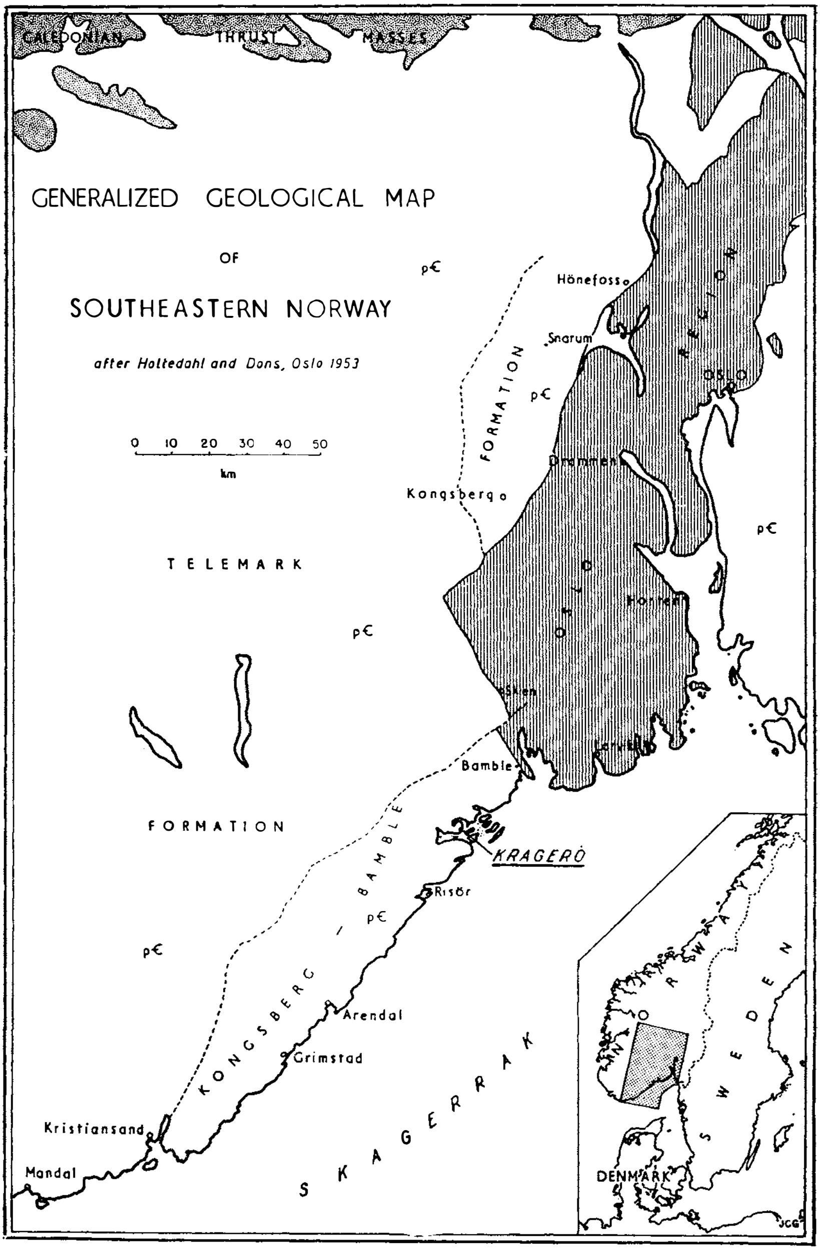
GEOLOGY OF THE STORKOLLEN—BLANKENBERG AREA, KRAGERØ, NORWAY

BY
JOHN C. GREEN

CONTENTS

	Page
Abstract	89
Introduction	91
Geological Environment	93
Structure	93
Petrography	96
Gabbros	97
Amphibolites	98
Schists	99
Quartzites	100
Albitites	101
Pegmatites	119
Iron Mineralization	128
Genesis of the Leucocratic Rocks	128
Albitites	129
Pegmatites	135
Conclusions	137
Acknowledgments	138
References	138

A b s t r a c t. The high-grade quartzites and schists of the pre-Cambrian Kongsberg-Bamle formation in the Storkollen-Blankenberg area, Kragerø, enclose small gabbroic stocks which were centripetally altered to amphibolite during the Sveco-fennide (?) metamorphism. Associated with the gabbros and probably derived from them are dikes and irregular bodies of granulose albitite containing varying amounts of other minerals, notable among which are quartz, microcline, rutile, and tourmaline. Certain areas of the large rutile-albitite body of Lindvikskollen (kragerøite) were found to contain corundum; this is a new locality for corundum in Norway. Euhedral tourmaline crystals in an albitite-amphibolite transition zone were found to be an Mg-rich variety;


CALEDONIAN THRUST MASSES
GENERALIZED GEOLOGICAL MAP
OF
SOUTHEASTERN NORWAY
after Holtedahl and Dons, Oslo 1953
0 10 20 30 40 50
km
TELEMARK
FORMATION
pЄ
Hönefoss
Snarum
OSLO
FORMATION
Drammen
Kongsberg
Horten
Bamble
KRAGERÖ
Risör
KONGSBERG - BAMBLE
Arendal
Grimstad
Kristiansand
Mandal
SKAGERRAK
SWEDEN
DENMARK

this is also a new locality. It is concluded that most if not all of the albitites were formed metasomatically from preexisting amphibolite.

Late in the orogeny, large, rare-earth bearing pegmatites were intruded in a highly liquid state, and cooled slowly with several stages of mineralization, including a partial replacement of microcline by cleavelandite.

Finally, after shearing stresses had locally faulted and brecciated the rocks, iron oxide mineralization took place along a small east-west fissure.

Introduction.

The Pre-Cambrian rocks of the south Norwegian coast from Langesundsfjord to Kristiansand are known as the Kongsberg-Bamle formation, which is separated from the main southeastern Norwegian Pre-Cambrian area by a major breccia zone (A. Bugge, 16[1]). Near the northern end of this strip lies the town of Kragerø, (see index map, p. 90), protected from the storms of the Skagerrak by a multitude of islands, or skjærgård. Just west of the town lies a unique area whose amphibolites contain many large pegmatites and albitite bodies. A geological study of this area was carried out during my stay in Norway under a United States Government Fulbright Scholarship for the year 1953-54.

Seven weeks of field work were undertaken in the fall of 1953 and one week in May, 1954, mapping, making detailed field observations, and collecting specimens. The winter and spring were spent at the Geological Museum of the University of Oslo, whose facilities were kindly made available to me by Prof. Dr. Tom. F. W. Barth, the Director. Detailed study of the collected material was carried out with the aid of refractive index determinations, thin sections, Universal stage methods, X-ray mineral determinations, chemical tests, and heavy-liquid and magnetic separation methods. The tables by Trøger (30) were used for most of the refractive index work, but use was also made of Larsen and Berman (23) and Tsuboi (31). A geological map was made to the scale of 1/5000, based on a topographic map drawn by myself from aerial photos and aneroid barometer observations. The mapped area is about 2 km^2 in area, its eastern edge passing through the top of the hill Storkollen, the northern edge lying in the Kalstad—Leirvik—Ånevik valley, and having the Kilsfjord as the southern and western limit. The less accessible portion west

[1] Numbers refer to list of references, p. 138.

of the Kammerfoss River was only roughly investigated (two days of field work), the bulk of detailed study being concentrated in the area between Storkollen and the river.

W. C. BRØGGER, OLAF ANDERSEN, and HARALD BJØRLYKKE have done most of the previous work in this area. BRØGGER led many excursions to Kragerø from the University of Oslo in the 1890's and the first quarter of this century, and studied his collected material in great detail. Within the area concerned in the present report, his main interest lay in the rare pegmatite minerals (12, 13) and the kragerøite and other leucocratic dikes (15). He also investigated the nodular granites and related rocks of the surrounding Bamle complex (14), but scarcely touched upon the gneisses in the immediate vicinity of this report.

V. M. GOLDSCHMIDT did considerable spectroanalytical work on the Kragerø pegmatite minerals (19).

OLAF ANDERSEN studied in particular the feldspars of the large pegmatites (1, 2, 3), mapped the area with T. F. W. Barth and also collected specimens in the albitites and surrounding amphibolites. I am greatly indebted to the Norsk Geologisk Undersøkelse for permission to use the thin sections and hand specimens of Andersen's collection.

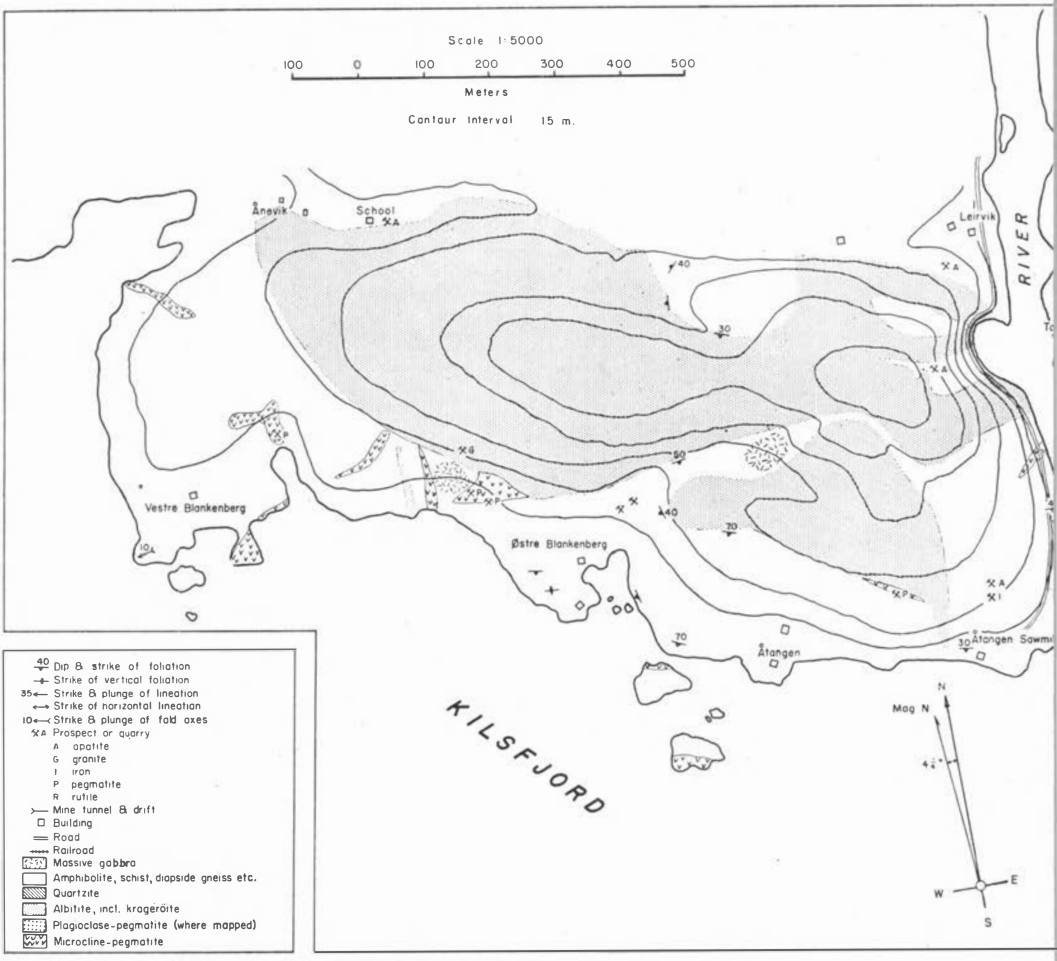
HARALD BJØRLYKKE also concerned himself with the large pegmatites, and wrote several papers on their mineralogy, deducing a system of pegmatite classification based partly on the Kragerø mineral associations (6, 7, 8, 9, 10, 11).

ARNE BUGGE mapped the regional geology around Kragerø in 19 , but has not completed or published his map. His large work published in 1936 (17) covers the whole Kongsberg-Bamle formation.

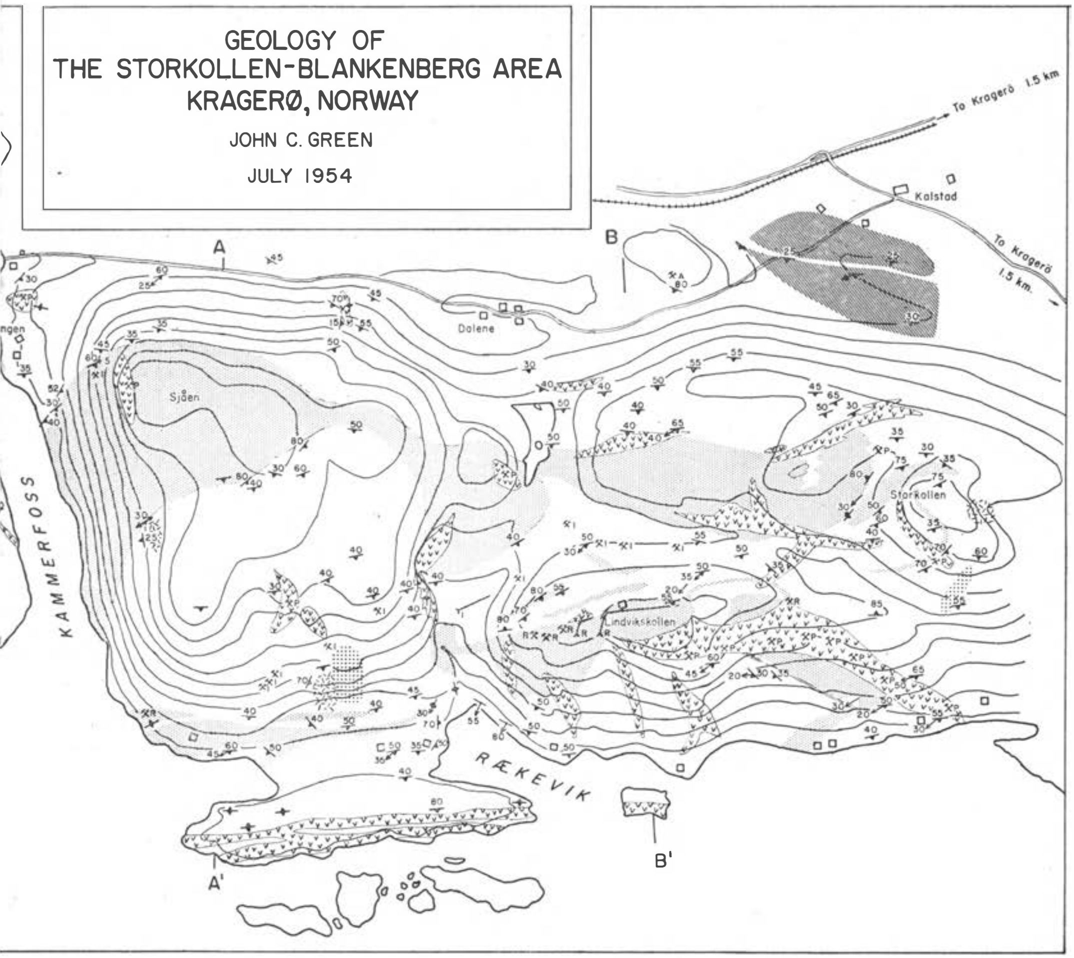
A more complete investigation of this formation was carried out by JENS BUGGE, beginning in 1937, and concentrating in the Arendal area to the southwest. His results were published in 1943 (18).

In 1939 BRIT HOFSETH mapped and studied the granite of the Levang Peninsula, immediately south of the present area, and in 1940 the dolomite occurrences in the Kragerø region. Her work was published in 1941 (21).

