PEGMATITE VEINS
AND THE SURROUNDING ROCKS

I. Petrography and structure.

BY

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CONTENTS

A b s t r a c t : A very detailed map of the island St. Hansholmen, Risør, southern Norway, is presented. The rock type on the island is the banded gneiss common along the south coast. It consists of alternating bands of gneiss and amphibolite with pegmatite veins and inter-boudin fillings confined to the amphibolite bands.

The amphibolite usually consists almost wholly of hornblende and plagioclase. The gneiss consists of plagioclase, quartz, sometimes microcline, with small amounts of biotite and magnetite. The plagioclase in both the amphibolite and gneiss lies in the range An_{36} to An_{27}, average An_{31}. The pegmatites are of three types. On the west end of the island there is a pink, microcline rich pegmatite vein which cross-cuts both the amphibolite and gneiss. Confined to the amphibolite bands there occur white pegmatites containing plagioclase An_{30} and, as fillings between boudins, there occur white pegmatites containing plagioclase An_{23}.

The structural elements of the island, contacts and foliation of the gneiss, are nearly vertical and strike ca. EW to WSW. A sharp, almost isoclinal fold is revealed on the island.

The pegmatite veins, confined to the amphibolite bands, tend to follow two directions with one of these dominant on both limbs of the fold. Postulating that the fold revealed on St. Hansholmen is a minor fold on the limb of a larger fold, this fact, along with the development of boudinage structure in the amphibolite and the occurence of pegmatite fillings between boudins, is explained as being due to differences in rigidity between the amphibolite and the gneiss during the dynamo-thermal metamorphism of the area.

Three posssible modes of origin for the pegmatites are discussed. They can be characterized as; (1) magmatic, (2) hydrothermal, and (3) by metamorphic differentiation. The conclusion is reached that the plagioclase pegmatite veins and pegmatite fillings between boudins can best be explained as the result of crystallization from a dispersed phase which diffused intergranularly towards the low pressure areas which arose during the deformation of the area. The alkali content of the feldspars in the surrounding gneiss indicates that the temperature of the environment in which these pegmatites formed was well below the range of magmatic temperatures. The suggestions offered account for the location, composition variations and relative grain size of the plagioclase pegmatites.

Very little can be said about the genesis of the pink microcline rich pegmatite which crosses the western tip of St. Hansholmen, on the basis of the present study.

The spacial variation in the microcline content of the gneiss may be interpreted such that it supports the genesis by metamorphic differentiation which has been suggested for the banded gneiss.

Introduction.

This paper is the first part of a study concerned with pegmatite veins and their relations to the surrounding rocks. The word pegmatite is used as a textural term without mineralogical implications.

The problem herein considered is that of the physical factors which control the localization of pegmatite material and, along with this, petrographic variations in the pegmatites and the surrounding rocks and their significance.

To begin this study an appropriate area of completely exposed rocks containing pegmatites was chosen for very detailed mapping. The island of St. Hansholmen, lying just outside of Risør on the south coast of Norway, was found to be satisfactory with the exception of the northwestern part which was mostly covered and therefore

not mapped. The mapping was done during the autumn, 1955, and spring, 1956, at the scale 1:200, using tape and compass. The map is presented here at the scale 1 : 600. The island is located in the southern part of the Kongsberg-Bamble formation and consists of the banded gneiss common along Norway's south coast in this area. The rocks are all pre-Cambrian and are part of the roots of an ancient mountain range. The metamorphic facies represented on St. Hansholmen is the amphibolite facies.

There has been considerable study of the southern part of the Kongsberg-Bamble formation and of particular areas and problems presented by the rocks therein. Studies in the area were begun as early as 1857 by an Englishman, Robert Forbes (19). Rather than summarize the results of previous investigations in the region here, in an attempt to place the area studied in its geologic setting, reference is made to the original works of O. Andersen (1), (2); T. F. W. Barth (3); H. Bjørlykke (6), (7), (8); W. C. Brøgger (9), (10), (11); A. Bugge (12), (13), (14), (15), (16); J. A. W. Bugge (17), (18); J. C. Green (22); B. Hofseth (23); O. Holtedahl (24); and Th. Kjerulf and T. Dahll (27). Work has aslo been done in the area by H. Ramberg (1943, M. A. Thesis, Univ. Oslo) and A. F. Frederickson who has not yet published the results of his studies.

Petrography.

The banded gneiss commonly found in the Kongsberg-Bamble formation in Sørlandet is the rock type present on St. Hansholmen. It consists of alternating dark and light bands of quite variable thickness. On St. Hansholmen the dark bands are amphibolite, generally not less than 15 cm. nor more than 6 meters thick, and the light bands are quartz-dioritic or granodioritic gneiss and are generally somewhat thicker than the amphibolite bands. Also present are pegmatite veins and fillings between amphibolite boudins.

AMPHIBOLITE

The amphibolite is generally quite homogeneous, dark, medium to medium-fine grained and shows reticular fabric and nematoblastic texture. It consists primarily of hornblende and plagioclase. Biotite and diopside are often present in small amounts. Apatite and opaque

minerals are always present as accessory minerals. In addition zircon, quartz, chlorite, calcite, sphene(?) and limonite are found as rare constituents. Hornblende needles are oriented approximately parallel to the band boundaries and dip steeply toward the west at about 60°—75°. The composition of the plagioclase is somewhat variable the range An_{36} to An_{27} having been observed in the thirteen thin-sections examined, the average being An_{31}.

The mineral composition of six sections from the amphibolite was determined. The composition of the plagioclase was determined by the maximum extinction angle together with the optical sign. The plagioclase grains are anhedral, generally slightly sericitized and smaller than the hornblende grains. Hornblende grains are generally idioblastic with ragged terminations and are quite well oriented. Hornblende shows pleochroism α = yellowish green, β = olive green, γ = deep green (the Hornblende in ØA 14 is somewhat brownish); absorption sceme $\alpha<\beta<\gamma$. Biotite generally appears as spots and small streaks in the hornblende, apparently an alteration product, except in the sections ØA 13 and ØA 15 where it exists as separate crystals and is also exceptionally abundant. The plagioclase in these two sections is less sericitized than usual. Diopside occurs in small, anhedral, pale green, non-pleochroic grains. Chlorite appears to be an alteration of hornblende when it is found. Calcite occurs in one section in a very thin vein crossing the section.

ØA 4
Plagioclase (An_{36}) 39.0
Hornblende 59.0
Biotite.................. 0.5
Apatite 0.3
Opaque 1.2

ØA7
Plagioclase (An_{28}) 48.0
Hornblende 45.4
Biotite.................. 1.2
Diopside 3.5
Chlorite 0.4
Apatite 0.1
Opaque 1.5
Quartz, Calcite .... < 0.1

ØA8
Plagioclase (An_{35}) 41.9
Hornblende 48.0
Quartz 5.1

ØA14
Plagioclase (An_{28}) 29.8
Hornblende 64.8
Diopside 4.1

ØA8 (cont.)

