PETROGRAPHY AND GEOCHEMISTRY OF GRANITES IN THE KONGSBERG AREA, SOUTH NORWAY

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The calcalkaline granites in the Kongsberg sector of the Kongsberg–Bamble areas are considered on the basis of petrography and geochemistry to be three distinct bodies and are referred to as the Kongsberg, Helgevatnet and Meheia granites.

The Kongsberg granite is characterized by rather low Rb (82 ppm), Th (3.78 ppm), U (0.99 ppm), Th/K (0.80), U/K (0.20) and high K/Rb (620), and is not considered to be of igneous (intrusive) origin.

The Helgevatnet and Meheia granites are, on the bases of field relations and chemistry, considered to have formed essentially by crystallization from melts but at different times.

Both granite bodies are characterized by marked depletion in potassium and appreciable increases in sodium and calcium in their contact zones with the Knute group amphibolite country rock.

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Nomenclature

The Precambrian granites in the western and southwestern parts of the Kongsberg sector in the Kongsberg–Bamble areas (Fig. 1) had been variously designated as 'Telemark granite' (Kjerulf 1861, C. Bugge 1917) and 'Coarse grained Kongsberg granite' (A. Bugge 1928, 1936). A. Bugge (1928, 1936) proposed that the fault zone north of the Bamble area and trending northwest-west-southwest of the town of Kongsberg be recognized as delimiting the Kongsberg sector to the east and the Telemark area to the west. He further suggested that granite bodies within the Kongsberg area be designated 'Kongsberg granites' as distinct from the 'Telemark granites' to the west, which he believed belong to a different orogenic cycle.

Within the Kongsberg area, those granite bodies occurring east of the mining area were designated 'fine grained Kongsberg granite' thus distinguishing them from the granite bodies to the west of the mining areas which were designated 'coarse grained Kongsberg granite'. A. Bugge's suggestions have been adopted in the subsequent literature (J. A. W. Bugge 1943: 116, Neumann 1944: 14, Barth & Dons 1960: 32, O'Nions & Heier 1972).

The present investigation reveals that the 'coarse grained Kongsberg granite' is made up of two texturally different granite bodies which are also believed to be genetically different. They have, therefore, for the purpose of this investigation been designated 'Meheia granite' to the west and southwest

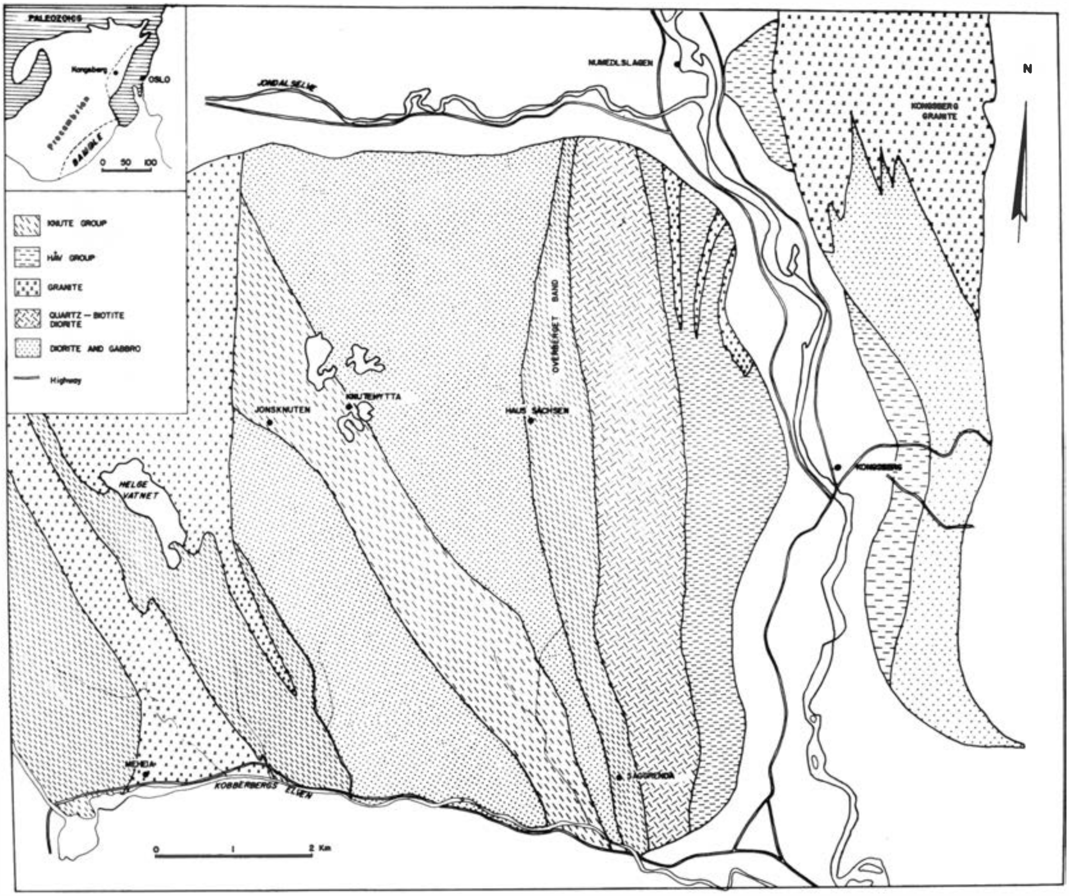


Fig. 1. Generalized geological map of the Kongsberg area showing the spatial relationship of the granite bodies (after J. A. W. Bugge 1943). Inset shows the locations of Kongsberg and Bamble areas in south Norway.

and 'Helgevatnet granite' to the north (Fig. 1). The 'fine grained Kongsberg granite' of the previous literature is referred to here simply as 'Kongsberg granite'.

Geological setting

C. Bugge (1917) and J. A. W. Bugge (1943) have given details of the regional geologic settings of the Meheia, Helgevatnet and Kongsberg granites and only the following brief and pertinent information will be given here.

The Meheia and Helgevatnet granites are set in an environment of metavolcanics and metasediments (Knute group rocks) and hyperites (gabbro diorite and quartz hornblende diorite). Within the area investigated, the Meheia granite is bounded by Knute group rocks with which it shows sharp, concordant, and in places interfingering contacts. Sometimes narrow fringes of the granite at the contact (maximum width observed was approximately 2 metres) give indications that their chemistry might have been somewhat modified. Analyses of samples from the contact zones show that the only significant modification that had taken place in these zones involve exchange of the alkali elements K (and Rb) and Na between the granite and the metavolcanics.

The Helgevatnet granite shows both concordant and discordant contact relationships with the adjacent Knute group rocks and hyperites. Veins or tabular bodies of the granite in the well-foliated Knute group rocks either follow the foliation in the host rocks or cut across it. Fig. 2 shows a discordant vein of the granite in the well-foliated country rock. The concordant veins are generally longer than the discordant ones.

These contact features indicate that the Helgevatnet is younger than the surrounding metavolcanics and metasediments and that these had already been metamorphosed prior to the emplacement of the granite.

Bugge (1917) indicated that the Knute group rocks and hyperites are intruded by a series of amphibolitic dykes (Vinor diabase), all of which were cut by the granites (i.e. both the Meheia and Helgevatnet granites), suggesting that the granites are younger than the amphibolitic dykes. Present investigation shows that some of the diabase dykes cut the Helgevatnet granite but none was observed within the Meheia granite. Rb–Sr geochronological

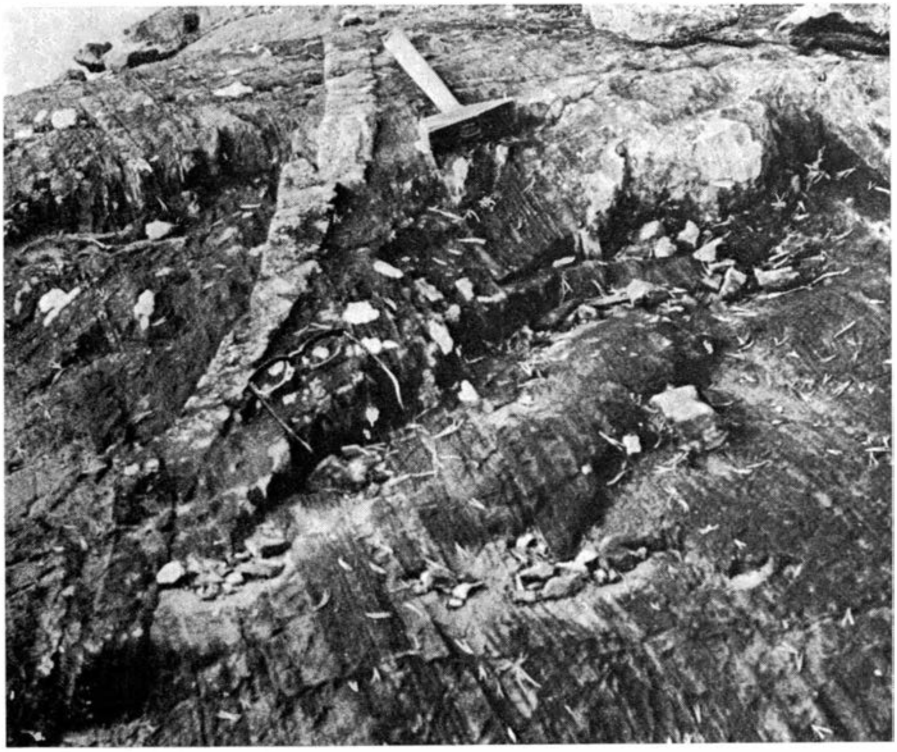


Fig. 2. Discordant and faulted vein of Helgevatnet granite in the well-foliated Knute group country rock. Photograph taken just off the southeastern shore of the lake.

study of these rocks currently in progress should throw some light on the age relationship.

