PETROLOGY OF THE VENÅS GRANITE AND THE SURROUNDING ROCKS, EAST TELEMARK, NORWAY

By

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Abstract. Metamorphic rocks of all three groups of the Precambrian Telemark suite occur in the Southern Tinnsjø area, East Telemark, Norway. These rocks have been complexly deformed but there is a tendency for southeast-plunging folds and lineations to predominate. Deformation apparently was accompanied by metamorphism of the rocks to grades ranging from the uppermost part of the greenschist facies to about mid-amphibolite facies of regional metamorphism.

A massive granite body was emplaced by late-or post-kinematic intrusion into the core region of a large southeast-plunging anticline. The presence of disoriented inclusions near the contact suggests that the granite was fluid and mobile during its emplacement. That the intrusion was forceful is indicated by the fact that enormous blocks of quartzite were pushed aside and by the divergence in the attitudes of foliation of the rocks flanking the granite. A systematic application of the two — feldspar geothermometer to a small dome, which forms part of the granite, yielded minimum temperature values ranging from 300° C at the center of the dome to 495° C at the borders. Isotherms were constructed and were found to be arranged more or less concentrically, parallel to the border of the dome. The dome is considered to be a separate diapir within the granite and the inference is made that the Venås granite was emplaced by upward movement of separate diapirs at successive intervals.

The granite has the chemical and mineralogical composition and texture of a "true" granite, except in the border regions where it has been contaminated by reaction with amphibolite and quartzite. Normative Or-Ab-Q distribution in the granite suggests that it originated either by selective fusion of low-melting components of other rocks or by reconstitution of rocks with a bulk chemical composition similar to that of the granite.

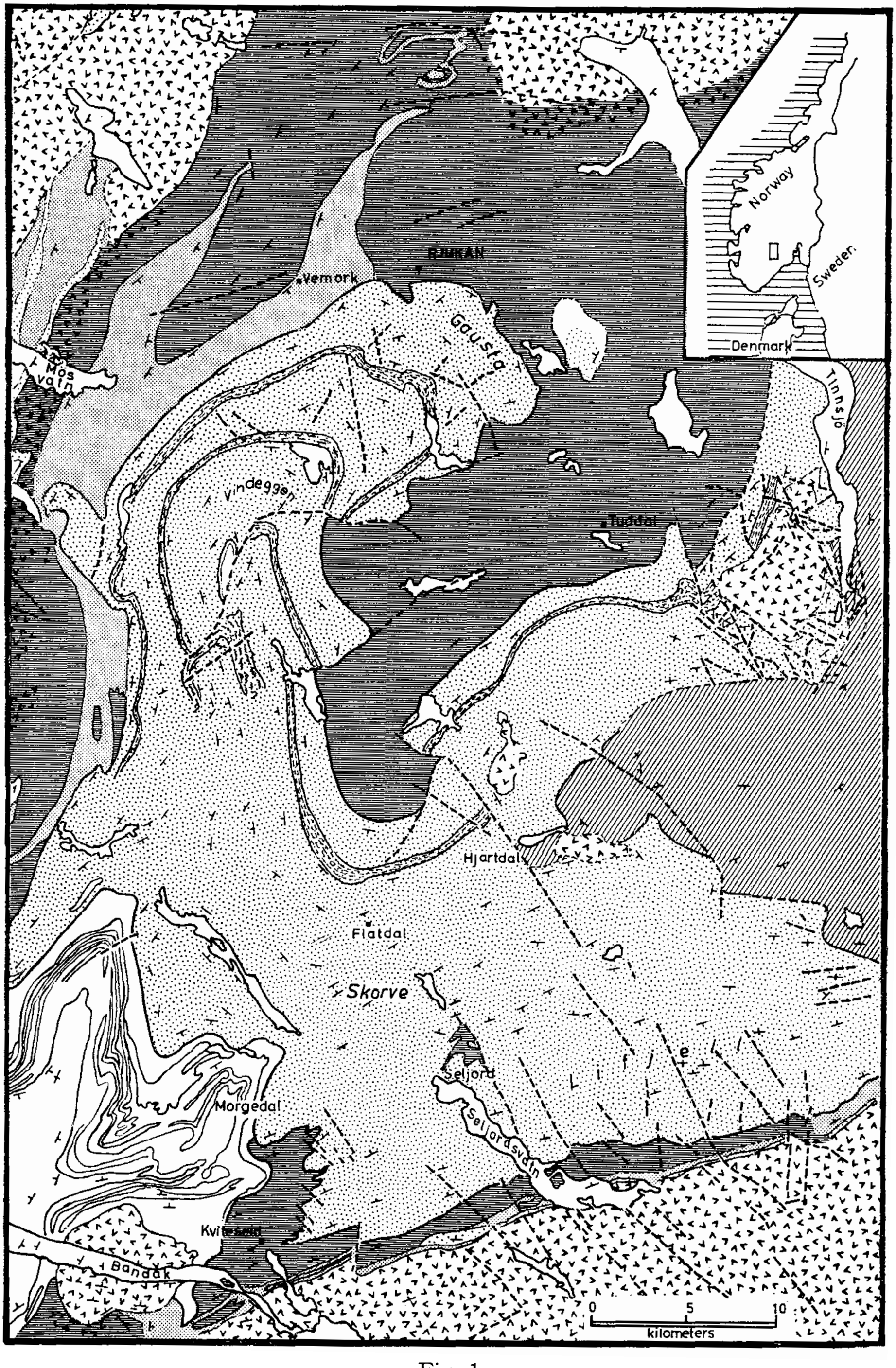
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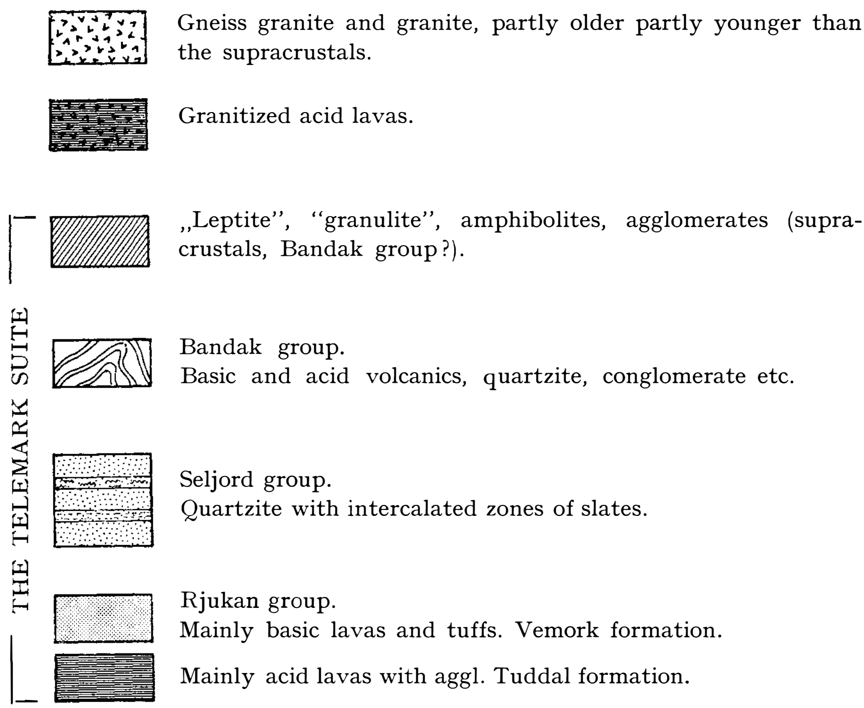
Fig. 1



←Fig. 1. Geologic map of the central Telemark area (compiled by J. A. Dons, 1961). The So. Tinnsjø area is located in the central-eastern part of the area, at the south end of Lake Tinnsjø.

Introduction

The area near the southern part of Lake Tinnsjø (hereafter called the So. Tinnsjø area) lies in the east-central part of Telemark county, Southern Norway. The Telemark Province includes a large part of the Precambrian Baltic Shield exposed in Southern Norway. The entire central Telemark area is underlain by metamorphosed Precambrian metasedimentary and metavolcanic rocks with a granite and gneissic granite basement (see fig. 1). Absolute age determinations on minerals from quartz veins and pegmatites which transect the youngest metasedimentary rocks give ages ranging from 620 to 950 million years (Neumann, 1960).


