On the Form and Mode of Emplacement of the Herefoss Granite.

By

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With 9 Text-figures and 4 Plates

Contents.

Introduction.

In the south-east part of Aust-Agder the geological map of Southern Norway is dominated by two, roughly circular bodies of rather homogeneous, coarse-grained granite which have partly conformable and partly cross-cutting contacts with the surrounding rocks. A map showing the geological environment of these two granites has already been published (in Holtedahl, et al., 1960, Plate 3) (see fig. 1). From their field associations, the granites can be shown to be younger than the gneissification that affected the enclosing rocks, but older than a Permian rhomb-porphyry dyke. Radioactive age determinations (Neumann, 1960) show that their age is about 900 m.y. and that they were formed during the closing stages of the petrogenesis associated with a PreCambrian orogeny.

Previous Work

The larger of the two masses,shown in the map referred to above, occupies an area about 260 sq. km and is well exposed. It was first referred to by A. Bugge (1928, p. 27) in connection with his description of the "Great Friction Breccia", an important zone of fracture in the PreCambrian rocks of South Norway which runs for 150 km. from Kristiansand to Porsgrunn. He called it the "Birkeland Granite" but on his map of the "Great Friction Breccia" only that part of the granite east of the fault zone is shown.

The first account of the granite proper was by Barth (1947). He was particularly impressed by what he regarded as the transitional rock series "gneiss, augen gneiss, granite" and suggested that the Birkeland granite was formed by a process which he termed "petroblastesis", in which "diffusible, migrating ions directly crystallize to a rock body". In subsequent references to this granite (Barth, 1955, 1956), he called it the "Herefoss Granite". As it lies north of Birkeland and largely in the parish of Herefoss, this name is used here.

The smaller of the two granites is about 6 km. in diameter from north to south but less than half of its probable surface area is exposed (see figure 1). A. Bugge (1928) referred briefly to its existence and called it the "Grimstad Granite"; this name was also used by Barth (1947, 1955, 1956) and will be employed here. It is also variously referred to as the "Fevik Granite" (Oftedahl, 1938, 1945) and the "Fevig Granite" (Taylor and Heier, 1960). The previous work on this body was carried out almost entirely by Oftedal who in his preliminary account of it (1938) regarded it as being magmatic in origin. His later work (1945, 1958) leads him to the conclusion that it is an anatectic body.

Current Work

The Herefoss granite has recently been studied from various different viewpoints. B. Nilssen (unpublished thesis, University of Oslo, 1961) has been concerned particularly with the feldspars of the granite as a clue to its temperature of formation; S. B. Smithson has been engaged on geophysical studies in the region (see accompanying paper in this journal). Further reference to these studies is made below.

The Present Work

The investigations of the author in this connection have concentrated mainly on the structural and field relationships of the granite. During preliminary studies of the geology of the area in 1957 it was discovered that the two parts of the granite east and west of the "Great Friction Breccia" have been considerably displaced relative to each other. Thus not only is the opportunity presented to study a granite at two different levels of exposure, but important inferences can be drawn regarding the age of the faulting and the genetic relationships between the surrounding rocks on each side of the breccia. Subsequent fieldwork in the summers of 1958 and 1959 revealed that the Herefoss granite has interesting and anomalous field relationships to the surrounding rocks;

in the writer's opinion these features are inadequately explained by earlier theories on the mode of emplacement of this rock.

Excellent air photographs formed the basis of much of the field work. As ground control, maps on the scale of 1 : 50,000 were used, the "Truppenkarte", which were published for the artillery during the German occupation. The grid from these war-time maps is reproduced in figures 2 and 6 and is used in the text to specify localities, where all eight numbers of the grid are quoted. Compass bearings are given from true north, measured clockwise and all angles are based on a 360° circle.

Acknowledgements

The studies upon which this paper is based were begun in 1957—1958 while the writer was a Norsk Statsstipendiat. Professor T. F. W. Barth was a constant source of encouragement and guidance during that time and thanks are due to him and his associates at the Mineralogisk-Geologisk Museum, Oslo, over which he so ably presided. The writer is especially indebted to Professor Barth and Mrs. B. Nilssen for providing the unpublished chemical analyses which appear in Table I and to them both and to Mr. S. B. Smithson for fruitful discussions and interchange of information on the Herefoss and Grimstad Granites.

Laboratory work was continued in 1959—61 at the Department of Geology, King's College, Newcastle-upon-Tyne, England and these studies formed part of a thesis for the degree of Ph. D. at the University Durham in 1961.

The expenses of field work in 1957 and 1958 were defrayed by the Norwegian Committee of the XXIst International Geological Congress and in 1959 by Norges Geologiske Undersøkelse. Grateful thanks are expressed to these organizations and to many other people, particularly the friendly inhabitants of Sørlandet, who assisted the author in this research.

Petrology of the Herefoss granite.

Introduction

Little has been written about the petrography of the Herefoss granite and Barth (1947, p. 174) merely states that it is a massive, red, coarse-grained granite of simple composition, in which perthitic microcline, forming crystals up to 3 cm. across, predominate over plagioclase (An_{11}). Comprehensive quantitative studies of its mineralogy and petrology were not undertaken by the writer during the present studies as these aspects of tahe granite were currently being investigated by Nilssen (1961). The following notes on the petrography of the granite, based on the writer's studies, are intended as a background to the structural and field relationships.

Petrography

The Herefoss granite is a coarse-grained holocrystalline rock with pink, elongate or tabular, euhedral to subhedral phenocrysts of microcline measuring about 2.5 to 1.5 cm. The groundmass consists of equigranular aggregates of quartz and greenish-grey plagioclase averaging 4 to 5 mm. and glomerogranular clots of ferromagnesian minerals, up to 2 cm. across, consisting chiefly of biotite with a grain size of 2 to 3 mm. Locally some of the quartz is stained red by haematite and sphene crystals, just large enough to be recognizable with a hand lens, are quite numerous.

The texture is hypidiomorphic granular and no directional structures are visible on the scale of a thin section. In addition to the minerals mentioned above, the following play an accessory role: allanite, apatite, chlorite, epidote, haematite, hornblende, ilmenite, magnetite, muscovite, pyrite and zircon. Traces of calcite and single grains of purple fluorite (often as inclusions in apatite) can be observed even in specimens which bear no signs of cataclasis.

Microcline

The phenocrysts of microcline show rectilinear outlines to the naked eye, but in thin sections the margins of the crystals are seen to be crenellated and crowded with inclusions of the groundmass. Microcline cross-hatching is always present but occasionally the microcline twinning is only feebly or patchily developed. The microcline is microperthitic and the perthite lamellae are irregular and sometimes anastomosing lenticular masses, usually in optical continuity. Some of the larger crystals of microcline are bordered by an irregular rim of plagioclase grains some of which are contiguous with or continue into the perthite lamellae.

The boundary between plagioclase and microcline is invariably irregular as apophyses of each mineral penetrate along the contact. As well as the perthitic intergrowth, larger inclusions of plagioclase in the form of rounded masses and euhedral crystals also occur in the microcline (Pl. I, fig. 1). Inclusions of quartz, biotite and more rarely hornblende also occur within the microcline.

Barth (1947, p. 180) was of the opinion that the microcline in the Herefoss granite is porphyroblastic. It seems likely than an alkali feldspar did crystallize fairly late during the formation of this rock but since that time there has been considerable unmixing of plagioclase from potash feldspar.

Plagioclase

As well as occurring as inclusions in microcline, tabular, subidiomorphic crystals of plagioclase up to 1 cm. across and often partly turbid due to alteration, occur in the groundmass. They are invariably twinned and combinations of albite, Carlsbad and pericline twins are seen, but zoning is confined to a sharply defined outer rim, 0.1—0.2 mm. thick, of an albitic feldspar round a central core of oligoclase. The optical data for the plagioclase of a typical granite sample are $N_x = 1.536$, $N_y = 1.540$, $N = 1.545$, max. symmet. extinction in zone normal to (010) is -6°, optically positive, 2V very large; the composition seems therefore to be about An_{14}. Comparison of the optical data of the plagioclases from different parts of the granite show that their compositions all lie between An_{10} and An_{20} with a tendency towards the lower end of the range. No systematic variations in the plagioclases from different parts of the granite were recorded. The larger inclusions in the microcline have the same composition as the plagioclase in the groundmass. Zoning in these inclusions is usually absent or else incomplete.

Quartz

Apart from occurring in rounded tubules in microcline and vermicular intergrowths in myrmekite, quartz is an important constituent of the groundmass. It varies in grain size, occurring both as allotromorphic crystals as large as 3—4 mm., and as aggregates of grains about 0.1 mm. across, with irregular sutured margins. The larger crystals are anhedral to feldspar and have patchy, undulatory extinction even in rocks far removed from the numerous faults which traverse the granite. They appear to be formed by recrystallization of finer-grained aggregates as they contain inclusions of various minerals as well as smaller crystals of quartz with different orientations. Certain of the inclusions of quartz in microcline have what appear to be late overgrowths. It appears that two generations of quartz formation exist in the rock, the second being concomitant with the recrystallization of the feldspars.

Biotite

This mineral occurs in glomerogranular aggregates associated with sphene, ores and hornblende. It normally has pleochroism $X =$ pale yellow, $=$ reddish brown, $Z =$ dark brown, but varieties with $X =$ pale yellow, $Y =$ yellow green, $Z =$ dark green have been observed. Minute inclusions of zircon with pleochoic haloes are common.

Hornblende

Hornblende occurs both as euhedral inclusions in microcline and as subhedral crystals in the groundmass. It is pleochroic with $X =$ yellow green, $Y =$ olive green, $Z =$ dark green and the extinction angle cZ on (010) is 18°. Commonly it occurs intergrown with biotite which appears to replace and pseudomorph it.

Accessory minerals

The commonest accessory minerals are sphene, and ores in the form of euhedral crystals of magnetite and skeletal masses of ilmenite, partly altered to leucoxene.

Varieties of the granite.

The granite, although fairly homogeneous, is not entirely uniform over the 260 sq. km. of its outcrop. Various occurrences of fine-grained red or grey granite, mylonitic granite and coarse-grained granite are shown in fig. 2. Apart from these, the remainder belongs to one of two groups easily distinguishable in hand specimen which can conveniently be termed the "western" and "eastern" facies of the granite, respectively.

The Western Facies of the Granite

The whole of the granite west of the "Great Friction Breccia" and parts of it along the southern boundary east of the breccia are composed of this rock. Its modal composition is microcline 45 % +, plagioclase 22—23 %, quartz 20—21 %, ferromagnesian minerals approximately 10 %; these last consist predominantly of biotite although sphene, ores and hornblende together comprise 1—2 % of the rock. The phenocrysts of microcline are often more than 3 cm. long and tend to lie with their tabular faces parallel forming a fairly well-defined planar structure. The dark minerals occur in aggregates which give the rock a characteristic patchy appearance and which enhance the planar structure.

The Eastern Facies of the Granite

This type of granite is more variable than the western facies but is always redder in colour and has a massive appearance; in it the large microcline phenocrysts are less regular and crowd together interfering with each others development. In the north-east part of the granite the rock contains 53—55 % microcline, 20 % quartz, 20 % plagioclase, and 5 % ferromagnesian minerals, mainly biotite. Hornblende has not been observed in the eastern facies. This rock resembles the Grimstad granite more than it does the western facies.

A variant of the eastern facies is common between Åmli (3970 1512) and Grøsle (4058 1429). The rock contains slightly more biotite and the microcline phenocrysts are smaller (2 cm.). The texture is therefore more equigranular and massive although there is sometimes a very faint linear structure. North of this the granite contains larger phenocrysts (3 cm +) and less ferromagnesian minerals. To the south, the phenocrysts are again larger and a feeble planar structure develops. There are occasional occurrences of granite of the western facies especially along the southern boundary. No sharp boundaries, other than faults, exist between the two facies; they grade into each other over distances of the order of 1 km.

Fine-grained Varieties

Various fine-grained granites are indicated in fig. 2. True aplites are relatively rare and are confined to small dykes often in or adjacent to pegmatites. Fine-grained granites produced by cataclasis are much more widespread, e.g. the west side of Tovdalselva at Slettane (3916 1396), similar occurrences could have been shown along all the fault lines. Apart from these, there are numerous dykes and sills varying in extent from centimetres to dekametres, which are composed of a red, equigranular microgranite with a grain size of 1—2 mm. and a composition like that of the eastern facies of the Herefoss granite.

A much larger mass of fine-grained granite covers an area of 12 sq. km. on the north-east side of the main granite (see fig. 6). This is a massive, equigranular, red, microadamellite, containing roughly equal amounts of microcline and oligoclase. It is richer in quartz than the main granite and contains muscovite as a primary constituent. Its field relations are discussed below (p. 31).

Hybrid Grey "Granites"

Several occurrences of fine- or coarse-grained grey granite are indicated in fig. 2. These rocks are variable in composition and texture, and include coarse-grained porphyritic adamellites and fine-grained gneissic granodiorites. They are characterized by a high content of oligoclase and by the presence of 10—15 % of biotite and only slightly more quartz. Hornblende is invariably present as intergrowths with biotite and ores. A fuller discussion of the field relations of these rocks is given below (p. 21) where it is suggested that they are partly granitized inclusions in the granite. Their composition and texture seem to be consistent with this view.

Comparisons with the Grimstad Granite

The chief type of the Grimstad granite ,in hand specimen and thin section, is identical with the Herefoss granite occurring between Åmli (3970 1512) and Grøsle (4058 1429); i.e. massive granite of the eastern facies with phenocrysts of microcline up to 2 cm. across. The general similarity between the Grimstad and Herefoss granites has already been remarked upon by Barth (1947, p. 175). Oftedal (1945) gives the following approximate values for the modal composition of the Grimstad granite: quartz 20 %, plagioclase ($An_{10—30}$) 20 %, biotite 1—4 %, sphene 0.2—0.6 %, ores 0.1—0.5 % and apatite 0.02—0.1 %. Thus we can deduce that the content of microcline perthite must be about 55 % as he states, "In the main granite microcline perthite is the dominant constituent; the plagioclase content is about 20 %". (Oftedal, 1945, p. 295—296, translated by the writer.)

The main variety of the granite is very constant in grain size and colouring but medium-grained and fine-grained grey adamellites also occur. J. Bugge (1940, p. 91) referred to these small masses of darker rock in the Grimstad granite and suggested that they were formed by the assimilation of amphibolitic rocks. Oftedal (op. cit., p. 297) has also suggested that these dark rocks represent "granitization" of older rocks but thought it more likely that they were originally mica schists or micaceous gneisses.

Table I.

Analyses of the Granites.

