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T.R. Neff

Petrology of the Holterkollen plutonic complex, Oslo Region, Norway

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The Holterkollen complex contains the following rock types (oldest to youngest): biotite granite with quartz porphyry phases, syenitic ring dikes, and hornblende granite dikes. Chemical data plots form similar and overlapping trends. Trend surface maps plotting chemical variations within the pluton show a series of 'highs' and 'lows' that cross-cut rock type boundaries. Quartz porphyry zones within the pluton were apparently formed by sudden volatile loss whereas the chemical variation pattern is the result of multiple magma injection. The dike rocks appear to have formed from one fractionation series and the plutonic rocks another. Their parent magmas were probably produced by immiscible separation into a felsic and mafic fraction of an original, mantle derived, basaltic melt.

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Location and previous work

The Holterkollen area is located approximately 20 km northwest from Oslo (Fig. 1) along the edge of the Oslo graben. Initial studies in the area were undertaken by Brøgger & Schetelig (1919, 1923). More recent investigations have been carried out by Naterstad (1971) and A. Gaut (pers. comm. 1973). Many of the contacts on the geologic map and cross sections (Figs. 1 and 2) were drawn by these workers. However, mapping within the Holterkollen pluton itself and other minor changes have been carried out by the senior author.

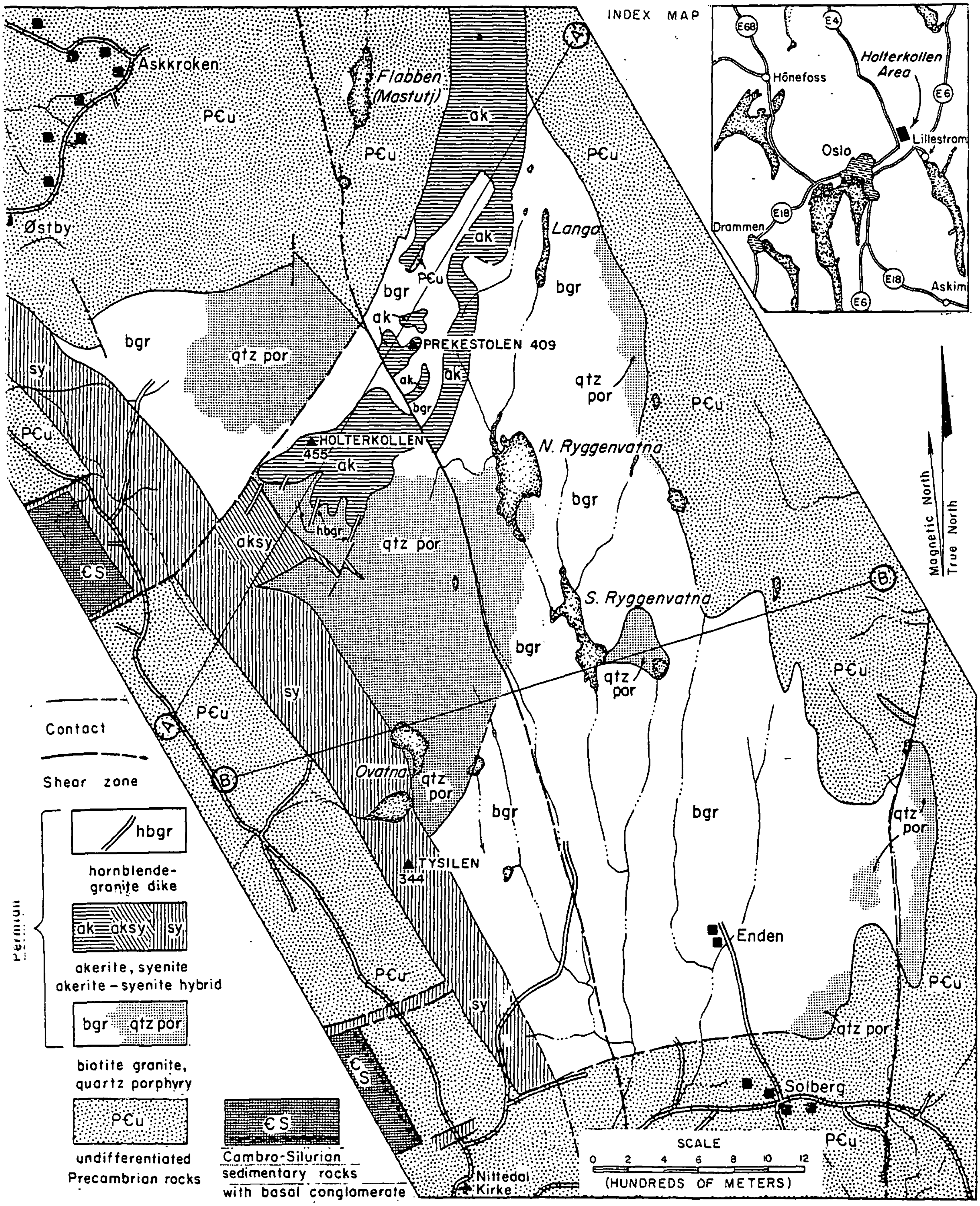
Field relationships

The major intrusive rock mass in the area is the Holterkollen pluton, which covers an area of approximately 12 km². The Holterkollen pluton is composed mainly of biotite granite and is similar to other biotite granite masses in the Oslo Region such as the Drammen granite and the Finnemarka complex (Czamanske 1965). The Holterkollen pluton is not all granite. Approximately one third of the pluton is composed of quartz porphyry. Contacts between quartz porphyritic and granitic phases of the pluton in most cases are gradational over distances as much as several hundred meters. However, in a few instances gradational contacts narrow to a few tenths of meters. One mass of quartz porphyry in the central part of the pluton is unusual in that it has very sharp contacts with the granite.

The Holterkollen pluton is surrounded on three sides by Precambrian gneiss, schist, amphibolite, and granitic rocks, and is on the very edge of the Oslo graben structural depression. Geophysical evidence (Ramberg 1976) indicates that the border of the Holterkollen pluton slopes gradually eastward (Fig. 2).

Where the pluton is in contact with metamorphic rocks, quartz porphyry is generally present. Border zones of quartz porphyry are, however, not always mappable. Some are only a few meters thick. Partially resorbed xenoliths are relatively common within 10 m of the contact, but the pluton as a whole is surprisingly xenolith free. Metamorphic rocks situated within a few meters of the pluton are commonly cross-cut with small (20 cm thick) aplite dikes and quartz-feldspar veinlets. Wallrocks also show a slight amount of alkali metasomatism.

The granite and quartz porphyry of the Holterkollen pluton are cut by syenite and akerite ring dikes associated with the Nittedal cauldron (Sæther 1946, 1962, Naterstad 1971). The akerite is a biotite-syenite porphyry, but the name 'akerite' is retained in this paper to preserve continuity with earlier works and regional maps. Both dikes have curving traces and are extensions of ring fractures or dikes within or outlining the cauldron. The syenite dike forms the eastern boundary of the cauldron and is an extension of the larger Grefsen syenite body


INDEX MAP
E68
E4
Hønefoss
Holterkollen Area
E6
Lillestrom
Oslo
E18
Drammen
E18
E6
Askim
Askkroken
Østby
Flabben (Mastutj)
A'
ak
PЄu
Langa
bgr
PREKESTOLEN 409
qtz por
HOLTERKOLLEN 455
N. Ryggenvatna
hbgr
aksy
sy
ЄS
S. Ryggenvatna
B'
A
B
Ovatna
TYSILEN 344
Enden
Solberg
Nittedal Kirke
Magnetic North
True North
Contact
Shear zone
Permian
hbgr
hornblende-granite dike
ak aksy sy
akerite, syenite
akerite - syenite hybrid
bgr qtz por
biotite granite, quartz porphyry
PЄu
undifferentiated Precambrian rocks
ЄS
Cambro-Silurian sedimentary rocks with basal conglomerate
SCALE
0 2 4 6 8 10 12
(HUNDREDS OF METERS)