Quartzitic conglomerate, and schist
Quartzo-feldspathic schist
Biotite-microcline-quartz-epidote schist
Quartzite with pegmatite
Acidic metavolcanics
Glacial till and cover
Amphibolite
Granite
Faults
Tinnsjö
Mt. Sjölju
Mt. Venås
Mt. Vin
Tinnoset
Gransherad
N
0 1/2 1 1 1/2
Kilometers
Geology by Neville L. Carter, 1958
Geologic Map of the area near the Southern part of Tinnsjö, E. Telemark, Norway

Fig. 2

The metamorphic rocks of central Telemark comprise the Telemark suite (DONS, 1960 a and b) which has been divided into three groups which are separated by major unconformities. The Rjukan group consists chiefly of metamorphosed basic and acidic lavas, tuffs and agglomerates. It is overlain by the Seljord group which is composed of quartzite with some intercalated arkosic schist, slate, and conglomerate. The Bandak group is the youngest and consists of various rock types including metamorphosed quartzite, quartz-mica-schist, conglomerate, acidic and basic volcanics, and marble.

The metamorphic rocks in Telemark are partly surrounded by the gigantic body of granite and gneissic granite which crops out so extensively in the Shield area in Southern Norway. Small bodies of granite occur within the metasedimentary sequence; some of these may be inliers but others certainly have been intruded into the metamorphic rocks. The metamorphic rocks have been complexly deformed into long, sinuous folds. The large south-plunging folds in the north-central of the area (fig. 1) give way to smaller, west-trending folds in the southwestern part of the area. DONS (1960 a and b) postulated that the south-plunging and east-west trending structures were produced by doming of the granitic basement which borders the rocks on the west and south. Local irregularities are ascribed to movements in the gneissic granite which underlies the metamorphic rocks.

Rocks representing the Rjukan, Seljord and Bandak (?) groups of the Telemark suite occur in the So. Tinnsjø area (fig. 2). These rocks have been complexly deformed into a southeast-plunging anticline and have been metamorphosed to grades ranging from the uppermost part of the greenschist facies to about the mid-amphibolite facies. A massive granite body occupies the core of the anticline.

The problem undertaken was to study the relationships between the granite and the country rocks and to determine, insofar as possible, the origin of the granite. The field work was accomplished during the summer of 1958. Mapping was done initially on aerial photographs with a scale of 1 : 50,000 and the data were subsequently transferred to a topographic map with the same scale. The petrographical and chemical work was done at the Mineralogisk-Geologisk Museum in Oslo during the academic year of 1958—1959. The only previous work done in the area was a geological reconaissance on the scale of 1 : 300,000 by WERENSKIOLD (1909).

The Rocks

Acidic Metavolcanics

Acidic metaporphyry, interlayered with a few thin beds of tuff and aggolmerate, underlies Mt. Sjølju in the northwestern corner of the area. These rocks form part of a fairly continuous series of acidic metavolcanics that extend about 50 kilometers to the north and west. They have been designated the Tuddal formation of the Rjukan group (DONS, 1960 a and b) and are believed to be the oldest rocks of the Telemark suite. WYCKOFF (1933) studied these rocks in detail in the Mt. Gausta region 15 kilometers WNW of the Southern Tinnsjø area. Both WERENSKIOLD (1909) and WYCKOFF (1933) observed that an angular unconformity separates the Tuddal metavolcanics from the overlying Seljord quartzite. Such a relationship is not present in the Southern Tinnsjø area probably because a fault separates the two units over most of the area of exposure and elsewhere the contact is poorly defined.

The metaporphyry in the So. Tinnsjø area is massive and consists of relict quartz and feldspar phenocrysts set in a fine-grained light gray to pinkish groundmass. Only a few thin layers of foliated tuff, the foliae of which are parallel to the tuff-porphyry contact, give the attitude of the metavolcanics. Small-scale cross-bedding noted at one locality in the tuffs suggests that they may have been deposited in water. An agglomerate layer a few meters thick, the pyroclastic fragments of which have been deformed and elongated so that their principal axes have a ratio of approximately 1 : 1 : 3, occurs at the eastern border of the unit.

The fine-grained material in the metaporphyry consists of a quartz-feldspar mosaic and bands of sub-parallel white mica flakes. Locally, microscopic folds are defined by mica-rich bands. The relict phenocrysts consist of poikilitic and perthitic microcline and, to a lesser extent, quartz and plagioclase. The plagioclase in one specimen contains 35 percent anorthite and has "low temperature" optics[1].

[1] All plagioclase compositions cited in this paper were determined optically using the universal stage. The optically determined angles were referred to the standard curves of Köhler and Reinhard (in TRÖGER, 1959), TURNER (1947), and van der KAADEN (1951). From two to five grains were analyzed in each sample and the An-values of grains within a single specimen deviated no more than 2 percent from the mean value for that specimen.

Some of the plagioclase grains show faint oscillatory zoning and some of them are slightly saussuritized. The grain boundaires of the feldspars are serrate or round and, in many grains, the twin lamellae are bent or sheared because of postcrystalline strain.

Biotite is common in the metaporphyry and commonly occurs in small sub-parallel grains which are fresh or are partially altered to chlorite. Epidote is a common accessory mineral. In one specimen, large idiomorphic twinned and zoned epidote crystals, some with a nucleus of allanite, make up about 15 percent of the rock. Zircon, sphene, allanite, apatite and magnetite are accessory minerals and one specimen contains several small garnet grains.

Apparently the rocks were originally rhyolitic or rhyodacitic extrusive rocks. The mineral assemblage described seemingly does not represent stable equilibrium. Partial alteration of biotite to chlorite, incipient saussuritization of some of the plagioclases, and partial replacement of the microclines by albite suggests that the volcanics have undergone incomplete diaphothoresis to about the albite-epidote-amphibolite subfacies of the epidote-amphibolite facies (BARTH, 1952).

Quartzite

Quartzite, a part of the Seljord group (DONS, 1960 a and b), comprises the thickest stratigraphic unit in the area. The quartzite with its included amphibolite sills defines the large southeast-plunging anticline, the largest structure in the area (fig. 2). In the main, the quartzite is nearly pure and snowy white but locally it grades into a quartz-mica schist. Zones of impure biotite-rich and feldspathic quartzite are present near the granite boundary. A thin layer of rose-colored quartzite occurs locally; the color is due to thin films of hematite on grain surfaces. Ripple marks and cross-bedding are remarkably well-preserved even in the most severely deformed parts of the quartzite. Pegmatites that consist of muscovite, quartz, oligoclase, and microcline are found in a few places near the granite.

The quartzite is composed of an interlocking mosaic of fine to medium-sized quartz grains (0.1 to 1 mm in diameter) with irregular serrated boundaries. Deformation lamellae present in many of the grains are normal to zones of undulatory extinction. The optic axes of the grains appear to have fairly strong preferred orientation as shown by examination with the gypsum plate. Small crystals of white mica with very weak preferred orientation occur interstitially but most of the mica is concentrated into thin foliae which constitute the divisional planes in the quartzite. The mica flakes that form the divisional planes are notably wrinkled probably as the result of post-crystalline deformation. Epidote (piedmontite and clinozoisite), zircon and magnetite occur sporadically in the "pure" quartzite.

The impure quartzite generally contains various proportions of biotite, chlorite, epidote, magnetite, feldspar, apatite and zircon. In a specimen near an amphibolite sill one-half kilometer from the granite contact there are large, incompletely terminated hornblende crystals that contain inclusions of all the matrix minerals. In places the hornblende appears to be altered partially to epidote and chlorite. In a rock a few meters from the granite border, there are large grains of chlorite which contain lenticular granular aggregates of epidote aligned parallel to the basal cleavage of the chlorite.

The feldspathic quartzite generally is composed of equigranular quartz, microcline and microcline-perthite, and plagioclase with the with the composition An_{27}. The feldspars, in large allotriomorphic poikiloblastic grains, contain many bleb-like inclusions of quartz, apatite, magnetite and, where present, biotite.

The mineral assemblages present in the impure and in the feldspathic quartzite correspond with quartzo-feldspathic assemblages in the epidote-amphibolite facies (BARTH, 1952) or with the staurolite-quartz subfacies of FYFE et al. (1958), that is, the lowest subfacies of the almandine-amphibolite facies.