	(1)	(2)	(3)	(4)	(5)	(6)
SiO_2	69.90	69.27	75.06	66.25	64.20	63.68
TiO_2	0.56	0.50	0.05	0.73	1.09	0.36
Al_2O_3	14.55	15.53	13.96	16.48	15.38	19.89
Fe_2O_3	1.59	0.96	0.55	2.21	2.55	0.70
FeO	1.07	1.15	0.87	1.96	3.76	—
MnO	0.04	—	0.03	0.06	0.09	—
MgO	0.88	0.55	0.12	1.01	2.42	0.13
CaO	1.63	1.56	1.05	3.26	2.85	1.38
Na_2O	3.90	4.28	3.59	3.45	3.54	2.35
K_2O	5.35	5.50	4.61	4.42	3.21	11.60
H_2O+	0.69	0.24	0.34	0.39	0.61	—
H_2O-		0.12	0.04	0.06	0.11	—
P_2O_5	0.15	0.03	0.02	0.07	0.12	—
F	0.41	—	—	0.08	—	—
CO_2	—	0.28	—	—	—	—
	100.52	99.97	100.29	100.33	99.91	100.15
O for F	—0.17	—	—	—0.03	—	—
	100.35	99.97	100.29	100.30	99.91	100.15

Localities

(1) Grimstad Granite, Strand Hotel, Fevik.
(2) Herefoss Granite, Reddal (Eastern Facies), Barth, 1947.
(3) Herefoss Granite, Espestøl (4991 1568) (Fine-grained facies).
(4) Herefoss Granite, Løland (3935 1526) (Western facies).
(5) Herefoss Granite, Stie (3992 1518) (Grey facies).
(6) Microcline from Herefoss Granite, Barth, 1947.

Table II.

Molecular Norms (Catanorms).

	(1)	(2)	(3)	(4)	(5)
Q	21.3	17.9	31.8	19.6	20.8
Or	31.9	32.7	27.5	26.3	19.5
Ab	35.3	38.7	32.6	31.2	32.7
An	6.5	6.4	5.0	15.7	13.7
C	—	—	1.4	0.3	1.4
En	1.9	1.5	0.3	2.8	4.6
Fs	—	0.4	0.9	0.14	2.7
Wo	0.3	0.5	—	—	—
Mt	1.4	1.0	0.6	2.3	2.8
Hm	0.1	—	—	—	—
Il	0.8	0.7	0.1	1.5	1.6
Ap	0.3	0.1	0.1	0.2	0.3

Table III.

Mesonorms.

	(1)	(2)	(3)	(4)	(5)
Q	23.6	19.8	32.8	21.8	25.2
Or	29.1	30.3	25.7	23.2	8.4
Ab	35.3	38.7	32.6	30.8	31.7
An	5.3	4.0	5.0	12.2	9.8
C	0.4	1.0	1.5	1.6	3.4
Bi	4.0	3.8	1.8	5.4	17.5
Mt	1.6	1.0	0.6	2.3	2.7
Ap	0.3	0.1	0.1	0.2	0.3
Sph	1.2	1.0	0.1	2.2	2.4

The minerals are as above except for Bi = Biotite, 1/8 $KMg_3AlSi_3O_{10}(OH)_2$, and Sph = Sphene, ⅓ $CaTiSiO_5$.

The chemistry of the Herefoss granite and comparisons with Grimstad granites.

Analyses of a specimen of the Herefoss granite and of the microcline in it have already been published (Barth, 1947). Table I presents new chemical analyses of the Grimstad granite (1), and the fine-grained facies (3), western facies (4) and grey facies (5) respectively, of the Herefoss granite (personal communication, Nilssen, 1961). The precise location of the granite whose analysis (2) was given by Barth (loc. cit.) is not known; Reddal lies at the south-eastern boundary of the Herefoss granite, near the southern end of Syndlevann (fig. 1). Thus the specimen analyzed undoubtedly comes from the eastern facies of the granite. Analysis (3) is of a specimen which was chosen as being typical of the fine-grained prolongation to the north-east of the main mass of coarse-grained granite.

For comparison, the analyses are expressed in Table II in terms of the molecular norm (Barth, 1955) using the C.I.P.W. normative minerals. As Barth (1959, p. 142) has pointed out, recalculations in terms of the C.I.P.W. norm are not entirely satisfactory as most granites contain minerals such as biotite and hornblende which find no expression in the conventional norm; the mesonorm he proposed is better suited for the purpose. The corresponding mesonorms are shown in Table III and the computed compositions of the alkali feldspars, given there, probably give a more realistic impression of the modal feldspars. In a further attempt to come closer to natural conditions, the titanium dioxide has been recalculated as sphene. These calculations have the effect of reducing the normative orthoclase and anorthite and slightly increasing normative quartz and corundum. As muscovite occurs in these rocks and the feldspars are slightly sericitized, at least part of the alumina in corundum might appear as muscovite in the mode: $2C + 5Or = 7$ muscovite.

The great similarity in composition between the Grimstad granite (1) and the eastern facies of the Herefoss granite (2) is at once apparent, but the western facies of the granite (4) is more mafic than either and the coarse-grained grey "granite" form is decidedly more mafic than the normal granite. The fine-grained granite is half as rich again in normative quartz as the remainder of the granite. As a working hypothesis it would not be unreasonable to regard these rocks as belonging to a simple magmatic differentiation series. We might then expect the fine-grained granite to be the last to crystallize; however it has a content of normative plagioclase intermediate in composition between that of the western and eastern facies. Presently it will be shown that the field relations of these grey "granites" are also inconsistent with this hypothesis.

The variation in composition of granites can conveniently be studied by comparison of the normative ratios of Q, Or and Ab of the various rocks. In fig. 3, the open circles represent the ratios of these three constituents for each of the rocks in Table II (catanorms) and the

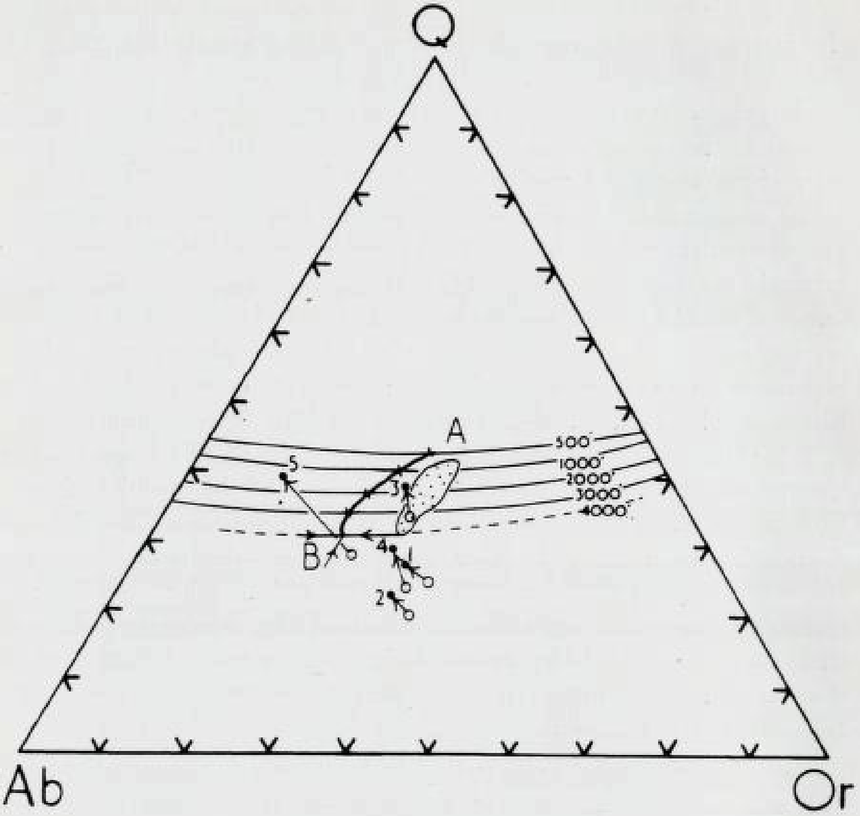

Fig. 3. Normative ratios of the analyses 1—5 in Table 1. The arrows combine the catanorm (open circle) and mesonorm (arrowhead). Superimposed is the effect of water vapour on the isobaric minimum in the system Ab, Or, Q and H_2O from 500—4,000 km/cm^2. The dotted area corresponds to the highest concentration of the projection points of granitic rocks, (Tuttle & Bowen 1958).
Ab-Or-Q forholdet i analyse 1—5 (Tabell 1).

arrowheads the corresponding ratios of the nesonorms from Table III. Also included in the diagram are data showing the effect of P.H_2O on the isobaric minimum in the system $NaAlSi_3O_8$—$KAlSi_3O_8$—SiO_2—H_2O (after Tuttle and Bowen, 1958, fig. 42), in terms of the molecular norm.

As Barth (1959) points out, if we are to make inferences about the genesis of a particular granite in terms of Bowen's "residual system of petrogenesis" (Bowen, 1937), we should use the mesonormative ratios rather than the catanormative ratios, as these reflect more closely the actual feldspars of the "residual melt". In these considerations we must neglect analysis (5) which contains less than 90 % normative Or, Ab and Q. The mesonormative ratios of the other four rocks all approach Bowen's thermal valley, but only the fine-grained granite has the same composition as the majority of granites, the others being poorer in quartz. We might conclude that the Herefoss and Grimstad have a chemical composition that could be formed by crystal-liquid equilibria. This must only be regarded as permissive evidence as there are no doubt numerous arkoses whose compositions would plot in the thermal trough.

In view of the fact that microcline is the dominant mineral in both the Herefoss and Grimstad granites, an interesting aspect of Tables II and III is that in every case the normative Or is less than the normative Ab. This implies that unless the granite contains other sodium-bearing minerals, which does not seem to be the case, a considerable amount of sodium must be present in the microcline microperthite. The analysis of microcline in Table I (6) certainly suggests that this is the case. (It corresponds to 68.4 % Or, 19.9 % Ab and 6.7 % An.) The manner in which the microcline was separated and prepared for analysis is not stated. It is possible that the majority of the sodium in this analysis represents perthic inclusions and only a small part of it is in solid solution.

Trace Element Studies

Oftedal (1958, p. 231) has shown that the large granites in Southern Norway, such as the Herefoss granite, are enriched in Ba relative to the surrounding gneisses. The granite pegmatite bodies, indigenous in the parent granites, are poorer in Sr and Ba than the granite proper and granite pegmatites outside the granites are even more deficient in these elements. He concludes that the large granites are anatectic as they contain much more Ba than could be derived from equal volumes of mixed gneisses. He proposes that all the pegmatites in the region developed from fluids which emanated from anatectic granites.

Taylor and Heier (1960, p. 57) have traced significant changes in the ratios Ba/Rb and K/Rb along a profile across the Grimstad granite. As the ratios decrease towards the centre of the granite they conclude that this points to a crystallization of the granite from the borders towards the centre. They have also observed that variations in these ratios occur in the Herefoss granite and that the offshoot of fine-grained granite to the north-east of the main mass has very low ratios. They conclude that a fractionation process has been operative in the Herefoss and Grimstad granites. They regard the fractionation as being a metamorphic process which took place at sub-magmatic temperatures and that the offshoot of the Herefoss granite consists of gneiss feldspathized by the Herefoss granite. In the opinion of the author, the distribution of these trace elements in these granites could equally well be due to progressive crystallization from a melt of granitic composition.

Temperature of formation of the Herefoss granite.

The distribution of alkalis between the different feldspars present in a rock may have an important bearing on its thermal history (Barth, 1934). Recently a great deal of work has been done on the temperature of formation of rocks in the PreCambrian of Southern Norway using Barth's twofeldspar geothermometer. Barth (1955, p. 124) originally gave the temperature of crystallization of the Herefoss granite at Reddal as 500° C but subsequently (1956, p. 29) revised this to 550° C and quoted the same temperature for the Grimstad granite at Fevik.

More recently Nilssen (1961) has carried out extensive investigations of the Herefoss granite along these lines and reports that the temperatures of crystallization range between 450°—600° C with a tendency towards the higher value near the boundaries of the granite. She has also observed that the microcline is perthitic, usually strongly triclinic, but in some cases exhibits a transition between triclinic and monoclinic symmetry. She concludes therefore that a temperature of about 500° C is about the correct order of magnitude for the temperature of formation of the feldspars.

The results published by Barth for the temperature of crystallization of other rocks in the general region are also of interest in this connection. He states (1956, p. 32) that the ordinary gneisses of the region crystallized at 400° C, the anatexe granites at 450° C, the Herefoss and Grimstad granites at 550° C, the small pegmatites at 570° C, the larger pegmatite dykes at 600° C and the augen gneisses at 640° C. The results obtained from these different groups of rocks appear to be remarkably consistent and this certainly would suggest that the figures obtained have some significance.

However geothermometry based upon the distribution coefficient of sodium between coexisting alkali feldspar phases can be criticized on various grounds. The temperature values are based on empirical data which have not been proved experimentally, especially at the lower end of the scale. It is not certain that ideal solid solution actually occurs. The effects of grain size, bulk chemistry and pressure may be appreciable. Finally there is the practical problem of determining the original alkali distribution when unmixing and recrystallization of an earlier feldspar phase has occurred. Thus the temperatures indicated may be considerably less than the highest temperature to which the rock has been subjected.

The low content of sodium in solid solution in the microcline can be viewed in the light of Tuttle and Bowen's classification of rocks whose composition lies near "petrogeny's residua system" (1958, p. 129). The Herefoss granite is a subsolvus granite (Group IIc), which completed crystallization at low temperatures. In the opinion of the author, the thermometric evidence only shows that the Herefoss granite did not crystallize directly from a magma. Two main possibilities exist: (a) it owes its origin to entirely non-magmatic processes, (b) since crystallizing from a melt its feldspars have adjusted to falling temperatures. The petrography and chemistry of the granite do not offer any decisive criteria as to which of these alternatives is correct. However the relative homogeneity of the granite is in favour of the latter process. The twinning of the microcline and its symmetry seem to have been inherited from an earlier monoclinic form, which also supports a magmatic origin. It will be shown below how field investigations also suggest that the granite went through a mobile phase.

Inclusions in the Herefoss granite.

Various enclaves in the Grimstad granite have already been mentioned in describing its petrology. Barth (1947, p. 177) also referred to inclusions in the Herefoss granite and described how they consists of gneisses in a high state of granitization. He wrote, "the schistosity usually conforms to the boundaries of the inclusions, but frequently they exhibit no sharp outlines; by transitions granite grades into gneiss; black amphibolite becomes grey and appears as ghost-like relics in the granite. Often diffuse granitic areas have developed within the inclusions . . . Mapping of the inclusions has not been attempted;

some of them are small, but it seems that others may be one or two kilometres long".

Several points in Professor Barth's excellent account can be amplified in the light of the present studies.