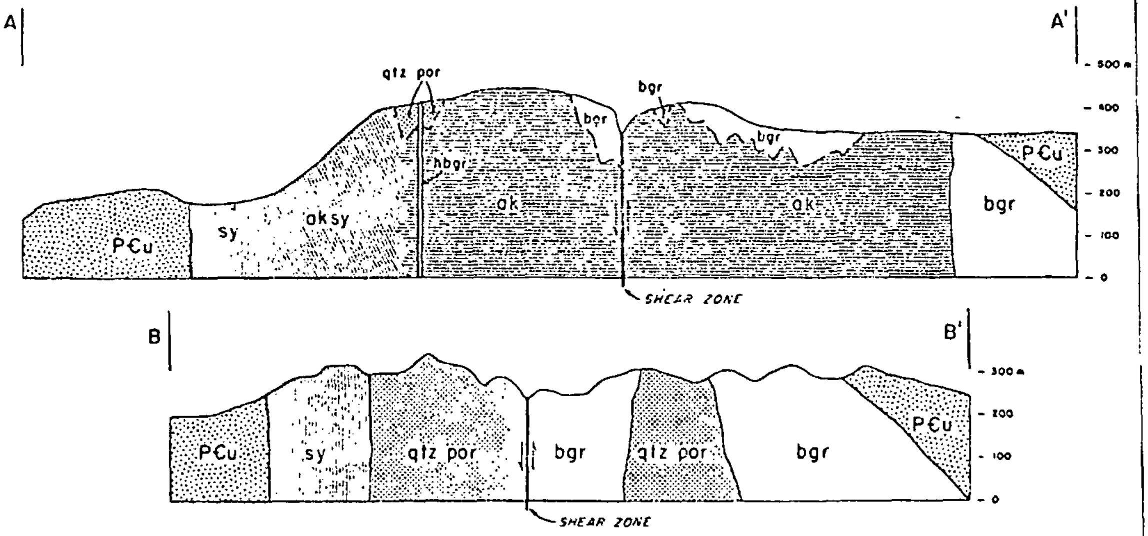


Fig. 2. Geologic cross sections of the Holterkollen area. A–A' and B–B' refer to Fig. 1.

which marks the southern boundary of the cauldron. Contacts of the syenite ring dike with plutonic and metamorphic wallrocks are very sharp with evident chilling of the syenite.

The akerite dike enters the Holterkollen area from the north and following an arcuate trace curves westward and crosses the northern third of the Holterkollen pluton to intersect the syenite. The akerite dike is discontinuous in part but its general trace can be ascertained by the alignment of separate masses of akerite within granite and quartz porphyry. The portion of akerite dike mapped between dashed contact lines in Fig. 1 contains in reality an intricate intermixture of akerite and granite with akerite predominating. However, contact relationships are not distinguishable at the map scale given. Contacts between akerite and granite, quartz porphyry, or metamorphic wallrocks are very sharp with evident chilling of the akerite. Moreover, granite xenoliths in akerite are common.

At the akerite-syenite intersection, contacts are very gradational and the rocks cropping out in this zone are mapped as hybrid types. Recent unpublished work by A. Gaut (pers. comm. 1974) shows that as the akerite dike is traced several kilometers northward out of the area of Fig. 1, it grades imperceptibly into syenite. These gradational relationships indicate that magmas producing akerite and syenite are intimately associated both in time and space.

Hornblende granite dikes not greater than 10 m in thickness cut the akerite, syenite, and quartz porphyry. Contacts are sharp and borders in the hornblende granite show evidence of chilling.

A prominent shear zone bisects the Holterkollen pluton and offsets the akerite dike both horizontally and vertically. Rock along the shear zone is highly brecciated, mylonitized, and hematite stained. The shear zone can be traced northward and southward to connect with a major mylonite belt that has evidence of being active in Precambrian, Eocambrian, Caledonian, and Permian times (Ramberg & Smithson 1975).

Petrography

Granite

The major rock type present in the Holterkollen pluton is biotite granite. Major mineral constituents of the granite are perthite (55%–70%), plagioclase (An_{15-20}) (10%–15%), and quartz (15%–30%). Accessory minerals are biotite (3–5%), magnetite (1–3%), and sphene (1%). Mineral grains are arranged in a hypidiomorphic

Fig. 1. Geologic map of the Holterkollen area. The geology is by A. Gaut, J. Naterstad & T. Neff. On the index map, E4 etc. refer to road numbers.

granular texture and vary considerably in size. Some granites contain perthite crystals as large as 5 cm in length.

The quartz, plagioclase, and biotite crystals are smaller but may be as large as 2 cm. As quartz porphyry contacts are approached, the grain size decreases until individual crystals (except for quartz) are 1 mm in diameter.

Granites are commonly porphyritic with phenocrysts being either perthite, plagioclase, or quartz. Phenocrysts may constitute as much as 50% (volume percent) of the rock. At times the groundmass texture is fine grained enough to be classed as aplitic. However, such samples appear as granites in hand specimen and are mapped as such. Wedge and bent feldspar twinning and crinkled micas which indicate protoclastic deformation are common. Also, some granites are cut by thin (2–3 cm) mylonite zones.

The perthite contains both string and patch exsolution lamellae sometimes existing side by side within the same crystal. Very minute secondary exsolution lamellae exist within the larger lamellae. Visual estimates suggest about equal amounts of Ab and Or. Rimming of perthite by plagioclase is well displayed in some specimens.

Quartz grains within the granite are generally anhedral, have sutured boundaries, and fill interstices between perthite and plagioclase crystals. Secondary, alteration minerals are sericite, kaolinite, chlorite, limonite, and hematite.

Quartz porphyry

The quartz porphyry appears as a massive buff to pink aplite, studded with rounded, glassy, quartz phenocrysts ranging up to 1 cm in diameter. Sutured potassium feldspar and quartz make up 60–70% and 25–35% of the groundmass respectively with plagioclase constituting about 5%. Visual estimation of the groundmass plagioclase composition shows that it varies from An_{10} to An_{15}. Accessory minerals present only in trace amounts are magnetite, rutile, and biotite. Some of the quartz porphyry specimens examined contain irregular patches of a micrographic, quartz-feldspar intergrowth.

Quartz phenocrysts are generally rounded and exhibit evidence of corrosion. Some phenocrysts also have hexagonal outlines and growth lines. Secondary overgrowths on rounded or hexagonal quartz phenocrysts are also common. These structures are shown in Fig. 3.

Two different types of quartz exist within the same rock and apparently reflect the following crystallization history:

Early development of phenocrysts by unimpeded crystal growth.

Disequilibrium and corrosion of phenocrysts,

Late quartz crystallization in the groundmass sometimes as a micrographic intergrowth with feldspar.

Phenocrysts of perthite, biotite, magnetite, sphene, allanite and zircon are sometimes present in addition to quartz. Most perthite phenocrysts are very similar to perthite grains within granite. However, unlike granite a significant number are corroded and have multiple rims e.g. a core of perthite will have a rim of plagioclase which is in turn surrounded by perthite. Multiple rimming of perthite is characteristic of akerite and syenite. Plagioclase phenocrysts have embayed and scalloped boundaries. Also bent, wedged and broken polysynthetic twinning is common.

Quartz porphyry exhibits more deuteric alteration than granite. Seritization and kaolinization of feldspars are sometimes quite advanced. In addition many biotite phenocrysts are completely chloritized. Also magnetite grains are partially or wholly altered to hematite or limonite. Small miarolitic cavities (2–20 mm in diameter) exist within some quartz porphyries.

Akerite

Akerite is a light to dark-gray porphyry whose groundmass is medium to fine grained and composed of interlocking subhedral and anhedral crystals. Major constituents of the groundmass are orthoclase (60–75%), plagioclase (An_{5-20}) (10–20%), quartz (5–10%), and hornblende (5–10%). Accessory minerals are biotite (1–5%), magnetite (1–5%), and trace amounts of augite, zircon, rutile, sphene, and apatite (percentages given are for portions of the groundmass only).

Phenocrysts vary in size from 1–10 mm and range from 10% to 60% of the total rock volume. Phenocrysts are composed of perthite (5–45%), plagioclase (An_{15-20}) (5–10%), biotite (1–5%), hornblende (1–5%), magnetite (1–1%), and augite (1%). (Phenocryst percentages are given for portion of total rock volume.) Perthite phenocrysts have string, bleb, and patchy exsolution lamellae. Microscopic examination of perthites indicate an equal Ab-Or ratio (mesoperthite).