Biotite-microcline-quartz-epidote schist

A distinctive greenish layer of schist occurs within the quartzite west of Mt. Venås and Mt. Vin. Its mineralogical composition is somewhat heterogeneous but quartz, feldspar and epidote are ubiquitous; the epidote gives the layer its greenish color. Actinolite and talc are also present in some places. The schistosity, which is parallel to the foliation in the adjacent quartzite, is well-developed and is transected locally by fracture cleavage. The layer is of variable thickness and it grades into the quartzite. The schist is not exposed between Mt. Vin and Mt. Venås, perhaps because of faulting or an irregularity in the granite boundary.

Examination of thin sections with a petrographic microscope indicates that the rocks are composed of alternating fine and coarse-grained layers consisting of quartz with some microcline, epidote, and interstitial biotite and muscovite. Some layers are made up of large allotriomorphic microcline porphyroblasts that contain stringers of inclusions of quartz and biotite which are aligned parallel to the layering. Epidote is abundant in all of the sections examined and occurs in small disseminated grains, granular aggregates, and in large beautifully zoned and twinned crystals, many of which have nuclei of allanite. Actinolite, partially altered to talc, occurs in some sections. Magnetite, sphene and zircon are accessory minerals.

The mineral assemblage quartz-microcline-epidote-biotite-muscovite-actinolite-talc and the absence of chlorite places these rocks high in the greenschist facies or low in the epidote-amphibolite facies (BARTH, 1952). The epidote-rich schist originally may have been a calcareous feldspathic sandstone.

Quartzo-feldspathic schist

A pinkish-gray quartzo-feldspathic schist unit lies to the east and south of the quartzite and is everywhere in fault contact with it. These rocks and the conglomerates to the east have been collectively termed "granulites" (WERENSKIOLD, 1909) and have been assigned to the Bandak (?) group by DONS (1960 a and b). They are schistose in some places but nearly massive in others. They are visibly granulated near the many faults which transect the unit. Quartz and feldspar are the major constituents and epidote, magnetite, and micas are common; the micas form the divisional planes. Locally, veins of orange-colored calcite fill fissures in these rocks. Epidote concentrated in the wall rock adjacent to the fissures originated by reaction between the calcite and wall rock.

Large equigranular feldspar grains, resembling relict phenocrysts, occur in a fine-grained matrix in a massive part of the quartzo-feldspathic unit in the central-southern part of the area. Lithophysae (?) occur at one locality on the east side of Tinnsjø, north of Tinnoset (fig. 3). The lithophysae (?) closely resemble some of the lithophysae associated with volcanic rocks which were illustrated and described by Iddings (1885). The feldspar porphyroclasts (?) and the lithophysae (?) suggest that these rocks originally were acidic volcanics that have been altered and recrystallized.

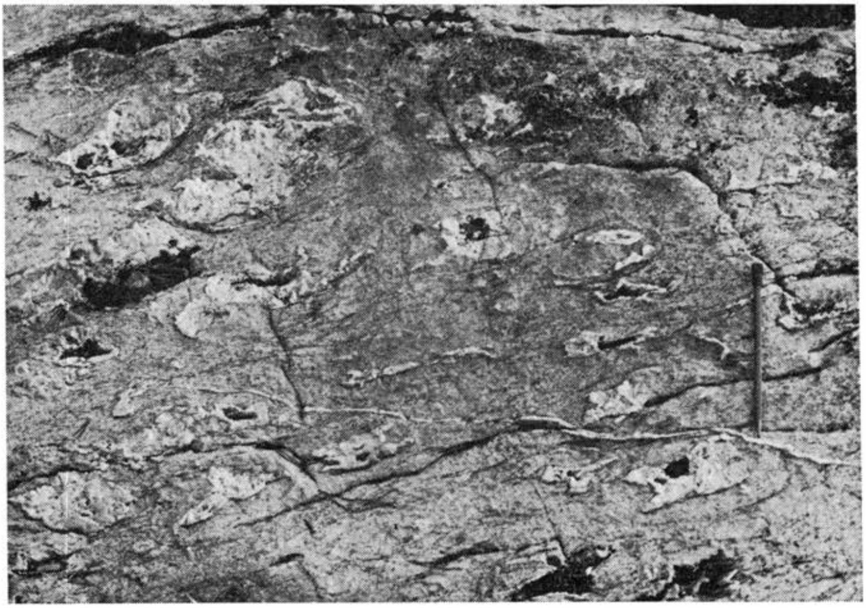


Fig. 3. Lithophysae (?) in the quartzo-feldspathic crystalline schist. Finely crystalline to massive quartzo-feldspathic material surrounds the cavities.

The quartzo-feldspathic schist has a crystalloblastic texture and is composed chiefly of a very fine to coarse-grained, inequigranular intergrowth of allotriomorphic quartz, microcline perthite, and some plagioclase (An_{16}-based on measurements from one specimen). Clusters and single large grains of quartz and microcline are surrounded by a fine-grained material. Biotite, typically in large flakes and epidote in small granules are quite common. Allanite, apatite and zircon are common accessory minerals. The zircon typically is granular and apparently has been partially replaced by magnetite.

Large hornblende crystals occur within discontinuous biotite-rich lenses in the fault-bounded crystalline schist block west of Tinnsjø and about two kilometers northwest of Gransherad. The hornblende contains many inclusions of the matrix minerals and appears to be partially altered to chlorite and epidote. Abundant piedmontite, associated with quartz veinlets, has been found at two localities in granulated portions of the unit.

A particularly interesting feature of the quartzo-feldspathic schist east of Tinnsjø is the abundance of dark "clots" of all sizes and shapes. Some of the "clots" have discrete boundaries and resemble deformed pebbles; others have irregular and diffuse boundaries. Also, these dark-colored zones occur as discontinuous layers parallel to the foliation in the pinkish schist. The "clots" owe their color entirely to the segregation into discrete zones of small blebs of magnetite. The borders of the zones containing magnetite are generally quite sharp, are parallel to the foliation, and are bounded by thin traces of preferentially oriented muscovite crystals. They transgress boundaries of single grains of quartz and microcline which may suggest that the felsic minerals are products of later recrystallization. No intrinsic difference between the quartzo-feldspathic material within and outside of the magnetite-rich zones is apparent.

The origin of the "clots" is problematical. Most probably they were originally thin continuous, perhaps cyclic, iron-rich deposits within the acidic extrusives and were subsequently disrupted by deformation. Recrystallization of the felsic components further masked their original character.

The most common mineral assemblage in the crystalline schist is quartz-microcline-sodic oligoclase-epidote-biotite-muscovite. This corresponds with a quartzo-feldspathic assemblage in the staurolite-quartz subfacies of the almandine-amphibolite facies (FYFE et al. 1958) or in the epidote amphibolite facies (BARTH, 1952).

Quartzitic conglomerate and schist

The uppermost stratigraphic unit, present in the eastern part of the So. Tinnsjø area, consists of a series of deformed conglomerates with interlayered schist. This unit is separated from the quartzo-feldspathic schist to the west by a fault but, in the southeastern part of the area, the two units appear to be gradational. There, the crystalline schist lacks the distinctive "clots" and contains lenses of agglomerate so that it is similar in appearance to the basal part of the conglomerate unit which is composed of deformed acidic volcanic clasts in a quartzo-feldspathic matrix. North of Gransherad, however, the rocks east of the fault which separates the two units contain abundant quartzite pebbles and comprise a distinctly separate unit of different origin.

The conglomerate has a dark greenish to gray appearance which is mottled by the white quartzitic clasts. The foliation, which, as in the quartzite, is parallel to the original layering, is readily recognizable because of the intercalated biotite-muscovite schist. The quartzite pebbles are surrounded by a material similar texturally and mineralogically to the schist. The pebbles range in size from two millimeters to 30 centimeters maximum diameter. They range in shape from almost spherical forms to mere streaks on the foliation plane. The estimated ratio of the lengths of principal axes of the pebbles is, on the average, approximately 10 : 4 : 1. The shortest principal axis is everywhere normal to the foliation and the longest axis is parallel to a penetrative lineation in the adjacent schist.