Chlorite 2.5

Zircon 0.7

Sphene(?) 0.2

Opaque 1.5

Apatite, Diopside .... < 0.1

ØA14 (cont.)

Zircon 0.9

Apatite 0.2

Opaque 0.2

ØA13

Plagioclase (An$_{35}$) 39.6

Hornblende 52.9

Biotite................... 8.2

Opaque 0.1

Apatite .... < 0.1

ØA15

Plagioclase (An$_{32}$) 44.7

Hornblende 40.7

Biotite................... 14.6

Diopside 0.1

Opaque 0.1

Apatite .... < 0.1

Sections ØA13 and ØA15 come from an amphibolite band which contains no pegmatite veins and which seems to have been unusually plastic during the deformation of the area.

GNEISS

The gneiss from St. Hansholmen is fairly light gray to pinkish gray with a distinct macroscopic parallel structure due to the orientation and parallel structure of biotite flakes. The strike of the foliation is generally near EW and is near vertical, dipping usually to the south. On the islands adjacent to St. Hansholmen dips to the north are occasionally encountered. The foliation of the gneiss is at all times conformable with the amphibolite bands. The gneiss is mostly homogeneous, commonly medium-fine grained (most grains close to or slightly less than 1 mm.) but sometimes medium grained occasionally showing thin «schlieren» or stringers of slightly larger grain size. These «schlieren» may be quite straight but more often are slightly bent, following small flexures in the foliation of the gneiss. They are most often found at the east and extreme west ends of the island but are not restricted to these areas. They are fully conformable with the foliation in the gneiss. There is no obvious or consistant macroscopic change in the gneiss relatable to the distance from an amphibolite band.

The gneiss consists of plagioclase, quartz, and biotite, sometimes microcline, with zircon and opaque minerals always present, and epidote, apatite, limonite, sphene (?), and garnet seen in less than half of the thin-sections examined. The plagioclase lies the range An_{36} to An_{27}, average An_{31} (identical with the figures obtained for the plagioclase in the amphibolite) constituting 66.8 % to 23.8 %, average 51.1 % of the rock. It is often somewhat sericitized. Quartz always shows undulatory extinction and constitutes from 40.9 % to 25.9 %, average 35.2 % of the rock. Microcline is generally perthitic and constitutes from 35.2 % to 0.4 % average 9.6 % of the rock when it occurs, but it was not present in 10 of the 25 sections examined. Biotite is usually at least slightly altered to pennine (which is included under biotite in the percentages) and generally shows pleochroic halos. It constitutes from 8.3 % to 0.4 %, average 3.6 % of the rock. The gneiss contains maximum 98.2 %, minimum 91.3 %, average 95.4 % of feldspars plus quartz.

The mineral content of 14 sections from the gneiss was determined. In all cases the plagioclase was determined by maximum extinction angle together with optical sign. Biotite shows pleochroism γ = dark reddish brown, brown or olive brown and α = pale yellow to almost colorless yellow. Garnet occurs as rather round or otherwise anhedral grains. Quartz shows undulatory extinction. With the exception of opaque minerals which sometimes occur as medium sized grains the remaining minerals are always fine grained.

ØG 19

Plagioclase (An_{33}) 57.5
Microcline 2.2
Quartz 31.6
Biotite.................. 8.3
Zircon 0.1
Garnet.................. 0.6
Epidote, Opaque .... < 0.1

ØG 25

Plagioclase (An) 57.9
Microcline 0.4
Quartz 38.4
Biotite.................. 2.6
Opaque 0.7
Zircon, Epidote.......... < 0.1

ØG 18

Plagioclase (An_{30}) 36.1
Microcline 22.6
Quartz 36.2

ØG 24

Plagioclase (An_{34}) 23.8
Microcline 35.2
Quartz 33.4

ØG 18 (cont.)
Biotite.................... 4.2
Opaque 0.6
Zircon, Epidote.......... < 0.1

ØG 17
Plagioclase (An$_{28}$) 55.4
Microcline 2.4
Quartz 39.2
Biotite.................... 1.2
Garnet.................... 0.6
Zircon 0.3
Opaque 0.9
Epidote .... < 0.1

ØG 16
Plagioclase (An$_{30}$) 53.8
Microcline 2.2
Quartz 39.2
Biotite.................... 3.5
Zircon 0.2
Opaque 0.6
Apatite, Limonite .... < 0.1

ØG 26
Plagioclase (An$_{32}$) 46.1
Microcline 21.7
Quartz 30.4
Biotite.................... 0.8
Zircon 0.1
Epidote 0.1
Opaque 1.0

ØG 20
Plagioclase (An$_{31}$) 58.4
Microcline 9.9

ØG 24 (cont.)
Biotite.................... 6.5
Zircon 0.1
Opaque 0.6

ØG 23
Plagioclase (An$_{30}$) 52.7
Microcline 3.7
Quartz 38.1
Biotite.................... 5.0
Zircon 0.1
Opaque 0.2
Limonite .... < 0.1

ØG 8
Plagioclase (An$_{30}$) 42.8
Microcline 19.0
Quartz 33.4
Biotite.................... 4.1
Opaque 0.7
Zircon, Epidote.......... < 0.1

ØG 12
Plagioclase (An$_{36}$) 55.5
Microcline 2.4
Quartz 38.6
Biotite.................... 2.0
Zircon 0.1
Opaque 1.3
Epidote, Apatite......... < 0.1

ØG 13
Plagioclase (An$_{34}$) 49.5
Microcline 3.7
Quartz 40.9
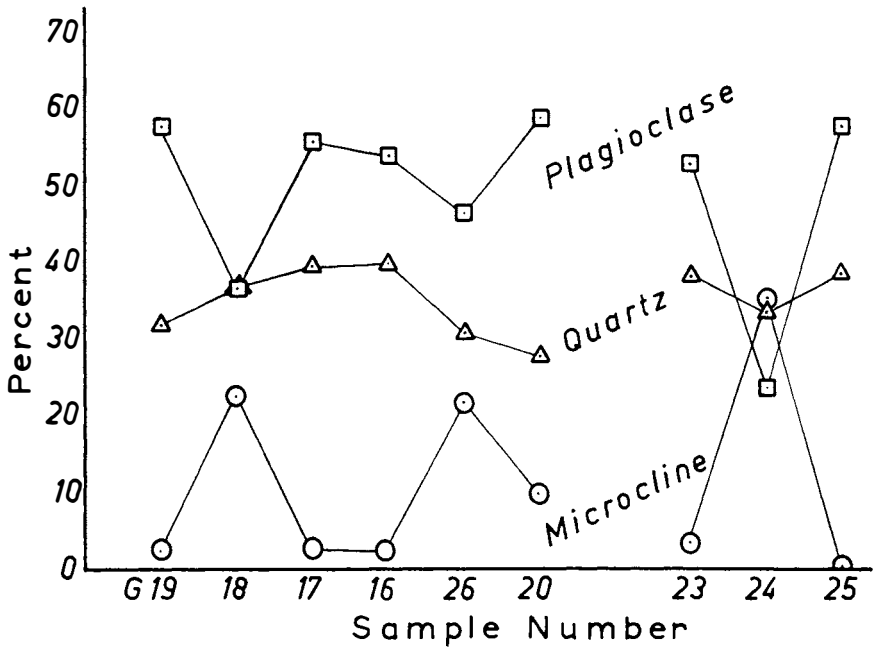Biotite.................... 5.5
Opaque 0.5