A. F. FREDERICKSON did field work in the Kragerø Peninsula in 1951—52, but his results have not as yet been published.



Scale 1:5000
100 0 100 200 300 400 500
Meters
Contour interval 15 m.
Ånevik
School
Leirvik
RIVER
Vestre Blankenberg
Østre Blankenberg
Åtangen
Åtangen Sawmill
KILSFJORD
Mag N
N
E
W
S
Dip & strike of foliation
Strike of vertical foliation
Strike & plunge of lineation
Strike of horizontal lineation
Strike & plunge of fold axes
Prospect or quarry
A apatite
G granite
I iron
P pegmatite
R rutile
Mine tunnel & drift
Building
Road
Railroad
Massive gabbro
Amphibolite, schist, diopside gneiss etc.
Quartzite
Albitite, incl. krageröite
Plagioclase-pegmatite (where mapped)
Microcline-pegmatite


GEOLOGY OF
THE STORKOLLEN-BLANKENBERG AREA
KRAGERØ, NORWAY
JOHN C. GREEN
JULY 1954
To Kragerö 1.5 km
Kalstad
To Kragerö 1.5 km.
Dolene
Sjåen
Storkollen
Lindvikskollen
KAMMERFOSS
RÆKEVIK
A
A'
B
B'

Geological Environment.

The Bamle formation at Kragerø is composed of a series of generally NE-striking interbedded banded gneisses quartzites, mica schists, and amphibolites, including granitic bodies (Levang granite), olivine-gabbros (Valberg Peninsula), and small to large albitite and pegmatite bodies, usually lensoid or dike-like in form. Post-metamorphic diabase dikes cut the rocks in a few places (Risø).

Many different types of local mineralization occur. Scapolite is a very common mineral in the Kragerø area, occurring as an alteration of plagioclase in the gabbros and as fissure-fillings, often with hornblende in large crystals, in amphibolites and gabbros. Of economic importance have been red apatite (found with hornblende, scapolite, rutile, calcite, and enstatite, in certain mineralized zones in crystals up to a meter long and 20 cm in diameter) and white dolomite, in hydrothermal deposits up to several meters wide occurring along fault zones and other fractures. Associated with the dolomite in two quarries visited by the author (near Aasen, Kammerfoss, just north of the map area) were found blue-green calcite, diopside, tremolite, talc, and pyrrhotite. Both apatite and dolomite have been intermittently mined for many years. A fissure containing iron oxides extends east-west across the map area, and has been worked at several places.

Structure.

The rocks in the Storkollen-Lindvikskollen-Sjåen area are characterized by a general E-W strike and a southerly dip ranging, with a few exceptions, from 35 to 60 degrees (see structure sections, Fig. 1, and geologic map). A lineation in the plane of schistosity is often present, plunging SW or WSW in nearly all observed instances, indicating conformity to a general regional deformation. The type of lineation ranges from a preferred orientation of tourmaline needles in albitite dikes through drawn-out clots of minerals in amphibolites to minor fold axes and cataclastic stretching features in the schists.

There are several local disruptions of this regional trend, however. The northwest flank of the hill Storkollen contains a gentle syncline plunging to the southeast, and the rocks forming the north flank of

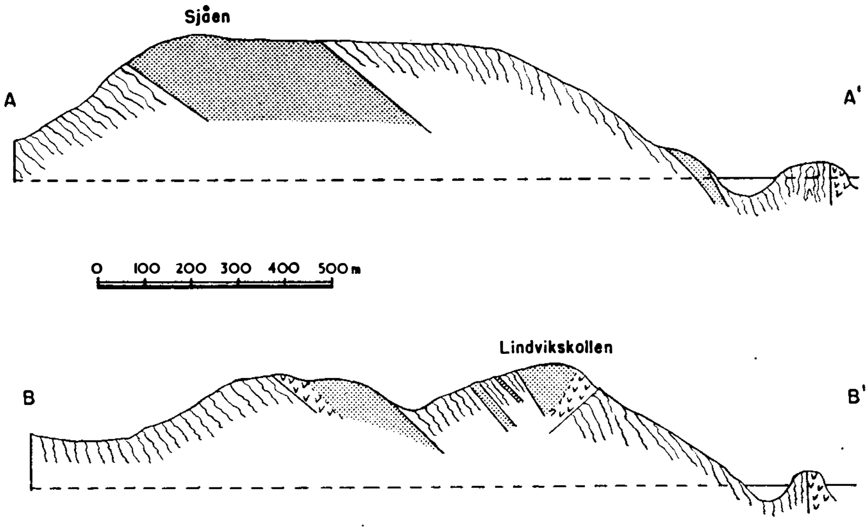


Fig. 1. Structure sections AA′, BB′ across map area.

the hill Sjåen, from the pond at Dalene almost to Tangen, strike NW to WNW. At the head of the cove Rækevik a considerable shearing deformation has taken place; the farm just to the west lies in the middle of a smooth anticline plunging steeply SE, and at the east-facing cliff 200 to 400 meters north of this, the rocks are vertical, close to normally oriented rocks only a few meters west of the cliff top. In the valley below the cliff, the rocks (here more schistose) show tight, small wrinkles, low-grade alteration, and other signs of late-metamorphic shearing movements. On the two-ended peninsula to the south the strike is uniformly E-W, but the dip rapidly becomes steep to vertical southward across the peninsula. Vertical, isoclinal folds occur towards the western end.

About 200 meters west of the top of Storkollen there seems to be another roughly N-S shear zone, separating two parts of an albitite body by a narrow band of schist and gneiss. Here also the schistosity is vertical with an anomalous strike, and a narrow valley has been cut along the shear zone. All along the northern edge of the mapped area, along the lower flank of the hill, the schists are considerably wrinkled into small-amplitude folds. The amphibolites east and north of the Tangen pegmatite are also highly and often sharply folded. At

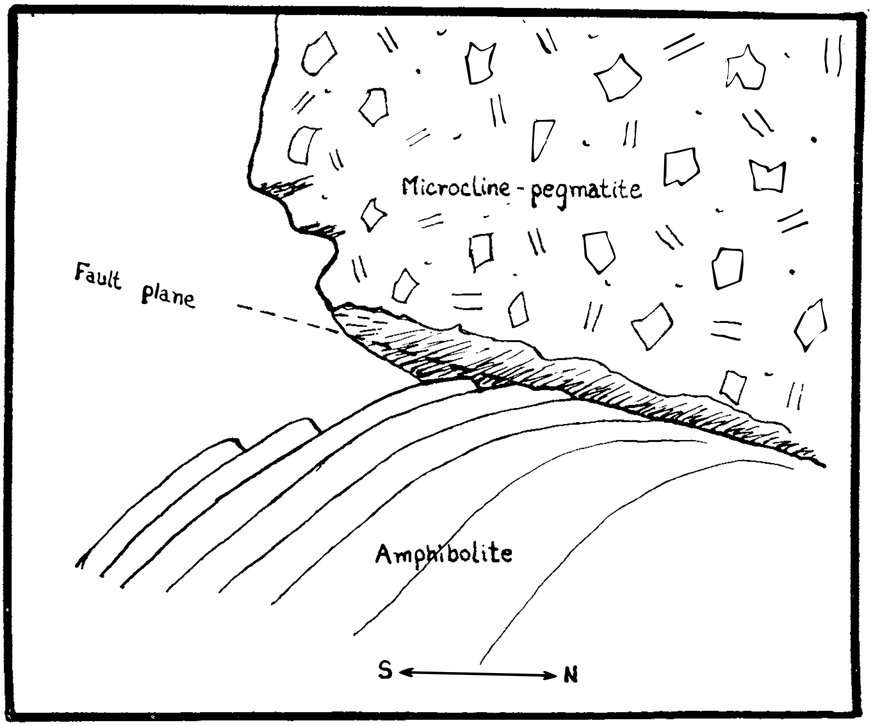


Fig. 2. Faulted pegmatite-amphibolite contact, Kalstadgangen quarry.

the mouth of the Kammerfoss River a narrow strip of schist between two conformable albitite bodies has acquired a vertical orientation.

Several post-metamorphic faults were observed, but their displacement could not be determined. The south contact of the eastern end of the Kalstad pegmatite lies in a fault plane dipping about 10° NE to N. It is especially well exposed at the quarry loading bins, where the underlying amphibolite has been dragged northward along the fault. See Fig. 2.

Two faults were observed in and bordering the main kragerøite body on Lindvikskollen; each of the two main rutile stopes follows one of these faults for some distance. In the smaller, western stope, the fault plane forms the north contact of the kragerøite against amphibolite, and has been laid bare by removal of the rutile ore on the south side. Here the fault plane strikes about E-W with a steep, irregular dip to the south. The texture of the slickensides indicates that at least in one movement, the south (kragerøite) wall moved down and to the west relative to the north wall. The larger eastern rutile mine follows the second fault for about twenty meters at its entrance tunnel, before turning east into the main stope. This fault strikes N9° E and is approximately vertical. These faults are characterized by the formation of a zone of biotite rock several centimeters thick; under the microscope the biotite is seen to bend around small lenses of muscovite, quartz, albite, and calcite.

Topographic evidence suggesting two or three N- to NE-striking faults can be seen towards the east end of Sjåen, but geologic evidence is difficult to find. From the relative positions of albitite, amphibolite, and an iron fissure on each side of the Kammerfoss River, it seems reasonable to infer a N-S fault along the river. A steeply dipping, arcuate fault is evident on the hill west of the river, where a narrow band of amphibolitic schist in a small valley separates a small albitite body from the major outcrop. The albitite lies conformably on the south-dipping schist of the southern block, which evidently moved upward relative to the north block.

An interesting phenomenon was observed about 500 meters east of the top of Storkollen, off the map area; a small pegmatite there has been partly brecciated, and the resulting compact, angular breccia has a matrix composed largely of calcite.

An albitite along the new road just north of Leirvik has also been strongly crushed.

Petrography.

The country rocks for the albitites and pegmatites in the mapped area would seem to represent a series of sediments and lava flows into which olivine-gabbro magmas have been intruded. Many varieties of similar, related rocks of this complex from elsewhere in the Kragerø area have been described by W. C. Brøgger (14, 15), Arne Bugge (17), and Jens Bugge (18). After the intrusion of the gabbros, the whole complex was subjected to the P, T conditions of the amphibolite facies. This has been referred to the formation of the ancient Sveco-fennide mountain range of southern Scandinavia by A. Bugge (1941) and Th. Vogt (1938). Age determinations on uraninite (without isotope determination of the lead) from pegmatites near Arendal gave about 1050 million years; the zircon age from pegmatite near Tvedestrand (also in the Bamle formation) gave 720 million years.

The cores of the largest gabbro bodies, however, escaped metamorphism and still retain their original ophitic texture and mineralogy. The preservation of the original character of these gabbro cores must be referrred to the dense, impermeable nature of the rock. As the P, T conditions within the solidified gabbros and outside them must have been roughly the same, it seems in this case that water, diffusing in from the surrounding sediments, was the active agent of metamorphism.

G a b b r o s. BRØGGER (15) has thoroughly described the largest gabbro bodies of the Kragerø area. Macroscopically the typical gabbro («hyperite») is a heavy, dark brownish-violet, medium-grained rock composed chiefly of large individuals of clinopyroxene enclosing smaller laths of labradorite, with lesser amounts of olivine, biotite, orthopyroxene, black ores, apatite, etc. Perhaps the most remarkable features of these rocks are the corona structures or reaction rims often developed around olivine and ore minerals when in contact with plagioclase (in the zones undergoing incipient metamorphism). Between olivine and plagioclase, hypersthene forms nearest the olivine, with hornblende including tiny spinels as an outer rim; biotite, hornblende, and garnet form the corona around the ore grains. Furthermore, parts of most of the gabbro bodies are often altered to scapolite-hornblende rock.

In the present area, I have found five separate ophitic cores of gabbro bodies, and it is quite possible that others have been overlooked, for the core areas are rather small. The westernmost one lies about halfway between Eastern (Östre) Blankenberg and Western (Vestre) Blankenberg. It contains a scapolite-hornblende facies. About 300 to 400 meters ENE of Östre Blankenberg another was found also containing scapolite. Its plagioclase, where not scapolitized, is a fresh, zoned labradorite. Another relict gabbro lies at the top of the cliff about 200 meters south of the Sjåen pegmatite. Olivine was seen in neither this nor the second-named outcrop, but very likely was originally present. The plagioclase at Sjåen is zoned and fresh, with cores An 72 and rims An 48. This gabbro differs from the great majority microscopically examined by Brøgger or myself in that it has reaction rims between the mesostatic clinopyroxene and the plagioclase. The corona consists of a pleochroic hornblende, oriented with its c-axis parallel to that of the pyroxene, and with minute quartz (?) grains strung along the boundary between the hornblende and pyroxene.

The next gabbro body was found to form a cliff about 200 meters northwest of the farm at Rækevik. A concentric foliation is particularly well developed around the borders of this roundish body; biotite schist lies at the most 50 meters from the ophitic, olivine-bearing core, which closely resembles the «hyperite» from Valberg described by Brøgger. The plagioclase has cores of An 68, and rims An 37. A fifth gabbro crops out at the top of the cliff on the east side of the top of Storkollen. It resembles in hand specimen the hyperite from Valberg, but has not been examined microscopically.

Amphibolites in the Storkollen—Lindvikskollen—Sjåen area crop out for the most part on the top and flanks of Storkollen, the south side of Lindvikskollen, and the large southern shoulder of Sjåen. Typically they contain from 50 % to 60 % of mafic minerals, preponderantly amphibole, and 40 % to 50 % of plagioclase, usually an andesine (An 35-40). Other common minerals are biotite, opaque ore, garnet, epidote, sericite, chlorite, calcite, and apatite. Less common are quartz, rutile, scapolite, prehnite, (as lenses in biotite), sphene, serpentine, and zircon.

The amphibolites have a gneissic to schistose structure formed by the parallel planar arrangement of amphibole and biotite, and very commonly a lineation formed by elongated clots of mafic or felsic minerals or by a parallelism of the hornblende prisms.

Several thin sections of macroscopically «typical» amphibolite seem, by their anomalous mineralogy, to be highly altered gabbros. They are scattered almost all over the map area. Some of these contain relict scraps of ortho- and clinopyroxene, being altered to amphibole; one contains plagioclase with a composition An 66; another has zoned plagioclase with cores An 60 and rims An 40; another is composed entirely of a ferrous amphibole (90 %) and large, inclusion-filled garnets; another contains only about 2 % plagioclase, which shows the typical complicated igneous twinning. Most of these rocks incorporate a number of these anomalous features. In fact, all gradations can be seen between the ophitic, olivine-bearing gabbro and the schistose, completely metamorphosed amphibolite, and it is clear that a very large portion of the present amphibolite originated as stock-like gabbroic intrusions.

All the amphibolite, however, cannot be assigned to gabbros directly. Sills, lava flows, and sediments have contributed their share. To cite an example, a persistent bed of amphibolite about four meters thick lies in an impure quartzite between the farms Kalstad and Dalene in the northeast corner of the map area. Considering the massiveness of the surrounding quartzite, it is reasonable to assume that this amphibolite was once a basaltic lava flow, and not an intrusive.

Garnet-rich horizons, traceable for considerable distances along the strike, are a common feature in the amphibolites. The garnets are up to 5 or 6 cm in diameter, and comprise up to 30 % of the rock. They are a common red almandine, crowded with inclusions of the other rock constituents. As they grew, they seem to have replaced plagioclase more easily than amphibole. No particular orientation of the inclusions was observed.

Scapolite-hornblende rocks were found both as an obvious alteration facies of the gabbro and as perhaps independent, locally-altered amphibolite. An occurrence of the latter type crops out near the top of the hill north of the Rækevik house, where a small quarry has been worked on an iron-bearing fissure. Considerable calcite has been introduced with the iron ores, and this may have been linked with the scapolitization of the surrounding plagioclase.

The amphiboles of the amphibolites are strongly pleochroic hornblendes and actinolitic hornblendes as a rule, with a high Fe/Mg ratio, according to refractive index determinations. An average of twelve amphibolite amphibole determinations, using Trøger's tables, gave an Fe/Mg ratio of 62/38. Weakly pleochroic gedrite is found in a few of the more schistose zones (north flank of Sjåen), evidently representing an aluminous bed in original mafic sediments. In one such specimen the gedrite has an Fe/Mg ratio of about 50/50 (mol.).