The quartzite pebbles are composed of an interlocking mosaic of large to medium-sized quartz grains with strong undulatory extinction. The quartz has a rather weak preferred orientation of *c*-axes as indicated by examination with a gypsum plate. Some interstitial muscovite grains and thin muscovite foliae occur. Secondary calcite, in minute veinlets and as interstitial crystals, is fairly common and a few grains of epidote and magnetite are present. The matrix typically is well foliated and the foliae conform to the shapes of the pebbles. It is composed chiefly of a fine to medium-grained, typically inequigranular intergrowth of quartz and partially sericitized microcline perthite and small amounts of plagioclase (too poorly preserved for An determination). Thin layers of preferentially oriented muscovite and, in some places, biotite, form the foliae. Biotite also occurs in large flakes which have altered partially to chlorite. Epidote, a very common constituent, forms thick bands which are parallel to the foliation but also occurs as small grains throughout the matrix. Magnetite, which locally is encased by epidote, also is very common. Apatite and zircon are the accessory minerals and secondary calcite is also present. Apparently the matrix is an altered and recrystallized feldspathic sandstone which had a calcareous argillaceous cement.

The mineral assemblage in the conglomerate unit is approximately the same as that in the quartzo-feldspathic schist. The facies assignment, therefore, is epidote amphibolite, approximately the same as that of the schists, although the conglomerate may be of slightly lower metamorphic grade.

Amphibolite

Sills of amphibolite form prominent linear ridges in the quartzite and in the quartzo-feldspathic schist in the southeast corner of the area. The intrusive nature of the material that was metamorphosed to form the amphibolite is indicated by stringers of amphibolite penetrating fissures in the quartzite adjacent to the contact, by the presence of quartzite fragments within the amphibolite, and by local decrease in the grain size of the amphibolite toward the quartzite contact.

The amphibolite is composed chiefly of hornblende and plagioclase and most commonly is massive. It exhibits relict igneous texture. In some of the thin sills, however, it has a distinct foliation commonly accompanied by strong linear parallelism of hornblende prisms. In some places the hornblende appears to have altered partially to biotite and in others it has altered partially to chlorite and yellowish iron-rich epidote. Large patches and stringers of magnetite appear to replace the hornblende, epidote, and zircon. Apatite is a common accessory mineral.

Plagioclase, in aggregates of fine-to medium-sized allotriomorphic to hypidiomorphic grains, is the only felsic constituent. Most of the plagioclase grains are zoned. Those grains that are zoned generally are not twinned and vice versa although some grains show both twinning and zoning. Possibly this twin-zone relationship supports EMMONS and MANN's (1953) view that "twinning replaces and is consequent on zoning." Most of the zoned grains show reverse zoning but some have oscillatory zoning. Universal stage analysis of one twinned and zoned plagioclase gave a value of An_{25} for the composition of the core and An_{33} for the composition of the rim. Analyses of two optically homogeneous twinned grains gave An_{28-29} as the composition.

The mineral assemblage hornblende-biotite-chlorite-calcic oligoclase-epidote may not be in stable equilibrium, although BARTH (1936) reports a similar mineral assemblage in defining the kyanite-schist subfacies, the highest-grade subfacies of the epidote amphibolite facies. This assemblage, excluding the chlorite, also corresponds with a basic assemblage in the staurolite-quartz or kyanite-muscovitequartz subfacies of the almandine amphibolite facies of FYFE et al. (1958).

Folds and Lineations in the Metamorphic Rocks

A cursory investigation of minor structures, chiefly folds and penetrative lineations, was carried out. Insufficient data were collected to warrant graphical presentation, however, and only a few generalizations are presented.

Most of the metamorphic rocks are highly deformed. Folds of several styles, types, and sizes occur in the quartzite, crystalline schist and conglomerate units. The area is not homoaxial because the orientation of the minor folds differs from place to place. Measurements of axes of many folds were obtained from the quartzite south of the granite where deformation appears to have been most intense. In that region, the folds range in style from rather open, typically asymmetrical flexural-slip folds to closely-appressed shear folds. The folding is not cylindroidal on the scale of an outcrop and, in many instances, the fold-axes are visibly bent on the scale of a hand specimen. A plot of the fold axes measurements indicated, however, that there is a tendency for these axes to plunge fairly steeply to the south, southeast, and west (the general axial orientations of folds in the entire Telemark area).

Poles of all of the foliation measurements in the area were plotted on a stereonet and were found to lie approximately in a great circle. The normal to the great circle, which can be considered to correspond with the fold axis on a regional scale, plunges 45° to the N 150 E[2]. This is in accord with the impression received from the outcrop pattern and with many of the observations on minor folds.

Lineation is common in the metamorphic rocks. The lineation is expressed variously as microscopic folds, wrinkles and larger crenulations in mica-rich foliae, intersection of cleavage and foliation, elongation of pebbles and prophyroclasts, and parallel alignment of hornblende prisms (in the amphibolite). In the intensely deformed area of the quartzite, in the central-southern part of the area, two and as many as three lineations with different orientations were observed in single hand specimens. Most commonly, the lineations are parallel to the axes of minor folds and therefore are considered to be lineations in *b*. The linear elements (exluding non-penetrative lineations, such as striae on slicken-sides) measured show approximately the same

[2] Compass directions are given in degrees.

orientations as the axes of minor folds. These structural relations indicate that the symmetry of the rock fabric on the scale of an outcrop is triclinic and that deformation has been complex.

The Venås Granite

General statement

The Venås granite occupies the central part of the So. Tinnsjø area. This granite body has been distinguished by WERENSKIOLD (1909) from the gneissic Telemark Granite which partly surrounds the metamorphic rocks in Telemark. The Venås granite has a rather uniform texture, is medium to coarse-grained, and has a pinkish color. Apart from fairly extensive jointing and faulting, the granite appears to be massive.

Evidence favoring intrusion of the Venås granite

There are abundant intrusive relationships between the granite and the country rocks. The granite contact transects the regional attitude of the foliation in several places; a notable example is the east-west trending contact on Mt. Venås. Contact phenomena are particularly marked especially along the western border on Mt. Venås. Along this mapped border the granite is filled with sub-rounded amphibolite xenoliths with a variety of sizes and shapes. In some places single inclusions of amphibolite are brecciated and the resulting fragments have a granitic matrix. Some of the xenoliths have been granitized to such a degree that they are recognizable only as faint schlieren but most of them are discrete and readily discernable. Marked differences in orientation of the foliation between neighboring xenoliths indicate that they have been rotated.

Coarse-grained granitic to fine-grained aplitic dikes and sills occur in the quartzite from the mapped granite boundary on Mt. Venås to nearly one kilometer west of it. Granite encases angular inclusions of quartzite and small-scale igneous breccias occur in many places. In one place, about 300 meters west of the granite boundary on Mt. Venås, the granite appears to have acted as a wedge to push an enormous block of quartzite into an orientation clearly different from that of the surrounding rocks (fig. 4). Analogous, perhaps, is the wedging effect of the granite on a regional scale. The rocks on the east and west of

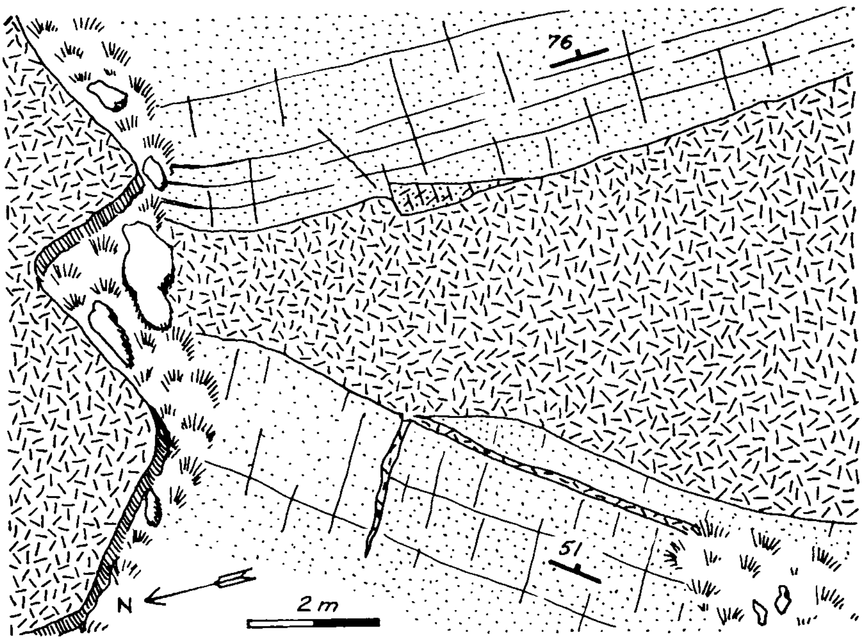


Fig. 4. Sketch of a granite-quartzite relationship 300 meters west of the mapped granite boundary on Mt. Venås. The granite appears to have forced itself into a divisional plane in the quartzite, and to have pushed aside an enormus block of quartzite (upper block).

the granite on Mt. Venås diverge by from 20 to 30 degrees in strike and merge at the north end of the granite.