The rocks in the areas in which these two granites are situated had undergone multiple metamorphism, some pre-dating and others post-dating the emplacement of the granites. Both granites show widespread evidences of tectonic effects like microbrecciation and shearing.

All rocks in the area show the regional N–S and NNE–SSW foliation.

The fault zone which A. Bugge (1928, 1936) suggested as the boundary of the Kongsberg area actually runs through the Meheia granite; according to current usage, parts of the same granite body are classed as 'Kongsberg' and 'Telemark' granites. To avoid this unfortunate situation, it is suggested that the expression 'coarse grained Kongsberg granite' be dropped and that the pink or red granite through which the fault runs in the vicinity of Meheia station be called the 'Meheia granite'.

The Kongsberg granite (as used in this paper) is to the east of the Kongsberg mining areas. The immediate country rock of the granite in the area covered by this investigation varies from amphibolite to migmatitic amphibole gneiss.

Petrography

The Meheia granite

The Meheia granite is essentially a light pink, medium grained rock with faint to distinct light green streaks giving faint or distinct foliation respectively.

Fine grained textural variants invariably show extensive microgranulation while those with schistose textures show definite effects of shearing. Variations in colour are related to amount and distribution of epidote minerals and chlorite minerals and range from light pink to darkish pale green. The rock is made up of potassium feldspar, sodic plagioclase, quartz, biotite, epidote minerals, chlorite and accessory iron oxide, sphene, zircon, apatite and allanite.

Potassium feldspars include large, sometimes porphyritic microcline perthites (up to 9 mm across) and smaller (1–5 mm and less) microcline. The microcline perthites show patch- and braided-perthites and are commonly surrounded and traversed by rims and veinlets of microgranulated and recrystallized quartz respectively. Slight sericitization of the K-feldspars is observed.

Sodic plagioclases (An_7–An_{12}) occur as large and small discrete grains and as exsolved phases in the potassium feldspar. Some of the patch perthites look very much like replacement perthites. The plagioclases, particularly the larger crystals show varying degrees of sericitization and saussuritization.

Quartz is primarily interstitial to the feldspars but some occur in the granulated and recrystallized rims and veinlets around and within the feldspars while some occur simply as inclusions in the feldspars.

Epidote minerals are present in almost all sections and vary in amount from accessory to major component, sometimes exceeding the normal ferromagnesian mineral. They show two modes of occurrence: (i) the greater amount occurs as alteration product of the plagioclase feldspars, especially in the sheared zones. Muscovite usually forms with the clinozoisite. Equation for the reaction could be represented thus:

$$\underset{\text{(An)}}{4CaAl_2Si_2O_8} + \underset{\text{(Or)}}{KAlSi_3O_8} + H_2O \rightarrow \underset{\text{(Clinozoisite)}}{2Ca_2Al_3Si_3O_{12}(OH)} + \underset{\text{(Muscovite)}}{KAl_3Si_3O_{10}} + \underset{\text{(Quartz)}}{2SiO_2}$$

The reaction involves loss of potassium and calcium by the feldspars and probably accounts for the dominance of sodic plagioclase in samples with high epidote minerals contents; (ii) a lesser amount occurs as discrete grains with no apparent relationship to the alteration of feldspars or any other mineral.

Biotite flakes have been chloritized to different degrees and are seldom found fresh. They have a greenish colour with green and yellow pleochroic colours.

Muscovite occurs as discrete flakes (including those formed as by-products of epidotization) and as alteration product of the feldspars.

Iron oxide, sphene, zircon, allanite and apatite occur as accessory minerals.

The Helgevatnet granite

The Helgevatnet granite is a medium to coarse (feldspar crystals up to 2,5 cm across) grained rock with distinct gneissic texture. The ferromagnesian minerals are drawn out in streaks between the rounded or ovoid feldspars, suggesting emplacement in a stressed field. Two varieties are distinguished in the field on the basis of colour: a mottled pink variety made up of pink feldspars (dominant), grey plagioclase feldspars (subsidiary), quartz, biotite and hornblende with accessory amount of garnet; the second variety is grey and is characterized by the absence of pink feldspars but similar in all other aspects to the mottled pink variety.

The large *potassium feldspar* crystals are microcline perthites with rod, braided, patch and replacement perthites. Some of the plagioclase (An_6) in the perthitic intergrowths are up to 2.5 mm $\times$ 1.8 mm with good polysynthetic twinning.

Plagioclase (An_{12}) also form large crystals, sometimes larger than the potassium feldspar crystals. They are commonly sericitized and saussuritized and many of the crystals show deformation twins and bent twin lamellae. Some crystals appear to be antiperthitic.

Quartz occurs interstitially; as inclusions in the feldspars; and as veinlet material filling fractures in the feldspars. Some of the interstitial grains show undulatory extinction.

Biotite is the main ferromagnesian mineral and its flakes, which may be aligned in streaks or may occur in clusters with epidote minerals, show varying degrees of chloritization. They are of green colour and the chloritized flakes show lower birefringence.

Hornblende with greenish blue to yellowish green pleochroic colours is present in most thin sections but the amount is invariably subordinate to that of biotite.

Epidote minerals occur in all sections both as alteration products of the feldspars and as discrete grains. Their veins cut through many of the other minerals and they appear to be younger than the other minerals except chlorite, which is another alteration product.

Accessory minerals include garnet, iron oxide, sphene, allanite, fluorite, calcite and zircon. Rutile was observed in the cleavage traces of some biotite.

Fluorite was observed on a joint surface in the granite near the northwestern shore of the lake. This joint surface fluorite is probably later than the accessory fluorite in the granite.

Veins of the granite in the country rock are invariably of the grey variety.

The Kongsberg granite

The Kongsberg granite is, to all appearances, a granite gneiss. It is medium grained and shows poor to well-developed augen structure. It is made up of quartz, alkali and plagioclase feldspars, hornblende, and biotite with accessory garnet, iron oxide, apatite, allanite, sphene and zircon.

The *potassium feldspars* include microcline perthites sometimes with rounded to subrounded inclusions and intergrowths of plagioclase.

Some of the *plagioclase feldspars* (An_7) are intensely altered while others are free of alteration. Some crystals are untwinned while others show polysynthetic twinning; some untwinned crystals show moderate normal zoning.

Quartz shows four modes of occurrence: interstitial to the feldspars – this is the mode of occurrence of most of the quartz crystals; as inclusions, especially in the feldspars and garnets; as vein materials filling fractures in the other minerals; and as vermicular or myrmekitic intergrowths.

Hornblende is the most abundant ferromagnesian mineral in the rock. It is relatively fresh and appears to be later than the feldspars, which are sometimes found as inclusions in it.

Biotite is of the brown variety with brown to light yellow pleochroic colours. It is also relatively fresh but is subordinate in quantity to hornblende.

Epidote minerals occur in smaller proportions compared to the Meheia and Helgevatnet granites.

Garnet occurs in amount varying between that of minor and accessory component. It is commonly poikiloblastic with inclusions of quartz, biotite and hornblende. It may be fractured and/or elongated parallel to the direction of gneissosity in the rock.

Geochemistry

Analytical methods

SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, CaO, and K_2O were determined by X-ray fluorescence spectrography on 9:1 fused pellets using disodium tetraborate as diluent. P_2O_5 and the trace elements, Rb, Sr, Ba and Zr were determined (also by XRFS) on pressed pellets; mass absorption measurements and correction for Rb, Sr, and Zr are as described by Norrish & Chappell (1967).

MgO was determined by atomic absorption spectrophotometry, FeO by titration with $K_2Cr_2O_7$ and Na_2O by neutron activation method according to Brunfelt & Steinnes (1966).

Except in the neutron activation analyses in which every fifth sample was duplicated all determinations were made on duplicate pellets or portions for each sample.

A number of international and house standards were run concurrently with the samples as unknown, for checks on precision and accuracy. Values obtained for the trace elements in some international standards together with standard deviation and range of values are given in Table 1. Except for the low Ba end in W–1 where the accuracy is $\pm 6\%$, all the other elements show good precision and accuracy relative to the recommended values.

The radioactive elements Th and U were determined by gamma ray spectrometry following the method of Morgan & Heier (1966). Results obtained on four international standards are included in Table 1.