S c h i s t s crop out along the north flanks of Storkollen, Sjåen, and Lindvikskollen, at the neck of the peninsula at Rækevik, west along the shore to Blankenberg, and at other places over the map area. They show all variation between amphibolites and quartz-mica schists, with such intermediate types as gedrite-biotite-andesine schist (N. Sjåen), biotite-hornblende-oligoclase-scapolite schist (W. Storkollen), and biotite-tourmaline-quartz-oligoclase schist (N. Sjåen). A schistose mica-quartzite from the northern base of Storkollen contains 78 % quartz, completely recrystallized, 22 % white mica, and traces of apatite and zircon. Brøgger has described several typical varieties of schist from the Kragerø region (14, 15), and for more thorough descriptions the reader is referred to these papers.

The above-mentioned schist from West Storkollen has a striking porphyroblastic structure. Roundish oligoclase crystals (An 19) are growing in a highly schistose matrix of biotite, hornblende, scapolite, apatite, and magnetite, partly replacing the other minerals and partly shoving them aside. The rock has a knotty appearance, and the porphyroblasts, which have attained a diameter of about 5 mm, contain countless oriented inclusions of the earlier minerals. Particularly interesting in this rock is the apparent compatibility of the scapolite crystals (which amount to 5 % of the rock) with the plagioclase.

A peculiar schist occurs in the shear zone in the valley north of Rækevik, at the old iron mine. It is fine-grained, has a shiny, grayish-green appearance, and consists of pale chlorite, 45 %; oligoclase (An 16), including small amounts of sericite and calcite, 40 %; magnetite, 5 %; and apatite, 1 %.

Q u a r t z i t e s, some of them very pure, crop out in the Kragerø area, and are quarried at several localities in the skjærgård (Berø, Blanktjern, etc.). In the present map area quartzites are limited to the northeast corner near Kalstad, and they are for the most part rather impure. One specimen from this locality contained 70 % quartz, 5 % microcline, 14 % plagioclase (An 63; the grains have been mostly altered to white mica, but the edges are often fresh), 9 % biotite, including interfoliar lenses of prehnite, 2 % of tiny sillimanite rods in zones parallel to the bedding, a few muscovite and apatite grains, and traces of zircon and rutile. The sillimanite shows a strong linear orientation plunging WSW, parallel to the regional lineation. A conformable «bed», about 3 mm wide, of quartz and fresh microcline runs through the specimen, having considerably larger grains than the groundmass. The original sedimentary compositional banding is very well preserved although the rock is thoroughly recrystallized.

The assemblage quartz-sillimanite-microcline-muscovite-plagioclase is of interest, as only four of these minerals would ordinarily be

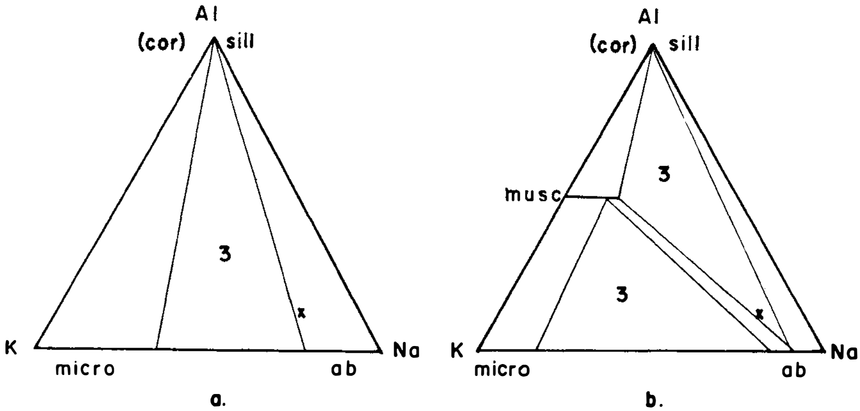


Fig. 3. K-Al-Na diagrams of aluminous rocks with excess (sillimanite) or deficient (corundum) silica; a: high amphibolite facies; b: medium grade.

expected at a random P, T, chemical potential H_2O. The muscovite is seen to be partly pseudomorphous after biotite; some biotite grains suddenly lose their color at an irregular but sharp line, but the crystal continues as a white mica. In other cases, muscovite is obviously an alteration product of plagioclase. A third type of occurrence is in intimate association with microcline, but both seem texturally to be equally stable. In one spot only was microcline seen next to sillimanite. Biotite is in a small area altered to chlorite.

The best explanation seems to be that metamorphic conditions exceeded the stability field of muscovite, giving sillimanite and microcline in stable association, but later introduction of water (possibly at a lower T) allowed retrograde action to re-form muscovite from the other minerals (see Figure 3a, b).

As most observers have noted, these various schists and quartzites undoubtedly represent an ancient sedimentary complex.

A l b i t i t e s. The great number of bodies of fine to medium-grained leucocratic rocks which crop out in the mapped area present a small problem in nomenclature, as no term in use today adequately applies to all these undoubtedly related rocks. They are characterized by a sodic plagioclase (An 0 to 12) as the major constituent, with highly varying amounts of quartz and microcline, plus accessory minerals such as biotite, rutile, hornblende, tourmaline, sphene, and zircon. These rocks vary in many respects, but it is evident that most of them, at least, have had a common origin, and it has been expedient to find a single, general, descriptive term which could be applied to all of them as a group. BRØGGER (15) has used the term «albitite», with apt mineral prefixes, and this seems to be the least confusing and most convenient name, although these rocks sometimes contain up to 50 % quartz or 30 % microcline, or an oligoclase-albite instead of an albite.

These albitites attain their greatest development in the area from Storkollen west across the Kammerfoss River to Ånevik. A few samples from this area have been studied by BRØGGER (15), who also described similar rocks from the islands east of Kragerø and from several other localities in the Kongsberg-Bamle formation even as far away as Snarum, 130 kilometers to the north.

The albitites occur as dike-like bodies from a few centimeters up to 400 meters in width. Two major bodies are present, the kragerøite of Lindvikskollen, approximately 350 × 60 meters, and the great quartz-albitite mass which extends WNW from the west flank of Storkollen for 2.6 kilometers, with an outcrop width ranging from less than 40 up to 400 meters. Many smaller dikes and smears of albitite are found, most of which have conformable but gradational contacts against the surrounding amphibolite.

W. C. BRØGGER studied and originally named the large kragerøite body which crops out on Lindvikskollen (15, pp. 181—197). It is a massive, granoblastic albite-rock with a grain size of about 1 to 3 mm, and having a gray to pink to white color when fresh. Its plagioclase is an albite, An 3-4, often slightly sericitized, with twins after the albite law. An alkali determination by Miss Erna Christensen in the laboratory of the Norwegian Geological Survey (Norges Geologiske Undersøkelse), 1954, gave Na_2O: 10.56 %, K_2O: 0.52 %, giving a three-component composition of Ab 94, An 3, Or 3. Aside from albite, which makes up the great bulk of the rock, the following minerals occur in at least accesoric amounts: rutile, biotite, tourmaline, apatite, iron ores (mostly pyrite), sphene, actinolite, chlorite, zircon, and calcite. The rutile is the most characteristic accessory in this body; Brøgger's name «kragerøite» refers to albitite with a considerable amount of rutile.

Five minerals other than albite attain fairly large volume percentages in various parts of this body. Quartz makes up from O to 25 % of the rock, and according to BRØGGER (15, p. 196) is most highly concentracted near the northern side of the occurrence. (During the course of my recent investigations, no kragerøite was observed with more than about 10 % quartz). This mineral occurs in rounded, usually interstitial grains with undulatory extinction.

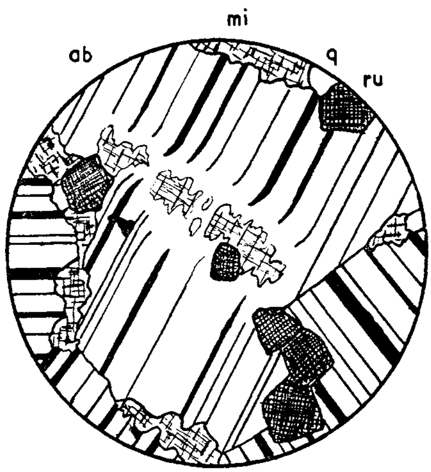


Fig. 4. Krg I 25. Kragerøite, Lindvikskollen. Ab, albite; ru, rutile; mi, microcline; q, quartz. x160.

Perfectly fresh microcline is usually present, and comprises up to 10 % of some specimens. Thin sections show the microcline to be, at least in part, replacing albite. It occurs along the grain boundaries of the albite, and in patches within it, with ragged contacts and twinning often parallel to the albite twinning. Some of this is probably due to exsolution, although a regular, subparallel antiperthite texture was nowhere seen. One large albite grain showed a stressed zone where its twin lamellae are bent; the twinning disappears toward the center of the zone, where an irregular patch of microcline is found (see Figure 4).

Small grains of pyrite comprise up to about 10 % of certain zones of the kragerøite body, especially at the east end of the large rutile mine.

A black tourmaline, in small clusters of grains ranging in size from $^1/_4$ to 3 mm, is found in the area of the smaller mine to comprise up to at least 16 % of the rock. It is pleochroic, O = brown or bluish-green, E = reddish or smoky, and its calculated composition from BRØGGER is here included in Table I, p. 00. This tourmaline has a somewhat higher Mg/Fe ratio than a typical schorl.

One of Brøgger's thin sections (Krg I 18) of a quartz-rich kragerøite specimen contains, besides microcline and a few grains of pale biotite, apatite, and ore, several small, corroded crystals of another

Table I

	A	B
SiO_2	35.23	36.67
TiO_2...............	0.38	0.97
Al_2O_3	34.31	31.70
Fe_2O_3 }	7.82	3.40
FeO }		0.57
MnO	0.12	0.00
MgO	5.13	9.91
CaO	0.13	0.95
Na_2O	2.19	0.60?
K_2O	0.75	0.22?

Partial chemical analyses of tourmalines from Lindvikskollen. A, tourmaline from tourmaline-kragerøite, Mine 3, Rødland analyst, 1923 (Brøgger, 15, p. 238). B, tourmaline from albitite-amphibolite transition, entrance to Lindvikskollen pegmatite quarry, E. Christensen analyst 1954.

variety of tourmaline. It is strongly pleochroic, O = blue, E = pale green, and is evidently an alkali-rich variety. Alkali tourmaline has been described so far from only one other Norwegian locality, a cleavelandite-quartz pegmatite at Åg in Meløy, Nordland (Oftedal, 26). The Åg tourmaline is zoned and contains considerable Na and Mn, and some Li, and is associated with spodumene. The newly described Kragerø variety does not show zoning, and has been found in too small amounts for a refractive index or spectrographic determination. Its occurrence in the albitite, however, suggests a high Na content.

Rutile attains the highest concentration of any mineral in the kragerøite, with the exception of albite. Although distributed throughout the body in amounts of at least 0.5 %, it is found in the easternmost part to form black streaks and concentrations which in the richest zones almost completely exclude all other minerals. These rutile «schlieren» are oriented parallel to the north wall of the body, and thus dip steeply south. The surrounding kragerøite contains roughly 5 to 8 % rutile. This deposit has been mined sporadically since 1901, but the ore is apparently at present prices and quality not economically mineable in competition with ilmenite from the large mine in Sogndal, southwestern Norway. There is a string of pits and quarries near the northern contact, and two large underground workings exist towards the top of the hill which connect with older surface holes. A single-span aerial bucket system took the ore down to a loading pier at sea level.

The rutile occurs as generally equidimensional grains, anhedral to euhedral, 0.5 to 2 mm in size, black in hand specimen but of a deep red color, pleochroic, in thin sections. The grains commonly occur grouped in small streaks, giving a weak gneissic structure to the otherwise massive rock.

Brøgger gives a figure of 6.32 % Fe_2O_3 for the iron content in the average rutile. A partial analysis by E. Christensen (1954) of rutile from a small pegmatitic zone in the kragerøite body gave the following results: 0.18 % Cr_2O_3, 1.08 % SiO_2, 1.05 % Fe_2O_3, or a considerably purer rutile than that of the finer-grained rock.

One specimen of typical gray, medium-grained kragerøite from the large mine contains a number of radial clusters of anthophyllite about 3 mm in diameter. The anthophyllite occurs as very fine fibers, with a silky sheen and a white to pale green color. Its refractive indices show it to be a pure Mg-amphibole. The clusters are often centered around small pyrite grains. This is as far as I know the first observation of this mineral in the kragerøite.

Small pegmatitic areas in the kragerøite body are made up of the same minerals as the surrounding kragerøite; thus, large grains of albite (slightly more calcic than usual, An 5—6), rutile, quartz, biotite, pyrite, apatite, and sphene. Microcline and tourmaline have not been identified in such pegmatites, but are to be expected. The pyrite occurs closely associated with biotite and quartz. The pegmatite can have rather sharp contacts against the normal albitite. Some of the pegmatitic albite has about 2 % of microcline in thin, antiperthitic lamellae. An alkali determination of albite from this kragerøite pegmatite (Christensen, 1954) gave 10.86 % Na_2O, 1.28 % K_2O, or Ab 95.5, An 4.4, Or 10.1.

A large volume of the rock lying between the two large mines is of a peculiar veined or patchy appearance (see Plate Ia). White veins seem to penetrate and interweave a grayish groundmass, giving the impression of a mineralized and then recrystallized breccia. Thin sections prove the opposite to be the case, however. The white «veins» are actually typical, medium-grained kragerøite (slightly sericitized albite, An 4, with minor rutile and biotite), while the darker patches are a finer-grained, fresher rock with decussate texture, consisting of fresh albite, biotite (15 %), tourmaline (4 %), rutile (3 %), and muscovite (not paragonite; 12 %), the latter usually surrounding tiny grains of corundum, which amounts to about 1 % of the rock (see Plate IIb). The corundum has very high relief, n $\approx$ 1.765, and is uniaxial negative. This is a new locality for corundum in Norway, and a rather unique mode of occurrence.

The appearance of corundum and muscovite in this rock presents an interesting problem. As the corundum is almost always surrounded by muscovite with the relations of a reaction rim, one is led to the conclusion that the muscovite formed as a synantectic mineral from the earlier association corundum-potassic albite. This would be completely analogous to the situation described above in an aluminous quartzite, where the introduction of water, probably at a lower temperature, produced the muscovite-bearing assemblage. On Figures 3a, b, the corundum-albitite would plot at x. The striking difference is the deficiency of SiO_2 necessary to produce the corundum, in a rock which otherwise has free quartz and never has been found to contain an aluminum silicate. This problem will be considered more fully in the discussion on the genesis of the albitites (p. 129).

The main body of kragerøite extends from the top of Lindvikskollen westward until it reaches a pegmatite striking N on the southwest corner of the hill. Approximately at this pegmatite the kragerøite proper ends, but it reappears as a narrow, conformable dike or sill above the houses west of Rækevik, and from there continues west into the fjord. Towards its western terminus this body divides into at least three branches, the northwesternmost showing the greatest resemblance to the kragerøite of Lindvikskollen. This branch has also been mined for rutile, but seems to be considerably poorer ore than the major deposit. The corundum-bearing rock is also found here. The central branch is the largest; much of it is a pure white, medium-grained, granulose albitite, containing 98 % albite and a little quartz and rutile, but the color and grain size are rather variable. An alkali determination of the pure albitite (Christensen, 1954) gave 11.28 % Na_2O, 0.24 % K_2O. In three components, the rock would plot at Ab

97.5, An 1.0, Or 1.4. Other minerals present in small amount in this branch are hloritce, biotite, sericite, microcline, tourmaline, sphene, apatite, and hornblende. The microcline seems to be replacing or exsolving from albite in several thin sections, though not as oriented antiperthite.

This western kragerøite body lies conformably in biotite schists, with rather sharp contacts wherever visible. The schist is often particularly biotite-rich just outside the contact.

At the northeast corner, the large kragerøite body on Lindvikskollen wedges out abruptly, but a thin, rutile-bearing albitite dike can be traced around the end of the hill to a prospect pit on the northern edge of the large pegmatite (see map). The rock prospected here is a heavily rutile- and sphene-bearing albitite also containing considerable biotite, penetrated by veins of a pure white, granoblastic oligoclase rock (An 13) which contains isolated crystals of green actinolite (Fe/Mg = 25/75). There is more sphene, at the expense of rutile, as the white vein is approached. The contacts of this body are not here exposed. A specimen of pegmatite from this prospect, cutting the rutile-sphene rock, contains highly altered albite, black tourmaline, fibrous actinolite in a shear plane, and massive, apple-green epidote.

