THE PRECAMBRIAN ROCKS OF THE TELEMARK AREA IN SOUTH CENTRAL NORWAY. III.

Geology of the Vrådal granite

By

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Abstract. The Vrådal granite is one of a number of small granitic bodies in southern Norway that was emplaced in gneiss and supracrustal rocks during the latter part of the Precambrian. It is a circular pluton about 6 km in diameter with a cross section similar to a steep-sided funnel. The foliation of the country rocks is concordant to the contact within a few hundred meters of the pluton, but it flattens gradually within one to two kilometers north and south of the contact. Country rocks adjacent to the contact are deformed into sheared isoclinal folds with near-vertical fold axes and with axial surfaces that are concordant with the contact.

The country rocks are comprised chiefly of granitic gneiss and lesser amounts of schistose amphibolite and quartzite: their mineral assemblages correspond with the lower amphibolite facies. There is no evidence of contact metamorphism

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in the country rocks adjacent to the granite, and the grain size of the granite does not diminish near contacts.

Large irregularly-shaped bodies of massive amphibolite occur randomly in the granite. The texture and mineralogy of the massive amphibolite is similar to Precambrian supracrustal lavas that crop out several kilometers north of Vrådal, which suggests that the massive amphibolite in the granite may represent roof pendants or stoped blocks of a former cover of supracrustal rocks.

Steeply-dipping shear fractures radiate from the center of the pluton and extend short distances into the country rocks. Other writers have suggested that a radial fracture pattern in a small pluton is evidence of deep-seated forcible emplacement of the body.

A diapiric mode of emplacement is suggested for the Vrådal granite in light of the close correspondence of the geological features of the pluton with those of salt diapirs and other granite diapirs.

Introduction

General Statement

This paper summarizes some important aspects of a field and petrographic study of the Vrådal granite. Geophysical, geochemical, and systematic structural studies were beyond the scope of this investigation, even though several writers maintain that it is hazardous to interpret the evolution of a granite body without such data. Other kinds of detailed studies are suggested throughout the paper that might add knowledge that could alter the interpretations and conclusions of this report.

Geographic and Geomorphic Features

The Vrådal granite is located about 140 km WSW of Oslo in Telemark "fylke" (county) between 59° and 59½° N latitude and between 8° and 9° E longitude. It is bounded by two large lakes: Kviteseidvatn on the northeast and Nisservatn on the west (Fig. 1 and Pl. 4). The pluton takes its name from the hamlet of Vrådal which is situated about one kilometer to the northwest at the north end of Nisservatn (Pl. 4).

The pluton is readily accessible by means of state and county roads that traverse it on three sides. Several logging roads and many trails penetrate nearly all portions of the pluton from several directions.

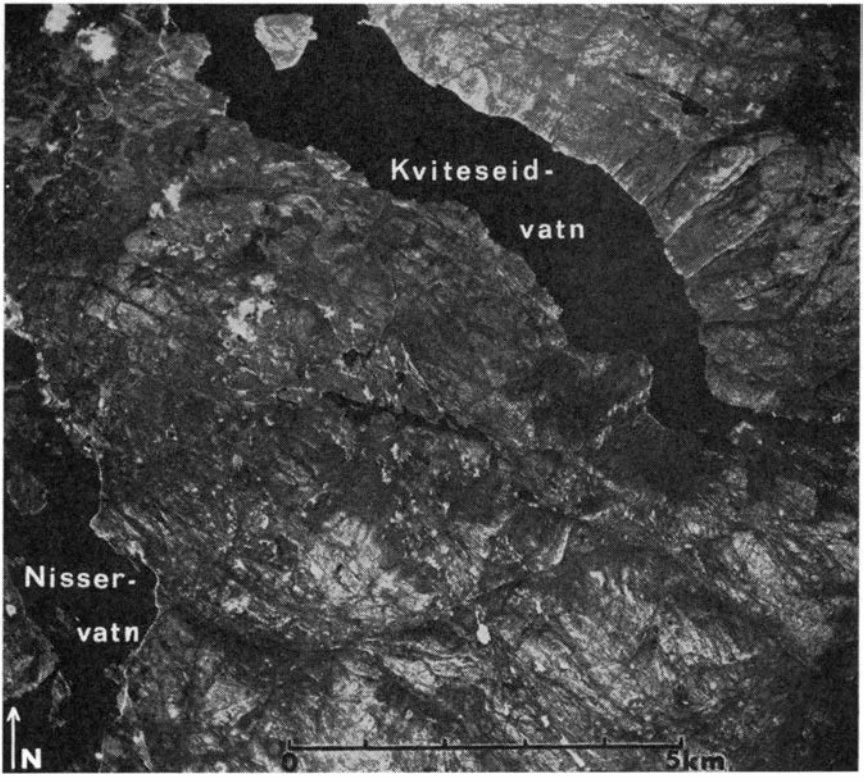


Figure 1. Aerial photograph of the Vrådal granite. Comparison with the geologic map (Pl. 4) shows the influence of the lithology and structure of the pluton on the geomorphology. The road, which is shown on the geologic map along the southwestern shore of Kviteseidvatn was not constructed when this photograph was taken.

The distinct crater-like morphology of the pluton which is evident in the aerial photograph (Fig. 1) derives topographic expression from several high rounded peaks: Åhomnut (843 m), Venelifjell (900 m), Skurven (803 m), Honlinut (827 m), and Vrålslinut (812 m). These peaks surround a central low area in which occur several small ponds and lakes, the largest of which is Honlivatn. Glaciation and later stream erosion have exposed large areas of barren rock; however, moraine and dense vegetation cover much of the pluton in the central and northeast portions of the area (Fig. 1).

Geologic Environment of the Pluton

The rocks of Telemark can be divided in a general way into gneiss, plutonic granitic rocks, and supracrustal rocks, all of which are of Precambrian age (Table 1; DONS, 1960b).

Table 1. Apparent age determinations in the area around Vrådal.* (data after NEUMANN, 1960)

Age	Method	Comment and locality
708 m.y.	Re/Os	Average of eight determinations on molybdenites from supposedly late hydrothermal solutions emanating from the "Telemark granite". Tarjeisberg, Telemark.
777 m.y.	K-Ar	One determination on mica from pegmatite which cuts "Telemark gneiss". South shore of Kviteseidvatn, Vrådal pluton, Telemark.
890 m.y.	K-Ar	Approximation from four determinations on micas from "Telemark granite". Various localities near Vrådal.

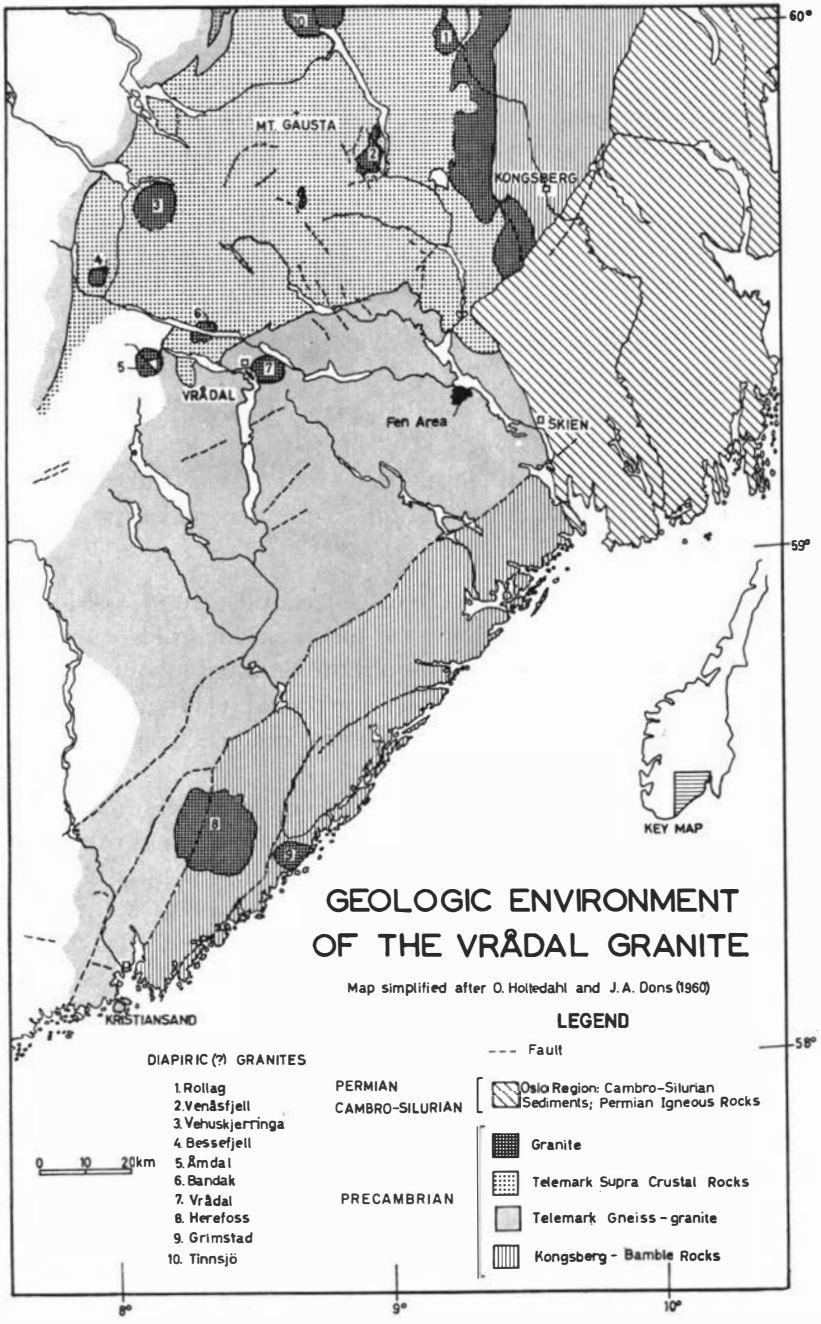
Gneiss, which is largely granitic in composition, crops out chiefly in the southern half of Telemark. Most writers consider the major fault zone that parallels the coastline as its southern boundary (Fig. 2). To the north the gneiss is covered by supracrustal rocks. BARTH

* While the manuscript was in press, Dr. W. R. Van Schmus of the Institute of Geophysics, UCLA, kindly consented to do Rb—Sr age determinations on mineral samples from a pegmatite that cuts the porphyric quartz monzonite of the Vrådal pluton. The specimens were collected from a vein, three meters thick, which is exposed in the roadcut at Lindestad farm, southwest shore of Lake Kviteseid (59° 20' N; 8° 35' E). Dr. Van Schmus' data are as follows:

Sample	Rb^{87}(ppm)	Sr^{87*}(ppm)(1)	Sr^{87*}/Sr^{87}	Age (m.y.)(2)
Muscovite	1089±16	13.64±0.20	0.99	896±27
Microcline ...	524±8	6.80±0.04	0.71	928±20

(1) Sr^{87*} = radiogenic Sr^{87}
(2) $\lambda\,(Rb^{87}) = 1.39 \times 10^{-11}$ yr^{-1}

The average of these two determinations, 910 m.y., probably represents the true age for this pegmatite, and is part of the 910 m.y. old event in southern Norway as discussed by KULP and NEUMANN (1961, p. 472).