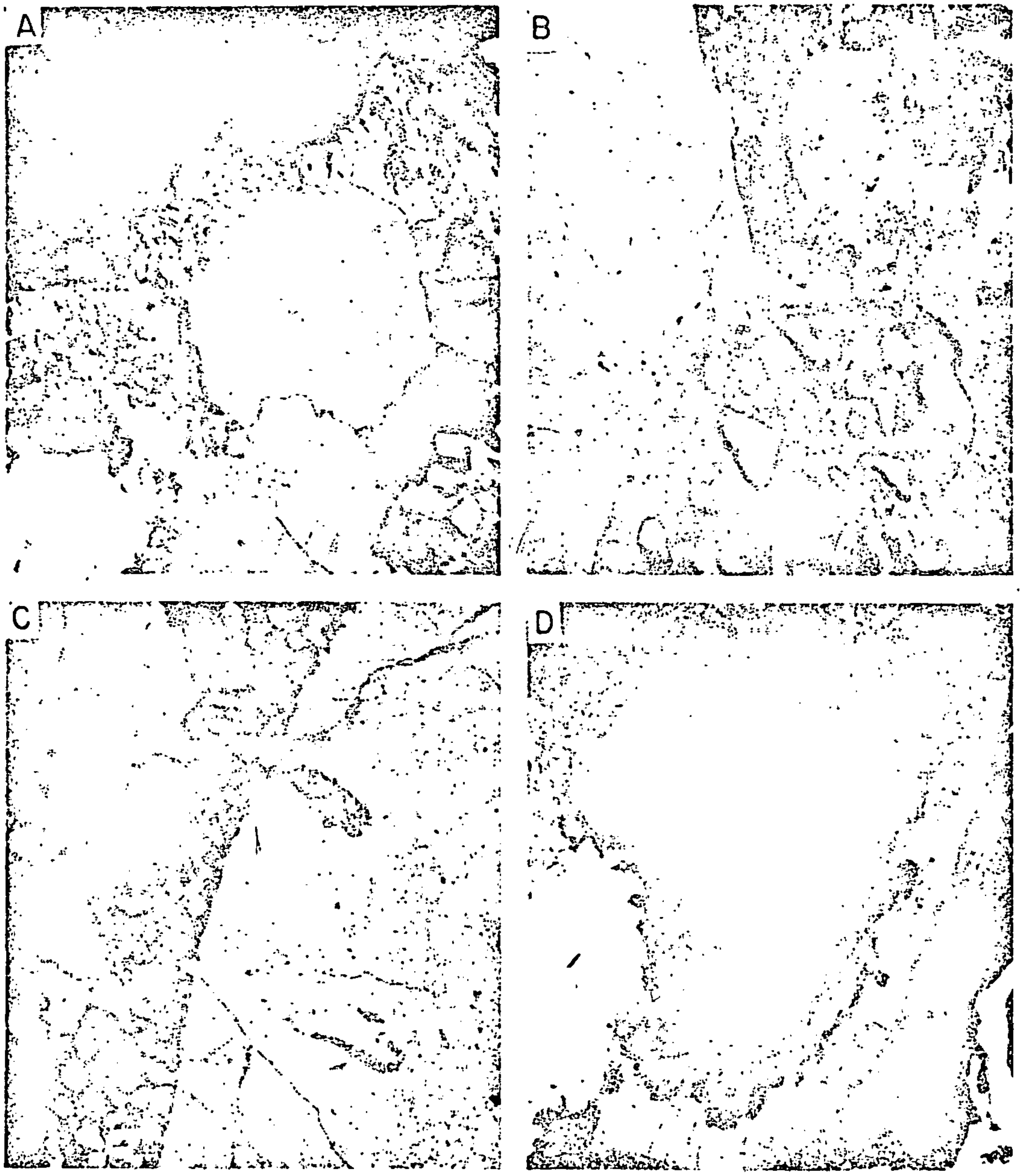


Fig. 3. A. Hexagonal quartz phenocryst in quartz porphyry. The groundmass is a micrographic intergrowth of quartz and K-feldspar. (X60). B. Detail of A. Showing the edge of the hexagonal phenocryst and micrographic intergrowth of quartz and K-feldspar. (X200). C. Edge of a rounded, corroded quartz phenocryst. The groundmass contains minute grains of secondary quartz. (X60). D. Multiple rimming of a feldspar phenocryst in syenite. The core and outside rim are perthite; whereas the intermediate rim is plagioclase. (X60).

Plagioclase and perthite both exhibit complex rimming. Two and sometimes three zones are recognizable in individual grains. Separate zones may be either plagioclase or perthite but identical compositions are never juxtaposed. For instance, a highly corroded core of perthite may be enclosed in a continuous rim of plagioclase or the opposite case may exist where plagioclase is the core and perthite the rim. Sometimes multiple rimming exists where in addition to the two rims described above, a third exterior rim has been added, identical in comparison to the core.

Coronas of hornblende enclosing augite are common. The rim width varies considerably. Some rims are only a thin selvage of hornblende on augite. In others, only a few specks of augite remain in the center of a hornblende crystal.

Akerite contains many rounded dark inclusions which may constitute as much as 5% of the total rock volume. Inclusions are uniform in appearance from one outcrop to another and contain no identifiable schistose or gneisose structures characteristic of metamorphic wallrocks. Moreover, there is no correlation between inclusion volume and wallrock type. Samples taken from the dark inclusions appear similar to akerite except that the mafic content is higher, ranging up to 30%.

Syenite

Syenite is a dark-buff porphyry whose groundmass has a hypidiomorphic granular texture generally coarser than akerite. Major constituents of the groundmass are orthoclase (65–70%), plagioclase (untwinned) (10–15%), quartz (5–10%), and hornblende (3–10%). Accessory minerals are magnetite (3–5%), biotite (< 1–1%), augite (< 1%), apatite (< 1%), sphene (< 1%), and zircon (< 1%).

Phenocrysts are generally euhedral to subhedral and make up 15–20% of the total rock volume. Phenocrysts are mainly perthite and are very similar to those in akerite both in texture and composition. Plagioclase is present only in concentrations < 5%. At times, magnetite, biotite, and hornblende grains are present as phenocrysts but only in trace amounts.

Feldspar and perthite phenocrysts have single or multiple rims and corroded cores similar to those present in akerite (Fig. 3, D). Information collected by detailed examination of these complex, rimmed crystals indicates that the separate rims are probably the result of successive stages of crystallization interrupted by periods of corrosion and not the result of exsolution. Lines of evidence supporting this are:

Crystal growth lines reflecting variations in An are visible in plagioclase rims. If exsolution was the producing mechanism then the rims should be uniform in composition.

Internal structures such as perthite lamellae and growth lines are abruptly terminated. Also, rims and cores are intricately embayed and scalloped which strongly suggests corrosion.

Syenite contains many rounded, dark inclusions similar to those within akerite.

Akerite-syenite hybrid

Samples from the akerite-syenite hybrid zone appear similar to akerite but the frequency and size of biotite phenocrysts are reduced, at a few locations to zero. There is, however, one major difference – many plagioclases in the groundmass occurring as phenocrysts are untwinned or partially untwinned (untwinned plagioclase is characteristic of syenite).

Plagioclase phenocrysts in specimens collected from the hybrid region commonly have twinned cores surrounded by zoned, untwinned rims, or vice versa. Both twinned and untwinned zones show corrosion and rimming by string, patch, and bleb perthite.

Corrosion and rimming while being present both in the akerite and syenite are more extensive in the hybrid rock, thereby indicating that disequilibrium and reaction have been active.

Hornblende granite dikes

Hornblende granite is fine grained, light buff in color, and even textured. Hornblende granite has a hypidiomorphic granular texture with grain sizes varying from 0.5 to 5.0 mm. Major constituents are perthite (65–70%), plagioclase (10–15%), and quartz (10–15%). Accessory minerals are hornblende (3–5%), magnetite (1–2%), biotite (1%), zircon (1%), allanite (< 1%) and pyrite (< 1%).

Exsolution lamellae in perthites are difficult to examine due to alteration but it appears that they are mesoperthitic. Plagioclase crystals belong to two separate types. The first type has no or very poorly developed polysynthetic twinning. Individual grains are invariably rounded, embayed, and rimmed by perthite or plagioclase of the second type described below. Plagioclase cores are highly fractured.

The second type occurs in smaller, angular grains that show good polysynthetic twinning (An_{24}–An_{28}). These crystals have cores and rims similar to those described above; however, both core and rim are polysynthetically twinned but not in optical continuity.

Table 1. Arithmetic means ($\bar{x}$) and standard deviation(s) for major and minor elements.