The large kragerøite body lies in amphibolite, and where its contact is not faulted or obscured by ground cover or later pegmatites, it is seen to be of a transitional nature. The diagram, Figure 5, p. 108, was constructed from petrological and mineralogical study of four samples from the transition zone, plus a chemically analyzed sample of «common» kragerøite from Brøgger (15, p. 188), plus values for «average amphibolite» compiled from four local amphibolites which did not show any relict gabbroic features.

As the figure indicates, the change from amphibolite to albitite is characterized by a gradual decrease in amount of femic minerals (biotite, amphibole, chlorite, tourmaline, apatite) and a parallel decrease in the An content of the plagioclase, while the amount of albite increases and the Mg/Fe ratio in amphibole increases. This transition zone is so wide in most places that an actual contact cannot be pointed out in the field; it is usually a matter of some meters. Actually a great variety of rock types are present in the contact zone, and their mineralogical properties do not always vary regularly with the dis-

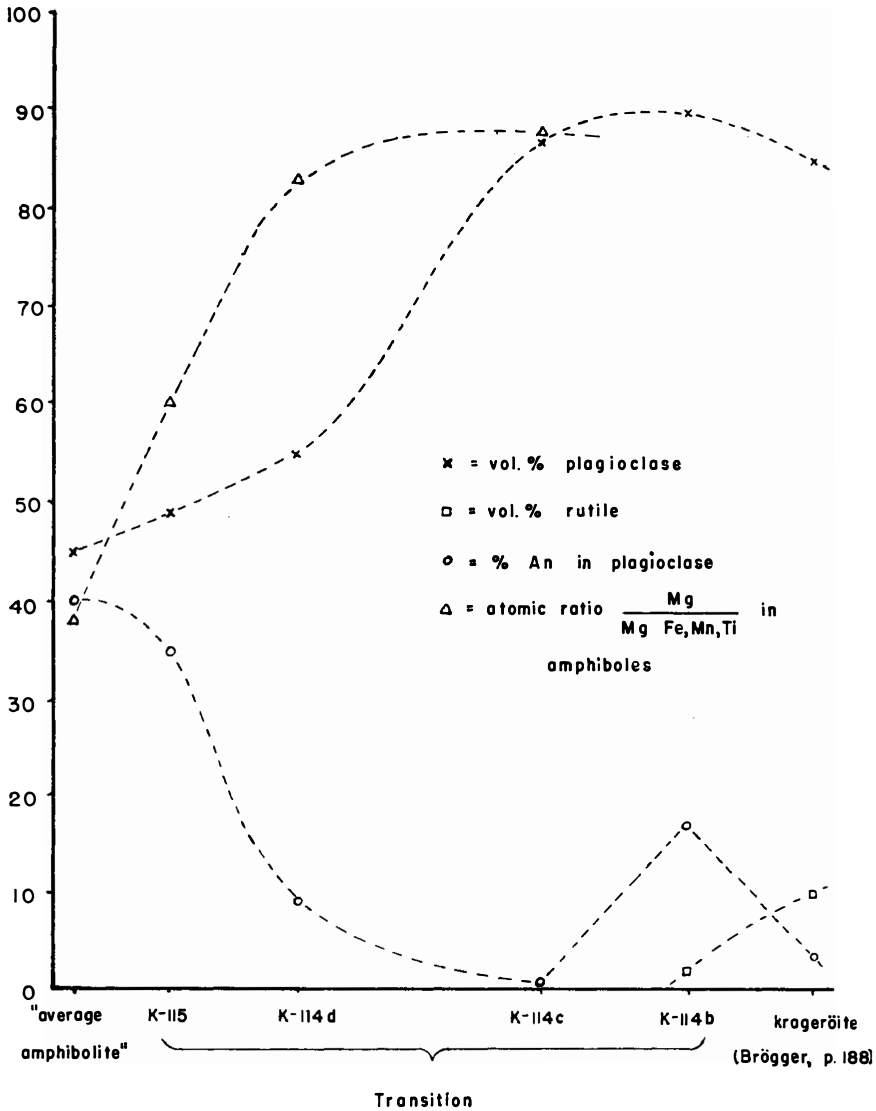


Fig. 5. Kragerøite-amphibolite transition, Lindvikskollen, west of rutile mines.

tance from either end of the system; the An content of the plagioclases plotted on the diagram illustrates this irregularity. The general trend, however, is unmistakable.

The Geologisk Museum in Oslo has in its collection a specimen of coarse-grained to pegmatitic rock from one of the rutile prospects on Lindvikskollen. The rock is predominantly albite, with some microcline and quartz and many euhedral crystals of apatite, clear brown sphene, and prismatic, green diopside. Diopside is a characteristic mineral of the contacts of other albitite bodies (see p. 133), and as it is not found elsewhere in the kragerøite or in any other plagioclase pegmatites, I interpret this specimen as coming from the kragerøite-amphibolite contact zone.

The large body of albitite which stretches with varying widths from Storkollen west to Ånevik is of a rather different character from the kragerøite. Its major mineral is again albite, but the anorthite content ranges from O to 10 %, and although the body is quite continuous (except for the erosional gap at the river) the relative amounts of the three main minerals vary greatly (see Figure 10). The rock is white to tan, inequigranular but finer-grained than the typical kragerøite, and often shows a weak gneissic to schistose structure due to large, elongated quartz grains or scattered, parallel biotite, chlorite, or hornblende. Brøgger mentions this rock (15, pp. 204 to 208) and gives two chemical analyses of it.

The albite shows the common albite twinning, and is usually slightly sericitized. Epidote or zoisite is present in some few grains, but is very subordinate to the sericite in amount.

Quartz comprises from 10 % up to at least 50 % of the rock. Its grains are large (up to 3—4 mm) to very small, and of various character. The largest are elongated, have smooth, rounded boundaries, and show undulatory extinction. Also characteristic for this body are small, rounded quartz grains poikiloblastically included in albite, microcline, or larger quartzes. A third type of quartz is irregular grains often with extremely wiggly grain boundaries; these occur in veinlets replacing the other minerals.

Microcline is also present in highly variable amounts; thin sections show a range of 0 to 23 % of this mineral. It resembles the microcline of the kragerøite in its textural relations with albite. A large majority of the thirty-six thin sections studied from this body contain less than 6 or 7 % of microcline, and it is interesting to note that the specimens containing the most microcline also contain

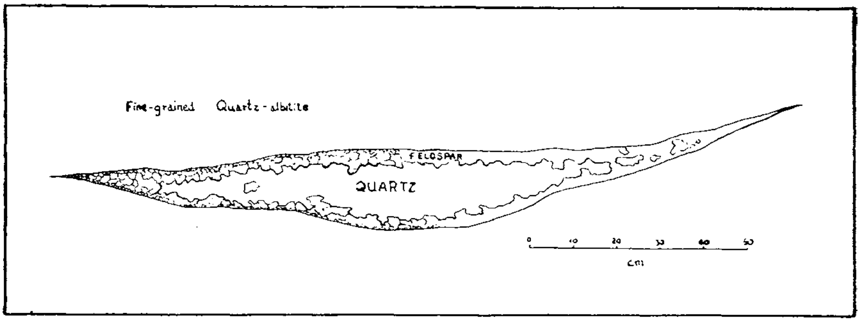


Fig. 6. Small concretionary pegmatite in quartz-albitite, west Storkollen.

considerable quartz (Fig. 10), although the inverse relationship does not hold. In nearly all cases, the degree of sericitization of the plagioclase clearly increases towards the fresh microcline patches. No systematic areal distribution of the quartz or microcline has been observed.

Other minerals occur only in accessory amounts and with irregular distribution. They include biotite, chlorite, amphibole, apatite, rutile, sphene, muscovite, epidote, zircon, tourmaline, iron ores, and prehnite (or epidote ?) as lenses in biotite and chlorite. The rutile in this body does not reach the high concentrations typical of the Lindvikskollen albitite. Neither sphene nor rutile here ever amount to more than about 2 % of the rock, and commonly are considerably less abundant than that.

The coarse-grained facies described below as «plagioclase pegmatite» (p. 127) makes up a considerable portion of this large quartz-albitite body, particularly west of the Kammerfoss River. The boundaries between the two are intricate and entail only an increase in grain size. Small concretionary pegmatites with sharp contacts are also found in this body, usually containing mostly quartz (Figure 6).

The large quartz-albitite is everywhere surrounded by amphibolite or later microcline pegmatite. The albitite-pegmatite contact will be treated later under the section on pegmatites; it will merely be mentioned here that the pegmatite is evidently the younger rock.

Except for one portion, the large quartz-albitite body shows a gradual transition into amphibolite — or vice versa. The transition zone has been observed to range from less than 50 cm to many meters in width. At the narrowest places, the transition from white to dark

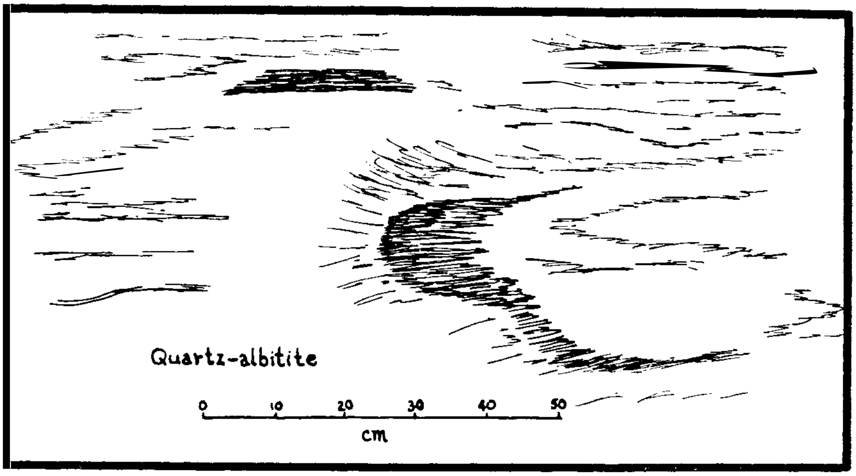


Fig. 7. «Ghosts» of amphibolite in quartz-albitite near southern contact, west Storkollen.

rock can appear very abrupt, perhaps complete within 10 cm, but a study of the mineralogy of the adjacent amphibolite shows that its plagioclase is albitic, and round quartz grains appear inside any or all of the amphibolite minerals.

The contact is never sharp, in the sense of that of a diabase dike; but a considerable length of the southern contact on the hill Sjåen is relatively sharp and cross-cutting, with only a thin (1—2 cm wide) layer of matted, light green tremolite (Mg/Fe = 90/10 mol) separating the quartz-albitite from the amphibolite, whose foliation is truncated by the contact. A small topographic valley follows this contact, usually just on the amphibolite side, for a long distance.

Elsewhere, the transitional contact is either concordant or cross-cutting. When discordant, it is always exceedingly gradual, such as towards the eastern end at Storkollen, where a large area is composed of a «transition gneiss». The transition rocks retain the foliation direction of the surrounding amphibolite. «Ghosts» of amphibolite in albitite are common near the contact, and many of these streaks have frayed ends (see Figure 7).

The quartz-albitite — amphibolite transition shows mineralogical variations closely comparable to those characterizing the kragerøite-amphibolite contact (Fig. 5). Figure 8 shows some of the most im-

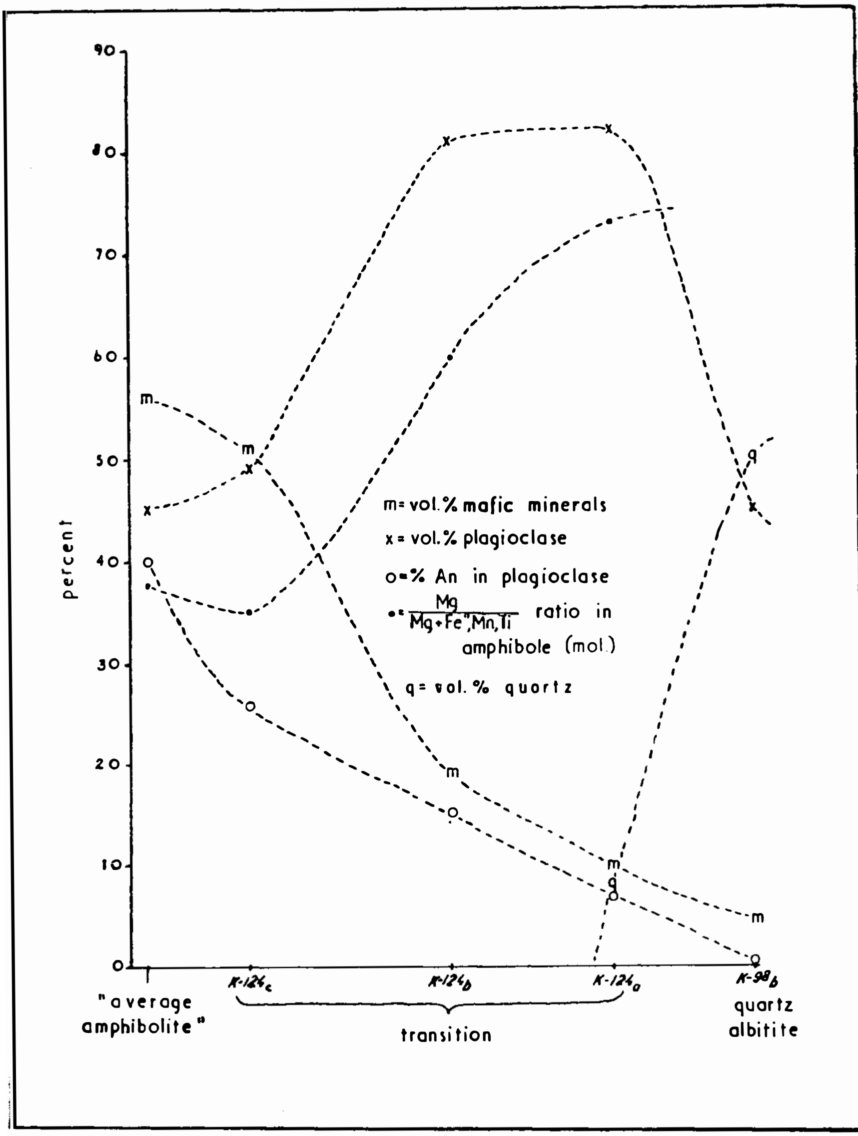


Fig. 8. Quartz-albitite-amphibolite transition, near top of hill southwest of Leirvik.

portant variables across the transition into the large quartz-albitite body at one place near Leirvik. The data were compiled from thin section study and refractive index determinations.

The general trends are seen to be analogous to those in the kragerøite contact. As the amount of dark minerals decreases, the Mg/Fe^{++} ratio in the amphiboles increases, the An content of the plagioclase decreases, and the bulk of plagioclase increases. Quartz occurs only in the albitite and the lightest zone of the transition. In a thin section of the latter, the quartz occurs as small, round grains, inside the other minerals, mafics as well as albite.

Besides the above-mentioned mineralogical changes, one other is characteristic and of interest in the albitite-amphibolite transition. A light green diopside, or more exactly salite (10 to 50 % hed.) is found in a substantial majority of these transition rocks, and is not found elsewhere, either in amphibolite or albitite. It occurs together with amphibole in most all cases, their volume ratio varying greatly. Several thin sections show the diopside altering to amphibole along cracks and other imperfections, and in a few cases only remnants of pyroxene grains remain inside larger, fresh amphiboles.

Sphene is another common mineral of these transition rocks, often surrounding cores of ilmenite or rutile.

The amphibole in the lighter rocks belongs to the tremolite-actinolite series according to Trøger's optical criteria, while that of the more amphibolitic rocks is generally a hornblende. The Mg/Fe ratio varies the same way in both types.

