

On an anatectic granite from Bygland, south Norway

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SUMMARY. The Pre-Cambrian granitic rocks of Bygland are structurally and texturally concordant with the metamorphosed country rocks. Both these rock types plot close together in Q-Or-Ab and Ab-An-Or normative diagrams; trace element distribution is also similar. The granite has been reconstituted from the country rocks under epidote-amphibolite facies conditions. Plagioclase feldspars show that the granite is not a 'mature' rock; they are, however, 'mature' in the country rocks and are products of typical regional metamorphism (Ohta *et al.*, 1968). Plagioclases in the granite are relicts of country rocks showing traces of a premetamorphic crystalline state. They have been rejuvenated with the introduction of alkali material during the reconstitution.

THIS paper describes the petrography and chemistry of the rocks from an area about 400 km south of Oslo in the Setesdal valley, around Bygland on the eastern flank of Byglandsfjord; they consist of Pre-Cambrian granites and granite-gneisses, surrounded by amphibolites, mica schists, sandstones, grey quartzose gneisses, and calc-silicate rocks. The granite is foliated, and the granite gneisses are distinguished in the field from the granite by their pronounced compositional banding. Pegmatites and aplites occur as cross-cutting veins in both the granite and the country rocks.

The amphibolites, grey gneisses, and mica schists are highly foliated; elongated quartz, mica, and hornblende define the plane of foliation, which can be followed into the granite without any distortion. No major discordant relation is visible and there is no sharp and definite contact between the two rock types.

The rocks have undergone repeated deformation during at least three phases of folding. The first phase, expressed in isoclinal F_1 folds, mainly embraces amphibolites, grey gneisses, mica schists, sandstones, and calc-silicate rocks. Two subsequent F_2 and F_3 phases were open types of folds, superposed on each other nearly at right angles. The combined structural geometry thus arising out of superposition has the form of an extended dome.

Petrography and mineralogy

The granitic rocks are made up essentially of inequigranular interlocking quartz, plagioclase, and potash feldspars with hornblende and mica mostly defining the plane of foliation along with some elongated quartz. Mica schists show lepidoblastic textures, while amphibolites are nematoblastic. In contact with younger pegmatitic intrusions amphibolites show profuse amounts of biotite, hornblende at the same time being epidotized.

The mineral assemblages of the several rock types are:

Granitic rocks, quartz–plagioclase–microcline–biotite–hornblende–muscovite–epidote–(allanite)–(sphene)–ores–(zircon)–(apatite).

Grey gneisses, quartz–plagioclase–microcline–hornblende–biotite–(sphene)–(zircon)–(apatite)–(ores).

Amphibolites, quartz–plagioclase–hornblende–biotite–epidote.