Fig. 1. The variation of the plagioclase, quartz and microcline is shown. The samples are arranged according to the position they had (see map, fig. 6) in the line across which specimens were taken.

ØG 20 (cont.)
Quartz 27.7
Biotite.................. 2.9
Zircon 0.1
Opaque 1.0
Garnet, Epidote .... < 0.1

ØG 21
Plagioclase (An$_{33}$) 66.8
Microcline 4.1
Quartz 25.9
Biotite................. 3.1
Sphene (?) 0.1
Zircon, Epidote, Opaque . < 0.1

ØG 13 (cont.)
Zircon, Epidote,
Apatite, Limonite........ < 0.1

ØG 15
Plagioclase (An$_{30}$) 58.0
Microcline 0.4
Quartz 38.5
Biotite................. 0.4
Scapolite (?).............. 1.9
Opaque 0.7
Zircon, Epidote.......... < 0.1

Sections ØG 19, 18, 17, 16, 26, and 20 constitute a cross-section between two amphibolite bands which passes close to the apex of a folded amphibolite band. Sections ØG 23, 24, and 25 constitute another cross-section between two adjacent amphibolite bands. The locations at which the samples were taken are shown on the accompanying map. It is to be noted that there is a distinct increase in the percentage of microcline in the gneiss away from the amphibolite bands. (Fig. 1).

PEGMATITES

There seem to be three kinds of pegmatite on St. Hansholmen. At the west end of the island there is a cross-cutting pegmatite vein varying between 1 and 3 meters in width. It is quite coarse grained, the feldspar crystals being ca. 4—5 cm. and the biotite flakes ca. 2 cm. The boundary against amphibolite is knife-sharp, but against the gneiss it is gradational over a few centimeters. This pegmatite is distinctly pink in color. It is mineralogically very simple, containing plagioclase, microcline, quartz, biotite and hornblende. Because of the grain size and the tendency to break between grains it is difficult to obtain thin-sections which can be considered representative of the rock. The plagioclase in the two sections examined was An_{35}. Microcline was not present in one section but field examination of the rock indicates that it constitutes a larger percentage of the rock than plagioclase. When seen in thin-section it showed very fine perthite (elongate blebs paralleling one twin direction) and coarse stringers of plagioclase (diagonal to the twinning directions). Quartz in both sections showed undulatory and mosaic extinction. Biotite in both sections was altered somewhat to pennine. Hornblende was not present in the thin-sections but was identified in the outcrop. The mineral composition of one of the sections of this pink pegmatite is:

ØP 17
Plagioclase (An_{35}) 34.3
Microcline (perthitic) 46.8
Quartz 17.6
Biotite................. 1.2

The other two types of pegmatite, hereafter referred to as «plagio-
clase pegmatites», are macroscopically very similar, being very light
(almost white) in color and their grain size distinctly less than that
of the pink pegmatite. Dark minerals are generally not abundant but
may be so locally. The differences between these two types of peg-
matite are their mode of occurrence and the composition of their
plagioclase. One type occurs between boudins of amphibolite and
the other occurs in veins (which look very much like crack fillings)
in the amphibolite bands. The plagioclase of the «inter-boudin» peg-
matites lies in the range An_{32} to An_{27}, average An_{29}. The plagioclase
of the «vein» pegmatites is always very close to An_{20} with one excep-
tion which is An_{28}. The specimem containing An_{28} is unusual in that
it is particularly rich in hornblende (18.7 %), a mineral which is
uncommon in the plagioclase pegmatites. Also found by the examina-
tion of 10 thin sections were quartz (always present and showing
undulatory extinction), microcline (in two sections), biotite (in 7
sections but in no case abundant), zircon (in only one section outside
of its occurrence in pleochroic halos in biotite), epidote (very rare),
hornblende (in three sections), apatite (rare in two sections), muscovite
(as an alteration of plagioclase in one section) and opaque minerals
(in four sections). For two sections the mineral composition was
determined.

ØP 14

Plagioclace (An_{20}) 62.4
Microcline 6.7
Quartz 30.4
Muscovite 0.5
Zircon, Epidote . . . . < 0.1

ØP 12

Plagioclase (An_{20}) 42.0
Hornblende 18.7
Quartz 33.2
Biotite 6.4
Opaque 0.1

The «inter-boudin» pegmatites, in four sections examined, con-
tained quartz (always present and showing undulatory extinction),
microcline (in two sections), biotite (in two sections), zircon (in three
sections), and in one section each, epidote, apatite, muscovite, chlorite,
hornblende, limonite, and opaque minerals. For two sections the
mineral composition was determined.

Fig. 2. The contacts between amphibolite and pegmatite are shown. At the extreme right the amphibolite-gneiss contact can be seen. There is a small concentration of dark minerals around the most centrally located of the «larger» pegmatites (directly below the hammer head).

ØP 10

Plagioclase (An_{28}) 71.3
Microcline 1.6
Quartz 26.9
Muscovite 0.2

ØP 15

Plagioclase (An_{27}) 62.7
Microcline 1.1
Quartz 33.9
Hornblende 2.1
Chlorite 0.2
Zircon, Apatite .... < 0.1

Sometimes there appears to be a narrow zone of concentration of dark minerals and along with this a slight increase in grain size in the amphibolite adjacent to the enclosed pegmatite veins. The concentration may be either hornblende or biotite but this bears no apparent relationship to the appearance, grain size, quartz content or dark mineral content of the pegmatite. The minerals of these concentrations are always conformable with the boundaries of the

pegmatites. There are on rare occasions thin dark stringers in the pegmatite veins. These are concentrations of biotite.