1. The enclaves are commonest near the boundaries of the granite both in the coarse-grained and the fine-grained types.
2. Near the boundaries of the granite the enclaves are frequently heterogeneous and randomly oriented and so resemble an intrusive breccia (see Pl. I, fig. 2).
3. Enclaves occur more frequently in the eastern facies than in the western facies of the granite. Relatively few occur west of the "Great Friction Breccia", (fig. 2) and these are usually of grey "granite".
4. Small clots of biotite, a few cm. long, which are often parallel to the planar structure of the granite, probably represent small inclusions.
5. Single crystals of hornblende, intergrown with and partly replaced by biotite also occur; these are probably xenocrysts.
6. Although orientated small inclusions occur, the dimensional and internal orientation of the larger inclusions is apparently unrelated to the structure of the granite or the surrounding rocks. An enclave which measures 2 km. x 0.5 km. trends N.E.—S.W. at Fossheiene (3965 1495). It consists of a banded series of gneisses which strike 130° and dip south-west at 40°—50° (fig. 2).
7. Many of the inclusions have sharp boundaries against the granite. Some of the larger ones have sharp boundaries in places and at other gradational relationships to the granite. The surrounding granite is then crowded with numerous smaller inclusions which show a higher degree of assimilation.
8. Dark micaceous "ghosts" or skialithic relics are common and often are several metres across. Porphyroblasts of microcline perthite, identical to those in the normal granite, occur within them (see Pl. II, fig. 1) and occasionally patches of coarse-grained granite, usually in the form of rounded masses, have formed within the skialiths. Paradoxically these patches of granite have a lower ferromagnesian content than the normal granite, but have distinct outlines emphasized by the development of a rim, a few mm. thick, enriched in biotite.

9. Various more or less diffuse patches of grey micaceous fine- or coarse-grained "granite", indicated in fig. 2, are thought to represent hybrid granites due to "assimilation" or "granitization" of xenoliths. The petrography and chemistry of these hybrid "granites" has already been described (p. 12). The largest occurrence, at Dalane in Risdalen (3934 1485), is almost 1 km. long and consists of a complex of small lenses or patches of grey "granite". Normally this rock forms such irregularly shaped lenses or angular patches but sometimes dykes. Large porphyroblasts of microcline are occasionally developed in these grey rocks and apophyses of coarse-grained red granite penetrate into it. Usually a zone of biotite enrichment occurs at the contact of the two rocks and the corners of the angular patches appear as dark shadowy relics in the red granite. These inclusions of grey "granite" appear to be in arrested stages of assimilation or granitization by the coarse-grained granite.

   At Birkedal (4021 1505)an interesting inclusion of grey "granite" forms a mass several hundred metres long. It is a coarse-grained granodiorite which grades into the normal eastern facies. Similar rocks ranging in composition from granodiorite to quartz-diorite also occur at Kollandsvann (4025 1512) and at Håland (4009 1483). Subidiomorphic porphyroblasts of antiperthitic oligoclase-andesine are the dominant feldspars and intimate intergrowths of biotite, hornblende and chlorite are the chief ferromagnesian minerals. Textural relations show that the mica is replacing and pseudomorphing the amphibole. As these rocks lie on the strike off a broad belt of amphibolites to the north (see figure 1), they could represent granitized relics of amphibolite but the evidence is not conclusive.

10. Although the majority of the inclusions in the granite can be matched with similar rocks immediately adjacent to its boundaries, some of them are exotic. i.e., are hypoxenoliths in the terminology of Goodspeed (1948). Hypoxenoliths occur just east of Søre Herefoss (3968 1501) at the northern end of the large inclusion at Fossheiene, described above. Here the granite is crowded with xenoliths which diminish in size and frequency towards the north and become more numerous towards the south where they coallesce into the large xenolith at Fossheiene.

Laboratory studies show that some of these inclusions are gneisses belonging to the granulite facies. For example, at the bend in the road near an old sawmill east of Søre Herefoss, is found an inclusion about 50 m. long consisting of banded gneisses. One of the darker bands is a fairly equigranular brownish grey rock with a grain size of 2 mm. and a faint gneissic texture. Anesine feldspar (about An_{35}, maximum symmetrical extinction angle perpendicular to (010) is 18°) in the form of equant, hypidiomorphic grains with a slight degree of saussuritization, comprises about half the rock. In places intergrowths of biotite and greenish-brown hornblende are the only dark minerals. Aggregates of two types of pyroxene, 3—4 mm, across, also occur in which clino-pyroxene sometimes surrounds a rhombic variety which appears to be hypersthene (pleochoism X = pale pink, Y = yellowish, Z = pale green). The clino-pyroxene is colorless to pale green, biaxial positive ,with large 2V and extinction c Z is 40°; it is probably diopsidic (Pl. II, fig. 2). These pyroxenes are partly intergrown with hornblende which may be diaphthoretic as it appears to replace and pseudomorph the pyroxene. Magnetite and apatite are present as accessory minerals. The banded nature of this rock and its mineralogy and texture are different from any of the altered diabases seen in the region. It also lacks the ophitic texture and the pigeonite and labradorite of the hyperites, so that it seems difficult to derive it from the granitization of these rocks. However in hand specimen and thin section it is identical with an arendalite from Heidal, west of Arendal, and according to J. Bugge's descriptions (1940, p. 83) belongs to the intermediate division of the arendalite-charnockite group.

Further confirmation comes from the east end of a pegmatite quarry mentioned by Barth (1947), about 400 m. south-east of the first locality (3969 1497). One of the inclusions consists of a coarse-grained granodiorite gneiss containing antiperthitic feldspar (about An_{15}), quartz, biotite, and hypersthene with accessory garnet, magnetite and apatite. This rock is certainly neither a diabase nor a hyperite but appears to be a charnockite similar to those belonging to the acid division of the arendalites (J. Bugge, 1940, p. 86).

In spite of their olive-brown colour ,it was not appreciated in the field that these inclusions were arendalites so their full extent was not determined. By far the majority of the author's specimens from the complex of inclusions at Fossheiene belong to the amphibolite facies of regional metmorphism.

Structural environment of the granite.

The PreCambrian strata of Southern Norway are characterized by complex structures and a high degree of metamorphism. Wegmann (in Holtedahl, et. al., 1960, p. 6) has recognized three main episodes in the structural history of the general region — an older deformation at shallow level, deformation at deeper level during which migmatites formed and a third period when the rocks were uplifted into the zone of fracture and broken by a widespread system of faults.

Structural studies in south-east Aust-Agder (Elders, 1961) confirm this view. The general strike of rocks throughout the majority of the region trends 030°, especially in the eastern part. North-east of the Herefoss granite in the district between Mjåvann and Trevann there exists a complex of major, apparently cylindroidal, almost isoclinal folds with subvertical axial planes striking east of north, the axes of which, with one exception, plunge south-south-west at angles up to 45°. Two of these folds, those lying nearest to the granite, are shown in figure 2.

South-east of the granite to the west of Lillesand, just off the border of the map, the structure is dominated by a major fold which has been designated the "Præsthalt-Kjellingland antiform" (Elders, 1961). Across it there is a reversal of dip operative and persistent over a wide area and the fold probably continues for 25 km. southwards along the axis. Thus it seems that, in the general region east of the "Great Friction Breccia", major folds with moderate plunge and steep axial planes, almost parallel to the general strike of the gneisses are commonly developed. These folds appear to be older than the migmatization and are believed to be the oldest structures in the area.

The emplacement of the Herefoss (and probably the Grimstad granite too) modified this structure considerably. Round the whole of its periphery, with the exception of that part formed of fine-grained in the north-east, the Herefoss granite appears to be surrounded by a conformable envelope of layered gneisses. This has been achieved by widespread folding into various fairly gentle major folds.

South-west of the granite in the vicinity of Oggevann (3840 1415) the folding takes the form of an S-shaped arc covering 40—50 sq. km., the major part of which is an open synformal fold with a hinge near Vesterheia (3850 1405). East of the "Great Friction Breccia" the strike of the foliation again swings into conformity with the southern boundary of the granite in what appears to be another approximately cylindroidal flexure in the vicinity of Grimevann (3960 1356). However the position of the axial trace shown in fig. 2 must be regarded as tentative as not enough is known about the structure of this region and in particular the role of faulting is not clear.

The relationships to the north of the Herefoss granite are more complex. Part of the northern boundary is shown in fig. 6 where it will be seen that the foliation of the gneisses is not deflected by the fine-grained prolongation of the granite to the north-east. In this region the general strike of the gneisses is the regional orientation common to most of the rocks east of the "Great Friction Breccia". However, north-west of the granite the foliation of the rocks, where observed, is parallel to the boundary of the granite. For example, the foliation between the western side of Herefossfjord (3971 1562) and Bjellandsvann (3948 1562) strikes east-west and dips generally at steep angles away from the granite. It is also interesting that this same orientation can be observed immediately east of the fjord in the patch of gneisses between the main granite and its northerly fine-grained extension (fig. 2). No indications of large-scale folding immediately north-west of the granite were seen in the field or on air photographs.

The Oggevann and Grimevann folds appear to have formed in connection with the emplacement of the granite. North of the granite it appears that such large flexures did not accompany the granite formation but, except for near the fine-grained facies, the strike of the gneisses does swing into conformity.

In this area immediately north of the granite minor cross-folds are well developed. In general, it appears that three phases of minor folding and lineations are present in the region, the youngest of which occurred in connection with the faulting which post-dated the granite. There exist two main period of minor folding, one of which appears to be congruous with the major north-south folds. The later one consists of chevron folds which were synchronous, at least in part ,with the pegmatite formation associated with the emplacement of the granite. These chevron folds probably represent minor, but widespread, crumpling during the emplacement of the granite. The stresses north of the granite seem to have been relieved by the multiplication of these minor folds rather than by the development of major ones.

Contact relations of the granite.

In his excellent account of the Herefoss granite, Barth (1947, p. 18) noted that the contact with the gneisses is usually sharp and that "the schistosity of the gneisses swings around the granite body and orients itself parallel to the walls so that no typical intrusive contact can be seen". This description is correct in many respects but requires some qualification.

The attitudes of the contacts as determined during the present studies are shown in fig. 2. The fact that such figures can be given for the inclination of the walls of the granite body is a reflection of their sharp nature. However care must be exercised in extrapolating these attitudes in depth as only a limited vertical range of exposure is available for observation.

The nature of the contacts of the granite with the gneisses are of two distinct types, although there are variations within these extremes. On the one hand there are contacts which are sharp and, on a broad scale, parallel to the strike of the gneisses but which on a smaller scale are strongly discordant. Where the strike of the gneisses has not been forced into general conformity with the boundary of the granite, especially to the north, the situation is much more complex. Fine-grained facies of the granite are developed and granite material seems to be intimately interwoven with the fabric of the country rocks forming a typical migmatite. Thus, in this case, the contacts are conformable on a small scale but disconformable on a large scale.

Sharp Contacts

As can be seen i fig. 1, the eastern, western, most of the southern and parts of the north-western boundaries of the granite are apparently concordent to the strike of the granite. Detailed examination of these contacts, however, shows that this appearance is to some extent illusory and that the contacts are intrusive. For example, the eastern margin of the granite is well exposed in a line of cliffs rising 100 m. above the surrounding quartzites, mica schists and amphibolites. In these cliffs numerous examples of discordant contacts occur.

East-west vertical sections through the contact at the north-western shore of Syndlevann (4059 1430) are shown in figs. 4 A and 4 B. The coarse-grained, red granite, seemingly without directional structures, has a sharp, discordant contact with a foliated, light grey, medium, to fine-grained quartzite containing a few, scattered microcline porphyroblasts, which is faulted against biotite schists and amphibolite. The contact dips outwards at 80°—85°, whereas the dip of the quartzites and schists is only 70°—80°, so that the granite gradually transgresses the layering of the metamorphic series as the contact ascends the cliff. This transgression is quite unrelated to the faulting referred to above, which dies out before the contact is reached.

The mica schist and amphibolite are intruded by an irregular, dilational dyke, 1 m. thick. This dyke is an offshoot of a sill of fine-grained granite. The apparent relationship between the dyke and the sill, which is at least 60 m. thick, is show i fig. 4 C. A huhdred metres further north, the sill, which has almost horizontal contacts, can be seen to step over the mica schist and amphibolite (fig. 4 D). The contacts of this rock with the coarse-grained granite are sharp and uniform, cutting across all the other rocks, as shown in the sketches. The sill contain irregular, diffuse patches of coarse-grained granite which resemble in every way the coarse-grained granite both above and below the sill. The sill rock has the same composition as the coarse-grained granite whereas the dyke is a microgranodiotite. However the two rocks grade into each other. Similar dykes occur in the metamorphic rocks further north.

The strike of the metamorphic series is parallel to the contact along the whole of this eastern boundary, but the dip is frequently divirgent. Another excellent east-west section through the contact is exposed at the north end of Tonnesølvann (4063 1487), where the attitude is entirely different. Typical coarse- grained red granite overlies the metamorphic rocks with an irregular junction which dips westwards at about 45°, as shown in fig. 4 E. Although the contact is sharp, there are no indications of this being a tectonic junction and apophyses of coarse-grained granite penetrate into the quartzite and schist. Numerous large enclaves of quartzite, mica schist and amphibolite form a large-scale agmatite near the contact (see fig. 4 F). These epixenoliths, derived from the local metamorphic series, by their heterogeneity angular shape and random orientation, give the granite an intrusive aspect. Although not far travelled, they appear to be displaced relative to each other.