GEOLOGIC ENVIRONMENT OF THE VRÅDAL GRANITE

Map simplified after O. Holtedahl and J. A. Dons (1960)

(1960, p. 35) notes that the gneiss is rather monotonous, and that even though bodies of metasediments are found in the gneiss, granitization has homogenized and almost completely destroyed the rocks and their structures over large areas. The relationship of the gneiss to the overlying supracrustal rocks is vague and not well understood (DONS, 1960a, p. 56).

Supracrustal rocks north of Vrådal (Fig. 2) have been subdivided by DONS (1960 a and b) into the following groups with a combined maximum thickness of more than 4000 m:

Bandak group (acid and basic lavas, quartz-rich sediments)
Unconformity
Seljord group (quartzite, conglomerate, schists)
Unconformity
Rjukan group (oldest) { Vemork formation: basic lavas and sediments
Tuddal formation: acid lavas and tuffs

These units have not been distinguished confidently in the gneissic area to the south, owing to increased metamorphic grade, tectonism, and erosion. Local occurrences of quartzite and amphibolite in gneiss around the Vrådal pluton, however, are probably vestiges of one of these groups of supracrustal rocks (DONS, personal communication, 1961).

The Vrådal granite is one of a number of small, discrete granitic plutons that has been emplaced in the Precambrian rocks of southern Norway. The plutons are similar to one another with respect to age, size, shape, structure, and petrography. BARTH (1947) was the first to postulate that some of these granites may have had a diapiric mode of emplacement; subsequent work by other geologists (HEIER and TAYLOR, 1959; CARTER, 1962; ELDERS, 1963; and SMITHSON, 1963a) has upheld this view.

Rocks that are younger than Precambrian have not been positively identified in Telemark even though sedimentation (chiefly Cambro-Silurian) and igneous activity (Permian) were dominant features of the geologic history of the Oslo region east of Telemark. A Permian rhomb porphyry dike transects the Herefoss granite (ELDERS, 1963), which suggests that some of the mafic dikes and sills in southern Telemark may be related to the Oslo igneous activity.

Southern Norway was active tectonically during the Tertiary, being affected particularly by faulting and jointing. The present configuration of the southern Norwegian coastline is ascribed to faulting at this time (HOLTEDAHL, 1960, p. 351), and contemporaneous (?) faulting and jointing in Telemark may have given rise to zones of weakness that were followed by valley glaciers during the Pleistocene. The present topography and geomorphology of central Telemark and the Vrådal granite are probably the products of these Tertiary tectonic events as well as erosion during the Quaternary.

Previous Work

Steinar Foslie mapped the southern half of the Vrådal pluton as a portion of the Nisser Quadrangle at a scale of 1:50,000.[1] Although Foslie's map has not been published, DONS has included much of its information in a geologic map of Telemark (DONS, 1960b, Pl. 4). The northern half of the Vrådal granite is included on a geologic map of the Kviteseid Quadrangle (NEUMANN and DONS, 1961) at a scale of 1:100,000. Other than these two works, no systematic mapping in Telemark includes the Vrådal granite.

J. A. DONS visited the Vrådal pluton in 1958 during preparations for one of the excursions of the XXI International Geologic Congress in Norden, 1960. He realized the fundamental structural relationship of the pluton to the country rocks by examination of aerial photographs of the body, and as a result of a few days of field reconnaissance during the summer of that year (DONS, 1960a, p. 20; 1960b, p. 56). He also found quartzite and amphibolite along its northern contact and suggested that these rocks may be remnants of a supracrustal roof series (DONS, personal communication, 1961). Later in the summer of 1958 DONS and E. WEGMAN visited the northern and southwestern portions of the contact. They concluded that the pluton may be a granite diapir, and that it merited a detailed investigation.

During the Fall of 1960, J. NATERSTAD collected several rock specimens near the mouth of Slokvikåi and attempted to determine the relative age relationships of the rocks. Naterstad's conclusions (DONS, personal communication, 1961) agree in general with those of this study, but not in detail. He did not publish the results of his work.

[1] Foslie's map and field notes were available to the writer.

Present study

The purpose of this study was to examine the field relationships and petrography of the Vrådal granite in order to shed light on its genesis and mode of emplacement. The field work was accomplished in the latter part of Summer, 1961, and Spring, 1962. The mapping, which was done on aerial photographs at a scale of 1:15,000, was limited to the granite and a belt of the surrounding country rocks that is from one to two kilometers wide. Laboratory work was carried out at Universitetets Mineralogisk-Geologiske Museum, Oslo, and at the University of California, Los Angeles.

Acknowledgments

It would not have been possible for me to undertake this study without the generous assistance of Professor Tom. F. W. Barth and Mr. J. A. Dons, who not only suggested the problem, but also placed the facilities of Universitetets Mineralogisk-Geologiske Museum in Oslo at my disposal. I am also indebted to Dr. S. B. Smithson of the same institution for his patient help and encouragement in my study of the granite.

The thin sections were prepared by Mr. E. Fjellet and Mr. E. Gonzales. Mrs. Peter Kurtz drafted Figures 3, 5, and Plate 4.

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Finally I express warm thanks to Sigrid and Torgeir Kråkenes of Krintolen near Vrådal for their kind hospitality and friendship, which made the field work a pleasure I shall always remember.

Petrography

Introduction

Six mappable rock units have been distinguished for the purposes of this investigation: granitic gneiss, quartzite, massive amphibolite, schistose amphibolite, quartz monzonite, and porphyric quartz

monzonite. Pegmatite and aplite dikes were not mapped, but a brief description of their occurrence and mineralogy is given below.

Terminology

SMITHSON (1963b, p. 12) points out the fact that many useful and necessary petrographic terms have genetic implications, even though they should be descriptive. It must be emphasized that they have only descriptive significance in this report. Some of these terms are defined below for clarity:

granite: a phaneritic rock composed essentially of quartz, potash feldspar, and/or sodic plagioclase (TURNER and VERHOOGEN, 1960, p. 330; SMITHSON, 1963b, p. 13). For purposes of classification the granite of the Vrådal pluton is a quartz monzonite.

megacryst: a large crystal that occurs in a finer-grained groundmass (used in place of phenocryst or porphyroblast when the origin is doubtful) (SMITHSON, ibid.).

porphyric: adjective applied to a rock containing megacrysts (SMITHOSN, ibid.).

inclusion: a crystal or fragment of another substance or a minute cavity filled with gas or liquid in a crystal (Glossary of Geology. AGI, 1962).

xenolith: a fragment of foreign rock (COMPTON, 1962, p. 285).

foliation: mesoscopically recognizable s-surfaces defined by lithologic layering, planar preferred orientation of grain boundaries, discrete fractures, or combinations of these (TURNER and WEISS, 1963, p. 97).

schistosity: foliations defined by the preferred orientation of tabular minerals, especially micas (TURNER and WEISS, op. cit., p. 100).

Analytical Methods

The An content of plagioclase was determined by measuring the crystals on a four-axis universal stage and referring the data to the standard curves of SLEMMONS (1962). The mean error of this method is about $\pm$ 2% An (SLEMMONS, ibid.).

The Or content of K-feldspar was determined by the powder x-ray diffraction method proposed by ORVILLE (1960). All samples

were heated 48 hours at 1025° C., mixed with $KBrO_3$ as a standard, and run on an 11.46 cm Guinier x-ray camera. The films were enlarged on a screen by means of a 35 mm slide projector and measured. The mean error is 1%, and the standard deviation is less than 0.5%. The An content was not determined, but is probably less than 3% (e.g., STEWART, 1956). Δ-values were determined by the same method.

Modal analyses of fine-grained rocks were done by point-counting unstained thin sections following the procedures given by CHAYES (1956). Slabs of coarser-grained rocks were stained with sodium-cobaltinitrite solution which colors the K-feldspar yellow (BAILEY and STEVENS, 1956). Plagioclase was readily distinguished from quartz because of the differential etching by HF acid, so that it was not necessary to stain it (SMITHSON, 1963c). A Zip-a-Tone dot pattern with a 1.0 mm grid was placed on the stained slabs for the point counting (JACKSON and ROSS, 1956), and about 1000 points were counted in each specimen.

THE COUNTRY ROCKS

Granitic Gneiss

Granitic gneiss almost completely surrounds the Vrådal pluton (Pl. 4). Typical exposures occur in roadcuts along Kviteseidvatn near Gamle Kviteseid Kirke and Sagabukti, and along Nisservatn south of Slokvikåi. It is a medium-grained rock consisting essentially of plagioclase (34%), quartz (32%), microcline (25%), biotite (4%), hornblende (3%), and minor amounts of sphene, magnetite, apatite, and zircon. Biotite and hornblende are concentrated in thin layers which define the foliation. The texture is granoblastic.

Microcline is xenomorphic, exhibits grid twinning, and has nearly maximum obliquity (Δ) values. Film perthite occurs in almost every grain; flame perthite is common in microcline grains that abut sericitized plagioclase crystals. Tabular, subidiomorphic grains of plagioclase (An_{11-12}) are commonly unaltered, but a narrow rim of albite occurs along the margin of plagioclase grains where they are in contact with microcline. Some myrmekite is observed in plagioclase. Quartz is xenomorphic with only a slight degree of elongation. Böhm lamellae, deformation lamellae, and undulatory extinction are evidences of