Results

The averages (arithmetic mean) of the analyses for the major elements and normative minerals for the three granites are presented in Table 2. Mesonorm, rather than C.I.P.W. or Katanorm has been calculated in accordance with Barth's (1966: 220) suggestion and the observation of post-formation evidences of metamorphic effects in the different rocks.

Some samples (21A, 21B, 21C, 23A, 23B, 23C, 24, 76, 96 for the Meheia granite and 36, and A for the Helgevatnet granite) taken to illustrate noteworthy chemical processes in the granites in their contact zones were not included in the calculations of group averages.

Complete lists of analyses and normative minerals are available at the Mineralogisk–geologisk museum, Oslo, on request.

Qtz–Ab–Or and An–Ab–Or relations

The normative quartz–albite–orthoclase and anorthite–albite–orthoclase for all samples analysed are shown in Figs. 3a and 3b respectively from which the following could be observed:

Most of the granite samples (excluding those meant to illustrate noteworthy chemical processes) have normative qtz–ab–an compositions that plot close to the ternary minimum between 0.5 and 2 kilobars (Fig. 3a).

Table 1. Recommended values of Rb, Sr, Zr, Ba, Th and U in some international standards and values obtained in this work.

Element		G–2	GSP–1	W–1	QMCI–3	QMCI–1
Rb	Recommended value	169	255	22		
	Value obtained in this work	169.51	255.96	21.62	–	–
	δ	0.60	1.45	0.59		
	Range	168.97 to 170.67	255.00 to 257.93	21.20 to 22.03		
Sr	Recommended value	475	235	190		
	Value obtained in this work	476.03	234.97	187.63	–	–
	δ	1.88	1.14	1.08		
	Range	474.58 to 480.49	232.93 to 237.00	186.86 to 188.39		
Zr	Recommended value	320	568	100		
	Value obtained in this work	320.74	570.58	97.48	–	–
	δ	3.62	6.43	1.31		
	Range	316.46 to 325.46	568.28 to 576.13	96.46 to 99.88		
Ba	Recommended value	1850	1250	160	700	500
	Value obtained in this work	1868.12	1256.34	162.64	710.34	507.43
	δ	23.36	1.49	9.61	9.61	2.02
	Range	1851.60 to 1884.63	1255.29 to 1257.39	151.89 to 169.16	703.54 to 717.13	506.00 to 508.85
		G–2	GSP–1	AGV–1	BCR–1	
Th	Recommended value	25.7	106	6.4	6.1	
	This work	24.6 ± 0.3	105 ± 1.0	6.1 ± 0.1	5.8 ± 0.1	
U	Recommended value	2.1	1.7	1.9	1.6	
	This work	2.1 ± 0.2	1.8 ± 0.4	1.7 ± 0.1	1.4 ± 0.1	

Both the Meheia and Kongsberg granites show slight enrichment in potassium relative to the Helgevatnet granite (Figs. 3a and 3b).

The Meheia granite shows up as being comparatively more homogeneous than either of the other two granites.

Table 2. Mean major elements (in wt. % oxides) and calculated norm ($\bar{X}$) for the granites with standard error of the mean ($\delta/\sqrt{N}$).

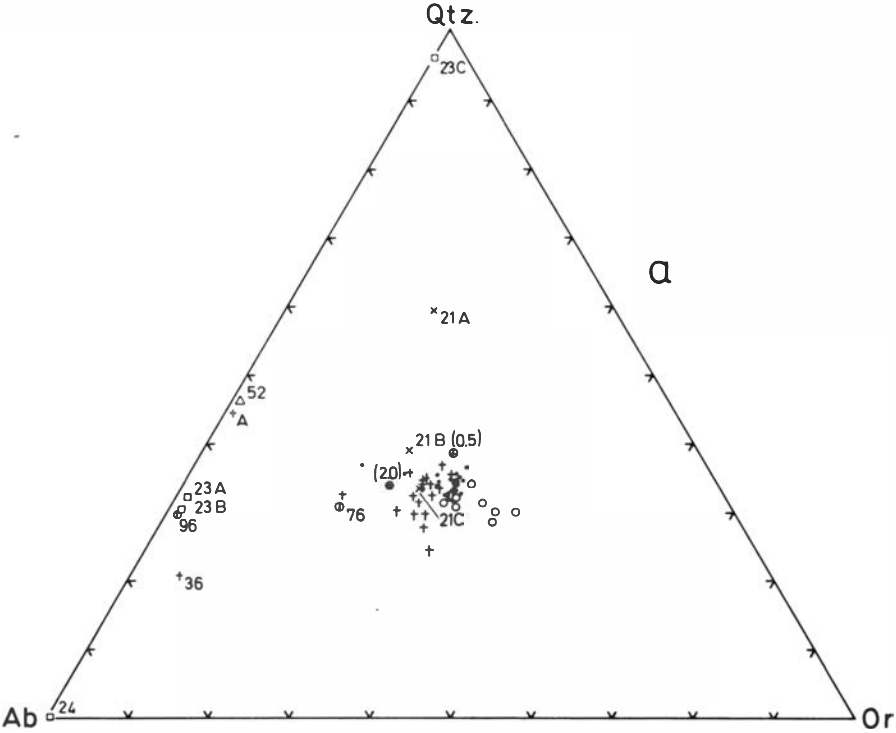
Oxides	Meheia 1a (n = 27)		Helgevatnet 1b (n = 17)		Kongsberg (n = 8)	
	$\bar{X}$	$\delta/\sqrt{N}$	$\bar{X}$	$\delta/\sqrt{N}$	$\bar{X}$	$\delta/\sqrt{N}$
SiO_2	75.74	0.16	73.71	0.35	73.27	0.33
TiO_2	0.25	0.01	0.27	0.02	0.24	0.05
Al_2O_3	11.94	0.06	12.58	0.06	13.43	0.16
Fe_2O_3	0.98	0.06	0.72	0.05	1.08	0.28
FeO	1.07	0.06	2.12	0.11	1.51	0.24
MnO	0.03	0.00	0.06	0.00	0.05	0.01
MgO	0.20	0.01	0.22	0.03	0.14	0.04
CaO	0.69	0.04	1.11	0.01	1.23	0.09
Na_2O	3.51	0.05	3.76	0.09	3.11	0.08
K_2O	5.22	0.09	4.81	0.10	5.98	0.21
P_2O_5	0.03	0.00	0.05	0.00	0.10	0.01
Loss on ignition	0.45	0.04	0.53	0.04	n.d.*	–
Total	100.11		99.94		100.14	
NORM						
Q	32.09	0.21	29.26	0.72	28.10	0.37
C	0.04	0.03	0.03	0.02	0.36	0.08
Or	30.48	0.58	26.82	0.68	34.28	1.41
Ab	31.90	0.47	34.35	0.86	28.27	0.77
An	1.64	0.21	3.26	0.23	4.40	0.30
Bi	1.38	0.28	3.32	0.34	2.40	0.36
Act.	0.76	0.18	1.60	0.41	0.44	0.29
Ri	0.22	0.15	–		–	
Di	0.25	0.10	–		–	
Sph	0.53	0.02	0.57	0.04	0.51	0.10
Mt	1.01	0.08	0.77	0.06	1.14	0.29
Ap	0.06	0.01	0.12	0.01	0.21	0.02
Wo	0.07	0.04	–		–	
He	0.01	0.01	–		–	

* n.d. = not determined
1a, 1b. These analyses show good agreement with those of 'Telemark granit' and 'Kongsberg granit' respectively given by C. Bugge (1917: 59), analyses X and IX.

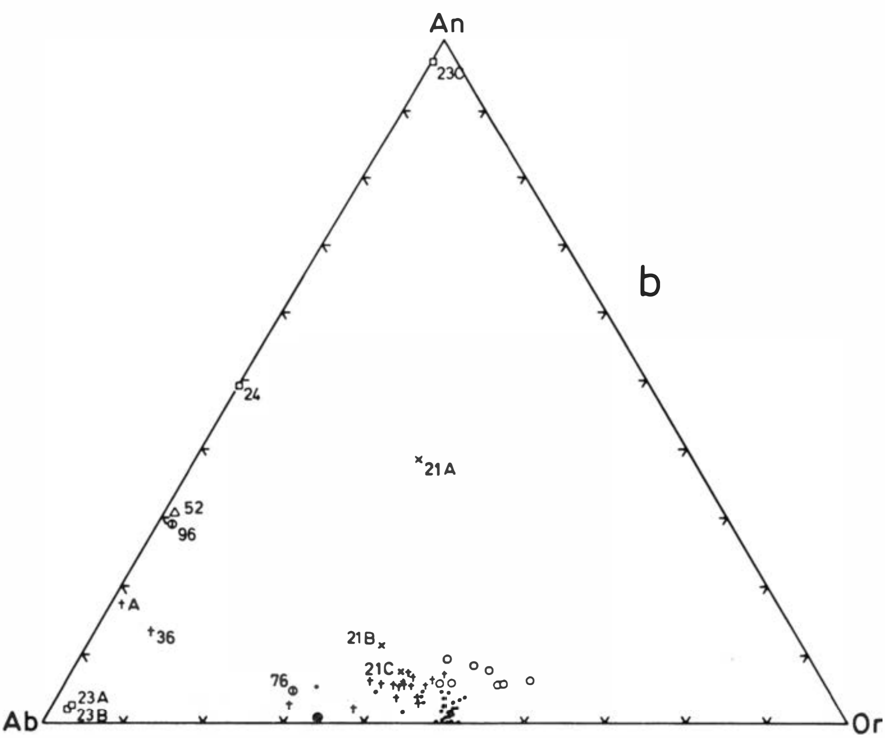
The three rock bodies are granites in the sense that their normative quartz + albite + orthoclase total above 80% (Tuttle & Bowen 1958, Marmo 1971).