The western contact of the Herefoss granite resembles the eastern contact in that, on a broad scale, the strike of the gneisses follows the

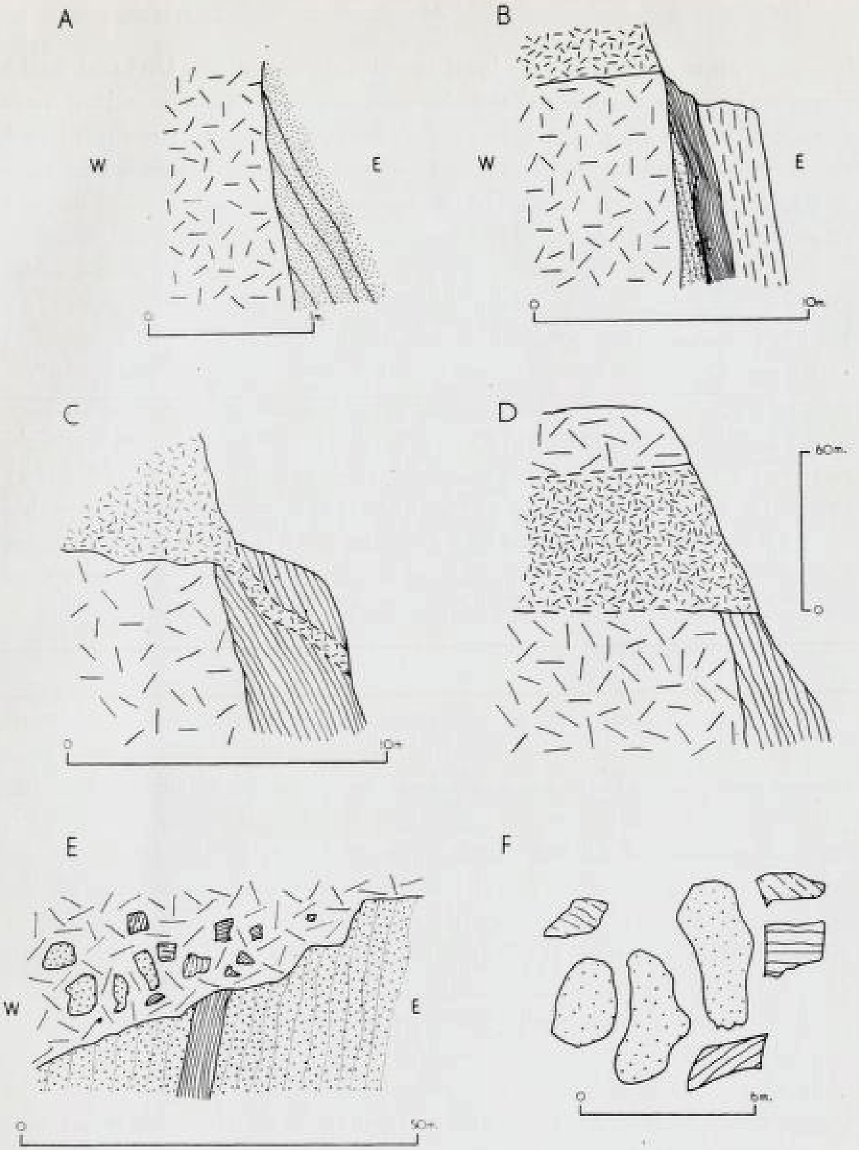

Fig. 4. Field sketches of the eastern contact of the Herefoss Granite.
A& B. Vertical exposures of the contact of the granite with quartzite (dots), mica schist (lines) and amphibolite (dashes).
C & D. Relation between fine- and coarse-grained granite at the same locality. The broken line is an inferred boundary.
E. Vertical section through the contact at Tonnesølvann. Coarse-grained granite with inclusions overlies quartzite and micaceous amphibolite.
F. Some of the enclaves at the same locality.

boundary, but again there are local angular discordances. Unfortunately along its western margin the granite does not form an upstanding mass so that although it is relatively easy to map, as exposures are good and the contact quite sharp, the attitude of the contact in depth can only be determined in a few places. At these points, the contact dips inward at moderate angles (see fig. 2).

The analogue of the situation at Tonnesølvann can be seen on the western boundary at Lunden, west of Støre Heimdalsvann (3902 1503). Normal coarse-grained granite overlies the regional migmatites and banded gneisses with a sharp contact dipping eastwards at 30°—40° (Pl. III, fig. 1). Similar contact relations can be observed further north at Simonstad (3916 1530) in a vertical cutting about 15 m. high. South of Lunden, the contact is steeper and at Breidtjern (3895 1458) and as far south as Verevann (3890 1429), it dips at 60°, conformable to the foliation of the gneisses and migmatites. Along the south-western boundary, west of the "Great Friction Breccia", the granite again forms cliffs above the surrounding rocks, which are chiefly banded gneisses. Here the contact again appears to be conformable, dipping towards the granite.

The southern boundary of the granite, east of the "Great Friction Breccia", is somewhat gradational in places. This is particularly true near Anderhuset (3919 1377), 2 km. north of Birkeland, where the coarse-grained granite appears to have a migmatic relationship with banded gneisses to the south. It is possible to draw a line for the boundary of the granite on the scale of the map presented, at the transition from granite to migmatite, to gneiss takes place in less than 20 m. Further eastwards at Øygarden (3933 1379) and Mandfaldmyren (3974 1369) the coarse-grained granite is rich in xenoliths near the contact, which appears to be abrupt and parallel, in strike at least, to the foliation of the banded gneisses.

In this region the contact is nowhere discordant to the strike of the gneisses. If the contact is also conformable in depth, it dips inwards at 60°—70°. At the south-east margin of the granite between Eftevann (3998 1364) and Nerebø (4040 1376) the strike of the surrounding rocks again swings round keeping parallel with the contact. In the Nerebø district, and continuing further north, the granite again forms steep cliffs above quartzites and mica schists which dip steeply away from the granite.

The Northern Boundary of the Granite

The foliation of the gneisses between the western side of Herefossfjord (3971 1562) and Bjellandsvann (3948 1562) strikes east-west, and dips generally at steep angles away from the granite. The contact itself appears vertical or else dipping steeply inwards. At the contact, a fine-grained, massive variety of the Herefoss granite forms an irregular body between 20 and 40 m. wide, and has a gradational boundary with the normal coarse-grained granite.

The relationships is similar immediately south-east of Bjellandsvann, where a zone of fine-grained granite, 50 m. wide, separates the coarse-grained granite from the "regional" migmatites. The coarse-grained and fine-grained varieties of the granite have a variable relationship to each other; in some places they grade into one another, while in others sharp contacts can be observed. Along its outer limit the fine-grained granite is crowded with agmatitic inclusions and again their random orientation and heterogeneity suggest that they have moved relative to each other.

A transverse section across the north-west boundary of the granite can be studied in excellent road cuttings along the western side of Kyllandsvann (3910 1540), and the relationships are sufficiently interesting to be worthy of a more extended description. In this locality the coarse-grained granite has a complicated transitional relationship over a belt which extends for 200—300 m., perpendicular to the "boundary". A hundred metres south of the lake the normal coarse-grained facies of the granite with a well-defined planar structure is developed. This passes northwards into a more micaceous, coarse-grained "hybrid" dark granite at the southern tip of the lake. For the next 150 m. fine-grained, pinkish-grey adamellitic granite predominates.

To the north, coarse-grained red granite again occurs. Both the contacts of the fine-grained grey "granite" with the coarse-grained Herefoss granite are sharp but irregular and in the fine-grained granite are dyke-like masses and lenticular patches of the coarse-grained granite, ranging from centimetres to metres in width. At the contacts of these red and grey rocks a rim of biotite a few mm. wide is invariably developed — a "basic front" in miniature. Furthermore the planar fabric of the fine-grained adamellite is conformable to the margins of the coarse-grained granitic patches (see fig. 5).

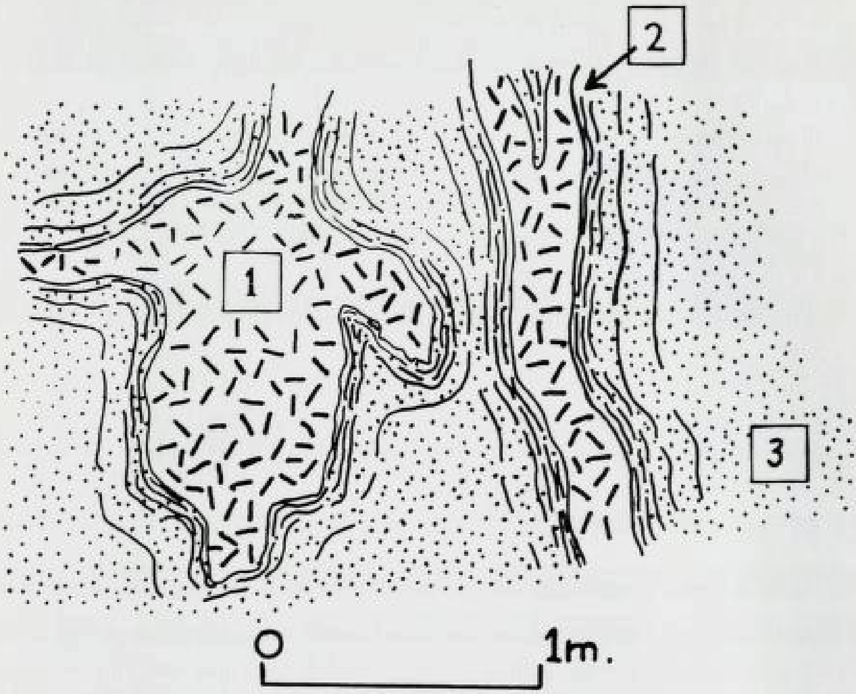

Fig. 5. Relation between red granite (1) and grey granite (2) with biotite-enriched zones (3), Kyllandsvann.
Forhold mellom rød (1) og grå (2) granit, anriket i biotit (3), Kyllandsvann.

To the north, the coarse-grained granite has the usual sharp, but irregular, contact with fine-grained grey "granite" which forms the matrix of an agmatitic migmatite grading into "regional" migmatites with a "lit-par-lit" structure. As usual, all these rocks are cut by late granite pegmatite and aplite dykes and even later quartz veining. The migmatites near the granite boundary at Kyllandsvann are characterized by extreme variability in the orientation of their foliation. These does not appear to be a strong tendency for the strike to conform to the boundary of the granite near the "contact".

The question of prime importance to the interpretation of the contact phenomena at Kyllandsvann is the relationship, if any, of the fine-grained grey "granite" to the main Herefoss granite. Similar rocks exist as isolated bodies within the main granite at several localities (fig. 2). However the same rock is frequently found in the "regional" migmatites far outside the Herefoss granite, commonly associated with granitic augen gneisses. In places it appears to be older, in other places younger, than the augen gneisses and migmatites. However the grey "granite" within the Herefoss granite almost invariably appears to be an older rock which has been granitized or assimilated. It seems that these widespread grey rocks originated in different ways at different times. Some of them may be granitized relics of older rocks and others intrusive rocks produced in the later stages of the regional migmatization. The occurrence of grey "granite" at Kyllandsvann may possibly be fortuitous but, in the opinion of the writer, it is more likely that it is a hybrid rock produced by the interaction of the Herefoss granite with the country rocks.

An even more complex boundary occurs on the north side of the granite, east of the "Great Friction Breccia". A large prolongation of fine-grained, red granite separates the main body from the country rocks (fig. 6). This rock is a fine-grained variety of the main granite, and differs from the grey "granite" gneiss, of Kyllandsvann, both in its mineralogy and absence of foliation.

Barth (1947, p. 177) noted that the north-eastern part of the granite is heterogeneous and that fine-grained and coarse-grained types may grade into each other or show sharp boundaries in this region. He was not able to determine the extent of the fine-grained granite or differentiate between the two types on his map (op. cit., fig. 2). The distribution of the two rocks and their relationship to the country rocks is shown in fig. 6, where it will be seen that the most northerly occurence of the main part of the coarse-grained granite is a Engebuvei on the east side of Herefossfjord (3975 1543). This point is more than 1.5 km. south of the boundary of the granite of the western side of the fjord, the displacement being due to the faulting associated with the "Great Friction Breccia".

Along the road to Engebu farm, rocks rather similar to those at Kyllandsvann occur, exhibiting agmatitic, nebulitic and embrechitic structures. Their general strike is east-west, parallel to the boundary of the coarse-grained granite. At the farm, the strike of the migmatites changes to north-south and immediately east of this point the fine-grained northern extension of the Herefoss granite begins. The transition from migmatite in which the granitic neosome comprises less than 50 % of the rock, to massive fine-grained, red granite occurs in the space of a few metres.

Within the fine-grained prolongation, the granite is remarkably homogeneous over the wide expanse of its outcrop but some diffuse areas of coarse-grained granite, seldom more than 10 sq. m. in area, are locally developed and aplitic or pegmatitic veins also occur. The positions of some of the larger inclusions of country rock are shown; only one of them (north-west of Espestøl) is large enough to appear as a discrete body on the scale of the map presented (fig. 6). Many of these enclaves are several dekametres long and they are particularly numerous near the margins of the fine-grained red granite.

The central portion of the fine-grained granite is particularly uniform and inclusions are scarce. Towards the margins of the body they become more numerous and narrow "tongues" of fine-grained granite penetrate for long distances along the strike, pinching out away from the main mass of the granite. They tend to occur between bands of different lithology, and when not following the strike, cut across it almost at right-angles. This relationship is repeated on both a large and small scale.

Pl. III, fig. 2 shows the end of one of the tongues of fine-grained granite pinching out against the gneisses. The discordant veins of granite which radiate out from the main "tongue", in the lower part of the picture, are clearly dilational but in their thinner parts, the veins tend to be pegmatitic. Pl. IV illustrates one of the points at which the contact is at right-angles to the strike of the gneisses, between two tongues of granite. The brecciated nature of the amphibolite is particularly striking and isolated fragments have been detached from the main mass.

The contact of the whole mass of fine-grained granite with the country rocks duplicates this relationship, especially along its northern and south-western margins, and several smaller, isolated bodies of fine-grained granite have similar boundaries. The emplacement of this fine-grained granite appears to have occurred in such a way that the surrounding gneisses were not thrust aside but rather incorporated in, or replaced by, the fine-grained granite. Many of the larger inclusions near the contacts retain their original orientation and show a kind of ghost stratigraphy. In other cases an agmatite with heterogeneous, randomly-orientated, angular fragments is developed. Brecciated fragments of gneiss in a matrix of granite have been observed which fit together like pieces in a jigsaw puzzle. Small enclaves, although disorientated as regards their internal structure, sometimes have a rough dimensional orientation, which is parallel to the boundary of granite with the

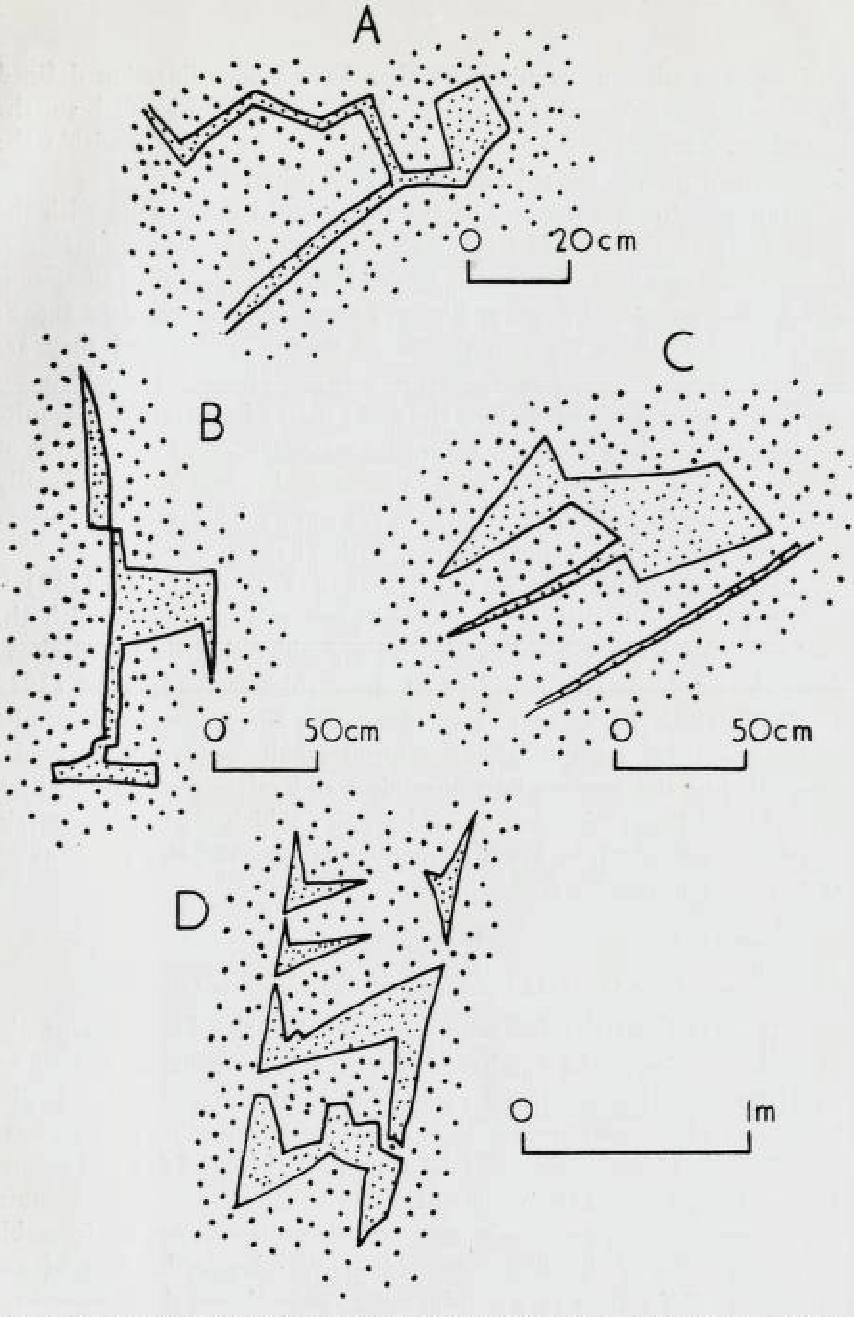

Fig. 7. Dykes of fine-grained granite in coarse-grained granite from various localities on Toplandsheia.