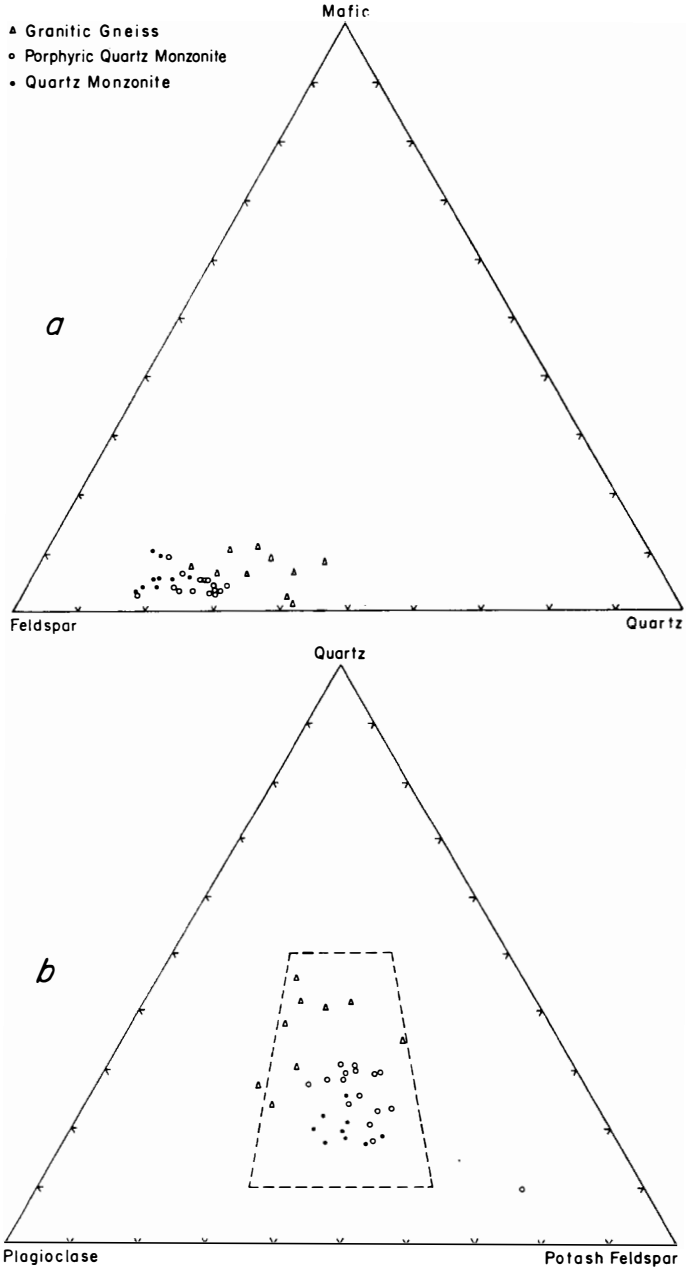

Figure 3. Thirty-four modal analyses of granitic gneiss, quartz monzonite, and porphyric quartz monzonite plotted on a QMF diagram (a) and on a Q-Pl-Or diagram (b). Dashed line in (b) delineates the field of quartz monzonite composition (BATEMAN, 1961, p. 1524).

postcrystalline strain of the quartz grains. Hornblende (Z, Y = dark green, X = light yellow green, $Z \wedge c = 20°$) occurs in irregularly-shaped grains from 1 to 3 mm long, and a few twinned individuals are observed. Biotite (Z, Y = green or brown, X = light tan) is partially altered to chlorite. Subidiomorphic to idiomorphic crystals of sphene and magnetite occur in association with hornblende and biotite. Ten modal analyses of the granitic gneiss are plotted on a QMF diagram and on a Q-Pl-Or diagram (Fig. 3).

The general aspect of the granitic gneiss changes markedly within 50 m of the contact with the granite. The foliation becomes less distinct in the granitic gneiss as the contact is approached, and the size and idiomorphism of the mineral grains decreases so that the texture is best described as aplitic. Biotite and plagioclase are completely altered to chlorite and sericite, respectively, in this zone.

The mineral assemblage, hornblende-microcline-quartz-plagioclase (oligoclase or more calcic), corresponds to the low temperature range of the amphibolite facies (BARTH, 1962, p. 321), which suggests that the temperatures attained during metamorphism were between 400° and 500° C. (RAMBERG, 1952, p. 156; BARTH, ibid.) at depths between 12 and 15 km. These conditions of metamorphism for granitic gneiss at Vrådal are in accord with those postulated by BARTH (1956, p. 32) for "ordinary gneisses" of southern Norway.

Quartzite

Although Precambrian quartzite of the Seljord group crops out over large areas in north and central Telemark, only one narrow strip of quartzite is found in the mapped area. It occurs on the northwest slope of Åhomnut where it is wrapped conformably around the northwest margin of the pluton (Pl. 4). The quartzite has been folded locally, sheared, and deformed by plastic flow and recrystallization into sill-like lenses that thicken and thin in short distances. Locally, the thinning is so extreme that the lenses are pinched into large boudins, the longest axes of which lie in the plane of the foliation; their shape and orientation in three dimensions could not be accurately determined.

The quartzite is composed essentially of quartz (94%), white mica (6%), and accessory amounts of biotite, chlorite, plagioclase, magnetite apatite, sphene, zircon, and tourmaline. The texture of the rock is allotrimorphic-granular.

The quartz grains are typically large (3 to 5 mm) with polygonal outlines and serrate borders. Deformation lamellae and undulatory extinction are evidence of post-crystallization strain of the grains, and their optic axes appear to be strongly oriented as shown by examination with a gypsum plate. White mica is concentrated in interstitial clots and in thin folia which define a weak foliation. Zircon occurs in subidiomorphic crystals (0.05 mm) scattered randomly throughout the rock. The other accessory minerals are concentrated in infrequent screens and lenses that are parallel to the weak foliation.

The mineral assemblage corresponds with assemblages that are stable in the amphibolite facies.

Amphibolite

Two varieties of amphibolite, massive and schistose, have been distinguished by the writer in the Vrådal area. Massive amphibolite is found only within the pluton where it occurs typically as irregularly-shaped bodies that vary upward in size from those of a hand specimen to mappable units. Locally, near the margin of the pluton, it grades into schistose amphibolite across distances of 10 to 20 m. Schistose amphibolite occurs chiefly as long, slender lenses that wrap concordantly almost completely around the pluton (Pl. 4), and as smaller lenses in porphyric granite. The two varieties of amphibolite are described separately, owing to fundamental differences in texture and in probable tectonic significance.

Massive amphibolite

Massive amphibolite is a fine- to medium-grained rock composed essentially of plagioclase (42%), hornblende (10%), biotite and chlorite (20%), quartz (12%), and microcline (8%). Accessory minerals include magnetite (2%), sphene (4%), apatite (1%), and trace amounts of zircon, fluorite, and epidote. Up to three percent epidote occurs locally.

Near outcrops of porphyric granite the massive amphibolite is characterized by a mottled or speckled appearance, owing to partial aggregation into clots of the mafic minerals which are separated by microcline and quartz. At distances from 10 to 50 m from contacts with porphyric granite the mottled aspect is not readily apparent,

and there is a marked decrease in the modal content of quartz and microcline in the rock.

Massive amphibolite has relict diabasic texture in thin section and exhibits granophyric intergrowths of microcline and quartz. Plagioclase (An_{28-34}) occurs in subhedral lathshaped crystals (0.1 to 1 mm long) that are almost completely sericitized so that polysynthetic twinning is nearly obliterated. A few large, relatively fresh crystals, however, show strong oscillatory zoning in sections parallel to {010.} Hornblende (Z, Y = green, X = light yellow green: $Z \wedge c = 21°$) occurs in raggedly-shaped laths, but euhedral outlines are common in sections cut normal to the *c*-axis. Biotite (Z, Y = light green, X = light yellow brown) occurs in ragged or subhedral laths. In many specimens, Fe-rich chlorite, which exhibits a vivid "Berlin blue" interference color, almost completely replaces hornblende and partially replaces biotite. In other specimens chlorite is sparse or not present. Subhedral crystals of apatite, sphene, and magnetite up to 3 mm long often occur in local segregations or clots together with biotite and hornblende. Microcline occurs interstitially and in large subidiomorphic megacrysts that are typically mantled by a thin envelope (1 to 2 mm wide) of oligoclase (An_{15-18}). Interstitial microcline exhibits sharp grid twinning that is dominated by the pericline law; the megacrysts are also twinned according to the Carlsbad law. Obliquity ($\triangle$) values of the megacrysts are nearly maximum. Almost every megacryst contains dimensionally oriented inclusions that are arranged geometrically in a peripheral zone parallel to crystal faces (Pl. 1, b). Plagioclase is the most common included mineral, but biotite, white mica, hornblende, and pyrite have been observed.

A characteristic feature of the massive amphibolite is the presence of roughly spherical bodies composed of one or more grains of quartz that are generally rimmed with small tabular hornblende crystals (Pl. 1, a). These are similar to, and are probably, amygdules. DONS (1960 a, p. 20) suggests that outcrops of massive amphibolite near Snaunes on Kviteseidvatn are former lavas, and he tentatively correlates these rocks with basic lavas of the Bandak series which are amygdaloidal and have diabasic texture (Dons, personal communication, 1963).

The mineral assemblage, biotite-hornblende-oligoclase-epidote, which is characteristic of the massive amphibolite, corresponds to the

oligoclase-epidote amphibolite subfacies of the epidote-amphibolite facies (BARTH, 1962, p. 319). Partial replacement of biotite and hornblende by chlorite indicates that the rocks have probably undergone retrograde metamorphism.

Schistose Amphibolite

The schistose amphibolite is distinguished from the massive amphibolite by the strong planar orientation of biotite flakes and hornblende needles and plates. The rock occurs chiefly in discontinuous lenses that almost completely encircle the pluton (Pl. 4), and in smaller isolated lenses in the granite. The schistosity of the rock is concordant with the granite contact except where it has been deformed into sheared folds.

The schistose amphibolite is a fine-grained rock with lepidoblastic texture. It is composed essentially of plagioclase (55%), hornblende (35%), biotite (10%), and minor amounts of apatite and magnetite. Quartz (~2%), microcline (~3%), epidote (~2%), and white mica (~0.5%) have been observed in a few specimens.

Plagioclase (An_{28-32}) occurs in equant xenomorphic crystals which are commonly sericitized to such a degree that twinning is usually obliterated. Hornblende (Z, Y = light green, X = pale green; $Z \wedge c = 20°$) occurs in raggedly terminated prisms bounded by {110}. Biotite (Z, Y = light brown or light olive green, X = light yellow) is partially altered to chlorite. Quartz is elongated in the plane of the schistosity. It commonly exhibits undulatory extinction and deformation lamellae that are evidences of post-crystalline strain.

The mineral association, hornblende-plagioclase, is characteristic of the amphibolite facies (BARTH, 1962, p. 321). The fact that epidote is not usually present in the schistose amphibolite places the rock a little higher in the amphibolite facies than massive amphibolite in which epidote is rather common.

In outcrops and roadcuts along Kviteseidvatn one can readily observe the transition of massive amphibolite to schistose amphibolite by progressive intensification of the schistosity and the decrease of epidote. The field relations indicate that the two map units of amphibolite were originally the same kind of rock and are different now only because of different tectonic histories.

Granitic Rocks

The granite of the Vrådal pluton is subdivided into two mappable units for this study on the basis of texture: (1) equigranular, medium-grained granite which is nearly void of K-feldspar megacrysts (hereafter called quartz monzonite), and (2) coarse-grained porphyric granite that is characterized by K-feldspar megacrysts (porphyric quartz monzonite). The two varieties of granite are described separately owing to their textural differences and field distribution.

Quartz Monzonite

Quartz monzonite comprises the central portion of the pluton (Pl. 4), and good exposures are found in road cuts near Ekrestøyl and Diplan. Locally, dikes of quartz monzonite cut both varieties of amphibolite. Abundant dikes of quartz monzonite occur in the granitic gneiss about one kilometer south of the pluton near Steane, but it is not known if they are definitely related to the rocks of the pluton.

