present but in very different amounts. When foliation is present the biotite is orientated parallel to the contact surfaces, but in many of the small gray beds no preferred orientation was observed. Quartz is always found and garnet is not uncommon. In some cases there is a marked enrichment of biotite in the schists on the contacts to the conformable beds of gray granite. This enrichment of biotite does not occur along all contacts against the gray beds, and its frequency does not seem to depend on the thickness of the bed. For these reasons the conclusion is drawn that the zones of biotite do not imply that all the matter forming the gray beds was derived from the schists. (Compare the biotite enveloping the pegmatitic lenses described earlier.) The dark zone of biotite can be caused by a minor extraction of the light minerals from the schists. The gray granite/tonalite matter cannot be entirely explained in this way — especially as the beds contain some biotite, which is usually extremely immobile during such metamorphic conditions as those ruling the metamorphism of the surrounding gneisses.

The mineralogical composition of the conformable beds has been determined. The following table gives the constituents in per cent by volume.

Table 7. Mineralogical composition of "light gray granite" in conformable beds

Locality	% by vol.					
	Quartz	Microcline	Plagioclase	Biotite	Muscovite	Epidote Garnet
372.620 . . .	32	23	35	7	3	—
361.535 . . .	48	18	10	17	6	1
287.792 . . .	35	13	39	9	3	1
303.748 . . .	22	1	67	3	3	4

Concerning grain size there is a general trend: the plagioclases which have the composition 12-35 % An are generally two or three times the length of quartz and biotite. Quartz is generally strongly undulatory except for rounded inclusions of 0.1—0.2 mm in the plagioclases. Biotite is pleochroic in brown to light brown and partly altered to a green biotite. The potash feldspar is secondary and penetrates the interstices between other minerals. Plagioclase is strongly sericitized. The gray tonalite bed on Hakenäset shows an extremely high proportion of plagioclase which, however, is not so surprising. When microcline occurs, it replaces the plagioclase. Thus the sum of feldspars is important, and this should be kept in mind when comparing the different volumetric analyses.

The volumetric analysis from 287.792 was performed on a specimen from a 5 cm thick, conformable granitic layer in the fine-grained gneiss. This layer is boudinaged, indicating that it is a deformed interstratification rather than a granitic dike.

The photograph from Hakenäset (Fig. 22) shows fine-grained, dark, supracrustal inclusions in the gray, slightly foliated, tonalitic matter. All the inclusions have the same dip and strike as the gneisses below and above the bed. The Hakenäset bed shows no microscopical features indicating a magmatic origin, such as idiomorphic and zoned plagioclases. The features in Fig. 22 could be explained in three ways:

1. The light plagioclase rock was mobile and brecciated the supracrustal formation during the emplacement. The emplacement took place very slowly during simultaneous folding causing the very faint foliation in the tonalite.
2. The bed was formed metasomatically *in situ* and the fine-grained supracrustal fragments are remnants of sediments which by some reason were more resistant to the metasomatic processes.
3. The gray tonalitic matter represents material syngenetic with the sediments. This matter has only been subject to slight metasomatism.

The present writer favours the last interpretation. The reasons for this will be discussed in a later part of this chapter.

The gray beds in the migmatite area on western Tjörn, for instance at 10.89 and on the islands of Kaurö and Skaboholmen, are petrographically very similar to the bed described above. The ratio plagioclase: microcline is smaller than in the rock already described, though the sum of the two feldspars is rather constant around 35—50 % by volume. This seems very important as the microcline almost always replaces plagioclase. Another conclusive observation is that these beds are always conformable to the adjacent gneisses.

The gray "granites" east of Kållekärr are also conformable to the fine-grained gneisses and schists. They contain fragments of gneisses and schists which are slightly displaced and disturbed. Their main dip and strike. however, coincide with the gneisses in the vicinity. Two volumetrical analyses have been performed on the brecciating rock.

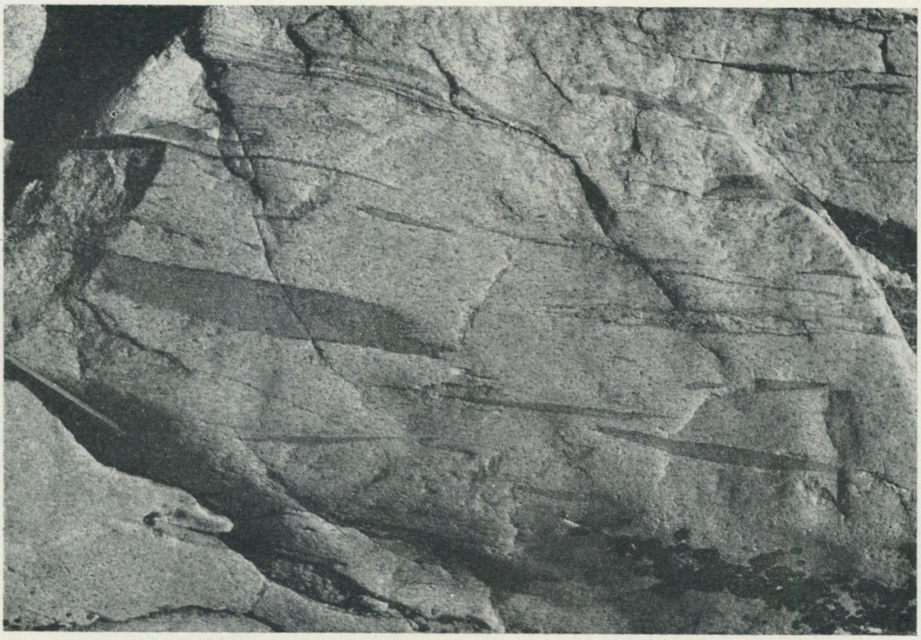

Fig. 22. Beds of gray plagioclase granite with supracrustal remnants. Hakenäset 303.748.

Table 8. Mineralogical composition of brecciating "light gray granite"

Locality	% by vol.					
	Quartz	Microcline	Plagioclase	Biotite	Muscovite	Epidote Titanite
270.778 . .	30	1	65 (An_{21})	3	1	—
275.804 . .	29	4	61 (An_{21})	5	—	1

Grain size is approximately 1—2 mm, the plagioclases being always the biggest crystals. The plagioclases often contain rounded, non-undulatory quartz inclusions. The quartz outside the plagioclases is strongly undulatory. Secondary alteration has formed minute sericite flakes inside the plagioclases. Biotite has been altered to penninite. Specimens from locality 270.778 have been analysed.

Table 9. Chemical composition of "light gray granite"

Locality	% by weight								
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
270.778 . .	70.92	0.24	16.80	0.10	1.12	0.64	2.88	5.42	1.18
Niggli values									
$al = 47.1$, $fm = 9.4$, $c = 14.9$, $alk = 28.6$, $si = 337$, $k = 0.13$, $ti = 0.86$									

Both microscopical and chemical investigations show that this rock has the composition of a tonalite (cf. Johannsen 1952, II, pp. 378—386).

The analysis shows low iron content and remarkably high sodium content. If the analysed rock is of sedimentary origin it must be a mobilized part of a rapidly deposited clastic weathering product. The low iron content favours such an interpretation.

The gray tonalite near Stenkyrka is very similar both to the Hakenäs type treated above and the brecciating tonalite from southern Tjörn and adjacent islands described below. The tonalite near Stenkyrka contains frequent gneiss fragments orientated parallel to the main direction of the strike, but there are also strongly displaced fragments. Along the western contact there are several amphibolite-gneiss fragments indicating that the amphibolites exposed from Röra to 202.812 have had a continuation southwards to the strongly deformed amphibolite at 20.76. The eastern contact between the tonalite and the pale red augen-gneiss is gradational.

The mineralogical composition is identical to those given in Table 8. Plagioclase dominates and the subordinate microcline is secondary. The tonalite here contains a garnet with n = 1.792 and a = 11.58 Å corresponding to an almandine-dominated garnet.

A chemical analysis was performed on a general sample of ten fragments of this rock from locality 202.804

Table 10. Chemical composition of "light gray granite"

Locality	% by weight									
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O
202.804	68.80	0.48	14.96	0.94	3.27	0.06	1.08	2.72	3.18	3.31
Niggli values: al = 39.9, fm = 23.4, c = 13.0, alk = 23.6, si = 311, k = 0.40, ti = 1.6										

The brecciating gray "granite" at Rönnäng and adjacent islands is characterized by its 2—3 mm long, rounded plagioclase phenocrysts in a dark matrix consisting mainly of biotite, plagioclase, and quartz. The grain size of the matrix is 1 mm or less. The amount of plagioclase phenocrysts varies — they can be very frequent, thus giving the rock a light gray colour, or so sparse that the rock is dark gray due to the high content of biotite. But also the texture varies. The rock is partly massive with no megascopically observed mineral orientation — or it can be strongly schistose. Inclusions are common in both the massive and the schistose type. On the map only the biggest inclusions of amphibolite are represented. The strongly penetrative force of the brecciating rock explains the distribution of tonalite and amphibolite in the Kärrsö—Risö archipelago, as seen on the map. This can also be seen in a smaller scale: brecciating tonalite contains non-orientated fragments of the supra-crustal rocks especially near point 17.63. The contacts against the fine-grained gneisses and schists at the northeastern boundary of the tonalitic rock (near point 18.64) are, however, conformable. Schistosity is not pronounced along this boundary, but very marked along the northwestern boundary from Tjörnekalv to a point 1 km SSW of Kuballe. The tonalite has occupied its present position synchronously with the folding of the sediments. It seems more than a coincidence that this obviously once mobile mass of tonalitic composition is found between the limbs of an anticlinal fold formed by the fine-grained gneisses and the schists. The dominating mineral of the "gray granite" is the plagioclase. The phenocrysts, 2—4 mm long, generally have an anorthite content of 20 %. The plagioclase in the matrix is generally more calcic with an anorthite content of 30 %. The phenocrysts always contain small clinozoisites (0.1 mm) showing very low interference colours, $2V_z = 85°$ and extinction $c/x = 3°—4°$. Quartz is strongly undulatory and has sutured boundaries. The biotite shows pleochroism in dark brown to yellowish brown colours, but it is sometimes altered to a green biotite. Pistacite is found together with the biotite. A volumetric determination of the mineral composition gave the following result:

Table 11. Mineralogical composition of brecciating "light gray granite"

Locality	% by vol.					
	Quartz	Microcline	Plagioclase	Biotite	Epidote	Acc.
228.603	19	6	50	18	6	1

Fig. 23 shows the plagioclase with its characteristic abundance of zoisite inclusions.

LIGHT GRAY GRANITE IN THE MIGMATITE

Diffusely limited pods and streaks of gray granitic material are one of the components of the migmatite. If sufficiently small specimens from the gray granitic parts in the migmatite are compared with the types of tonalites described above the similarity concerning grain size, texture, and mineralogy is obvious. There is, however, one important exception: the gray granite in the migmatite does not contain plagioclases with clinozoisites as does the brecciating tonalite found on southern Tjörn.

DISCUSSION ON THE ORIGIN

Due to the strict conformity of the beds of plagioclase granite in the fine-grained gneisses it seems very unlikely that they have been injected to their

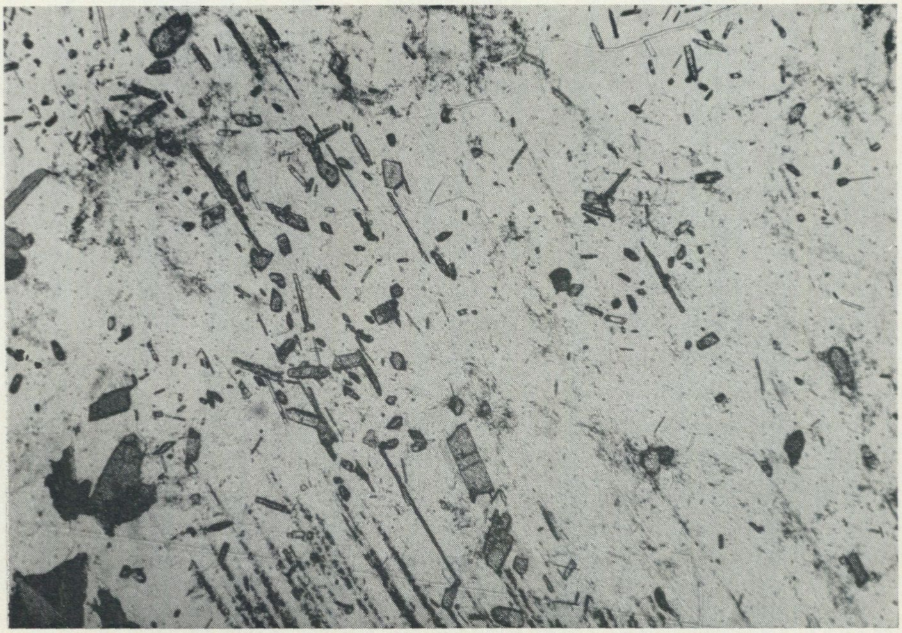

Fig. 23. Clinozoisite in plagioclase. Tonalite. Hättan 226.604. Ord. light. 30 ×.

present positions particularly as the gneisses are nearly horizontal. Such an injection would necessitate a considerable lifting up of the gneisses which in earlier chapters were proved to be of sedimentary origin. The close structural connection between the sediments and the beds implies an origin syngenetic with the gneisses. The chemical analysis of the bed on Hakenäset, which is a good example of the least altered beds, has an Na_2O : K_2O ratio of more than 4.5. This figure is extreme, but still it is obvious that there is an excess of sodium in all the plagioclase granites, unless there has been a secondary supply of potassium. If a sedimentary origin is postulated, the high sodium content eliminates an ordinary process of weathering and transportation of the break-down products from a terrain consisting of magmatic or metamorphic rocks. The reason for excluding this possibility is that sodium is commonly one of the earliest substances lost in aqueous solutions. Consequently an unusual source of the rock waste and/or an unusual type of disintegration are required to explain the high Na_2O : K_2O ratio unless a secondary enrichment of sodium is anticipated. If, however, disintegration is fast and transportation is short, and the primary rock source of the products of the disintegration was a plagioclase granite or an albitic schist, then the sediments formed would have been graywackes of, more or less, the chemical composition given in the analyses above. The absence of detrital rock fragments is no positive evidence of this rock type not being of a graywacke type. (Compare Engel and Engel 1958 and Eskola 1932.) A similar rock type as that dealt with here is described by Hjelmqvist in his paper on the Larsbo series (1938) in Central Sweden. Hjelmqvist postulates a detrital origin, the mother rock being mafic (p. 24). However, re-deposited tuffaceous material could also be a constituent in the oligoclase gneisses of the Larsbo series. The present features of the granitic beds in the Tjörn area were determined during the regional metamorphism. During this phase of the evolution the beds, consisting of mafic detritus, were very sensitive to metamorphism. Recrystallization easily took place and the primary features were destroyed.

The metamorphism would easily cause the rock matter of these beds to become mobile and in minor details traversing. The small conformable, broken interlayers in the granite from Hakenäset (Fig. 22) are interstratifications of clayey sediments in the beds of graywacke type. During increased PT-conditions the graywacke beds were changed into their present form. Possibly there was an increase of sodium during this metamorphism caused by the taking up of sodium from the captured saline water in the beds of detrital matter. Orogenic movements in connection with metamorphism caused the brittle sediments in the graywackes to break, while the latter acted in a plastic or pasty manner. The slight enrichment of biotite in the gneisses on the contacts to the beds which is observed in some places, can be explained by a moderate exudation of the light minerals from the gneisses into the plagioclase-rich beds, comparable to the similar enrichment of biotite around the pegmatitic exudations treated in chapter 2. In the latter case, however, this exudation process is of quite another scale and is completely responsible for the light minerals in the pegmatites.

In consequence of the discussion above the beds are regarded to be pararocks. The tonalitic rock from Rönnäng and adjacent islands form together with the gneisses beautiful breccias which clearly indicate that they were formed while the tonalite was in a mobile state. The tonalitic mass intruded into flexures in the supra-crustal rocks and broke up the amphibolites. In a paper from 1953 Lundegårdh assumes a similar plagioclase granite immediately south of Gothenburg as generally being a magmatic rock (p. 42) though a very similar rock "bears strong evidence of granitization *in situ*" (p. 42). The plagioclase granite shows intrusive characteristics in some places and is thus regarded as magmatic (p. 42). According to Lundegårdh this plagioclase granite is certainly secondary, formed by mobilization of the deeper parts of the downfolded sediments.

The present writer agrees fully with Lundegårdh concerning the formation of the plagioclase-dominated granites. The scheme given by Lundegårdh can be applied to the plagioclase-rich rocks of the Tjörn area with only slight modifications. The most important one is that certain beds in the sediments were more likely to change into their present plagioclase-dominated composition because they were primarily composed of graywackes. This composition is also responsible for the higher degree of mobility compared to that of the ordinary sediments. The higher mobility is responsible for the intrusive character of the plagioclase rock in the Rönnäng—Risö region, where it is found between the limbs of schists forming an anticlinal fold. The plagioclase granites east of Kållekärr 27.80 and 29.80 have only been moderately displaced. The "Stenkyrka tonalite" was more vigorously displaced. This is concluded from the disorder of the incorporated gneiss fragments. From the field obserations it is easy to conclude that the emplacement was simultaneous with the folding of the sediments, and that the positions of the intrusions were determined by low pressure. It seems certain that the plagioclase granite once occupied a greater mass than at present. The reasons for supposing this are that the central gray granite near Stenkyrka has a rather high content of potash feldspar. It is, however, secondary and replaces the plagioclases. The contact at point 208.800 is also gradational. There is a continuous increase in potash feldspars and a decrease of plagioclases going over the contact zone from west to east. This contact zone between the two rocks could have been formed by a transgressive potassium front invading the plagioclase granite, and successively transforming it into a potassium-dominated rock.

Concerning the gray granite in the migmatite, there are indications that this granite has been formed by selective anatexis of the plagioclase-rich layers in the gneisses. The experiments of Winkler and von Platen (1961 a) on anatectic melting of graywackes prove that tonalites (or sometimes granodiorites) are the final stages in anatectic alterations of previous graywackes. (Compare also the dikes of gray granite traversing the migmatite treated in chapter 7.)

CONCLUDING REMARKS

The rock with the tentative name "gray granite" is shown to have a composition from tonalite or plagioclase granite to granite. The potash feldspars are secondary. They are formed of plagioclases which have been converted into microclines by potassium metasomatism. The tonalitic beds are mainly conformable, and are believed primarily to have been graywacke beds in the ordinary, more sandy-clayey sediments. Where thick graywacke beds were subject to regional metamorphism they became plastic and could intrude into low-pressure volumes during the folding of the sediments. Some brecciation of the sediments took place. Later potassium metasomatism influenced the plagioclase-rich rock in parts.

Chapter 9

Hornblende porphyrite

This kind of rock is found at three localities within the investigated area, two near the southern boundary of the map: on the island of Nordön 27.51 and immediately southeast of the quarry at Tjuvkil 300.537. Certainly they

Fig. 24. Tectonized uralite porphyrite. Stordal 210.825.

belong to the same bed of hornblende porphyrite. On Nordön, where dips are very steep and exposures are excellent, it is easy to establish the concordant relationships of the contacts vis-à-vis the schists and fine-grained gneisses. This can also be observed in the quarry at Tjuvkil, though the dip of the gneisses there is slight (15°) so that observations are not so easily performed. The third occurrence of hornblende porphyrite is found in the central part of Tjörn at Stordal 22.83. There the contacts are obscured by overburden except in the southern part of the massive where the contacts are observed to be concordant.

On the map the Stordal hornblende porphyrite shows a typical phacolithic cross-section. N. B. that the dips and strikes, both in the gneiss east of the hornblende porphyrite and in the amphibolite west of the massive, are concordant. Also the observed lineations in the amphibolite support the conclusion, that the hornblende porphyrite is forming a phacolith in a crest of an anticlinal fold. But also the Nordön—Tjuvkil porphyrite is found near the crest of the anticlinal fold formed by the fine-grained sediments. At Stordal small angular fragments of fine-grained quartzite are found as inclusions in the dark rock which is characterized by a lineation which coincides with the general fold axis directions observed in the area. The hornblende porphyrite is here cut by pegmatitic dikes and quartz veins. The tectonization is not homogeneous straight through the bodies of the discussed rock. There is no strongly tectonized marginal zone and a massive core. The non-tectonized parts occur quite irregularly in the more lineated ones. The lineation is marked by aggregates of hornblende (Fig. 24). Where lineation is pronounced, the rock displays a darker colour than where lineation is not so strong, or absent. The porphyritic texture is, in places, very obvious with the black hornblendes (8—15 mm) lying in a gray to dark gray, fine-grained matrix. Two planimetrical determinations of the mineral content have been performed; one is on the dark type, the other on a more massive type. The results are given in Table 12.

Table 12. Mineralogical composition of uralite porphyrite, Stordal

Type	% by vol.				
	Quartz	Plagioclase	Hornblende	Biotite	Acc.
Tectonized	3	31 (An_{45})	62	3	1
Massive	4	55 (An_{45})	36	4	1

Quartz shows moderate wavy extinction. Plagioclase and quartz form a mass of small grains 0.3—0.4 mm between the porphyroblastic hornblendes. The anorthite content of the plagioclase keeps remarkably constant at 45 % with deviations of a few per cent. The plagioclases are either untwinned or they show few lamellae of the Albite type. The hornblende is light greenish yellow (X) and olive green (Z); $N_x = 1.650$ and $n_z = 1.668$; $c/z = 16°$; $2V_x = 75°$. These optical data correspond to an ordinary hornblende with 37 % of the Fe-Mn-Ti molecule (Tröger 1959, p. 77). The hornblende is partly altered to a brown biotite. Poikiloblastic quartz inclusions are frequently met with in the hornblendes. Titanite and pistacite are accessory minerals. Ore grains are extremely scarce. A general sample from Stordal has been analysed. As a comparison the average compositions of diorite and norite are also given. These analyses are taken from Johannsen (1952), vol. 3, p. 168 and p. 236.

DISCUSSION ON THE ORIGIN

Strong metamorphism has obscured all primary features of the rock. Is the rock effusive or intrusive? (A sedimentary origin is out of the question because of the angular fragments of quartzite.) A hint is given by the grain size of the light minerals. They are much smaller than would be expected if an infracrustal rock — say an ordinary norite or diorite — were exposed to regional metamorphism. One of the main results of metamorphism is just the increase of grain size. The very small plagioclases preclude the idea of a deep-level origin unless metamorphism were preceded by a process decreasing the grain size. There are no signs of such a process. It is then logical to conclude that the primary rock was very fine-grained. The rather coarse hornblendes do not contradict this conclusion. The poikilitic quartz in the hornblendes is a metamorphic texture and not a magmatic. Compare the secondary hornblendes in the supracrustal rock from Bockholmen (p. 28).

From this comparison it is evident that hornblende can form large crystals

Table 13. Chemical composition of uralite porphyrite at Stordal compared to the average compositions of diorite and norite

	Uralite porphyrite Stordal	Average diorite	Average norite
	% by weight		
SiO_2	53.55	53.35	51.38
TiO_2	0.89	0.92	0.90
Al_2O_3	16.14	19.19	17.19
Fe_2O_3	2.32	0.97	2.55
FeO	5.66	6.91	7.70
MnO	0.14	0.06	0.15
MgO	7.58	5.10	7.17
CaO	0.08	7.52	8.37
Na_2O	2.54	3.94	2.61
K_2O	1.64	1.28	0.82
P_2O_5	0.17	0.13	0.19
	Niggli values:		
al	24.0	29.6	24.6
fm	45.2	37.0	46.4
c	21.9	21.1	21.7
alk	8.8	12.3	7.3
si	136	140	124
k	0.29	0.18	0.16
ti	1.7	1.7	1.6

during metamorphic conditions. Johannsen (1952, III) states that in diorites inclusions of quartz in amphibole are rare (p. 152). Concerning quartz occurring in diorites Johannsen says it is "the last mineral to crystallize; consequently it fills the interstices between the others" (p. 153). The presented data make it impossible to regard the hornblende porphyrite as being an ordinary, metamorphosed norite or diorite. Lundegårdh (1958) has dealt with similar problems in his paper on the Göteborg—Kungälv region. He has not encountered a rock identical to this, but related mafic rocks occur frequently in the area investigated by him. He has found criteria *both* of supra- and infra-crustal origin of gabbroic and dioritic rocks (p. 56) which are of the same kindred as the hornblende porphyrite from the present area. When interpreted as supra-crustal rocks the primary material was, according to Lundegårdh, a tuff or a lava (p. 56). When regarded as intrusive Lundegårdh finds the primary material to have been a norite intruded as sills.

A similar interpretation concerning the hornblende porphyrites as Lundegårdh's first type seems probable. Their composition is equivalent to that of an ordinary andesitic lava.

Field evidence favours an interpretation along magmatic lines of thought. The hornblende porphyrites are regarded as superficial intrusions of basaltic-andesitic lavas which were synchronous with the folding of the sediments. This would explain their positions in the fold crests and their strong metamorphism.