The pegmatite vein — gneiss contacts and the inter-boudin pegmatite — gneiss contacts are usually very sharp but occasionally there is a zone (ca. 1—2 cm. broad) over which the line of contact is arbitrary. This occurs when the line of contact between pegmatite and gneiss is relatively long (over ca. 15 cm).

The amphibolite — gneiss contacts and the amphibolite — pegmatite contacts are always perfectly sharp, though the latter especially may be higly irregular (see e.g. fig. 2).

There is generally not a marked disconformability between the pegmatite vein boundaries and the schistosity of the amphibolite. Where there is a concentration of dark minerals at the boundary there is always conformability. Occasionally, when the pegmatite veins change direction very sharply, there is disconformability at the point of the turn.

In no case is there zoning within the pegmatites.

It is noteworthy that all the microcline containing samples of the gneiss and of the plagioclase pegmatite were collected on the eastern half of St. Hansholmen. However, though all of the gneiss samples taken from the eastern half of the island contain at least some microcline, not all of the pegmatite samples do.

Structure.

The most striking structural feature of the rocks on St. Hansholmen is a fold which can be very clearly seen on the eastern half of the island. Both limbs of the fold are revealed; the northern one more completely than the southern one. The northern limb strikes very nearly EW and the southern one about S 65—70 W. The fold axis strikes about S 75—80 W and plunges at about 60° to the SW. The axial plane is near vertical, dipping only slightly to the south. The strike of the gneiss surrounding the amphibolites parallels the bands and is at all places conformable with the amphibolite. The dip of the foliation in the gneiss and the boundaries of the amphibolite bands varies between vertical and 75° to the south.

The amphibolite bands contain many pegmatite veins and stringers which do not penetrate into the gneiss. These pegmatite

veins, although often irregular and bifurcating, on the whole give the impression of being predominantly in two directions, essentially following two diagonal directions across the amphibolite bands, with one of the diagonals being dominant (i.e., for an EW amphibolite band the pegmatite veins tend to follow the directions NE SW and NW SE, with the former being dominant). This is the case on both limbs of the fold. At the apex of the fold, however, the amphibolite bands are completely broken and exist as boudins or, as is more common, there are pegmatite veins crossing the bands, these being essentially perpendicular to the band boundaries, approaching the orientation of the axial plane of the fold. (See map, fig. 6).

It appears that the sites occupied by the pegmatite veins conform to the primary zones of low pressure (fracture and/or shear) to be expected if a relatively rigid layer is folded while surrounded by relatively plastic material, the whole being subjected to confining pressure, and the fold visible on St. Hansholmen being a minor fold on the flank of a larger fold.

If the fold seen on St. Hansholmen is a synclinal fold on the southern limb of a larger syncline (or somewhat overturned anticlinal fold on the southern limb of an anticline) one should expect the development of shear primarily in the direction NE SW in *both* limbs of the minor fold. If there is simple compression normal to a layer one should expect shear planes to develop in two directions, namely NE SW and NW SE. If there is plastic flowage of the material around a given layer during compression one should expect the deformation to result either in shear planes in the directions NE SW and NW SE (or, perhaps in just one of these directions) or in simple rupture (NS) resulting in boudinage structure in the layer. A combination of the above types of deformation should then be expected to result in shear planes being developed in the directions NE SW and NW SE, with the former being the more predominant, and in boudinage structure, except at the apex of the fold where the shearing would approach the axial plane of the fold.

At a number of places boudinaging of the amphibolite bands can be seen with pegmatite developed in the area between or at the ends of the boudins. Therefore, it seems that the pegmatites in and associated with the amphibolite occupy those zones where one should expect low pressure to be developed during the deformation of the area.

At the extreme eastern end of the island it is to be noted that
there is a part of a band of amphobolite which is unusually devoid
of pegmatite. This amphibolite seems also to have been exceptionally
plastic in its deformation. Samples from this band were especially
rich in biotite. It is well established that, for example, mica schists
are very plastic during deformation and it is probably due to the
especially high biotite content that the deformation here was rela-
tively plastic, thereby not giving rise to low pressure zones where
pegmatites could form as easily as in most of the amphibolite.

There is a greater frequency of boudins noted in the amphibolite
bands on the north limb of the fold. This may be due to the fact
that the shear stress couple would be less strong here than on the
south limb if this is a minor fold as suggested. The development of
shear zones in the amphibolite would then be less dominant on the
north limb than on the south limb and deformation by boudinaging
might be expected to be more common. However, it is also possible
that as the bands on the north limb are generally thinner than those
on the south limb the development of boudinage structure would
be facilitated and hence be more frequently seen.

The response of the surrounding gneiss at the points at which
the amphibolite bands have separated suggests relatively high plasti-
city of the gneiss during deformation, the gneiss being completely
conformable even as there occur abrupt variations in the thickness
of the amphibolite. The relative thickness of the layers of the gneiss
between boudins suggests that the pressure at these places was rela-
tively low, the layers tending to be thicker between than alongside
the boudins.

The fact that the pegmatite veins stop at the boundaries of the
amphibolite bands and do not penetrate into the surrounding gneiss
suggests that the gneiss was not sufficiently rigid to maintain low
pressure zones in which the pegmatite veins could be formed.

That the fold revealed on St. Hansholmen is a minor fold on
the flank of a larger fold cannot be directly established on the basis
of the studies conducted by the author, but this contention is sup-
ported by the findings of a brief structural survey conducted on the
islands adjacent to St. Hansholmen (see fig. 3). There is a fold present
which can be traced across the southern end of Olafsholmen and to
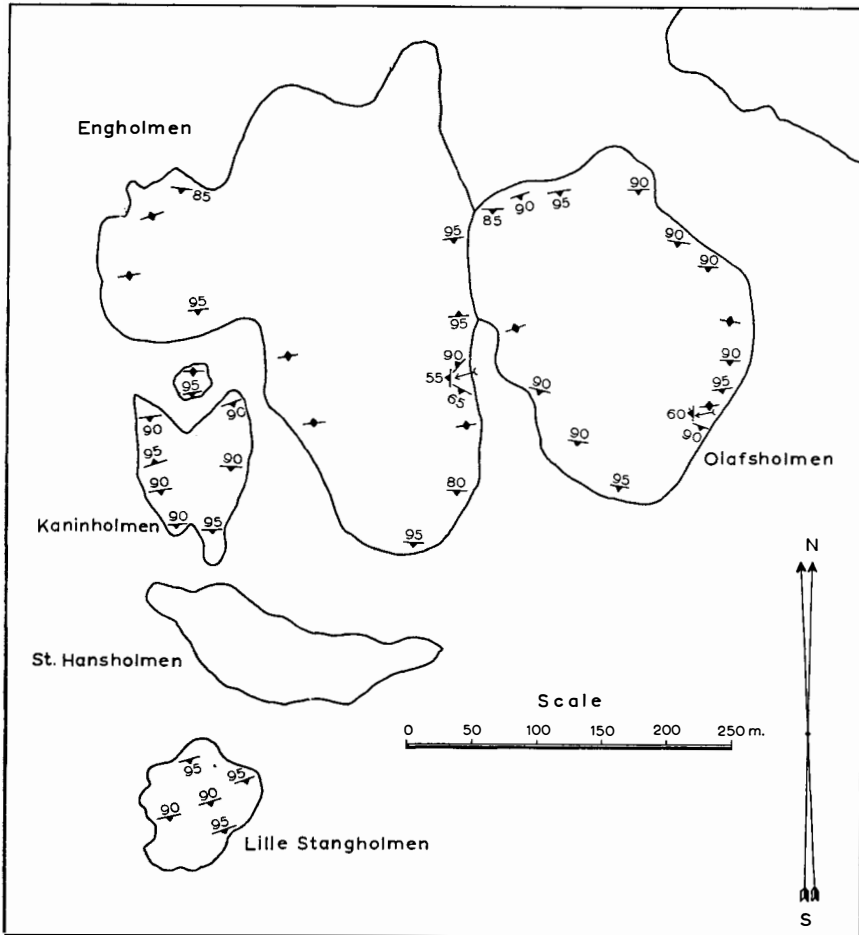the east side of Engholmen, after which it is covered by vegetation.