Compositional differences
Mineralogical differences between the granite bodies have been indicated earlier on. In spite of these, however, very marked differences in major elements geochemistry will be unusual in granitic rocks whose compositions closely approach the ternary minimum.

The $\frac{Mg}{Fe^{++}+Mg}$, $\frac{Fe^{++}}{Fe^{++}+Fe^{+++}}$ and $\frac{Ca}{Ca+Na+K}$



Qtz.
a
23C
21A
52
A
21B (0.5)
(2.0)
23A
23B
96
76
21C
36
24
Ab
Or



An
b
23C
24
21A
52
96
A
36
21B
21C
76
23A
23B
Ab
Or

ratios in the analysed samples of the three granites have been plotted against cation per cent Si in Figs. 4a, 4b and 4c, respectively.

Table 2 and Figs. 3 and 4 reveal significant differences in the major elements geochemistry of the granite bodies.

Chemical processes at the contact zones

Meheia granite. – Observable contacts of the Meheia granite with the surrounding amphibolitic rocks are of the sharp, concordant and in places, interfingering type. To observe possible chemical modifications in the contact zones, samples 23A and 23B were taken from the granite 10 and 5 cm respectively from the contact. Samples 23C and 24 were also taken from the amphibolite at the contact (23C) and about 3 metres away from the contact respectively.

Sample nos. 23A and 23B are modified versions of the Meheia granite in which the modal composition has changed from the group average of about 30% quartz, 30% alkali feldspars, 28% plagioclase feldspars, 5% epidote minerals, 5% biotite and accessory minerals to 44% quartz, 50% plagioclase feldspars, 5% epidote minerals and 1% biotite and muscovite. Potassium feldspars are completely lacking in both 23A and 23B and this absence was confirmed with sodium cobaltinitrite staining of the thin sections. The plagioclase feldspars in these samples are mostly untwinned while secondary twinning and bent twin lamellae are observable in the few twinned crystals. The feldspars which are subhedral to rounded are mainly phenocrystic in a groundmass of finer grained and, in places granulated quartz and feldspar.

The epidote minerals are mainly confined to the granulated zones while biotite and muscovite flakes are irregularly distributed in the sections.

Sample no. 24 is the parent amphibolite Knute group rock in the contact area. It is made up of 80% actinolitic amphibole, 12% quartz – mainly in segregated lenses within the amphibole, 5% iron oxide, 2% biotite and 1% epidote minerals. The rock shows very good lineation of the amphibole minerals but is not well foliated.

Sample 23C is the modified version of the amphibolite at the contact with the granite. The rock is made up of 60% biotite, 30% epidote minerals and 10% quartz. The rock is texturally finer grained than the parent amphibolite and is also well foliated.

Analyses of these samples are shown in Table 3 in which the group average of the Meheia granite has been included for ease of comparison.

Fig. 3(a). Plot of the normative quartz + albite + orthoclase in the Meheia (filled circles), Helgevatnet (daggers) and Kongsberg (open circles) granites in the Qtz–Ab–Or–H_2O system. Isobaric ternary minima for 0.5 and 2 kilobars P_{H_2O} have been superposed. Symbols used in the other diagrams are as shown in this figure. (b). Plots of the normative anorthite + albite + orthoclase of the three granite bodies (symbols as in Fig. 3(a)) in the An–Ab–Or system. Ternary minimum at P_{H_2O} = 2 kilobars (encircled cross) is indicated.

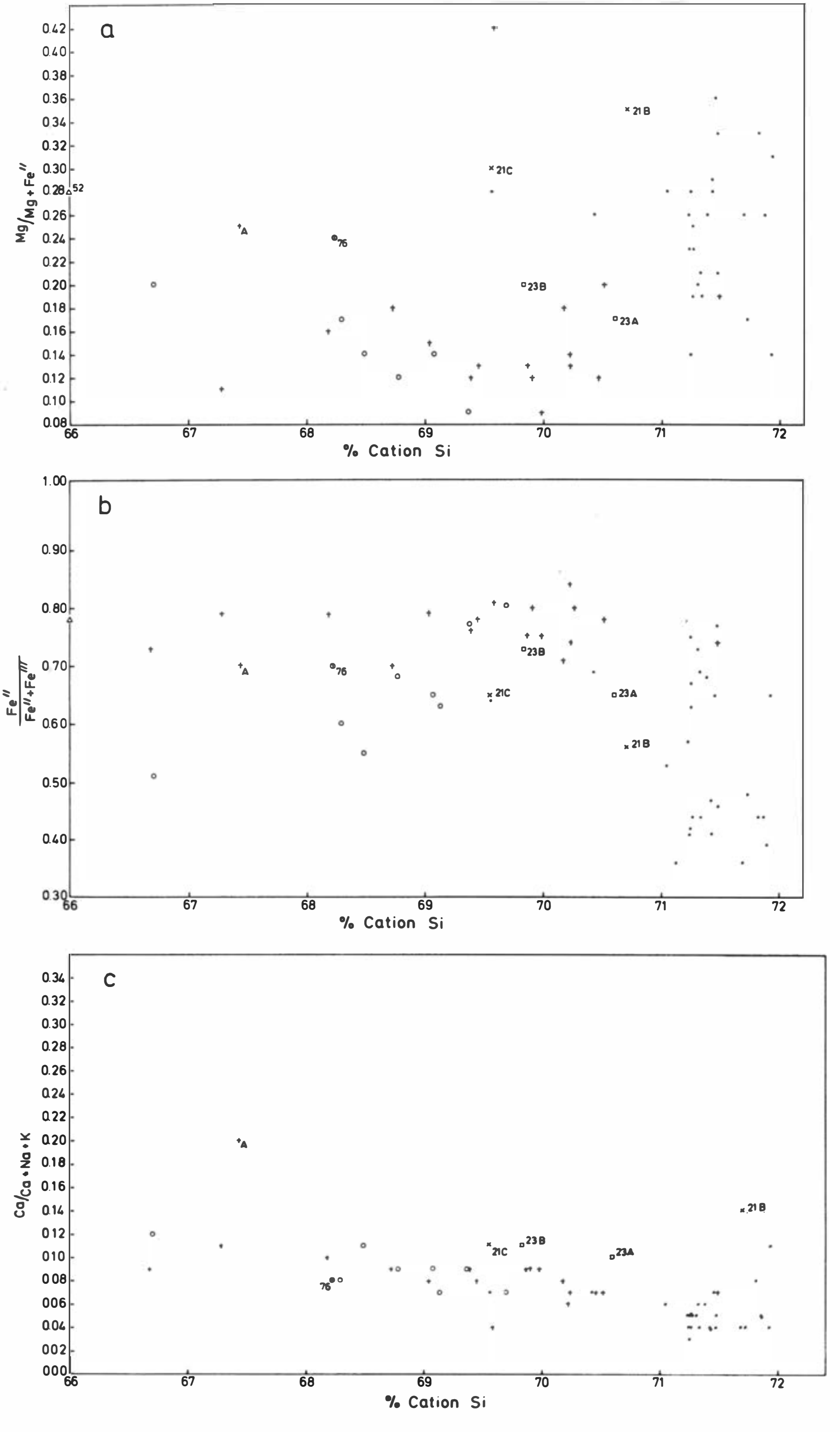

a
Mg/Mg + Fe''
% Cation Si
b
Fe''/Fe''+Fe'''
% Cation Si
c
Ca/Ca + Na + K
% Cation Si
21B
21C
23B
23A
76
A
52

Table 3. Analytical data showing contact and 'assimilation' effects in Meheia granite (wt. % oxides).*