The quartz monzonite is a medium-grained equigranular rock that is composed essentially of plagioclase (40%), microcline (35%), quartz (20%), and biotite (5%). Nine modal analyses of the rock are plotted on QMF and Q-Pl-Or diagrams (Fig. 3). The characteristic accessory minerals are sphene, apatite, magnetite, and zircon. Orthite, chlorite, fluorite, and molybdenite are often observed in the rock. The texture is hypidiomorphic-granular. A characteristic feature of the rock is the presence of fresh or partly digested mafic xenoliths. Many of these are probably fragments of massive amphibolite.

Plagioclase (An_{13-19}) occurs in subhedral tabular crystals that vary in length from 0.1 mm to 3 mm. The crystals exhibit oscillatory zoning and are twinned according to the albite law. Their borders are rimmed by albite where they are in contact with microcline. The plagioclase is commonly partially or completely sericitized. Microcline occurs in nearly equant anhedral or subhedral grains that vary in diameter up to 3 mm, and exhibit both diffuse and sharp types of grid twinning. It is commonly perthitic; film and patch perthite are typical. Biotite (Z, Y = greenish brown, X = light tan) occurs in raggedly-terminated lath-shaped crystals (0.1 to 2 mm long) that are partially or completely altered to chlorite. Zircon is commonly included in biotite, and is surrounded by pleochroic haloes. The accessory

minerals occur in subhedral and euhedral crystals that vary in size up to one millimeter. They are observed typically in close association with biotite. Orthite occurs in subhedral crystals that are less than one millimeter long. It is not a common mineral in the rock and appears to be secondary. Fluorite and molybdenite are readily observed in hand specimens and typically occur together. Their spatial distribution in the pluton has not been defined.

The quartz monzonite is commonly foliated in the peripheral zone of the central mass of the granite, but in the center of the pluton around Honlivatn the foliation is weak or not recognizable. It is defined by the parallel orientation of biotite flakes.

The quartz monzonite dikes in the massive amphibolite are commonly less than one meter wide. Textural and mineralogic variations within the dikes were not observed, but the host rock appears to have been granitized slightly at the contact as a result of their emplacement. The geologic and genetic relationships of quartz monzonite with other rocks in the pluton, however, are not well known at this time and await future detailed study.

Porphyric Quartz Monzonite

The porphyric quartz monzonite is perhaps the most interesting feature of the Vrådal pluton. It occurs chiefly in a subcircular ring that surrounds the central mass of quartz monzonite (Pl. 4), and "puddles" of porphyric quartz monzonite dot the peripheral zone of the quartz monzonite core. The "puddles" are irregularly-shaped masses that vary from 5 m to 20 m across their longest dimension. A few concordant lenses of porphyric quartz monzonite, about 20 m long and one meter wide, occur locally in granitic gneiss near the main body of the pluton, particularly on Högöy and on the island near Slokvik. The horn-shaped lens of porphyric quartz monzonite north of the pluton (Pl. 4) is the largest mass of granite outside the pluton.

The most characteristic feature of the porphyric quartz monzonite is the parallel orientation of {010} of large microcline megacrysts and smaller tabular plagioclase crystals, which defines a coarse foliation in the rock (Fig. 4). The plane of the foliation is concordant with the contact between the granite and the country rocks. The microcline megacrysts are slightly more resistent to weathering than the other minerals in the rock so that, coupled with their dimensional orienta-

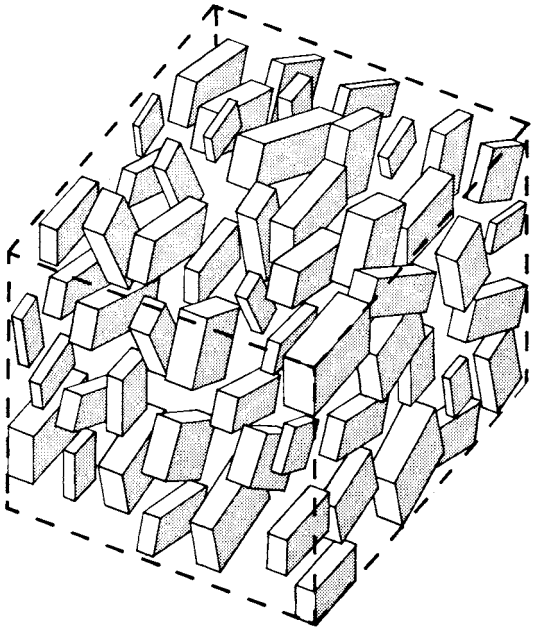

Figure 4. Schematic orthographic projection of a block of porphyric quartz monzonite demonstrating the planar fabric as defined by the parallelism of {010} (shaded faces) of microcline megacrysts. The fabric was determined by study of the orientation of Carlsbad twin planes and of the cleavage planes.

tion, the megacrysts on weathered surfaces resemble trains of caterpillars.

The porphyric quartz monzonite is a coarse-grained rock composed essentially of microcline (35%), plagioclase (30%), quartz (25%), and biotite (5%). The accessory minerals, sphene, magnetite, and apatite, comprise the remaining five percent. Sixteen modal analyses of this rock are plotted on QMF and Q-Pl-Or diagrams (Fig. 3). Orthite, epidote, zircon, fluorite, and white mica are present in minor amounts. The texture is hypidiomorphic-granular; biotite and accessory minerals are typically segregated in glomeroporphyritic clots.

Microcline (Or_{80-90}) occurs in anhedral patches (0.1 to 1.0 mm in diameter) and in subhedral and euhedral megacrysts that vary in length from 2 mm to 5 cm. Their obliquity ($\triangle$) values are nearly maximum. The grid twinning is typically sharp. Film, vein, and patch perthite are common in the megacrysts. Dimensionally oriented inclusions occur typically in the larger megacrysts; they are described more fully below. Plagioclase (An_{13-20}) occurs in subhedral tabular crystals that vary in size up to 10 mm. They are twinned according

to the albite law, and some crystals exhibit different orientations of twin lamellae within a single individual. Oscillatory zoning has been observed in only a few plagioclase crystals. More frequent, however, is the observation that the cores of some of the crystals are more sericitized than their peripheral zones. The margins of plagioclase crystals are composed of albite where they are in contact with microcline. Large plates of white mica locally replace highly sericitized plagioclase grains. Quartz occurs in anhedral crystals that vary in size from 0.1 mm to 5 mm. They are dusted with minute inclusions and possess linear trains of bubble inclusions. The quartz grains are invariably highly strained, showing extreme undulatory extinction and well-developed deformation lamellae. Many of the crystals are cracked but not granulated. Biotite (Z, Y = greenish brown, X = light brown) occurs in raggedly-terminated, lath-shaped crystals up to 2 mm long. Pleochroic halos are observed around zircon and apatite crystals that are included in the biotite. Locally, biotite is partially or completely altered to Fe-rich chlorite. Sphene, apatite, and magnetite occur in subhedral and euhedral crystals that vary in length up to 2 mm. Sphene tends to be slightly pleochroic. Orthite occurs in euhedral crystals up to one millimeter long and exhibits faint pleochroism. Epidote (Z, X = light yellow green, Y = colorless) occurs in anhedral crystals up to 0.5 mm in diameter that occur chiefly with the mafic and accessory minerals and along cleavage planes in biotite. Zircon occurs in subhedral crystals up to 0.2 mm long in minor amounts in all specimens of porphyric quartz monzonite. Anhedral crystals of fluorite occur sporadically in the clots of mafic and accessory minerals.

The color of the granite depends on the color of quartz and K-feldspar. Quartz is frequently "smoky" or light grey and imparts a dark or mafic aspect to the granite. K-feldspar is typically pale pink, but in proximity to faults it is brick red, owing, evidently, to exsolution of iron from the crystal lattice (BARTH, personal communication, 1962).

A common feature of the K-feldspar megacrysts is the numerous small plagioclase inclusions that are dimensionally and crystallographically oriented in peripheral zones parallel to crystal faces of the host. They exhibit polysynthetic twinning which is in optical continuity with that in the vein perthite. Their composition (An_{15-18}) is about the same as that of the plagioclase in the groundmass, and each

grain is mantled with an envelope of albite. Small laths of biotite are included in the megacrysts less frequently than plagioclase, but they, too, are dimensionally oriented parallel to crystal faces. Several writers (i.e., MAUCHER, 1943; FRASL, 1954; SCHERMERHORN, 1956; DIETRICH, 1961; BATEMAN *et. al.* 1963) regard the oriented inclusions as evidence that the host (and, thus, the granite) crystallized in a fluid medium, wherein groundmass plagioclase crystals were absorbed on the faces of growing K-feldspars and were rotated into dimensional conformity as the host continued to grow. But when the oriented inclusions are observed in K-feldspars that occur isolated in country rocks (e.g., Pl. 1, b), various writers have had to invoke a metasomatic process which rotates the inclusions in the solid state (DRESCHER-KADEN, 1948; RAMBERG, 1962; SMITHSON, 1963b, p. 127—130).

One of the features of the porphyric quartz monzonite which was first reported by DONS (1960a, p. 20) is the presence of large K-feldspars that are mantled by a thin envelope of plagioclase (An_{18}). They occur only where porphyric quartz monzonite is in contact with massive amphibolite. A short description and an hypothesis for the origin of these features has been put forward by SYLVESTER (1963). Other works bearing on mantled K-feldspars that must be mentioned are the studies of GATES (1952) and STEWART (1959).

Mafic xenoliths are common in the quartz monzonite, but not in the main body of porphyric quartz monzonite. Discrete spindle-shaped xenoliths of massive amphibolite are abundant in porphyric quartz monzonite, however, in the contact zone of the granite near Lindestad and Kleivhamar (Pl. 2, a). The longest axes of the xenoliths plunge vertically, and the weak foliation of each individual appears to vary slightly in attitude from that of its neighbors. These relations are similar to features observed near granite contacts in the Sierra Nevada, California (BATEMAN, *et. al.* 1963). There the mafic xenoliths have been deformed into triaxial masses; the longest axis is parallel to the direction of transport in the granite, and the shortest axis is parallel to the direction of lateral expansion in the pluton. According to BALK (1949, p. 1818), oriented xenoliths in granites are analogous to oriented anhydrite crystals in salt domes. He notes that the crystals exhibit strong vertical lineation, which is parallel to the direction of maximum flow within the salt diapir. Thus, it may be concluded that the mafic xenoliths in the porphyric granite at Vrådal

are probably of protoclastic origin and were deformed slightly and oriented by the granite during its emplacement.