Fig. 3. The primary structure of the islands adjacent to St. Hansholmen is shown.

This fold could well be the necessary adjacent minor anticline (or overturned syncline). The axis of this fold strikes about N 85 W and plunges about 50° to 55° to the west. The axial plane is near vertical, dipping perhaps slightly to the south. The work done previously be J. A. W. Bugge (18) and by B. Hofseth (23) in the Søndeled and Kragerø areas respectively, which are the investigated areas closest to the one covered by the present study, do not cover areas

which are critical to establishing the existence of the postulated structure. Neither do these investigations rule out the possibility suggested here.

Genesis.

PLAGIOCLASE PEGMATITES

The foregoing is believed to indicate quite strongly that the pegmatite veins and inter-boudin fillings on St. Hansholmen occupy areas in which there occurred fractures or zones of low pressure during the deformation of the area. Fractures or zones of low pressure are thermodynamically unstable during metamorphism and hence, when these developed, material was introduced until stable pressure relationships were re-established.

It seems that there are three possible modes of origin that can be suggested for the material now constituting the pegmatites. They are: (1) a magma introduced into the present sites where it then crystallized; (2) a hydrothermal solution which carried the material in and there deposited it; and (3) a dispersed phase of ions, molecules, or atoms which diffused toward the unstable low pressure areas and there consolidated.

On purely physical grounds the first possibility seems to be unsatisfactory. The pegmatite occurs in veins which in some cases are completely enclosed in the amphibolite and which in some cases are no wider than the width of a single crystal. In most cases, however, it cannot be shown to be comlpletely impossible that a network of cracks existed forming a narrow conduit communicating with the supposed magma. It might then be considered advisable to propose two modes of origin, but because the pegmatite veins which are without possible doubt completely enclosed by the amphibolite are mineralogically and petrographically indistinguishable from the others, one explanation for both would be more satisfactory.

The physical objection to postulating a magmatic origin for the pegmatites is that due to the viscosity of any type of silicate melt the introduction of the melt into any area through the intergranular spaces of a compact rock (i. e., through sub-microscopic channels) is impossible. The isolated location of some of the pegmatites requires that the material now constituting these pegmatites moved, at least over some distance, through the intergranular pore spaces of the
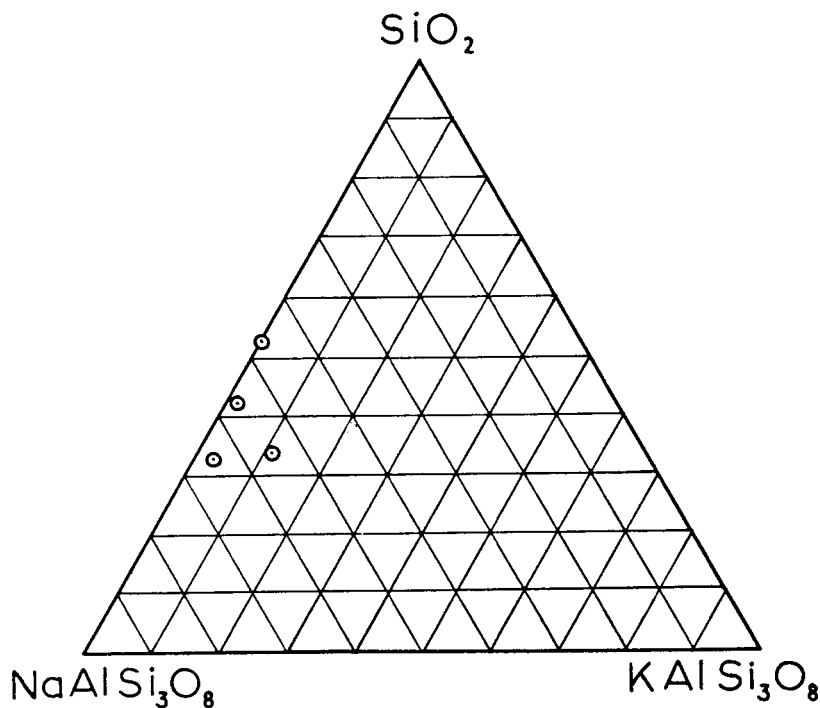
Fig. 4. Three-phase SiO₂-alkali feldspar diagram on which the composition of four of the plagioclase pegmatites is plotted.

amphibolite. The gneiss, which has been shown to have been quite plastic at the time the pegmatite material was introduced, would provide an even poorer avenue of transport for a magma than the amphibolite.

The chemical composition of the pegmatites does not in any way suggest that they were derived from a magma — especially not a magma enriched in the residual products of differentiation, such as is usually proposed for pegmatites. They are not rich in volatiles, in hydrated minerals, or in rare minerals. Also, if the compositon of the pegmatites is plotted on the three-phase SiO₂-alkali feldspar diagram (fig. 4) it is seen that the points fall well away from the low tempera-ture trough where one should expect the composition of magmatically derived pegmatites to fall.

It seems, therefore, highly unsatisfactory to attempt to ascribe to these pegmatites a magmatic origin.

If the pegmatites are of hydrothermal origin, then just as a magma would have had to have moved through the rock intergranularly at least in part, so also would the hydrothermal solution carrying the pegmatite-forming material. Again the gneiss as an avenue of transport can be ruled out because in it the existence of openings of sufficient size and continuity to allow the passage even of a fluid having as low viscosity as has a hydrothermal solution is impossible. Hence, a hydrothermal solution would have been confined to the amphibolite, but this is quite all right as the pegmatites are also strictly confined to the amphibolite bands.