Chapter 10

Light gray granitic gneiss

On the northeastern part of Tjörn there is a seven km long and at most two km wide anticlinal crest of light gray granitic gneiss. The contacts against the fine-grained sediments are always easily distinguishable. The sediments are gray and often strongly schistose; on the other hand the granitic gneisses are often on the weathered surface gray with a distinct reddish tint. But also differences in grain size and textures make mapping of the contacts easy. The lack of pronounced foliation in the granitic gneiss, and the extreme foliation in the sediments also give pronounced differences in the sculpture of the outcrops of the two rock types. The granitic gneiss forms rounded outcrops — the schists, on the other hand, give more rough surfaces.

In places where it is possible to examine the contacts in detail they are always found to be concordant. The sediments always dip in the direction away from the granitic gneiss and would, if they were extended upwards, form an anticlinal roof above the granitic gneisses. This is easily seen in the northern extension of the granitic gneiss at point 34.91. East of the mapped area the gneisses have a moderate easterly dip. The sedimentary fine-grained gneisses and the amphibolites at the southern end of the granitic gneisses, would have covered the granitic gneisses if they were extended upwards. Further there are a few lineation observations in the surroundings of the anticline indicating a homoaxial folding of the surrounding gneisses and the granitic gneiss. They, also, indicate the anticlinal structure of the terrain in question. A northwestern plunge can be observed both in sediments and in the granitic gneisses on the northern end, and a southwesterly plunge, though not so convincing — in the southern end. Near the contacts the sediments exhibit steep dips. The anticline seems to be rather steep and the lateral synclinal folds are — contrary to the anticlinal folds — rather flat. It is not surprising to find all contacts concordant in their main trends. There are, however, details which show that the granitic gneiss has been so mobile that it has been able to break up the roofing sedimentary gneisses. This can be seen in the road cuttings at point 331.904 where slabs of the supracrustal fine-grained gneisses or veined gneisses derived from mica schists are lying in the granitic gneiss. The big inclusion of medium-grained, veined flasergneiss at point 35.89 could be a part of the roof — hardly a roof pendant. However it must be stated that the brecciating character of the granitic gneiss is restricted to the borders, and even there this type of behaviour is more an exception than a rule.

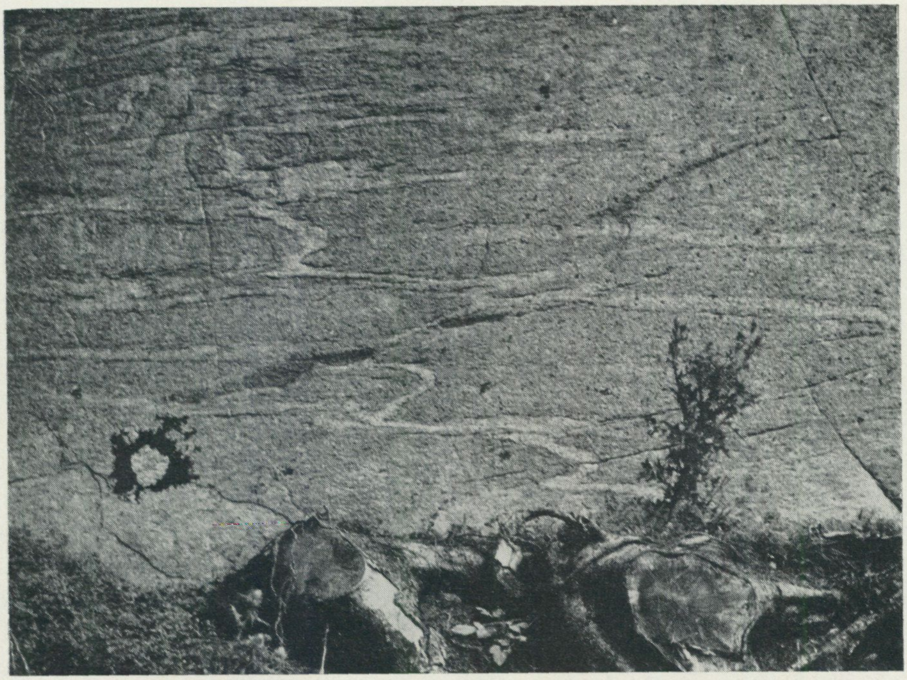

Fig. 25. Diffuse veins in light gray granitic gneiss. Hakenäset 332.797.

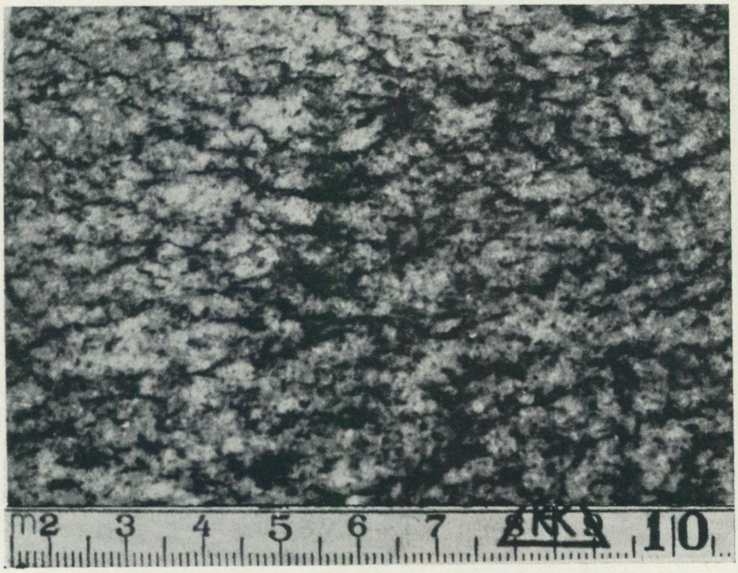

Fig. 26. Polished specimen of light gray granitic gneiss. Myggenäs 340.871.

The granitic gneiss forms an elongated anticlinal crest. Within this crest the rock does not show any distinctive variations except those described below. An important feature of the granitic gneiss is the diffuse veining occurring nearly everywhere. See Fig. 25. When the diffuse veining is absent the gneissic texture is marked by a slight orientation of the biotite (Fig. 26). Often, however, biotite forms continuous layers in the granitic gneiss. These layers are folded in a delicate way reminiscent of the migmatite found on western Tjörn. It must be stressed that there is no predominant direction of foliation. Though as a whole the anticlinal crest is homogeneous, there are minor heterogeneities. One of them is touched upon as it is regarded as important from a genetical point of view.

At point 347.882 a bed of pegmatite has been disrupted and the granitic gneiss has — because of the highly plastic state it possessed during the tectonical stage — fixed the pegmatite bed in its broken position.

In the granitic gneiss with porphyroblasts of microcline there are often ghostly remnants in the form of biotite-rich schlieren. They are regarded as pre-granitization textures which have been preserved because they were more resistant to the processes which have veiled the primary textures to some extent. The transitions from the obvious gneissic parts to the more granitic are gradational and give a conclusive indication of the origin of the granitic gneiss. Grain size seldom exceeds 1 mm though the porphyroblastic microclines in places are up to 4 mm in cross-section.

Volumetric analyses of the more granitic parts have been performed. See Table 14.

Table 14. Mineralogical composition of granitic gneiss, eastern Tjörn

Locality	% by vol.				
	Quartz	Microcline	Plagioclase	Biotite	Epidote
340.871	30	17	40	11	2
311.784	29	20	34	15	2

Quartz is generally extremely undulatory when occurring in its ordinary position outside the other minerals. But when it forms inclusions in the feldspars it is not undulatory.

Plagioclase is anhedral and is strongly clustered with sericite flakes. Twinning is not always present. The anorthite content is approximately 20 %. Some of the plagioclases contain rounded quartz grains of 0.1—0.2 mm diameter (Fig. 27). Observe that the size of the quartz inclusions is the same as the size of the detrital quartz grains in the best preserved fine-grained sediments. Myrmekite is common and is found when plagioclases are bordering microclines. Myrmekite is never observed where quartz and plagioclase are lying in contact with each other. Microcline is the youngest of the minerals. It penetrates the interstices

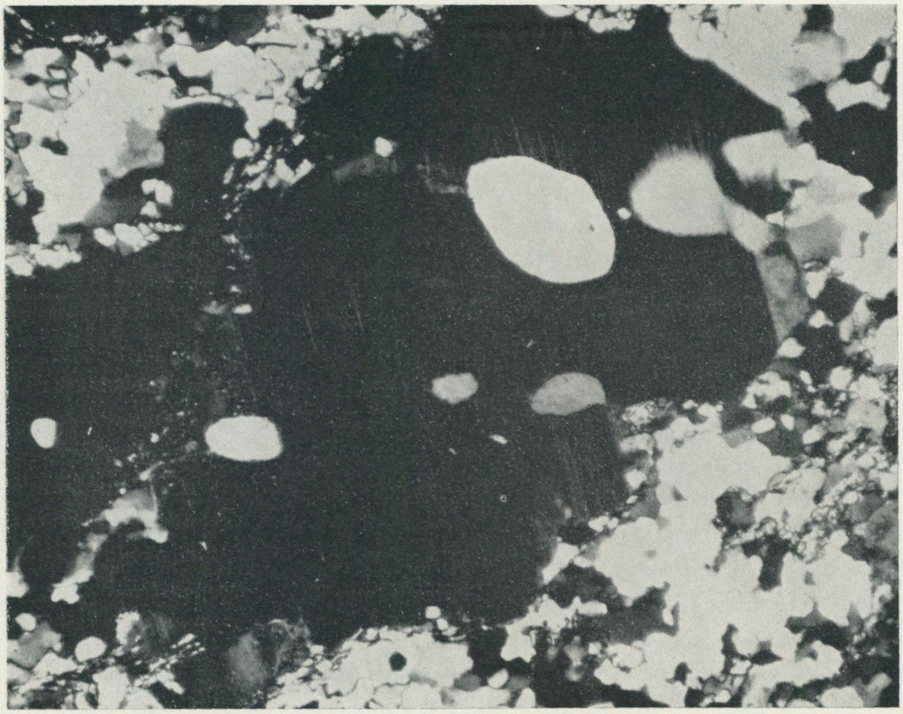

Fig. 27. Quartz relicts in plagioclase. Höviksnäs. 355.841. Nic. +.100×.

and attacks the plagioclases. When doing so the sericite flakes disappear from the plagioclase in a rim of 0.05—0.1 mm bordering the microcline front. Determination of 2V in microcline gave values between 84° and 88°. This holds true both for the larger microcline porphyroblasts and the interstitial potash feldspar. Some of the larger microclines contain rounded, 0.1—0.2 mm, non-undulatory quartz inclusions (cf. the plagioclase). Biotite is dark brown to pale green. Euhedral epidote is found together with the biotite. Finally a chemical analysis is presented. It has been performed on a general sample from a road cutting.

Table 15. Chemical composition of granitic gneiss, eastern Tjörn

Locality	% by weight										
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O^-	H_2O^+
340.871	70.16	0.23	15.82	0.63	1.91	1.19	2.80	4.01	2.57	0.08	0.78
Niggli values: $al = 42.8$, $fm = 17.7$, $c = 13.8$, $alk = 25.7$, $si = 323$, $k = 0.30$, $ti = 0.83$.											

DISCUSSION ON THE ORIGIN

The tectonical picture of the gneisses in the environment shows that the elongated crest of granitic gneiss is an anticline with rather steep sides. A similar type of folding has recently been observed by Kranck (1960). He calls it a "dome and basin structure" where the domes are just elongated anticlinal crests. "It is", writes Kranck, "significant that dome and basin structure in gneiss terrains occur where we have comparatively unaltered supracrustal rocks together with highly granitized gneisses" (p. 440). Kranck regards this type of folding as having been "affected by a highly plastic substratum, under a more rigid supracrust" (p. 440). Similar thoughts are not new, however. Already in 1916 Geijer coined the term "anticlinal batholiths" (p. 55) after having reviewed international and Swedish investigations on concordant granites enclosed by sedimentary rocks of various metamorphic degree. The non-transgressive behaviour is explained by intrusion and folding as simultaneous processes brought forth by the same prime cause (p. 56).

In this paper Geijer only deals with the granites proper in the anticlines. He does not consider the anticlines with a core of migmatitic composition. These are, however, considered by Wegmann (1935). In his very important work *Zur Deutung der Migmatite* Wegmann distinguishes between "Oberbau" and "Unterbau". The migmatites are found in the Unterbau (substratum), which conformably follows the folding of the Oberbau (supracrust) and is thus found in the anticlines of the supracrust. Wegmann regards the migmatites and granites, found in anticlines, as masses which have come to their present positions by flowage, comparable to diapire tectonics (see also Wegmann 1930). Observations very similar to these are plentiful, though the interpretations are a little different. From the Caledonides Faddegon (1940) reports that sediments in the anticlines are granitized — the granitization being most complete in the core of the anticline and decreasing in the direction away from the core (p. 193). Haller (1956) has also studied the Caledonides but on East Greenland. He has found a synorogenic granitization of psammitic sediments in the anticlinal folds. The preserved gneissic textures are conformable to those in the covering sediments. Haller believes that granitization is accompanied by a considerable increase of volume. Similar observations have also been made in the Alpine mountain chain. From the Mont Blanc massive Oulianoff (1960) reports a tectonic phase causing gneissification of the schists in the synclinal zones accompanied by a granitization at a slightly higher temperature in the anticlines (p. 158).

But similar observations and conclusions are also encountered in papers dealing with Archean terrains. From east Siberia Frowola (1953) reports concordant granite bodies in folds, especially in anticlinal folds, which are often tilted (p. 58). According to Frowola the granites have originated by granitization (= ultrametamorphism) of para-matter. Migmatite is regarded as an example of incomplete granitization (op. cit., p. 63).

Finally a few lines from Perrin (1956) will conclude this short review on the granitization and/or migmatitization processes observed in the anticlines of metamorphic terrains, ". . . it is not abnormal that when granitization involves a change in volume it occurs preferably in the anticlines" (p. 6).

We shall now return to eastern Tjörn. The granitic gneiss with its diffuse pegmatitic veins and remnants consisting of biotite-rich schlieren is regarded as a product of homogeneization of primary sediments probably of more or less the same composition as those already described. These sediments, which have been homogeneized, are now found in the anticlinal fold. The structures indicate that the rock matter has been in a highly plastic state. This is also proved by the occurrence of sharp-edged inclusions of gneisses in the marginal zones of the granitic gneiss. These inclusions cannot be regarded as proof that the granitic gneiss was intruded (as a magma). The contact relationships give no evidence of a mighty diapiric upheaval nor an intrusive behaviour. The inclusions only prove that the granitic gneiss has locally become so mobile that a very local brecciation has occurred. These local mobilizations are found only a few metres away from the contact to the fine-grained gneisses. The microscopical observations prove that the homogeneization/feldspathization also caused an increase of grain size. Potash feldspar is strongly aggressive towards the plagioclase. The small inclusions of non-undulatory quartzes in the plagioclases are the result of the plagioclase metablastesis. Some of the quartzes in the neighbourhood of the growing plagioclase blasts were captured by these blasts. The inclusions are of the same size as the quartz grains in the least altered sediments. During the tectonical processes, which are traced in the anticline these inclusions escaped stress while the quartz grains outside the plagioclases were subject to stress, and thus became strongly undulatory. Potash feldspar is the youngest of the minerals. Some of the larger microclines also contain minor, rounded, non-undulatory quartz inclusions. These are no doubt relicts from the quartz-bearing plagioclases as the plagioclases have been replaced by potash feldspars. This is seen from the frequently occurring myrmekite textures in the contact zones between the microclines and the plagioclases.

The 2V values, both of the larger porphyroblasts and the interstitial potash feldspars, fall within 84—88°. These angles indicate a rather low temperature of formation of the microclines (Spencer 1937). The thin veinlets of potash feldspar penetrating the grain boundaries indicate a very low viscosity of the solutions which formed the potash feldspars. The metasomatic processes acting on the rock matter in the anticlinal crest, will be discussed in detail in the next chapters which deal with the augen-gneiss and the augen-granite.

Chapter 11

Pale red granitic augen-gneiss

The central part of Tjörn consists of coarse augen-gneisses. The rock is found on the island 098.582, which is the southernmost point where the rock in question is exposed. From here the augen-gneisses are exposed in a NNE direction

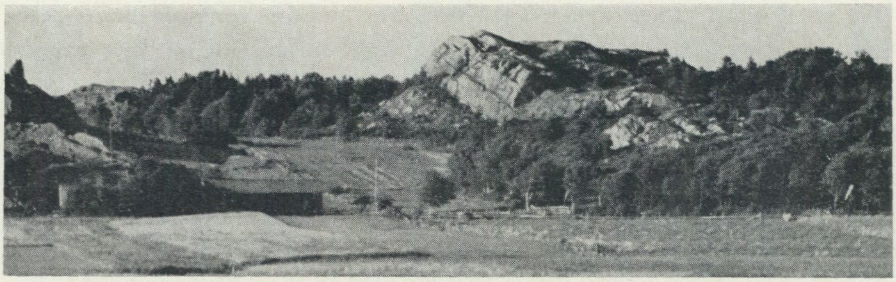

Fig. 28. Cuesta in granitic augen-gneiss seen from the south. Hovlanda 19.81.

over Tjörn, on the islets in Stigfjorden, and also to the northern extension of Orust. The gneisses in contact with the augen-gneiss always dip moderately eastwards. On the western border, where the augen-gneiss comes into contact with the migmatite, for instance at 14.70, both rock units dip steeply eastwards and they are concordant. The granitic augen-gneiss often forms a cuesta landscape with the gentle slope dipping 25°—60° eastwards, and the sharp dipping at right angles to the gentle slope (Fig. 28). The gentle slopes coincide with the planes of foliation. Foliation is not always present. Folding is frequently observed as soft bows in the augen-gneiss (Figs. 29, 30). Folding sometimes occurs in a delicate pattern, but is most often obscured by a strong feldspathization (Fig. 31).

There is a very close structural connection between the supra-crustal rocks and their higher-metamorphic derivatives, the migmatites and the granitic

Fig. 29. Folding in granitic augen-gneiss. Furusäter 247.851.

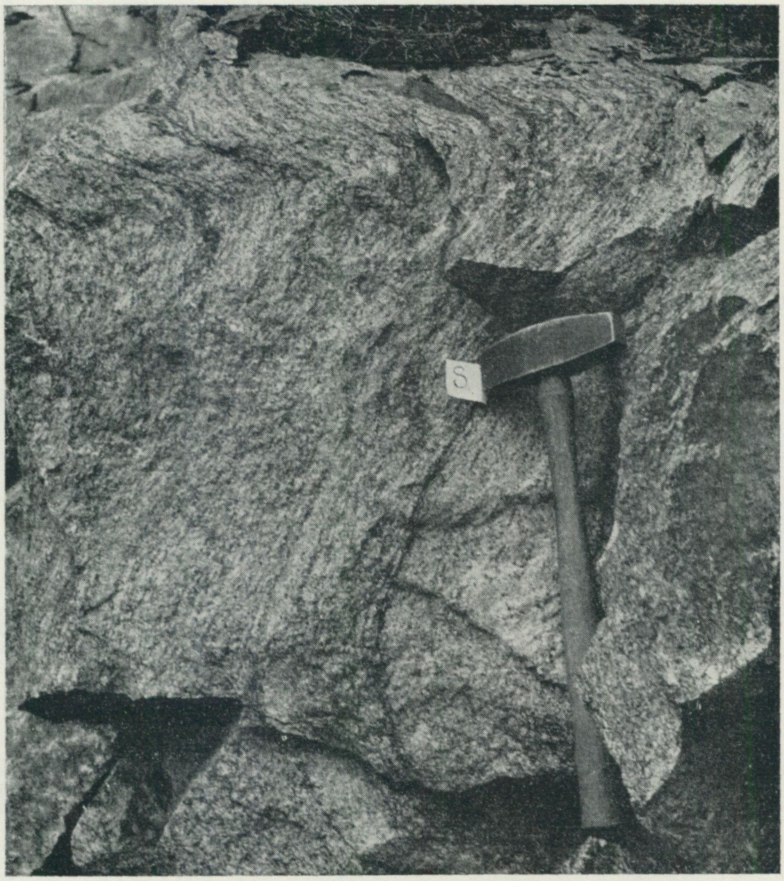

Fig. 30. Folding in granitic augen-gneiss. Varekilsnäs.

augen-gneisses. This may be seen on the light gray schlieren of fine-grained gneisses in the coarse, red augen-gneiss (Fig. 32). It is out of the question that these light gray gneiss slabs are nothing else but remnants which have escaped potassium metasomatism which resulted in the formation of microcline metablasts. Next figure (33) shows that the primary material — a medium-grained gneiss — is strongly feldspathized in its lateral parts. Parts of this rock characterized as an augen-gneiss are more veined than augen-bearing, as for instance, at 175.775. Lineation is a very characteristic feature of the rocks in the central parts of Tjörn. Lineation is often extraordinarily well developed which is seen in Fig. 34. The two polished surfaces are cut nearly at right angles to each other, and show the elongated "cigars" of flesh red microclines, plagioclases, and quartzes. The lineations accounted on the map were observed in such "cigars" as those in Fig. 34. In the specimen photographed foliation is absent. In some cases, however, both foliation and lineation are present. In this case the lineations lie in

Fig. 31. Plastic folding obscured by feldspathization. Granitic augen-gneiss. Röseliden 217.804.

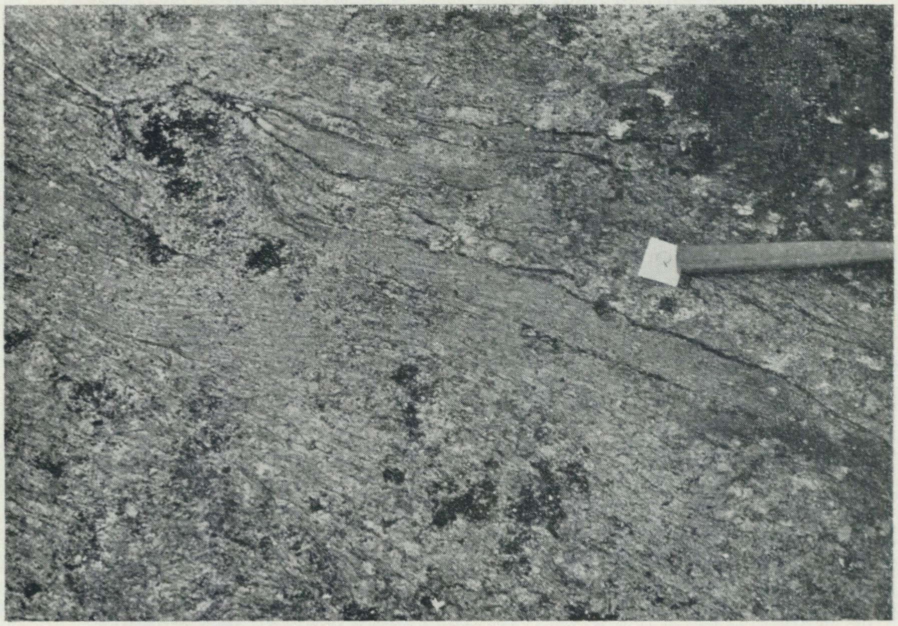

Fig. 32. Fine-grained supra-crustal remnants in granitic augen-gneiss. Kållekärr 228.812.

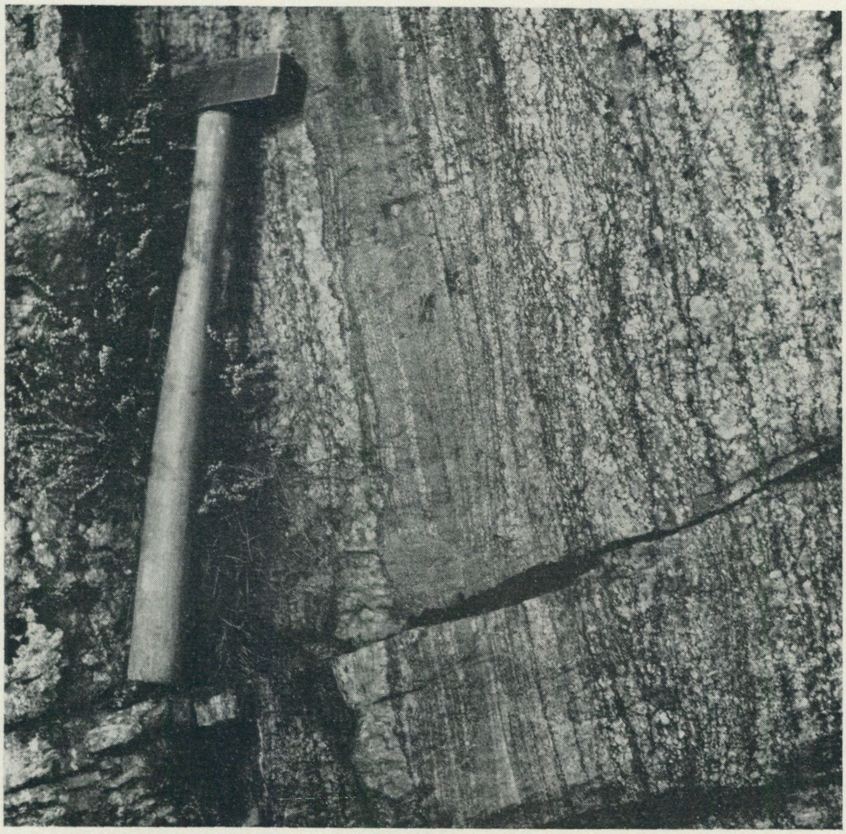

Fig. 33. Medium-grained gneiss septum in granitic augen-gneiss. Bleket 133.638.

the plane of foliation. Often the gentle slopes of the cuestas are strongly lineated by microcline aggregates. The lineations mainly strike in the direction N 20°—70° E and plunge 16°—70°. Intermediate values are the most common.