A small body of quartz-albitite occurs just east of the top of Lindvikskollen, apparently unconnected with the kragerøite. This body is peculiar in its content of euhedral red garnets as the major dark mineral. They range from 1 to 3 mm in size and are scattered unevenly throughout the body, probably amounting to 2 or 3 % of its volume. Its x-ray powder pattern indicates that the garnet belongs to the common metamorphic almandine-spessartine series. A little black tourmaline is also present. The plagioclase is an albite-oligoclase, An 11, and sometimes contains myrmekitic quartz near microcline grains. The plagioclase in a small pegmatitic facies is antiperthitic, with oriented lamellae of microcline.

Independent microcline (not antiperthitic in albite-oligoclase) makes up about 5 % of the rock, while quartz, with undulatory extinc-

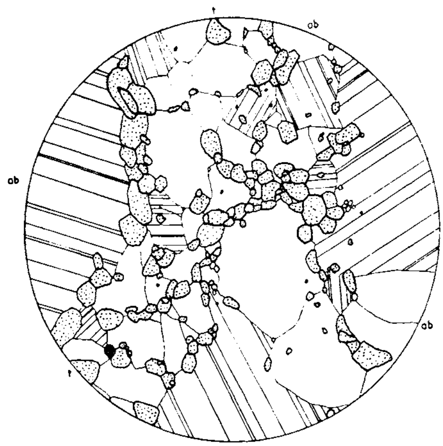


Fig. 9. K-22b. Tourmaline-albitite, at entrance to Lindvikskollen pegmatite. Ab, albite; t, tourmaline; one rutile grain. x100.

tion, comprises about 20 %. As in the large quartz-albitite body, the plagioclase is highly sericitized where directly adjacent to microcline.

The garnet-albitite body has a transitional contact against the big pegmatite to the south, but rather abrupt contacts against amphibolite to the north and west. Along the cross-cutting western contact, a faint concentration of minute biotite, hornblende, and tourmaline crystals can be traced parallel to the contact but from two to four meters within the albitite.

A band of albitite which strikes W to SW down to the sea from below the large pegmatite (see map) also contains red garnets, though scattered more sparsely than in the body near the top of the hill. This lower body seems to be lying on top of the amphibolite on the slope, and may have been originally connected with the upper one.

A small albitite body is exposed at the entrance to the Lindvikskollen pegmatite quarry. It is only 1—4 meters wide, but extends for a good distance east and west of the quarry entrance. Its contacts against the surrounding amphibolite are always transitional, and no connection with the large pegmatite can be seen. This albitite body contains a little rutile ($\sim$ 1 %), unevenly distributed light brown mica (0—8 %), and several percent of very small grains of a black tourmaline arranged in a net-like pattern in the granoblastic albite matrix (Figure 9). The tourmaline is a common schorl with strong pleochroism in brown, and refractive indices $\varepsilon = 1.633$, $\omega = 1.664$. The albite is twinned after the albite law and occurs in slightly sericitized grains about 1—2 mm across. In the vicinity of the tourmaline veinlets the albite is recrystallized into smaller, less altered grains. Octahedral pyrite crystals up to 1 mm in size were observed on a joint plane (?) in the rock. The rock has a remarkable appearance

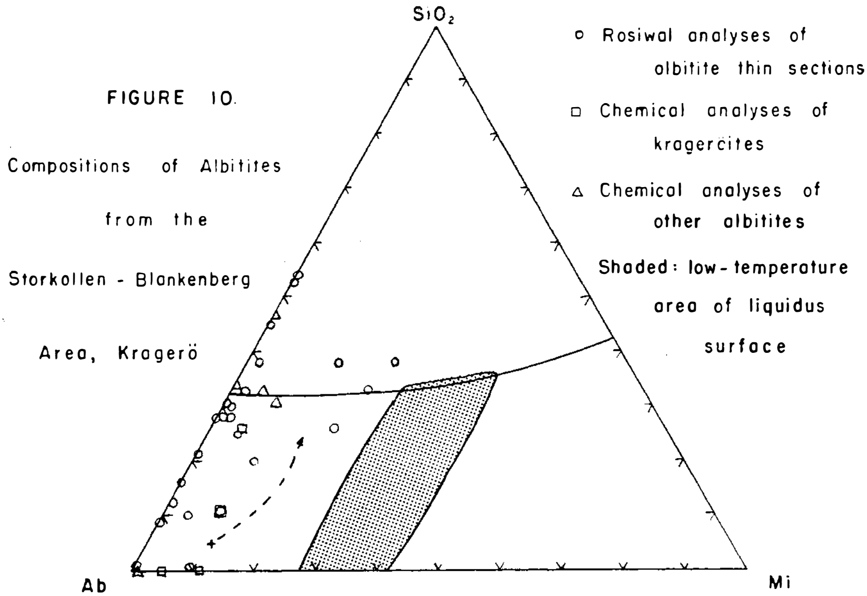


Fig. 10. Compositions of albitites from the Storkollen—Blankenberg area, Kragerø.

attributable to the tourmaline veinlets, which have obviously been formed after the formation of the albitite in which they occur.

The transition to amphibolite consists of successively darker rocks containing increasingly calcic plagioclase, biotite, eventually amphibole as the amphibolite is approached, tourmaline, and accessoric apatite. The diagram, Figure 11, shows the trends of the major mineralogic variations across this transition. The rock is completely recrystallized, all minerals being fresh (except for slight sericitization of the feldspar).

The tourmaline in this contact zone is of especial interest. It occurs in well-formed porphyroblastic crystals up to at least 2 cm in diameter, black with a shiny vitreous luster on the crystal faces. The crystals are approximately equidimensional, showing short, unstriated prism and rhombohedral faces. The refractive indices are $\varepsilon = 1.625$, $\omega = 1.643$, uniaxial negative, with strong pleochroism; E = pale blue-green, O = olive-brown. A partial chemical analysis of this tourmaline (Christensen, 1954; see Table I) and a spectrographic

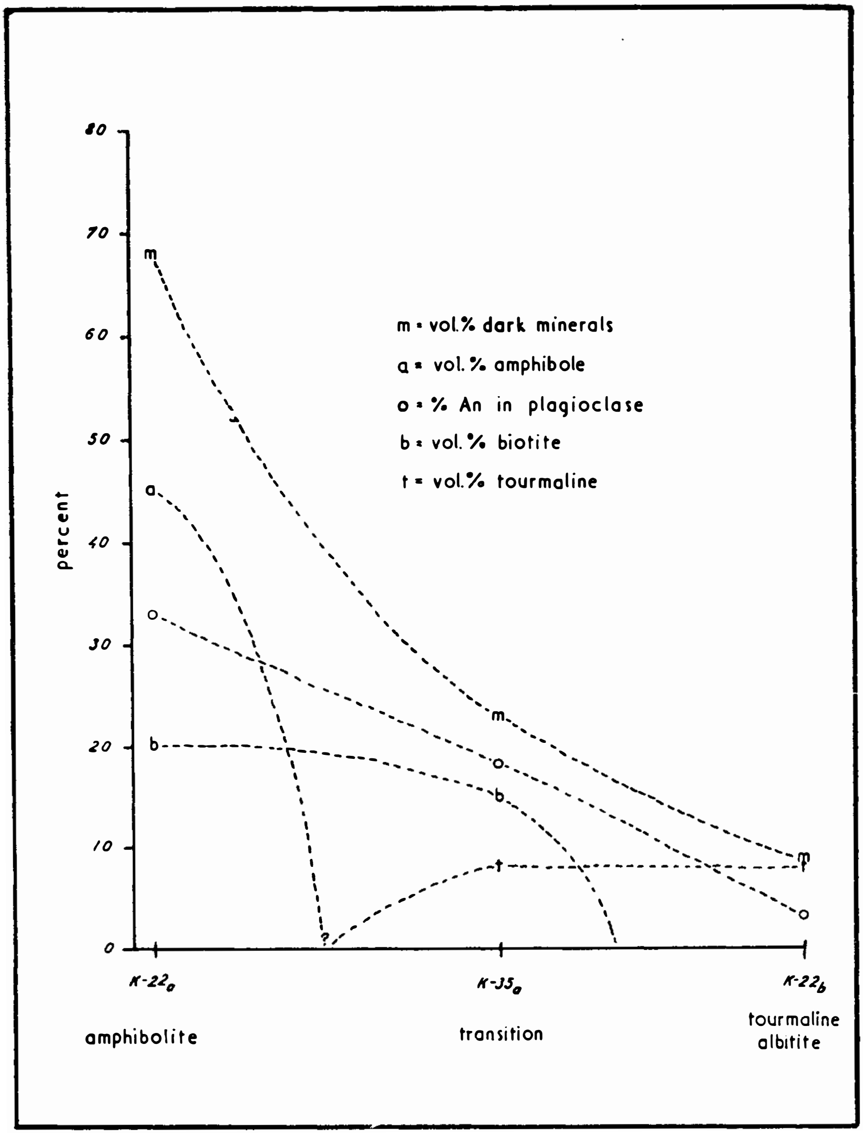


Fig. 11. Tourmaline-albitite — amphibolite transition, entrance to Lindvikskollen quarry.

investigation indicate that this mineral is a magnesium-rich variety, belonging to the uvite-dravite series. The spectrograph showed no trace of lithium. The transition from schorl in the albitite to Mg-tourmaline in the contact zone has not been studied.

This is a new locality for magnesian tourmaline. OFTEDAL (25, p. 30) lists Melkedalen in Ofoten, Arendal, and Modum as previously reported Norwegian occurrences.

The tourmaline in the corundum-bearing kragerøite near the top of the hill, although fine-grained, has similar pleochroism and refractive indices ($\varepsilon = 1.624$, $\omega = 1.651$), and is most likely also a magnesian tourmaline.

Many smaller, narrow, and more or less longitudinally extended dikes of various sorts of albitite crop out in the map area. Like the large bodies, they contain varying amounts of albite, quartz, and microcline, which three minerals make up the great bulk of the rocks. These dikes are both concordant and discordant, and have as a rule relatively sharp contacts, although some, as Brøgger noted on Langø in the skjærgård to the east, have the typical diopside-bearing transition gneiss (15, p. 299). Most all of them show structures parallel to the structures in the surrounding amphibolite or schist, many of which are formed by the preferred orientation of new minerals (quartz, tourmaline) foreign to the dark rock. A common feature is foliation produced by tiny parallel lenses of undulatory quartz (comprising from 20 to 45 % of the rock); perhaps as common is lineation produced by tourmaline needles (schorl, comprising up to 3 % of the rock) oriented parallel to the regional lineation. Some dikes send apophyses into the country rock, and some develop coarse grain size where they are widest. Some contain streaks of dark minerals (biotite and actinolite). Other minerals encountered are sericite, apatite, garnet, black ore, and chlorite, each in only accessoric amount.

Marked inequality of grain size is a common feature of these dikes (except for the most monomineralic ones). Some have albites up to 3 mm across, with much smaller quartz and microcline grains interstitial or enclosed by albite. One dike contains perthitic microcline crystals up to 2 cm across in an otherwise fine- to medium-grained groundmass of albite, quartz, and microcline. The microcline, here comprising up to at least 20 % of the rock volume, often shows smooth, rounded contacts against the other minerals, but jagged edges, parallel

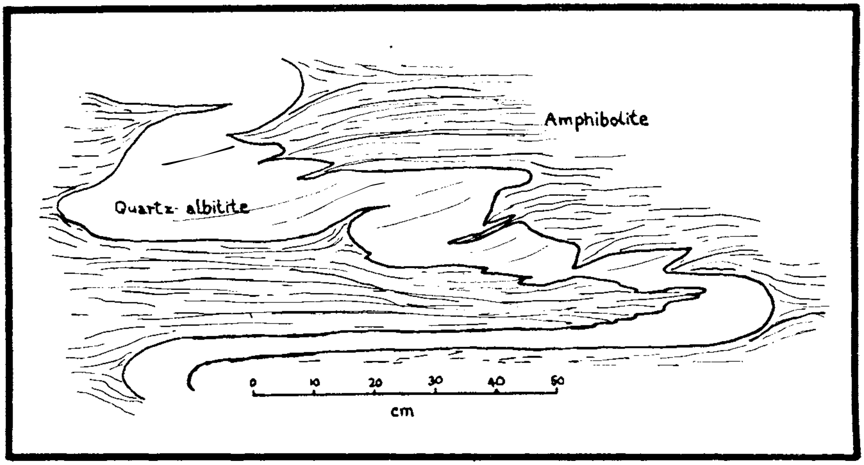


Fig. 12. Small, deformed quartz-albitite vein in amphibolite, west Storkollen.

growth, increasing sericitization, and myrmekite are also often seen at albite-microcline contacts (as is the case with the large microclines mentioned above). The plagioclase is usually an albite (measured values An 0, 3, 8, 10, etc.), but one narrow cross-cutting dike with much quartz oriented at an angle to the sharp contact contains oligoclase to andesine, with measured values ranging from An 17 to An 34. The higher value approaches that of the adjacent amphibolite.

A small, highly distorbed albitite vein on the west shoulder of Storkollen shows sharp, cross-cutting contacts against the amphibolite. It contains a faint gneissic structure which is roughly parallel to that of the surrounding rock. The amphibolite foliation is bent by the growth (or existence?) of the vein, but the general discordance is obvious (see Figure 12).

A small occurrence of fine-grained quartz-plagioclase rock was observed in a road cut of the Havna road in the southwestern corner of the town (east of the map area). Only about two meters long and of various width, it is centered around a fissure in the dark, gneissic amphibolite. The most striking feature of its appearance is the obvious suggestion of replacement it gives, with its very irregular shape, always transitional contacts, and retention of the structure of the amphibolite in the form of planar blotches of small black ilmenite grains. This spotted rock is seen only immediately surrounding the fissure, and the ilmenite lenses can be traced into the amphibolite, where they become sphene.

Microscopically the white rock was found to consist 85 % of fine- to medium-grained granulose oligoclase-andesine (An 30), and 10 % of small, rounded quartz grains lying in and between the plagioclase crystals. The remaining 5 % is mostly ore, with small amounts of apatite, sphene, hornblende, biotite, and chlorite. Aside from the streaks of ore and the An content of the plagioclase, this rock closely resembles the quartz-albitites of the map area to the west.

P e g m a t i t e s. A great number of dikes, pods, and more irregular bodies of pegmatite occur in the mapped area, of all sizes up to what Bjørlykke reported in 1937 (9) as being the largest in Norway. They can be divided mineralogically, structurally, and genetically into two general types, which I shall here call, in oversimplification, microcline-pegmatites and plagioclase-pegmatites. BRØGGER (15) has investigated a few plagioclase pegmatite dikes from Kragerø, and OLAF ANDERSEN (1, 2, 3) and HARALD BJØRLYKKE (9, 10, 11) have done much work on the microcline pegmatites in the present area, Andersen concentrating on the feldspar and Bjørlykke on the rare minerals. The latter author also devised a scheme of classification for the Norwegian pegmatites, based on their mineralogies.

The microcline pegmatites range in size from small to large, and are mostly very coarse-grained except close to their contacts. They occur as both concordant and discordant bodies, the same pegmatite often showing both types of relations to its country rocks. Two appear to be completely surrounded by albitite; the others lie in amphibolite.

The largest microcline pegmatites have all been quarried at various times for feldspar and, more rarely, for quartz. Besides microcline-perthite, graphic granite, and quartz, they contain considerable amounts of plagioclase (albite and sodic oligoclase) and tourmaline, both relatively scarce in other Norwegian pegmatite areas, and biotite, magnetite, amphibole or pyroxene, apatite, and yttrotitanite (keilhauite). This abundance of calcium-bearing minerals places these pegmatites in Bjørlykke's Ca-rich Group (7). The three largest bodies are famous for their rare minerals, mostly rare-earth varieties, of which alvite $(Zr,Hf)SiO_4$ and orthite (allanite) are the most widespread.

The largest pegmatite is the Lindvikskollen—Kalstad body, which extends from the very top of Lindvikskollen eastward diagonally down the slope, finally reaching the sea almost due south of Storkollen's summit (see map). It has been quarried extensively all along its length; two of these prospects, the Lindvikskollen and Kalstadgangen quarries, are famous for their rare minerals. Its southern contact is sharp against amphibolite, and dips north at from 10 to 40 degrees except for the extreme eastern end which is close to vertical. At one place near the eastern end, it lies on a fault plane (Figure 2), but in most exposures, such as at the entrances to the three westernmost quarries, the pegmatite has a sharp, wavy contact. The pegmatite is here fine-grained next to the amphibolite, rapidly becoming coarse-grained with development of biotite, actinolite, and albite crystals perpendicular to the contact, in a zone up to 5 cm wide. The contact is not well exposed near the middle where the microcline-pegmatite lies against plagioclase-pegmatite.