	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SiO_2	Rb/Sr.	
$\bar{x}$	.31	13.13	1.87	.70	.05	.35	.78	4.27	4.64	.10	73.95	2.17	Granite
s	.18	.80	.67	.22	.02	.22	.40	.34	.36	.06	2.22	2.37	(34 spec.)
$\bar{x}$	.21	12.28	1.61	.74	.03	.21	.43	4.09	4.67	.07	75.89	3.49	Quartz porphyry
s	.10	.59	.54	.28	.01	.14	.25	.37	.38	.04	1.75	2.27	(23 spec.)
$\bar{x}$	.69	15.32	3.16	1.41	.15	.62	.97	5.55	5.35	.17	67.46	1.18	Syenite
s	.17	.98	.47	.31	.01	.23	.11	.37	.24	.07	2.17	.79	(7 spec.)
$\bar{x}$	.72	16.64	3.60	1.75	.17	.79	1.80	5.34	5.29	.20	65.13	.25	Akerite
s	.06	.21	.13	.47	.04	.12	.16	.41	.11	.02	1.28	.22	(5 spec.)
$\bar{x}$	.67	16.30	3.51	1.75	.15	.68	1.64	5.73	5.30	.10	65.76	--	Akerite-syenite
s	.07	.33	.23	.31	.01	.10	.21	.21	.13	.03	.88	--	(5 spec.)
	.26	14.72	2.77	2.23	.14	.15	.38	5.29	5.49	.06	68.94	4.34	Hornblende granite (1 spec.)

Quartz fills angular interstices between plagioclase and perthite. All hornblende granite invariably shows extensive deuteric alteration.

Chemical relationships

Analytical methods

All major elements except MgO, Na_2O, and FeO were determined by x-ray fluorescence using fused pellets prepared by mixing 1 part rock powder with 9 parts of Na-tetraborate before melting. Calibration curves were determined by using international and Mineralogisk-geologisk museum house standards.

Determination of MgO and Na_2O was by atomic absorption using synthetic standards. The ferrous iron amount in the total iron value determined by XRF was ascertained by titration using $K_2Cr_2O_7$.

Determination of Rb/Sr was by x-ray fluorescence using pressed rock powder pellets. Mass absorption corrections were used in the calculations.

Average composition of rock types

Table 1 lists the mean and standard deviation for each major element and Rb/Sr. Numbers of analysis are also given. The standard deviations indicate that there is much variation within each rock type.

There are no significant compositional differences between granite and quartz porphyry. The akerite and syenite are also chemically similar. However, the akerite is slightly richer in Al_2O and CaO and slightly poorer in SiO_2 than the syenite. Moreover, the Rb/Sr ratio is higher in syenite. The akerite-syenite appears petrographically to be a hybrid type, but differs compositionally from akerite only with respect to Na_2O.

Major and minor element oxide percentages for hornblende granite indicate that this rock type is intermediate in composition between the ring dike rocks and those of the pluton. The Rb/Sr ratio, however, is not intermediate but higher than the mean value of the other rock types.

Chemical analyses of ten Precambrian wallrocks are shown in Table 2. The samples analyzed were collected from locations on the north, east, and west of the Holterkollen pluton. On the south side outcrops are lacking due to a continuous alluvial cover. Representative samples chosen for analysis include gneiss, schist, and amphibolite.

Chemical trends

Fig. 4 shows the separate major and minor elements plotted against (1/3 Si+K) – (Ca+Mg). Correlation between separate rock types shows that steadily decreasing trends exist for all major and minor elements except K. Moreover, there is a considerable amount of overlap between akerite and syenite and particularly between quartz porphyry and granite. The

Table 2. Arithmetic means ($\bar{x}$) and standard deviation(s) for major and minor elements in wall rocks.

Rock Type	TiO_2	Al_2O_3	Total Fe Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SiO_2	Total
Gneiss	.65	14.85	3.90	.06	1.45	3.20	4.51	2.35	.20	67.63	98.79
Gneiss	.65	15.40	4.03	.04	1.24	3.14	4.84	2.43	.26	66.36	98.39
Schist	.71	14.68	5.94	.07	3.04	1.70	1.33	4.60	.20	65.46	97.75
Schist	.68	14.45	4.51	.07	1.53	2.00	3.18	3.21	.11	68.50	98.25
Amphibolite	.69	14.66	10.37	.21	4.86	5.00	2.31	2.41	.17	57.06	97.74
Amphibolite	1.20	17.54	10.02	.24	7.83	6.89	3.09	3.33	.23	48.70	99.11
Schist	1.80	15.35	9.56	.14	5.39	3.42	2.98	3.13	.39	55.16	97.18
$\bar{x}$	.91	15.28	6.90	.12	3.62	3.62	3.13	3.07	.22	61.27	98.17
s	.44	1.06	2.96	.08	2.50	1.80	1.20	.80	.09	7.63	.67

hornblende granite plots on the general trend for all major and minor elements except possibly for Fe^{++}.

Fig. 5 shows the Rb/Sr ratio plotted against (1/3 Si + K) − Ca + Mg). Considerable scatter is present but a definite increase in the Rb/Sr ratio is evident on the right side of the diagram. Hornblende granite plots off the trend but due to the fact that only one analysis of hornblende granite was run it is not possible to ascertain whether this is the result of an actual basic difference in chemistry between hornblende granite and the other rocks or only analytical imprecision.

All of the Holterkollen rocks have a differentiation index (normative Q + Ab + Or) greater than 80 and therefore can be treated as part of the 'granite system' (Tuttle & Bowen 1958, Luth

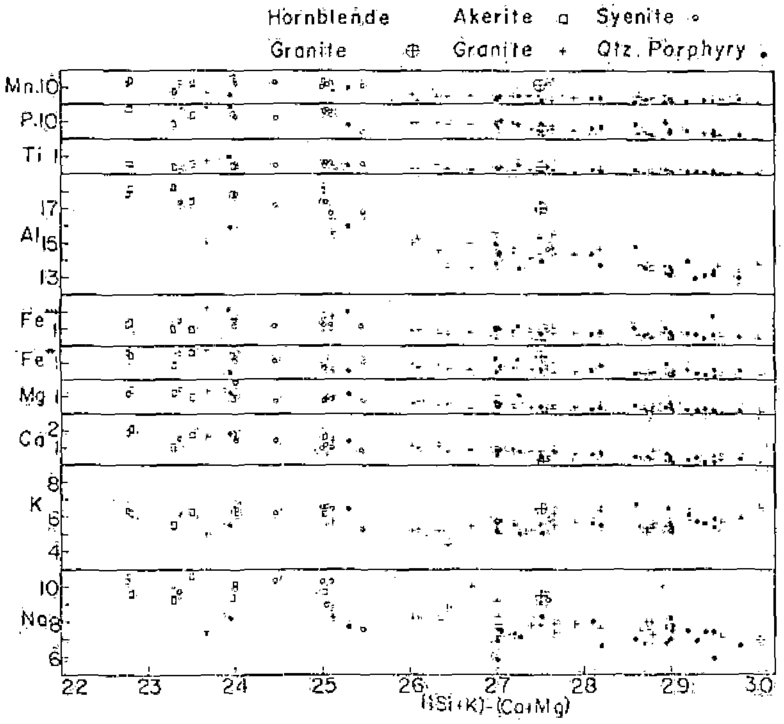


Fig. 4. Major and minor element variation diagram.

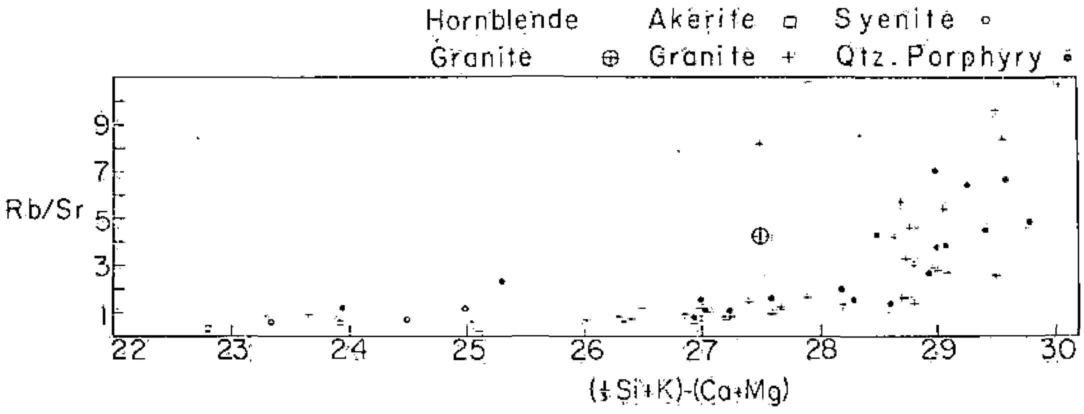


Fig. 5. Rb/Sr variation diagram. Only part of the rocks were analyzed for Rb/Sr.

et al. 1964, Steiner et al. 1975). Granite system plots shown in Fig. 6 establish a clear path which includes hornblende granite. Moreover, the trend coincides approximately with the thermal trough at 0.5 Kb^{ar}.