	21A	21B	21C	Mean Meheia granite	23A	23B	23C	24
SiO_2	73.98	74.66	73.50	75.74	75.49	74.83	48.20	46.56
TiO_2	0.34	0.35	0.33	0.25	0.28	0.30	2.77	2.79
Al_2O_3	12.06	12.25	12.67	11.94	12.07	12.23	13.21	13.96
Fe_2O_3	2.66	1.20	0.88	0.98	0.80	0.62	4.03	3.08
FeO	0.62	1.35	1.47	1.07	1.35	1.51	10.64	11.49
MnO	0.08	0.05	0.05	0.03	0.03	0.04	0.27	0.31
MgO	0.31	0.40	0.38	0.20	0.15	0.21	6.25	6.38
CaO	4.70	1.80	1.44	0.69	1.36	1.67	7.35	8.52
Na_2O	1.79	3.40	3.61	3.51	6.82	6.96	0.07	2.80
K_2O	2.19	3.90	4.62	5.22	0.24	0.23	3.82	1.09
P_2O_5	0.09	0.07	0.06	0.03	0.03	0.04	0.58	0.61
Loss on ignition	1.00	0.74	0.59	0.45	0.59	0.86	2.30	0.97
Total	99.82	100.17	99.60	100.11	99.21	99.50	99.49	98.56
Trace elements (in ppm) and ratios								
Rb	114	166	176	211	19	18	327	67
Sr	303	141	125	43	69	88	182	177
Zr	311	357	326	320	304	326	179	174
Ba	219	388	317	366	183	132	291	195
Th	29.34	27.54	27.33	24.88	25.72	25.93	4.50	1.70
U	11.61	10.68	10.58	5.84	8.19	8.37	1.97	0.65
K/Rb	159	195	218	212	106	105	97	135
K/Ba	83	83	121	131	11	14	109	47
Rb/Sr	0.38	1.18	1.41	6.19	0.27	0.21	1.79	0.38
Th/U	2.53	2.58	2.58	4.45	3.14	3.10	2.28	2.62
$Th/K \times 10^4$	16.17	8.51	7.13	5.47	131.90	135.76	1.42	1.87
$U/K \times 10^4$	6.40	3.30	2.76	1.39	42.00	43.82	0.62	0.71

* Explanation in text.

Examination of the analyses of these samples reveals significant changes in the K_2O, Na_2O, CaO and iron contents of the contact rocks relative to the group average for the granite and sample 24 for the amphibolite. The potassium contents of the granite samples from the contact zone fell from the group average of about 5% K_2O to 0.24% (a factor of 21) while the sodium and calcium contents increased each by a factor of about 2. The amphibolite at the contact (23C) shows a marked increase in its K_2O content (compared to sample 24), from 1.09% to 3.82 (a factor of 3.5). Its sodium value however fell by a factor of 40 – from 2.80% in sample 24 to 0.07% in 23C.

Mineralogically, the cation exchanges at the contact resulted in the con-

Fig. 4(a). $Mg/Mg+Fe^{++}$ vs. % cation Si in the granites. (b). $Fe^{++}/Fe^{++}+Fe^{+++}$ vs. % cation Si in the granites. (c). Ca/Ca+Na+K vs. % cation Si in the granites.

version of *all* the actinolitic amphibole in the amphibolite (sample 24) into biotite and epidote minerals thereby changing the rock from an amphibolite into a biotite epidote schist (sample 23); the granite on the other hand was converted into a 'granodiorite' (samples 23A and B, Figs. 3a and 3b). Maximum width of zone is 31 cm. Some of the cation exchanges in these contact rocks are illustrated on the right hand side of Fig. 5.

Sample no. 76, which is from one of the thin marginal zones of the Meheia granite at its contact with the Knute group rocks, shows similar but less pronounced changes as do samples 23A and 23B.

Sample no. 96 is from one of the small (15 × 15 cm) concordant granitic lenses found in the Knute group rock at a contact with the Meheia granite. It is believed to be part of the Meheia granite, injected lit par lit into the well foliated Knute group rock. The analysis shows that it has, like 23A/B and 76, been converted into granodiorite. The small lenses must have been completely surrounded by the amphibolitic rock at the time they were injected thus facilitating ionic exchanges between the two rock types.

Helgevatnet granite. – Samples 36 and 'A' of the Helgevatnet granite were taken for the purpose of observing possible changes in the composition of the granite in the vicinity of the amphibolitic country rock.

Sample 36 is from a concordant vein of the granite, about 30 cm wide, in the country rock. The vein material is grey, medium grained (cf coarse grained parent rock) and is immediately flanked on both sides by a thin and distinct selvedge of biotite.

Sample A is from the granite at its contact with the Knute group rock at Kolhusdalen. Large (1 × 1.5 m) xenoliths of the Knute group rock could be observed within the granite in this area, but sample A was taken from an area free of inclusions, about 30 cm from the contact. The analyses of the two samples indicate that changes observed in the chemistry (compared to the non-contact samples of Helgevatnet granite) are similar to and of similar extent as those observed in samples 23A and B of Meheia granite.

The similarities of the chemical reactions at the contacts of the two granite bodies and the limitation of the reactions to very narrow zones in the rocks affected suggest that they must have been effected at the time of emplacement of the granite bodies. They are primary contact reactions and effects of subsequent metamorphism on them must have been very slight.

Similarity of the contact reactions between the Meheia and Helgevatnet granites and the adjacent amphibolitic Knute group rock would suggest similarities in the physical states of the granite bodies at the time/s of their emplacement.

As indicated earlier, the Helgevatnet granite is an intrusive body probably emplaced in a molten state.

It is suggested that the Meheia granite was also emplaced in a similar state; lack of discordant contacts with the Knute group rock would be due to the presence of well-developed foliation planes in these rocks prior to the emplacement of the granite.

'Assimilation' effects in the Meheia granite

Non-feldspathized (non-granitized) inclusions of Knute group rocks could sometimes be observed in the Meheia granite. When such inclusions are caught in sheared-zones, they get 'mixed' with the granite thereby modifying the appearance, mineralogy and composition of the granite. Samples 21A, B and C show the effects of such 'mixture' or 'assimilation' on the granite. The samples were taken on the north side of the road, some 250 metres west of Meheia Turisthytte on the Kongsberg–Notodden road. 21A is from the middle of the sheared zone where the granite shows distinct light to dark green colours resulting from abundant epidote and pale green muscovite on the shear planes. The rock here has a pronounced schistose texture. Sample 21B was taken 10 cm east of 21A, away from the sheared-zone and 21C was taken another 10 cm farther to the east of 21B where there is little indication of 'mixing' but only evidence of shearing.

Sample 21A looks more like an albite–muscovite–epidote schist than a granite in thin section. The feldspars, which are preponderantly sodic plagioclase (An_7), have been saussuritized to produce more than half of the epidote in section. There is also abundant development of muscovite, in streaks as well as in association with epidote, in granulated zones. Samples 21B and C show increasingly diminishing effects of epidote and muscovite formation as well as of shearing.

Analyses of the samples show significant increases in CaO and Fe_2O_3 relative to the average Meheia granite, the increase being most pronounced in 21A (more than a factor of 6). While showing increases in CaO and Fe_2O_3, sample 21A lost about half its Na_2O and K_2O contents. Samples 21B and 21C also show similar but less marked changes. The higher CaO contents could be attributed partly to relative losses of Na_2O and K_2O and partly to assimilated amphibolite.

Sample 21A in particular clearly shows that shearing stress was a positive factor in the development of epidote minerals in these granites. The association of muscovite and epidote in sheared and granulated zones also shows that the formation of epidote was accompanied by alkali metasomatism. Some of these chemical changes are illustrated on the left hand side of Fig. 5.

Trace elements

Group averages of the trace analyses and ratios are presented in Table 4; distribution of the elements in the three granite bodies are illustrated in Fig. 6.

Rb and K/Rb ratios

Rubidium content of Meheia granite varies between 118 and 270 ppm, with a group average of 211 ppm. Some of the potassium-depleted samples, which are not included in the calculation of group averages, have as low as 18 ppm

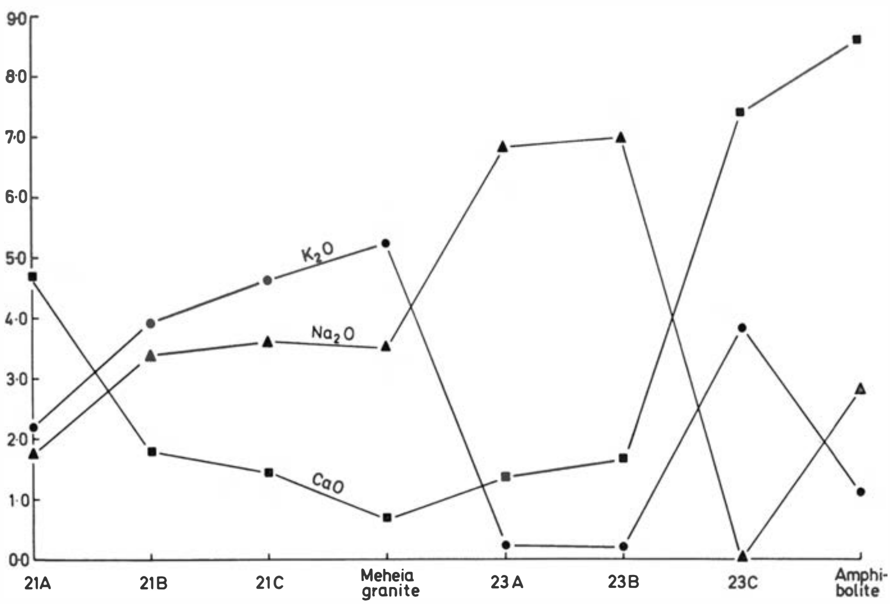


Fig. 5. Graphical representation of some of the chemical modifications due to contact and 'assimilation' effects in the Meheia granite.