In the wall of the quarry next to the east from the Lindvikskollen quarry, a large block of amphibolite with sharp contacts can be seen completely surrounded by pegmatite. Its foliation is not parallel to the amphibolite foliation outside the pegmatite.

The pegmatite's north contact dips north, but at an unknown angle. At the west end the pegmatite shows a seemingly completely gradational, unmappable contact against the adjacent kragerøite and the garnet-albitite body, but a specimen taken from inside the rutile mine shows large microcline crystals poikilitically including and apparently replacing the small kragerøite grains. As such microclines are unknown from elsewhere in the kragerøite, this specimen has probably come from the pegmatite-albitite contact, and indicates that the pegmatite is the younger of the two. Elsewhere, the north contact can be mapped, but is nevertheless gradational over some few centimeters whether against amphibolite, albitite, or plagioclase pegmatite. It is definitely discordant with all three. Much of the amphibolite on the north side is full of small albitite and plagioclase-pegmatite stringers and dikes, and resembles the «transition gneiss» mentioned above.

The Kalstad-Lindvikskollen pegmatite contains a rich assortment of minerals. A complete list of minerals known at present from this body follows, with comments on modes of occurrence.

Microcline-perthite makes up the bulk of the pegmatite. The color varies from greenish to reddish to buff. It occurs commonly in large crystals, (including euhedral Carlsbad twins), some attaining a width of several meters as exposed in the quarry face.

Quartz occurs in small grains to large masses several meters across, and in considerable amount.

Plagioclase of white to gray to tan color is a major constituent of this pegmatite, and its composition ranges between An 5 and An 15.

A large specimen full of lustrous, prismatic crystals of *scapolite* up to 3 cm long, with black pyroxene and dark brown sphene, was collected at the Lindvikskollen quarry in 1953. A refractive index determination gave $\omega = 1.551$, $\varepsilon = 1.542$, indicating a composition of about 80 % Ma. The relation of this loose block to the pegmatite itself is not certain. Schetelig in 1915 (29) mentioned another scapolite ($\omega = 1.567$, $\varepsilon = 1.550$) supposedly from a Kragerø pegmatite, but the exact locality is unknown.

Tourmaline occurs in rather large quantities. It is a common black schorl type.

Apatite was found in blue-green, prismatic crystals up to 3 cm across. According to Bjørlykke (9) it contains small amounts of rare-earth elements.

Sphene, an yttrium-bearing type, is present in considerable quantities. It is brown to gray with an adamantine luster, but is sometimes highly altered.

Biotite is more common in the Lindvikskollen quarry than elsewhere in the dike. It is dark brown, altering around the edges to chlorite, and occurs in large platy growths several meters across by only a few centimeters thick, branching apparently perpendicular to the (110) faces.

Magnetite occurs abundantly in roughly spherical crystals showing perfect octahedral cleavage.

Ilmenite is found as platy intergrowths with plagioclase, the alternating lamellae ranging from 1 to 15 mm in thickness. Rare minerals often occur in the acute angles where pairs of ilmenite plates join.

A *hornblende* from near the amphibolite contact was found by refractive indices to have an Mg/Fe'' at. ratio of 70/30. An amphibole from the dump was closely associated with magnetite; its optical properties are $\alpha = 1.659$, $\beta = 1.675$, $\gamma = 1.680$, $-2V \sim 70°$, $Z:c = 21°$.

Muscovite is found in small quantities as a relatively late mineral in the Lindvikskollen quarry, and also as small (up to 5 mm across) rounded prisms with a peculiar greenish color, associated with *calcite*, *clay minerals*, quartz, and *pyrite* in a late-stage breccia zone and fissure fillings in the Kalstadgangen quarry.

The pyrite has the pyritohedral form, often with penetration twins, in crystals up to 2 cm in diameter.

BJØRLYKKE (9) observed small fragments of pink calcite embedded in microcline.

Small amounts of *phenacite* have been collected from this pegmatite, as colorless, prismatic crystals.

The following dark minerals were determined provisionally by their x-ray powder patterns, heating the metamict specimens to 700° or ~ 1030° C.

Euxenite occurs in seemingly late-stage fractures, mostly as irregular masses. It is black, shiny, and metamict.

Orthite (*allanite*) is found in large quantities in this pegmatite as brown, shapeless masses and blackish, often tapering prismatic crystals up to at least 10 cm in diameter. Both kinds are covered with a tan alteration product, and are partly metamict. The unheated powder of the first variety gives a few unrecognizable lines on an x-ray film; the second gives a recognizable orthite pattern. A spectrographic investigation confirmed the identification of the first variety as orthite. According to Goldschmidt (19) the orthite from Kalstadgangen contains La, Ce, Pr, Nd, Sm, Gd, Dy, Er, and Yb.

The Lindvikskollen quarry is the original locality for the mineral *hellandite* (12). It occurs in small, prismatic crystals, usually much altered.

Bjørlykke records observing *thorite* (possibly *orangite*) in small red nodules in microcline, and also lists *alvite* as occurring in this dike.

In the course of investigation these dark minerals by x-ray powder patterns, I came across a specimen of *fergusonite*, which, to my knowledge, has not been heretofore recorded from Kragerø pegmatites. The specimen is brownish black, shiny, and metamict. It occurs together with yttrotitanite, euxenite, tourmaline, and microcline.

A brown mineral, previously unknown, was discovered by C. T. Johne of Kragerø in the Kalstad pegmatite a few years ago. X-ray, chemical, and spectrographic investigations of similar material collected by Johne from a rare-mineral pegmatite at Gryting, Gjerstad, indicate that the new mineral has the gadolinite-datolite structure, but contains a large amount of Ca in place of the Fe of gadolinite.[1] It occurs at Gjerstad closely associated with gadolinite, probably as an alteration product.

The other famous pegmatite body in the map area is the Tangen pegmatite, which was owned and worked by the late mineral collector Peder Tangen. It lies on the east bank of the Kammerfoss River near the northern boundary of the map area. It is much smaller in outcrop than the Kalstad—Lindvikskollen body, measuring only about 40 by 50 meters. The surrounding amphibolite varies greatly in strike and dip over short distances, and was evidently influenced by strong, localized stresses.

The pegmatite-amphibolite contacts are mostly cross-cutting and fairly sharp, and are characterized by the formation of a black biotite in the amphibolite. A thin section of one such contact specimen showed considerable sphene and apatite, and pure albite and quartz penetrating the ferromagnesian minerals. The larger feldspars show evidence of strain.

The Tangen pegmatite differs from the Kalstad—Lindvikskollen body mainly in that it consist to a great degree of the blady variety of albite, *cleavelandite*. This mineral occurs in large radial aggregates and thin fissures in the surrounding *microcline*-pegmatite. It is pure white to gray, and has the molecular composition Ab 96.3, An 0.7, Or 0.9 (rest 2.1), according to Andersen (2, p. 43).

The original *plagioclase* in this pegmatite contains varying amounts of anorthite, from O to about 15 %. Andersen (1) states that these plagioclases usually are antiperthitic, with between 3 and 10 % of pure microcline in thin stringers, and none dissolved in the groundmass.

Quartz is a common mineral here, occurring both in the microcline and cleavelandite facies.

Black *tourmaline* is abundant, sometimes as intimate intergrowths with quartz.

Magnetite balls, up to 3 or 4 cm in diameter, are scattered widely in the microcline-pegmatite. Where the latter has been replaced by cleavelandite, the magnetite is commonly changed to *hematite*. The magnetite contains considerable Ti and Mn (Bjørlykke, 9).

Pyrite in twinned pyritohedra occurs here, as well as small lumps of *chalcopyrite*.

[1] T. F. W. Barth, K. Heier, personal communication 1954.

A *pyroxene* was collected by Andersen in 1923 from the Tangen pegmatite; its optical properties identify it (after Trøger) as an augite, containing about 20 % of the aegirine molecule.

Considerable well-formed *phenacite* has been collected from this locality, this and the Kalstad-Lindvikskollen pegmatite being the only known occurrences of the mineral in Norway.

Topaz labeled «Tangen, Kragerø» is found in the collection of the Mineralogical Museum of the University of Oslo, but none of the recent investigators has found any in the pegmatite itself.

Yttrotitanite is commonly found here associated with the other dark, rare-earth minerals. *Alvite* appears as good-sized clumps of gray-brown crystals, usually with curved terminal faces. Much *columbite* has been collected, in well-formed crystals weighing up to 50 kg. According to Bjørlykke (9), it contains more Mn than Fe.

Betafite, thorite, and *orangite* occur together, in considerable amount The betafite is metamict, with a waxy luster and an orange to brown color. The thorite is red to brown, not completely metamict, and also has a waxy luster. The orangite is metamict, with a resinous appearance and orange to brown color.

BJØRLYKKE (11) also lists *orthite, euxenite,* and *hellandite* as occurring in the Tangen pegmatite.

The Sjåen pegmatite (also called Dalene, or Høisjåen) crops out at the edge of the west-facing cliff at the top of the hill Sjåen, at an elevation of 150 meters (see Plate XVII). It has the form of an elliptical pod, extending almost vertically down into the hill. It seems to be completely surrounded by a large quartz-albitite body, against which it has fairly sharp contacts.

The Sjåen pegmatite closely resembles that at Tangen, and may well be connected with it underground. It has undergone the same cleavelandite-quartz mineralization, and contains a similar mineral suite: *microcline-perthite, plagioclase,* (An 5 and An 11 were determined by refractive index), *quartz, magnetite, tourmaline, aegirinaugite* (about 28 % aegirine molecule), *apatite, yttrotitanite, euxenite, betafite,* and according to Bjørlykke (9, 11), *alvite* and *orthite.* An unusually coarse graphic granite is common, consisting of intergrowths of quartz with microcline-perthite.

Several smaller microcline-pegmatites are also shown on the map. One of these, cropping out near the top of the south slope of Stor-

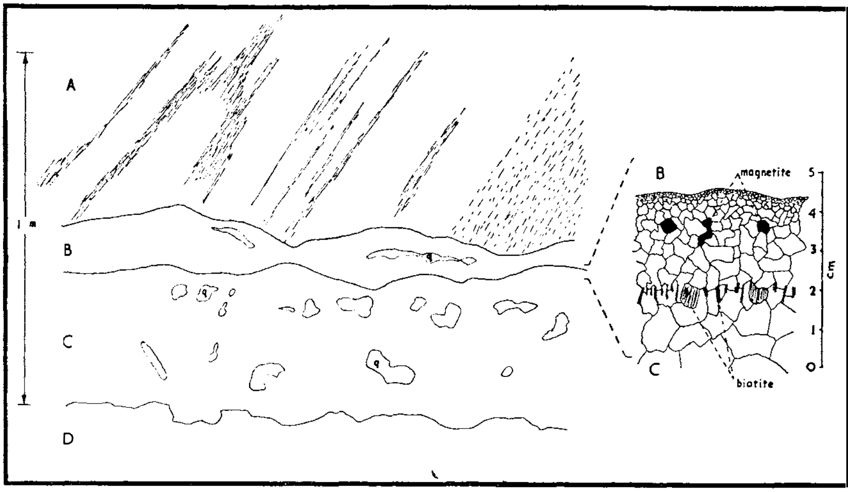


Fig. 13. Contact of pegmatite with albitite-amphibolite transition gneiss, in quarry just west of Dalene pond.

kollen, is particularly dike-like in form. It has been worked for feldspar. It is about 15 m wide and stretches for over 100 m along the hillside; its eastern end is blunt and abrupt, whereas the northwestern end tapers out to nothing. The dike has moderately to very sharp contacts, dipping steeply to the north and northeast. One contact, discordant against the amphibolite, has a contact zone about 1—2 cm wide which weathers out in relief. This was found to consist mostly of chlorite and albite (An 8), filled with small scraps and grains of sericite, calcite, epidote, and rutile. At another point, the pegmatite-amphibolite contact shows a wider reaction zone up to 20 cm in thickness, and of quite a different character. It contains black tourmaline prisms in a quartz matrix, strongly pleochroic hornblende, apatite, biotite and chlorite including lenses of prehnite, pyrite, highly altered plagioclase (fresh where next to the chlorite), scapolite with scraps of opaque ore near biotite, calcite, and tiny zircons in the biotite.

The pegmatite proper contains *microcline-perthite, plagioclase,* and *quartz* (often in large masses), *biotite, magnetite,* much *tourmaline,* and *orthite* and *fergusonite.*

A pegmatite which crops out in quartz-albitite just west of the Dalene pond has also been worked. It has an irregular shape, and apparently dips steeply into the hill. The contacts are well exposed in a few places, and are especially interesting (see Figure 13). The country rock is a light phase of the albitite-amphibolite transition gneiss, containing albite-oligoclase, quartz, diopside, and hornblende. Its dark minerals are here slightly concentrated in bands, giving the rock a gneissic appearance. (A in Fig. 13). About 10—20 cm from the actual pegmatite contact, this structure is cut off by a zone of structureless albitite with a few quartz lenses parallel to the contact. (B). At the contact proper, and going into the pegmatite, the grain size suddenly grows from about 1 mm to about 4—5 mm, and there is an abundance of magnetite crystals in this zone, which is about 2 cm wide. Then appears a narrow zone of small biotite flakes which have grown perpendicular to the contact, and there follows a typical pegmatite zone (C) with coarse-grained quartz and feldspar which gives way to a large quartz mass (D) 40 cm in from the contact.

Apophyses of pegmatite into albitite were also seen. One contact specimen resembles that described from the pegmatite-kragerøite contact. It consists of $\sim$ 1 mm rounded grains of albite (An 8), salitic pyroxene, biotite, sphene, apatite, and zircon «floating» poikilitically in a groundmass of large (2—5 cm) microcline crystals.

Minerals to be found in this pegmatite are *microcline-perthite, quartz, plagioclase* (An 0 to 11), *black tourmaline, hornblende, biotite, sphene, magnetite,* and *calcite.* The calcite occurs as large crystals with pure albite and quartz in a vein. Rare minerals have not been observed here.

The smaller coarse-grained microcline-pegmatites usually have amphibole, magnetite, sphene, and alvite as the dark minerals.

Several microcline-pegmatites in this area do not show the very coarse grain size which is so typical of those described above. These, whose grains range mostly between 0.5 and 2.0 cm in diameter, contain as a rule few dark minerals, mostly biotite partly altering to chlorite, but also commonly euhedral magnetite, and sphene. They are usually cross-cutting bodies, but sometimes they follow the boundary between albitite and amphibolite. A specimen from such a contact between kragerøite and a small pegmatite on Lindvikskollen shows again large microclines including the crystals of the fine-grained rock. Similar relations are found at the pegmatite on the western end of Storkollen just above the pond (see Figure 14).