Holterkollen rock compositions when plotted in the system CaAl$_2$Si$_2$O$_8$ – NaAlSi$_3$O$_8$ – KAl Si$_3$O$_8$ (Franco & Schairer 1951. Yoder et al. 1957, James & Hamilton 1969, Morse 1970) (Fig. 7) establish a pattern where all rock type fields overlap. However, there is more scatter than on the 'granite system' plot.

Holterkollen rock compositions when plotted on an AFM diagram also fall into a small area forming an overlapping pattern. It is clear from Fig. 8 that the akerite-syenite and granite-quartz porphyry fields define a clear trend extending almost to the Na+K apex. Hornblende granite plots slightly off this trend.

Spatial variations

In an effort to determine whether the chemical variations noted in the granite and quartz porphyry analyses are systematic, a trend surface analysis of selected oxides, ratios, and norms was carried out. Maps were drawn by computer using a program by O'Leary et al. (1966).

The value of a trend surface analysis is that the pattern generated is more generalized than an ordinary isopleth map, i.e. insignificant varia-

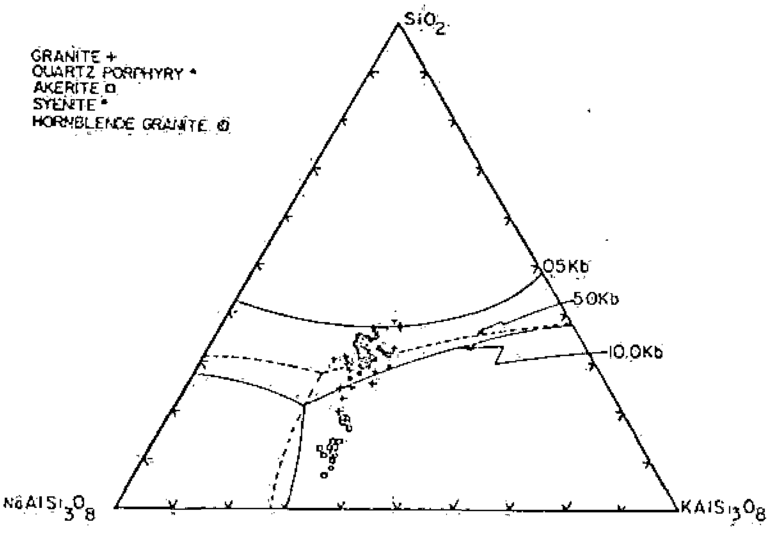


Fig. 6. Holterkollen rock compositions plotted in the 'granite system.'

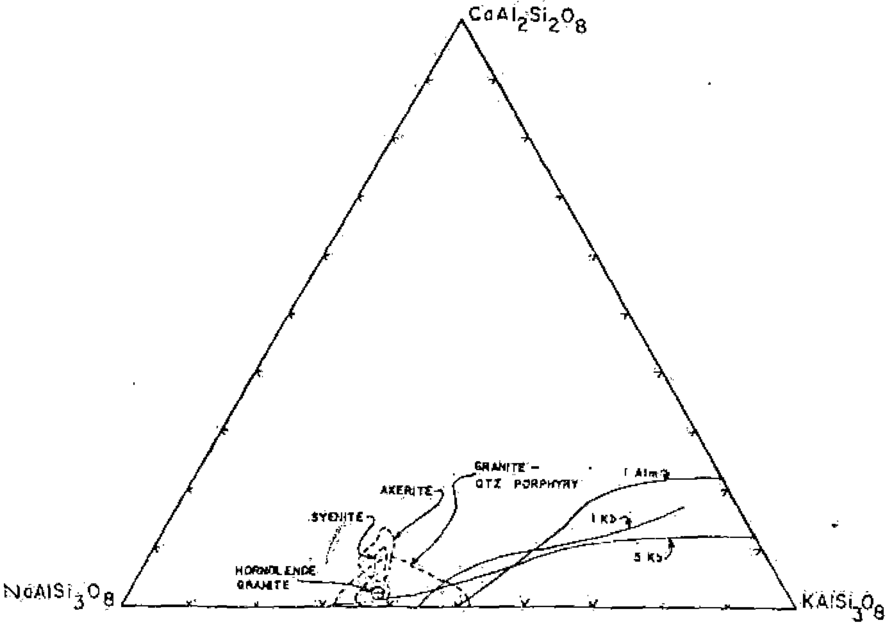


Fig. 7. Holterkollen rock compositions plotted in the system An-Ab-Or.

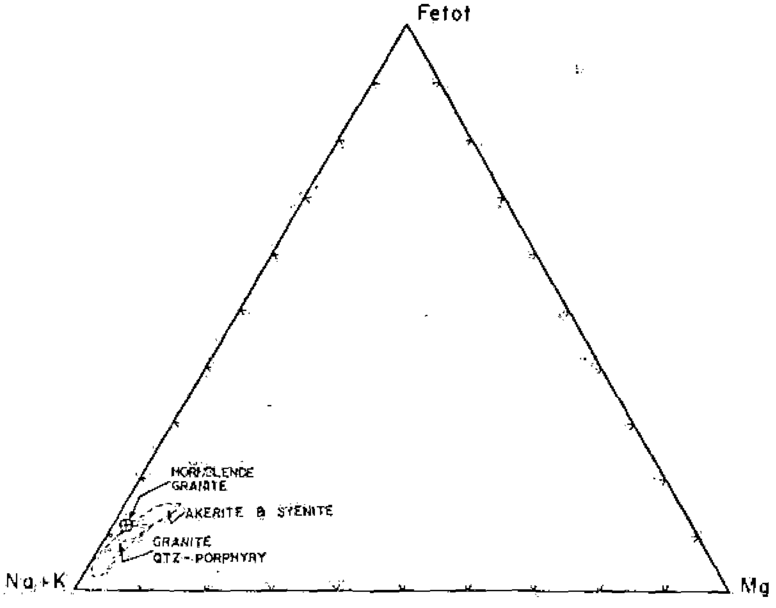


Fig. 8. Holterkollen rock compositions plotted on an AFM diagram.

tions are excluded. Even though surfaces of 2nd through 6th degree were drawn for each parameter; the 5th degree surface was used because it best fitted several preliminary hand drawn maps. These maps were constructed for the purpose of choosing the correct trend surface. Fifty-one data points from the Holterkollen pluton were used. The samples were not taken in a grid pattern due to a natural uneven spacing of outcrops, but every effort was made to achieve an even distribution.

The trend surface maps do not exhibit a simple quasi-concentric spacing of contours as shown, for example, by the Grimstad granite (Christie et al. 1970). Instead, all maps have a series of 'highs' and 'lows', i.e., areas of closed contours.

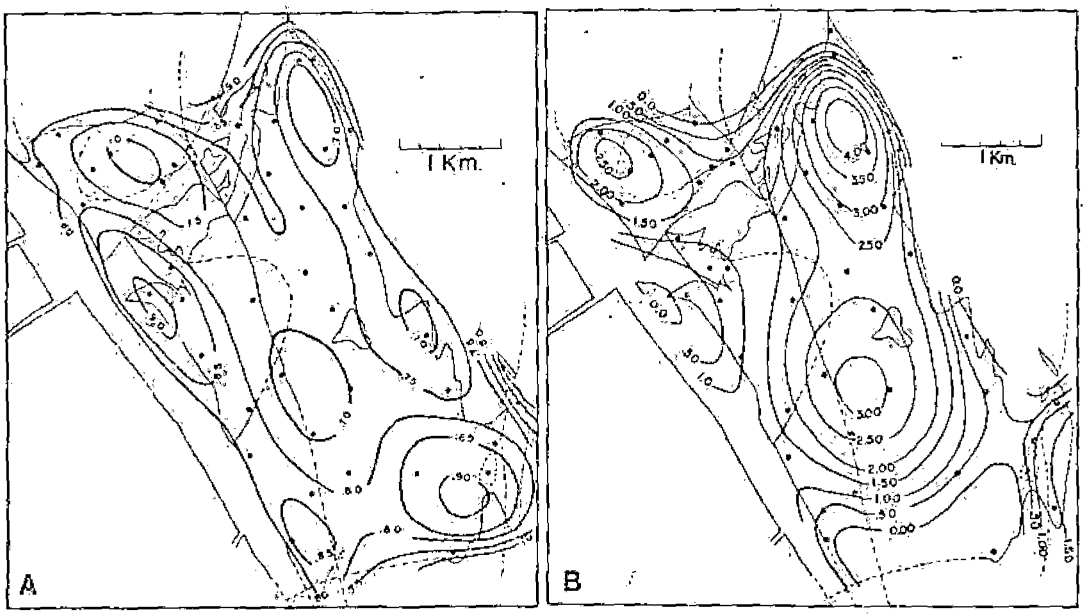


Fig. 9. A. Fifth degree trend surface showing variations in $Fe^{+++} + Fe^{++}/Fe^{+++} + Fe^{+++} + Mg$. *B.* Fifth degree trend surface showing variations in normative An.