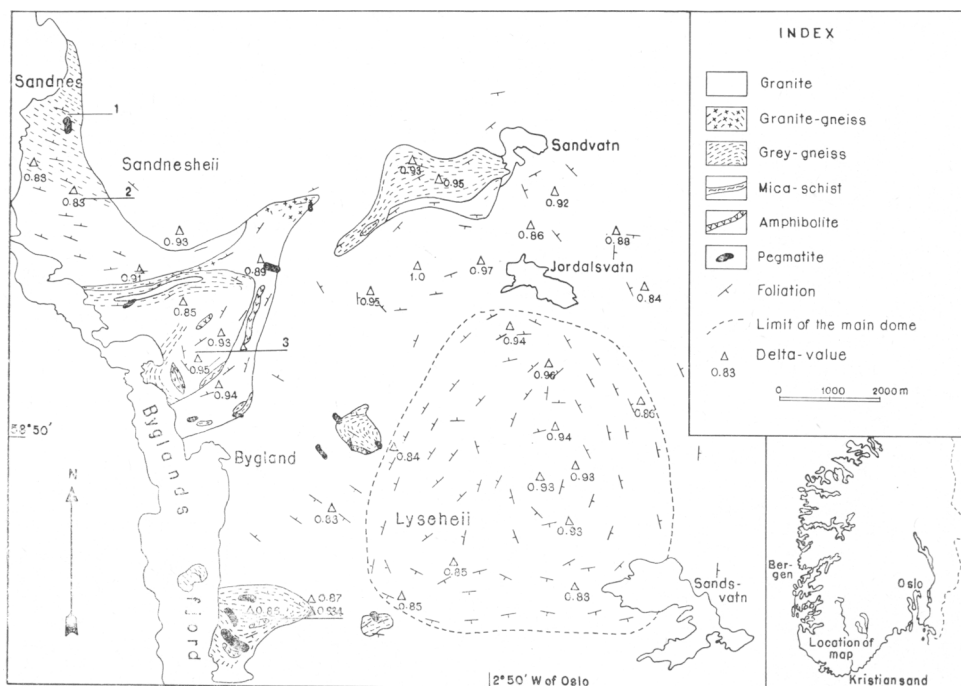


FIG. 1. Lithological map of the Bygland area showing Δ values.

Sandstone, quartz–plagioclase–biotite–(microcline)–(ores).

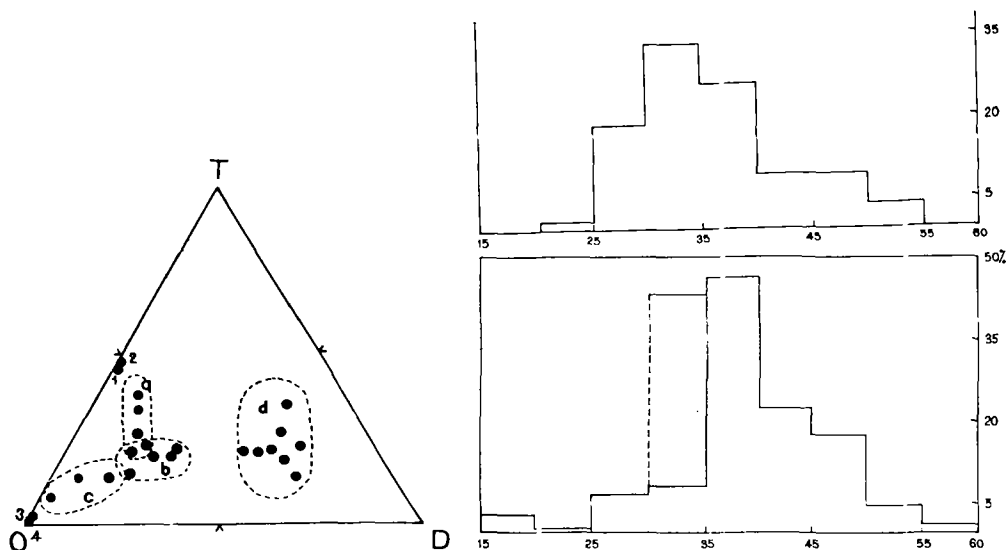
Mica schist, quartz–plagioclase–biotite–muscovite–cordierite–microcline (no garnet); also quartz–plagioclase–biotite–muscovite–(microcline)–hornblende; and quartz–plagioclase–biotite–hornblende–(muscovite)–garnet–chlorite (cordierite is absent; the garnet is almandine, and the chlorite secondary).

Calc-silicate rocks, epidote–hornblende–diopside–calcite–(quartz)–plagioclase–(apatite)–sphene–biotite.

These mineral assemblages clearly indicate that the highest grade of metamorphism attained by these rocks conforms well with the epidote–amphibolite facies (Turner and Verhoogen, 1960).

Plagioclase feldspars occur as fine-grained interstitial crystals and as coarser phenocrysts both in the granite and in the country rocks. Sericitization of these feldspars is common in all rock types. Different stages of vanishing albite twin lamellae are seen

in thin sections. There is a wide range of variation of the An content of plagioclases from grain to grain in all rock types. Anorthite contents, deduced from extinction angle measurements on 20 to 30 grains in each of 10 sections of each rock, show the same range for the granite and granite gneisses (fig. 2*b*) as for the country rocks (fig. 2*a*). The plagioclases of the grey gneisses when plotted on a transitional-order-disorder diagram, fig. 3, show a high maturity. Similar results were observed for the metamorphosed Himalayan gneisses (Ohta *et al.*, 1968).