Rb. The range in the Helgevatnet granite is from 70 to 273 ppm with group average of 151 ppm while Rb values in the Kongsberg granite vary between 59 and 94 ppm with a group average of 82. The low Rb content of the Kongsberg granite, including the pegmatitic phases, is not in accord with the observed Rb contents of crustal igneous granitic rocks (cf. 170 ppm Rb of low Ca-granites (Turekian & Wedepohl 1961)) and suggests either non-availability of Rb in the environment or a non-igneous genesis for the rock.

The K/Rb ratios for the samples analysed are given in Table 4, and the % K vs. ppm Rb plots are shown in Fig. 7.

As seen in Fig. 7, the Kongsberg granite is characterized by high K and low Rb contents giving it K/Rb ratios between 487 and 755. The amphibolite country rock of the Kongsberg granite has a K/Rb ratio of 400. The high K/Rb ratios obtained for the Kongsberg granite and its amphibolite country rock fall within the range of K/Rb ratios known for amphiboles and amphibolites (Griffin et al. 1967, Christie et al. 1970).

The high K/Rb ratios in the Kongsberg granite could not be due to the hornblende content of the granite; the granite is very rich in potassium, and even the pegmatitic phases, with negligible amphibole and high potassium contents give K/Rb ratios between 607 and 630. The granite could not have formed by normal crystallization from a granitic melt. The similarity between the K/Rb ratios of the amphibolite country rock and the granite might suggest a genetic relation between the two.

Table 4. Mean trace elements (in ppm) and elements ratios of the granites ($\bar{X}$) with standard error of the mean ($\delta/\sqrt{N}$).

	Meheia (n = 27)		Helgevatnet (n = 17)		Kongsberg (n = 8)	
	$\bar{X}$	$\delta/\sqrt{N}$	$\bar{X}$	$\delta/\sqrt{N}$	$\bar{X}$	$\delta/\sqrt{N}$
Rb	211	7.97	151	11.61	82	4.56
Sr	43	3.38	63	2.56	72	5.83
Zr	320	9.21	429	35.13	514	35.78
Ba	366	20.79	699	44.07	1067	96.32
Th	24.88	0.50	14.73	1.25	3.78	0.79
U	5.84	0.27	4.43	0.29	0.99	0.05
K/Rb	212	8.09	284	16.86	620	34.03
K/Ba	131	9.05	65	8.45	49	4.33
Rb/Sr	6.19	0.68	2.51	0.30	1.21	0.16
Th/U	4.45	0.19	3.36	0.22	3.80	0.68
$Th/K \times 10^4$	5.47	0.26	3.72	0.29	0.80	0.19
$U/K \times 10^4$	1.39	0.09	1.13	0.08	0.20	0.02

The bulk of the K/Rb values for the Meheia granite cluster between 230 and 150 and that of the Helgevatnet values lie between 300 and 230. Notwithstanding the spread of values within each of the granite bodies, a distinction could be made between them on the basis of K/Rb ratios with the Meheia granite showing lower K/Rb ratio than the Helgevatnet granite.

K/Rb ratios from contact zones and small veins

Samples of granites from either the contact or marginal areas or from small veins within the amphibolitic country rock all show relative enrichment in Rb compared to their normal counterparts. Samples 23A and 23B give K/Rb ratios of 106 and 105 respectively in spite of the marked depletion in potassium. Horstman (1957) observed that at igneous contact and immediately inside the intrusion, rubidium is lost relative to the preferred ion, potassium. Observations from the contact zones of the two granites – Meheia and Helgevatnet – show enrichment in Rb relative to K (Fig. 7). In the contact zones of both granites as well as in the small granitic tabular bodies within the amphibolite Knute group rock, potassium feldspar is virtually non-existent and the main contributors of potassium in these rocks are biotite and muscovite.

Tauson (1965), showed that biotite can accommodate about 4½ times more Rb atoms than potassium feldspar can for a given number of potassium atoms; the greater tolerance of Rb by biotite would account for the relative enrichment in Rb in the contact zones of the Meheia and Helgevatnet granites.

The higher than 300 K/Rb ratios shown by some of the Helgevatnet granites could have resulted from redistribution of Rb by the hydrothermal process that deposited fluorite on joint surfaces. Samples 26 (K/Rb = 432) and K–71–27 (K/Rb = 351) for example, were taken near the fluorite site.

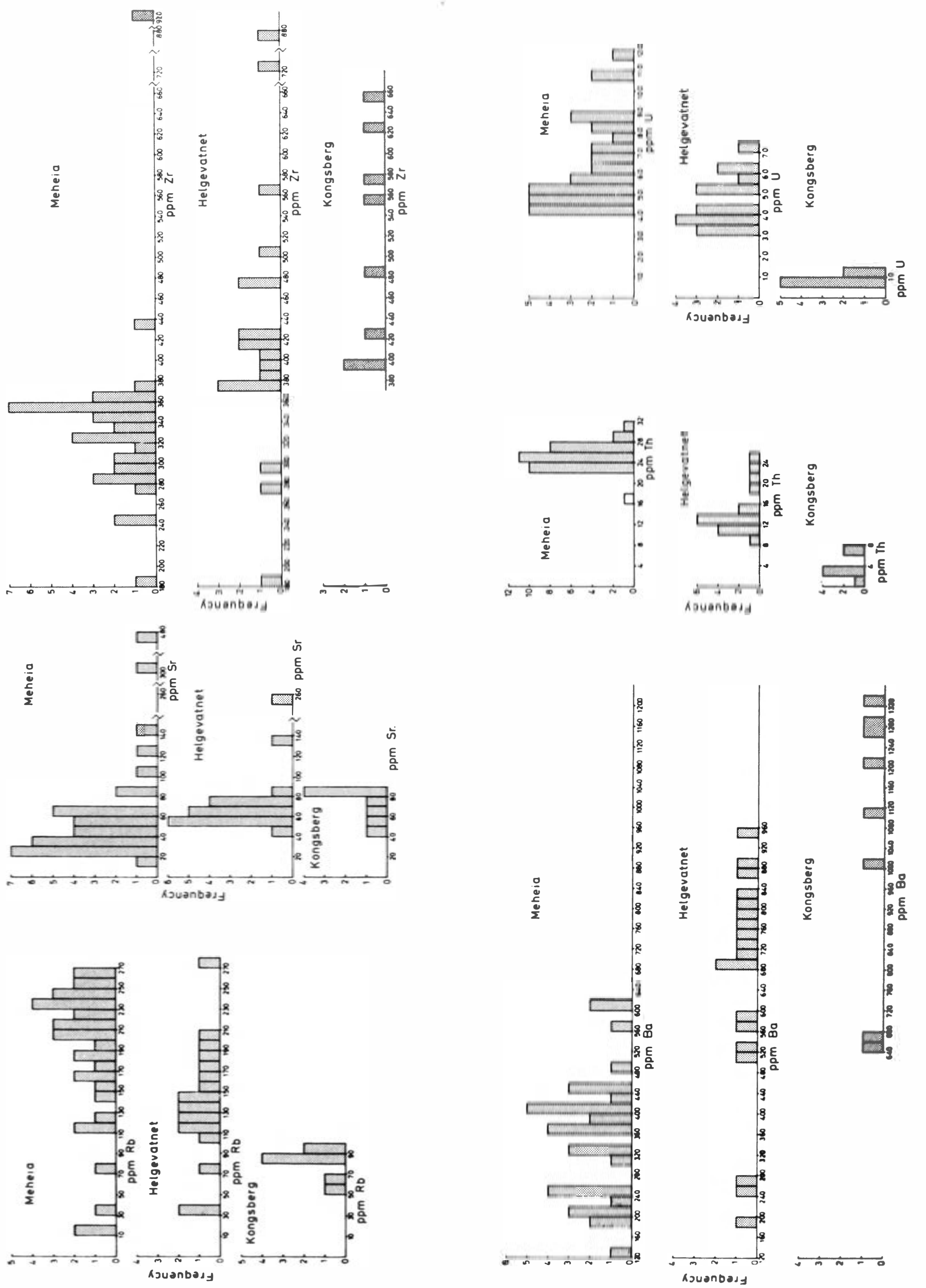
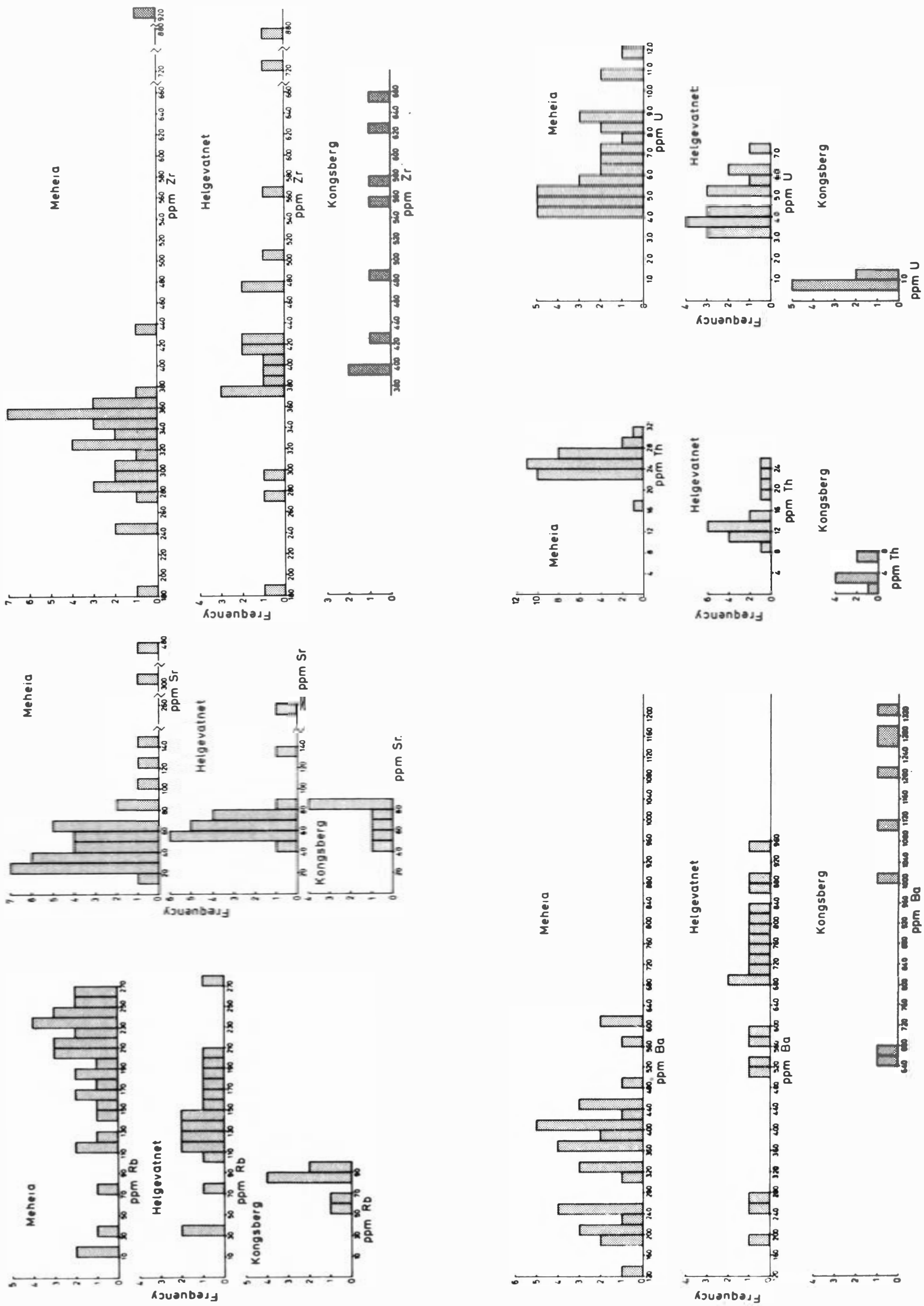