Assuming that the amphibolite was sufficiently permeable to allow the intergranular passage of the hydrothermal solution over the required distances it is neccessary that the solution would have had to have thoroughly «soaked» the amphibolite in order to have given rise to pegmatites such as those shown in fig. 2. That the amphibolite bands were «soaked» with a solution bearing the constituents of the pegmatites seems unlikely for two reasons. First, there is not found interstitial quartz in the amphibolite which should be expected to result from a solution which had penetrated into all the intergranular spaces and was in the process of precipitating the pegmatites. That is, if the hydrothermal solution had «soaked» the amphibolite there should be some traces of this in the form of interstitial quartz. Second, if the plagioclase in the pegmatites (An_{20} in the veins and An_{28} in the inter-boudin fillings) had been precipitated from a hydrothermal solution then this solution must have been in equilibrium with plagioclase of this composition. (The two types of pegmatite may have formed at different times, the composition of the solution having changed between the times, but nevertheless, the composition of the solution must have been in equilibrium with the plagioclase being precipitated at any given time.) However, if this solution had «soaked» the amphibolite it would not (at either time) have been in equilibrium with the plagioclase of the amphibolite which is An_{31}. Hence, had the amphibolite been «soaked» one should expect to find zoning or at least some sign of reaction between the solution and the rims of the plagioclase grains. This is not the case. The plagioclase grains in the amphibolite are quite uniform from the centers to the boundaries.

Friedman (20), in a study of the system H_2O—Na_2O—SiO_2—Al_2O_3,

says» .... that one can have a solution at relatively low temperature (450° C) which contains components in solution that are capable of yielding rock-forming minerals. For example, a solution of [composition ca. 1.50 % Al_2O_3, 4.25 % Na_2O, 4.25 % SiO_2, and 90 % H_2O by weight %] can, if cooled from 450° to 300° C., deposit albite and quartz.» Such a solution, with some CaO in place of some of the Na_2O, moving from a warmer area (e. g., the granulite facies area to the southwest (18)) into the area of St. Hansholmen, would be just the kind of hydrothermal solution required to form the pegmatites. (Appreciably greater percentages of dissolved material seem unlikely from Friedman's diagram.) Assuming that through this temperature change 10 % of the dissolved material were precipitated in the form of plagioclase and quartz (sufficiently generous, I think, considering the ratios of the oxides in solution in relation to the ratios contained in the desired precipitate) and that the specific gravity of the precipitate is 2.6, then for every cm^3 of plagioclase and quartz precipitated from this solution through cooling it would be necessary for 244 cm^3 of solution to have passed through the amphibolite. Stated another way it can be said that for a thin sheet-like pegmatite veinlet but one centimeter thick, one meter long, and extending inwards into the rock for only one meter, 244,000 cm^3 of solution would have been necessary.

The effect that change in pressure would have on the solubility of the constituents in the hydrothermal solution is uncertain. Gibson (21) concludes «.... that only in somewhat exceptional cases is the solubility of a solid in a liquid raised by pressure ....». He lists carbonates, sulfates, sulfides, fluorides, hydroxides of some alkalis, the alkaline earths, and the heavy metals in water as exceptions. A watery solution of Al_2O_3—SiO_2—Na_2O is not included in this list.

This would suggest that one should not expect precipitation from this solution in low pressure areas. Kennedy (26) gives curves showing greater solubility of quartz in water with increase of pressure, but below ca. 700 bars these curves pass through a solubility maximum in the vicinity of 350° to 400° C. But Friedman(20), in reference to the solution of composition such that on cooling from 450° to 300° it could deposit quartz and albite, also notes that at 450° the field (from which the composition percentages given above were determined) «is occupied at intermediate pressure by albite and at low pressure

by solution.» This suggests that reduction of pressure does not cause precipitation for this composition, but rather the reverse.

In the preceding discussion of a hydrothermal origin for the pegmatites it has been assumed that the amphibolite bands were readily permeable by a hydrothermal solution. It is not certain that such a solution would be sufficiently non-viscous to move through the tiny intergranular spaces of the rather dense amphibolite without having left traces of its passage, especially as such large quantities would have been required to have passed through.

The lack of volatiles or hydrated minerals in the pegmatites makes it seem somewhat unlikely that they were formed from a hydrothermal solution which, at least normally, should be expected to be greatly enriched in volatile constituents.

For the above reasons the author finds it unsatisfactory to attempt to explain the pegmatites as a precipitate from a hydrothermal solution.

That the pegmatites are the result of the migration of a dispersed phase of ions, molecules, or atoms into fractures or zones of low pressure followed by the consolidation of this phase to form the mineral grains now present seems to be the most preferable theory for the genesis of the veins and inter-boudin fillings on St. Hansholmen. On structural grounds there is no objection to this mode of origin. As has been demonstrated, the pegmatites occupy zones of shear or fracture and hence are in the places of lowest pressure during the dynamothermal metamorphism of the area. It is towards low pressure areas that diffusion of a dispersed phase is to be expected. Visible openings in the rocks surrounding the pegmatites are not required for the transport of the dispersed phase, nor is there to be expected evidence in the surrounding rocks of the passage of the diffusing material. Neither is there to be expected a reaction between the minerals of the surrounding rocks (e. g., the amphibolite bands) and the dispersed phase becaused the dispersed phase is present only because of the decomposition of the minerals in the host rock at the P,T conditions prevailing. The low pressure zone is, however, a «sink» into which the dispersed phase moves until equilibrium pressure relationships have been re-established.

The temperature of the environment during the metamorphism of the area, 460 °C, determined by the alkali content of the feldspars in
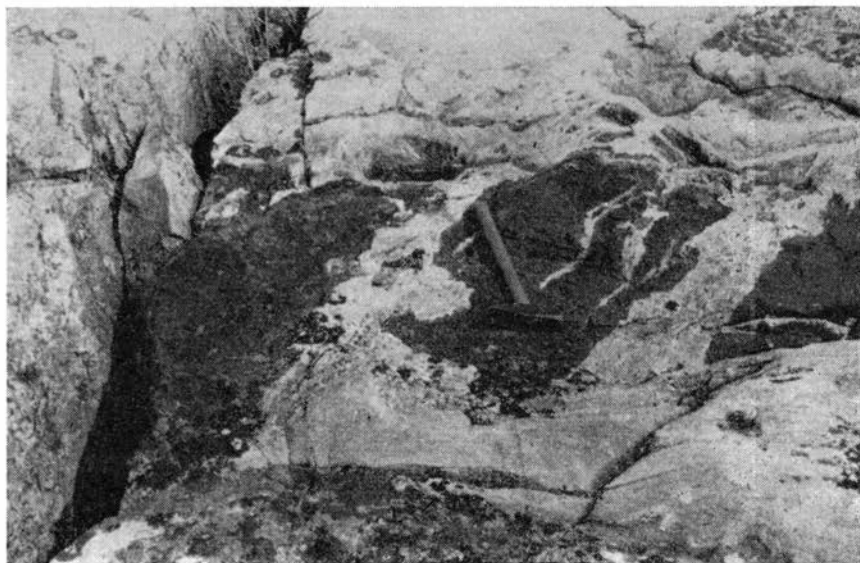
Fig. 5. Boudinage structure with the line of separation between boudins not perpendicular to the amphibolite band boundaries but following the shear direction, as revealed by the thin pegmatite veins in the boudin.