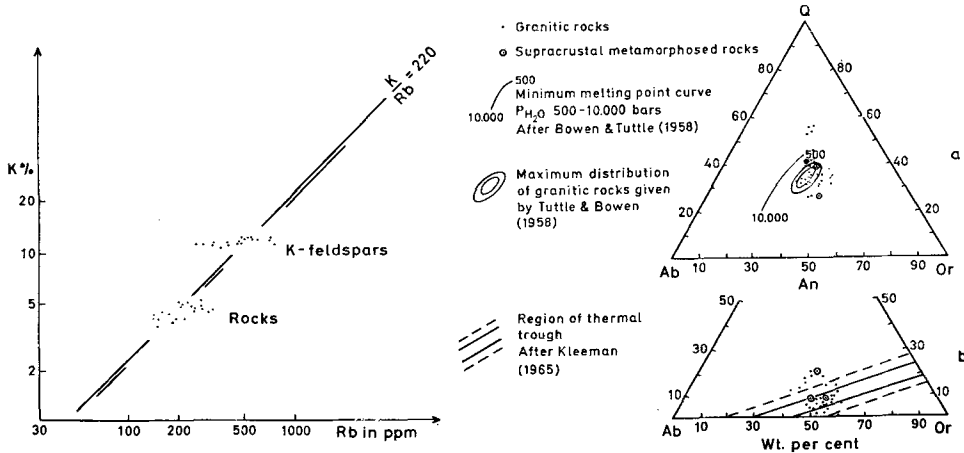
FIGS. 2 and 3: FIG. 2 (left). Transitional (T)-order (O)-disorder (D) diagram. 1, the plot for granite, 2, for granite gneiss, and 3, for grey gneiss; 4 is the plot for samples from the Himalayan gneiss. FIG. 3 (right). Histograms to show the frequency distribution of different compositions of plagioclase feldspars in different rock types: *a*, top, in country rocks; *b*, bottom, in granites and granite gneisses.

The interstitial fine-grained plagioclases in the granites most frequently show a composition between An_{25} and An_{35} , which corresponds to the common compositional range of plagioclases in the adjoining country rocks. The coarser phenocrysts lie between An_{35} and An_{40} . Some of these grains exhibit dusty zones along their boundaries, while others show complete replacement by microcline. Microcline occasionally contains serrated plagioclases, which are remnants of the original grains.

Intergranular albite is common in the granite, occurring either as complete rims around perthite or as columns between two microcline porphyroblasts. The albite column is seen to contain tube-like structures across its elongation. The rim type of albite has the same optical orientation as the soda-rich perthite lamellae in the microcline. $2V$ measurements of the lamellae and the rims show the same range of values; $2V_y$ 82 to 84° in the perthite lamellae, 82 to 85° in the albite rim.

Microcline feldspars mainly occur as porphyroblasts. They are also observed as fine interstitial grains between the plagioclases. Replacement of the latter by micro-

cline is common in both granitic rocks and grey quartz gneisses. The potash feldspars in all the rock types are more restricted in composition than the plagioclases; 38 samples gave: K_2O 14.05–14.70, Na_2O 0.9–1.4, CaO 0.04–0.08, FeO 0.04–0.09%. The K/Rb ratio in the potash feldspars is similar to that in the host rocks (fig. 4). There is a relative increase in microcline content from the country rocks to the granite and a corresponding decrease in plagioclase and quartz content.



FIGS. 4 and 5: FIG. 4 (left). K/Rb ratio in potash feldspars and in host rocks from which the analysed K-feldspars were separated. FIG. 5 (right). Q–Ab–Or normative diagram following Bowen and An–Ab–Or diagram following Kleeman.