Returning to the contacts on the eastern side of the granitic gneiss one can observe a rather remarkable change in the strike of the contact near 22.75. This change in direction can be explained by the plunge of the lineations in the granitic augen-gneiss. The augen-gneisses dive under the sedimentary gneisses and disappear in the direction of the plunge where the schists have a very gentle NE dip. The augen-gneiss is always concordant to the fine-grained gneisses, though the very strong lineation at some places (for instance at 240.885) gives the impression that the augen-gneiss is discordant to the gneisses. A careful study shows that both the planes of foliation and the lineations are concordant. The latter are very pronounced in the red augen-gneiss but in the schists they hardly exist, while the opposite is valid for the planes of foliation.

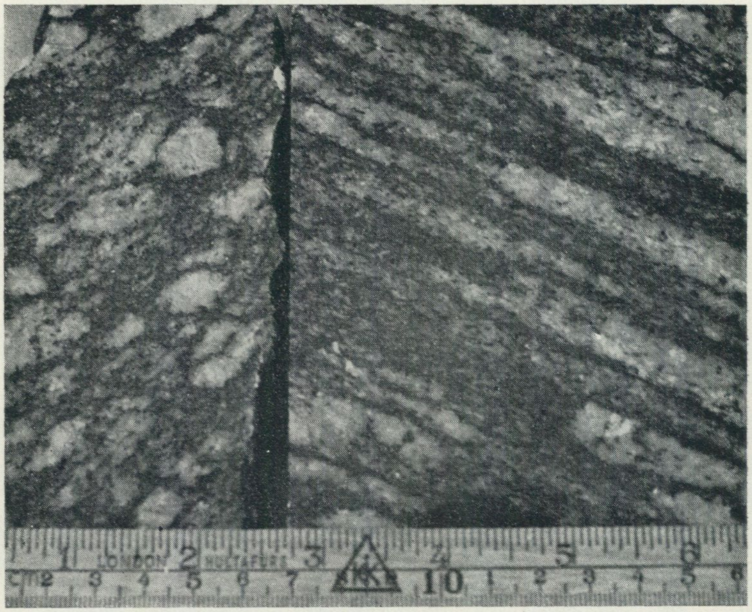

Fig. 34. Lineation in granitic augen-gneiss. Surfaces cut perpendicular to each other. Bockholmen 112.646.

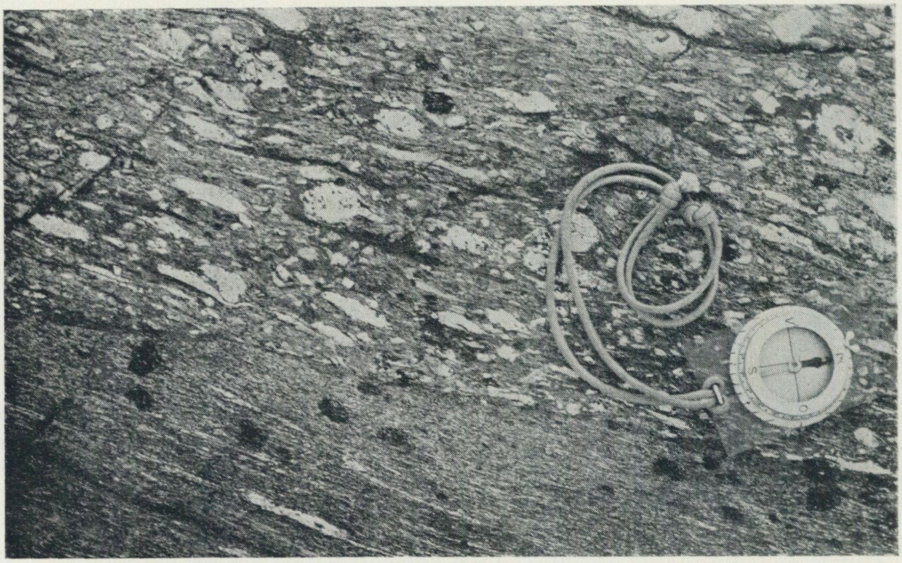

Fig. 35. Microcline porphyroblasts in amphibolite-gneiss. Bockholmen 115.645.

Fig. 36. Coarse, microcline-rich granitic augen-gneiss. Valsäng 159.870.

At the eastern contact, between the fine-grained schists and the coarse augen-gneiss, there are some localities with breccias. The inclusions consist of sharp-edged schist fragments lying in a matrix of non-schistose, microcline-rich augen-granite which gradually changes into the normal, granitic augen-gneiss. Such breccias are found on the geological map at points 181.666, 200.695, 222.794. The brecciation is caused by a local mobilization which has occurred at the contact where the schists lie over the granitic augen-gneiss; it is the same phenomenon as was described in a previous chapter on the granitic gneiss on eastern Tjörn. In later chapters, local mobilization will be treated in detail.

Half a kilometre west of the church at Stenkyrka there is a 2 m thick bed of fine-grained amphibolite with strike and dip concordant to those of the surrounding augen-gneiss. The same is valid for the amphibolites at 185.820 and for the gneiss slab at 17.85. These inclusions of what are undoubtedly supra-crustal rocks, are always orientated strictly parallel to the schistosity of the augen-gneiss, and, according to the writer, are relicts which have been more resistant to the general increase of the content of potash feldspar. Amphibolites are — in most positions — very resistant to the potassium metasomatism, and are thus unaffected by the invasion of microcline. Where local conditions have been favourable, however, there is an invasion of microcline porphyroblasts even in the amphibolites (which may be seen in Fig. 35 from Bockholmen 115.645).

Fig. 37. Enrichment of feldspars in flexural fold in granitic augen-gneiss. Varekilsnäs.

The stated facts prove that the area is far from homogeneous due to non-feldspathized relicts. But also the granitic augen-gneiss shows differences in habit. Grain size and texture are not uniform. Fig. 36 shows a coarse microcline-rich variety and Fig. 31 a more normal type. It is quite evident from Fig. 37 that dilatation has caused felsic minerals to accumulate along the low-pressure surfaces.

THE EXPOSURES AT VAREKILSNÄS

A detailed study of the granitic augen-gneiss and its relationships to the fine- and medium-grained gneisses has been performed at Varekilsnäs (location, see Fig. 3). This locality is outside the mapped area but, as it gives certain very important information on the granitic augen-gneiss, the results of that investigation are presented here. Exposures are excellent because of road cuttings.

Fig. 38 is a drawing of the exposed rocks. It shows the relations between the

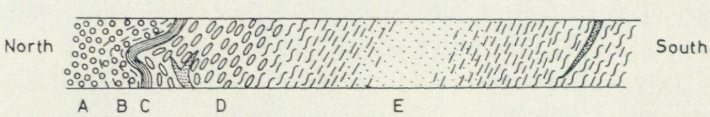

Fig. 38. Exposure along roadcutting. Varekilsnäs.

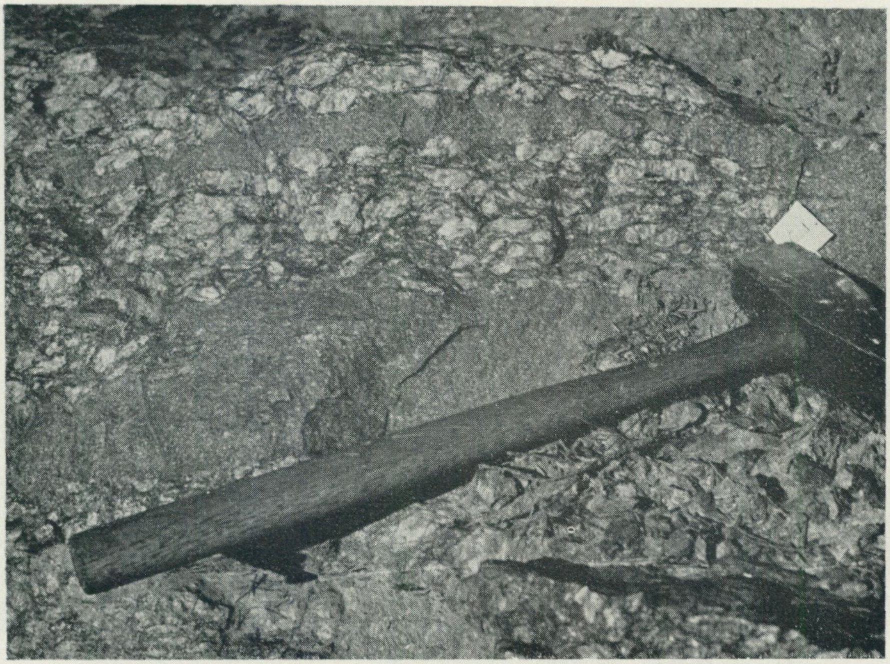

Fig. 39. Aplitic veins in augen-gneiss. Observe that the augen penetrate the aplite. Varekilsnäs.

different rock types. Beginning from the northern end of the exposure at A, we find a coarsely medium-grained microcline augen-granite. The matrix between the augen is a little foliated, and the augen are slightly elongated along the direction of lineation. The rock displays the features of a faintly gneissic augen-granite, but the writer wants to call it a granitic augen-gneiss because of the close connections to the gneisses at the locality. At B there is a dark, medium-grained, biotite-rich gneiss with coarse, reddish microcline augen. These augen often form a pattern reminiscent of boudinage. They are partly euhedral and partly rounded. This augen-gneiss is folded and concordant to the granitic gneiss at A. There is a transitional boundary between the two rocks treated above. The augen-gneiss is also concordant to the folds of the dark biotite-garnet amphibolite which is intricately crenulated (at C). On each side of the amphibolite the augen in the augen-gneiss are light gray instead of the ordinary light red colour. The light gray porphyroblasts are forming a 5—7 cm wide zone on each side of the amphibolite. A fine-grained, grayish red aplite (in Fig. 38 heavily dotted) cuts the fold structures in the augen-gneiss, but also concordantly penetrates the gneisses as seen in Fig. 39. The porphyroblasts in the gneiss are seen to expand into the aplite on the contacts but there are also some new-formed potash feldspars in the aplite. The aplite is post-tectonic and the

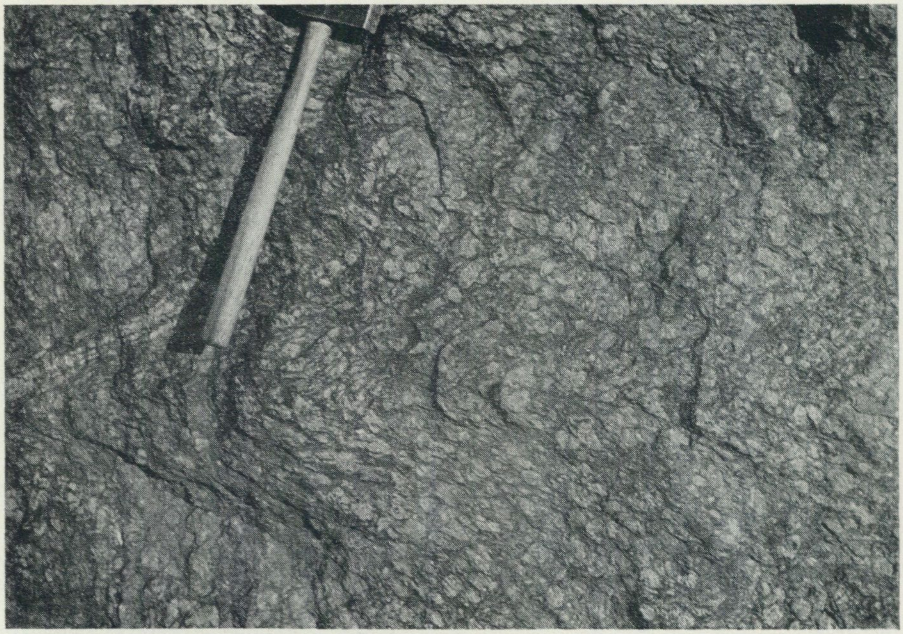

Fig. 40. Folded augen-gneiss with elongated porphyroblasts. Varekilsnäs.

augen in the gneiss are also post-tectonic and post-aplitic, too. At D the augen in the gneiss gradually become more disc-shaped and elongated. They are polycrystalline in contrast to the augen at A and B which are monocrystalline. Towards E the gneiss grades from a schlieren-gneiss to a flaser-gneiss, and at E it is a fine-grained, supra-crustal gneiss (Fig. 41) of the same type as described in chapter 2. Further south a veined gneiss is exposed which has the same strike and dip as the finegrained, sedimentary rocks at E.

Due to recent blastings in the granitic augen-gneiss 200 m NNW of the northern end of the presented section of the road cutting, there is another good exposure. Fig. 42 is from that exposure and shows a medium-grained, schistose gneiss (at the pencil) and to the right an augen-gneiss. The transition between two similar rocks is also seen in Fig. 43 with veined gneiss at the label "E" and augen-gneisses in the direction of the strike (to the right). The augen which are both mono- and polycrystalline are very often orientated with their longest diagonal parallel to the plane of foliation (Fig. 44). The augen are frequently polycrystalline. An example of this may be seen in Fig. 45 which shows how a layer of biotite which is seen in the gneiss continues through the microcline-dominated avgen. The augen are very often extremely elongated in the direction of lineation (compare Fig. 34). The direction coincides with the minor fold axes observed in the medium-grained gneiss relicts.

Fig. 46 shows veins which have partly recrystallized to augen.

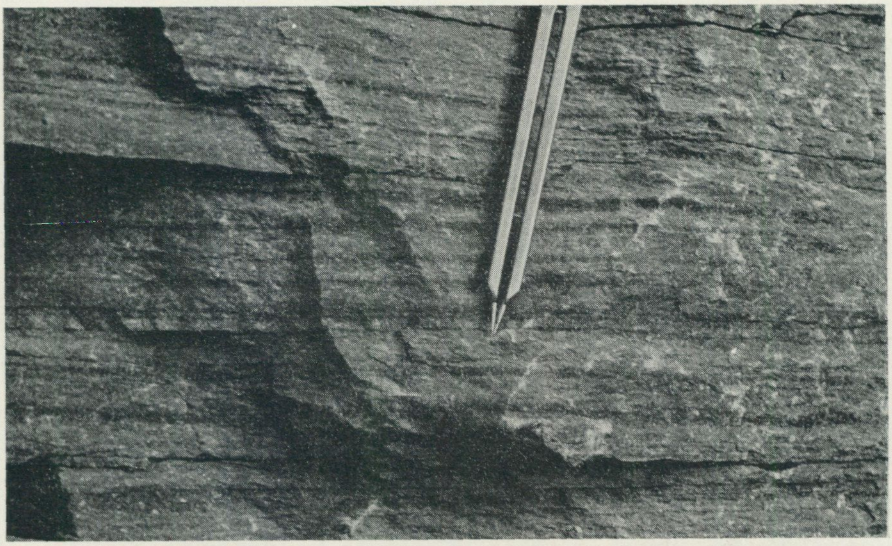

Fig. 41. Fine-grained, banded sediment. Varekilsnäs.

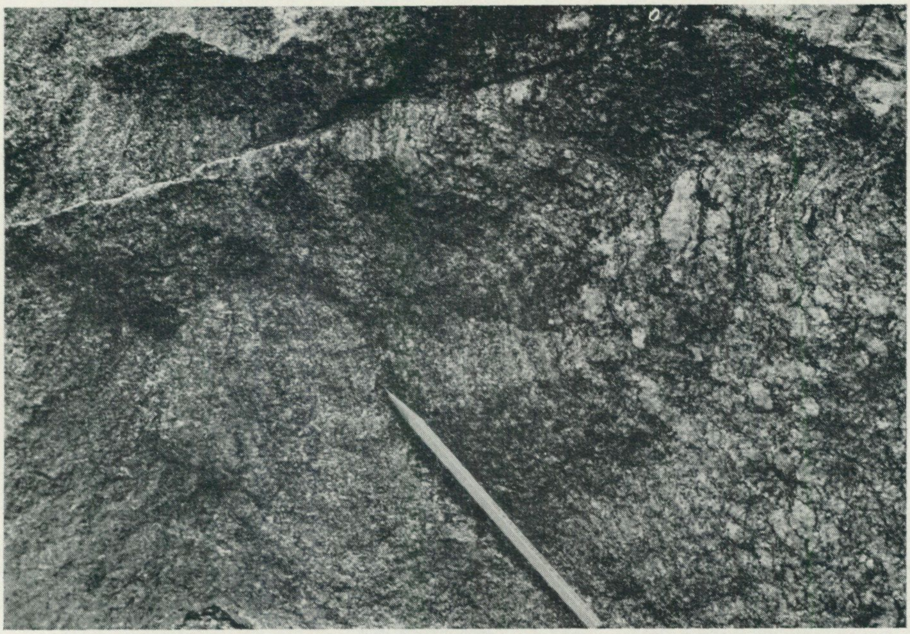

Fig. 42. Gradational contact between even-grained gneiss and augen-gneiss. Varekilsnäs.

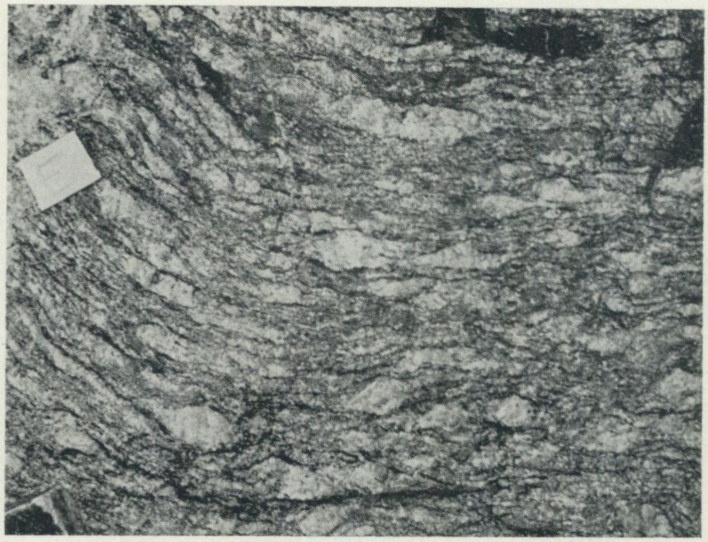

Fig. 43. Transition between veined gneiss (left) and augen-gneiss (right). Varekilsnäs.

Fig. 47 proves how tectonization boudinates the veins. These boudins are still polycrystalline and their length direction coincides with the fold axis. After the boudination recrystallization has caused the granular boudins to form more or less uniform crystals, often with two tails of granular matter (compare Fig. 46) in the direction of the lineation. Due to tectonic conditions, however, the feldspar of the veins can recrystallize to more rounded augen in a matrix which was weakly foliated or massive. As a comparison Fig. 48 shows how a concordant quartz vein in a mica-rich gneiss has been deformed. The quartz vein is boudinated and each boudin has a rectangular cross-section. One diagonal

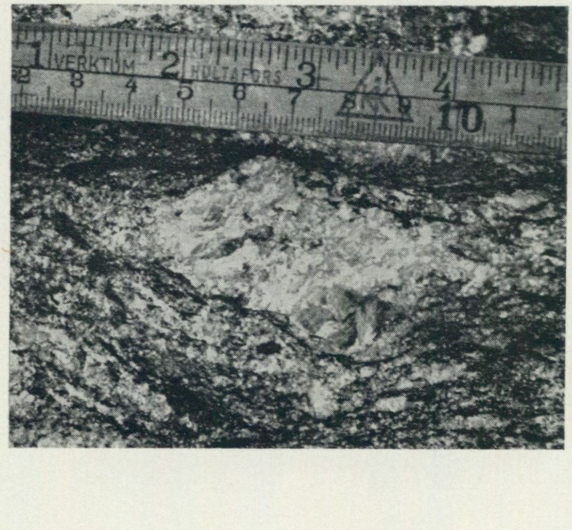

Fig. 44. Microcline porphyroblast with its long diagonal parallel to the schistosity. Varekilsnäs.

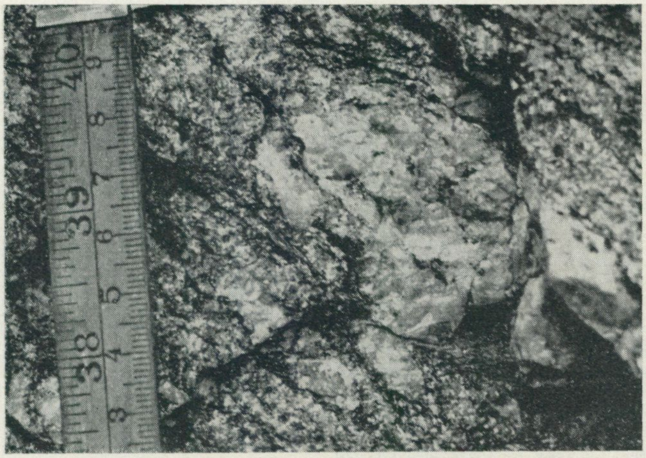

Fig. 45. Biotite layer from matrix passing through microcline porphyroblast. Varekilsnäs.

is parallel to the plane of foliation. The observation proves how deformation can form boudins of a rectangular cross-section.

The felsic bands in the gneiss at Varekilsnäs have been deformed in the same manner as the quartz vein. The form of the boudins has been modified by the post-deformational recrystallization, which tended to form a few large crystals from the primary many small crystals in the veins or boudins. The occurrence of biotite stringers through the augen eliminates the possibility of interpreting the augen-gneiss as a strongly tectonized granite. The section (Fig. 38) from the road cutting, too, rejects such an interpretation. The observations related indicate the following sequence:

Fine-grained gneisses → Veined gneisses → Augen-gneisses

We shall now see if the microscopical data, which hitherto have not been taken into consideration, support or reject the observations and conclusions reached in the field.

Fig. 46. Vein, partly recrystallized to augen. Varekilsnäs.

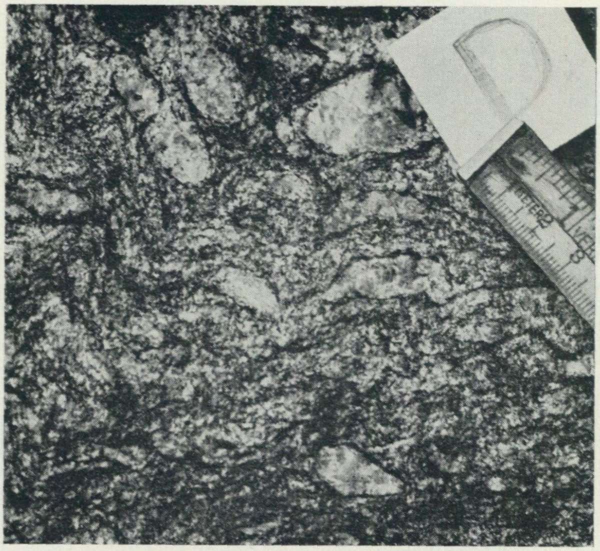

Fig. 47. Boudinated veins. The boudins have recrystallized to augen. Varekilsnäs.

The fine-grained supra-crustal rock at E (Fig. 41) contains up to 45 % of quartz (size 0.15—0.30 mm), feldspars 21 %, and the rest micas and epidote. The light bands are devoid of biotite — the dark bands get their colour from biotite. Tourmaline is present as an accessory mineral.

The amphibolite at C is black and strongly schistose and crenulated. It mainly consists of conformable hornblende prisms. Marginally the hornblende is altered to a yellow—light brown biotite. Strongly undulatory quartz forms long lenticles and veinlets parallel to the hornblende prisms. Epidote is very common. Garnet occurs.

The mineralogical composition of this amphibolite differs from those described earlier in the fact that it lacks plagioclase. This discrepancy is hardly a reason for

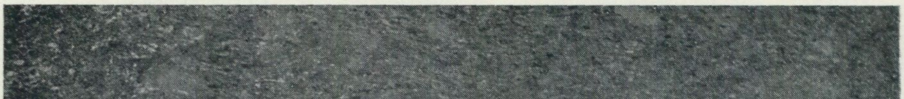

Fig. 48. Defo med quartz vein. The boudins are rectangular. Kållekärr 220.814.

supposing any other origin than that of the other amphibolites in the area. The rock thus certainly a product of volcanic activity.