the gneiss and according to the scale given by Barth (5), is in support of this theory for the genesis of the pegmatites, being well below the temperatures of magmas. (Alkali content of feldspar determined by Miss Erna Christensen with the flame photometer.)

Provided that the assumption that diffusion may occur in rocks during metamorphism is granted, such things as the difference in the composition of the plagioclase in the pegmatites as opposed to the plagioclase in the amphibolite bands and gneiss, and the difference between the plagioclase of the two types of pegmatites can be readily explained.

As it seems quite likely that calcium is somewhat less mobile than sodium one should predict a difference in the composition of plagioclases formed by crystallization from a diffusing dispersed phase if the crystallization were at two different times. The prediction should be that earlier-formed plagioclases will be more albitic than those formed later. In the present case it seems likely that the shear zone low pressure areas caused by the bending of the amphibolite bands

would have developed before the rupture of the bands to form boudins, which was caused by the compression and consequent plastic flowage of the gneiss around the amphibolite bands. The boudins shown in figure 5, where the line of separation or fracture is not perpendicular to the band boundaries but follows the predominant shear direction indicate the validity of this assumption. The fact that the vein pegmatite plagioclase is more sodic than the inter-boudin filling plagioclase (An_{20} and An_{28} respectively) corresponds with the theory of pegmatite formation through diffusion, the former having been formed before the latter, while the dispersed phase was being enriched in the less mobile constituent (calcium) through time.

That the plagioclase of the pegmatites is more sodic than that in the amphibolite and gneiss follows from the greater diffusibility of sodium as compared with calcium.

That the grain size of the pegmatites is greater than that in the amphibolite and gneiss can also be explained assuming formation from a dispersed phase.

The dispersed phase envisioned by the author exists in equilibrium with the host rocks at the prevailing P,T conditions and at low concentration. With the development of a local low pressure area a concentration gradient is created and the dispersed phase diffuses toward it. Another consequence of the development of a local low pressure zone might be the development of a nearby zone of increased pressure where the host rock minerals would, at least partly, decompose and replenish the dispersed phase. The free energy of the minerals which began to grow in the low pressure zone would be less than the free energy of the same minerals in the surrounding area. Hence there would also be a free energy gradient towards the low pressure zone. (For a more thorough account of the process of metamorphic differentiation due to heterogeneous pressure according to the diffusion theory see Ramberg, 1952, pp. 215—220). However, with a dispersed phase of rather low concentration, nucleation of minerals would not be rapid. Because a lower critical concentration is necessary for continuation of accretionary growth than for nucleation, the few nuclei formed (assuming a concentration near the critical concentration for nucleation) would continue to grow and, eventually, not being opposed by a high density of other growing grains, attain considerable size.

Sometimes zones of concentration of dark minerals around the pegmatites can be seen. These may be due to a later reaction between the pegmatites and amphibolite rather than to a selective concentration due to «leaching» of the light minerals. These zones are always very narrow (ca. 1—2 cm at most). The dark minerals are always slightly coarser grained in these zones than in the average amphibolite and are always completely conformable with the pegmatite, suggesting that the process giving rise to them involved recrystallization after the pegmatite had formed.

The numerous examples of pegmatite fillings between boudins show exactly those features which Ramberg (30), (31) has mentioned in relation to similar pegamatites studied in Greenland and elsewhere. The arguments advanced by Ramberg concerning the formation of pegmatite fillings between boudins and pegmatite veins such as occur on St. Hansholmen were convincing to the author and it is believed that the same arguments can be advanced in the present instance.

PINK PEGMATITE

On the basis of the present study nothing conclusive can be said concerning the genesis of the pink pegmatite. There have been revealed no features which are diagnostic of any one particular mode of origin. However, more detailed investigation of this pegmatite and the immediately surrounding rock is planned and it is hoped that something conclusive can be said in a later publication.

The alkali content of the perthite from sample ØP 17 was determined with the flame photometer by Miss Erna Christensen. From this determination and the optical determination of the composition of the co-existing plagioclase, the feldspar thermometer as explained by Barth (5) indicates that 610° C was the approximate temperature of formation of this pegmatite. It is perhaps noteworthy that this is very close to the temperature of 620° C. determined from a pegmatite on the nearby island of Risøen described by Andersen (1), (2). It also lies below the commonly accepted low temperature boundary for magmatic rocks.

BANDED GNEISS

The cause and origin of the banded structure in gneiss' such as those on St. Hansholmen has been much discussed, but, as far as the

author knows, there has as yet been offered no unanimously accepted explanation.

The following origins for the banded structure have been suggested:

1. Differentiation processes in a solidifying magma.
2. Primary stratification of supracrustal rocks.
3. Lit-par-lit intrusion of magma along bedding planes or dominating shear planes in an older rock.
4. Metamorphic differentiation of rocks with a different structure previously.

In his work on the Kongsberg-Bamle formation J. A. W. Bugge (18) discusses in considerable detail these origins and the work done by proponents of each of them. His studies lead him to emphasize the importance of metamorphic differentiation as an agent in the formation of the banded structure, although he notes that as there exist rocks of indisputable sedimentary origin following the primary strike direction, a contribution to the banding due to primary stratification cannot be ruled out.

The present study was over a very limited area and, based on it, it is impossible to offer any new suggestion as to the origin of this structure or to criticize previous attempts to solve this problem.

Concerning the possibility that the structure is due to primary stratification of supracrustal rocks very little can be said.

There were observed no rocks on St. Hansholmen in which primary sedimentary or effusive structures were to be seen. This is not surprising as the metamorphic recrystallization is quite complete.

Based on the mineral percentages determined using the point counter the approximate weight percent chemical composition of five microcline containing samples was re-calculated. The composition taken for biotite is that suggested by T. F. W. Barth (4) for use in calculating meso- and epi-norms from the chemical analysis. It is $KAlMg_3Si_3O_{10}(OH)_2$. This was done in order to make comparison with possible sedimentary and effusive compositions. The average of the these five recalculations is given below along with the composition of a rhyodacite (25) and one part average arkose plus one part average graywacke (28).