The Δ -values of microcline feldspars are high on the noses and hinges of the folds and lower on the limbs. There is a relative increase in the Δ -value in the prominent F_2 – F_3 fold interfering zones as compared with the weak interfering zones. Boudins and augen-shaped bodies formed with F_2 and F_3 folds show microcline with high Δ -values. These facts agree well with Dietrich's suggestion (1926) that deformation may promote an increase in obliquity. Recently Makhlaev (1968) has reported the occurrence of potash feldspar porphyroblasts from synorogenic metasomatites whose Δ -values vary from 0.8 to 1.0 and $2V$ varies from 80° to 88° . It is interesting to note the similarity of his figures with those in the present area (Δ 0.83 to 1.0, $2V$ 84° to 88°). A wide range of perthites is observed in the granite of the present area: film perthites, patchy perthites, flame perthites, and drop perthites (Andersen, 1928).

Myrmekites in the granite and grey gneisses are commonly of plug-like shapes or subhedral wedges with vermicules of quartz. Myrmekite with blebs of quartz in the feldspar host is also found, the blebs having no definite orientation. The crystal axes of feathered quartz grains have no definite relationship to the crystal axes of the feldspars (Shelley, 1967). The vermicular intergrowths were slightly bent during the penetrative phases of F_2 and F_3 folds at the highest peak of metamorphism. Biotites are occasionally noted around the myrmekites, with no definite orientation.

Biotites are nearly constant in chemical composition in all the rock types and do not show any considerable variation from grain to grain; mean values are:

	Al ₂ O ₃	FeO	MgO	MnO	K ₂ O	TiO ₂
Biotite from country rocks	15.15	20.06	10.54	0.27	9.5	3.01
Biotite from granite	14.9	20.35	10.57	0.27	9.55	3.01

They are mostly elongated along the plane of foliation of the rocks, and some interstitial biotites are seen occasionally between plagioclase and microcline; they are generally pleochroic in shades of brown, and may be altered to chlorites. Green

TABLE I. *Electron-microprobe analyses of coexisting biotite (BB₁ and BB₂) and garnet (G₁ and G₂) from the pelitic schist*

Sample Nos.	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O
BB ₁	35.4	3.55	15.32	20.6	0.27	10.61	0.09	0.13	8.66
G ₁	38.01	0.11	21.36	33.62	1.22	5.19	1.67	0.02	0.01
BB ₂	—	—	—	20.4	—	10.60	—	—	—
G ₂	—	—	—	33.61	—	5.20	—	—	—

* Total iron as FeO.

TABLE II. *Partial analyses of potash feldspars from granite (Gr.), country rocks (C.R.), and boudins or augen-shaped bodies (B/A) from four localities (1-4, fig. 1).*

Localities	Total iron	Sr	CaO	Na ₂ O	K ₂ O	Rb	
1.	Gr.	0.048 %	622 p.p.m.	0.087 %	1.493 %	12.76 %	408 p.p.m.
	C.R.	0.048	614	0.088	1.502	12.84	401
	B/A	0.044	616	0.101	1.481	12.64	403
2.	Gr.	0.067	578	0.142	1.058	13.59	410
	C.R.	0.065	560	0.050	0.906	13.34	406
	B/A	0.092	601	0.090	1.011	14.03	442
3.	Gr.	0.093	163	0.059	1.021	14.56	492
	C.R.	0.062	192	0.091	0.966	13.90	504
	B/A	0.063	209	0.103	0.827	13.76	465
4.	Gr.	0.0546	50	0.083	1.1006	13.88	729
	C.R.	0.0797	37	0.091	1.111	13.72	746
	B/A	0.0693	46	0.080	0.9056	13.89	730

hornblendes are nematoblastic and align themselves along the foliation; they show bleaching effects, and may be altered to brownish-green biotite and in places to epidote.