Composition of the Granite

Modes of sixteen specimens of porphyric quartz monzonite, eight specimens of quartz monzonite, and nine specimens of granitic gneiss are plotted in Q-Pl-Or and QMF diagrams (Fig. 3). The data show that the granite is richer in K-feldspar than the granitic gneiss, and that the quartz monzonite is a little richer in plagioclase than porphyric quartz monzonite. But even more important than the slight differences among the rocks is the rather close correspondence in their modal compositions. The modes of granitic rocks of the Vrådal pluton also correspond closely to those of New England granites (CHAYES, 1952) and the Flå granite (SMITHSON, 1963). The conclusions that can be drawn from these facts are discussed below.

Contact Relations

Contacts between the granite and the country rocks are sharp locally, but they are commonly gradational zones that vary in width from a few centimeters to several tens of meters. Contact breccias are not common, except as mentioned above (p. 464) where porphyric quartz monzonite is in contact with massive amphibolite at Lindestad and Kleivhamar. There is no evidence of a contact metamorphic aureole in the country rocks around the pluton, nor does grain size in the granite diminish at contacts.

The contact between granite and massive amphibolite in the central portion of the pluton is commonly a gradational zone from 5 to 30 m wide. At first the zone is characterized by the appearance of a few microcline megacrysts that occur as isolated individuals or in small aggregations in the massive amphibolite (Pl. 3, a). Then as one proceeds across the zone toward porphyric quartz monzonite, various-sized domains of massive amphibolite are segregated by a lacy network of granitic material and numerous microcline megacrysts (Pl. 3, b). In the part of the contact zone nearest the main body of the porphyric quartz monzonite the domains of massive amphibolite are so isolated by feldspathic material that they may be called xenoliths (Pl. 3, c). Finally, all that remains of the mafic xenoliths in porphyric

quartz monzonite several meters from the contact zone are diffuse, ghost-like relicts comprised of mafic minerals, chiefly biotite and magnetite. These relations demonstrate clearly the effects of local granitization and selective replacement of massive amphibolite (BATEMAN, *et al.* 1963), and they are in accord with the predictions of TUTTLE and BOWEN (1958, p. 91—93) for the reaction effects beween a hydrous two-feldspar granite and amphibole-bearing rocks.

Schistose amphibolite appears to have been more resistent to granitization than the massive variety. Its contacts with granite are generally sharp, even where it occurs as isolated lenses in porphyric quartz monzonite. Locally, the schistose amphibolite may contain a few sporadically distributed K-feldspar megacrysts. METZGER (1947) postulated that amphibolite and marble acted as physical and chemical barriers to the advancement of anatectic granitic material in the Finnish Precambrian. The field relations around the northern contact of the Vrådal pluton suggest that schistose amphibolite and quartzite have played a similar role in containing the Vrådal granite.

The contact between quartz monzonite and porphyric quartz monzonite is gradational and irregular. Its delineation is hampered by vegetation and by the diffuse "puddles" of porphyric quartz monzonite that occur so frequently in the quartz monzonite. Exposures were not found where the temporal relations between the two varieties of granite could be established with confidence, although outcrops were carefully scrutinized for clues. The gradational contact, however, suggests that the two phases of granite probably formed contemporaneously.

PEGMATITE AND APLITE

Veins of coarse pegmatite are common throughout the area, particularly in the granite. They vary in width up to 3 m, and up to 50 m in length.

The essential minerals of the pegmatites are microcline, sodic oligoclase, and quartz; biotite and white mica are locally abundant. Large amphibole crystals (about 5 cm long) occur in the veins where they cut massive amphibolite. The microcline crystals may be quite large (greater than 45 cm in length) and are white, pink, brick red, or pale green. Other minerals that are present locally and in minor amounts

include garnet (probably spessartite), magnetite, sphene, pyrite, chalcopyrite, and bornite. Patches and crystals of fluorite, as much as 10 cm in diameter, are found in some of the larger pegmatite veins. A few such veins near Bergstöyl were mined for molybdenite during the First World War. Masses of molybdenite as much as 30 cm in diameter are reported to have been found, but most were not larger than 3 or 4 cm.

Aplite dikes are very common in the granite, but they are too small and too numerous to show on the map. Individual dikes may be as long as 10 m and are rarely more than 20 cm wide. They are comprised chiefly of quartz, microcline, plagioclase, and a little biotite and fluorite.

Structure of the Pluton

Macroscopic structure

The areal distribution of granite and country rocks describes a pattern of nearly concentric rings (Pl. 4). Contacts and foliations of the rock units dip toward the center of the pluton so that its structure in three dimensions corresponds to a steep-sided funnel. The wall of the "funnel" is the porphyric quartz monzonite around which schistose amphibolite and quartzite are concordantly wrapped. Massive amphibolite is distributed randomly in the quartz monzonite core and locally transects the wall of the "funnel".

Field observations show that the foliation of the granitic gneiss is largely horizontal over a large area around the pluton (Fig. 5 and Pl. 4). At distances of about one to three kilometers from the contact, however, the foliation is inclined gently toward the center of the pluton. As the contact is approached the dip increases gradually to steep or vertical attitudes that are conformable with the granite contact. Although the low relief in this zone of tilted foliation and the lack of distinct lithologic units in granitic gneiss do not permit a confident determination of the structure at depth, it is likely that the country rocks are warped into a rim syncline, the axial surface of which is inclined steeply toward the center of the pluton (Fig. 6).

Geophysical investigations have shown that rim synclines, or peripheral sinks (PARKER and MCDOWELL, 1955), occur typically around salt diapirs (*e.g.*, NETTLETON, 1943; BALK, 1953; WEBER, 1956; and TRUSHEIM, 1960). That such a syncline forms as a result of the empla-

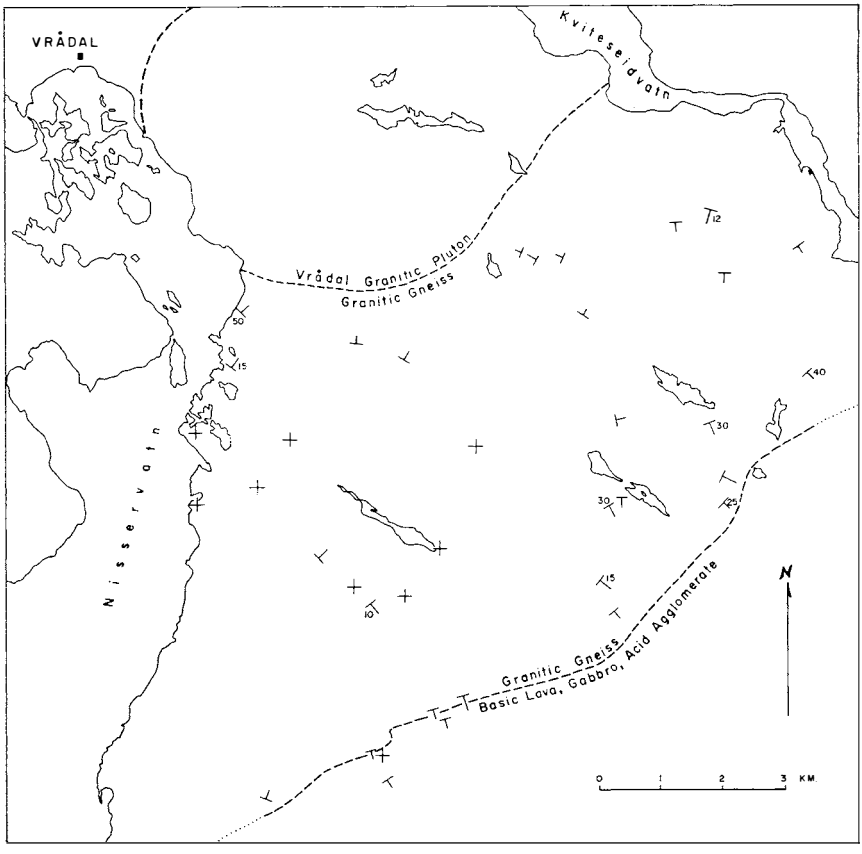

Figure 5. Sketch map of attitudes of the foliation of granitic gneiss south of the Vrådal pluton (after S. Foslie, unpublished map of the Nisser Quadrangle). In general, a short dip symbol indicates a steep dip for those which are not plotted with a numerical value. A "plus" symbol indicates a horizontal attitude.

cement of the diapir has been demonstrated experimentally by NETTLETON (1934), PARKER and MC DOWELL (*op. cit.*) and RAMBERG (1963). By means of centrifuged scale-models Ramberg has shown (1) that initially horizontal strata are dragged into conformity along the surface of the rising material, and a peripheral syncline forms as a result; (2) that the amplitude of the peripheral syncline increases with depth; (3) and that a peripheral syncline is more symmetrical and better developed if the rising material behaves as a plastic mass rather than

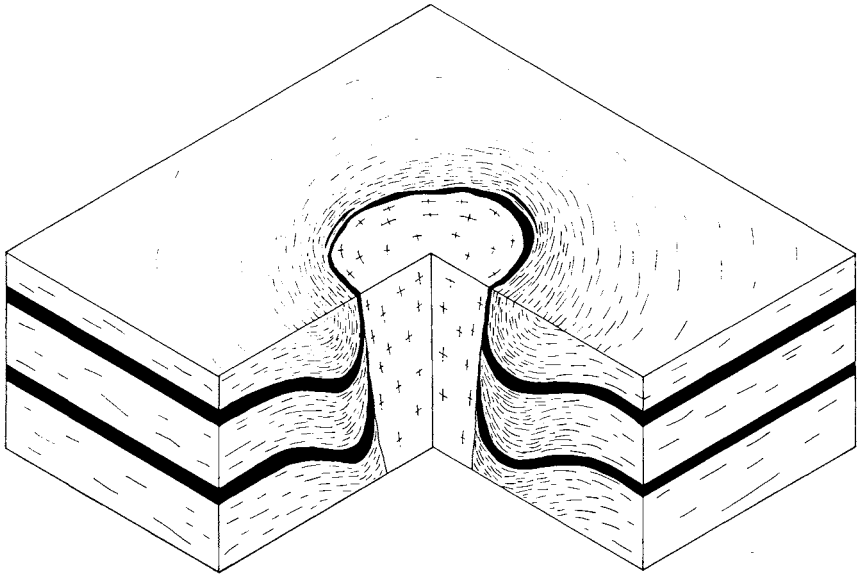

Figure 6. Schematic representation of the relationship of the Vrådal pluton to its country rocks (compare with Pl. 4). A rim syncline in the country rocks is indicated by the folded amphibolite (black) and granitic gneiss. The foliation of the granitic gneiss is most pronounced near the pluton and is weak or indistinct from two to three kilometers from the contact.

a fluid. Now, if a granitic pluton is emplaced as a mobilized plastic mass analogous to the emplacement of salt diapirs, it is reasonable to suppose that a synclinal structure would be produced in the surrounding country rocks (WEGMANN 1930; RAMBERG, *op. cit.*) This hypothesis is favored by the present writer for the interpretation of the structure at depth of the country rocks around the Vrådal pluton, but more detailed studies are needed for confirmation.