With regard to the veined gneisses and the augen-gneisses, the thin-sections give no information other than that there was a pronounced secondary formation of K-feldspar at the expense of plagioclase. The strong potassium metasomatism has also influenced the aplites, which in their composition differ from the gneisses in the respect that their content of ferro-magnesian minerals is low. The field observations showing that the aplites are pre-potassium-metasomatic are thus confirmed.

It is quite evident that the fine-grained gneiss and the amphibolite belong to rocks of supra-crustal origin. The field observations and microscopical data confirm that these rocks have been subject to a considerable increase of K-feldspar, probably first as a veining. Tectonization boudinated the veins and the boudins which then were formed have recrystallized into larger augen. Certainly this is not the only way in which augen were formed. In a later part of this paper an example of another origin of the porphyroblastic augen-gneiss will be dealt with. Before we leave Varekilsnäs with its excellent examples of augen-gneiss formation Backlund's (1950) ideas on augen-gneiss formation may be cited, as they, in some respects, coincide with the present writer's. Backlund says that the rigified feldspathic bands during tectonization reacted with boudinage. This was followed by a flowage of the adjacent mica-rich layers (op. cit., p. 35). However, Backlund gives no microscopical or other documentation of this. He concludes the cited paper with suggestions on the formation of augen-granites by potassium metasomatism of basalts, ideas for which the present writer finds no proof in the present area. In the same paper, Backlund also reports that gray augen of microcline occur in a calcic environment, the red augen being a sign of a calcium-deficient milieu.

In this connection it may be observed that the augen in the immediate vicinity of the amphibolite with its high amount of epidote minerals are gray, and not red, as they are in the rest of the augen-gneiss.

THE EXPOSURES AT RÖRA

We shall return to the granitic augen-gneiss on Tjörn and now consider the geology at Röra 21.88. A section is shown in Fig. 49. The section is along the 880 line between 20 and 24 according to the grid system on the geological map. The section is seen from the south. The letter A represents the augen-gneiss with the augen often elongated and indicating the lineation. B is a massive augen-granite with no foliation or lineation. Its massive character is also obvious from the rounded outcrops formed by this type of granite. C is a garnet amphibolite. Above the amphibolite there is a slab of medium-grained gneiss marked D. At the contact to the amphibolite the gneiss is fine-grained

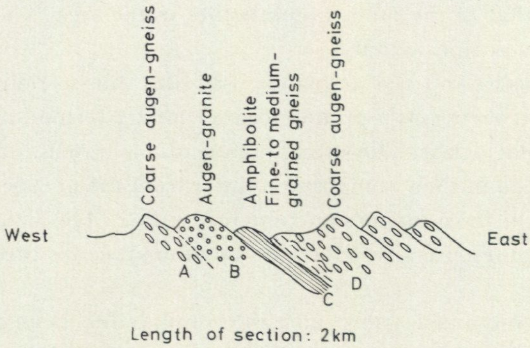

Fig. 49. Section at Röra.

but further away from the amphibolite the grain size in the gneiss has increased. In the medium-grained part of the gneiss slab there is a bed of white quartzite, which seems to have been unaffected by the general increase in the grain size. The increase of grain size is accompanied by an increase of the red-feldspar content. The feldspar forms veins and porphyroblasts. (See Fig. 50.) The quantity of microcline porphyroblasts increases further up in the gneiss, but still there is a distinct difference between the feldspathized gneiss slab and the granitic augen-gneiss. The gneiss septum is medium-grained while the granitic augen-gneiss is coarsely medium- to coarse-grained. The presented section shows that the gneiss is very little affected by potassium metasomatism *near* the amphibolite, and that further away from the amphibolite metasomatism and recrystallization have increased. Thus the amphibolite has preserved the gneiss. The gneiss immediately above the amphibolite has a general grain size of 0.5 mm. It contains porphyroblasts (1—2 mm) of plagioclase (composition An_{20}). The groundmass

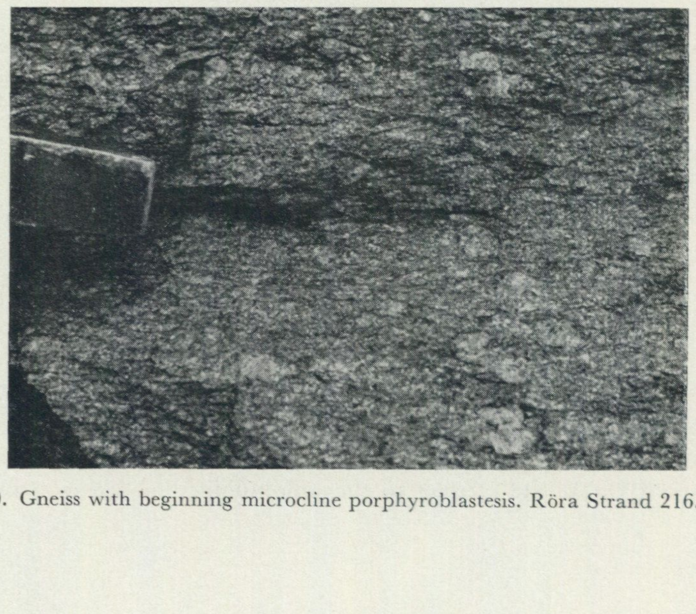

Fig. 50. Gneiss with beginning microcline porphyroblastesis. Röra Strand 216.892.

consists of strongly undulatory quartz, green biotite, and muscovite. Potash feldspar is present though in minor amounts. It is secondary, and when plagioclase and microcline contact each other, a typical myrmekite texture is formed in the plagioclase. The microscopical investigation proves the rock to be a normal gneiss of a type frequently seen as paleosome in the migmatite area.

The results derived from this section permit the following conclusion. The amphibolite seems to have prevented the solutions causing potassium metasomatism and recrystallization from affecting the rocks above and near the contact to the amphibolite. Thus the amphibolite is responsible for a comparatively low metamorphosed rock, *viz.* the medium-grained gneiss, which forms a thin coating east of the amphibolite and hornblende porphyrite. At the southern extension of the amphibolite 204.815 the dip is much steeper (65°) than near Röra (30°). Where dips are steep the lower metamorphosed gneiss septum is much thinner than where dips are flat. This can be explained by the more or less "shadowing" effect of the amphibolite stratum which was impermeable to ascending metamorphosing solutions. Where the dip of the shadowing amphibolite is steep, the unaffected rock volume is small or absent, as at the southern end of the amphibolite (at 204.815), but when dips are flat the unaffected volume is considerable, as in the section south of Röra.

COMPOSITION OF THE GRANITIC AUGEN-GNEISS

The mineralogy of the granitic augen-gneiss is shown by the volumetric analyses given in Table 16.

Table 16. Mineralogical composition of granitic augen-gneiss

Locality	% by vol.					
	Quartz	Microcline	Plagioclase	Biotite	Epidote	Acc.
171.859 . .	23	48	19	8	2	Gar. Tour.
163.716 . .	30	36	19	10	5	Gar. Tour.
176.790 . .	27	36	30	6	1	Gar.

Gar. = Garnet. Tour. = Tourmaline.

Fig. 51 shows a polished specimen of granitic augen-gneiss.

The gneissic texture is caused by the parallel alignment of the biotite and the lenticles and stringers of quartz, which show wavy extinction. Grain size varies from 0.5—5 mm in the matrix. In this matrix there are large microcline porphyroblasts of up to 30—40 mm diameter. There is a close connection between the grain size of the matrix and the size of the porphyroblasts, so that increasing grain size of the matrix is accompanied by an increase of the size of the blasts.

Quartz occurs as two types. The "external" quartz is of the same size as the predominant grain size in the matrix. It forms undulatory grains often elongated in the plane of foliation. The external quartz is thus an integral part of the

Fig. 51. Granitic augen-gneiss. Polished specimen. Häller 176.794.

groundmass. The second type, "internal" quartz, forms small, rounded grains of 0.3—0.5 mm diameter which are not undulatory. These small grains are found as inclusions in plagioclase and in microcline.

Microclines are partly cross-hatched, partly of flame-perthite type, and partly clear. Microcline is the youngest mineral. It is strongly penetrative and forms veinlets between the other minerals. It is also found to attack the plagioclase and replace it in the same manner as described in earlier sections of this paper. 2V values have been determined in both the interstitial potash feldspar and in the porphyroblasts. The determinations gave results between 85 and 86° indicating a low temperature of formation.

Plagioclase is strongly dusty. The dust consists mainly of sericite but there is also a little clinozoisite. The grain boundaries of the plagioclases are corroded. Myrmekite is frequently met with where plagioclase is attacked and partly replaced by potash feldspar. The An-content is 23—10 % and varies in the same thin-section. The plagioclases are sometimes found to be bordered by a 0.05 mm wide rim of dust-free albite (Fig. 52). Biotite always occurs in distinct layers. It is pleochroic in light brown and yellowish brown and is partly altered into a green biotite.

Epidote occurs in the biotite layers. The iron content seems to be connected

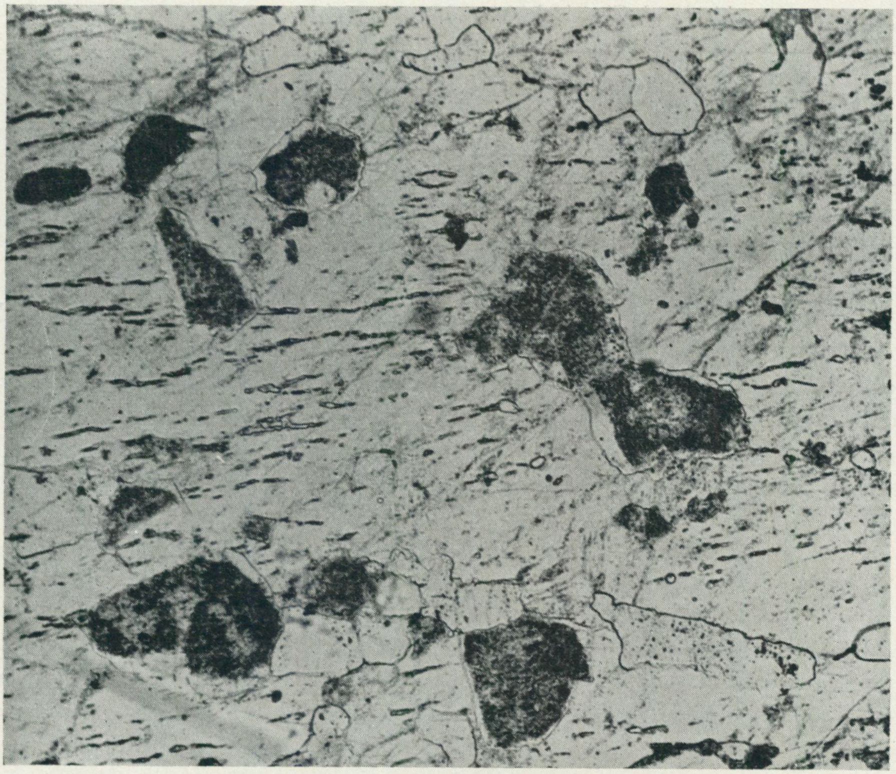

Fig. 52. Microcline containing relicts of sericite-dusted plagioclase with a rim of clear albite. Ord. light. 30 x.

with the total biotite content. Thus in the specimens with high biotite content, pistacite dominates, in those with lower biotite content clinozoisite is predominant. It may also be observed that there occur in the same thin-section both clinozoisite in the felsic layers and pistacite in the mafic layers. Accessory minerals are garnet and tourmaline. The garnet has n = 1.786 and unit-cell dimension of 11.66 Å, corresponding to a composition of about 50 % almandine and 30 % grossular. The tourmaline is a schorlite, i. e. the same tourmaline which was found in the low-metamorphic sediments at for instance Tjuvkil.

Compared to the fine-grained sediments the granitic gneiss has a higher content of feldspars and a lower content of quartz. Other differences are not significant.

The writer is aware of the danger of drawing conclusions from chemical analyses of rocks unless these are made on a wide statistic scale. However, the following results (Table 17) are put forward even if from a genetical point of view they are of minor importance. The specimens analysed are from Dyreby 176.790. The mineralogical composition of that rock is given in Table 16. As seen from this table the mafics are rather scarce. This can also be concluded from the analysis.

Table 17. Chemical composition of granitic augen-gneiss

Locality	% by weight								
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
176.790 . .	75.27	0.38	12.11	0.57	2.30	0.44	0.83	2.59	4.92
Niggli values: *al* = 42.7, *fm* = 18.3, *c* = 5.4 *alk* = 33.7, *si* = 449, *k* = 0.55, *ti* = 1.8.									

A comparison with the low-metamorphic sediments gives the obvious result that this rock contains more alkalies than the sediments. The lower content of Fe and Mg in the granitic augen-gneiss does not mean that these elements have been withdrawn by metasomatism. It is a primary feature. It must be mentioned that the fine-grained gneisses and schists also are influenced by potassium metasomatism, though not to the same extent as the augen-gneiss.

DISCUSSION ON THE ORIGIN

The mineralogical composition indicates a sedimentary origin. The internal quartz can be explained as relicts of the primary quartz, which was captured in the growing plagioclases and therefore escaped the recrystallization and deformation which characterize the external quartz (compare p. 79). The plagioclase gives no sure indication of the origin of the rock. Some of the plagioclases are faintly porphyroblastic and all of them are strongly "dusty" due to inclusions mainly of secricite. The formation of sericite is the first sign of potassium metasomatism (compare p. 43). The dust-free border zone of albite is also a result of the potassium metasomatism. Potassium replaced sodium in the feldspar lattice and the expelled sodium formed a border zone of albite. The small inclusions of clinozoisite in the plagioclase are also the result of the breaking down of the plagioclases. The plagioclases are so intimately connected with the microcline that their testimony cannot be separated from that of the microclines. As mentioned above the K-feldspar is the youngest mineral, and its strongly penetrative character is beyond all doubt. Its tendency to replace the plagioclase is also evident. An indication of this is, of course, the remnants of plagioclase in the microclines, and the small rounded quartz inclusions which have survived the transformation of the plagioclases into microclines (Fig. 52). The epidote minerals frequently occurring are no doubt the minerals which have captured the calcium set free from the plagioclases which were altered to microclines. The comparatively high 2V values indicate that the microclines have been formed at moderate temperatures. The light-coloured biotite is also an indication of low temperatures as magmatically formed biotite is generally dark. The accessory mineral tourmaline gives an indication from origin from sediments of the same kind as those occurring in the eastern part of the mapped area.

The field observations — especially illustrative at Varekilsnäs, but also at many other localities within the augen-gneiss areas — point to the metasomatic formation of veins and augen in a groundmass which has a mineralogical composition and a texture very similar to the para-rocks met with on the eastern and western parts of Tjörn. The formation of veins and augen requires supply of potassium, as the other elements needed for the secondary formation of K-feldspar, *i. e.* Si and Al, are abundant in the primary material. Small-scale metamorphic differentiation cannot be responsible for the enrichment of the potash-feldspar matter in the porphyroblasts, as there is an increase of *total* potassium. The formation of microcline porphyroblasts in amphibolite has to be regarded as a positive indication of a migration of the matter forming microcline, though it is not a proof of a long-distance migration. The traversing micro-veinlets of K-feldspar so frequently encountered everywhere in the granitic augen-gneiss, indicate a high degree of mobility of the matter forming the feldspar veins. This matter has been able to infiltrate and permeate the country rock and react with it. The introduction of matter must have been performed by aqueous solutions which had a viscosity low enough to permeate the rocks transformed. The structural continuity of the feldspathized rocks (granitic augen-gneisses) and the thin septa of fine- to medium-grained low-metamorphic gneisses and fine-grained amphibolites is a criterion of the replacement origin of the granitic augen-gneiss rather than a criterion on a magmatic, intrusive origin. The microscopic observations confirm that feldspar-forming solutions were extremely penetrative.

As there has been an addition of matter it is not surprising to find an increase of *volume* of the metasomatically altered rocks. The feldspar porphyroblasts have grown in a texturally unchanged groundmass (cf. Figs. 44, 45). The potash-feldspar porphyroblasts amount to at least 20 % of the total volume. An increase of volume seems unavoidable unless there has been an equal loss of matter simultaneously with the growth of the porphyroblasts. Loss of water has occurred. The amount of the decrease in volume due to this loss is difficult to estimate, but it has not been of the same order as the increase. The balance points to an increase of volume. There are no signs of a loss of ferro-magnesians which would perhaps be expected — as discussed in connection with the analysis. It is very difficult, however, to establish an increase of volume when the metasomatism was synkinematic. Metasomatic reactions are, by numerous authors, regarded as processes which do not change volume (Lindgren, Goldschmidt, Barth, and others). Opposition to the constant-volume "law" is, however, also strong. Poldervaart (1953) has proposed a method of petrological calculations which gives the amount of change in volume. He is aware of the difficulties in calculating volume changes and states, ". . . the writer believes that the problem of volume changes during metamorphism is probably attacked best by detailed studies of field relations" (p. 496). The observations indicating increasing volume during granitization and metasomatism are manifold. As early as 1904 van Hise assumed that metamorphism was normally attended by changes in volume (Poldervaart, op. cit., p. 494). Wegmann (1935) said that the formation of light minerals (potash-feldspar porphyroblasts) in some cases caused an increase of volume (p. 324). Rosenqvist (1943) published a paper on metamorphism from the Opdal area in Norway. On p. 173 he writes about, "considerable increase in volume by transformation of hornblende schist into augen-gneiss." In a later paper Rosenqvist (1952) delivered a strong criticism on Barth's standard-cell calculation, which is based on the theory of constant volume. "The whole idea of the standard cell of constant volume, containing 160 atoms of oxygen, is thus based upon a false premise and if applied to metamorphism it may in certain cases lead to severe errors" (op. cit., p. 90). The increasing volume in connection with granitization is stressed by Eskola (1950, p. 11) though he maintains that granitization is caused by a granitic magma. But in this connection, when only the volume problem is considered, this is of no relevance. Misch (1949 b) has studied the volume problem connected with granitization. He has found that, unless there was a removal of material, the feldspathization obviously causes an increase of volume (p. 400). This idea is also advocated by Perrin (1954). Recently Marmo (1956) has studied how the metasomatic introduction of K and Si causes an increase of volume. If the tectonical conditions were favourable the metasomatically swelled rocks would appear in domes (p. 487). Later Marmo (1958) is more exact in his statements on these problems. He writes that K and Si migrate to the least compressed areas and reappear in the crests of folds, there causing a feldspathization (pp. 37—39).

Many more examples of increasing volumes during granitization/feldspathization could be cited but these suffice to show that in this connection, increasing volume can be regarded as a universal phenomenon. Which are then the signs of increasing volume? Poldervaart (1953) has expressed his view in the following way, "Volume changes result in the deformation of the rocks, rendered plastic by the existing higher temperatures and permeation by the aqueous fluids. Thus, the intricate foldings often observed in metamorphic terrains are believed to be, at least in part, the outcome of these volume changes which in turn result from the rise in temperature. This last factor initiates metamorphism and granite formation" (pp. 501—502). The observations on the granitic augen-gneiss on Tjörn establish the existence of a folding in an intricate pattern (cf. Fig. 31). That same type of folding which caused a plastic flow is not observed in the low-metamorphic area of schists and fine-grained gneisses, but is found in the migmatite area. The conclusion is then that this type of folding is closely connected with a high degree of metamorphism where secondary feldspathization has played an important role, and thus also an increase of volume has occurred. Other, but also important, indications in the same direction are the frequent breccias on the eastern border of the granitic augen-gneiss (compare Ljunggren 1954, p. 35).

They also indicate the volume increase and the mobility which — in connection with tectonical movements — resulted in the formation of breccias. These and similar breccias will, however, be treated in a later chapter.

In earlier sections of this chapter the problem of the matter introduced has been touched upon. We shall now consider this question more in detail.

WHAT HAS BEEN INTRODUCED?

As seen both megascopically and in the microscope there has been an increase of potash feldspar. Short-distance metamorphic differentiation has played a minor role and the introduction of matter a major role. The following lines are intended to give an answer on the question above.

As mentioned in earlier sections K, Na, and Si are found to be extremely mobile elements, as numerous workers on metamorphism have established. The low mobility of Ca and also of Al is more controversial but anyhow it can be agreed that these elements are much less mobile than the first mentioned. For the secondary formation of potash feldspar, potassium and silica are necessary, but also aluminium. In many investigations dealing with feldspathization there is often only a short statement that potash feldspar is formed by solutions containing K and Si, and the source of Al is overlooked. Ljunggren (1954), however, has considered the aluminium problem in detail. He connects the secondary formation of microcline with the muscovite content of the rock unaffected by metasomatism which, according to the present author, conforms with the experiences on Tjörn. The following formula is a possible explanation of the potash-feldspar formation out of muscovite, quartz, and potassium.

$$2K^+ + KAlSi_3O_{10}(OH)_2 + 6SiO_2 \rightarrow 3KAlSi_3O_8 + 2H^+ \qquad (1)$$

Mol. vol.: 137 ml 136 ml 327 ml

Increase of volume: 20 %

The amount of new-formed feldspar is more than twice the volume of the consumed muscovite. However, there are also other sources of aluminium for the feldspar formation. Cordierite has been observed in the schists and could also be a possible — though minor — source of Al. As seen in the volumetrical analyses, muscovite is an essential mineral in the fine-grained gneisses and schists, but absent or nearly so in the granitic augen-gneiss. If all muscovite in the sediments were converted into microcline, the total amount would easily reach the microcline values given in Table 16.

No doubt all K wanted for this transformation need not necessarily be introduced from outside. If sodium were introduced, the following reaction which liberated K may take place:

$$3Na^+ + KAl_3Si_3O_{10}(OH)_2 + 6SiO_2 \rightarrow 3NaAlSi_3O_8 + K^+ + 2H^+ \qquad (2)$$

Albite is formed and the liberated $K+$ may react with other muscovite according to formula (1). It is difficult to estimate the amount of silica introduced on one side and the silica omnipresent on the other having been used in reactions (1) and (2). Undoubtedly silica was introduced together with the potassium but also the quartz content of the primary material could have been used in the reactions (1) and (2). Where microcline porphyroblasts are found in an extremely dark groundmass introduction of Si must have occurred as the groundmass is devoid of quartz. Biotite and albitic plagioclase are the dominating minerals in such rocks. In cases where the silica is of local origin, which means that it is taken from the immediate vicinity of the new feldspars, the increase of volume is naturally much less than when the blasts were formed by introduced K *and* Si. When, however, the potash-feldspar porphyroblasts and/or veins are found in a ground-mass of a composition identical to the fine-grained gneisses and schists, a simultaneous supply of both K and Si must be assumed. When the solutions containing K and Si reached a rock with sufficient amount of aluminium for feldspar formation, microcline was formed. Pure quartzites are resistant to secondary growth of potashfeldspar due to their lack of Al, and not as recently pointed out by Stålhös (1962) depending on the low permeability of those rocks (p. 69).

When the solutions percolating through the rocks reached an amphibolite, the outer zone of it was biotitized (Wegmann 1935). Undoubtedly the mantle of biotitized hornblende would prevent — or at least make resistance to a further penetration of the solutions into the amphibolite due to the abundance of mica flakes. The core of the amphibolite would be unaltered. This is just the case observed on Tjörn, where the amphibolitic beds are biotitized marginally (compare p. 38).

From the discussion above it is obvious that the phenomena observed in the granitic augen-gneiss, and in the inclusions of structurally concordant amphibolites, can be explained by ascending water solutions of mainly K and Si. However, the possibility of these solutions also making Al mobile over restricted areas should not be overlooked. Gavelin (1960) has given a very interesting view on granitization. Following quotation from him clarifies how Al can become mobile.

"The role of water as a catalyst in metasomatic formation has been emphasized by many investigators. The occurrence of water, even in very small amounts, is therefore believed to facilitate greatly the diffusive transfer of matter. As concerns such kinds of mineralization as feldspathization, which is one of the most important processes in granitization, a very interesting hypothesis has been proposed by Gabrielle Donnay, Whyart, and Sabatier (1959). They found experimentally that water acted as catalyst in the substitution of Al — Si and that the formation of silicates through the diffusion of Si and Al in the solid state is thus greatly facilitated by the presence of even very small amounts of water. A mechanism was proposed by these authors, which involves that OH^-ions enter the SiO_4-tetrahedra in silicate structures, thus creating strong polarizing effects which weaken the bonds and facilitate a migration of Si and Al through the lattices" (op. cit., p. 267).

If this holds true some of the new-formed microclines need not use the "local" supply of Al in the form of muscovite for their formation. The solutions have themselves had all the constituents required for the feldspar formation. This is certainly the case concerning the microcline porphyroblasts in mafic rocks.