Boudins and augen-shaped bodies in a granitic area are considered to represent low-pressure zones (Ramberg, 1952). Thus there should be a tendency for migration of lighter elements like Na and K from the granites to this zone when granite is forcefully emplaced and the area is in a mobilized state. From the map, fig. 1, if the dome-shaped granite is considered to be an intrusion there should be an increase in

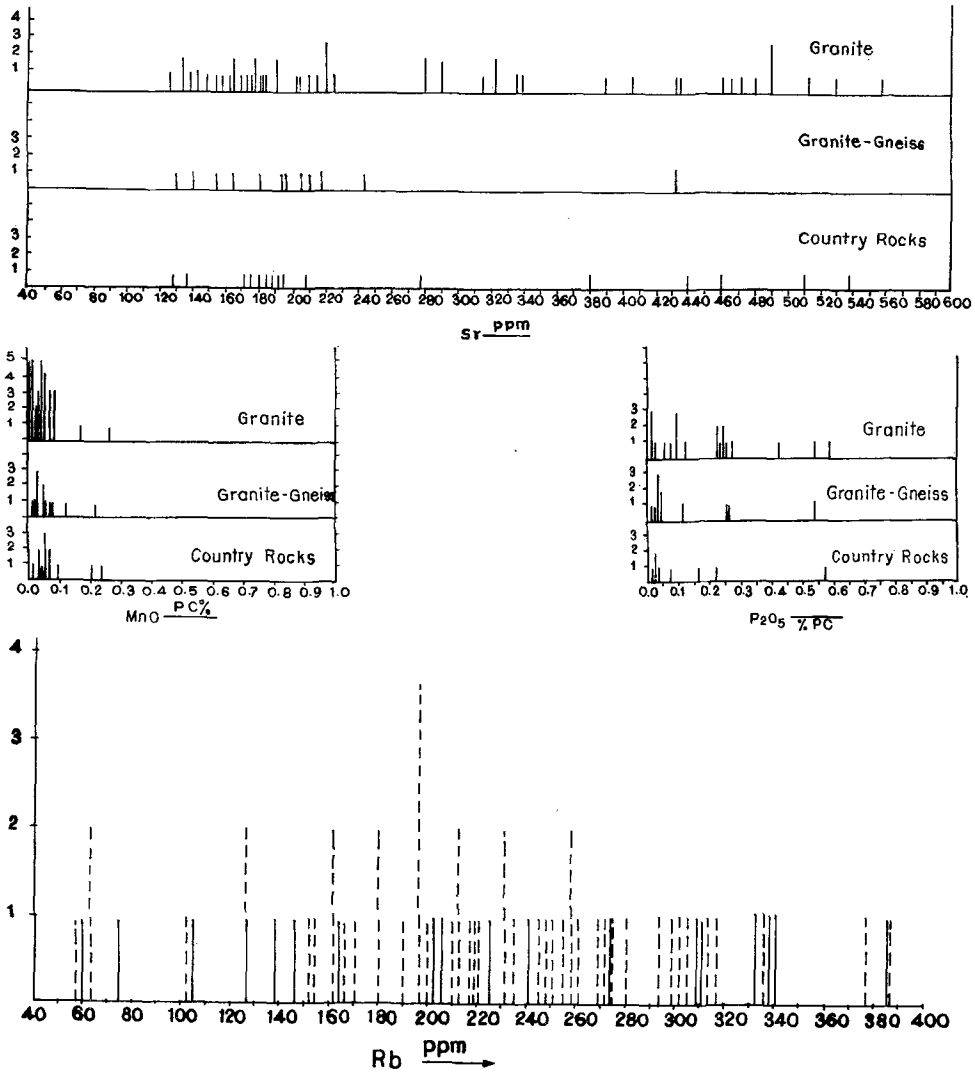


FIG. 6. Trace element distribution for granite and country rocks along the contact.

lighter elements from the granite towards the boudins or augen-shaped bodies in the grey gneisses (mainly occurring to the west); no such increase is noted. On the contrary, the chemical compositions of the potash feldspars of the boudins and augen-shaped bodies are very similar to those of the granite and augen gneisses (table II); it would therefore appear that they did not act as low-pressure zones, which indirectly points to a non-intrusive origin of the granite.