Evidence for intrusion at the eastern granite-quartzite contact is much less spectacular although small-scale igneous breccias and dikes are fairly common. Generally, a gradational zone which is tens of meters wide separates granite from pure quartzite. Quartzite in the gradational zone, near the granite, has been so feldspathized that, macroscopically, it is very difficult to distinguish from the adjacent granite. Microscopically, however, the relict mosaic texture of the quartzite can be seen and actually the rocks are very rich in quartz.

Relative age of the intrusion

A careful search for structures in the Venås granite was carried out. But, even with the aid of extensive jointing which provided excellent three-dimensional exposures in many places, the search was unsuccessful. Apart from rare vestiges of foliation near the granite border (considered to be granitized inclusions of amphibolite) the granite contains no penetrative structures visible on outcrops. This is significant because the metamorphic rocks within and outside of the So. Tinnsjø area are severely deformed. This suggests that the main deformation of the area preceded the intrusion of the granite. The fact that the granite transects the regional foliation in many places supports this suggestion. Thus the granite is interpreted as being late-kinematic or post-kinematic in its emplacement and to have been forcefully intruded into the core region of the large southeast-plunging anticline.

A great deal of faulting has taken place in the So. Tinnsjø area in contrast to most of the other mapped areas in central Telemark (see fig. 1). Most of the boundaries separating major stratigraphic units in this area have been surfaces of movement. The inclination of all of the fault surfaces is steep or vertical. In general, the faults are arranged either nearly perpendicular to or subparallel with the border of the granite. Most of the radial faults are continuous from the granite into the surrounding metamorphic rocks; many of them appear to be pivotal with greater apparent separations nearer to the granite. The concentric faults show, in most places, apparent normal separation with upthrow on the granite side. These relationships indicate that most of the faulting did not precede the emplacement of the granite.

The pattern of faults in the So. Tinnsjø area is typical of diapir granites (see for example, OERTEL, 1956). The fault pattern and apparent separations suggest that the faulting may have been a result of forceful intrusion of the granite; alternatively, the faulting could have postdated the intrusion. The faults do not appear to have been folded and are considered to represent the latest deformation of the area.

Petrography and Chemistry

Although on the scale of the whole area the granite is uniform in texture and appearance, locally, particularly on Mt. Venås where the rock exposure is excellent, three varieties can be distinguished. On Mt. Venås there is a complete gradation from a coarse-grained mafic variety on the western border through a coarse-grained pink variety into a medium to coarse-grained felsic variety. The femic and felsic varieties are restricted in extent as compared with the typical pink

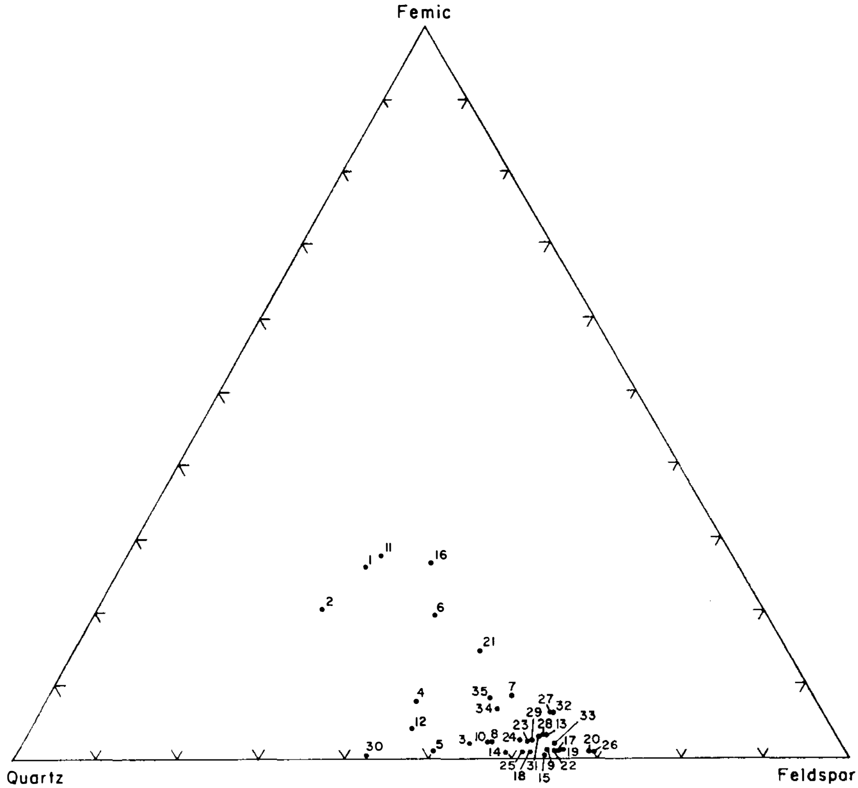


Fig. 5. Mineral composition diagram showing the modal composition of the granite. Points are based on modal analyses of thin sections (ca. 2000 counts for each section) from 35 specimens collected from seven selected west to east traverses across the granite. Numbers 1, 6, 11 etc. correspound to specimens obtained from the western border of the granite. Plots are based on the volume percentage of quartz, feldspar, and the femic minerals, biotite, chlorite, and hornblende; accessory minerals are excluded.

granite which covers most of Mt. Venås and nearly all of the granite area to the south.

The mafic variety of the granite is in contact with amphibolite along most of the western border on Mt. Venås. This variety becomes increasingly darker toward the amphibolite and locally the contact between the two is scarcely discernable. It owes its dark appearance to an enrichment in femic minerals, particularly biotite (up to 27 percent) and magnetite. Plagioclase with 33—35 percent anorthite

Table I

Chemical analyses, norms and modes of specimens from the Venås Granite (Analyst, R. Solli).

	Rock 13 — pink variety						Rock 15 — felsic variety						Rock 21 — mafic variety					
	Wt %	Cat-ion %	Mole cular-Meso-norm	%	Observed Mode	%	Wt %	Cat-ion %	Mole cular-Meso-norm	%	Observed Mode	%	Wt %	Cat-ion %	Mole cular-Meso-norm	%	Observed Mode	%
SiO_2	73.71	69.7	Q	32.4	Quartz	33.3	76.57	72.4	Q	35.5	Quartz	35.5	67.06	64.2	Q	33.1	Quartz	33.0
TiO_2	0.38	0.3	Or	25.4	Feldspar	60.1	0.22	0.2	Or	32.9	Feldspar	62.6	1.16	0.9	Or	2.1	Feldspar	45.0
Al_2O_3	12.67	14.1	Ab	31.5	Biotite	3.5	11.84	13.2	Ab	27.5	Biotite	0.2	13.06	14.8	Ab	33.4	Biotite	13.0
Fe_2O_3	1.48	1.1	An	4.0	Epidote,		1.74	1.2	An	0.5	Muscovite,		3.20	2.3	An	12.0	Epidote,	
FeO	1.45	1.1	C	0.7	Apatite,		0.29	0.2	C	0.8	Epidote,		4.36	3.5	C	1.5	Apatite,	
MnO	0.04	—	Bi	3.35	Sericite,		0.02	—	Bi	0.8	Apatite,		0.10	0.1	Bi	11.0	Sphene,	
MgO	0.48	0.7	Ti	0.9	Magnetite	3.1	0.26	0.3	Ti	0.6	Sphene,		1.24	1.8	Ti	2.7	Zircon,	
CaO	1.13	1.1	Mt	1.65		100.0	0.27	0.3	Mt	0.6	Zircon,		3.59	3.7	Mt	3.5	Magnetite	9.0
Na_2O	3.43	6.3		99.9			3.04	5.5	Hm	0.8	Magnetite	1.7	3.61	6.7	Ap	0.6		100.0
K_2O	4.63	5.5					5.58	6.7		100.0		100.0	1.51	2.0		99.9		
P_2O_5	0.02	—					0.00	—					0.27	0.2				
H_2O	0.45	—					0.25	—					0.73	—				
Sum	99.87	99.9					100.08	100.0					99.89	100.0				
Associated Anions		Anion %						Anion %						Anion %				
O —		171.1						173.9						169.2				
OH —		2.4						1.2						4.3				
Anions		173.5						175.1						173.5				

(five specimens analyzed), and which includes epidote, zircon and apatite, is the most common felsic mineral. Quartz is fairly common. Potash feldspar is rare. In the mineral composition diagram (fig. 5) the six points above the main grouping represent mineral compositions of granite specimens collected from the western border zone on Mt. Venås.