FROM WHERE?

Ramberg has coined, and frequently used, the expression "chemical squeezing", thereby meaning the pushing out of K, Na, Si, O, and H_2O from deap-seated rocks in the granulite facies. These deap-seated rocks have been the source of the mobile, feldspar-forming solutions (Ramberg 1952, p. 247). The solutions have migrated to low-pressure areas and there precipitated their cation content. Similar thoughts are frequently met with in recent investigations on the origin of granites. Marmo (1961) has clearly stated that the potassium — if not juvenile — is derived from the clay minerals in the sediments. Potassium was expelled when the sediments were subject to regional metamorphism. "The potassium thus expelled may reappear in the interstices of other rocks and result in granitization" (p. 137). "Under tectonically favourable conditions and sufficiently large free-energy-gradient levels, the expelled material may be concentrated by hot waters and form granitic and aplitic veins and dykes"(pp.137—138). Mehnert, Perrin and Roubault, Reynolds, Read, and others have expressed similar thoughts.

But how do these ideas look in the light of the results of experimental anatexis reached by Winkler and co-workers? They have performed isochemical metamorphic experiments on common sediments with excess of water at pressures of 2 000 atm. and temperatures up to complete melting. The pressure during the experiments corresponds to that prevailing at 7—8 km depth in the crust. Experiments on illite-quartz clay show that at 700° C there is a partial anatexis. The melt is, compared to the primary material, enriched in SiO_2, potassium, and sodium. The unmelted remainder contains more Al_2O_3, MgO, and iron oxides than the primary clay. From these experiments we see, that when the temperature rises to the point where partial melting begins, the elements required for feldspar formation are set free from a sediment of so ordinary a composition as an illite-quartz clay. It is, however, certainly not the *melt* containing Si, K, Na, and H_2O which has formed the porphyroblasts, but *solutions* derived from anatectic melts. The high values of the optical angles in the microclines indicate that the feldspars were formed at moderate temperatures (Spencer 1938) and not out of a melt. Marmo (1961) concludes from his experience "... that microcline may indicate a slow accumulation of granite-forming material under moderate temperature. If this accumulation is more rapid, or the temperature elevated, orthoclase will be formed instead of or in addition to microcline" (op. cit., p. 138).

In the next chapter some very important tectonical factors will be treated.

The importance lies in the close connection between tectonical position and degree of feldspathization.

Chapter 12

Folding and other tectonical factors affecting granitization

The lineations in the central part of Tjörn generally plunge 20°—30° in a northeasterly direction. Important exceptions are found in the migmatite area at 13.68 where fold axes plunge in southern to southwestern directions. This confirms the interpretation that the pinching out of the granitic augen-gneiss to the south is caused by a plunge of the fold. Lineations in southern directions are very sparse, probably due to the very strong lineation in a northeastern direction, which was impressed in a stage after the formation of the anticlinal crest.

An anticlinal crest is also found on eastern Tjörn north and south of Höviksnäs. The anticlinal crest form is proved by the strikes and dips of the enclosing gneisses. Though sparse, the lineations also speak in favour of interpreting the pale red augen-gneiss-granite as an anticlinal crest. There are lineations plunging south in the southern part of the crest and northerly plunges are seen in the northern part. Generally these lineations — which are true fold axes — are better preserved in the enclosing schists than in the anticlinal core, where primary textures are veiled by strong granitization.

For these reasons, the few fold axes plunging south must be regarded as conclusive evidence of my interpretation of the central south parts of Tjörn as an anticlinal crest. The eastern limb of the central anticline has been deformed. The result of this deformation is a flexural fold on the eastern limb. But this deformation only occurs in the southern part of that limb. Further north the same deformation caused the compression of the synclinal fold in the fine-grained gneisses (Fig. 53).

In earlier chapters the "up and down" relations of the gneisses were treated. In a later connection the relationships between the gneisses and the granitoid rocks were discussed. We are now going to study the sections which on the geological map are marked AA^1, BB^1, and CC^1 (Fig. 53).

Observations in the field suggest two limbs of an anticlinal fold in the section AA^1. The presumed limbs dip outwards from each other, but the vertical and easterly dips at 145.700 make it possible that the presumed anticline is tilted a little westwards. The septa of medium-grained veined gneiss and amphibolite are interlayers in the folded mass. They have escaped metasomatic granitization. In a part of the anticlinal fold there is a slightly gneissic augen-granite. The gneissosity in this part is very much less pronounced than in the granitic augen-gneiss. In some parts the rock lacks parallel structures. This rock type which

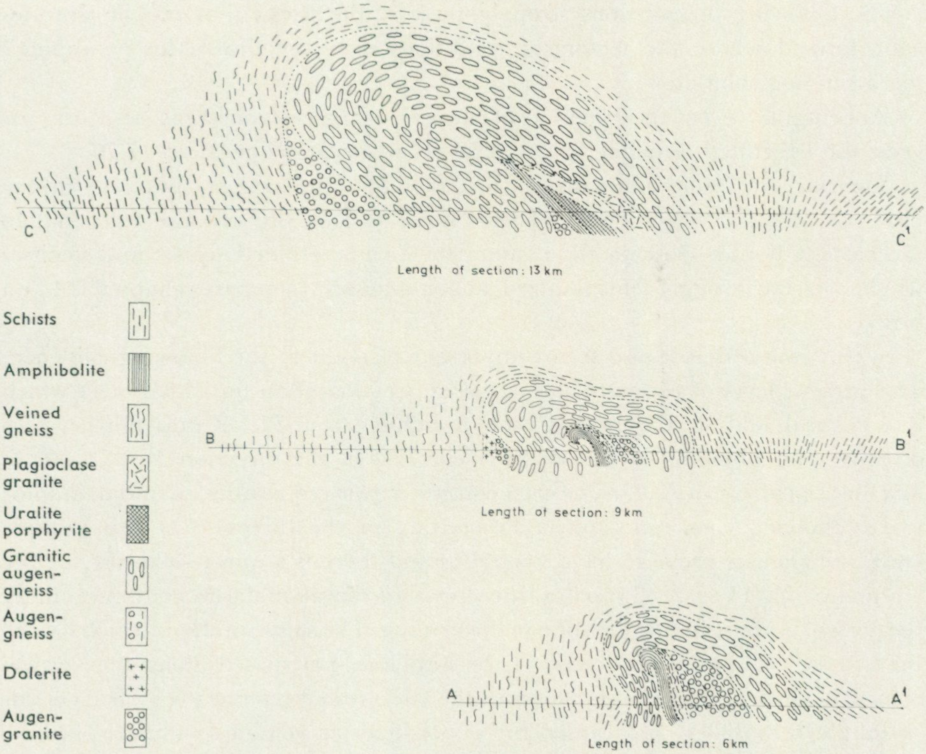

Fig. 53. Sections through the reconstructed anticlinal fold, central Tjörn, also showing the compressed synclinal fold (near B^1 and C^1).

occurs under the presumed flexure, and the previously treated augen-gneiss can, in the field, be separated by the lack of large-scale structures in the former (compare the questas) and also by its slightly lighter appearance.

In section BB^1 the anticline is much more overtilted than in the previous section. The slightly gneissic augen-granite diminishes due to a plunge in a northeastern direction. Under the overtilted part of the anticline, there is a completely non-structured augen-granite, which contains strongly displaced and rotated fragments of coarse-grained veined gneisses.

The section along the line CC^1 shows, to the east, the syncline of fine-grained gneisses and schists, the central part of which is compressed, and thus has steep dips. The "roofing" position of the gneisses on the granitic augen-gneiss is seen in the section. The "shadowing" effect of the amphibolite is also evident from the unaltered fine-grained gneisses *above* the amphibolite. The ascending solutions assembled under the amphibolite and caused an intense feldspathization and mobilization there. The mobilization is evident from the fragments of amphibolite which are found in the augen-granite at 21.85 and 205.880. But the transporation of the fragments was surely restricted to very short distances.

The following observations strongly support the thesis that mobile granites were formed where the tectonical conditions were favourable for "trapping" the ascending solutions:

— Augen-granite occurs either *under* impervious greenstones (as at Röra) or *under* the overtilted anticline as at 15.80 or *in* the anticline as at 17.70.

— Breccias are found not only in the augen-granite proper, but also in the pale red, granitic augen-gneiss. There, however, the breccias are restricted to the eastern border close to the contact to the fine-grained schists and gneisses which roof the strongly feldspathized augen-gneisses (compare chapter 14 on breccias).

In this connection it also seems important to point to the following evidence: The present level of exposure shows the upper part of an anticlinal crest which is a flexural fold of the eastern limb stretching from Bleket in a northeastern direction and plunging at its northern end 20° in the direction N 40°—50° E, and disappearing at 22.75. The crest consists of pale red granitic material, in some places showing weak gneissosity. Proceeding in the direction of this granitic crest, the gneisses prove to have steep dips and there is a quartz-feldspar veining (compare pp. 11—12). Probably the crest of granitic material continues under the present surface in the direction of the veining. The same solutions which caused the intense feldspathization seen in the anticline, percolated along the vertical or nearly vertical planes of foliation in the compressed part of the schist syncline (from 23.76 to 32.93) and caused the quartz-feldspar veining. (compare pp. 11—12) The importance of these features lies in their confirming the interdependence of metamorphism and tectonics (folding). The paths of the ascending metamorphosing solutions were determined by the degree of permeability of the bedrock. The permeability was reduced by flat sheets of amphibolite. Anticlinal arcs diminished permeability due to the content of phyllosilicates which, when orientated perpendicular to the flow (that means horizontally or nearly so), prevented permeation or made it difficult. Where the solutions passed through the bedrock, moderate changes occurred as in the area of medium-grained, veined and migmatitic gneisses on western Tjörn. Dips in this area are rather steep, thus enabling the solutions to pass through. In other areas, as on eastern Tjörn where dips are flat, the degree of metamorphism is low and secondary microclinization is weak. In places where the solutions were captured under a mantle of amphibolite or in an anticlinal crest, most intense alterations of the primary rock occurred. When the amphibolite sheet is less flat as at point 205.816 the capturing effect does not exist and no intense feldspathization occurred.

It seems as if the depth to which the sediments were buried was of minor importance for the degree of feldspathization and mobilization compared to the factors discussed above. Rocks of different metamorphic degree are found very close to each other (compare Read 1957, p. 357). As suggested, among others by Marmo, the altering solutions were also transferring heat. If this explanation is applied to the area investigated the present distribution of rocks is easily explained. The rocks which were once mobile are found where, for one reason or other, ascending solutions were captured. In the chapter on breccias the same phenomenon, namely mobilization of granitic material under an impervious cover, will be discussed.

Chapter 13

Light red augen-granite

The light red augen-granite occupies four distinct areas. The most uniform, non-schistose augen-granite is found at Röra 210.885 in the lenticular granite body stretching along and under the flat roof of amphibolite.

The vast areas of augen-granite along the western border of the granitic augen-gneiss are not so uniform as the geological map implies. A general trend is that the gneissosity of the groundmass between the augen increases from east to west. This will be dealt with when treating a locality near Hällebäck 155.767. The fourth area of light red augen-granite is near Bleket. On the island of Bockholmen, immediately southwest of Bleket, an extremely coarse-grained type of augen-granite was found.

The light red augen-granite is easily distinguished from the granitic augen-gneiss by the absence of gneissosity in the matrix. In the field there is also an easily discernible difference in the morphology of the outcrops of the two rock types, owing to the presence or absence of gneissosity. There is, however, a continuous variation in this respect observed in the granite area west of Stenkyrka.

The grain size of the matrix is generally between 0.5 and 2 mm — the augen are 5 to 10 mm in diameter. The colour of the weathered surface is light red to grayish red. The fresh rock is more gray. Microcline is the dominating mineral. The optical angle 2V is very nearly 78°. The microclines are beautifully cross-hatched. A rim consisting of round plagioclase grains, 0.1—0.3 mm in diameter, often borders the microcline augen, which are most often round or a little elongated. Where the granite contains fragments of supra-crustal rocks, as for instance at Röra, some of the augen are idiomorphic (see Fig. 54). Where the granite brecciates supra-crustal rocks, the augen are monocrystalline and have a slightly violet tint. However, their composition is that of ordinary microcline.

The plagioclase is generally strongly sericitized except along a thin dust-free border zone. Remnants of plagioclase are also found in the cross-hatched microclines (Fig. 55). The composition of the plagioclase is that of albite-oligoclase. The biotite is brown. Hornblendes are found in small quantities in the matrix. An iron-rich epidote also occurs there. Quartz is found as undulatory small grains, with sutured boundaries.

On the island of Bockholmen an extremely coarse-grained granite type is

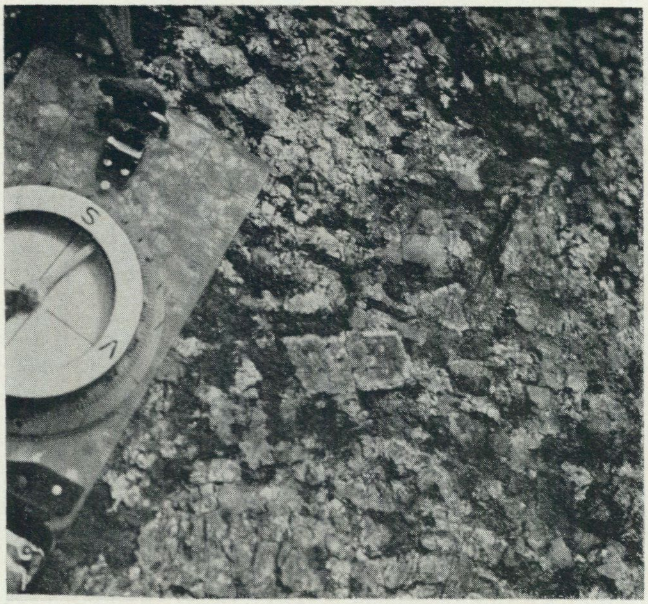

Fig. 54. Idiomorphic microcline with albite rim. Augen-granite. Röra 206. 880.

encountered. Observations prove that this type of granite does not border distinctly the granites of similar composition but of ordinary grain size. The coarse granite, here called gross-granite, is grayish pink which is the colour of the dominating mineral — the potash feldspar. There are crystals of K-feldspar up to 10 cm long. Between the very large potash feldspars there is a subordinate mineral mesh with biotite and quartz as megascopically discernable minerals.

The matrix also contains medium-grained plagioclase which is secondarily altered to a high degree. It contains plenty of clinozoisite (length 0.04 mm) and sericite (length 0.2 mm). Calcite was also found in the plagioclase. Its composition was determined in both altered and fresh crystals. In the latter the anorthite content is 30 %, in the former 5—15 %. In the sericitized plagioclase the muscovite flakes are orientated parallel to (010). The biotite in the matrix is yellowish brown to light green. Titanite is frequently found together with the biotite.

Though the large potash feldspars are single crystals, they are far from homogeneous. They contain inclusions of quartz, biotite, and often milky white plagioclase. The plagioclase is sometimes seen to form a coating about one mm thick around the potash feldspars. These are veined by minute albite veins. The plagioclase in the border, which consists of small discrete grains, contains plenty of clinozoisite. The plagioclase of the inclusions is thus identical to that of the surrounding matrix. The optical angle 2V of the gross-feldspars is 80° to 81°.

A chemical analysis of matter from one of the augen in the gross-granite from Bockholmen has been performed:

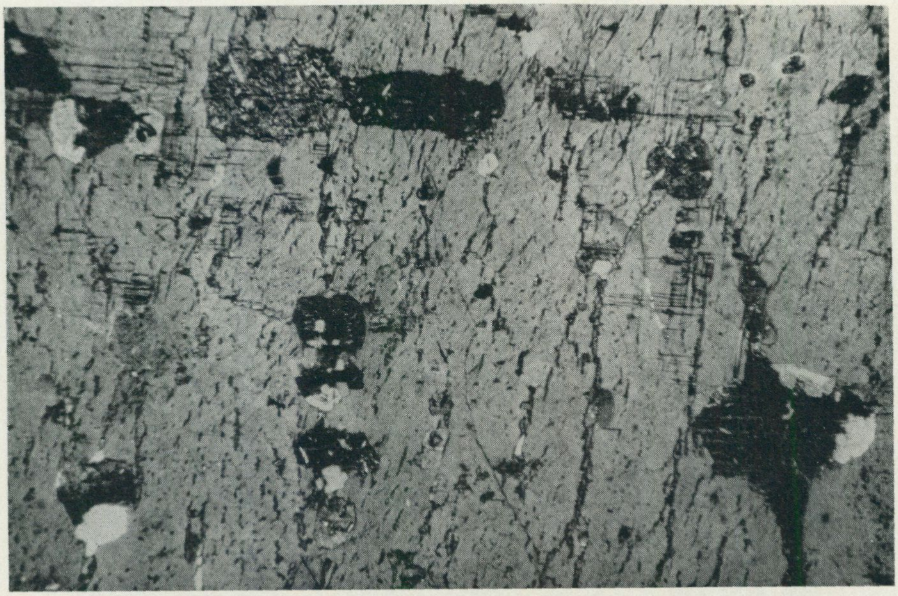

Fig. 55. Remnants of plagioclase in microcline. Nic. +. 25×.

Table 18. Chemical composition of feldspar augen, Bockholmen

% by weight						
SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O
64.82	0.06	18.65	0.45	0.88	1.99	12.39
Computed feldspar composition: Or = 77 %, Ab = 18 %, An = 5 %						

Table 19. Chemical composition of augen-granite

% by weight											
Locality	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O^-	H_2O^+
165.738	65.94	0.84	13.54	1.98	5.34	0.10	0.92	2.74	2.36	4.91	0.10	1.09
Niggli values: *al* = 33.4, *fm* = 31.4, *c* = 12.4, *alk* = 22.8, *si* = 278, *k* = 0.58, *ti* = 2.5												

The next section will deal with a more intricate part of the augen-granite. It has granular augen and a gneissic matrix — thus showing transitions to the granitic augen-gneiss.

THE OUTCROPS NEAR HÄLLEBÄCK

Along the road to Hällebäck 155.767 which traverses the southern part of the western granite area, there are several outcrops showing features that indicate beyond doubt that the granite has behaved in a mobile way. These features are breccias with strongly displaced fragments of fine-grained supra-

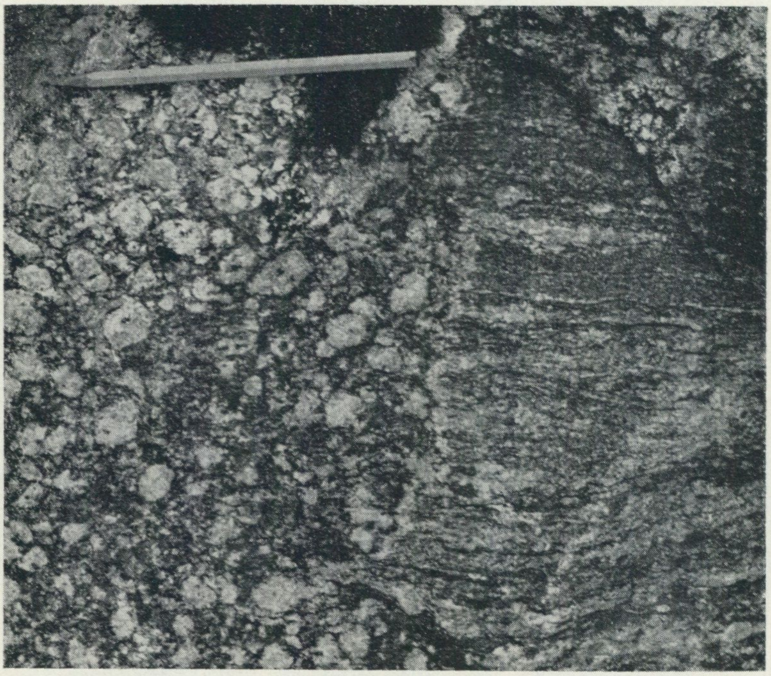

Fig. 56. Augen-granite with fragment of veined gneiss. Hällebäck 155.767.

crustal rocks and fragments of veined gneisses lying in the coarse augen-granite. But there are also features such as gradational transitions from true supra-crustal rocks over augen-gneisses to non-structured augen-granites indicating a metasomatic origin of the granite. Fig. 56 shows the normal brecciating character of the augen-granite with strongly displaced fragments of veined gneisses. This granite has non-granular augen and is found in the eastern part of the granite body. Further westwards there are supra-crustal discs in the augen-granite. These fine-grained, often mafic discs are transformed into augen-gneisses in their lateral parts, with a distinct gneissosity formed by biotite schlieren (Fig. 57). Further away in a direction perpendicular to the strike the gneiss character successively disappears. Decreasing gneissosity is quite naturally observed when mobility increases.

The augen are granular as long as the matrix still has a gneissic structure. Non-granular augen consisting of one single or a subordinate number of crystals are found in the brecciating granites. Even if this generally holds true there are several exceptions. There are augen close to each other — one granular and the other consisting of few large potash-feldspar crystals. There are examples of beautifully rounded augen with a diameter of 20 mm having a 5 mm thick outer rim of uniformly crystallized pale red to pink potash feldspar, surrounding a grayish mesh of plagioclase and quartz (Fig. 58).

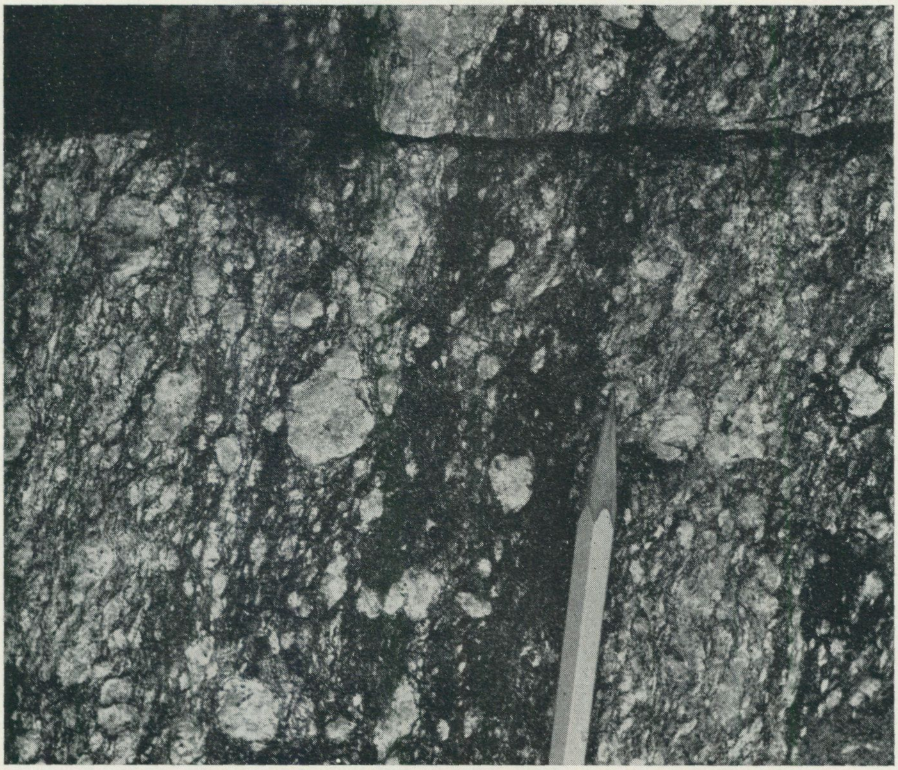

Fig. 57. Microcline porphyroblasts in mica-rich matrix. Hällebäck 155.767.

The granular augen are light gray. When recrystallization increased the size of the crystals in the augen these became pinkish. A microscopical study reveals that the granular augen consist of 0.5 mm large plagioclases, which are strongly dusty, cross-hatched microcline, and some undulatory quartz. The plagioclase-microcline ratio determines the colour. When plagioclase still dominates, the colour is gray — the pinkish tint comes with increasing microcline content (which also depends-on the grain size) and a less mafic matrix.

Two augen of similar grain size — one gray and the other reddish — were taken out of their dark matrix and partially analysed. Mafic constituents were separated by means of bromoform. The results of the analyses are given below in Table 20.

Analyses and computed formulas support the results reached by microscopy, viz that the reddish colour is coupled with the potash-feldspar content.

The augen lie in a very biotite-rich matrix. They often contain flakes of biotite. The orientation of the "internal" biotite is, as it seems, arbitrary.