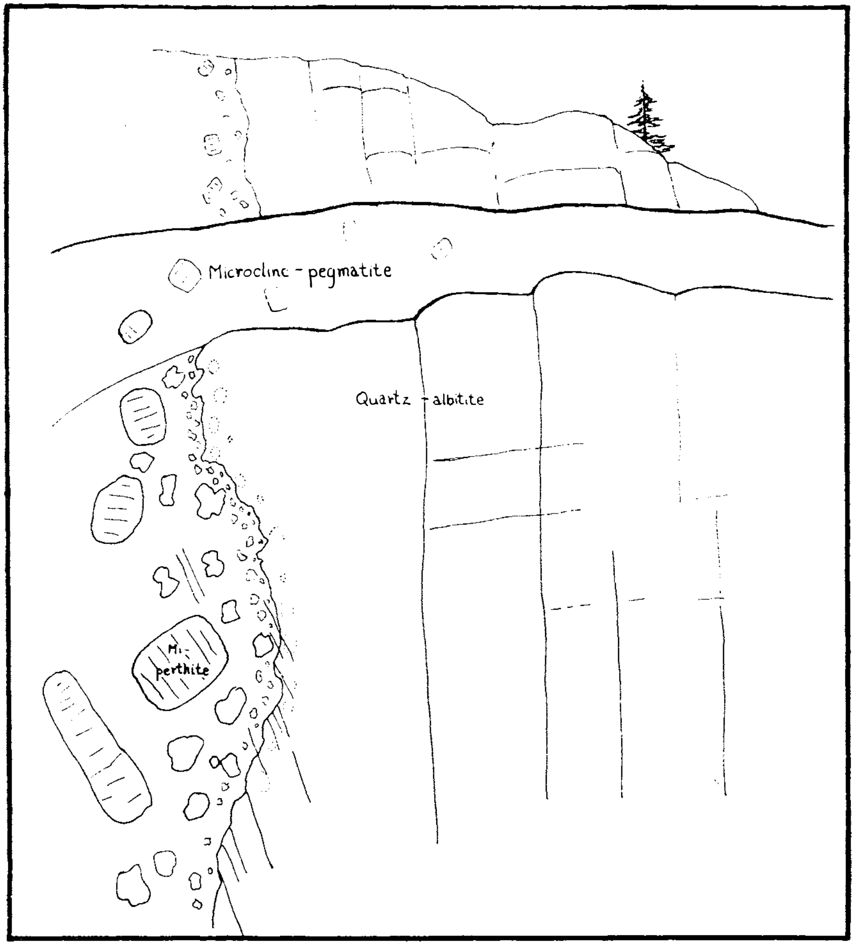


Fig. 14. Contact of pegmatite with quartz-albitite, west end of Storkollen.

The plagioclase-pegmatites never attain the large grain size of some of the microcline-pegmatites; most grains are between 0.3 and 3.0 cm across. The bodies are extremely irregular in shape, occurring both as coarse-grained stringers and masses without sharp boundaries in albitite and as independent, dike-like bodies. They consist mostly of an albite or albite-oligoclase, with considerable quartz and lesser amounts of microcline, biotite, hornblende, chlorite, apatite, and tourmaline. This mineralogy closely resembles that of the albitites, both in phases and proportions, and I consider these plagioclase-pegmatites to be merely a coarse-grained facies of the albitite suite. A more coarse-grained pegmatite within the main body of kragerøite in Lindvikskollen offers a fine example of this relationship. Although adjacent to the large microcline-pegmatite, the kragerøite pegmatite contains only the minerals of the surrounding kragerøite, and in approximately the same proportions; thus, albite, rutile, quartz, biotite, pyrite, apatite, and sphene.

Iron Mineralization. A series of small iron oxide deposits of varying character, size, and value occurs in a roughly east-west line across the map area. Many small to medium-sized prospects have been worked; one tunnel has been driven into the northwest corner of Lindvikskollen and a considerable volume of ore stoped out (see map). These mines, called the «old Kalstad iron mines», have not been in operation for a number of years. The ore minerals are magnetite and hematite, introduced together with quartz, calcite, and pure albite, in a stratiform zone. The ore minerals occur in a number of different ways: rich disseminations in biotite schist (often with specular hematite plates parallel to the schistosity); large, striated, tabular hematite crystals in quartz lenses; disseminations in small quartz-albitite dikes; frothy mixtures of magnetite and calcite; grainy, bedded concentrations of hematite and magnetite in amphibolite and schist; and so forth.

An amphibole close to a small magnetite bed from the tunnel was found by optical means to have an Fe''/Mg at. ratio of 73/27, unusually high in iron.

Concentrations of magnetite and hematite occur in pegmatite as well as amphibolite and schist along the «fissure», indicating a relatively young age for the iron mineralization. At the old Kalstad iron mines, the schist shows extreme evidence of «stretch-brecciation», probably the result of stresses imposed after the period of deeper, more plastic deformation, and possibly related to the introduction of the iron minerals.

Genesis of the leucocratic rocks.

All observers seem to agree on the origin of the scapolite and apatite deposits of the Kragerø area. Their close association in space and time with the gabbros, the autometamorphic scapolitization of

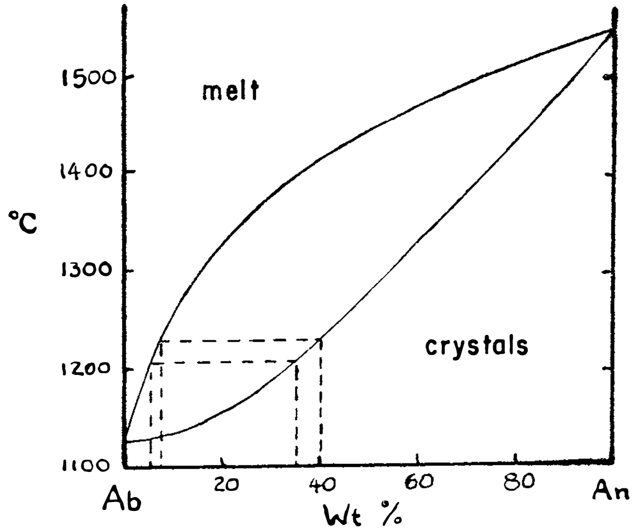


Fig. 15. Plagioclase melting diagram (after Bowen, 1913) showing possible relationship between gabbros and albitites.

some of the gabbro bodies, and the volatile nature of the constituents (P, Cl, F, OH, etc.), all suggest that gabbro magma was the ultimate source of these mineral deposits.

The albitites present somewhat more of a problem. Previous workers (BRØGGER, J. BUGGE) have here again pointed to the gabbros as the source of most if not all of them, citing mainly the close space-time association of albitites and gabbros throughout the Kongsberg-Bamle formation. The albitites would thus represent the residual, intergranular fluid of nearly-crystallized gabbro, squeezed out by orogenic movements and thus intruded as dikes into the surrounding sediments.

Such a hypothesis is admirably supported by some of the available information. In Figure 15, the plagioclases of the gabbros and albitites have been plotted on Bowen's experimental liquidus-solidus curves for plagioclase. The zoned plagioclases of the gabbros regularly have outer rims of the composition An 35 to 40. According to Bowen's curves, the last remaining liquid in equilibrium with these rims would be an albite of the general composition of the albitites (see Fig. 15). The anorthite content of the plagioclase rims of the gabbros varies somewhat, and so does that of the albitites, but the graphical relationship is evident.

The other major reason for attributing the albitites to the gabbros is the absence of any other suitable magmas of which they might be differentiates. The large granite plutons in the Kongsberg-Bamle formation are assumed to be younger than the albitites, and at any rate it is difficult to imagine a method of magmatic differentiation by which a granite could give rise to a nearly monomineralic, albitic product.

On the other hand, the present investigation shows that the composition of the albitites (except, perhaps, for the Lindvikskollen kragerøite) is so variable, even within a single body, that its explanation as a low-melting residual liquid of a gabbro or even several gabbros also becomes difficult. Figure 10, p. 115, is a triangular diagram of the system SiO_2 — $NaAlSi_3O_8$ — $KAlSi_3O_8$ (after SCHAIRER, Jour. Geol. 1950) with the compositions of several of the kragerøites and other albitites plotted on it. These highly leucocratic rocks are rather accurately represented by such a diagram.

The very last liquid remaining in the course of crystallization of a gabbroic magma would be expected to have a composition projecting in the low-temperature trough indicated by the shaded area on the diagram. None of the albitites and quartz-albitites studied plot in the low-temperature composition trough; all lie to the side away from potash feldspar. A few are seen to lie close to the albite-quartz eutectic and cotectic, but the large majority correspond to no kind of low-temperature composition. Analyses of Kragerø gabbros show a markedly low potash content; thus, any residual differentiate would be expected to approach the low-temperature trough from the albite side, not the orthoclase side. The plotted albitites do indeed fall on the albite side of the minimum trough, but as some potash is present in all the gabbros, the residual liquid would be expected to contain at least as much potash, if not more, as the «parent magma». In the Ab — SiO_2 — Or system, a liquid of composition such as shown by $\approx$ on the diagram would crystallize out alkali-feldspar with increasing Or content as the temperature is lowered, the crystals always being more sodic than the liquid in equilibrium with them. The liquid takes the course shown on the diagram, while the crystals move towards the minimum-melting composition of alkali-feldspar at Ab 65, Or 35 (assuming a temperature above the solvus). Thus the residual liquid of a gabbro would be expected to become relatively enriched in potash as albite crystallized. The diagram shows little evidence of this; a large preponderance of the Kragerø rocks fall on or very close to the silica-albite join.

The abundance of quartz-albitites plotting far into the quartz field also can be counted as evidence against an origin as the residual liquid of a gabbro magma. The available gabbro magmas crystallized abundant plagioclase and only very minor and occasional associated quartz; discounting the potash component, a residual liquid from such a magma would have to fall somewhere on the Ab — SiO_2 join between Ab and the albite-quartz eutectic, and never towards the SiO_2 corner from this eutectic.

It must be kept in mind that the gabbros were intruded before or during the early stages of the regional metamorphism of the Kongsberg-Bamle formation, and any comagmatic intrusions would be expected similarly to have undergone metamorphism. As has been mentioned above, the various Kragerø albitites do show linear or foliar structure, generally in the form of elongated grains or trains of quartz but also trains and schlieren of rutile, and oriented micas, hornblende, and tourmaline, parallel to the regional structures and not the local contacts. The quartz everywhere shows undulatory extinction. The complete absence of chill structures, the equigranular allotriomorphic texture (in the purer albitites) and the preponderance of conformable contacts cannot then be taken as evidence against an igneous origin for these rocks, considering this later metamorphism.

A brief resumé of the field relationships is of value at this point. Although some of the smaller albitite bodies are narrow, sharply defined, and cross-cutting, most easily explainable as dikes, the two largest bodies show markedly different contact relations. The southern contact of the large kragerøite body is obscured, while that of the large quartz-albitite body to the north is through most of its extent sharp; that is, its southern albitite-amphibolite transition is complete over a distance of a few centimeters or so. The northern contacts of both bodies are characteristically gradational, the change being complete only over a considerable distance. That these bodies could have been intruded as conventional dikes seems then highly unlikely.

W. C. Brøgger (15) and J. Bugge (18) attribute some of the Kongsberg—Bamle albitites to replacement processes. «The occurrences within the Kragerø region mentioned above of 1) dykes and veins of albitite, and 2) of banded, albite-amphibolites, undoubtedly originated by the metasomatism of former scapolite-rocks, certainly prove that a number of the albite-rocks of the Kragerø region are of secondary, metasomatic origin.» (Brøgger, 15, p. 236). «Closer studies show that during the last part of the period of migmatization, an extensive albitization has taken place in the rocks in large parts of the Kongsberg-Bamle formation.» (Bugge, 18, p. 49).

As the various possibilities for a magmatic origin of the Kragerø albitites have been found to be somewhat less than satisfactory, the possible role of metasomatism will now be considered.

The Gibbs Phase Rule states that the number of independent variables in a system in equilibrium cannot exceed the number of components plus P, T, minus the number of phases; or, $f = c + 2 - \varphi$. V.M. Goldschmidt's Mineralogical Phase Rule, $\varphi = c$, merely states that at any random, P, T, the number of phases will not exceed the number of components. D.S. Korjinsky extended the application of the Phase Rule to systems with mobile components; where the μ_m, or chemical potential of each mobile component, is variable, then the Gibbs Phase Rule simplifies to $f = c_m + 2$ (variance equals the number of mobile components plus P, T) and $\varphi = c_f$ (the number of phases does not exceed the number of fixed components).

Thus in any metasomatic process, where one or more components are mobile, equilibrium mineral assemblages will tend to be simplified, not complicated; the more components are mobile, the fewer phases there can be.

In their highest development, the albitites at Kragerø attain one of the simplest mineral assemblages imaginable — all albite. Their granoblastic texture indicates that they have reached textural equilibrium, which in turn implies (though does not guarantee) attainment of chemical equilibrium. Thus the albitites seem theoretically amenable to consideration as metasomatic rocks.

Many of the contact phenomena of the albitites are easily explainable by metasomatic processes. The gradual variation in the compositions of solid-solution minerals, such as plagioclase and amphibole, were necessarily accomplished by action of this sort. This presence of major minerals with variable compositions helps to explain the general absence here of sharp metasomatic «fronts» which are to be expected when only fixed-composition minerals are involved. With the increase of Na_2O and SiO_2, the plagioclase, being the major phase at high metamorphic grades capable of holding much soda, becomes more and more albitic while the CaO thus released changes hornblende into diopside (found only at albite-amphibolite contacts). These reactions might be expressed thus:

$$\underset{}{Na_2O} + 4SiO_2 + \underset{\text{An}}{CaAl_2Si_2O_8} \rightarrow \underset{\text{Ab}}{2NaAlSi_3O_8} + CaO$$

$$3CaO + 2SiO_2 + \underset{\text{Actinolite}}{Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2} \rightarrow \underset{\text{Diopside}}{5Ca(Mg,Fe)Si_2O_6} + H_2O$$

Eventually the diopside too is removed. Sometimes, as in the little plagioclase body on the Havna road, diopside is not formed and plagioclase replaces hornblende directly.

When it is recalled that the albitites have undergone metamorphism, these contact phenomena are seen actually to be equally explainable by the original reaction of mobile, albitite-forming ions with the amphibolite, or by the reaction of already-present albitite (whether magmatic or metasomatic) with adjacent amphibolite, during subsequent metamorphism. In either case, mobility of ions and metasomatic action are evident, at least in the contact zone, and the real problem becomes, as in most cases of «granitization», to what extent beyond what we actually observe, was metasomatism operative?

As the evidence afforded by the contact phenomena cannot be safely extrapolated to provide conclusions as to the origin of the albitites themselves, the albitites themselves must provide the answer if any is to be found.

The source of the albitic material, whether it became emplaced as magmas or by metasomatism, seems inescapably to be the gabbroic magmatic complex (if the source is assumed to be in evidence). We have seen how residual magmas with compositions of most of the albitites are highly unlikely if not impossible, and we have seen that a monomineralic rock such as the purest Kragerø albitites is just what might be expected to result from a high degree of ion mobility. Metasomatism is thus the alternative which seems best suited to the observed facts.

Some special cases deserve particular notice. Many of the smaller albitite bodies (*e.g.* north side of Lindvikskollen) are narrow, persistent, and dikelike in form, and show clearly cross-cutting relations. These often turn out to be the ones compositionally most amenable to a magnatic explanation; that is, they lie away from the quartz-albite join of Fig. 10, towards the cotectic or the low-temperature area. For these it is perhaps not necessary to propose a metasomatic origin; a residual magma would answer quite well enough.

The problem at once arises, what did the albitites replace? The large, and varying, amount of quartz in the large quartz-albitite body might suggest that the original rock was an arkosic sediment, carrying locally variable amounts of quartz and K-feldspar. On the other hand, the body is seen to grade into amphibolite, not a granulite, along the strike to the east; and it is evident in any case that there has been an increase in silica during the metasomatism. The albitites are all surrounded by amphibolites, and were most probably formed from this rock.

The origin of the rutile, pyrite, tourmaline, and corundum in different parts of the kragerøite body must also be explained. Pyrite and tourmaline, containing relatively volatile constituents, are common in ore deposits and other residual products of igneous differentiation. The tourmaline of the small Lindvikskollen albitite body may be directly referred to schorl-bearing pegmatite only a few meters away; the Mg-rich variety in the contact zone is probably only a reaction product of this with the ferromagnesian minerals of the amphibolite.