'Highs' and 'lows' situated at the margins of the pluton are real and not the result of edge effects because they are present also on the hand drawn maps.

Twelve maps were constructed using the following paramenters: $Fe^{+++} + Fe^{++}/Fe^{+++} + Fe^{++} + Mg$, Ca, Na_2O, normative An, normative quartz, MgO, CaO, Rb/Sr, K_2O, TiO_2, Al_2O_3 and P_2O_5. All variables are sensitive to chemical fractionation, especially Rb/Sr. Due to space constraints only six are given here – $Fe^{+++} + Fe^{++}/Fe^{+++} + Fe^{++} + Mg$, normative An, normative quartz, Rb/Sr, Na_2O, and TiO_2 (Figs. 9, *10*, and *11*). The six were chosen because they are typical and reflect different types of variables mapped. The normative An and quartz are from a meso-norm by Barth (1962). As shown by Figs. 9, 10, and 11, all maps correlate well one with another with only slight deviations in the positions of centers.

Strontium isotope relations

Three of the rock types – akerite, syenite and granite-quartz porphyry – have been radiometrically dated (B. Sundvoll pers. comm. 1977). Ages of the syenite (261 ± 3 *my*) and granite-quartz porphyry (270±3 my) agree with field relationships. The akerite isochron, however, is anomalous because it falls on the granite plot but with considerably more scatter. The age inconsistency and scatter can be explained by taking into account the contamination of akeritic magma with Precambrian wall rocks – a conclusion reinforced by the presence of numerous inclusions in the akerite. Initial ratios for syenite (0.7045 ± .0002) and granite-quartz porphyry (0.7056 ± .0002) are similar to those determined by B. Sundvoll, and Heier & Compston (1969) for similar rocks elsewhere in the Oslo rift.

Discussion

Petrographic phenomena

Multiple rimming of feldspars. – Akerite, syenite, and hornblende granite all contain feldspars exhibiting multiple rimming which is apparently not the result of exsolution. This rimming therefore must reflect a complex petrogenetic history punctuated by periods of crystallization interrupted by stages of disequilibrium producing corrosion.

Two processes causing the rimming are possible – fluctuations in temperature and changes in volatile partial pressure or both. Magma in a

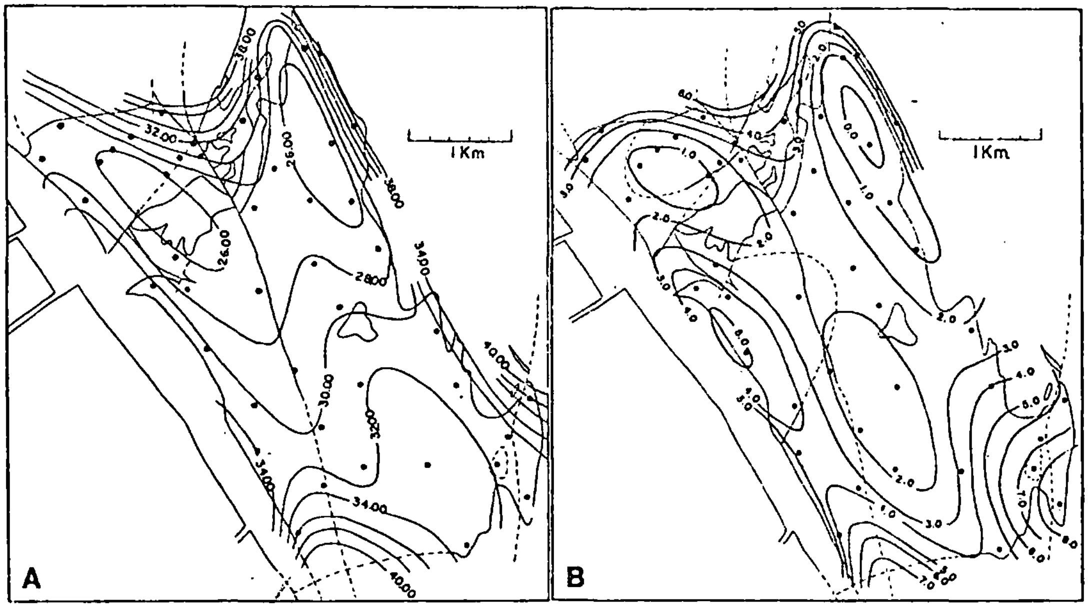


Fig. 10. A. Fifth degree trend surface showing variations in normative quartz. B. Fifth degree trend surface showing variations in Rb/Sr.

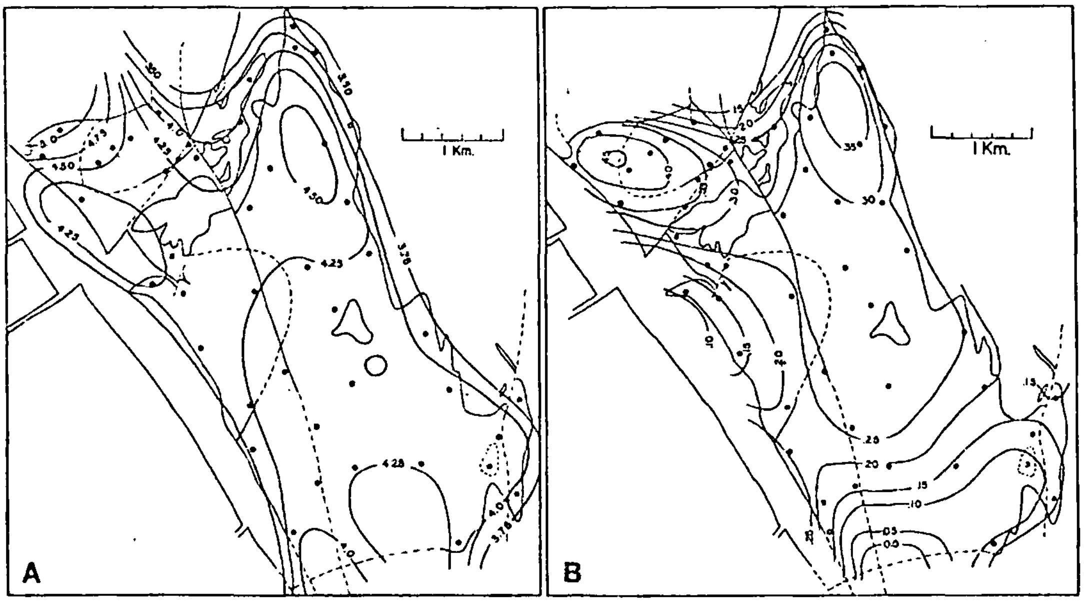


Fig. 11. A. Fifth degree trend surface showing variations in Na_2O. B. Fifth degree trend surface showing variations in TiO_2.

chamber could slowly cool and start to crystallize. Before the magma in the chamber was completely solidified additional melt from depth carrying heat could be added to the system causing elevation of the temperature above the crystallization point. This would cause previously formed crystals to corrode. When cooling and crystallization again commenced a rim would form.

Fluctuations in volatile partial pressure would have essentially the same effect. Water vapor emanating from magma crystallizing at depth and entering into another higher level magma would cause the liquidus temperature to be depressed and earlier formed crystals to become unstable and corrode. Upon further cooling or loss of vapor, crystallization would begin again and a rim would be deposited.

It is probable that changes in temperature and vapor content were both active at different levels within the crust as the magma series responsible for akerite, syenite, and hornblende granite worked its way upward.