Rocks of the pink and felsic varieties generally are impoverished in the femic minerals. The pink variety contains 2—5 percent femic minerals and the felsic variety, less than one percent. These rocks are truly granitic in mineral composition and texture. Micrographic or granophyric texture is very common (especially in the center of the bedrock area of the granite), and is represented by cuneiform intergrowths of microcline and quartz. The quartz is commonly arranged in irregularly-shaped radial stringers and blebs; the individual stringers increase in width outward from the center of the microcline grains. In many of the specimens, however, there are potash feldspar grains which are free of graphic intergrowth. Generally, the potash feldspars are perthitic, with the exsolved plagioclase lamellae in "film" and "string" relations. Plagioclase in the pinkish granite variety contains 26—28 percent anorthite (six specimens analyzed) and that in the felsic variety near the border has 28—33 percent anorthite (ten specimens analyzed).

Chemical analyses obtained for one specimen from each of the three granite varieties are shown in Table I. Weight percentages were recalculated to cation percent and molecular norms were calculated from these. The observed mode of each of thse rocks as determined by mineral counts is included for comparison. All of the samples contain over 65 weight percent silica and therefore may be generally classified as acidic.

The molecular mesonorm compares very well with the observed mode of the three rocks analyzed; the mesonorm was calculated using the rules set down by BARTH (1959). Therefore, if the mineral assemblages in these rocks are equilibrium assemblages, as they appear to be petrographically, these rocks apparently originated in the mesozone which "centers around the amphibolite facies" (BARTH, 1959, p. 136). The significance of this zonal relationship will be discussed further in a later section.

Normative albite-orthoclase-quartz distribution in the Venås granite

The normative albite-orthoclase-quartz distribution in the Venås granite was investigated in an effort to limit the possibilities of modes of origin of the granite. To this end, alkali analyses were made on the same 35 rocks represented by plots on the mineral composition diagram (fig. 5). Analyses were made using flame photometric techniques (see, for example, KNIGHT et al., 1951) and the results (in ppm) were recalculated into weight percent Or and Ab. If biotite was present in a specimen (volume percentage determined by thin section counts), Or was first alloted to the biotite according to the general equation for normalized biotite (BARTH, 1959, p. 137):

$$3\ Mg' + 5\ Or = 8\ Bi,$$
$$3\ MgO + KAlSi_3O_8 + (H_2O) = K\ Mg_3AlSi_3O_{11}\ (H_2O).$$

The remaining Or was alloted to pure K-feldspar. All Na was alloted to albite. Percentage of quartz was obtained by mineral counts. Expression of this as volume percent is considered to be sufficiently accurate because the rocks have an average measured specific gravity of 2.7. The results of the analyses are listed in Table 2.

The total weight percent of the three constituents (volume percent of quartz) in each specimen was recalculated to 100 percent and the results were plotted on the orthoclase-albite-quartz ternary diagram (fig. 6). Also shown on the diagram is the equilibrium minimum crystallization curve for the system Or-Ab-SiO_2 under from 500 to 4000 atmospheres of water vapor pressure as determined experimentally by Tuttle and Bowen (in BOWEN 1954). The dashed line represents the 5 to 7 percent frequency contour of the normative (weight norm) composition (Or-Ab-Q) of 571 granitic and syentic rocks analyzed by Tuttle and Bowen (in BOWEN, 1954). BOWEN (1954) regarded the close correspondence of the composition of the granitic rocks to the minimum crystallization curve as confirmation of the hypothesis that they originated by crystallization of a soda-potash-alumina-silica-rich liquid which was a residuum of fractional crystallization of complex liquids containing all of the rock-forming oxides. He suggested, alternatively, that "this minimum crystallizing liquid would also be the first liquid formed in the selective fusion (melting) of random rock material" (1954, p. 11).

Table 2.
Orthoclase-albite-quartz composition of specimens from the Venås Granite.

Spec No	Wt % Na_2O	Wt % Ab	Wt % K_2O	Wt % Or*	Vol % Q	Recalc Wt % Ab	Recalc Wt % Or	Recalc Vol % Q	Sum Ab+ Or+Q
1	2.77	23.4	3.90	7.6	43.4	31.4	10.2	58.3	99.9
2	1.38	11.7	2.17	4.1	35.8	22.7	7.9	69.4	100.0
3	3.35	28.3	5.36	30.9	42.0	24.2	32.1	43.7	100.0
4	3.45	29.2	5.15	26.0	44.3	29.3	26.2	44.4	99.9
5	4.25	35.9	4.48	26.1	46.8	33.0	24.0	43.0	100.0
6	3.11	26.3	3.58	9.9	36.5	36.2	13.6	50.2	100.0
7	3.60	30.4	4.22	19.8	35.2	35.6	23.2	41.2	100.0
8	5.04	42.6	3.87	22.8	41.0	40.0	21.4	38.5	99.9
9	3.46	29.2	5.57	32.4	35.0	30.2	33.5	36.2	99.9
10	3.68	31.1	5.34	31.1	38.2	31.0	31.0	38.1	100.1
11	3.57	30.2	3.73	5.2	41.0	39.5	6.8	53.7	100.0
12	3.72	31.4	4.82	26.3	49.1	29.4	24.6	46.0	100.0
13	3.43	28.9	4.63	25.2	33.3	33.1	28.8	38.1	100.0
14	3.38	28.6	5.68	32.8	39.0	28.5	32.7	38.8	100.0
15	3.04	25.8	5.58	32.9	35.5	27.4	34.9	37.7	100.0
16	2.64	22.3	4.00	7.6	33.8	35.0	11.9	53.1	100.0
17	4.22	35.7	4.20	24.2	32.5	38.6	26.2	35.2	100.0
18	3.68	31.1	5.55	32.7	37.1	30.8	32.4	36.8	100.0
19	2.98	25.2	5.87	34.2	31.4	27.7	37.7	34.6	100.0
20	2.88	24.3	5.86	34.6	30.0	27.3	38.9	33.7	99.9
21	3.61	30.6	1.51	0.8	33.0	47.5	1.2	51.2	99.9
22	3.85	32.5	4.60	27.2	32.9	35.1	29.4	35.5	100.0
23	3.35	28.3	5.35	31.6	36.9	29.2	32.6	38.1	99.9
24	3.25	27.5	5.40	30.9	37.6	28.6	32.1	39.2	99.9
25	2.99	25.3	5.86	34.5	35.6	26.5	36.2	37.3	100.0
26	2.85	24.1	7.24	42.7	28.4	25.3	44.8	29.8	99.9
27	3.51	29.7	4.72	24.2	31.8	34.7	28.2	37.1	100.0
28	3.54	29.9	6.03	35.6	35.1	29.7	35.4	34.9	100.0
29	3.61	30.5	6.34	36.2	35.5	29.8	35.4	34.7	99.9
30	3.03	27.9	2.61	15.3	49.8	30.0	16.4	53.5	99.9
31	4.11	34.7	4.32	23.7	34.4	37.4	25.5	37.1	100.0
32	3.97	33.5	4.94	25.4	32.0	36.8	27.9	35.2	99.9
33	3.80	32.1	5.17	29.3	33.8	33.7	30.8	35.5	100.0
34	3.47	29.3	5.38	27.9	38.2	30.7	29.2	40.4	99.9
35	4.00	33.8	4.78	23.0	37.4	35.9	24.4	39.7	100.0

* Values listed have been corrected for Or contained in normalized Bi (see text).