Rutile is found abundantly in the other gabbro differentiates, the scapolite and apatite veins. Its peculiar association with albite in the kragerøite may be mere chance, but it bears a close resemblance to the disseminations of rutile in pre-Cambrian andesine anorthosite near Roseland, Virginia (Ross, 28). Apatite is here also closely associated with the rutile mineralization. The Roseland anorthosite body is much larger than the kragerøite (13 miles long, 22 square miles in area) and was evidently formed at a high temperature, as indicated by the high degree of solid solution in its feldspar (Ab 51, An 24, Or 25). Ross concludes that the major Ti content was introduced by pneumatolytic TiF_4 «after the granulation and consolidation of the anorthosite and [is] absent in the primary uncrushed feldspar. The titanium minerals are evidently the result of replacement and not of magmatic segregation or of pyrogenic processes» (p. 1). The Kragerø rutile deposits show no evidences of brecciation or granulation, but on the other hand they have most probably been metamorphosed and recrystallized after the introduction of the rutile. As a result, no definite conclusions can be reached as to the precise mode of emplacement of the rutile. Two points are of especial significance in this regard, however: 1. the rutile, aside from the low-concentration dissemination throughout the body, is concentrated in «schlieren» near and parallel to the north contact, which has been faulted; and 2. the Kragerø occurrence bears striking similarities to the Roseland deposits. It would not then seem unwarranted to propose for the Kragerø rutile deposits an origin similar to that proposed by Ross for the Virginia deposits after long and careful study of unmetamorphosed material.

The corundum which appears in two widely separated places but both in the kragerøite body poses another problem. If the kragerøite is considered magmatic, the magma would have had to assimilate a very highly aluminous sediment locally to result in a corundum-bearing rock, when the normal kragerøite contains some quartz. The presence of other «impurities», biotite and tourmaline, perhaps supports this hypothesis. If the kragerøite is metasomatic, the explanation is simpler if no more reasonable; if less silica were available locally during the metasomatism, the reaction might have progressed thus:

$$Na_2O + 2SiO_2 + \underset{An}{2CaAl_2Si_2O_8} \rightarrow \underset{Ab}{2NaAlSi_3O_8} + \underset{Cor.}{Al_2O_3} + CaO.$$

The textural evidence is confusing; the corundum is localized in the secondarily recrystallized areas of the kragerøite (see p.). Also, no transition zone to normal kragerøite has been found, containing aluminum silicates, which would be expected in any case. The origin of the corundum in this rock remains uncertain.

The large microcline pegmatites of the present area are notable for their abundance of rare-earth minerals and their complex history. The pegmatites are everywhere seen to be younger than their country rocks, whether amphibolite or albitite. The minerals at their contacts are often found to be oriented perpendicular to the contact, reminiscent of comb quartz in an open-fissure ore deposit. Harald Bjørlykke, who has studied the South Norwegian pegmatites exhaustively, contends «that the Norwegian granite pegmatites carrying rare elements have been formed as follows: after the injection of the younger pre-Cambrian granites, the residual granite magma, enriched in volatiles and rare elements, was intruded along cracks in the surrounding rocks. The temperature, however, was still high enough for the magma to remain in a liquid condition in these rocks for a long time. Through orogenic movements the magma was kneaded into the surrounding rock, part of it forming smaller or larger bodies without connection with other pegmatite material. During this time the initial crystallization stage was reached, the early mineral phases thereby becoming subjected to mechanical deformation as previously described, the adjacent rock at the same time developing a schistosity parallel to the pegmatite bodies . . . Some granite pegmatites were subsequently influenced by solutions and gases following cracks in the already congealed magmatic pegmatite, thus forming deposits of hydrothermal-pneumatolytic origin (cleavelandite, quartz, etc.), which are not of course in equilibrium with the magmatic minerals.» (10, p. 244). The Levang granite, a large stock just to the south across Kilsfjord from the present area, was studied by Brit Hofseth (12). It contains considerable oligoclase, and is a reasonable source for the pegmatite magmas of the Kragerø peninsula.

Jens Bugge concludes that a great deal of granitization has taken place in the Kongsberg-Bamle formation, but that «In cases where it is possible to show that an enrichment of rare earths in proportion to the granites has taken place, it is reasonable to suppose that [the pegmatites] belong to the [residual melts of palingenic granites] type, as there seems to be relatively little rare minerals in the metatectic rocks» (18, p. 127).

The structural and textural evidence cited above seems to support Bjørlykke's explanation. The Kragerø pegmatites fit admirably into the scheme of successive stages of mineralization set up by Fersman (as reported in TURNER and VERHOOGEN, 32, p. 332). Seven out of Fersman's ten types of pegmatite mineralization, grouped into pegmatitic, pneumatolytic, and hydrothermal stages with decreasing temperature, are represented in the Lindvikskollen—Kalstad body, for instance. According to this scheme, the rare earth minerals and related heavy-element minerals crystallize in the early, pegmatitic stage (roughly 800 to 600° C); in the following pneumatolytic stage (roughly 600 to 400° C), tourmaline and muscovite are formed, and later on, albite (cleavelandite) replaces microcline. In the lowest temperature, hydrothermal stage (roughly 400 to 100° C), carbonates, sulfides, and finally kaolin are formed.

Conclusions.

The Kongsberg-Bamle formation in the Kragerø region had a complex history during the pre-Cambrian era. Sediments of widely varying types (sandstones, arkoses, aluminous shales, etc.), intermixed with basalt lavas, were laid down in a sedimentary basin and intruded by small gabbroic stocks and sills and plugs before or during the Svecofennide (?) revolution. Mobile differentiates of these gabbroic magmas autometamorphosed parts of the gabbros to scapolite-hornblende rock, penetrated the surrounding rocks and the gabbros themselves, and produced scapolite-hornblende veins, apatite-rutile veins, and dikes and oddly-shaped bodies of albitite. The available evidence indicates a metasomatic origin for most if not all of the albitite bodies, mainly on the basis of the unlikelihood of residual magmas of the required composition.

The sediments with their gabbro intrusions were broadly folded and subjected to the P, T conditions of the high amphibolite facies (sillimanite zone), during which the sediments were transformed into schists, quartzites, and gneisses, and the outer portions of the gabbros were altered to amphibolites, through the diffusion inward of water from the surrounding sediments. The foliation developed during the metamorphism bends around the tough, resistant cores of these gabbros.

During the later stages of orogeny, the Levang granite was intruded into the metamorphic rocks immediately to the south of the map area, and pegmatitic residual magmas developed. These were intruded, while completely liquid, into the country rocks, and crystallized while cooling slowly, to form the pegmatites of the Kragerø Peninsula. Several successive stages or waves of mineralization in the pegmatite are evident, the most striking of which is the replacement of earlier microcline perthite by cleavelandite, as in the Tangen pegmatite.

At some unknown stage after the peak of metamorphism, (perhaps at the time of the granite intrusion) the rocks became at least partially adjusted to an environment of slightly lower temperature or slightly more water, or both, within the stability range of muscovite but still in the sillimanite zone.

At some later time the rocks were again subjected to strong shearing stresses, which produced faulting and brecciation locally in the now rigid rocks. Iron oxides, in a gangue of quartz, calcite, and albite, were deposited along a fissure extending roughly east-west across the map area.

The last two or three events were probably associated with uplift of the area into a mountain chain, and erosion, including Pleistocene glaciation, has been the only agency in evidence since that time.

Acknowledgments.

I wish to express deep gratitude to the United States Fulbright Committee, under whose Student Grant the present work was accomplished. Great thanks are also due to Prof. T. F. W. Barth for making available to me the facilities of the Geologisk Museum of the University of Oslo, and for critically examining the manuscript. I wish to thank Erna Christensen of Norges Geologiske Undersøkelse for her kindness in performing several partial chemical analyses of minerals, and Prof. Ivar Oftedal of the University of Oslo for two spectrographic studies. Thanks are due to Miss B. Mauritz for the photomicrograph appearing in this paper, and to Don Charles Foote, who drafted the geologic map. I also wish to thank Knut Heier and Dr. Gunnar Kullerud for many valuable discussions, both geological and otherwise.

REFERENCES

1. ANDERSEN, OLAF. The genesis of some types of feldspars from granite pegmatites. Norsk Geologisk Tidsskrift *10*, p. 116 (1928).
2. — Feldspat II. Norges Geologisk Undersøkelse *128b* (1929).
3. — Discussion of certain phases of the genesis of pegmatites. Norsk Geologisk Tidsskrift *12*, p. 25 (1931).
4. BARTH, T. F. W. Om opprindelsen av enkelte grundfjellsamfiboliter i Agder. Norsk Geol. Tidsskrift *11*, (1930).
5. — Theoretical Petrology. John Wiley and Sons, N. Y. (1952).
6. BJØRLYKKE, H. Ein Betafitmineral von Tangen bei Kragerø. Norsk Geol. Tidsskrift *12*, p. 73, (1931).

7. BJØRLYKKE, H. The mineral paragenesis and classification of the granite pegmatites of Iveland, Setesdal, Southern Norway. Norsk Geol. Tidsskrift *14*, pp. 211—310, (1935).
8. — Litt om granitiske pegmatittganger. Norsk Geol. Tidsskrift *16*, pp. 299—303, (1936).
9. — Mineral paragenesis of some granite pegmatites near Kragerø, Southern Norway. Norsk Geol. Tidsskr. *17*, pp. 1—16, (1937).
10. — The granite pegmatites of Southern Norway. Amer. Mineral. *22*, No. 4, (1937).
11. — Feltspat V — De sjeldne mineraler på de norske granitiske pegmatittganger. Norges Geol. Undersøkelse *170*, (1948).
12. BRØGGER, W. C. Hellandit von Lindvikskollen. Zeits. für Kristal. *42*, p. 417, (1906).
13. — Die Mineralien der Südnorwegischen granitpegmatitgange I. Skrifter Norske Videnskaps-Akad i Oslo, I Mat. Naturv. Klasse, No. 6, (1906).
14. — Nodular granites from the environs of Kragerø; On several Archaean rocks from the south coast of Norway I. Skrifter Vid. Akad. i Oslo, Mat. Nat. Kl., (1933).
15. — The south Norwegian hyperites and their metamorphism; On several Archaean rocks from the south coast of Norway II. Skrifter Vid. Akad. i Oslo, I Mat. Nat. Kl., Bd. 1, pp. 1—421, (1935).
16. BUGGE, ARNE. En forkastning i det sydnorske grunnfjell. Norges Geol. Undersøkelse *130*, (1928).
17. — Kongsberg—Bamble Formationen. Norges Geol. Undersøkelse *146*, (1936).
18. BUGGE, JENS. Geological and petrological investigations in the Kongsberg—Bamle formation . Norges Geol. Undersøkelse *160*, pp. 1—150, (1943).
19. GOLDSCHMIDT, V. M. and L. THOMASSEN. Geochemische Verteilungsgesetze III. Skrifter Vid. Akad. i Oslo. I Mat. Nat. Kl., No. 5, (1924).
20. HJELMQVIST, SVEN. Über Prehnit ab Neubildung in Biotit-Chlorit. Geol. Fören. Stockholm Förhandl. Bd. 59, Heft 2, pp. 234—244, (1937).
21. HOFSETH, BRIT. Geologiske undersøkelser ved Kragerø, i Holleia og Troms. Norges Geol. Undersøkelse *157*, (1942).
22. KORJINSKY, D. S. Mobility and inertness of components in metasomatosis. Acad. Sci. U.S.S.R. Bull., ser. geol. 1, pp. 35—60, (1936).
23. LARSEN, E. S. and H. BERMAN. The microscopic determination of the nonopaque minerals. U. S. Geol. Surv. Bull. 848, pp. 1—266, (1934).
24. OFTEDAL, IVAR. Enrichment of lithium in Norwegian cleavelandite-quartz pegmatites. Norsk Geol. Tidsskrift *20*, (1940).
25. — Oversikt over Norges mineraler. Norges Geol. Undersøkelse *170*, pp. 1—48. (1948).
26. — En litiumførende granittpegmatitt i Nordland. Norsk Geol. Tidsskrift *28*, pp. 234—237, (1950).
27. RAMBERG, HANS. The Origin of Metamorphic and Metasomatic Rocks. Univ. of Chicago press, Chicago, (1952).

28. ROSS, C. S. Occurrence and origin of the titanium deposits of Nelson and Amherst Counties, Virginia. U.S. Geol. Surv. Prof. Paper 198, (1941).

29. SCHETELIG, J. Scapolite from granite-pegmatite in Southern Norway. Norsk Geol. Tidsskrift *3*, No. 6, pp. 1—19, (1915).

30. TRÖGER, W. E. Tabellen zur optischen Bestimmung der gesteinsbildenden Minerale. E. Schweizerbart'sche Verlagsbuchandlung, (1952).

31. TSUBOI, S., Mineral. Mag., *20*, No. 108, (1923).

32. TURNER, F. J. and JEAN VERHOOGEN. Igneous and Metamorphic Petrology. McGraw-Hill, N. Y. (1951).

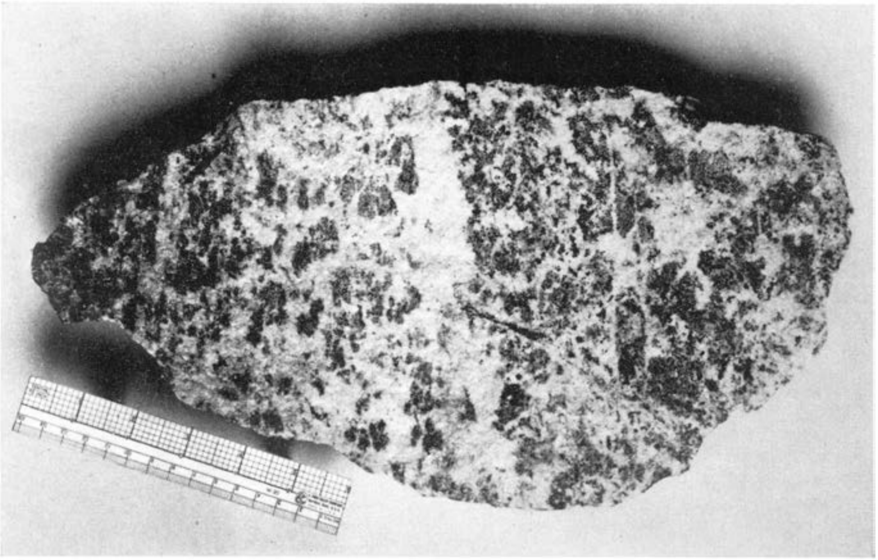
Manuscript received, September 9, 1955.

Printed august, 1956.

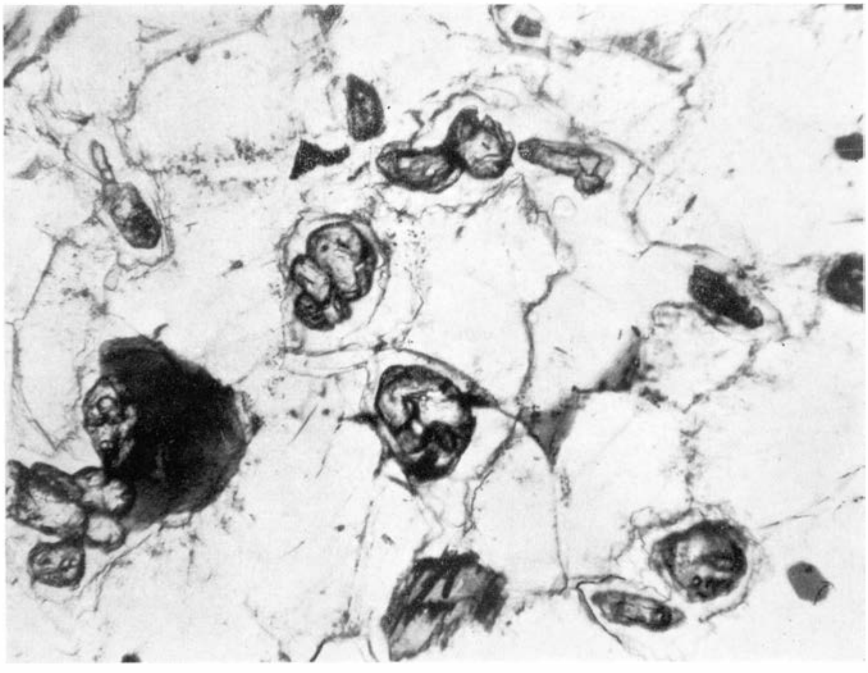
PLATE I

PLATE I.

a. Corundum-bearing kragerøite, Lindvikskollen. b. Corundum-bearing kragerøite, Lindvikskollen. High relief corundum, medium relief muscovite, low relief albite, dark biotite. Plane light × 116.



I a



I b