Finkornete granittganger på Toplandsheia.

3 a

gneisses. The adjacent granite may then have a poor lineation defined by the larger microcline crystals which is also subparallel to the boundary. These features suggest that some of the enclaves within the fine-grained granite moved relative to each other.

The approximate boundary of the fine-grained red granite with the main mass of the Herefoss granite to the south is shown in fig. 2. Near this boundary the coarse-grained granite contains numerous dykes of fine-grained granite. Some of these are illustrated in fig. 7; their angular shapes are reminiscent of tension gashes and they are undoubtedly younger than the main granite. These dykes widen towards the north and merge into the main mass of fine-grained granite at the position shown in fig. 1 for the boundary. This confluence of dykes occupies a belt 4—5 m. wide in horizontal extent but occasionally the boundary is indistinct and there appears to be a gradual passage from coarse- to fine-grained granite, without sharp contacts.

The contact of the granite south-west of Toskedal (4030 1532) is rather different in that coarse-grained granite is in contact with the gneisses. This contact is migmatic and resembles that described above from the south-eastern boundary of the granite at Anderhuset (3919 1377). Dark, hybrid, coarse-grained granite, fine-grained red granite and epixenoliths of amphibolite and quartzite all occur in close association. Within the surrounding quartzites and micaceous amphibolites, several large lenses of coarse-grained granite, which themselves contain xenoliths, occur. There are also many smaller ones, the positions of which are indicated by crosses in fig. 2.

Discussion on the Contact Relations of the Herefoss Granite

It is clear from the foregoing account that the formation of the Herefoss granite could not have occurred by the granitization of an equal volume of the regional rocks. The emplacement of the granite involved an enormous increase in volume; the surrounding gneisses have been pushed aside and thrown into a number of large folds and countless smaller ones so that on a broad scale the contacts are conformable. To the north of the granite the strike of the gneisses is not conformable to the outcrop of the coarse-grained granite; herein lies one of the interesting differences between the coarse-grained and the fine-grained granites. Whereas round most of the perimeter of the Herefoss granite, the gneisses are conformable to the contact on a large scale, but discordant on a small scale, the relationship of the gneisses to the contact of the fine-grained granite is exactly reversed.

Barth regarded the contact phenomena north-east of the granite as being proof of the petroblastic origin of the Herefoss granite. He wrote (1947, p. 178), "Thus an area of fairly homogeneous granite by gradual transitions is transferred into a complex of augen gneisses and fine-grained gneisses interwoven with ridges of pegmatite and lenses of aplite". After discussing the augen gneisses in relation to the breccia, he concluded (op. cit., p. 179)that "by gradual transitions it (i.e. the Herefoss granite) shades into augen-gneisses, and the field evidences indicate that the same agents that made the feldspar augens grow in the gneisses, also made all feldspar crystals grow in the Birkeland (Herefoss) granite".

If one thinks in terms of kilometres only, one might perhaps describe the coarse-grained granite as grading through a fine-grained variety into regional gneisses and migmatites, but such a description would, in the opinon of the author, be misleading. The main body of the granite is separated from the gneisses by a large mass of homogeneous fine-grained granite. Furthermore, no augen gneisses, other than isolated occurrences a few metres across, are developed within 5 km. of the north-eastern boundary of the granite. The nearest occurrence of augen gneisses in any quantity is north of Herefoss on the west side of the "Great Friction Breccia" (3976 1591); and these, as will be shown presently, belong to a different structural level (see p. 42).

The following facts must be taken into consideration: (1) The fine-grained granite is a relatively homogeneous body except where crowded with inclusions near its outer limits. (2) Its composition is similar to that of the main granite, being only slightly more silica rich and poorer in alkalies than the eastern facies (table 1, p. 13). (3) The dykes of fine-grained granite in the surrounding gneisses are dilatational. (4) Although randomly orientated, angular inclusions are seen in the fine-grained granite, many of them appear to be displaced relatively little with respect to the regional trends. (5) Both sharp and gradational contacts exist between the coarse- and fine-grained granites. (6) Whereas patches of coarse-grained granite within the fine-granite are diffuse, well-defined dykes of the latter penetrate the former.

It seems, therefore, that the body of fine-grained granite is genetically related to the main Herefoss granite, and was formed later than the main body. The alternative seems to be that this is an older rock in which large alkali feldspars did not form during the petroblastesis which allegedly formed the Herefoss granite. This latter suggestion is rejected in the light of the evidence presented above. The agmatitic xenoliths, in the opinion of the writer, indicate that the rock passed through a liquid, or at least a plastic stage. However the large numbers of inclusions, near the margins of the body, which have not been displaced, and the peculiar migmatic relations to the country rock indicate a relatively peaceful mode of emplacement. It is difficult to imagine how a viscous silicate melt could penetrate the country rocks in this way. Possibly this fine-grained granite crystallized from the later, more mobile phases of a magma which was also the parent of the main Herefoss granite. It is perhaps even more likely that it was partly formed by the interaction of these late-stage emanations from the magma upon the country rocks.

The internal structure of the granite.

Planar and Linear Structures

Barth (1947, p. 177) was of the opinion that the Herefos granite is massive and wrote, "In most places one can see no indication of either flow or foliation". The present field studies have shown that, on the contrary, the western facies of the granite, in particular, has a well-marked platy parallelism which manifests itself in one or more of the following ways: (a) tabular microcline crystals lie with their crystal faces parallel; (b) there are parallel clots or nests of biotite crystals; (c) enclaves are arranged in parallel planes; (d) thin layers of granite deficient in mica are present. Of these factors, the first is by far the most common.

Planar structures also occur in the eastern facies of the granite, but at best are never strongly developed and structures of type (a) are usually absent. Planar structures of type (c) are most common adjacent to enclaves and are probably inherited from them. Both feldspar and quartz crystals frequently tend to be elongated and occasionally exhibit a feeble lineation which, in the eastern facies of the granite, is unrelated to any visible planar structure. In the western facies, this linear fabric lies in the plane of platy parallelism.

The planar structure is present over the whole of the granite west of the "Great Friction Breccia" and is also developed in the southern part of the granite to the east of it (see fig. 2). In the north-east part of the coarse-grained granite, the planar structure is either absent or only feebly developed with variable orientation. Elsewhere it is most strongly developed near the boundaries of the granite and is concentric to them with only a few exceptions. Apart from this general conformity of strike of this structure to the contacts, the only other systematic variation in its attitude is that, in the western facies of the granite, the dip lessens and the strike becomes more variable towards the centre of the granite.

The linear structure of the granite is seldom obvious so that it is usually necessary to make a careful scrutiny at each exposure before it becomes apparent, if it is present at all. For this reason it is undoubtedly more widespread than fig. 2 suggests; It has not yet been studied exhaustively. The measurements that have been made show that at many places, on both sides of the "Great Friction Breccia" it strikes 120°—140° and usually plunges at 20° or less. This is especially true on the plateau at Toplandsheia (3980 1529) where this direction is also the dominant trend of aplite dykes. However in other places other orientations have been observed and further work is required before more authoritative statements can be made on the orientation of this structure.

Discussion

Planar and linear structures similar to those in the Herefoss granite are characteristic of many granite bodies. After the classic researches of H. Cloos, they have long been regarded as "primary flow structures" (Balk, 1937, p. 7) or "caracteristiques orientées de la phase plastique", (Raguin ,1957, p. 96) formed during the consolidation of a granite magma. However, Professor Barth is of the opinion (verbal communication, 1958) that they do not represent "granittektonik" (i.e., in the sense of Cloos). If we accept this postulate, the following possibilities remain: (a) the structures are inherited from older rocks which have been transformed in situ (e.g. by solid diffusion); (b) the structures were formed due to the plasticity of the environment during granitization; (c) they are deformation structures younger than the consolidation of the granite.

We can reject the first possibility in the light of the contact relations previously described. Furthermore the phenomena described as platy structures bear no sign of brittle deformation; some degree of plasticity seems to be inherent in their formation. Processes falling into the category (b) might well produce structures indistinguishable from those formed during the cooling of a magma. A high degree of mobility is not necessarily implied.

The Jointing of the Herefoss Granite

The Herefoss granite has a well developed system of joints which remains remarkably constant over the whole of its outcrop. No systematic variations in the attitude of joints with respect to the planar structures were observed and the joint pattern appears to be quite independent of the boundaries of the granite.

The granite has a well-defined system of vertical joints, with much less regular, flatlying joints. During the first attempt to determine the joint pattern of the granite, measurements were made of the joints on a traverse from the centre of the granite at Åmli (3967 1504) to its eastern boundary on the west shore of Syndlevann (4059 1431), a distance of 13.5 km. The technique employed was to stop every 200—300 m. and make several measurements of joint orientation. Joints were chosen for measurement which did not show slickensides or other traces of movement. Small faults are extremely numerous and there is a complete transition from such faults to joint planes on which movement has occurred.

It was found that the joint system was surprisingly regular, with two dominant sets of vertical joints. A series of stereographic projections showing the poles to joints was prepared as the traverse progressed but there was no significant difference in the joint direction over the whole section, from the centre of the granite to its boundary. The results for the different subareas are therefore combined in fig. 8 A. It shows that the dominant trends are subvertical joints striking 115° and 028° respectively.

On the same traverse a number of belts of brecciation and small faults were observed. Their orientation is shown in fig. 9 B and the percentage of fault azimuths occurring in each direction is also indicated. Often it is difficult to determine the hade of these faults and many of them are arbitrarily shown as vertical in the absence of other information.

Numerous larger faults and other tectonic lines are indicated in fig. 2. All of these are obvious on air photographs and within the granite most of them have been investigated in the field. An analysis of

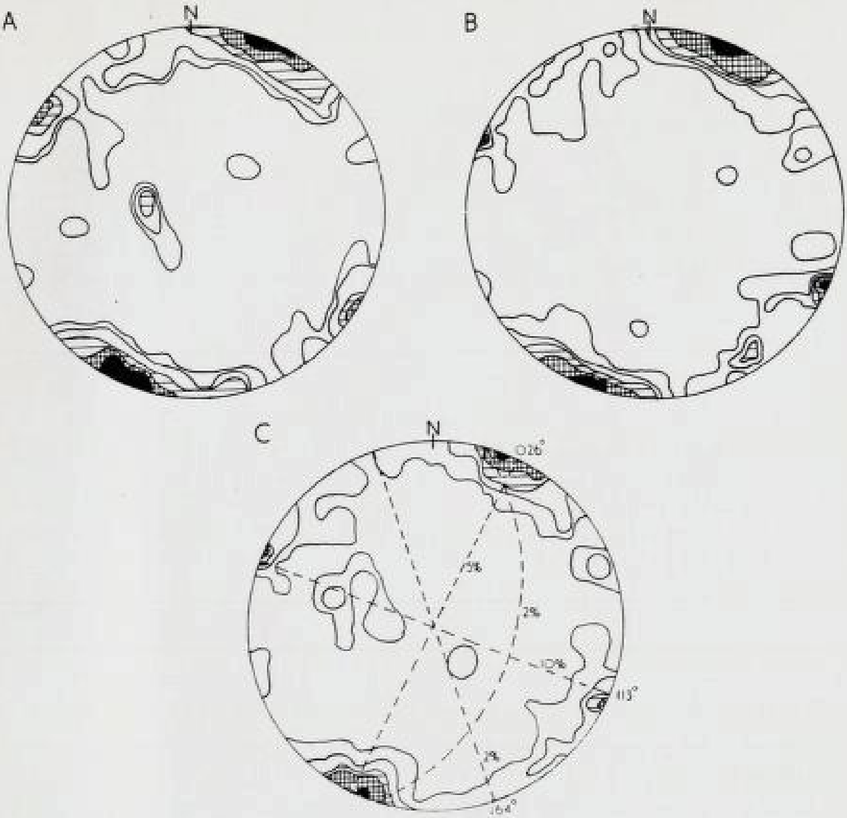

Fig. 8. The joint pattern of the Herefoss granite.
A. Poles to 350 joints on the traverse between Åmli and Syndlevann.
B. Poles to 141 joints on Toplandsheia.
C. Poles to all the joints measured in the Herefoss granite (687), excluding those in faults and breccias.
Lower hemisphere Schmidt projections, contours 1, 2, 3, 5, 10 % per 1 % area.

Sprekkesystemet i Herefossgranitten.

the direction of these larger faults in the granite is shown in fig. 9 A. This was prepared by measuring the azimuth and length of each of the faults in the granite in each 2 km. square of the grid in fig. 2, grouped in 5° classes, including the lines indicating the "Great Friction Breccia". This rosette diagram shows that the chief concentration of fault directions is between 025° and 030°. This is to be expected as this is the main direction of the "Friction Breccia" within the granite.