The random distribution of the large bodies of massive amphibolite in the pluton and the resemblance of the rock to basic lavas suggest that the bodies may be stoped blocks or roof pendants of supracrustal rocks which are now partially granitized. It is tempting to conclude from a cursory glance at the areal distribution of schistose amphibolite that it is the vestige of a ring dike. The fact that it is conformable to the quartzite and foliation of granitic gneiss, however, suggests that it may have been a flow or a sill that was folded with the other rocks

into conformity with the pluton's contact (Fig. 6). The evidence, however, is not conclusive, and more detailed field observations are needed. Its schistosity is probably derived from differential movements between the pluton and its country rocks during the emplacement of the granite (BUDDINGTON, 1959, p. 734).

Faults and Joints

Steeply-dipping shear fractures radiate from the center of the pluton and extend short distances into the country rocks (Fig. 1). Several of these have been located approximately on the geologic map (Pl. 4) from interpretation of aerial photographs, owing to poor exposures in the field. Detailed mapping along some of these fractures demonstrates that differential movement has occurred, but it was not possible to determine the amounts or senses of the displacements.

WEGMANN (1930, p. 62) and KAITARO (1956, p. 63) suggest that a radial fracture pattern would be developed over a small pluton that is emplaced in a deep-seated environment. Once the pluton begins to rise, the overlying rock mass would move aside by gravitation. This would be a slow process, owing to the low compressibility of the country rocks. Radial compressive stress and tangential tension, caused by the emplacement of the body, would be relieved by radial tension fractures and faults. Only if the emplacement was very sudden and forceful would a pattern of ring fractures be developed, because the strain would relax in the upward direction (ANDERSON, 1936). The theoretical aspect of radial fractures is also discussed by BELOUSSEV (1962, pp. 557—559), who concludes from experimental evidence that such a fracture system would be produced in a sheetlike mass that is deformed by a slow, upward-rising mass. One might expect that the fractures would extend into the granite as soon as it was solid enough to transmit shear stresses. Movement along the fractures may have occurred in response to increments of late upward movement in the nearly solid pluton.

A set of long subparallel faults, which are parallel to the longest axis of Kviteseidvatn, cuts the northeastern portion of the pluton. They dip steeply toward the lake; striations on the fault surfaces plunge at steep angles. The amount and sense of the relative displacement on the faults could not be determined, but from a geomorphic standpoint, it appears that they are normal faults with a relative dis-

placement of at least a few hundred meters. The faults strike nearly parallel to regional alignments and bear no apparent structural relationship to the pluton. It is concluded, therefore, that they are probably of late generation (Tertiary?) and that they have no tectonic significance with respect to emplacement of the pluton.

Conjugate sets of near-vertical joints are conspicuous in the porphyric quartz monzonite, particularly on the summits of the higher peaks where they are not obscured by vegetation. The joints appear to be related to the radial shear fractures and may have been caused by a horizontal couple induced by the tensional fracturing (BILLINGS, 1954, p. 119).

Minor Folds

The schistose amphibolite and quartzite show evidence of strong deformation near the pluton in the form of sheared isoclinal folds whose maximum amplitude is about one meter. The axes of the folds are steeply inclined, and their axial surfaces are concordant to the contact with the pluton. The similarity of these folds to those described by BALK (1949, 1953) that occur around salt diapirs is striking, and it is possible that a detailed systematic study of them will shed much light on the kinematics of the granite during its emplacement.

Small folds occur in granitic gneiss only in a small area near Sandviki (Pl. 2, b). The foliation in the granite is not folded.

Emplacement of the Pluton

Temperature and Depth of Emplacement

It is usually not possible to determine the crustal level of emplacement of a particular body of granite in a deeply eroded Precambrian basement complex. If an approximation of its emplacement temperature can be made, however, one may estimate the depth, depending on the choice of geothermal gradient.[2] The granitic gneiss and schistose amphibolite that surround the Vrådal granite exhibit mineral

[2] TUTTLE and BOWEN (1958, p. 118) state that "thermal gradients of 50° C/km are rare, gradients of 40° C/km are common, and gradients in the vicinity of 30° C/km are most common." For the purposes of this discussion, the minimum value is used.

assemblages characteristic of the lower metamorphic grades of the amphibolite facies, which corresponds to a temperature range of 400° to 500° C. (RAMBERG, 1952, p. 167) and a depth between 12 and 15 km. BARTH (1956) has shown that the temperature of some discrete granite bodies in southern Norway was about 550° C. These granites are similar to the Vrådal granite with respect to size, shape, structure, composition, and age. It seems reasonable to assume, therefore, that the temperature of the Vrådal granite was also about 550° C. when it was emplaced in rocks with temperatures between 400° and 500° C. Now the fact that there is no contact aureole around the Vrådal pluton suggests that the granite and its country rocks were in approximate thermodynamic equilibrium when the granite was emplaced, and indeed, it does not seem likely that contact metamorphic effects would be important or even evident with a temperature differential of only 50° to 150° C.

Other clues to the depth and temperature come from the radial shear fractures in the Vrådal pluton and the nature of perthite in the K-feldspar of the granite. WEGMANN (1930) and KAITARO (1956) postulate that a radial fracture pattern in a small pluton is favored by the high load pressure of a *thick* section of rocks overlying the pluton. ROSENQVIST (1950) maintains that vein and film perthite, types that are common in the Vrådal K-feldspars, form at temperatures between 450° and 650° C. These conditions of emplacement are in accord with those determined by BARTH (ibid.) for granites in southern Norway that are similar to the Vrådal granite.

Thus the estimated temperature and depth of emplacement of the Vrådal granite, as well as many of its geologic features, indicate that it was emplaced in the upper catazone or lower mesozone according to the depth zone classification of BUDDINGTON (1959).

Mode of Emplacement

Any hypothesis that satisfactorily accounts for the origin and emplacement of the Vrådal granite must take several facts into consideration. These are listed in Table 2 together with the conclusions and deductions that seem reasonable in light of the field and laboratory observations. A lengthy discussion of the various interpretations that other writers have invoked to explain similar features in other granites is not attempted here. Instead the reader may draw his own conclusions

Table 2. A list of facts with the conclusions and hypotheses that can be drawn therefrom.

Facts	*Conclusions and Hypotheses*
The foliation and areal distribution of granite and country rocks exhibit almost ideal axial symmetry.	The symmetry of the pluton probably reflects the symmetry of its movements during emplacement.
The geometry of the pluton in three-dimensions resembles a steep-sided funnel.	Funnel-shaped granitic plutons are thought to have a diapiric mode of emplacement.
The foliation of the granitic gneiss is nearly horizontal over a large area around the pluton, but nearby it is gently inclined toward the pluton and steepens gradually as the contact is approached; at the contact the dip of the foliation is steep and conformable with the foliation of the granite.	The granitic gneiss has evidently been warped into a rim syncline by the emplacement and lateral expansion of the pluton.
Schistose amplibolite and quartzite are folded, sheared, and drawn into lenses and boudins around the periphery of the pluton, but granitic gneiss is not similarly deformed.	Deformation and yielding of the country rocks, which was accomplished by folding and shearing, was most intense at the periphery of the pluton.
Spindle-shaped xenoliths of massive amphibolite occur locally in the contact zone around the pluton with their longest axes oriented vertically.	The country rocks were brecciated locally, and the fragments were oriented as a result of the differential movement between the pluton and the country rocks.
The mineral assemblages of the country rocks correspond to the amphibolite facies.	The country rocks were metamorphosed at a depth between 12 and 15 km, and at temperatures between 400° and 500° C.
The country rocks do not exhibit evidence of chemical reactions resulting from contact metamorphism by the granite.	The granite was in approximate thermodynamic equilibrium with its country rocks during its emplacement.

Table 2, cont.

Facts	*Conclusions and hypotheses*
Near the contact with the granite the foliation in the granitic gneiss is obscure, size and idiomorphism of the minerals decrease, and biotite and plagioclase are altered to chlorite and sericite respectively.	The granitic gneiss may have been partially mobilized adjacent to the granite and was incorporated in the movements of the pluton during its emplacement.
The grain size of the granite does not diminish near contacts.	The granite was in approximate thermal equilibrium with the country rock during its emplacement, so that it did not chill at contacts.
Foliated granite does not show evidence of granulation or mylonitization.	Movement within the granite did not occur after it solidified, except, perhaps, along the radial fractures and faults.
The modal composition of the granite corresponds closely to the minimum-melting composition in the granite system.	The granite may have originated by fractional crystallization or by partial anatexis of older rocks.
The granite can be subdivided into a medium-grained quartz monzonite that is surrounded by a ring of coarse-grained porphyric quartz monzonite.	Growth of large crystals in the peripheral zone may have been favored by a content of water that was higher relative to that in the center of the pluton.
The K-feldspar megacrysts in porphyric quartz monzonite exhibit strong preferred orientation of {010} parallel to the plane of the foliation.	The orientation of the K-feldspar megacrysts may have been influenced by lateral compressive stress of the expanding pluton.
K-feldspar megacrysts enclose inclusions that are geometrically arranged in peripheral zones which are parallel to crystal faces.	Inclusion and orientation of the early-formed grains, and therefore, the growth of the megacrysts, *may* have occurred in an environment in which a liquid phase was present.
Oscillatory-zoned plagioclase crystals are common in quartz monzonite, but are rare in the porphyric quartz monzonite.	Plagioclase in the porphyric quartz monzonite crystallized under conditions approaching chemical equilibrium.

Table 2, cont.

Facts	*Conclusions and hypotheses*
Contacts of granite with other rocks are typically gradational across distances of a few meters.	Partial granitization of older rocks accompanied emplacement of the granite.
The granite is confined by a ring of schistose amphibolite and quartzite.	Schistose amphibolite and quartzite acted as a chemical barrier to the advance of granitic material.
K-feldspar megacrysts, which are characteristic of the porphyric quartz monzonite, occur also in massive amphibolite.	Feldspathization and granitization of massive amphibolite was contemporaneous with growth of K-feldspar megacrysts in porphyric quartz monzonite.
Mafic xenoliths are common in quartz monzonite, but occur only locally in porphyric quartz monzonite as ghost-like relicts.	Mafic xenoliths that were formerly in porphyric quartz monzonite have been granitized.
Large, irregularly-shaped bodies of massive amphibolite that resemble supracrustal rocks in northern and central Telemark occur randomly in the pluton, but they are not present outside the pluton.	The large bodies of massive amphibolite in the pluton represent roof pendants or stoped blocks of supracrustal rocks.
Dikes of granite are not common in country rocks surrounding the pluton.	Lithostatic pressure at the crustal level of emplacement may have been too high for fractures to open which could be filled with granitic material.
The pluton is dissected by a pattern of shear fractures and faults that radiate from its center.	A radial pattern of tension fractures in the overlying rocks extended into the granite after it was almost completely solidified and during the final increments of the upward movements.

about the Vrådal granite from the geologic evidence in light of his own experience; attention is called, however, to the excellent reviews of BUDDINGTON (1959), MEHNERT (1959), WALTON (1960), and SMITHSON (1963b) who compare and contrast many interpretations of features similar to those described in this paper. It does seem expedient,

however, for the present writer to express his own views about the emplacement of the Vrådal granite in a short discussion that makes use of the geologic evidence.