Perthite compositions. – All igneous rock types present in the Holterkollen area appear to have perthites that contain roughly equal amounts of Ab and Or (mesoperthite). Plots of Holterkollen rock compositoins in the 'granite system' Fig. 6 show that all fall in the 0.5 Kbar thermal valley. This position is roughly midway between the Ab and Or corners of the diagram. Therefore, perthites existing in all Holterkollen rocks must necessarily be mesoperthitic.

Textural variations within the pluton. – A comparison of the trend surface maps (Figs. 9–11) with the geologic map (Fig. 1) shows that chemical zonation within the pluton does not correlate with textural variations. It is apparent, therefore, that the different textural zones present are genetically unrelated to the processes which formed the chemical pattern and are probably the result of some phenomena occurring after the rocks had achieved their final composition but before crystallization.

The aplitic texture of the quartz porphyry is probably due to pressure release quenching. According to Luth et al. (1964) aplitic textures are the result of rapid volatile loss during cooling which causes the melt to quench as the crystallization point is suddenly changed to a higher temperature. Chilling at contacts is not considered to be a major factor because most of the quartz porphyry is situated on the interior of pluton.

Vapor pressure when the granite and quartz porphyry commenced crystallization was approximately 0.5 Kbar (at least according to the granite system plots). This corresponds roughly to the probable depth of emplacement of the pluton which is 2,500 m. Field relations indicate that the Holterkollen pluton was situated just under the base of the Cambro-Silurian alum shale during solidification (J. Naterstad, pers. comm. 1973). The total volcanic and sedimentary section stacked above the base of the alum shale equals 2,500 m.

When the granitic magma during its upward migration encountered the alum shale, water vapor would tend to collect because the shale would act as an impervious barrier. Moreover, volatiles naturally move up the pressure gradient to collect at the top of a magma column. As the vapor pressure increased the barrier would begin to be penetrated. Slowly at first, fracturing would occur and the fluid would bleed off to work its way through the overlying sedimentary and volcanic column. Finally, when the surface was reached, a vapor explosion would occur, suddenly reducing the vapor pressure to 1 Atm in places directly under the fractures. At this time the granitic magma would quench, forming the aplitic groundmass of the quartz porphyry.

It is possible that some magma may have been ejected with the vapor. Felsite porphyries (ignimbrites) described by Brøgger (1933) from nearby areas could have been derived in part from vents above the Holterkollen pluton. Chemical analyses reported by Brøgger show a striking similarity to the Holterkollen quartz porphyry and granite analyses.

Quartz porphyry phenocrysts. – Two explanations appear as possible for the generation of the quartz porphyry phenocrysts:

Assimilation of quartz grains by ingestion of metamorphic wall rocks during upward migration of the melt,

Primary crystallization of the grains.

Assimilation seems unlikely because glassy quartz grains as large as 1 cm are unusual in rocks that have undergone metamorphic deformation. Moreover, if an assimilation model is assumed the grains at the time they were ingested by the moving magma would necessarily have been several times larger than they now are because considerable corrosion is evident. In addition the phenocrysts show no undulatory extinction which is characteristic of metamorphic quartz. However, it is possible that later annealing would remove the strain induced by metamorphism.

The supposition that the phenocrysts were produced by primary crystallization is supported by the existence of grains with hexagonal crystal outlines. It seems likely that the only way to produce such a shape is by unimpeded crystallization from a melt.

Quartz is usually late in the crystallization sequence of 'granite system' rocks. However, the Holterkollen quartz porphyry contains phenocrysts that evidently crystallized early and quartz in the groundmass that apparently formed late. Therefore, especially since the phenocrysts are generally highly corroded, the genesis of the quartz must have been by a two step process separated with a period of quartz instability.

For quartz to be the first mineral to crystallize in quartz porphyry given their bulk compositions as plotted in the 'granite system' (Fig. 6), the vapor pressure would have to be high enough to shift the phase boundary far enough toward the $NaAlSi_3O_8 - KAlSi_3O_8$ edge to allow the quartz porphyries to lie in the quartz phase field. High vapor pressures are required for this to occur. A problem with the hypothesis is that the quartz porphyry and granite all plot in or close to the 0.5 Kbar thermal trough/which seems inconsistent with a beginning of crystallization at high vapor pressures. It is possible, however, that after the quartz phenocrysts formed and the magma moved upward to higher levels in the crust, a *new* crystallization trend was established for 0.5 Kbar. The compositions plotted on the diagram are adjusted to the final conditions of crystallization *not* to the initial ones i.e. re-equilibration of crystallization from high pressures to 0.5 Kbar would produce a shift of the crystallization path and cause the rock compositions after solidification to be significantly different from that of the magma in which the quartz phenocrysts were forming. According to Steiner et al. (1975), crystallization trends in the granite system are difficult to predict. Therefore, the actual trace of melt composition change accompanying the re-equilibration necessitated by a lowering of the vapor pressure to 0.5 Kbar cannot be ascertained exactly. However, the magma compositions at the time of phenocryst formation would necessarily be situated to the left and toward the Ab-Or edge of the diagram relative to the plotted quartz porphyries and granites. Vapor pressures during phenocryst generation cannot be determined with accuracy because of the path shift, but must have been between 5 and 10 Kbar.

During the upward migration of the magma and throughout most of the time of final solidification, quartz phenocrysts would corrode because the magma composition due to the vapor pressure decrease would no longer lie in the quartz phase field. Rounded, corroded quartz crystals do not occur in granite because slow cooling would give enough time for the quartz grains to be totally consumed, whereas, in the case of the quartz porphyry, the rock solidified too rapidly to allow the quartz grains to be destroyed.

Spatial variations in chemistry

Diffusion during cooling. – According to Bateman et al. (1963) and Neff (1969), chemical variations within a pluton may be produced by diffusion during cooling of an originally homogenous magma. The variation patterns generated by this mechanism are simple concentric ones quite unlike those of the Holterkollen pluton (Figs. 9, 10, and 11). Therefore, the complex contour arrangements that do exist in the Holterkollen pluton are probably not the result of a simple single stage magma injection with later slow cooling accompanied by diffusion. A more complex explanation is needed.

Wall-rock contamination. – The pattern shown by the trend surface maps (Figs. 9, 10, and 11) appears at first glance to be compatible with an assimilation model. Centers (areas of closed contours) occur near the edges of the pluton and in the interior. Those of the interior may possibly be due to the consumption of roof pendants because the top of the pluton is barely exposed, wheras those on the edges may conceivably be the result of piecemeal stoping at the pluton's margin. This hypothesis is apparently strengthened by the fact that the pluton's eastern contact slopes gradually outward. A detailed examination of the maps and chemistry of the adjacent wall rocks tends to weaken this argument, however, by showing that many centers of both 'highs' and 'lows' do not correlate well with the country rock composition. For example, Fig. 9A, the $Fe^{++} + Fe^{+++}/Fe^{++} + Fe^{+++} + Mg^{++}$ map, has three 'highs' and four 'lows' (areas of high Mg^{++} appear as lows on the map). If the assimilation model is correct *all* centers should be lows because the wall rocks are significantly higher in MgO (Table 1) than the plutonics. It may be argued though, that a 'low' would be present where wall-rock contamination took place and a 'high' where it did not. It seems unlikely, however, that centers of the mapped intensity would be produced where nothing was added. Some active mechanism would have to be in operation to cause such sharp deviations either higher or lower from the average quartz porphyry-granite composition.

The normative An map (Fig. 9 B) has four 'highs' and two 'lows'. Again, because the wall rocks are significantly higher in CaO than the plutonics, *all* centers should be highs if the mechanism producing the pattern was assimilation. Another interesting feature of the normative An map is that more than half of the plutonic-wall rock contact is traced or closely paralleled by the 0.0 contour. This relationship would seem unlikely if assimilation was active.

Fig. 11 A (Na_2O) is not significant as far as the assimilation model is concerned because the Na_2O content of the wall rocks varies considerably. The average is slightly less, however, than the quartz porphyry and granite.

Figs. 10 A and 11 B (normative quartz and TiO_2 and indeed the rest of the maps constructed, but not printed, give essentially the same results as those discussed above. A series of 'highs' and 'lows' exist, some of which are explainable by assimilation considering the average wall rock content of the variable in question and some which are not.

In summary, it appears from the chemical data that wall rock contamination can explain only part of the observed pattern of 'highs' and 'lows'. This conclusion is reinforced by the scarcity of xenoliths in the Holterkollen pluton even within a few meters of the contact.