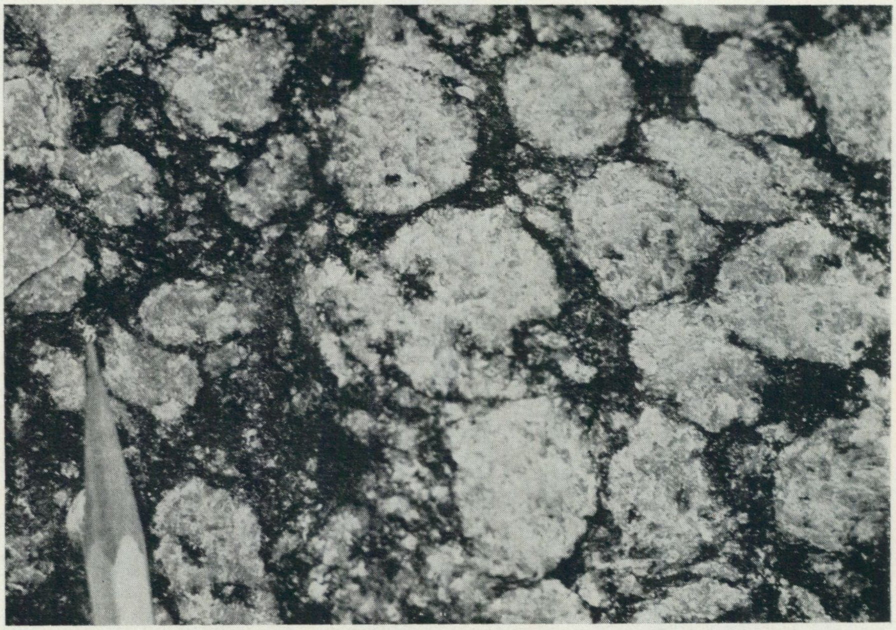

Fig. 58. Round, polycrystalline augen in a gneissic matrix. Hälleback 155.767.

Table 20. Chemical composition of gray and red augen, Hälleback

Type	% by weight						
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O
Gray augen .	65.80	0.06	19.31	0.55	1.26	2.52	10.10
Red augen .	65.37	0.04	19.06	0.51	0.77	2.57	11.22

Computed feldspar composition
Gray augen: Or = 66 %, Ab = 26 %, An = 8 %
Red augen: Or = 71 %, Ab = 25 %, An = 4 %

DISCUSSION ON THE ORIGIN

On pages 82—88 the origin of the granitic augen-gneiss was discussed, and the observations were, according to the opinion of the author, satisfactorily explained.

The gray and pink, rounded augen of polycrystalline matter, such as those seen in Fig. 58, cannot be explained in the same way, however. The following events are the possible explanations of this type of augen formation;

1. The original matter was of mafic-calcic composition and of volcanic or, more probable, of sedimentary origin.

2. The processes forming the rounded plagioclase clusters were of the same type as those responsible for the formation of cigar or spindle structures found in the leptites of

Central Sweden (Geijer 1923, Magnusson 1925, Hjelmqvist 1942, and Bergström 1959). An important difference between the cigar structures of Central Sweden and the augen from Hällebäck is that the latter form rounded clusters contrary to the cigars and spindles of the leptites. The round clusters must have been formed during a static phase — the fusiform clusters in the leptites during a dynamic phase (compare Bergström 1959, p. 666).

3. The plagioclase has partly been replaced by potash feldspar. This seems to be a rule within the investigated area. The new-formed potash feldspars readily form monocrystalline augen. Naturally the question arises how the porphyroblastic augen were formed but before discussing this the following facts have to be stated:

a) The primary clusters are fine-grained and contain a high percentage of plagioclase. b) Potash feldspar replaces the plagioclase except along an outer zone — other minerals remain unaffected by the potassium metasomatism. c) Simultaneously with the feldspathization the new-formed microclines recrystallized into a joined lattice. This lattice was partly capable of freeing itself from foreign mineral lattices either by rejection or resorption.

The primary plagioclase-dominated clusters were the result of specific PT conditions, favouring a concretionary accumulation of plagioclase matter to certain spots. The country rock in which they grew could easily deliver plagioclase matter in sufficient amount by short-distance transport. (Clusters of fine-grained plagioclase of similar type as those found in the gneisses, but generally very much smaller, are observed in amphibolites subject to special pressure-temperature conditions.) The conditions did not favour the formation of large plagioclase crystals.

The formation of microcline porphyroblasts which in this case is a transformation of the plagioclase clusters, must according to Drescher-Kaden (1948) have taken place by means of solutions surrounding the growing porphyroblasts (p. 219). This is necessarily the case when, for instance, potash-feldspar porphyroblasts are formed in an amphibolite which in itself is devoid of potash feldspar (compare p. 69 in this paper).

Drescher-Kaden also gives an explanation of the formation of porphyroblasts with a rim of minerals from the groundmass. He regards the porphyroblast as being capable freeing itself from of the minerals foreign to it and of incorpo--rating other minerals in its lattice. The former occurs when the solutions are still in an active phase. In a less active phase, the solutions are not capable of the intense dissolving of inclusions — this resulting in a rim of mineral fragments in the porphyroblasts (op. cit., pp. 219—223).

If these ideas are applied to the augen-bearing rocks at Hällebäck they are easily understood. The potash-containing solutions, which also supplied heat, collected in the sites of the plagioclase clusters and transformed the plagioclases there to microcline perthite. Biotite which occurred in the clusters was foreign to the porphyroblast, and was thus rejected from the lattice. On the other hand the albite component of the plagioclase is in this case akin to the porphyroblasts, and is thus incorporated and forms the albitic veins of the microcline perthite.

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When the activity of the solutions was declining, the plagioclases were not transformed but enclosed in the consolidating microcline crystal (cf. Ljunggren 1954, p. 73). Eskola (1952) has described granitization starting with the formation of veined gneisses (p. 136) but also how gneissic rocks with porphyroblasts were gradually transformed into augen-granite. Lacy (1960) assumes that the microcline augen in a granite formerly were porphyroblasts.

The investigation of the augen-granite on Tjörn shows that there is no fundamental difference between the granitic augen-gneiss and the augen-granite.

MOBILITY AND PORPHYROBLAST FORMATION

The mobility of the augen-granites is estimated 1) by the ability of brecciating supra-crustal rocks, and 2) by the type of augen. This has been touched upon earlier (compare p. 94). Idiomorphic augen and mono-crystalline augen occur where mobility has been high. A possible explanation of this is proposed by Ljunggren (1954). He says, "During these transformations, especially at the rebuilding of plagioclase into microcline, the lattice is naturally in a very active state, and to a certain degree also mobile" (p. 62). This is surely one of the factors causing mobility of the augen-bearing rocks on Tjörn. But there is another factor: the high content of hot solutions which were necessary for the transformation of plagioclase into microcline. These factors are intimately interdependent and co-operate to the same goal: namely the complete transformation of plagioclase into microcline. Both heat and water content increased mobility.

The geological environment where these factors converge is at places where ascending solutions for some reasons were trapped. In the present case that happened under the isoclinally overtilted anticline. Thus the brecciating granite is found to the east and far under the roof. The described gneissic augen-rocks are found further west where the roofing effect of the overtilted anticline is less pronounced, and thus the capturing effect was also less pronounced. Certainly both the composition of the initial matter and the position of this matter in relation to tectonical units were important for the transformations.

The next chapter concerns breccias — a secondary effect of the mobility of the granite.

Chapter 14

Breccias

The investigated area gives a clue to where and why breccias occur. This was mentioned briefly in earlier chapters. A short recapitulation is justified, however. Breccias are found along the eastern contact between schists and augen-gneiss, under the roof of the amphibolite at Röra, and along the eastern contact

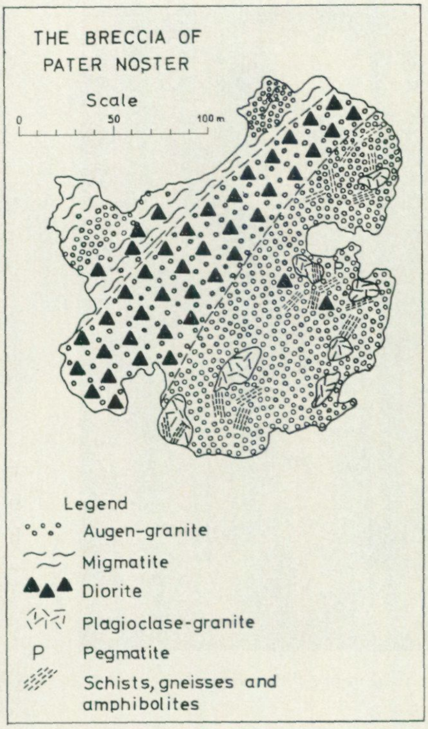

Fig. 59. The breccia of Pater Noster.

of the western granite area. The mentioned breccias occur along borders and are explained by a more or less pronounced local mobilization of the matter under the roof, which captured the ascending solutions. Where they were accumulated a mobilization occurred.

In this chapter we shall consider another type of breccia which can only be found in connection with minor occurrences of mafic rocks. The most spectacular breccia of this type is situated on the island of Pater Noster 005.526.

THE BRECCIA OF PATER NOSTER

During the years of 1882 to 1885 Blomberg visited the island three times. According to his field books he described the rock on the island as a mosaic of angular diorite fragments in a gneiss. On his last visit he modified his first conclusions, now regarding the brecciating rock matter as a granite. Beside these very vague statements, he gives no information on the petrography of the rocks on the island nor any interpretation of their genesis.

The distribution of the rock types is seen in Fig. 59, a map of the island. Three main zones are distinguishable: one western, one central, and one eastern zone. They strike N 40°—45° E and are thus conformable to the general direction of

Fig. 60. View of the breccia. Central zone, Pater Noster.

Fig. 61. Fragments in augen-granite. Central zone, Pater Noster.

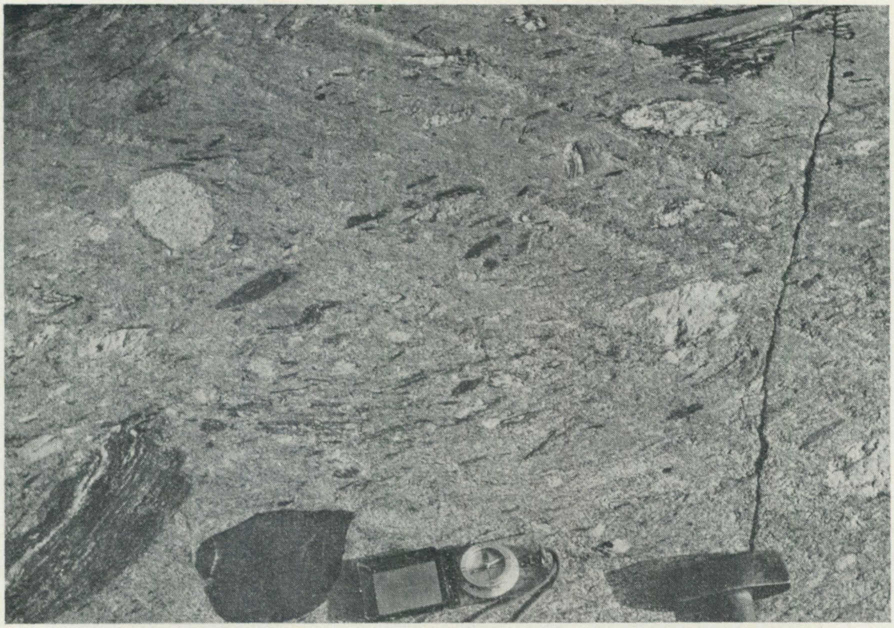

Fig. 62. Fragments in "mobilized" gneiss. Western zone, Pater Noster.

the strike in the Tjörn area. The dip is vertical or steeply westerly. In the central and eastern zone, the breccia character is very striking. Fig. 60 shows a general view of the central part with the dark inclusions. Fig. 61 is a detail of the same part. Fig. 62 is from the western zone showing fragments of different rock types in mobilized gneiss. Fig. 63 is from the eastern zone. The adjacent skerries show monotonously uniform rock types and are devoid of breccias.

ROCK DESCRIPTIONS

The central zone is characterized by its high content of angular mafic fragments of sizes from 15 cm to one m in diameter. Some fragments show parallel structures but some are completely non-structured In the gneissic types the schistosity is marked by thin layers of light minerals: plagioclase and subordinate quartz. These layers are one mm thick or thinner — the intercalated dark layers are of 5 to 10 mm thickness. They consist mainly of uralitic hornblende, which is orientated almost parallel to the light layers. The grain size is 0.2 to 0.4 mm. The primary pyroxene, which is frequently found in the cores of the amphiboles, has birefringence = 0.017 and 2V more than 60°. According to Tröger (1959) this is a clinohypersthene containing 33 mol. % of ferrosilite. The uralitic hornblende has changed into a biotite with Z pale green and X yellow. The biotite has ragged edges.

Fig. 63. Amphibolitic gneiss as an inclusion in even-grained granite which is an inclusion in augen-granite. Eastern zone, Pater Noster.

The unaltered plagioclase has a mean composition An_{37}, but most of the plagioclases are strongly secondarily altered, in which case they are clouded with epidote and sericite. They often form hypidiomorphic grains. Undulatory quartz grains occur in small amounts. Ore and chlorite are accessory constituents.

These petrographical features do not coincide with those of a supracrustal amphibolite, a rock type very frequent in the Tjörn area. The amphibolites in the area are characterized by a plagioclase which is far more albitic than the one found here, and their hornblende is in no case proved to be uralitic. The features of the present rock rather imply a deep-seated origin, probably closely connected with the next type of rock described, namely the massive mafic inclusions.

The main constituents of this rock (grain size 0.2 to 2 mm) are hornblende and a brown and yellow biotite. The biotite is secondarily formed from hornblende. Plagioclase occurs as laths without preferred orientation in the mass of mafic minerals. Some of the plagioclases have a somewhat lower anorthite content in their rims as compared to their central parts. The anorthite content in the cores varies between 25 and 45 %. Clinozoisite with anomalous blue interference colours is found in the plagioclase and is evidently an alteration product, more fre quently occurring in the albitic plagioclase than in the anorthite-richer ones. As mentioned above, the plagioclase is lath-formed and constitutes — together with the mafic minerals — a doleritic texture. The composition of the rock type is that of a diorite. The massive fragments are more frequent than those with gneissic structure.

Field observations indicate that displacement of the fragments in the central zone has been moderate. It seems reasonable to suppose that the mafic rocks once formed a continuous dike, which was later brecciated by the augen-granite. The brecciating augen-granite will be dealt with when all types of fragments in the three zones have been treated, because the same augen-granite is found in all of them.

The eastern zone is not so spectacular as the central, but is, from a geological point of view, extremely interesting. This part of the island consists of a heterogeneous breccia, and the fragments are of different genesis. The fragments belong mainly to the supra-crustal rock series described in chapter 2. There are fine-grained schists, medium-grained veined gneisses of the same type as those encountered on western Tjörn, and amphibolites of the same kind as those found at several places on Tjörn, as for example Röra, and Hakenäset 31.76 (compare p. 22). There are also pegmatitic fragments. A gray medium-grained granitic rock occurs as inclusions, too. Some of these fragments contain, in their turn, fragments of the more or less metamorphosed supracrustal rocks. Thus there are *two* generations of brecciating granite, Fig. 63. There are also fragments of massive, medium-grained, dark green hornblendite.

The fine-grained supra-crustal fragments have a general grain size of 0.3 mm (though the grain size in some fragments reaches 0.8 mm). The parallel structure-which is always present, depends on biotite in thin layers. Two typical fragments have been volumetrically analysed. The results are seen below:

% by vol.					
Quartz	Microcline	Plagioclase	Biotite	Epidote	Muscovite
31	19	27	13	4	6
32	15	26	21	—	6

The quartz is strongly undulatory with intricately sutured boundaries. The microcline is clear and fills the interstices between the other minerals. The plagioclases show hypidiomorphic forms. The biotite is pleochroic with Z brown and X light yellow. Apatite, calcite, clinozoisite, and ore grains are found as accessory minerals.

The pegmatite inclusions are light pinkish with a grain size up to 10 mm, sizes of 0.1 to 0.4 mm being predominant. The parallel alignment of the minerals shows that the pegmatite fragments are of the same type as the pegmatitic beds occurring in the fine-grained gneisses at, for instance, Rörtången and on the island of Katten. The plagioclases are strongly dusty and of albitic composition. The microcline is younger than the plagioclase. and behaves transgressively against both plagioclase and quartz. There are accumulations of small quartz grains along the borders of the microclines. There are also quartz grains inside the microclines. Greenish brown biotite is found in the pegmatite, which both in general appearance and petrographically is very similar to those found within the schist area (cf. p. 18).

The fragments of veined gneisses, which are similar to those found in the western area of Tjörn, have not been microscopically investigated. Megascopically, however, they do not differ from the common types of veined gneisses found elsewhere in the area, and their origin is obviously the same.

The fragments of light gray plagioclase granite are partly completely non-structured and partly have a slight gneissosity. These fragments are rounded. They also contain fragments of supra-crustal rocks. This fact is indicated on the map and is seen in Fig. 63. The grain size varies between 0.2 and 1.5 mm. The plagioclases are often slightly larger than the other minerals. Strong secondary alterations forming a dust of clinozoisite, sericite, and some calcite have reduced the primary anorthite content, which has certainly been considerably higher than at present (8—15 %).

Volumetrical analyses of two typical granites of this type are given below:

% by vol.					
Quartz	Microcline	Plagioclase	Biotite	Muscovite	Epidote
35	21	23	10	8	3
26	12	28	10	9	15

The quartz is in part strongly undulatory and shows intricately sutured boundaries, but there is also quartz with even boundaries. In the latter case wavy extinction is moderate or absent.

The microcline is clear in most of the investigated thin-sections. Perthites are not frequent. The microcline is, in minor amount, interstitial — most of it appears as xenomorphic grains which are integral parts of the mineral association.

The plagioclase — contrary to the microcline — has a slight idiomorphism, and generally forms the largest grains thus looking like augen.

Accessory minerals are apatite and magnetite.

The composition of this gray plagioclase granite differs in no significant way from the rock types described in chapter 8 on "light gray granite". The gray granite forming a triangular area on southern Tjörn contains fragments of amphibolite, schists, and veined gneisses. It seems most probable that the plagioclase-granite fragments found on Pater Noster were, before brecciation, united in a larger mass of gray plagioclase granite which contained fragments of the supracrustal rock series, identical to the area on southern Tjörn.

The western zone does not exhibit any new type of fragments. The main rock type in this zone is a migmatite, which already during the field work was classified as a mobilized gneiss. The bulk of the rock is gray and finely medium-grained. The composition is granitic. The structure is generally slightly gneissic with the micas forming planes of schistosity. Within this mass there are frequent minor fragments of the same rock types as those described above (see Fig. 62). The "mobilized gneiss" has, in places, phenocrysts or porphyroblasts of plagioclase.

The composition of the gneiss is:

% by vol.				
Quartz	Microcline	Plagioclase	Biotite	Accessory minerals
37	21	19	22	1

The augen-granite which appears in all three zones is characterized by its purplish red microcline augen of a diameter of 10 to 20 mm. They are usually round — however, both lenticular and idiomorphic augen were observed. There is often a whitish gray rim around the augen.

These augen lie in a dark groundmass dominated by biotite. Quartz, feldspars, hornblendes, and garnets are megascopically recognizable. The microcline augen are either cross-hatched or of vein type. Where the veins reach the border of the feldspar, they are often considerably wider, thus making the veins look funnel-shaped. These "funnel" vein perthites occur in connection with strongly undulatory quartz. Where the perthites are of grid type, the quartz is less undulatory. This gives a suggestion on the origin of the vein perthites; the funnel-shaped veins are the drainage system for the albite component (cf. Gates 1953). This drainage system was opened during the same tectonical phase as that which deformed the quartz lattice.

Around the potash feldspars there are zones of very small (0.1 mm), completely sassuritized plagioclases. These small plagioclases are, in their turn, surrounded by a dust-free rim. This rim is absent where the small plagioclases are in contact with quartz. Outside the complex augen there is often an accumulation of small clear potash feldspars of the same size as the plagioclase inclusions in the augen.

The matrix is dark. It contains quartz, plagioclase (An_{12}), brown biotite, hornblende (c/Z 19°, X yellow, Z dark green), clinozoisite, pistacite, garnet, ore, titanite, and apatite. It should be noticed that potash feldspar is only observed adjacent to the augen and not as an integral mineral component.

DISCUSSION

The formation of the augen-granite has followed the scheme lined out in earlier chapters. The porphyroblastic augen were formed from solutions containing the necessary components. The plagioclase rims are relicts which have escaped microclinization. The primary material is believed to have been of a sedimentary origin. The processes forming the potash-feldspar porphyroblasts are identical to those discussed on pages 96—98. Thus potash- and silica-bearing solutions have transformed the pre-existing plagioclases to microcline perthites. When the sediments were sufficiently soaked, but also heated by these solutions, the transformation plagioclase → microcline perthite took place. A certain degree of mobility accompanied this transformation. Undoubtedly the high content of water, too, made the rock matter mobile. Sufficiently great accumulations of ascending solutions with K and Si were reached under the impermeable mafic rock. Thus the formation of the granite and the brecciation of the mafic dike by the new-formed granite may be explained in the same manner as the formation of the augen-granites under the amphibolite roofs and in similarly roofed positions. The mafic, non-permeable rock is thus the necessary condition for the formation of the granite.

In the western zone there are no sharp boundaries between the mobilized gneiss and the augen-granite, but this fact is readily understood as the augen-granitic matter is derived from the gneisses; thus there must be transitional boundaries between the two rock types.

The central zone — which is a spectacular breccia — reminds one of the agmatite of Sederholm (1923). According to Sederholm's definition, the agmatite consists mainly of basic fragments included in a granite (op. cit., p. 117). Sederholm also explains the formation of an agmatite, "... the metabasalts ... have been brittle rocks, and devoid of well developed schistosity which would cause a more intimate 'lit par lit' injection. All these circumstances explain why we observe mainly such stages of granitization where 'agmatites', i. e. breccias with angular fragments were formed" (op. cit., p. 128).

The central zone of Pater Noster is, in the sense of Sederholm, an agmatite. The reason for the formation of angular fragments is the same as given in the quotation above. No doubt the diorite of Pater Noster reacted in a brittle way, which the angular fragments indicate. The eastern zone of Pater Noster is, however, not an agmatite but a common breccia. It should be emphasized that the fragments of the gray granite are rounded and not angular. Possibly this is an indication that this rock type was tough and reacted in a less brittle manner than the diorite.

The present distribution of rocks on Pater Noster can be explained in the following way. The primary rocks were gneisses. Part of them were brecciated by the rock matter now forming the plagioclase granite (tonalite). (Similar tonalite breccias are found on southern Tjörn, (cf. p. 51.) Along the border between gneisses (to the west) and plagioclase granite with inclusions of supra-crustal rocks (to the east) the diorite intruded. The marginal zone of the diorite received a slight gneissic texture. The diorite acted as a plug for the ascending solutions which collected under it. Intense transformation of the supra-crustal rocks then took place and the augen-granite was formed. This new-formed granite acted in a mobile way and intruded into the broken diorite. However, the adjacent tonalite with supra-crustal inclusions was also broken up by the same forces as those which deformed the diorite, and the mesh of augen-granite intruded into this rock as well. The rounded forms of the tonalite inclusions can also be the result of a slight assimilation (cf. Fig. 63). There are some observations indicating that the augen-granite corrodes the plagioclase granite. That would explain the non-angular form of these fragments. The close genetical relationship between the migmatite and the augen-granite is demonstrated by the transitional boundaries between them.

THE BRECCIA ON STORA BUSKÄR 050.575

On the western point of the island there are two minor breccias of great interest. The brecciating matter consists of the same augen-granite as on Pater Noster, but the brecciated matter is a little more uniform than on Pater Noster. There is, however, one similarity between the two breccias and that is that the augen-granite is closely connected to an occurrence of a mafic rock — in this case a dolerite.

Fig. 64 is a map of the western breccia on Stora Buskär. The bedrock consists of migmatitic veined gneiss with amphibolitic beds. The main strike is N 50° E and the dips are vertical or steep easterly. The migmatite is agmatitic: amphibolite-gneiss fragments are interwoven by light, medium-grained, granitic matter. The felsic parts of the gneiss became mobile and filled the space between fragments of the amphibolite-gneiss which was brittle and non-plastic (Fig. 65). The microscopical investigation proves that the brecciating rock matter has the same mineralogical composition as the surrounding gneisses. The main mineral is plagioclase. The rock shows signs of having been subject to potassium metasomatism. Potash feldspar replaces the plagioclase. The plagioclase/potash-feldspar ratio is the same in the brecciating matter as in the gneisses. The brecciating matter is evidently a mobilized gneiss similar to the rock type occurring on western Pater Noster.