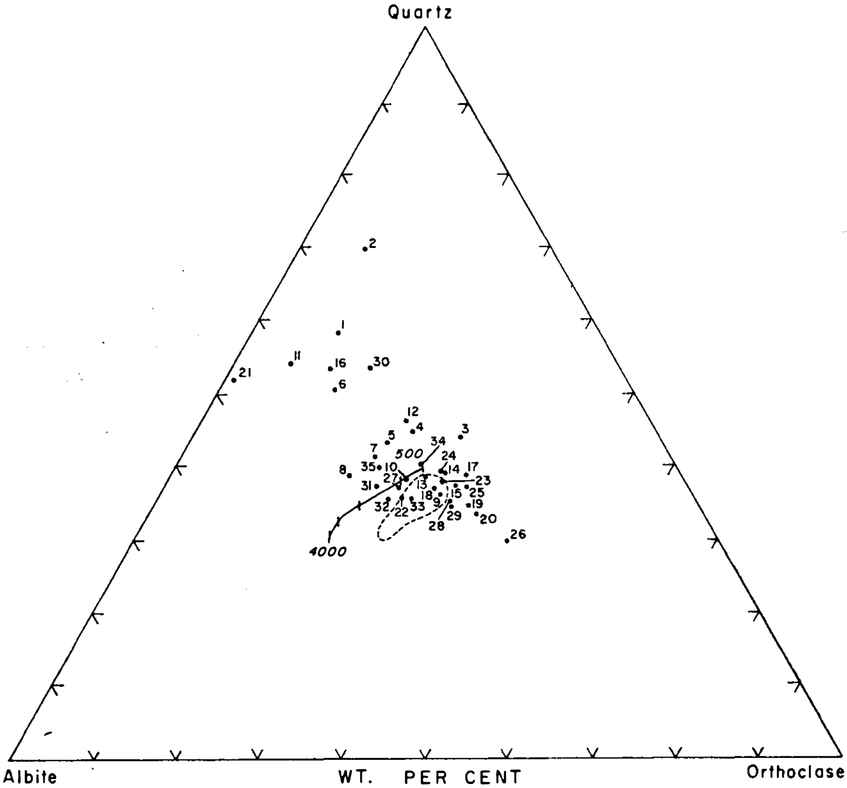


Fig. 6. Diagram showing the normative (weight norm) Or-Ab-Q distribution in 35 specimens from the Venås granite as determined by alkali analyses (Or and Ab) and mineral counts (Q). The dashed line represents the 5 to 7 percent frequency contour of the normative (weight norm) Or-Ab-Q composition of 571 granitic and syenitic rocks analyzed by Tuttle and Bowen. The full line shows the minimum crystallization composition in the system Or-Ab-SiO_2 under from 500 to 4000 atmospheres water vapor pressure as determined experimentally by Tuttle and Bowen (in Bowen, 1954).

The points representing the normative (weight norm) orthoclase-albite-quartz composition of rocks from the Venås granite show a marked tendency to cluster around the minimum melting curve and the frequency maximum. The six points located outside the cluster on the mineral composition diagram (fig. 5) also occur away from the grouping in figure 6. This is because those rocks of the femic granite variety are relatively enriched in quartz and plagioclase and impoverished in potash feldspar. Point 30 represents the analysis of a specimen of feldspathized quartzite from the gradational zone at the eastern border of the granite on Mt. Venås.

Possible genesis of the Venås Granite

From the preceding discussion, it seems likely that the granite originated either as a residual product of fractional crystallization or as a product of selective fusion of low-melting components in rocks. The latter possibility seems particularly attractive in view of the great quantities of granitic constituents of the basement in the Telemark area. In this explanation, partial anatexis would have taken place in the mesozone (as suggested by the rock analyses). The resulting magma could have coalesced and risen as a diapir, and have forcefully intruded the overlying rocks.

The femic and felsic granite varieties would seem to have originated by deuteric reaction between the wall rock and the granitic constituents rather than as a product of crystal settling as suggested by (WERENSKIOLD (1909). This is suspected because the femic variety persists only in regions where the granite is in contact with amphibolite and the felsic variety is present in zones where quartzite is in contact with granite. Reaction and metasomatism, or both, between the granite and the quartzite produced the SiO_2-rich felsic granite and the zone of gradation between the felsic granite and the quartzite. Similarly, reaction between the potash-rich granitic materials and the amphibolite produced the femic variety with most of the potassium being used in converting the hornblende to biotite thus leaving little to combine as potash-feldspar. The foregoing interpretation offers a possible explanation for the deviation of the points representing specimens of femic and felsic granite varieties from the main cluster of points on the mineral composition diagram (fig. 5) and on the Or-Ab-Q ternary diagram (fig. 6).

Alternatively, the granite could have originated by recrystallization of rocks of similar bulk chemical composition (e.g. the acidic metavolcanics) and could have risen as a "hot crystalline body" in the manner suggested by BARTH (1956, p. 33) for the diapir granites in Southern Norway. The presence of large, granular zircon grains which are partially replaced by magnetite in the Venås granite and also in most of the country rocks could be construed to support this hypothesis.

However, the apparent fluidity and mobility of the granite and the presence of aplite dikes along its flanks suggests the presence, at least locally, of a liquid phase. Moreover, a liquid phase would facilitate reaction and metasomatism, processes which appear to have been extensively operative near the granite boundary.

Nevertheless, these two hypotheses for the origin of the granite are essentially similar and there is little known at present to favor preference of one or the other.

Application of the Two-feldspar Geothermometer

The two-feldspar geothermometer, suggested by Barth in 1934 and later developed by him (1956), was applied systematically to the Venås granite in a further attempt to shed light on the genesis of the granite. Temperature values cited below are from the "1956 values for the feldspar crystallization temperatures" (BARTH, 1956, p. 14). For detailed discussion concerning the geothermometer, see BARTH (1956), DIETRICH (1960, p. 40—53), HEIER (1960, p. 145) and WINKLER and von PLATEN (1958, p. 99—102).

Twenty-one specimens for use of the geothermometer were selected on the basis that: (1) plagioclases were fresh and their composition could be determined accurately; (2) a sufficient percentage of alkali feldspar grains were fresh and free of graphic intergrowth; and (3) the mineral assemblage apparently was an equilibrium assemblage. Molecular percentages of Ab and Or in the alkali feldspars were determined chemically. Specimens were ground to approximately 90 mesh and separated using heavy liquids and the Franz isodynamic separator. The last four (lowest sp. gr.) concentrates were collected and the last two fractions were analyzed by flame photometric techniques. The results are probably accurate to $\pm$ 2 mole percent.

Since this work was done, the preliminary results of DIETRICH (1960, p. 52) have suggested that the Or:Ab ratio in the alkali feldspars may range within single grains and therefore that the successively lighter fractions separated using the density-sensitive heavy liquids method contain less and less Ab. This suggestion recently has been confirmed by B. Nilssen (DIETRICH, personal communication). Therefore, because only the last two fractions were analyzed in this study, the absolute temperatures recorded are incorrect (lower than those

Table 3.
Feldspars from the Venås Granite.