Fig. 6. Frequency distribution (histograms) of Rb, Sr, Th, U, Ba and Zr in the three granites.


Meheia
Helgevatnet
Kongsberg
Frequency
ppm Rb
ppm Sr
ppm Zr
ppm Th
ppm U
ppm Ba

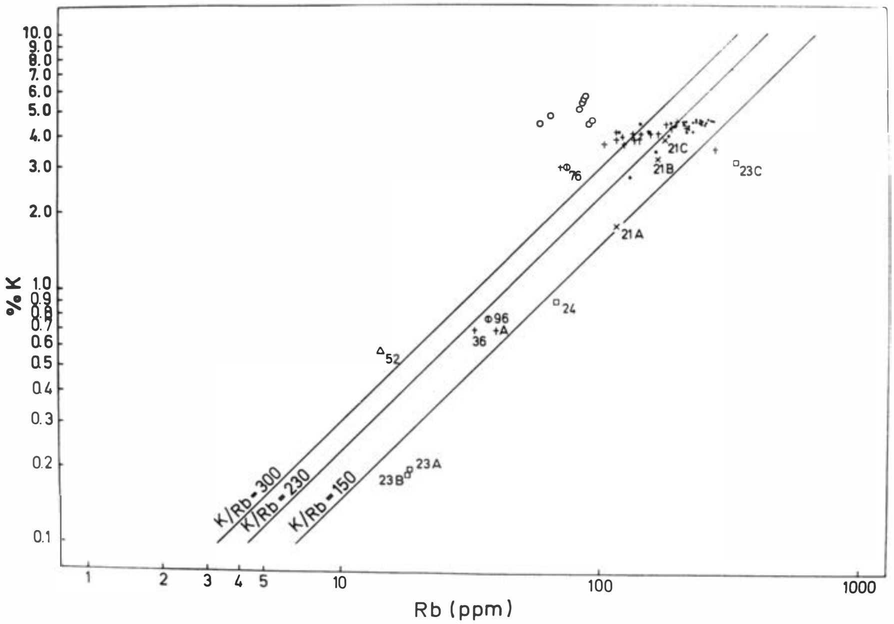


Fig. 7. K/Rb relationships in the granites (symbols as in Fig. 3(a)).

Sr

All three granite bodies show lower Sr contents than the 100 ppm value for low Ca-granites given by Turekian & Wedepohl (1961). The average Sr contents are: 43 ppm for Meheia granite, 63 ppm for Helgevatnet granite and 72 ppm for the Kongsberg granite. The low Sr values tend to produce high Rb/Sr ratios in both Meheia (average Rb/Sr = 6) and Helgevatnet (average Rb/Sr = 2.5) granites. The Kongsberg granite which has lower than normal Rb content shows Rb/Sr ratios (average 1.2) lower than the average of 1.7 calculated from the data of Turekian & Wedepohl for low calcium granites. Distribution of Sr within the different granites are shown in Fig. 6.

Ba

Barium, like Rb is geochemically related to K and can be used as an indicator of differentiation trend in magmatic crystallization (Nockolds & Allen 1953, Heier & Taylor 1959). Distribution of Ba in the analysed samples is shown in Fig. 6. The Kongsberg granite has the highest and Meheia granite the lowest Ba contents. The K/Ba is lowest in the Kongsberg granite (K/Ba = 49) and highest in the Meheia granite (K/Ba = 130.5) while the Helgevatnet granite has a K/Ba (65) that falls between the other two.

The average Ba contents of the Meheia (366 ppm) and Helgevatnet (699 ppm) granites are all lower than the 840 ppm Ba given by Turekian & Wedepohl (1961) for low calcium granites.

Zr

The Zr-content of Meheia granite varies between 180 and 379 ppm (average 320 ppm), that of Helgevatnet between 188 and 505 ppm (average 429 ppm), while that of Kongsberg granite is between 397 and 651 ppm (average 514 ppm). As indicated by Nockolds & Allen (1953: 138) Zr tends to be enriched in the most acid member of a differentiation series.

The average Zr content of low calcium granites is 175 ppm (Turekian & Wedepohl 1961). As seen from Table 4 and the Zr ranges given above, all the granites in the Kongsberg area are comparatively enriched in Zr.

Th and U

Group averages of the Th and U contents of the analysed samples are given in Table 4 and the Th vs. U, Th vs. K and U vs. K relations are plotted in Figs. 8, 9, and 10 respectively. The geochemistry of these radioactive elements has been treated by a number of authors (Adams et al. 1959, Taylor 1964).