Funnel-shaped bodies of granite are thought to be rare, but those comprised of mafic rocks are relatively common (BALK, 1937, p. 57; BUDDINGTON, 1959, p. 737). GROUT (1945), however, postulates from experimental evidence that granitic plutons of the mesozone may have had feeders from the catazone shaped like salt diapirs with pinched-off roots, and that the lower parts of such bodies should have inward dips. He suggests that geologic evidence for their existence may be found in shield areas and in old, deeply eroded mountain chains. Geophysical studies indicate that the Herefoss granite may have a funnel-shaped feeder, and a diapiric mode of emplacement for the granite has been invoked (SMITHSON, 1963a; ELDERS, 1963). Likewise the Vrådal granite may have been emplaced as a granite diapir, and the present erosion surface probably exposes its mid-section which flared out to a higher, more extensive body of granite.

Now such a granite, whose composition lies near the minimum-melting composition in the granite system, could have originated by fractional crystallization or partial anatexis of older rocks (CHAYES, 1952; TUTTLE and BOWEN, 1958; WALTON, 1960). The latter possibility is more attractive because of the great quantities of granitic rocks in the basement complex of southern Norway. The partial melting may have occurred in the core of a geosyncline (TUTTLE and BOWEN, op. cit.; WYLLIE and TUTTLE, 1960; BARTH, 1961), and then, by means of orogenic forces that may have been associated with uplift of the geosyncline, the newly-generated material was mobilized and began to rise.[3] The driving forces that caused the material to continue to rise were probably lithostatic pressure (GUSSOW, 1962), buoyancy, and orogeny.

[3] The mobilization of granitic material and how it rises are carefully discussed by WEGMANN (1930) and SMITHSON (1963a and b). Wegmann postulates how the material would seek structural weaknesses in the overlying rocks as loci for upward movement, and he suggests what dynamic influences the granite would have on the country rocks. Smithson shows that granites are typically less dense than their country rocks, so that a driving force for the upward movement is obtained. The difference in temperature between the Vrådal granite and its country rocks may have accounted for a density difference during its emplacement.

Finally the mobilized granitic material reached the crustal level now exposed at Vrådal. It is hazardous to guess what the physical nature of the material was before it reached this level,[4] but at Vrådal it appears to have been a viscous mass that was able to shoulder aside and plastically deform its country rocks. Granitization of the country rocks, by means of K-feldspar metasomatism, was locally important. The quantitative importance of the process, however, is difficult to estimate; but the strong deformation of the country rocks suggests that granitization played a role subordinate to the forceful emplacement of a large portion of the granite mass.

The geologic evidence indicates that initially horizontal layers of granitic gneiss and supracrustal rocks were pierced by the granite. At first they were simply dragged upward into conformity by the rising pluton, but as the pluton expanded upward, it also expanded laterally. The lateral expansion of the granite deformed the country rocks further into conformity by means of plastic flow and recrystallization, and it warped them into a rim syncline. Upward expansion of the pluton caused stoping and block foundering of the overlying rocks.

At the contact granitic gneiss was partially mobilized and incorporated in the movements. Schistose amphibolite, which was tightly folded by the lateral expansion of the pluton, was intensely sheared by the differential movements between the granite and its country rocks. Locally, the wall rocks were brecciated, and the fragments were oriented by the rising pluton.

There was also differential movement in the viscous granitic mass between a region of relatively high velocity (the central zone) and a region of lower velocity (the peripheral zone). This gave rise to well-developed concentric foliation in the granite in the peripheral zone. It must have developed before the pluton had solidified completely, because the rocks are not mylonitized or granulated.[5]

The granite first began to solidify completely in the peripheral zone

[4] BARTH (1962, p. 353) summarizes the opinions of several writers about the nature of the anatectic material and how it behaves during the mobilization.

[5] WATERS and KRAUSKOPF (1941) cite brecciation and no contact metamorphism of the country rocks, and granulation and mylonitization of the peripheral zone of the Coleville batholith as evidences that the granite was nearly solid during emplacement.

of the pluton,[6] owing to a negative heat balance (WEGMANN, 1930, p. 65), and water and alkali silicates migrated along intragranular films from the central zone upward and laterally toward regions of lower temperature and pressure.[7] The result was that K-feldspar metasomatism occurred (ESKOLA, 1956; ORVILLE, 1963). Additional K-feldspar may have been derived from the biotite-chlorite transformation in massive amphibolite (CHAYES, 1955). In the presence of water the growth of large crystals was favored (JAHNS, 1962; SMITHSON, 1963b, p. 176), giving rise to the formation of porphyric quartz monzonite. Lateral compressive stress of the expanding pluton before it solidified completely may have played a role in the orientation of K-feldspar megacrysts during their crystallization.

Slow upward expansion of the pluton caused a radial pattern of tension fractures to be formed in the overlying rocks. As soon as the pluton became solid enough to transmit shear stresses, the fractures extended into the granite. Small amounts of differential movement along the fractures might have occurred to compensate for any final increments of upward movement of the pluton.

The original features of the Vrådal pluton have not been modified by any subsequent regional metamorphism. Thus, the final events in the pluton's history, tectonism and Quaternary glaciation and stream erosion, have determined the present level of exposure and the geomorphology.

Summary

Geologic evidence supports the conclusion that the Vrådal pluton should be added to the growing list of late- or post-kinematic granite diapirs that have been emplaced in the Precambrian basement complex of southern Norway. The granite probably originated by partial anatexis, was mobilized by orogeny, and rose as a viscous mass that

[6] HEIER and TAYLOR (1959) postulate from trace element studies that the Grimstad (Fevik) granite crystallized from the peripheral zone inward to the center.

[7] KENNEDY (1955) suggests that water in a magma chamber would tend to migrate to zones of lower temperature and pressure. ORVILLE (1963) shows that alkali transport is dependent upon temperature, and that alkali ions tend to migrate toward regions of low temperature.

warped and dragged the country rocks into conformity with its contact. Upward expansion of the pluton caused stoping and block foundering of overlying supracrustal basic lavas. The peripheral zone of the pluton and narrow zones of country rocks in contact with the granite were modified by K-feldspar metasomatism.

Further work may shed light on the physical nature of the viscous granitic mass, the detailed kinematics of the pluton during its emplacement, and the quantitative aspects of the K-feldspar metasomatism.

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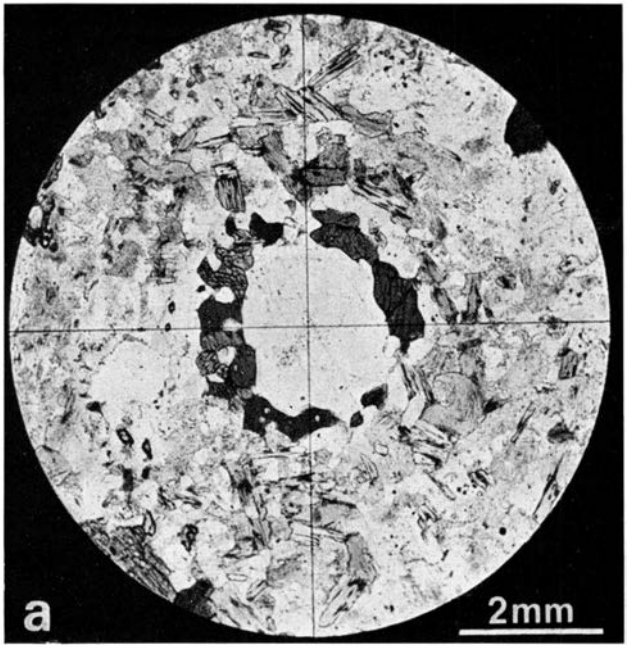
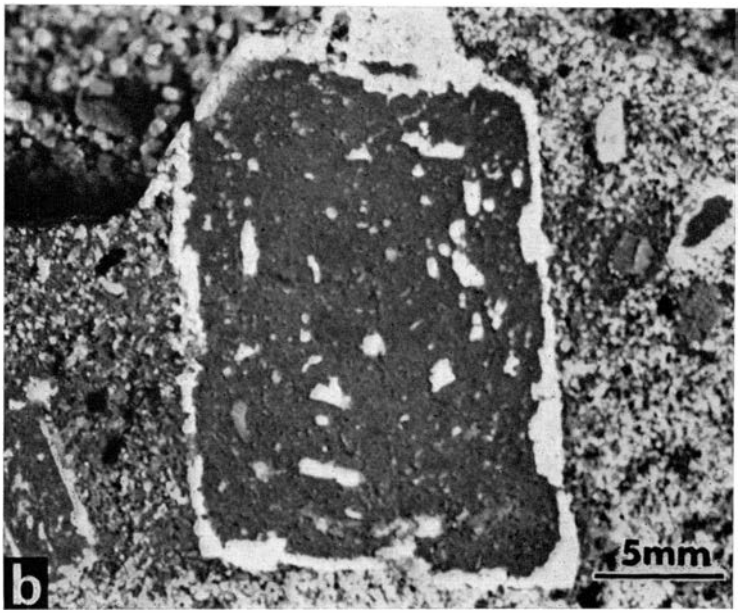
PLATES I—IV

PLATE I

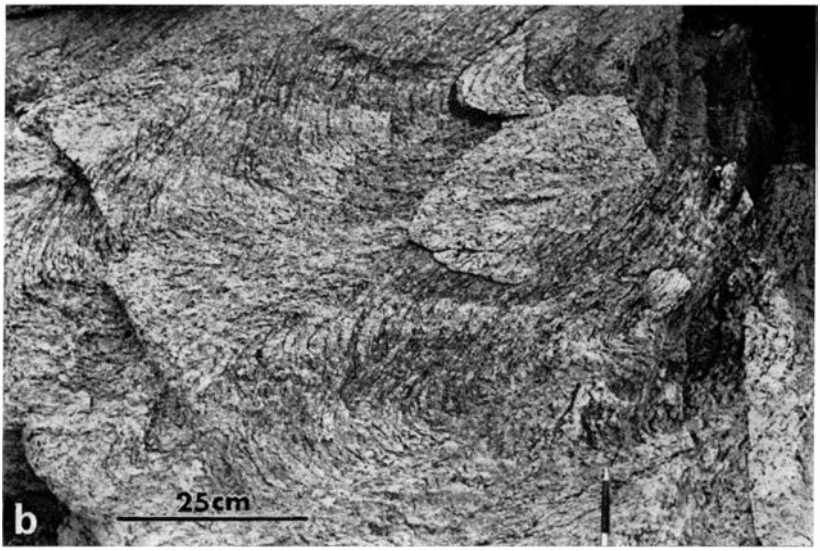


a. Photomicrograph of a quartz grain surrounded by hornblende crystals. These structures are common in massive amphibolite, and they are probably amygdules. Plane polarized light.