Specimen Number	3	4	8	9	10	12	13
Na_2O	1.05	1.02	0.61	1.30	0.81	0.69	0.56
K_2O	15.20	15.28	15.47	14.50	15.40	15.81	15.95
Normative Ab....	8.9	8.6	5.2	11.0	6.9	5.8	4.7
Normative Or ...	89.9	90.4	91.5	85.8	91.1	93.5	94.4
Mol. prop. Ab ...	9.5	9.2	5.7	12.0	7.3	6.1	5.0
Mol. prop. Or	90.5	90.8	94.3	88.0	92.7	93.9	95.0
Ab of assoc....... plagioclase	65	68	69	71	67	73	72
K (T, P)	.15	.135	.08	.17	.11	.08	.07
Temperature °C* .	425	410	340	450	370	340	300

Specimen Number	14	15	17	18	19	23	24
Na_2O	0.67	1.35	1.09	0.81	0.68	0.92	1.57
K_2O	15.71	15.20	15.00	15.50	15.40	15.35	14.50
Normative Ab....	5.7	11.4	9.2	6.9	5.7	7.8	13.3
Normative Or ...	93.0	89.9	88.8	91.7	91.1	90.8	85.8
Mol. prop. Ab ...	6.2	11.7	9.9	7.3	6.3	8.4	14.2
Mol. prop. Or	93.8	88.3	90.1	92.7	93.7	91.6	85.8
Ab of assoc ...... plagioclase	67	67	68	67	69	73	66
K (T, P)	.09	.175	.145	.11	.09	.115	.22
Temperature °C* .	350	460	425	370	350	380	495

* Temperature values of less than 360° C are based on an extrapolation of Barth's (1956) curve.

which would have been derived if the alkali feldspar had been "homogenized" before separation) and even the relative temperatures may be suspect. The writer feels, nevertheless, that the values are probably not greatly in error and should be recorded.

The distribution coefficient, k, was calculated[3] for the several samples and the k values were referred to the curve relating temperature to

[3] $k_{(t.\ p)} = \dfrac{\text{Mole fraction of Ab in alkali feldspar}}{\text{Mole fraction of Ab in plagioclase}}$

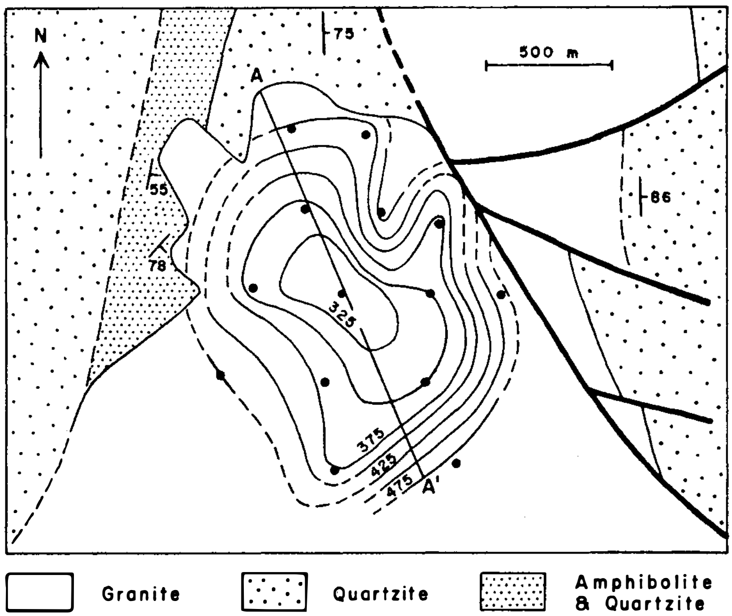


Fig. 7. Isothermal contour map of the granite on Mt. Venås. Isotherms represent the most recent lowest temperatures at which equilibrium between the co-existing feldspars was attained. Points mark localities of the specimens used for the analyses and, reading from the top, left to right, they correspond, in increasing numerical order, to the analyses shown in table 3.

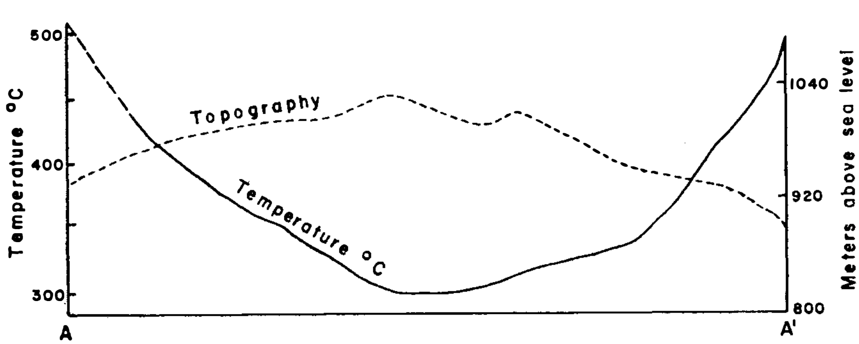


Fig. 8. Diagram showing the temperatures recorded in relation to their position in the granite dome forming Mt. Venås.

the composition of the contiguous feldspar phases (BARTH, 1956, p. 15). Fourteen of the temperature values thus obtained were from specimens collected from Mt. Venås where the intrusive relations are particularly clear and the granite is well exposed. Table 3 shows the results of analysis of these specimens. The temperature values were placed on a map at the geographical location of the specimens and then were contoured at 25° C intervals (fig. 7). The isotherms are essentially concentric; the contours are parallel to the granite border on Mt. Venås[4]. The lowest temperature, 300° C, is at the center of the granite dome forming Mt. Venås and the temperature becomes higher at an increasingly rapid rate toward the borders where the highest temperatures, 460° C and 495° C are recorded. Figure 8, showing the temperatures in relation to the topography, brings this out clearly.

The isothermal contour pattern shown indicates that equilibrium between the two feldspar phases was reached at a higher temperature at the border than at the center of the granite forming Mt. Venås. This may well be due to rapid cooling at the border so that after a critical stage, the two feldspar phases did not have sufficient time to adjust to the rapidly falling temperature whereas in the center of the granite mass, where cooling presumably was much slower, the feldspars were able to readjust their Ab-Or-An equilibrium continuously to a lowering temperature.

The above suggestion may be corroborated by the alkali feldspar studies of HEIER and TAYLOR (1959) on the intrusive Fevig granite in Southern Norway. The Fevig diapiric granite presumably crystallized from the border inward and the Na content in the alkali feldspars is lowest at the center of the granite (lowest temperature). Moreover, they show that the K/Rb ratio in the alkali feldspars decreases from the border to the center; the resulting cross-sectional curve (op. cit. p. 291) is very similar to the temperature curve in figure 8. The variation at the K/Rb ratio seems to be analogous to that of the Na/K ratio in the alkali feldspars.

The granite on Mt. Venås represents about one-eighth of the granite exposed in the So. Tinnsjø area. Scattered temperature determinations

[4] Mt. Venås is the highest place in the area and the granite forming Mt. Venås rises nearly 500 meters above the granite directly south of the southernmost contour in figure 7. For the present, it is expedient to consider the steep slope separating these two granite areas as the southern border of Mt. Venås.

(300—445° C) elsewhere in the granite indicate that the isothermal contour pattern on Mt. Venås does not continue much farther southward. As mentioned in footnote 4, Mt. Venås stands high above the rest of the granite area to the south. This topographic expression together with the isothermal contour pattern suggests that the granite on Mt. Venås may be a small diapir within the whole diapiric granite; it may represent the last pulse of the intrusion. Probably there are other such small diapirs within the granite (such as Mt. Vin), but this must await further study.

If the above implication is true, it suggests that some diapiric granites do not move as one continuous mass but that there are pulsational movements of different parts of the granite mass at different times with each pushing past the surrounding rocks (whether granite or bedrock) which serve as the wall rock for that intrusion. That some mobile granites could be emplaced in such a manner has been shown structurally by CLOOS (1936), BALK (1937), and OERTEL (1956). Wegmann recently found structural evidence indicating that the Herefoss granite in Southern Norway could have been emplaced in this manner (BARTH, personal communication). Such a mechanism has also been suggested for the emplacement of salt diapirs (BALK, 1949). Tentatively, therefore, the two-feldspar geothermometer may be a useful structural tool in detailed studies of the development and emplacement of mobile granites, particularly in granites which show no megascopic structures (as the Venås granite) or in which three-dimensional exposures are insufficient for an adequate structural analysis.

Whether or not the above implications are borne out by future work, this application of the two-feldspar geothermometer may serve to illustrate how systematic application of the geothermometer may be extremely valuable in petrologic investigations. Unfortunately the temperature values derived (300—495° C) do not elucidate independently the conditions under which the granite originated. To be sure, the temperatures are submagmatic. However, as has been pointed out by DIETRICH (1960, p. 46), "Whereas a magmatic temperature can be cited as evidence for magmatic origin, a submagmatic temperature cannot be cited as evidence against an ultimate magmatic origin", because of the possibility of continuous attainment of equilibrium at lower temperatures.

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