Within the agmatite and veined gneiss there is a composite dike striking E—W and dipping vertically or steeply south. This dike is 3—4 m wide and can be followed for 40 m. It consists of fragments of fine-grained, greenish black dolerite, plastically deformed veined gneiss, and angular amphibolite in augen-granite. The dolerite fragments are corroded by the augen-granite

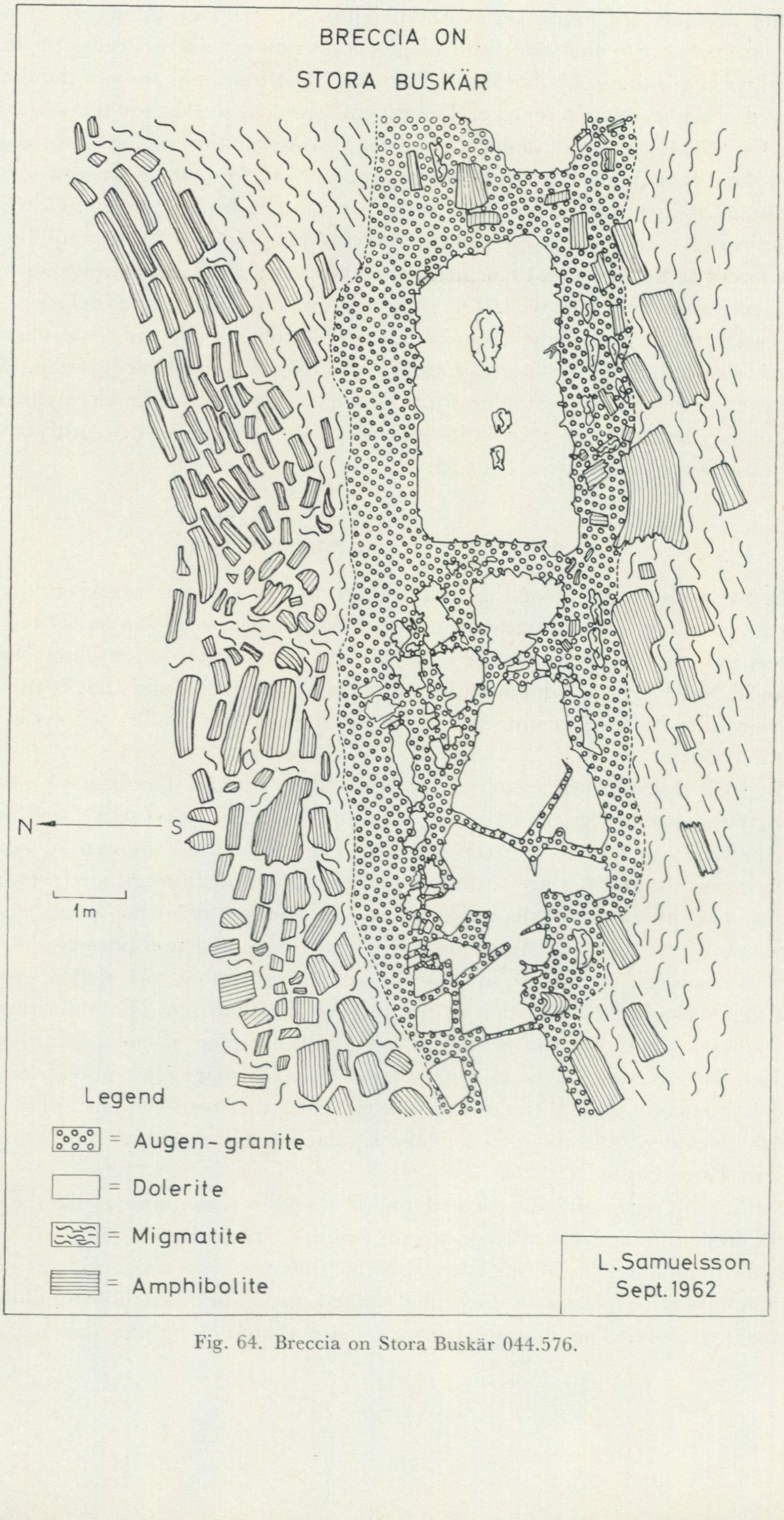

Fig. 64. Breccia on Stora Buskär 044.576.

Fig. 65. Amphibolite-gneiss fragments interwoven by mobilized gneiss.
Stora Buskär 044.576.

(Fig. 66), except along cracks which were formed in a late stage when the corroding effect of the augen-granite had ceased.

In the largest dolerite inclusion there are fragments of a light gray gneissic rock. The fragments are corroded by the dolerite. The dolerite is also lighter in a 30 cm wide zone around the gneissic fragments. The contact relationships indicate that the gneissic rocks are inclusions, which have been corroded by the dolerite. Parts of the inclusions have been assimilated by the dolerite and have altered the composition of the doleritic magma around the fragments. This can be seen from the lighter colour.

The field observations are interpreted in the following way:

1. The bulk of the rock consisted of a sedimentary pile of varying composition. It gave rise to amphibolite and felsic gneisses.

2. During metamorphism and tectonization the mafic rocks were subject to brittle deformation. The felsic rock matter became mobile. This mobile mass was pressed out into the cracks between the amphibolite fragments.

Fig. 66. Corroded dolerite fragments in augen-granite. Stora Buskär 044.576.

3. When PT conditions were lowered to that point when the rock became brittle, it was intruded by a doleritic magma. Fragments from the wall rock were incorporated by the dolerite and became partly assimilated.

4. The augen-granite is geographically restricted to the immediate vicinity of the dolerite dike, which was brecciated by the augen-granite. The granite used the same path of intrusion as the dolerite.

5. Possibly the dolerite dike is responsible for the formation of the augen-granite because of its roofing effect — thus in analogy to the factors causing formation of the augen-granite described earlier.

Only 30 m south of the described dolerite dike brecciated by the augen-granite there is a similar but smaller dolerite dike which is also brecciated by augen-granite. There are no connections between the two granite occurrences in the present surface. The granite is restricted to the two doleritic dikes.

OTHER AUGEN-GRANITE OCCURRENCES CONNECTED WITH MAFIC ROCKS

On the island of N. Teste 045.596 there is a massive medium-grained diorite. This mafic rock is penetrated by augen-granite which has corroded the mafic

Fig. 67. Penetrating and corroding augen-granite. N. Teste 045.596.

fragments (Fig. 67). Similar formations can be seen at several other places together with massive mafites. On the eastern point of Klädesholmen 102.645 there is an amphibolite-gneiss fragment in the migmatite. The central parts of the fragment have been penetrated by augen-granite. This rock is also found on the contacts immediately around the amphibolite fragment, but not elsewhere. The same phenomena are to be seen on Vannholmarna 06.61 and Väggen 090.612 and on the island of Tjörn at point 167.718.

From these examples of small augen-granite occurrences it is evident that it is the mechanical properties of the mafic rocks (and not their petrographical properties) which are important for the formation and fixation of this augen-granite.

The dolerite with quartz inclusions found between Stenkyrka and Skärhamn at 16.74 is penetrated by augen-granite, too. This mafic rock differs from the dolerite on Stora Buskär in the presence of ellipsoidal, milky blue quartz inclusions of up to 6 mm length, occurring in the most fine-grained parts of the dike. The inclusions consist of many undulatory quartz grains. They also contain small blebs of potash feldspar. The matrix consists of plagioclase laths and chlorite. In the central parts of the dike pyroxene is preserved. The texture is doleritic. In the middle of the dike the grain size reaches up to 5 mm whereas the marginal parts are fine-grained and show a slight schistosity. In the coarser parts cubes and octahedrons of magnetite are to be observed.

Because of the large augen-granite occurrence east of the dike, it is not remarkable that some of the most mobile parts of this granite have penetrated the mafic rock.

DIKE OF AUGEN-GRANITE

Augen-granite has been found at one place, forming a dike in other rocks than mafic ones. The dike cuts through the migmatite. It is found on Klädesholmen and is marked on the map. It traverses the eastern point of the island. It is 80 cm wide, strikes N 40° E and dips 85° NW. The adjacent bedrock strikes N—S. The dike contains fragments of veined gneiss. The augen in the dike have a violet tint and are hypidiomorphic and monocrystalline. The matrix has a moderate gneissosity parallel to the boundaries of the dike. This is the only place where granite of this type is found without any obvious connection with a mafic rock.

This dike proves that the augen-granite has acted independent of mafic rocks and in a mobile or pasty way. It has been emplaced when the PT conditions were such that the migmatite was brittle and thus formed cracks, which were filled with mobile augen-granite matter.

CONCLUSIONS ON THE BRECCIAS

Goodspeed (1953) has dealt with different kinds of breccias. He distinguishes between 1) igneous plutonic breccias, 2) replacement breccias, and 3) rheomorphic breccias.

The first type is characterized by angular fragments often disturbed by magmatic flow and influenced by deuteric metamorphism. The surrounding matrix can contain typical phenocrysts. It displays flow structures and there are also finer-grained borders towards the fragments.

The second and third types of breccias have many characteristics of the matrix in common. The matrix contains typical porphyroblasts showing various stages of development. The matrix shows no finer-grained borders against the fragments. In a replacement breccia the fragments are undisturbed. According to Goodspeed the replacement breccia is caused by granitization commencing along a joint system. The replacement breccia is formed during static conditions, and this is a characteristic feature.

The third type is the rheomorphic breccia. The matrix contains beside porphyroblasts idiomorphic phenocrysts. The fragments of the rheomorphic breccias are either rounded or angular and sometimes also plastically deformed. In this type of breccia they are always markedly displaced. The rheomorphic breccia was formed by movement of metamorphosed rock material. The relationship between the two last described types of breccias may be understood by quoting Goodspeed, "Many mobilized and rheomorphic breccias are similar to replacement breccias, since they have been derived from them during a later stage of granitization. They exhibit features indicative of plastic flow . . ." (op. cit., p. 466).

If the system for subdividing breccias proposed by Goodspeed is adapted to the breccias in the Tjörn area described above it is evident that the orthomagmatic plutonic type of breccias has not yet been encountered. The breaking up of the amphibolite seen on the map of Stora Buskär is a rheomorphic breccia. The other breccias as well, such as those forming the central and eastern zone of Pater Noster and the augen-granite breccia on Stora Buskär, are rheomorphic breccias in Goodspeed's sense. but more displaced. In the breccias there was a local mobilization of the metasomatized mass. Relicts of lower metamorphic degree than the augengranite are found as dislocated fragments in this granite.

The treated breccias are evidently younger than the main period of migmatitization, though the formation of the brecciating augen-granite is a result of the same processes which caused the migmatitization.

The dike of augen-granite on Klädesholmen is considered to be a rheomorphic dike. Possibly the granitic dike is connected with the coarse-grained granite on Bockholmen (cf. pp. 92—93). The formation of this very coarse granite requires an abundance of heat-bearing solutions. Thus it is probable that the new-formed granite was so mobile that it could intrude into a joint and form a dike as the one found on Klädesholmen.

Chapter 15

The norite-anorthosite complex on the islands of Brattön and Älgön

The bedrock of these islands has previously been a subject only for brief investigations. Svedmark (1888) just mentions the pyroxene-bearing rocks. In the description to the geological map of Gothenburg Blomberg (1902) describes the gabbro which is surrounded by schists and gneisses. He concludes that the gabbro (which in fact is a norite) forms laccolithic bodies in the schists.

Ljungner (1927) called the rocks on Brattön and Älgön the "Hakefjord massive". He gives a short survey of the field relationships and describes the noritic rock with its anorthositic "segregations". He regards the mafic rocks as an initial basic precursor to the sub-Jotnian rapakivi-granites.

Sederholm (1928) paid a short visit to Brattön. He fully accepted and endorsed the ideas of Ljungner (p. 75).

As seen on the map and in Fig. 68 the sediments dip towards the mafic bodies. On the northern shore of Brattön the sediments are steep or vertical. This zone of vertical sediments continues northwards, over the islands of Äggelös 31.61 and Lövön. The zone of vertical dips does not continue south of Brattön.

The contacts between the gneiss and the norite are distinct. The grain size

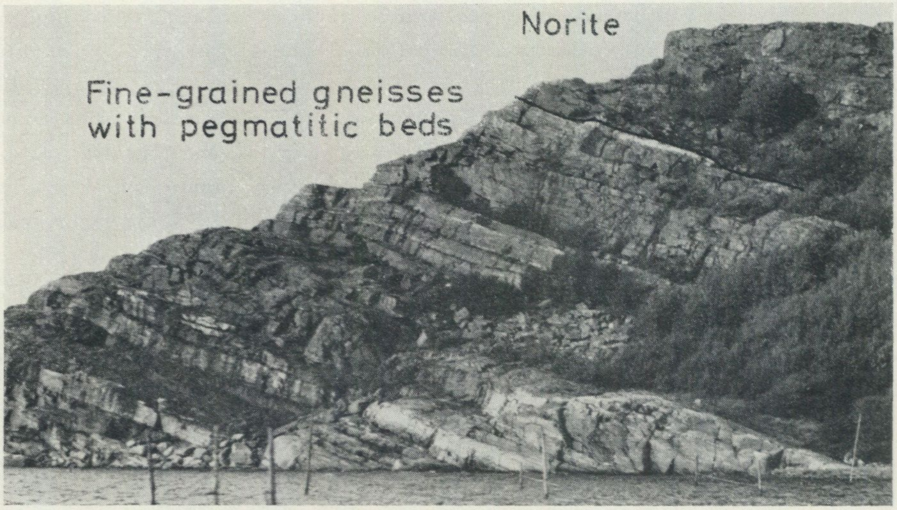

Fig. 68. Western part of Brattön seen from the south.

Fig. 69. Gneiss fragments in norite. Brattön 334.577.

Fig. 70. Anorthosite fragments in norite. Älgön 242.587. Height of the cliff about 25 m.

in the norite does not decrease near the contacts, except in the breccias. The gneiss is not altered on the contacts to the norite.

The breccias in which the grain size of the norite is smaller than usual occupy several square metres, Fig. 69. They contain fragments of fine-grained gneisses. Fragments bigger than 30 cm have not been observed. They are extremely disordered. Some fragments are corroded. The norite in the breccias is generally a little lighter than in the norite body proper, due to hybridization. These breccias are in the sense of Goodspeed (1953) igneous breccias, and prove the intrusive behaviour of the norite.

The norite also contains inclusions of greenish white anorthosite, Fig. 70. The size of the inclusions varies from a few cm up to 15 m. The inclusions are most frequent on the southeastern part of Brattön and on the east and west parts of Älgön. In other parts of the islands there is hardly any anorthosite at all.

NORITE

The norite is often rusty brown in colour, due to weathering. Apart from the weathered surface there are two kinds of norite: one altered and the other unaltered. The unaltered norite contains no hornblendes — in the altered norite all pyroxenes are more or less secondarily altered into hornblende. The grain size is 1—2 mm.

In the unaltered norite more than 50 % of the rock volume consists of hypi-

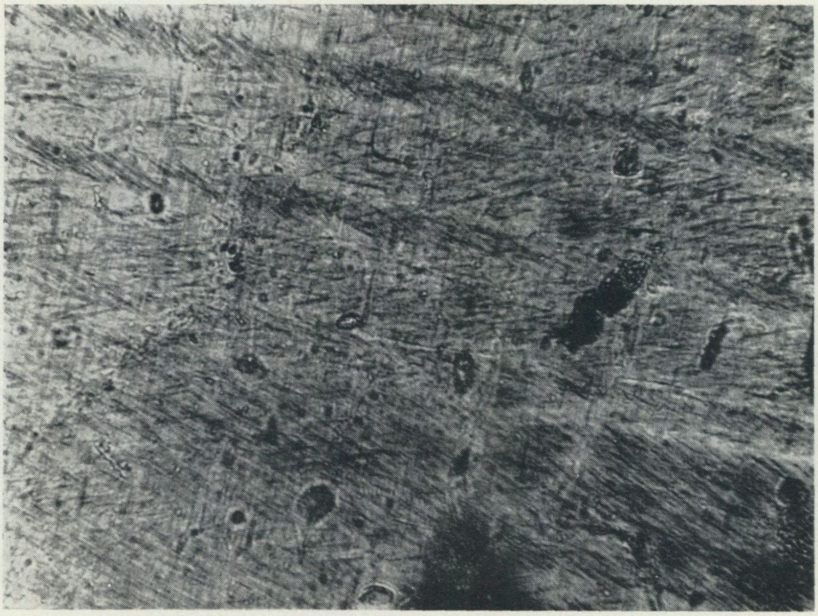

Fig. 71. Needles of rutile in plagioclase. Norite. Brattön. Ord. light. 100×.

diomorphic plagioclase which most frequently is twinned according to the Albite law. It contains 47—48 % of anorthite. The plagioclase has exclusively low-temperature optics. The cores of the plagioclase contain clusters of dark brown needles forming a characteristic pattern, Fig. 71. They have optic properties indicating that they consist of rutile. The plagioclase has also, occasionally, a rim of a slightly more albitic composition.

The orthorhombic pyroxene has $2V_x = 68—70°$, $n_x = 1.690$ (red), $n_z = 1.702$ (green). That corresponds to a hypersthene with 30 % of $FeSiO_3$. In some thin-sections, another pyroxene was observed, but sparsely. It is metallic gray, has high refringence, low birefringence (0.01), and $2V_z = 78°$, $c/Z = 33°$. It is not pleochroic. It has a striation // (010), which possibly is a twinning, as the optical properties are rather peculiar. Krokström (1932) has described a similar pyroxene from the mafic Breven dike in Central Sweden. He discusses the striation as a possible twinning, but draws the conclusion that the simple mineral must show similar optical properties. Thus, "the abnormal optical properties ... cannot be explained by assuming a polysynthetical twinning only, and consequently the question arises what kind of pyroxene it is" (p. 279). Krokström assumed that the mineral is jadeite. Probably the Brattö pyroxene is jadeite, too. To find jadeite in this kind of rock is not unique. (For example Seki et. al. (1960) have described jadeites from gabbroic rocks in Japan.) Biotite occurs as a primary mineral in the norite. It is pleochroic in light brown and dark reddish brown.

Ore is an essential constituent. The ore grains are 0.3 to 0.6 mm and they are generally rounded. The ore is most frequently associated with the biotite. Polished sections prove that one third of the ore grains consist of ilmenite and the rest of magnetite. Pyrite is subordinate. The ilmenite shows no exsolution textures which is a remarkable fact.

Non-undulatory quartz is found between the plagioclases. As an accessory potash feldspar occurs.

What processes gave the norite its present state? The low-temperature optics of the plagioclase are not surprising even if a magmatic origin is assumed. As van der Kaaden (1951) notices, plagioclase with high-temperature optics is extremely rare in plutonic and metamorphic rocks.

The rutile needles in the plagioclase are characteristic but not easily explained. Mac Gregor (1931) has described similar needles in plagioclase and regards them to be a result of high-temperature thermal metamorphism. Also Davidson (1943) suggests that rutile needles in garnet, scapolite, pyroxene, amphibole, and plagioclase may depend on regional metamorphism.

Possibly the rutile needles in the plagioclase of Brattön—Älgön are relicts from an ultra-metamorphic ancestry.

Several investigators of mafic rocks containing ilmenite and magnetite have drawn the conclusion that the unmixing of ilmenite from magnetite is closely connected with tectonization. Uytenbogaardt (1953) has pointed to the interrelation between metamorphism of amphibolites and the unmixing of ilmenite from magnetite in amphibolites. The same type of unmixing is also observed by Ramdohr (1951) in the regionally metamorphosed charnockites in the Varberg area. The cited examples have in common the fact that the unmixing occurs where strong metamorphism has been active.

As mentioned above, unmixing has not occurred in the ore minerals of the norite, though they contain rather high proportions of titanium (cf. Tables 22 and 23). The reason for this could be that there has not been a regional metamorphism in the investigated area after the emplacement of the norite.

ALTERED NORITE

The alterations have led to a mineral association stable at moderate PT conditions at the presence of water. Plagioclase is altered into a mesh of sericite, clinozoisite, and calcite. Tremolite-actinolite homoaxially coats hypersthene. Anthophyllite is also found to be an alteration product of pyroxene. The anthophyllite is altered to chlorite. During the retrogressive metamorphism the primary biotite was altered into diabantite ($n_\gamma = 1.625$). Quartz is slightly undulatory in the secondarily altered norite.

The volumetrical analyses, one from an unaltered and the other from an altered norite, show the mineralogical differences:

Table 21. Mineralogical composition of norite, Brattön

Type	% by vol.							
	Plagio-clase	Quartz	Pyr-oxene	Horn-blende	Biotite	Chlorite	Apa-tite	Ore
Unaltered norite . .	53	9	15	—	8	—	7	8
Altered norite . . .	50	8	—	10	7	12	4	9

This table, however, does not fully illustrate the secondary alterations, as the plagioclase in the altered norite is nearly completely sassuritized, but in the table above this is not seen. There is also a slight enrichment of ore in the altered norite. The ore grains are found in connection with the chlorite.

The alterations are illustrated by the following scheme:

Minerals		
Primary	Secondary	Final
Plagioclase	Epidote, sericite	Epidote, sericite, calcite
Hypersthene	Actinolite, tremolite	Biotite, chlorite, ore
	Anthophyllite	Chlorite
Brown biotite	Green biotite	Chlorite, ore
Quartz non-undulatory . .		Quartz undulatory
Ilmenite . .-		Titanite
Pyrite		Limonite

Fig. 72 shows an interesting type of norite alteration. The norite is interwoven by 0.02 mm thick veinlets filled with pale green chlorite. The chlorites are orientated perpendicular to the veinlets. Along the centre of the veinlet there is a dark line which is the border between the chlorites growing from each side of the walls of the veinlet. The veins traversing the norite are parallel. They penetrate the plagioclase, but not the pyroxenes or their pseudomorphs. The veins seem to emanate from the altered pyroxenes as they are wider close to them and pinch out at some distance. Furthest away from the pyroxene the veinlets are not filled with chlorite.

The alteration from pyroxene over hornblende and biotite into chlorite requires the presence of water, and as Buerger and Washken (1947) point out, water is necessary for recrystallization unless a critical temperature is reached.

In the present case the thin veinlets contained pore solutions which caused the transformation pyroxene → hornblende. The micro-vein system was formed by strain after the consolidation of the norite, but the temperature was above the point where the reaction pyroxene → hornblende occurs. This deuteric reaction is accompanied by an increase of volume. The strain caused was released in the already existing system of veinlets. The veinlets became wider than before the transformation of the hornblendes. If only the expansion caused by the mineral transformation were responsible for the formation of the veinlets, they ought to radiate from the altered pyroxenes, and not, as the case is, be

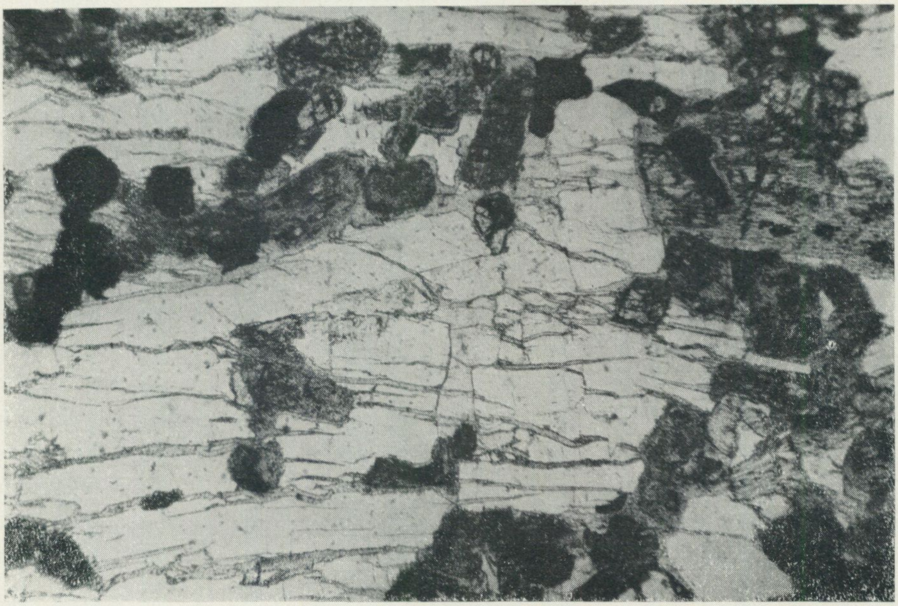

Fig. 72. Veinlets of chlorite in norite. Brattön. Ord. light. 25×.

parallel. It is not surprising that the veinlets in part are filled with chlorite, nor that the pyroxene is altered into fibrous hornblende but the remarkable thing is that the plagioclases are completely unaltered.

The slightly altered norite has been analysed; the results are given in the table below. Also the V, Cr, Co, Ni, and Ti contents have been determined in seven specimens of norite.

Table 22. Chemical composition of norite

	% by weight
SiO_2	46.73
TiO_2	5.10
Al_2O_3	15.27
Fe_2O_3	3.27
FeO	10.10
MnO	0.14
MgO	6.74
CaO	6.03
Na_2O	2.09
K_2O	0.81
H_2O −	0.55
H_2O +	2.54
P_2O_5	0.37
V_2O_5	0.04
S	0.22
F	0.12

Niggli values:

al = 23.0
fm = 54.0
c = 16.6
alk = 6.4
si = 119
k = 0.19
ti = 9.8

Table 23. Some trace-element contents in norite, given in p. p. m.