Chemistry of the rocks

The granitic rocks are chemically inhomogeneous but all contain more than 66 % of silica. The normative quartz, orthoclase, albite, and anorthite proportions of the granitic rocks, pelites, and grey gneisses are compared in fig. 5 with the experimental data and naturally occurring granites of Tuttle and Bowen (1958) and with the Or–Ab–An data of Kleeman (1965). Both the country rocks and most of the granitic

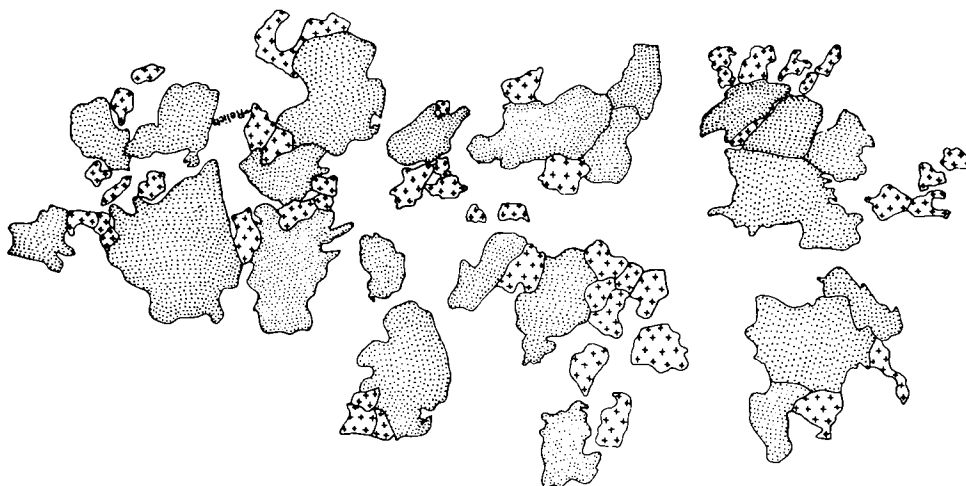


FIG. 7. Interstitial plagioclases (crosses) and relict plagioclase phenocrysts (dots) in a thin section. The distinction was made on the basis of the An content, as determined optically (see text).

rocks are in sufficiently close accord with the composition of the experiments of Tuttle and Bowen; they also support Kleeman's view (1965) that there is a close relation between the average granitic composition and the low-temperature trough in the Q–An–Ab–Or system. A few of the rocks show quartz enrichment. Moreover, the country rocks fall in the field of anatectic granites (Winkler and von Platen, 1961; Winkler, 1965). Granite and the country rocks along the contact zone have been analysed for MnO, P₂O₅, Rb, and Sr; the frequency diagram (fig. 6) shows that the trace element composition of the granite covers the whole range of that of the country rocks, as has been noted earlier in the case of the plagioclase feldspars. This probably suggests that the country rocks have been transformed by reconstitution to granitic composition.

Conclusions. The structural and textural geometry of the granite is the same as that of the metamorphosed country rocks. Plagioclase feldspars in the granite and in the country rocks have nearly the same range of composition. Various stages of replacement of plagioclase by microcline along with relict plagioclase suggest that during metamorphism with accompanying introduction of alkalis the reactions did not attain complete equilibrium. The existence of relict plagioclase feldspars in the granite (fig. 7) points to a transformation of the country rocks into granites. Relict feldspars having the same range of composition as those in the country rocks are regarded as indicating non-attainment of chemical equilibrium during metamorphism.

Granite and country rocks plot close together in the Q–Or–Ab and Ab–An–Or normative diagrams, which suggests the rejuvenation of the country rocks to form the granite. Trace elements in both granite and country rocks, grey gneisses, mica schists, and sandstones show similar ranges of composition.

The inhomogeneity of the granites may be due to the fact that they have not attained maturity during crystallization and metamorphism. The wide range of anorthite content from grain to grain in the plagioclase feldspars, while there is very little change in the composition of the biotite and potash feldspars, indicates a breach in the rock evolution without attainment of equilibrium.

Thus it is concluded that the pre-existing country rocks have been reconstituted to form the granite; a quartz fabric study of the granite and the country rocks also points to the reconstitution of country rocks to form the granite (Sen and Mukherjee, 1971).

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