As can be seen the correspondence between the gneiss and either the effusive or the mixed sediment is about equally good and with

	Av. 5 gneiss'	Rhyodacite	1 pt. arkose plus 1 pt. graywacke
SiO_2	74.0	68.98	71.8
Al_2O_3	14.7	15.24	13.4
Fe_2O_3, FeO, MnO, MgO ..	1.5	4.39	4.9
CaO	3.0	3.01	2.0
Na_2O	3.6	3.88	2.3
K_2O	3.0	3.53	3.9

only small changes the gneiss could correspond excellently with either.

The study made of the gneiss on St. Hansholmen seems to support, at least in one respect, origin by metamorphic differentiation. The change in the microcline content of the gneiss in relation to the distance from an amphibolite band has already been pointed out (fig. 1). This change cannot be explained as due to a «leaching» process during the formation of the pegmatites in the amphibolite bands, because these pegmatites either contain no microcline or are very poor in microcline. However, it may be explained as being due to the same process as gave rise to the banded structure. The microcline was very probably among the most mobile and plastically deformable minerals present and hence was concentrated in the middle of the bands containing the relatively mobile and plastically deformable minerals. For more complete discussions of the process here mentioned the reader is referred to the works of J. A. W. Bugge (18), F. J. Turner (34), B. Sander (32), and W. Schmidt (33).

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REFERENCES

1. ANDERSEN, O.: Feltspat II. Norges Geologiske Undersøkelser Nr. 128b, 1931.
2. — Discussions of Certain Phases of the Genesis of Pegmatites. Norsk Geologisk Tidsskrift, Bind 12, 1932.
3. BARTH, T. F. W.: Feltspat III. Norges Geologiske Undersøkelse, Nr. 128b. 1931.
4. — Presentation of Rock Analyses. Jour. Geol. Vol. 63, 1955.
5. — Studies in Gneiss and Granite I: Relation between Temperature and the Composition of the Feldspars. Vid. Akad. Skr. Oslo 1956, No. 1.
6. BJØRLYKKE, H.: Mineral Paragenesis of Some Granite Pegmatites Near Kragerø, Southern Norway. Norsk Geologisk Tidsskrift, Bind 17, 1937.
7. — The Granite Pegmatites of Southern Norway. The American Mineralogist, Vol. 22, 1937.
8. — Feltspat V. Norges Geologiske Undersøkelse Nr. 154, 1937.
9. BRØGGER, W. C.: Die Mineralien der Südnorwegischen Granitpegmatitgange L. Vid. Selskap. Skr. Mat.-Nat. Kl. No. 6, 1906.
10. — On Several Archean Rocks from the South Coast of Norway I. Vid.-Akad. Skr. I, No. 8, 1933.
11. — On Several Archean Rocks from the South Coast of Norway II. Vid.-Akad. Skr. I, No. 1, 1934.
12. BUGGE, A.: Nikkelgruber i Bamble. Norges Geologiske Undersøkelse Nr. 87, 1922.
13. — Et forsøk på inndeling av det syd-norske grunnfjell. Norges Geologiske Undersøkelse Nr. 95, 1922.
14. — En forkastning i det sydnorske grunnfjell. Norges Geologiske Undersøkelse Nr. 130, 1928.
15. — Kongsberg-Bamble Formationen. Norges Geologiske Undersøkelse Nr. 146, 1936.
16. — En oversikt over arbeidet i det sydnorske grunnfjell. Norsk Geologisk Tidsskrift, Bind 21, 1941.
17. BUGGE, J. A. W.: Geological and Petrographical Investigations in the Arendal District. Norsk Geologisk Tidsskrift, Bind 20, 1940.
18. — Geological and Petrographical Investigations in the Kongsberg-Bamble Formation, Norges Geologiske Undersøkelse Nr. 160, 1943.
19. FORBES, D.: Gæologiske undersøgelser over det metamorfiske Territorium ved Norges Syd-kyst. Nyt Mag. f. Naturvid., Bind 9, 1857.

20. FRIEDMAN, I.: Some Aspects of the System $H_2O-Na_2O-SiO_2-Al_2O_3$. The Journal of Geology, Vol. 59, 1951.

21. GIBSON, R. E.: On the Effect of Pressure on the Solubility of Solids in Liquids. Am. J. Sci. Ser 5, Vol. 35A, 1938.

22. GREEN, J. C.: Geology of the Storkollen—Blankenberg Area, Kragerö, Norway. Norsk Geologisk Tidsskrift, Bind 36, 1956.

23. HOFSETH, B. Geologiske Undersøkelser ved Kragerø, i Holleia og Troms — Petrography of the Levang Peninsula (Kragerø, Norway). Norges Geologiske Undersøkelse Nr. 157, 1942.

24. HOLTEDAHL, O.: Norges Geologi Bind I. Norges Geologiske Undersøkelse Nr. 164, 1953.

25. JOHANNSEN, A. A Descriptive Petrography of the Igneous Rocks Vol. II. The University of Chicago Press, 1932.

26. KENNEDY, G. C.: A Portion of the System Silica-Water. Economic Geology, Vol. 45, 1950.

27. KJERULF, Th. and DAHLL, T. Om Jernertsens Forekomst ved Arendal, Næs og Kragerø. Nyt Mag. f. Naturvid. Bind 11, 1861.

28. PETTIJOHN, F. J. Sedimentary Rocks. Harper & Brothers, 1949.

29. RAMBERG, H.: The Origin of Metamorphic and Metasomatic Rocks. The University of Chicago Press, 1952.

30. ⸺ Natural and Experimental Boudinage and Pinch-and-Swell Structures. The Jour. of Geol., Vol. 63, 1955.

31. ⸺ Pegmatites of West Greenland. Bull. of the Geol. Soc. of Am., Vol. 67, 1956.

32. SANDER, B.: Gefügekunde der Gesteine. J. Springer, Berlin, 1930.

33. Schmidt, W. Tektonik und Verformungslehre. Verlag Boerntraeger, Berlin, 1932.

34. TURNER, F. J.: The Development of Pseudo-stratification by Metamorphic Differentiation. Am. Jour. Sci., Vol. 239, 1941.

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Geology of St. Hansholmen

RISÖR, NORWAY

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Legend:

- Gneiss
- Amphibolite
- Plagioclase pegmatite
- Pink pegmatite
- Water
- 90 — Dip and strike of foliation
- Strike of vertical foliation
- 60 — Strike and plunge of grooving at fold axes
- x 20 — Location and number of a sample

Scale 1:600

0 2 4 6 8 10   15   20   25   30 meters

mag.N N