Locality	V	Cr	Co	Ni	Ti	Ti/V
325.581	400	16	63	85	26 400	66
330.584	260	10	37	33	18 000	69
334.585	230	19	24	28	18 000	78
322.580	270	33	42	38	17 400	64
252.590	190	230	33	32	13 800	72
270.588	280	11	45	50	19 800	76
293.589	260	10	34	33	18 600	71

A comparison between the analyses given above and those in Johannsen (1952, III, p. 236) gives the result that this specific norite has a slightly lower content of SiO_2, Al_2O_3, and CaO than the mean, but that it has a considerably higher TiO_2 content. The ratio Ti/V is fairly constant. The relations between Cr, Co, and Ni are mainly Ni > Co > Cr. Lundegårdh (1949) has published trace-element analyses of norites with the same relations between these elements. He gives the following explanations, "... the development of an early crystallized phase high in chromium and the separation by squeeze of a residual basic magma very low in this metal. The residual magma should have been rich in volatiles and thus apt to intrude more rapidly into higher parts of the crust than the remaining original magma ..." (p. 20). If these ideas are adapted to the norite in question, it should have emanated from such a chromium-deficient, but volatile-rich magma as Lundegårdh describes in the quotation above. However, I do not regard these comparatively few analytic data as sufficient to explain the origin of the norite according to the quotation.

INCLUSIONS OF PARA-ROCKS

As seen on the map and in Fig. 69 breccias exist in the norite near the contacts to the gneiss. The breccias are, as mentioned earlier, of the ortho-magmatic type (cf. p. 112). The fragments of fine-grained, more or less mica-rich feldspar quartzites and veined gneisses are only found near the contacts. Megascopically some of the fragments look like "ordinary", mica-rich sediments. But the dark minerals, forming layers suggestive of biotite, consist of pyroxene with $2V_z$ = 52°; c/Z = 40°; n_z = 1.715; n_x = 1.689.

The pyroxenes contain small quartz grains in their marginal zones and small ore grains in their centres. The contact relationships prove that the pyroxene is the youngest mineral.

The plagioclase contains 45 % of anorthite. The gneissic fragments in the norite are slightly enriched in Ca and Fe. This is traced in the new-formed pyroxene, in the An-content of the plagioclase, and in the magnetite powdering of the pyroxene. This enrichment could also be a secondary effect of the subtraction of Na, K, and Si — the most mobile elements.

There are also corroded xenoliths of quartzite with a grain size of 0.3—0.6 mm. The fragments are rimmed by 1—2 mm long hornblende needles perpendicular to the surface of the fragments. The quartz has no wavy extinction in these fragments, which are found sparsely all over the massive.

The two types of inclusions presented naturally originate from the surrounding supra-crustal formation, parts of which were incorporated by the norite during its intrusion. The formation of late pyroxene is explained in the following way: the biotite-rich fragments suffered a progressive metamorphism when they were captured in the norite magma. The biotite was then altered into pyroxene.

Earlier Bugge (1945) found such an alteration, "charnockitization", which is the formation of hornblende and pyroxene from biotite. The iron-ore content of the pyroxene comes from the primary biotite, which had a higher iron content than the new-formed pyroxene. Some of the fragments with feldspar and mica were altered so that they now have an enderbitic composition — others were assimilated. But the quartzite fragments resisted assimilation and are thus found as fragments distributed through the whole massive of norite.

SCHLIEREN IN THE NORITE

Medium-grained, reddish, up to 50 cm long and a few cm wide schlieren are distributed irregularly in the norite. Ljungner (1927) calls them micro-pegmatite (p. 28) and Sederholm (1928) granitic secretions. The reddish feldspar is a plagioclase containing only 10 % of An. Beside albite there is uralitic hornblende, biotite, some microcline, magnetite, and apatite in these secretions.

The mineral association is the same as that of the norite except for the composition of the plagioclase. Thus these schlieren do not seem to be a late product of differentiation. It seems probable that the sodium which was expelled from the gneiss fragments (cf. p. 120) can be put in relation to the albitic schlieren.

INCLUSIONS OF DARK ORTHO-ROCK

On a shelf 244.586, accessible only from the sea, some black, rounded inclusions in the norite were observed (Fig. 73). The grain size in the dark inclusions is less than 0.2 mm. They contain plagioclase (An_{24-35}) a pale yellow pyroxene with $c/Z = 31°$; $2V_z = 50°$ and birefringence 0.031, some biotite, and oxide ores. The latter constitute one fifth of the total volume, Fig. 74. A trace-element analysis has been performed on such a fragment giving the values below:

Ti	V	Cr	Co	Ni	
39 000	200	45	80	42	p.p.m.

The titanium content is remarkably high; other trace elements do not contribute significantly to the interpretation of these fragments.

Fig. 73. Inclusions of dark ortho-rock (dolerite) in norite. Älgön 244.587.

One possible explanation of the origin of these fragments is that they were incorporated from a source outside the norite, *e. g.* a doleritic dike. There is another plausible explanation, based on the assumption that the dark inclusions were formed from a low part of the norite magma, where heavy constituents were accumulated by gravitative separation.

INCLUSIONS OF ANORTHOSITE

Whitish, angular fragments of anorthosite can be seen on both Älgön and Brattön (Fig. 70). The anorthosite is white on weathered surface and thus contrasts strongly against the dark norite. The unweathered anorthosite is either greenish white or dark gray. The gray type is devoid of fissures. The light type is interwoven by a net of fissures along which there is plenty of sericite. The anorthosite is distributed unevenly on the islands. The biggest accumulations are found in the eastern parts of norite on Brattön and on the eastern and western points of Älgön. There are all gradations from polycrystalline anorthosite aggregates to solitary plagioclase phenocrysts in the norite. The phenocrysts are generally a few mm in cross-section, but there are also phenocrysts up to 10 cm long (Fig. 75). It may also be seen how a few phenocrysts aggregate and form an accumulation of anorthosite. The plagioclase forming the anorthosite and the phenocrysts has an anorthite content of 46—50 %. The plagioclase is not zoned, and the crystals forming the anorthosite are xenomorphic. The plagioclase

Fig. 74. Dolerite inclusion. Älgön 244.587. Nic. +. 30×.

generally has an outer zone which is crushed. The fragments in this zone are only moderately displaced as compared to the orientation of the neighbouring plagioclase. In connection with the crushed zones the albite lamellae are bent (Fig. 76) and thus show wavy extinction (cf. Wheeler 1960, p. 1758). The

Fig. 75. Plagioclase phenocryst in norite. Älgön 244.587.

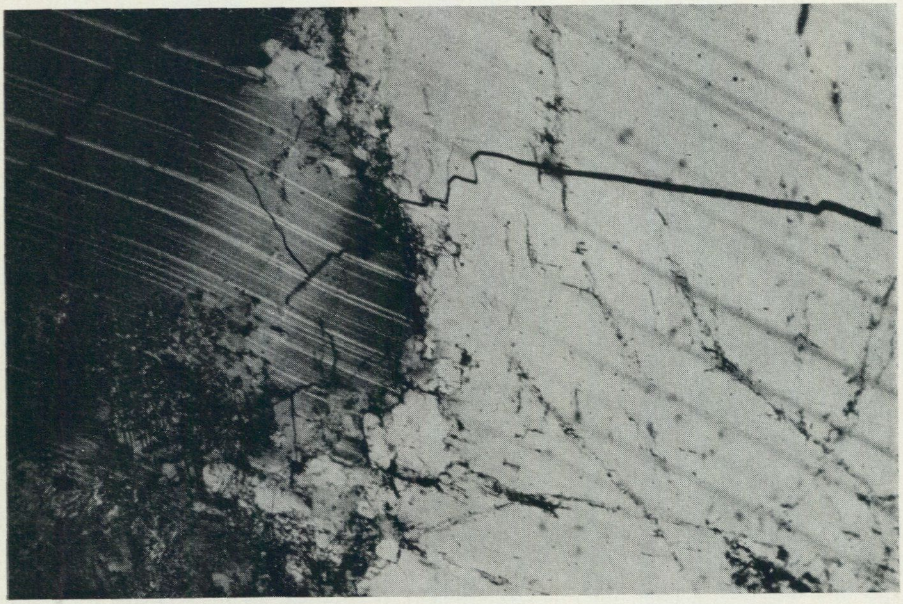

Fig. 76. Deformed plagioclase in anorthosite. Brattön. Ord. light. 30 x.

crushing is believed to be a protoclasis, a phenomenon frequently observed in anorthosite (cf. Loewinson-Lessing 1923, and Osborne 1949).

The anorthosite was primarily monomineralic, but now several secondary minerals occur. As mentioned above sericite is found along the fissures. Zeolitic minerals with optical properties corresponding to those of chabasite are found in cracks in the anorthosite. Potash feldspar forms antiperthite in the plagioclase of the anorthosite, but also minor veinlets between the plagioclase crystals.

From the anorthosite on western Älgön, one single pure crystal has been analysed. The same crystal was also investigated optically by means of the universal stage. The optically determined composition is $An_{47}Ab_{53}$.

Table 24. Chemical composition of plagioclase crystal in anorthosite

% by weight									
SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	BaO
57.32	0.16	26.30	0.35	0.32	0.26	8.96	4.84	1.16	0.04
Computed feldspar composition: Or = 6 %, Ab = 45 %, An = 49 %									

The high titanium content can be explained by the presence of submicroscopical rutile needles (cf. p. 117). Antiperthitic plagioclase has been observed in the anorthosite. The analysis above shows a remarkable proportion of K_2O, and this potassium content is obvious in the normative orthoclase. The thin-section of the analysed plagioclase crystal shows no antiperthite; the content of K-feldspar must be hidden in the plagioclase lattice. As a consequence, the antiperthite observed in other sections must be the result of exsolution as Andersen (1929) stated.

THE GENESIS OF THE ANORTHOSITE AND NORITE

The genesis of the anorthosite is one of the controversial problems of petrology. Both metasomatic and magmatic ways of formation have been advocated. Hietanen (1954) has found that quartzites and biotite schists in Idaho have been transformed into anorthosites and garnet amphibolites by a metasomatic introduction of two or more elements (p. 288). In "The transformation of the upper part of the Pretoria series" van Biljon (1949) described how the sedimentary series in the direction of the strike have been transformed to syenite, gabbro, norite, granophyre, and anorthosite. The final rock type was determined by the primary sediment. The transforming agencies were ascending hydrothermal solutions. van Biljon found that pure quartzites were not altered by the solutions. The anorthosites were, according to van Biljon, formed out of calcareous chert which metasomatically received Ca, Al, and Na. Simultaneously K, Mg, and Si were driven out.

Buddington (1939) regards gabbroic magmas as complementary to anorthositic masses, mainly because of the gradational transitions between these rock types. "The order of succession indicated is definitely from anorthosite to saturated gabbro or norite" (p. 215). "In addition to the saturated gabbros which are so similar and directly related to the anorthositic rocks, there are the undersaturated gabbros which form a discrete group with no gradational relationships to the anorthositic rocks" (p. 215).

The anorthosite-norite complex on Brattön-Älgön shows no evidence of having been formed metasomatically *in situ.* The contacts are sharp and partly unconformable. Breccias occur. Both norite and anorthosite are devoid of parallel structures. The anorthosite occurs as fragments in the norite, which also contains phenocrysts of plagioclase of the same composition as the plagioclase in the anorthosite. The plagioclase in the norite is slightly zoned; the plagioclase in the anorthosite, on the other hand, is devoid of zoning. The formation of the large unzoned phenocrysts (Fig. 75) proves that the large crystals were in equilibrium with their mother liquid. The plagioclases formed later are slightly more albitic in their outer zone than in their core. This proves that a modest differentiation has occurred, but it also strengthens the opinion that the anorthosite was formed out of the norite magma. According to Beskow (1929) the early plagioclases were lighter than their mother liquid and thus strove upwards during growth. Hjelmqvist (1950) has also found that the plagioclase crystals moved upwards in Smålands Taberg. Buddington (1943) has treated the problem of stratified intrusions and says, "... many petrologists have concluded that the course of crystallization of a basalt leads to a concentration of iron in the residual liquid" ... "there is one course of differentiation of basalt and norite, or gabbro, which leads to concentration of iron and titanium in the residual liquid up to a maximum in the later stages of consolidation ..." (p. 125).

We shall now see in what respect these ideas are applicable to the norite-anorthosite on Brattön—Älgön.

When the noritic magma crystallized, the first-formed plagioclases were lighter than the residual liquid, and thus rose and formed an anorthositic crust in the upper part of the norite. Simultaneously there was an enrichment of mafic minerals downwards due to the sinking of early-crystallized, heavy minerals. Possibly these minerals formed a crust on the bottom of the magma container.

If for some reason conditions now became dynamic, the unsolidified norite would break up the anorthosite and cause protoclasis of the margins of the plagioclase crystals. The early-formed bottom crust would have been brecciated, too.

All observations point to a magmatic, and not a metasomatic origin. Concerning the origin of the magma which formed the norite and anorthosite, the question arises: Is it a primary or a secondary magma? Undoubtedly Barth (1961) is right in many respects when he says, "The diversification of igneous rocks is caused by sedimentary processes" (p. 325). But as Winkler has proved in many experiments, also a partial melting can contribute to the manifoldness of igneous rocks. Winkler and von Platen (1960) have treated calcite-bearing, illitic clays with different contents of Na_2O at 2 000 atm. water pressure. At 740° C an anatectic melt begins to form. With rising temperature the composition of the melt changes from aplitic over granitic to granodioritic. The amount of anatectic melt comprises up to 80 % of the metamorphosed clay, and the remainder, the unliquefied crystals, are predominantly An-rich plagioclases which are accompanied by mafics, seldom by a little quartz. "This leads to the suggestion that anorthosites might possibly also be looked upon as the crystalline remainder not liquefied in the course of metamorphism ..." (p. 294).

Kranck (1961) says when reviewing the anatectic formation of anorthosites, "... it may give the key to the formation of anorthositic magmas" (p. 302).

The problem of the anorthosite and norite on Brattön—Älgön is not solved by assuming only a selective melting; the problem also involves the emplacement and age. An intrusive behaviour is proved by the breccias. The age of the norite-anorthosite massive is definitely lower than that of the surrounding gneisses. Still doubt remains concerning the age relations between the augen-granite and the norite-anorthosite. The cutting granitic-aplitic dikes on western Älgön (marked on the map) could either be of the same age as the augen-granite or younger.

The last section deals with rocks which are closely related to norite and gabbro, namely dolerites.

Fig. 77. Dolerite dike with two generations of intrusion. Brattön 338.585. Ord. light. 30 x.

Chapter 16

Doleritic dikes

Doleritic dikes are found in the area on the western parts of Tjörn and in connection with the norite on Brattön. There are two dikes on Brattön. They strike N70° E and dip vertically. Close to the norite they are wider than further away. On the west side the dike is 1.3 m close to the norite and 1 m at the sea. The dike on the east side is 1.5 m close to the norite and 0.5 m on the shore.

Fig. 77 is a microphotograph showing the contact against the bedrock. Area I consists of devitrified glass with few plagioclase laths. Area II consists of glass on the contact to area I. In the central parts of the dolerite the grain size increases.

The figure proves Ljungner's (1927) observations in the field, *i. e.* that there have been two intrusions into the dike on eastern Brattön. The plagioclase of intrusion II is an andesine with 30—48 % An. The highest An-contents determined were found in the cores of zoned plagioclase laths, and the lowest in the very thin, last crystallized laths. The plagioclase is altered and so is the matrix which now consists of chlorite. Ore is frequent and forms dendritic crystals. The texture is typically doleritic.

Some trace elements have been determined from the second intrusion:

Ti	Cr	Co	Ni	
15 600	10	39	35	p.p.m.

The distribution of these elements is the same as that found in the norite (cf. p. 120).

Ljungner has interpreted the dolerite on Brattön as apophyses to the norite massive (p. 27). The contact relationships indicate that the dolerite magma intruded into a cold bedrock, as there is a felsitic contact zone in the dolerite. The norite, on the other hand, has no such zone.

The dolerite dikes could either be apophyses to the norite massive as proposed by Ljungner (1927, p. 27) or they could have been formed before the norite intrusion. The present writer favours Ljungner's opinion for the following reason:

As stated earlier, the anorthosite and the mafic bottom layers (cf. p. 122) were formed during a static phase. This phase was interrupted by a dynamic phase which caused the unsolidified norite magma to brecciate the anorthosite crust. At the same dynamic stage, some of the norite was forced out into the already solidified dolerite dike, and caused the second intrusion.

There are some other doleritic dikes within the area. They are of two different kinds: one is disconformable and cuts the migmatitic veined gneisses without any simple relations to the dip and strike of the gneisses. Dolerites of this type are found at 11.67 and around point 10.87. The other type is conformable to the S-surfaces of the pale red granitic augen-gneiss and is found at 174.840.

Petrographically these dikes are identical. They are fine-grained and their doleritic texture can be seen megascopically. Zoned plagioclase laths lie in a mesh of epidote and chlorite. Occasionally a pyroxene with $n_x = 1.712$; $n_z = 1.713$ and with extinction $c/Z = 44°$ has been observed. These optical data correspond to those of ferrosalite (Tröger 1959, p. 63). Opaque oxide minerals are found between the plagioclase laths in the chlorite-epidote mesh. According to Lundegårdh (1958, p. 72) the alterations in similar doleritic dikes are deuteric.

Certainly this is true also concerning the dikes within the Tjörn area.

Fig. 78. View from Bleket westwards.

Concluding summary

The main purpose of this investigation has been to point to the close genetical relationships between the schists, gneisses, and granitoids.

The events which formed the rocks were those in the synclinal phase and those in the following orogenic phase.

The first process was characterized by the accumulation of marine sediments of varying composition. They were interstratified by volcanic ashes.

The second phase was characterized by folding, mafic intrusions, and simultaneous sinking of the accumulated sediments to depths where conditions permitted metamorphic and metasomatic reactions.

Rising temperature caused an increase of the grain size. When sufficiently high temperatures were reached parts of the sediments became mobile.

The metasomatic alterations were caused mainly by ascending aqueous solutions of potassium and silica from deeply buried sediments. These solutions contributed to the rise of temperature in the solid rocks through which they passed. The permeability of the metamorphosed sediments was increased by steep dips and it was decreased by horizontal position. Consequently the least altered sediments are those with horizontal stratification and/or schistosity whereas the vertical ones have been more intensely altered. Some rock types, such as mafics, seem to have been impermeable to the ascending solutions.

There are some mafic intrusions younger than the tectonizing phase, but older than the mobile granitoid masses which were formed out of primary sediments. Such a formation of granite occurred where the solutions were captured, *e. g.* in anticlinal arcs or under impermeable mafic rocks.

At the final stages of the orogenic phase the norite—anorthosite magma was intruded.

References

Some frequent abbreviations:

BGIU	= Bulletin of the Geological Institutions of the University of Uppsala
GFF	= Geologiska Föreningens i Stockholm Förhandlingar
KVA	= Kungl. Vetenskapsakademien (Stockholm)
SGU	= Sveriges Geologiska Undersökning
NGT	= Norsk Geologisk Tidsskrift
NGU	= Norges Geologiske Undersökelse
Bull.géol.Finl.	= Bulletin de la Commission géologique de Finlande

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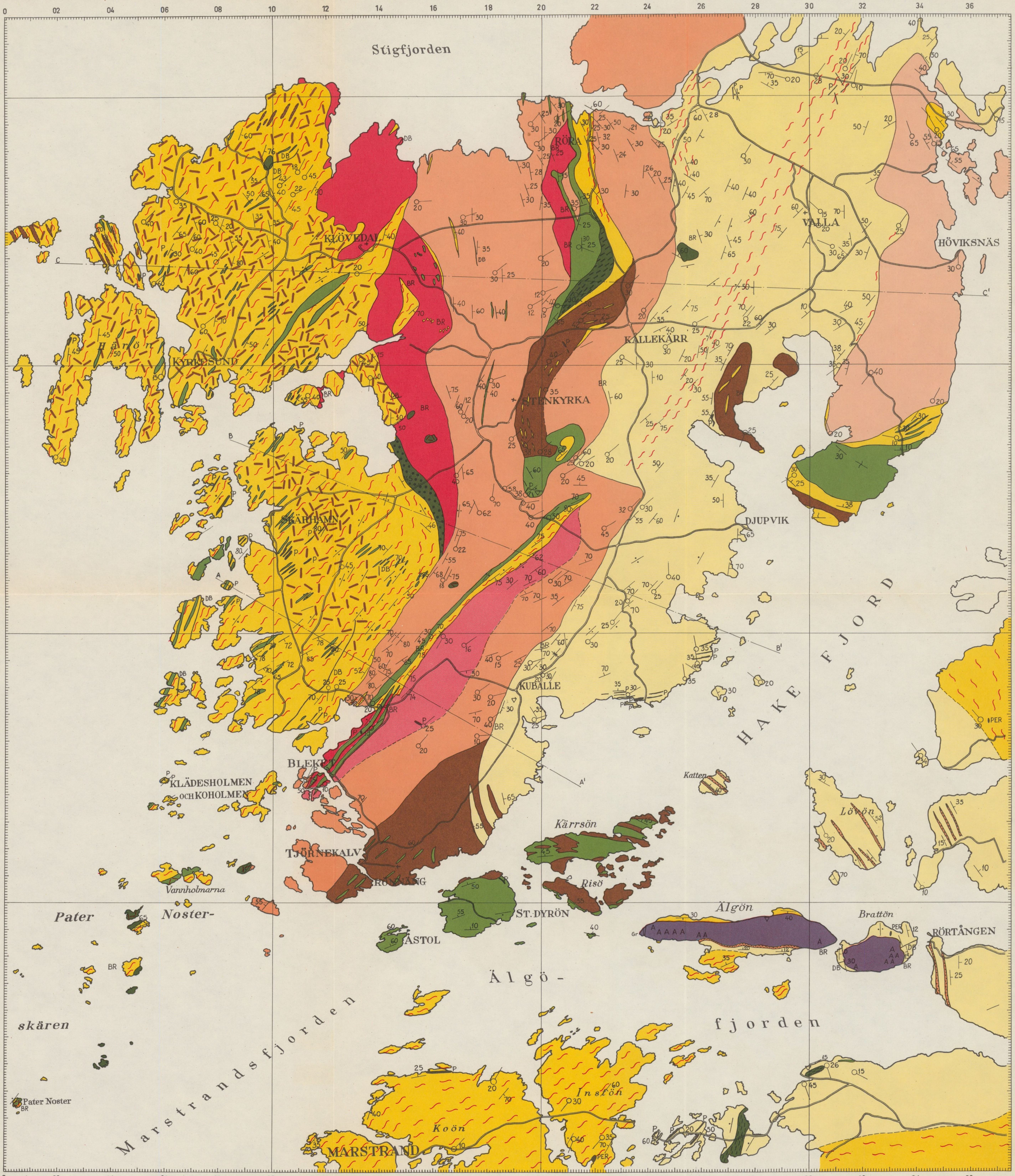

GEOLOGICAL MAP OF THE TJÖRN AREA

by

LARS BERGSTRÖM, 1961

Scale 1:50.000
1 cm = 500 m

LEGEND

- Cross-sections — *Tvärprofiler*
- Quarry — *Stenbrott*
- Gradational contact — *Oskarp bergartsgräns*
- Lineation — *Stänglighet*
- Syncline — *Synklinal*
- Strike and dip of foliation (in degrees-nearly horizontal) — *Planstrukturens strykning och stupning (angivet i grader resp. nära horisontell)*
- BR Breccia — *Breccia*
- Granitic dikes — *Granitgångar*
- DB Doleritic dikes — *Diabasgångar*
- AA Anorthosite in norite — *Anortosit i norit*
- Norite — *Norit*
- Light red augen-granite — *Rödlätt ögongranit*
- Dolerite with quartz inclusions — *Diabas med kvartsinneslutningar*
- Non-schistose diorite, gabbro and hornblendite — *Massformiga grönstenar*
- Pale red augen gneiss-granite — *Gråröd ögongnejsgranit*
- Pale red granitic augen-gneiss — *Gråröd granitisk ögongnejs*
- Light gray granitic gneiss with diffuse veins — *Ljusgrå granitisk gnejs med diffus ådring*
- Hornblende-porphyrite often with strong lineation — *Hornbländeporfyrit ofta med utpräglad linjärstruktur*
- Light gray granite in migmatite — *Ljusgrå granit i migmatit*
- Light gray granite — *Ljusgrå granit*
- P Pegmatitic dikes — *Pegmatitiska gångar*
- Conformable layers of "pegmatitic" composition — *Konforma lager av »pegmatitisk» sammansättning*
- Pegmatitic veins — *Pegmatitiska ådror*
- PER Peridotite — *Peridotit*
- Medium-grained gneisses — *Medelkorniga gnejser*
- Amphibolite — *Amfibolit*
- Schists and fine-grained gneisses — *Skiffrar och finkorniga gnejser*

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