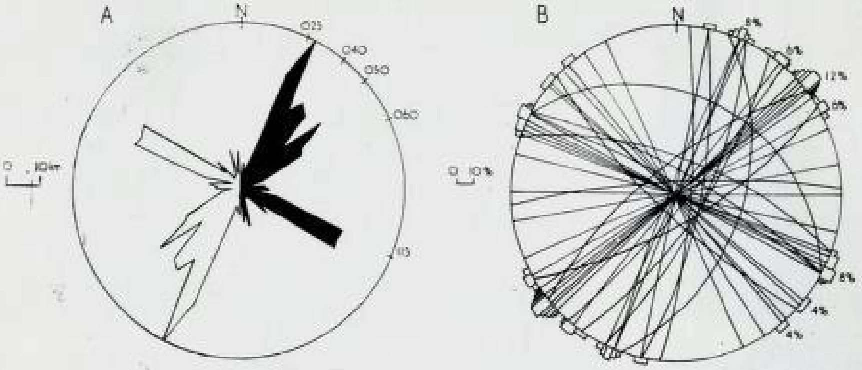

Fig. 9. Faulting in the Herefoss granite.

A. Rosette diagram compiled of 397 measurements of the length and azimuth of the faults in the granite shown in fig. 2, grouped in 5° classes.

B. Cyclographic projection of 50 minor faults obesrved on the traverse between Åmli (Søre Herefoss) and Syndlevann. The histogram on the circumference of the circle shows the percentage of azimuths falling in each 1 % of the circumference.

Forkastninger i Herefossgranitten.

There is another maximum at 115°—120° and secondary maxima at 040° and 060° respectively. In comparing this diagram with fig. 8 A it is seen that the main concentrations are similar, except that fewer small faults run parallel to the "Great Friction Breccia".

It was appreciated that the joint directions measured along the traverse from Åmli to Syndlevann (fig. 8 A) might not be representative of the granite as a whole. The roads across the granite follow lines of faulting and furthermore, low angle joints tend to be rounded off by glacial activity or covered by drift.

In an attempt to see to what extent the jointing is influenced by these factors, an area was chosen for further study in which their effects were at a minimum. An area of 1 sq. km. on the south side of Toplandsheia (3992 1530) was chosen. This is an almost bare, level, plateau of coarse-grained granite at an altitude of 300 m., in the north-east part of the granite. Although Toplandsheia is bounded to the south-east, south-west and north by faults they are relatively minor ones and none of them traverse the area chosen. In the area, jointing is not as abundant as in the stretch from Åmli to Syndlevann. The joints are further apart but appear as well-developed plane surfaces. The orientation of the joints is illustrated in fig. 8 B and is identical with that of fig. 8 A.

Fig. 8 C is a diagram complied from all the measurements of the jointing made in the granite excluding that observed actually in the fault zones. The diagram is weighted in favour of the south-east quadrant of the granite as it includes the data from fig. 8 A. Once more it shows that there are two sets of vertical joints trending 026° and 113°. These correspond to the two main directions of faults shown in fig. 9 A.

Thus it is clear that the conjugate set of sub-vertical joints, which strike 113° and 028° is part of the later regional fracture pattern. If the Herefoss granite ever had a primary fracture system of "Cloosian" type (Cloos, 1922), it has been so modified by later faulting that extremely detailed field-work would be necessary before it could be recognized. However it may be significant that some of the linear structures observed are subparallel to the 113° direction of jointing.

Contact relations and structures of the Grimstad granite.

The smaller Grimstad granite is not well exposed as its eastern half is covered by the waters of the Skagerakk. Where exposed, the western boundary runs parallel to the regional strike of the gneisses and is extremely sharp. Large scale folds such as that which cause the gneisses to curve round the Herefoss granite have not been recognized, only to the north-west does the strike change to follow the contact for a short distance. Both north and south of the pluton, the contacts are strongly discordant (fig. 1).

Oftedal (1945, p. 301) describes the contact zone to the south as being shot through by granitic dykes. A large mass of fine-grained granite occurs near Grimstad Church which is similar to the fine-grained apophysis to the north-east of the Herefoss granite. Oftedal *(loc. cit.)* describes this as being so full of gneiss inclusions that is has the appearance of an eruptive breccia. It will be seen that there are similarities between the contact relations of the Herefoss and Grimstad granites; both have fine-grained marginal facies, both are locally concordant and locally discordant to the gneisses but on the whole, the Grimstad granite is the more discordant of the two.

Oftedal does not mention the existence of linear or planar structures in his account of the Grimstad granite. The writer has observed faint structures analogous to those in the eastern facies of the Herefoss granite in fresh exposures of the Grimstad granite. For example, a feeble platy structure is just discernable in the large granite near Fjære Church. These structures have not as yet been mapped.

The jointing of the Grimstad granite was not studied during the present investigations, but according to Oftedal (1945, p. 298), four directions of steeply dipping joints are usually developed, i.e. E.-W. and N.-S., N.E.-S.W. and N.W.-S.E. The E.-W. and N.E.-S.W. joints are dominant but Oftedal gives no estimate of the relative frequency of the different directions of jointing or their geographical distribution.

It would appear, at first sight, that the jointing of the Herefoss granite is quite unlike that of the Grimstad granite. However Oftedal *(op. cit.)* also mentions that, in many cases, the joints are close together and very variable in orientation, especially in the valleys which traverse the granite. In these zones the granite is sheared. It seems therefore that the Grimstad granite has also been subjected to brecciation and faulting. The fact that these phenomena are much more important in the case of the Herefoss granite is doubtless due to its being cut by the "Great Friction Breccia".

The Herefoss granite in relation to the »Great Friction Breccia«.

A. Bugge (1928, 1936, 1939, 1941) has repeatedly taken the view that the "Great Friction Breccia" is a major crustal fracture of great significance in the PreCambrian of South Norway. He suggested that it separates supracrustal rocks to the north-west, which he terms the "Telemark Formation", from the upthrust deep-seated rocks along the Skagerrakk coast, of the so-called "Bamble Formation". In his first account Bugge (1928, p. 115) stated that the Herefoss granite had been only slightly fractured by the Breccia and concluded that the Herefoss granite is younger than the main period of faulting. Since then (A. Bugge, 1939, p. 93; 1941, p. 21), he has stoutly maintained that the "Bamble Formation" was upthrust "from afar" against the "Telemark Formation" before the emplacement of the granite and that since that time the granite has been affected by relatively insignificant movement.

In his account of the Herefoss Granite, Barth (1947, p. 173) stated that the friction breccia cuts through the granite "without noticeably displacing one part of it in respect to the other". The observation of the present writer that the granite boundary is displaced at both the north and south boundaries by the Breccia suggests that these opinions on the nature of the later movements and the age of the granite intrusions require modification.

The most recent published accounts of the "Great Friction Breccia" (Selmer-Olsen, 1950) indicate that at Gjerstad, 60 km. north-east of Herefoss, it is a normal fault throwing down to the south-east. The detailed observations of the writer (Elders, 1961) show that, in the Herefoss district, the Breccia is a complex zone of faults striking roughly 025° and dipping south-east at 45°—50°, running along Herefossfjord (fig. 2). It attains its maximum development in this zone in the most easterly of the faults and there are numerous lesser faults to the west. The boundaries of the granite show a dextral offset of 2 km. at the southern margin and 1.8 km. at the northern margin. Along the river fine-grained granites are extensive, but they are mylonitic in origin. Within the granite the deformation is as least as intense as elsewhere and there is no geological evidence to suppose that the granite is younger than the main period of faulting. The slight differences in the nature of the Breccia within and outside the granite are the result of differences in the physical properties of the rocks affected. The gneisses tended to yeild by movement along pre-existing foliation planes and the granite by brecciation and cataclasis.

Reference has already been made to the differences in composition and texture of the eastern and western facies of the Herefoss granite but other significant differences between the two parts of the granite also exist. The attitudes of the contacts on the eastern and western boundaries of the granite is markedly dissimilar. South-east of the Breccia zone the granite is in contact with quartzites, mica schists and other meta-sedimentary rocks which have a much less migmatic aspect than the rocks to the north-west. The distribution and nature of the enclaves is also of interest in this connection. North-west of the fault zone the enclaves are rather few and consist either of small, skialithic relicts in a high stage of granitization or inclusions of the grey "granite" gneiss. South-east of the fault, xenoliths are much more numerous and less affected by reaction with the granite; at least one of them is large enough to appear to scale on the accompanying map. The granite of the eastern facies is much more heterogeneous than and lacks the uniform planar structure of the western facies. A further difference, often commented upon by local quarry owners, is that numerous large pegmatites occur in the granite south-east of the fault but they are absent to the north-west of it. No feldspar quarries exist in the granite north-west of the "Great Friction Breccia" for that reason (fig. 2). All these facts seem to indicate that the two parts of the granite represent different levels of erosion and that the south-eastern part was formed at the higher level.

Discussion of the Faulting of the Granite

If we assume that the northern and southern granite contacts are steeply inclined in depth, the shift of the outcrop of the granite at the present level of erosion indicates that the Breccia is a dextral, transcurrent fault. The hypothesis of transcurrent movement is also supported by the branching of the Breccia, as shown in fig. 2. The Steinsvann branch (4020 1519) and the Bjorvann branch (3858 1320) might be considered as "splay faults" (Anderson, 1942, p. 150) or gigantic "feather joints" (Cloos, 1932, p. 391). They both make angles of 10°—12° with the main breccia and would indicate a dextral movement had occurred. On the other hand, the petrological evidence that the movement was that of a normal fault. The relatively low dip of the fault planes (40°—50°) also suggests that the fault is not a purely transcurrent one.

It is possible that there have been different phases of movement distinctly separated in time, which were almost at right-angles to each other. There is evidence that older mylonites and breccias have themselves been fractured and faulted in the Breccia zone. Unfortunately the amount of vertical movement on the Breccia cannot be determined with any accuracy by ordinary geological mapping. However, numerous measurements in the fault zone (minor faults, joint patterns, slickensides, drag-folds, etc.) indicate that the sense of, at least, the later stages of the movement is that of an oblique- slip normal fault throwing down to the south-east (Elders, 1961). According to these measurements, the direction the net shift produced by these late stage movements pitches at 50° to the south, in the plane of the fault. If these are valid criteria for the direction of movement and this direction is applicable to the total displacement, it would imply that the dip slip has the same order of magnitude as the strike slip. However, such a large vertical displacement is not entirely borne out by certain geophysical observations referred to below.

Geophysical studies of the granites.

As part of a recent study of the gravity contrast in the PreCambrian of Southern Norway Smithson has carried out gravity surveys of the Herefoss-Grimstad district. His results are published elsewhere in this journal (Smithson, 1962) and will be only briefly referred to here. His work shows that the Grimstad granite appears to be a cylinder 2.6 to 4 km. deep depending on the model chosen. The much larger Herefoss granite has a much smaller anomaly than the Grimstad granite, but the similarity between the gravity picture of the eastern facies of the Herefoss granite to that of the Grimstad granite is quite striking.

The model he suggests for the Herefoss granite is a circular disc about 1 km. thick with a vertical eastern contact and an inward sloping western contact. In addition, in the eastern half of the granite there is a cylinder 2 km. deep and 4 km. wide, centered under a gravity minimum of minus 6 milligal. A closure of the gravity contours in the eastern part of the granite corresponds almost exactly with the large inclusion mapped by the author at Fossheiene (3945 1495). Smithson has also shown that the average density of the eastern part of the Herefoss granite is slightly less than that of the western part, but the former has a more variable density. The Grimstad granite is lighter still and more homogeneous than the Herefoss granite.

At Hynnekleiv, 10 km. north of Herefoss, Smithson interprets the change in the Bouguer anomally across the "Great Friction Breccia" as indicating that a downthrow of at least 0.5 km. to the south-east has occurred. However along the breccia within the Herefoss granite he has detected no gravity anomaly that could be attributed to fault displacement in depth. His results show that in places the eastern part of the Herefoss granite is 1 km. thicker than the western part, but this thickening apparently begins 7 to 8 km. east of the Breccia.

This discrepancy between the petrographic and field evidence for vertical displacement on the "Great Friction Breccia" and the geophysical evidence against could mean that Bugge's hypothesis is correct; i.e., there was movement on the "Great Friction Breccia"before the emplacement of the Herefoss granite; alternatively there may have been a scissor-like movement on the fault so that the throw increases to the north. Both of these alternatives are thought to be unlikely in view of the geological evidence presented above. In fact, the discrepancy between the geophysical and the geological evidence is more apparent than real. The density contrast produced by granite faulted against granite is, in these circumstances, too small to serve as a basis for calculation of the throw. The gravity anomalies within the granite are not definitive of large scale movements but they are not inconsistent with throws of as large as 2 km. of vertical displacement. The figure of 0.5 km. at Hynnekleiv must also be regarded as a minimum value. (Smithson, personal communication, 1962.)

The thickening of the granite in its eastern part may be partly due to vertical movements on the various faults east of the "Great Friction Breccia". For example, the Steinsvann branch of the "Breccia", which runs in a well-defined, narrow valley north-eastwards from Steinsvann to Birkedal (4020 1519), has all the characteristics of the main fault, to a lesser degree. A zone of brecciation varying between 20—30 m. wide can be seen immediately north-east of Steinsvann. It contains the usual reddened mylonitic granite with milky white quartz, epidote and calcite veins, ultramylonite and kakirite. A second similar fault runs parallel to this 2 km. to the east. Preliminary measurements in these fault zones (Elders, 1961) suggest that both throw down to the east.

Discussion on the form of the granite.

The granite appears to have a diameter about nine times its maximum thickness at the present time. It is conceivable that erosion has now laid bare a section several kilometres below its former roof, so that only the deepest parts of it are preserved. We cannot, of course, reconstruct the original form of the granite with certainty but the following suggestions might be made. It seems reasonable to suggest that even before erosion, the diameter of the granite was several times its thickness and that it was roughly symmetrical. There is persuasive evidence that the eastern facies of the granite formed nearer the roof of the body than did the remainder and the large inclusions could possible be regarded as roof pendants.

The fact that different levels in the granite are now exposed may be due to tilting of the whole body before it was eroded. A more likely explanation, in the opinion of the author, is that it is simply due to faulting. If the body was symmetrical, we can assume that the attitude of the western contact at the present surface is mirrored about 1 km. below the eastern contact. If we extrapolate upwards and across the "roof pendants", it appears that the upper part of the body, before the postulated faulting and erosion, had the form of the familiar mushroom-shaped cloud. We can even postulate a stalk beneath the main part of the granite; a feeder 1 km. in diameter and 5 km deep could give a Bouguer anomaly of only 1 milligal, too small to appear on Smithson's gravity map.

Summary remarks on the Herefoss granite.