Multiple injection. – Centers on the trend surface maps (Figs. 8, 9, 10 and 11) can be classed as either 'salic' or 'mafic'. 'Salic' centers are high in normative quartz, $Fe^{++} + Fe^{+++}/Fe^{++} + Fe^{+++} + Mg$, Na_2O and Rb/Sr, and low in normative An and TiO_2. The reverse is true for 'mafic' centers.

A comparison of the maps one with another shows that the 'centers' correlate well in regard to location as well as type. There is some ambiguity, however, in the case of Na_2O. One Na_2O high in the northeastern corner of the pluton is a mafic center for all other parameters mapped. This anomalous Na_2O high is possibly due to an unusual concentration of Na^+ by fluid transfer. Na^+ is soluble in the fluid phase (Krauskopf 1967) and may have migrated upward with vapor to collect under the alum shale water barrier.

This close correlation of 'highs' as well as 'lows' both in composition and location is best explained by multiple injection of various magma compositions. Trends established within the quartz porphyry and granite magma series as shown on Figs. 9, 10, and 11 indicate that some sort of chemical fractionation was taking place. The spread in quartz porphyry and granite compositions indicates that the granitic magma was probably undergoing filter pressing or gravity stratification in a chamber existing below the Holterkollen area. As this process continued periodic pulses of activity channeled upward masses of magma of varying composition. At least 5 and possibly 7 separate injections took place as indicated by the number of map centers.

Petrogenesis

The dike rocks (akerite, syenite, and hornblende granite) coincide or form a definite trend on all diagrams plotted. In addition they have striking petrographic similarities. Therefore it appears that they belong to the same fractionation series – a supposition that is supported by all recent workers in the Oslo Region. Moreover, it is generally assumed that the parent magma was mantle derived. In addition, it is quite apparent that the difference between the quartz porphyry and granite phases of the pluton is only textural. The major questions left to resolve are: how the dike rocks are related to the plutonic rocks and what is the origin of the granite-quartz porphyry magma?

Several workers have commented on this question. According to Barth (1954), all plutonic and dike rocks belonging to the Oslo graben magma series originated by anatexis of Precambrian crustal rocks. Heat necessary for melting was released from basic mantle derived magma which had invaded the lower crust. Czamanske (1965), in a localized study of the Finnemarka complex, accepted Barth's hypothesis and concluded that all of the plutonic rocks in the complex were related by differentation of the same parent magma. The rock types in question included akerite, granite, and syenite.

Barth's hypothesis was challenged by Heier & Compston (1969), who concluded that all of the igneous rocks in the Oslo graben were mantle derived. This conclusion was based on Sr^{87}/Sr^{86} isotopic data. Their data, however, were collected by the analysis of a limited number of samples which did not include any from the Holterkollen area.

Raade (1973), on the basis of U-Th distribution information, concluded that some Oslo plutonic rocks were mantle derived and others the result of deep seated anatexis. According to his classification scheme, the akerite-syenite-hornblende granite series is mantle derived whereas the granite-quartz porphyry magma originated by anatexis.

A work by Ramberg (1976) based mainly on geophysical evidence considers that the entire Oslo igneous rock series is most probably of mantle origin. The Oslo graben was produced by crustal extension and thinning over a spreading center. During this phase, mafic mantle derived magma invaded the lower crust. Differentiation of the mafic melt produced felsic magma which moved upward as diapiric masses to form the cauldron complexes and plutons. Ramberg, even though he favored a mantle origin for the biotite granite bodies, did accept the possibility that a minor amount of anatexis may have taken place in the lower crust and the biotite granite plutons one of which is the Holterkollen may have originated in this manner.

Recent unpublished $Sr^{87}Sr^{86}$ data (B. Sundvoll, pers. comm. 1977) apparently disproves an anatectic origin for the biotite granite and confirms the conclusion by Heier & Compston (1969) that all igneous rock phases present in the Oslo Rift are mantle derived. Initial ratios of both syenite and granite-quartz porphyry from the Holterkollen area strongly imply a parent magma produced by partial melting in the upper mantle.

The chemical data generated by this work appear at first glance to favor a single crystal fractionation trend for the entire Holterkollen rock series. This is shown for instance by the good negative correlations and overlaps on Fig. 4 – the major and minor element variation diagram. Fig. 5, the RbSr ratio plot, also shows overlap between the dike and plutonic rocks. In addition the granite system (Fig. 6) shows a strong correlation of all rock types with the 0.6 Kbar thermal trough. The AFM plot (Fig. 8) has overlap between all rock types even though the rock compositions fall only on a small part of the diagram. In the system An-Ab-Or (Fig. 7) the Holterkollen rocks also form a relatively smooth trend. However, in this case, there is a greater amount of scatter than on the other diagrams, especially with the quartz porphyry-granite points.

The single trend hypothesis does not hold up too well, however, when examined in detail. In the first place, the akerite-syenite-hornblende granite trend forms a part of the Nittedal Cauldron series which includes nordmarkite (aegirine syenite) and culminates in ekerite (aegirine granite). This creates a major obstacle to the hypothesis. How can a single process of magmatic differentiation produce *two* large volume granitic end points, ekerite and biotite granite? This appears to be very unlikely.

Another problem is the difference in age. The syenite is 9 my younger (261 ± 3 my vs. 270 ± 3 my) (B. Sundvoll, pers. comm. 1977) than the biotite granite, its supposed differentiation product. This age difference is supported by chilled border and other field relationships which show that the Holterkollen pluton was intruded before collapse of the Nittedal cauldron and intrusion of the ring dikes.

These two inconsistencies, namely the difficulty of producing two large volumes granitic rock types by a single process of differentiation and the age difference between the ring dike syenite and the biotite granite, strongly imply that all of the Holterkollen rocks did *not* form a single differentiation trend. It appears that two distinct fractionation trends were in operation, one producing the dike rocks (akerite, syenite, and hornblende granite) and the other the plutonic rocks (biotite granite and quartz porphyry).

How did these two trends originate? One untested, theoretical possibility is that the parent magmas for the two trends were formed by immiscible splitting of the original basaltic, mantle derived melt into felsic and mafic fractions. This process was proposed by Philpotts (1978) to explain the common felsic-mafic bimodal distribution of igneous rocks associated with rift zones. Philpotts (pers. comm. 1977) considers that the igneous rock suites of the Oslo graben show strong evidence of a bimodal distribution produced by immiscible splitting.

According to the most likely petrogenetic model, the felsic separate migrated almost directly from near the base of the crust to form the Holterkollen pluton and other biotite granite masses. Some fractionation had to take place during upward migration of the magma to produce the chemical variations shown by the Holterkollen pluton. The presence in the quartz porphyry of early generated quartz which crystallized at high pressures possibly as much as 10 Kbar, suggests strongly that a felsic magma was indeed present at lower levels in the crust.

The mafic split rose more slowly through the crust and differentiated en route to produce the various alkalic rocks such as syenite and akerite. It is also possible that the akerite has been subjected to contamination as indicated by its scattered isochron.

Another major enigma remains. Why, if the chemical variations shown by all Holterkollen area rocks are the result of *two* unique fractionations, do the chemical data have apparently smooth correlations between the dike and plutonic phases? The best explanation is that even though two separate fractionations were taking place, they were proceeding under essentially identical conditions of temperature and pressure. This may have caused the curves to overlap. Also the two magma series did have a common parent. In addition, the magmas were in such intimate association at depth and during migration to the earth's surface, that there may have been some cross-assimilation which would tend to dampen differences. Moreover, the reported chemical data treat only a part of the Nittedal cauldron series. If ekerite and nordmarkite had been analyzed and plotted, a considerable divergence might have emerged. This is implied on several diagrams where hornblende granite plots slightly off the general trend.

Conclusions

Major conclusions resulting from the Holterkollen study, many of which are of necessity tentative and may be changed by later work, are summarized below:

The dike rocks have had a complex intrusive and crystallization history.

Patches of quartz porphyry within the Holterkollen pluton were produced by 'pressure quenching' due to sudden volatile release.

Quartz porphyry phenocrysts were produced by crystallization of a quartz rich magma at high vapor pressures ranging between 5 and 10 Kbar.

Spatial variations in chemistry within the pluton resulted from multiple magma injection before cooling.

Sr^{86}/Sr^{87} initial ratios show that all Holterkollen igneous rocks are mantle derived.

Immiscible splitting of a basaltic parent magma produced a felsic separate which migrated toward the surface and crystallized as the biotite granite-quartz porphyry pluton.

The remaining mafic split became the parent magma of the syenite-akerite-hornblende granite series.

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