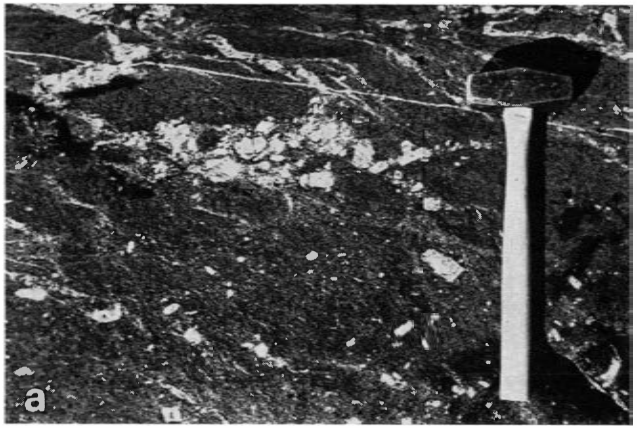


b. Photomacrograph of a massive amphibolite slab containing K-feldspar megacrysts (grey) mantled by an envelope of plagioclase (white). Plagioclase inclusions in the largest individual are dimensionally oriented parallel to crystal faces. The slab has been stained with sodium cobaltintrite solution to distinguish the two feldspars.

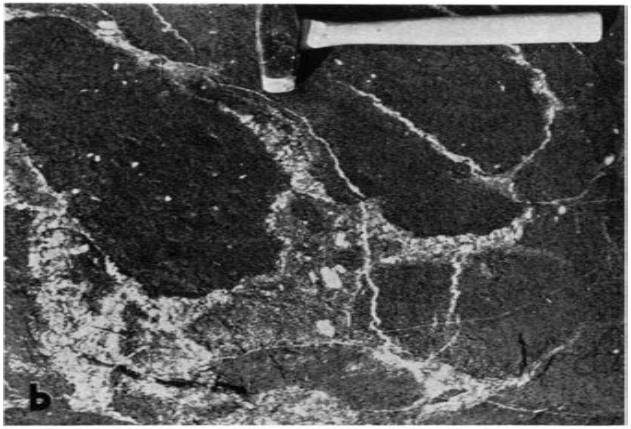
a. Oriented spindle-shaped xenoliths of massive amphibolite in porphyric quartz monzonite in roadcut 100 m southeast of Lindestad. Surface is vertical across the face of the outcrop.

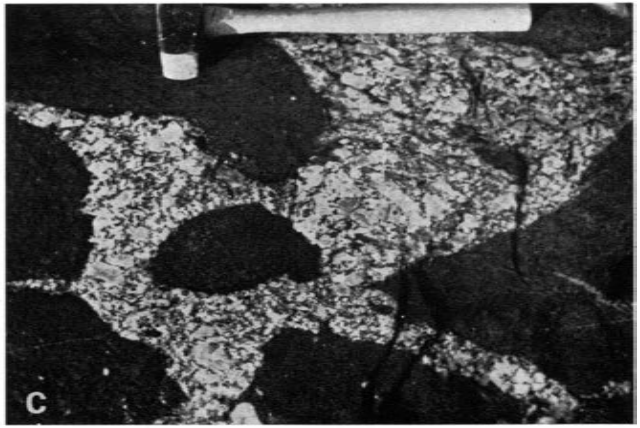


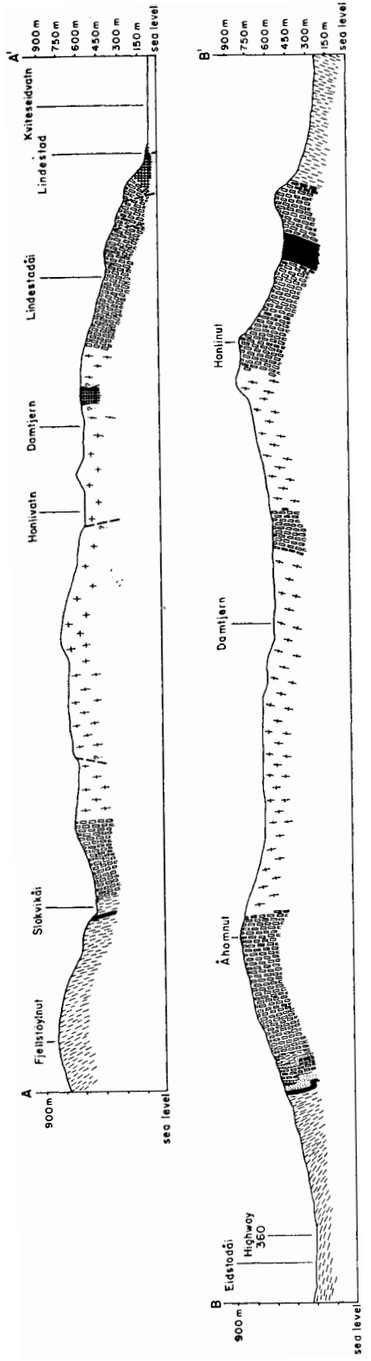
b. Outcrop of highly deformed granitic gneiss in roadcut about 400 m southeast of Sandviki. Small folds are sheared, and the shear planes are filled with pegmatite. Surface is vertical across the face of the outcrop.

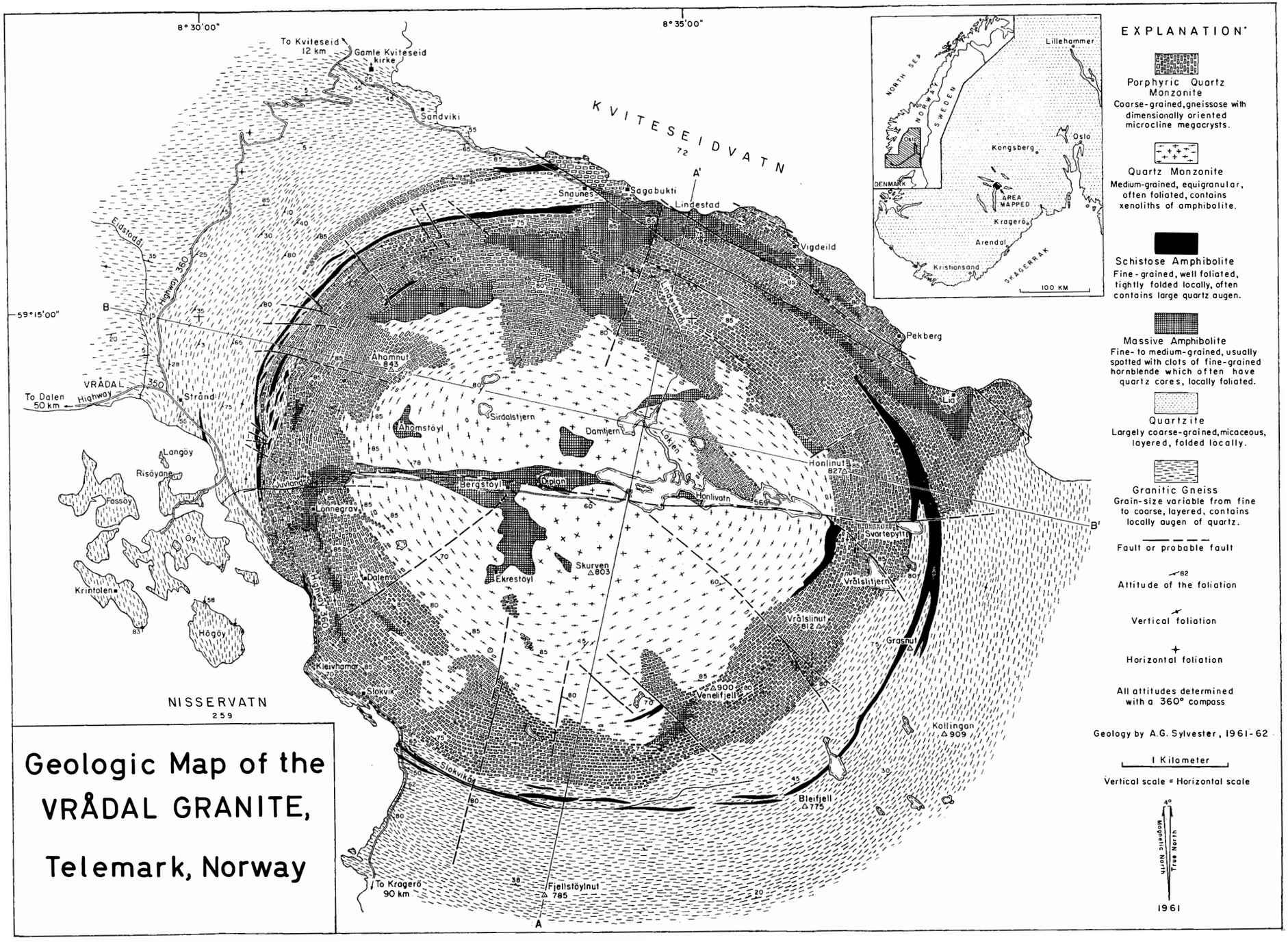


Progressive granitization of massive amphibolite. Photographs were taken at Lønnegrav at a roadcut which crops out continuously from homogeneous massive amphibolite to nearly homogeneous porphyric quartz monzonite. The three photographs show clearly how domains of massive amphibolite are "blocked out" by feldspathic material to the point where they become true xenoliths in porphyric quartz monzonite. All of the microcline megacrysts in this feldspathized zone are mantled by plagioclase feldspar. The surface of each outcrop is nearly horizontal. The length of the hammer is 38 cm.









Geologic Map of the VRÅDAL GRANITE, Telemark, Norway

EXPLANATION

Porphyric Quartz Monzonite
Coarse-grained, gneissose with dimensionally oriented microcline megacrysts.

Quartz Monzonite
Medium-grained, equigranular, often foliated, contains xenoliths of amphibolite.

Schistose Amphibolite
Fine-grained, well foliated, tightly folded locally, often contains large quartz augen.

Massive Amphibolite
Fine- to medium-grained, usually spotted with clots of fine-grained hornblende which often have quartz cores, locally foliated.

Quartzite
Largely coarse-grained, micaceous, layered, folded locally.

Granitic Gneiss
Grain-size variable from fine to coarse, layered, contains locally augen of quartz.

Fault or probable fault

82 Attitude of the foliation

Vertical foliation

Horizontal foliation

All attitudes determined with a 360° compass

Geology by A.G. Sylvester, 1961-62

1 Kilometer

Vertical scale = Horizontal scale