(1) The Herefoss granite has been shown to belong to the class of "granites en massifs circonscrits" in the sense of Raguin (1957, p. 27). The contacts of the granite are conformable in a general way but discordant on a smaller scale.

(2) Several lines of evidence suggest that, although its present maximum thickness is only 2 km., it originated as a diapir.

(3) Movements associated with the "Great Friction Breccia" faulted down the south-eastern portion and moved it southwards relative to the north-western part. Thus the opportunity is presented to study a granite at two different levels of exposure.

(4) Widespread synmigmatic folding accompanied the emplacement of the granite. More than two-thirds of it has a well-defined, concentric planar structure which, in the western (or lower) part, dips towards the centre of the body.

(5) Near the contacts and the supposed position of the roof in the eastern (or higher)part of the granite, disorientated, heterogeneous xenoliths occur. Some of these are rocks which belong to the granulite or hornblende granulite facies and appear to be arendalites.

(6) In the north-east part of the granite a fine-grained prolongation occurs which forms a typical migmatite with the country rocks. It appears to be genetically related to the Herefoss granite and crystallized after the main part of the body.

(7) The petrography and chemistry of the eastern facies of the Herefoss granite and the main facies of the Grimstad granite are remarkably similar; their composition is fairly close to petrogeny's residua system.

(8) Trace element studies show that these rocks could not have formed by isochemical recrystallization of an equal volume of the regional gneisses.

(9) The alkali content of the feldspars shows that they crystallized at submagmatic temperatures, as they appear at present. Their texture shows that considerable unmixing of plagioclase from potassium feldspar has occurred.

Discussion — The Origin of the Granite

Non-magmatic granite-making processes have clearly been extremely important in the region under consideration. Viscous silicate melts of the relevant composition could scarcely pervade the older rocks and form the intimate ad mixture of banded gneisses and granite which the regionally developed migmatites and augen gneisses represent. In addition to the migmatites there are countless bodies of more homogeneous, massive or weakly foliated granite, from a few metres to kilometres long, endemic in the gneiss of South Norway. Parts of the large folds 4—5 km. north-east of the Herefoss granite are occupied by these rocks.

One such body, measuring 6 x 1½ km., the Oddersjå granite, near Kristiansand, has recently been described (Barth, et.al., 1960, p. 19). It is perfectly conformable to and grades into the regional gneisses and is elongate parallel to the regional strike. The Oddersjå granite seems to be a larger version of the many apparently rootless granite masses, a few metres across, which are so common throughout the region and for which an origin by granitization is not unreasonable.

The Herefoss granite, in contrast, is a circular and partly discordent body. Its emplacement had a marked effect on the surrounding rocks, shouldering them aside and folding them into conformity with the contacts. The surrounding rocks belong to the almandine-amphibolite facies of region metamorphism. The Herefoss granite, in common with the normal granites of the mesozone is without a metamorphic aureole. This merely illustrates that these granites belong to the same facies as the rocks into which they were emplaced.

The contact relations, the displaced and possibly far-travelled xenoliths and the internal structure of the granite, all indicate that the major part of the granite went through a mobile phase. Thus, in the opinion of the author, the Herefoss granite is an anatectic body, formed in the later stages of the same cycle of metamorphism which produced the non-magmatic granites of the region. Reynolds (1958, p. 380) states that metamorphism with change in chemical composition culminating in movement is not incompatable with movement. Locally the granitized material, being less dense, was able to migrate "en masse" down the P.T. gradient and intrude older strata. This implies, but does not prove, that at last part of it was in a magmatic condition.

The chief objection to this interpretation is that the feldspars appear to have formed at about 500° C. Tuttle and Bowen (1958, p. 121) state that a granite of average composition begins to melt at 640° C and 4.000 kg/cm^2, P.H_2O, which with an assumed geothermal gradient of 30° C/km. corresponds to a depth of 21 km. It seems extremely likely, however, that the temperatures determined by Nilssen (1961) represent recrystallization reactions of the feldspars in response to falling temperatures.

Conclusions

The Herefoss granite (and Grimstad granite) was emplaced, in a mobile condition, as an anatectic magma. Its emplacement was an episode in a widespread granitization during the rocks surrounding the granite yielded by both large- and small-scale folding. The fine-grained offshoots of the granite did not thrust aside the gneisses but penetrated for long distances along their strike, their contacts are broadly conformable to the layering of the gneisses but locally disconformable. These fine-grained granites were probably formed by reaction of the later, more mobile, phases of the magma upon the gneisses.

Sammendrag.

Om Herefossgranittens form og dannelse

Det geologiske kart over S.Ø. Aust-Agder er dominert av to nesten sirkelrunde granittmassiver, Herefossgranitten (Birkelandgranitten) og Grimstadgranitten (Fevikgranitten). Et kart over den geologiske omgivelse av disse to granitter er alt offentliggjort av forfatteren (i Holtedahl, 1960, pl. 3). Feltundersøkelser viser at granittene er yngre enn gneissene, men eldre enn den permiske rombporfyrgangen som skjærer Grimstadgranitten. Radioaktive aldersbestemmelser (Neumann, 1960) viser at granittene ble dannet for omkring 900 millioner år siden under den siste fase av en prekambrisk orogenese.

Det største av massivene, Herefossgranitten som dekker et område på 260 km^2, deles i to av den store sydnorske forkastningssone (A. Bugge, 1928, p. 28). Granitten er tydelig eldre enn forkastningen og den østlige del har beveget seg nedover og mot sør i forhold til den vestlige del. Derfor er det mulig å undersøke granitten på to forskjellige dyp.

Under granittens dannelse, ble de omgivende gneisser foldet rundt granitten og samtidig migmatisert enkelte steder. Skarpe grenser forekommer hvor gneissenes strøkretning er parallel med kontakten. Hvor grensen er diskordant, særlig langs den nordlige kontakten forekommer grensemigmatit. Største parten av granitten har en veldefinert konsentrisk planstruktur som i den vestlige (nedre) del faller inn mot granitten. Uensartete, uorienterte, oppbrudte inneslutninger av gneissbruddstykker forekommer ofte langs grensen og i den østlige del av granitten. En del av disse tilhører granulit fasies og ser ut som arendalit. Mot nordøst er det en finkornet, dels migmatisk, utløper som har krystallisert etter hovedgranitten.

Den kjemiske sammensetning av den østlige typen av Herefossgranitten og hovedtypen av Grimstadgranitten er nesten identisk (tabell 1). Sporelementundersøkelser (Oftedal, 1958; Taylor and Heier, 1960) viser at disse bergarter ikke ble dannet ved isokjemisk omkrystallisering av Kongsberg-Bamble formasjonens gneisser. Feldspattenes natrium innhold tyder på at disse mineraler har krystallisert ved omkring 500° C (Nilssen, 1961), men det er mulig at disse temperaturbestemmelser referer seg til en senere omkrystallisering.

Ut fra flere standpunkter kan man slutte at granitten, skjønt dens nåværende maksimale tykkelse er bare to kilometer (Smithson, 1962), har blitt intrudert som en diapir. Granitten oppsto under en periode med intens granitisering mens de omliggende bergarter var plastiske og de mest lettflytende komponenter trengte seg opp til høyere nivåer som magmaer.

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Fig. 1. Plagioclase (P) and Quartz (Q) inclusions in Microcline (M). The white line is 1 mm long. Crossed polars.
Plagioklas og Kvarts inneslutninger i Mikroklin.

Fig. 2. Agmatitic enclaves in the Herefoss granite, Tonnesølvann.
Gneissbruddstykker i Herefossgranitten, Tonnesølvann.

Fig. 1. Skialithic enclave with microcline porphyroblasts, Herefoss granite, Birkedal.
Mørk skygge med mikrolin porfyroblaster, Herefoss granitt, Birkedal.

Fig. 2. Thin section of an arendalitic inclusion in the Herefoss granite. Ordinary light.
The line measures 0.5 mm. P - plagioclase, Bi - biotite, Hy - hypersthene,
Hb - hornblende, Di - diopside?.
Arendalit inneslutning i granitten.

Fig. 1. Granite overlying gneiss along the western contact at Lunden, looking south.
Granitt som ligger over gneiss ved Lunden.

Fig. 2. Dilatational dykelets of fine-grained granite in banded gneiss, Krokevann.
Finkornete granittganger i bandgneiss, Krokevann.

Fig. 1. Contact of fine-grained granite with amphibolite band, Krokevann.
Kontakt mellom finkornet granitt og amfibolit, Krokevann.

Appendix B
Station Data.

Station Number		Latitude N. ° ′	Longitude W. of Oslo ° ′	Elevation Meters	Observed Gravity Milligals	Combined Free Air & Bouguer Corrections Milligals	Bouguer Gravity Anomaly Milligals
S	1	58 23.3	2 02.1	9.23	981 803.7	+ 1.8	+ 9.7
	2	23.7	01.6	7	809.9	1.4	+ 15.1
	3	22.8	02.4	37	794.3	7.3	+ 6.5
	4	22.2	05.2	57	785.8	11.2	+ 2.9
	5	22.1	06.2	36.96	788.7	7.3	+ 1.9
	6	22.7	04.8	29	793.1	5.9	+ 4.1
	7	23.5	06.0	49	790.4	9.8	+ 4.4
	8	23.2	04.2	18.2	795.5	3.8	+ 3.7
	9	23.8	04.0	40	796.3	8.1	+ 8.0
	10	24.4	04.7	35.70	800.9	7.0	+ 10.8
	11	25.3	05.9	55.3	796.8	10.3	+ 9.8
	12	24.3	05.9	52	794.1	10.8	+ 8.0
	13	23.9	07.4	50	792.2	10.4	+ 6.2
	14	22.7	07.2	85	779.1	16.9	+ 1.2
	15	22.1	08.6	51	786.4	10.4	+ 2.9
	16	22.2	07.4	47.6	785.3	9.7	+ 0.8
	17	20.4	07.5	13.80	795.5	3.0	+ 7.2
	18	14.9	20.3	21.44	778.4	4.2	— 1.7
	19	15.4	21.2	39	771.8	7.7	— 5.5
	20	15.9	22.8	45.69	772.0	9.0	— 4.7
	21	16.2	23.5	42	771.9	8.4	— 5.7
	22	16.9	25.4	49	771.4	9.9	— 5.8
	23	17.2	25.8	51	771.6	10.6	— 5.3
	24	17.9	26.5	60	769.1	12.6	— 6.6
	25	18.2	27.0	65	769.6	13.6	— 5.6
	26	18.4	27.9	69.61	770.0	14.1	— 4.8
	27	19.1	28.0	71	770.0	14.4	— 5.6
	28	16.2	31.3	109	762.0	22.5	— 2.6
	29	15.9	30.4	137	756.5	27.2	— 2.2
	30	14.8	29.9	87	765.1	17.5	— 1.0
	31	13.8	28.0	47	771.9	9.3	— 0.2
	32	12.8	25.8	1.1	780.5	0.3	— 0.7
	33	21.2	10.2	45.79	788.4	9.0	+ 4.6
	34	23.7	13.2	78	776.9	15.8	— 3.5
	35	23.2	14.4	90	770.5	19.4	— 5.6
	36	23.7	15.7	147	760.3	29.3	— 6.6
	37	24.1	17.3	158	756.8	31.5	— 8.4

Station Number	Latitude N. ° ′	Longitude W. of Oslo ° ′	Elevation Meters	Observed Gravity Milligals	Combined Free Air & Bouguer Corrections Milligals	Bouguer Gravity Anomaly Milligals
S 38	58 24.4	2 19.0	155	981 758.9	+ 30.6	— 7.6
39	24.6	19.5	157	760.0	31.1	— 6.2
40	25.5	20.6	185	757.0	36.6	— 5.0
41	26.0	21.7	189	757.1	37.6	— 4.6
42	26.4	22.5	187	759.2	37.2	— 3.4
43	26.2	23.4	207	753.8	41.1	— 4.7
44	27.0	23.1	179	760.8	36.9	— 3.0
45	27.4	21.9	205	757.0	41.0	— 3.2
46	27.3	22.5	151	765.7	31.6	— 3.7
47	27.6	23.0	100	775.6	21.9	— 1.1
48	26.9	23.7	80	780.0	17.8	— 2.8
49	25.2	25.9	76	774.8	17.4	— 6.1
50	25.7	26.3	117	768.3	25.1	— 5.5
51	26.6	26.5	159	760.7	33.3	— 6.0
52	27.1	26.6	161	761.0	33.7	— 6.0
53	28.3	26.8	231	750.4	46.5	— 5.4
54	28.8	27.0	221	751.6	45.3	— 6.1
55	29.3	27.3	220	753.4	45.1	— 5.1
56	30.4	28.2	196	759.4	39.4	— 6.4
57	30.5	28.5	187	759.7	37.6	— 8.0
58	30.8	29.0	187	759.8	37.3	— 8.6
59	31.3	29.0	172.25	763.4	34.2	— 8.8
60	30.1	30.8	224	752.3	44.8	— 7.7
61	29.8	24.9	281	744.0	55.8	— 4.6
62	30.1	26.2	289	742.1	57.3	— 5.3
63	28.4	29.4	287	740.1	57.1	— 5.2
64	28.5	28.0	315	734.0	62.6	— 6.0
65	27.6	30.2	322	731.9	64.0	— 5.5
66	27.1	30.1	336	728.8	66.6	— 5.4
67	27.2	28.2	272	742.1	54.0	— 4.8
68	27.0	18.0	175	763.8	35.3	— 1.5
69	26.3	28.6	174	761.0	35.1	— 3.6
70	25.6	29.7	166	760.4	33.3	— 5.0
71	23.2	16.5	92	769.2	18.7	— 7.6
72	22.7	19.5	145	757.3	29.1	— 8.5
73	22.1	21.8	190	748.7	37.8	— 7.5
74	21.4	23.5	177	749.3	35.1	— 8.6
75	21.1	23.7	177	748.9	35.5	— 8.3
76	20.6	24.6	166	751.4	33.0	— 7.6
77	20.6	25.9	196	747.3	38.8	— 5.9