Heier & Rogers (1963) found an average of 17.36 ppm Th in 166 granitic rocks and an average of 4.75 ppm U in 755 granitic rocks. Clark et al. (1966) suggested 20 ppm Th, 4.26% K and 4.7 ppm U for silicic igneous plutonic and hypabyssal rocks. From Table 4 it is seen that all the average K, Th and U values for Meheia granite are higher and all those for Helgevatnet granite lower than the suggested values. No sample of the Meheia granite has lower than 4 ppm U and only one has less than 20 ppm Th

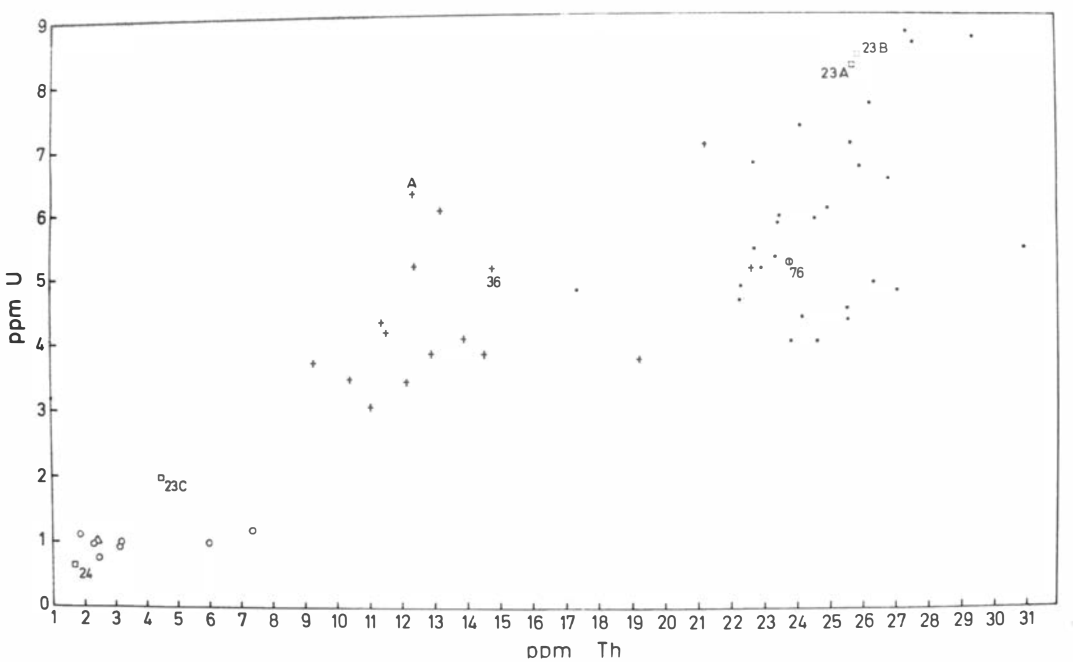


Fig. 8. U vs. Th values in the granites.

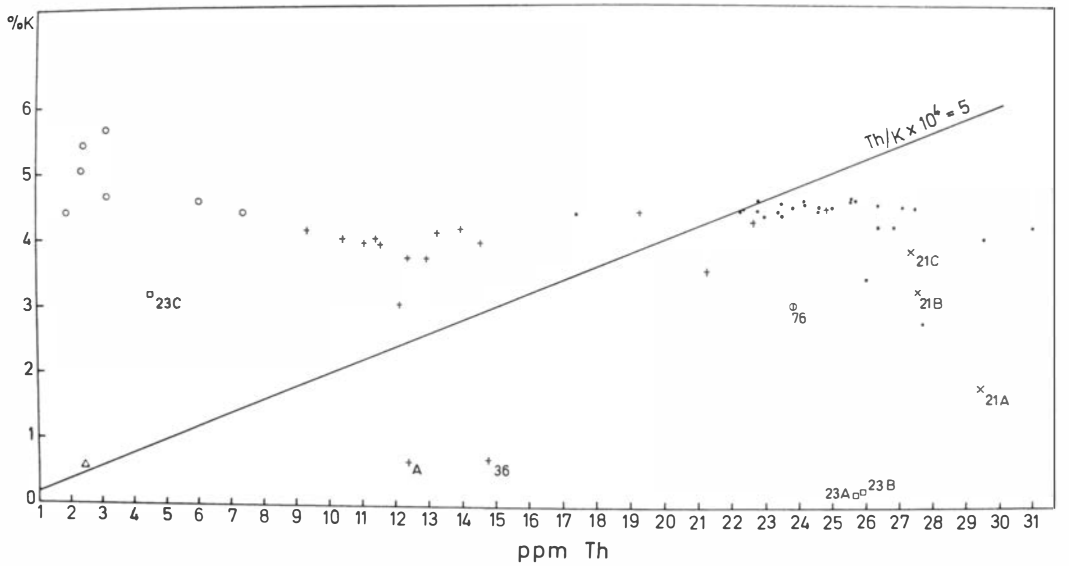


Fig. 9. K vs. Th values in the granites.

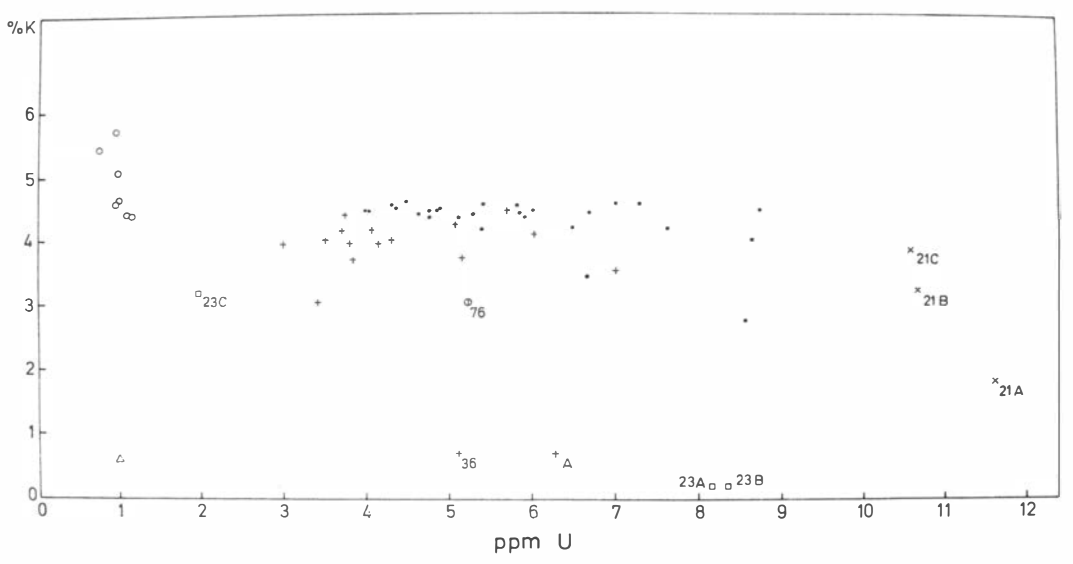


Fig. 10. K vs. U values in the granites.

(sample 8A with 17.4 ppm Th). The spread in the U values of this and the other granites indicates that U has probably been leached from parts of the granite bodies.

Th values in the Helgevatnet granite are generally about half of the Meheia values while U-values are only slightly lower than in Meheia granite.

The Th and U values in the Kongsberg granite are distinctly lower than the suggested averages by Clark et al. (1966) but the K-values are higher. The Th and U values in the Kongsberg granite are similar to those for the amphibolite country rock as well as to those for the amphibolite from Meheia (Figs. 8, 9 and 10).

The Th/U and the Th/K plots show the granites as three distinct and separate bodies.

Conclusion

Kongsberg granite

Geographical considerations and trace-elements contents in particular indicate that the Kongsberg granite is not genetically related to the Meheia and Helgevatnet granites.

Compared to the average granite, the Kongsberg granite has rather low Rb (82 ppm), Th (3.78 ppm), U (0.99 ppm) contents, low Th/K, U/K and high K/Rb ratios. It may possibly be genetically related to its amphibolitic country rock, which also shows low Rb (14 ppm), Th (2.46 ppm) and U (1.00 ppm) and high K/Rb (400) ratio.

Helgevatnet granite

The Helgevatnet granite shows from its contact relations with the adjacent Knute group rock that it is an intrusive body. The granite, however, shows an appreciable degree of inhomogeneity particularly in its trace elements contents. Such inhomogeneity could not be ascribed to contamination and contact effects alone. Post emplacement hydrothermal activity could effect redistribution of elements, particularly the alkali metals and U. The spread in the U values of the granite is not as large as in the Meheia granite, suggesting that post emplacement hydrothermal activity is not the sole cause of the inhomogeneity.

Observation of amphibolitic dykes within the granite and the higher grade of metamorphism shown by the mineral assemblage in the Helgevatnet granite both indicate that it is probably older than the Meheia granite. If this were the case, then the series of metamorphism to which the granite had been subjected as well as the other factors mentioned above must have contributed to the observed inhomogeneity.

Meheia granite

Observable contacts of the Meheia granite are of the sharp, concordant and interfingering type and the demonstrated modifications to the chemistry of the granite at the contact with the amphibolitic Knute group rock are neither characteristic of nor indicative of granitization. The marked alkali ions exchange could only have taken place in a hydrothermal medium and in response to temperature and chemical gradients. These two features suggest that the granite must have been emplaced in a moderately hot fluid state.

The presence of unfeldspathized inclusions of the country rock in the granite is also not in accord with a granitization origin.

The possibility that the granite could have been derived by isochemical metamorphism of acid effusives is rejected on the grounds that such a conversion would involve a grade of metamorphism much higher than that of upper greenschist lower epidote–amphibolite facies indicated by the country rock.

Absence of migmatization in the Meheia granite's country rock rules against possible local anatectic origin. It is, however, possible that anatexis was effected at lower level in the crust and the molten fraction moved upwards for emplacement at higher levels.

Both major and trace elements chemistry of the rock are in accord with those of granites formed by direct crystallization from a melt. The conformable and interfingering contacts shown are not unusual in late kinematic granites to which it shows many similarities (Marmo 1971: 82–107).

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