Station Number	Latitude N. ° ′	Longitude W. of Oslo ° ′	Elevation Meters	Observed Gravity Milligals	Combined Free Air & Bouguer Corrections Milligals	Bouguer Gravity Anomaly Milligals
S 78	58 20.8	2 27.5	135	981 758.9	+ 26.9	— 6.5
79	22.6	24.6	214	744.8	42.5	— 7.5
80	21.7	25.9	214	744.4	42.4	— 6.8
81	20.3	29.3	51	773.6	10.6	— 7.4
82	20.0	26.1	180	749.9	35.9	— 5.4
83	22.7	31.3	236	745.5	46.8	— 2.5
84	22.8	32.0	251	741.8	49.6	— 3.5
85	24.2	31.9	250	743.2	49.8	— 3.8
86	24.0	31.6	263	740.9	52.0	— 3.7
87	22.2	29.7	178	753.4	35.5	— 5.2
88	22.4	28.3	192	750.9	38.5	— 5.1
89	21.7	28.6	128	761.3	26.1	— 6.0
90	21.3	28.2	48	774.0	11.1	— 7.9
91	20.7	19.9	197	747.6	38.9	— 5.6
92	21.2	17.6	109	764.5	22.6	+ 5.7
93	21.0	16.3	52	774.9	12.0	+ 5.6
94	21.0	07.3	20	792.5	3.9	+ 3.9
95	21.7	06.5	1.1	795.6	0.2	+ 2.3
96	24.1	01.4	4	813.8	0.8	+ 17.9
97	23.7	01.0	0.6	813.5	0.1	+ 17.4
98	08.9	42.8	7.34	775.3	1.4	— 0.4
99	08.4	44.6	22	771.3	5.2	+ 1.0
100	08.2	45.3	6	774.5	1.7	+ 0.9
101	09.3	53.8	17	770.6	3.8	— 2.4
102	09.7	55.7	88	756.6	18.5	— 2.2
103	08.6	52.1	17	769.8	4.1	— 1.9
104	08.6	51.0	46	764.9	10.6	— 0.3
105	08.6	48.7	89	757.5	18.5	+ 0.2
106	08.5	46.7	65	764.2	14.0	+ 2.6
107	09.5	41.9	7	774.4	1.4	— 1.2
108	10.8	41.6	7	775.7	2.2	— 0.9
109	10.9	42.4	8	776.0	2.0	— 0.9
110	11.2	42.8	20	773.8	4.4	— 1.1
111	11.6	43.0	27	772.4	5.9	— 1.6
112	11.9	43.7	144	749.7	29.1	— 1.5
113	12.1	44.4	130	751.0	26.4	— 3.2
114	12.3	44.9	119	752.8	24.3	— 3.7
115	12.4	45.7	119	753.4	24.6	— 2.9
116	12.5	46.3	119	754.0	24.2	— 2.8
117	12.8	47.1	15	772.9	6.5	— 2.1

Station Number	Latitude N. ° ′	Longitude W. of Oslo ° ′	Elevation Meters	Observed Gravity Milligals	Combined Free Air & Bouguer Corrections Milligals	Bouguer Gravity Anomaly Milligals
S 118	58 12.8	2 47.6	7.4	981 774.7	+ 4.7	— 2.1
119	13.5	48.5	51	769.0	10.9	— 2.5
120	13.9	49.7	118	755.7	24.4	— 2.8
121	34.7	34.4	210.67	759.3	42.2	— 9.4
122	35.1	38.0	255	749.2	52.2	—10.0
123	34.7	41.5	322	735.0	64.9	—11.0
124	34.7	42.6	330	733.1	66.3	—11.5
125	34.7	43.7	338	730.8	67.7	—12.4
126	34.6	46.3	385	722.6	76.8	—11.4
127	34.6	48.1	403	723.6	80.4	— 6.9
128	34.6	49.0	403	725.7	79.9	— 5.2
129	34.8	50.3	403	727.6	79.8	— 3.7
130	34.5	52.6	246	756.1	49.9	— 4.7
131	35.1	54.9	184.65	765.5	37.6	— 8.5
132	33.8	56.7	173	765.7	34.9	— 9.2
133	34.4	2 58.1	185	762.0	38.8	— 9.8
134	35.3	3 00.6	199	758.2	43.7	— 9.8
135	35.1	3 01.7	180	761.6	38.9	—11.1
136	34.5	2 59.5	177	761.9	37.6	—11.2
137	31.4	53.0	340	739.0	68.3	+ 0.7
138	30.5	47.8	389	729.6	77.6	+ 1.9
139	29.1	47.7	324	738.4	64.6	— 0.6
140	27.4	48.2	208	751.9	42.2	— 7.0
141	27.3	49.9	231	748.8	46.7	— 5.5
142	27.4	51.2	238	745.2	47.7	— 8.3
143	23.9	48.3	135	763.2	27.6	— 5.7
144	23.2	49.5	124.9	764.2	26.2	— 5.1
145	25.5	47.8	183	755.4	37.2	— 6.0
146	25.4	46.3	263	738.3	52.4	— 7.8
147	25.5	45.2	253	739.5	50.4	— 8.7
148	26.0	42.7	206	751.8	41.2	— 6.2
149	25.2	41.0	199	751.9	39.6	— 6.7
150	24.6	38.0	197.05	751.5	39.0	— 6.9
151	26.6	36.4	202.65	751.8	40.5	— 7.8
152	30.5	09.5	75	791.6	16.0	+ 2.2
153	31.5	16.3	243	758.8	48.9	+ 1.0
154	33.5	16.5	272	756.1	54.0	+ 0.8
155	32.7	17.0	294	751.4	57.9	+ 1.1
156	32.7	17.7	272	754.7	54.0	+ 0.4
157	31.1	17.5	306	746.7	60.6	+ 1.2

Station Number	Latitude N. ° ′	Longitude W. of Oslo ° ′	Elevation Meters	Observed Gravity Milligals	Combined Free Air & Bouguer Corrections Milligals	Bouguer Gravity Anomaly Milligals
S 158	58 31.0	2 18.9	293	981 746.8	+ 58.0	— 1.8
159	31.0	19.8	266	750.5	52.9	— 3.6
160	30.9	21.4	179	763.3	36.6	— 6.0
161	31.4	22.1	80	781.5	18.3	— 6.8
E39T.23	32.1	22.0	106.61	777.4	22.2	— 7.8
162	36.0	17.0	165	773.2	34.5	— 5.0
163	36.5	22.0	176	771.6	35.1	— 6.7
164	35.5	22.5	151	774.1	30.6	— 7.2
165	35.1	19.0	177	768.7	35.9	— 6.9
166	33.5	20.7	109	779.1	22.4	— 7.9
167	30.1	2 22.7	86	778.1	19.7	— 6.9
168	58.4	1 03.5	0.1	892.2	0.0	+ 49.5
169	57.3	05.8	0.1	891.0	0.0	+ 49.9
170	56.6	07.7	0.1	888.7	0.0	+ 48.5
171	55.8	09.4	1.6	885.8	0.3	+ 47.0
172	57.4	26.3	87	843.6	17.1	+ 19.4
173	58.1	27.4	66	844.3	13.0	+ 15.0
174	58.8	28.2	66.5	837.5	13.1	+ 7.4
175	58.7	30.0	61.5	833.2	12.1	+ 2.3
176	52.1	27.5	81.5	849.0	16.0	+ 30.8
177	50.9	27.9	77.5	849.0	15.2	+ 31.6
178	49.7	26.9	0.4	863.3	0.1	+ 32.3
179	49.7	25.1	0.1	866.5	0.0	+ 35.5
180	50.7	21.5	0.0	871.4	0.0	+ 39.0
181	51.0	18.8	1.2	875.5	0.2	+ 42.9
182	50.6	18.1	54	863.7	10.6	+ 42.1
183	49.6	19.5	42	866.7	8.3	+ 44.1
184	49.0	20.4	26	868.5	5.1	+ 43.5
185	47.8	20.8	1.4	874.6	0.3	+ 46.4
186	48.0	17.8	1.0	878.4	0.2	+ 49.8
187	47.6	18.5	0.4	877.3	0.1	+ 49.1
188	52.7	32.2	121	835.8	23.8	+ 24.6
189	48.8	38.6	105	837.2	20.7	+ 28.0
190	46.7	37.9	10	857.0	2.0	+ 31.9
191	45.8	38.4	12	857.6	2.4	+ 34.2
192	42.9	36.0	1.0	860.1	0.2	+ 38.4
193	43.0	34.9	0.3	861.6	0.1	+ 39.5
194	43.1	31.2	0.8	865.2	0.2	+ 43.2
195	43.2	29.0	1.3	867.5	0.3	+ 45.4
196	41.8	36.8	2.0	858.4	0.4	+ 38.3

Station Number	Latitude N. ° ′	Longitude W. of Oslo ° ′	Elevation Meters	Observed Gravity Milligals	Combined Free Air & Bouguer Corrections Milligals	Bouguer Gravity Anomaly Milligals
S 197	58 41.4	1 34.5	1.0	981 862.7	+ 0.2	+ 43.0
198	41.5	32.6	0.2	866.3	0.0	+ 46.2
199	41.5	30.5	2.0	868.8	0.4	+ 49.1
200	41.0	38.9	1.2	858.6	0.2	+ 39.4
201	43.1	37.5	25.5	853.7	5.0	+ 36.5
202	44.3	43.4	121	832.5	23.8	+ 32.4
203	45.1	44.4	137	816.3	27.0	+ 18.4
204	45.2	48.6	178	808.2	35.0	+ 18.2
205	46.8	51.2	190	796.9	37.4	+ 7.2
206	47.9	51.3	189	797.3	37.2	+ 5.9
207	47.8	55.7	189	795.1	37.2	+ 3.8

Appendix C.

Density Data by Rock Types.

Rock Type	No.	Mean Density gm/cm^3	Corrected Standard Deviation gm/cm^3	Range gm/cm^3
Aplite	6	2.62	0.023	2.58—2.65
Quartzite	6	2.64	0.017	2.62—2.67
Marble	1	2.71	—	—
Garnetiferous granite gneiss	2	2.72	—	2.69—2.76
Biotite granite gneiss	16	2.66	0.038	2.59—2.71
Hornblende granite gneiss	2	2.73	—	2.70—276.
Augen gneiss	9	2.72	0.052	2.67—2.83
Biotite gneiss	22	2.78	0.049	2.67—2.88
Migmatitic biotite gneiss	6	2.74	0.024	2.70—2.76
Migmatitic hornblende gneiss	2	2.89	—	2.83—2.95
Banded hornblende gneiss	6	2.93	0.059	2.88—3.04
Biotite hornblende gneiss	10	2.90	0.043	2.82—2.97
Amphibolite	13	3.03	0.080	2.86—3.17
Gabbro	3	2.96	—	2.86—3.03

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Sammendrag.

Gravimetriske undersøkelser på Sørlandet.

Tyngdeanomalier på Sørlandet blir behandlet og tolket ut fra de geologiske forhold. Tykkelsen av to granitter er beregnet på grunnlag av tyngdeanomaliene. Granittene er fra 2 til 5 km tykke. Evjeamfibolitten er beregnet til å være 1,25 km tykk. På grunnlag av tyngdeanomaliene blir det også fremsatt noen teorier for granittdannelse.

0 1 2 3 4 km
Herefoss
Birkeland
Lillesand
Grimstad
Arendal
58°40' N
Coarse Grained Granites 1
Fine Grained Granites 2
Rhomb Porphyry Dyke 3
Limestone and Skarn zones 4
Hyperite Dykes 5
Arendalites 6
Border Migmatites 7
Augen Gneiss 8
Granitic Gneisses 9
Quartzite 10
Banded Gneisses 11
Amphibolites 12
Migmatites 13
Covered 14
Tectonic lines 15
Linear Structures 16
Folds 17
Planar Structures 18
Geological environment of the Herefoss & Grimstad granites
— Compiled by W.A. Elders 1959 —

Figure 1.


0 1 2 3 4 km
Herefoss
Birkeland
Grimstad
Lillesand
Coarse Grained Granites 1
Fine Grained Granites 2
Rhomb Porphyry Dyke 3
Limestone and Skarn zones 4
Hyperite Dykes 5
Arendalites 6
Border Migmatites 7
Augen Gneiss 8
Granitic Gneisses 9
Quartzite 10
Banded Gneisses 11
Amphibolites 12
Migmatites 13
Covered 14
Tectonic lines 15
Lineal Structures 16
Folds 17
Planar Structures 18
Geological environment of the Herefoss & Grimstad granites
— Compiled by W.A.Elders 1959 —

Figure 4.

Figure 2.

STRUCTURAL MAP OF THE HEREFOSS GRANITE

STRUKTURKART OVER HEREFOSS GRANITTEN

W. A. ELDERS 1961

0 1 2 3 4 5 km

Within the Granite. — (I Granitten.)

◡	Normal Coarse-grained Granite. Normal grovkornet granitt.	▨	Fine-grained Granite. Finkornet granitt.
Cg	Coarse-grained Grey Granite. Grovkornet grå granitt.	Fg	Fine-grained Grey Granite. Finkornet grå granitt.
Fr	Fine-grained Red Granite. Finkornet rød granitt.	M	Mylonite. — Mylonitt.
P	Pegmatite. — Pegmatitt.	X	Enclave. — Inneslutninger.
↦	Dip of Contact. Fall langs kontakten.	⊥	Planar Structure. Planstruktur.
→	Linear Structure. Lineasjon i granitten.	⊥	Foliation in Enclaves. Foliasjon i inneslutninger.

Other Structures. — (Andre strukturer.)

▨	Trace of Foliation in Gneisses, etc. Foliasjon i gneissene, osv.	⇙	Axial Trace of Major Fold. Aksesone for større folder.
		⇙	Inferred Axial Trace of Major Fold. Antatt aksesone for større folder.

Strike and Dip of Foliation.
Strøk og foliasjonsfall.

+	< 9°
⅄	10° - 20°
⅄	30° - 59°
⅄	60° - 85°
⅄	> 85°

━	Known Fault. Observert forkastning.	Thickness gives relative magnitude. Tykkelse angir relativ mektighet.
- - -	Inferred Fault. Antatt forkastning.	


THE NORTH EASTERN BOUNDARY OF THE HEREFOSS GRANITE.
W.A. ELDERS.—1960.
0 500 1000 2000 m.
Coarse Grained Granite.
Fine Grained Granite.
Banded Gneiss with Mica Schist.
Banded Gneiss chiefly Amphibolitic.
Quartzite.
Limestone.
Migmatite.
Pegmatite.
Pegmatite Quarry.
Xenolith.
Basic Dyke.
Mapped Boundary of Granite.
Inferred Boundary of Granite.
Junction of Coarse Grained and Fine Grained Granite.
Foliation in Gneiss.
Foliation in Granite.
Foliation in Xenoliths in Granite.
Lineation in Granite.
Minor Fold Axes in Gneiss.
Faulting and Brecciation.
COORDINATE SYSTEM GAUSS-KRÜGER II. NORWEGIAN GRID
HEREFOSS
Nes
CHURCH
Landstveitvann
Fiskvann
Langemyr
Bjorvann
Bua
Main Breccia
Scree
Cliffs
Hisvann
Espestøl
Espestølvann
Holtebu
Holtebuvann
Stien
Engebu
HEREFOSSFIORD
Krokevann
Not Mapped
Sandvannene
Topland
Krokvann
Storvann
Covered
Tjørnarn
Ørneland
Taskedal
Hunsdal
Granite Cliffs
N
396
397
398
399
400
401
402
403
404
152
153
154
155
156
157
158

Figure 6.