Meta-andesites in the Caledonides in the Suldal Area, Ryfylke

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Meta-andesites interlayered with quartz-mica schists, phyllites, and tuffites of supposed Cambro–Silurian age cover an area of about 120 km² in the Suldal area, Ryfylke. Recrystallized meta-andesites are also found in the overlying Gneiss Unit. Petrographical studies and chemical analyses indicate that all these meta-andesites probably belong to the same petrographic province, and that the recrystallization observed in the meta-andesites in the Gneiss Unit is isochemical. These conclusions indicate that most of the Schist Unit (traditionally thought to be of Cambro–Silurian age) and the overlying Gneiss Unit must be regarded as one tectono-stratigraphical Unit. The meta-andesites belong to the alkali–calcic to calcic series of Peacock, the strong Pacific suite of Rittmann, and the hypersthenic rock series (derived possibly from a high-alumina basalt magma) of Kuno.

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Introduction

The location of the investigated area is shown in Fig. 1. The area has been mapped on a scale of 1:50,000 over a total period of 8 months between 1959 and 1968.

The area has previously been subject to reconnaissance mapping by Kaldhol (1903, 1909) and Feyling-Hansen (field diary from 1947, at Norges geologiske undersøkelse). The present paper concerns a group of rocks found to be of special interest. A general description of the whole area will follow in a later publication.

Geological setting; aims of the work

A simplified picture of the general geology of the area is given in Figs. 1 and 2. The bedrock in the area consists of Precambrian gneisses, migmatites and supracrustals, overlain by rocks of the Schist Unit (traditionally thought to be of Cambro–Silurian age) and the Gneiss Unit (unknown age). The present study is concerned only with rocks belonging to the Units overlying the Sub-Cambrian peneplain.

The *Schist Unit* can be divided into a lower and an upper part. A bipartition is typical for most sections through the Unit, but is based on quantitative differences, as most of the lithologies in one part are also found in the other. The *lower part* of the Schist Unit typically consists of *black or grey phyllite* with or without layers of meta-arkose, monzogranitic cataclasites, quartzites (sometimes 'blue quartzite') and dacitic tuffs or tuffites. The *upper part* of the Schist

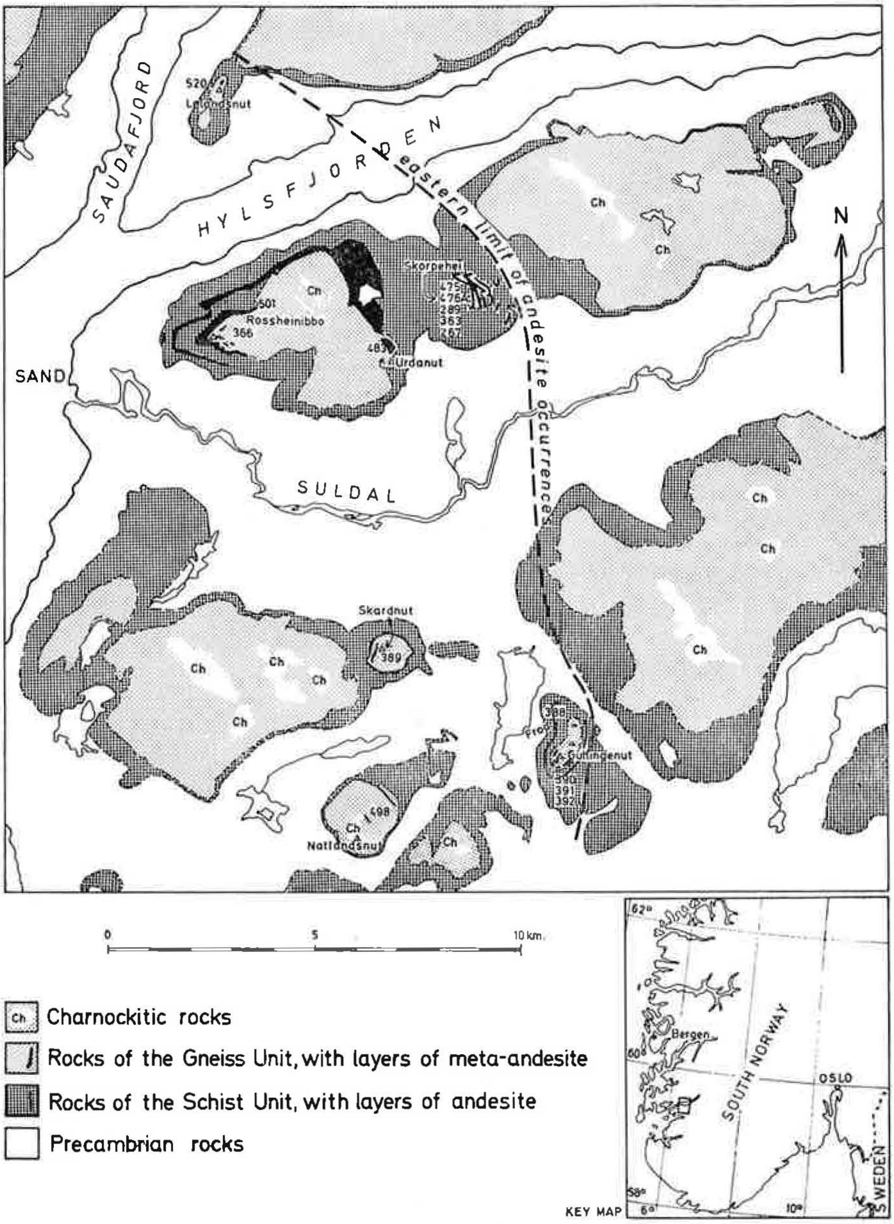


Fig. 1. Simplified geological map of the Suldal area.

Unit consists of *quartz-mica schist* with or without layers of meta-andesite, tuff or tuffite, leptite, phyllite, serpentinite, 'blue' quartzite, and kyanite-chloritoid schist.

The *Gneiss Unit* consists of light-coloured quartz-microcline-albite gneisses, (possible meta-arkoses and acid meta-vulcanites), augen gneisses, garnet-oligoclase porphyroblast gneisses, and thin zones of quartzites and mica schists. Intruded into the Gneiss Unit are charnockitic rocks, and rocks probably associated with them, such as albitites and amphibolites.

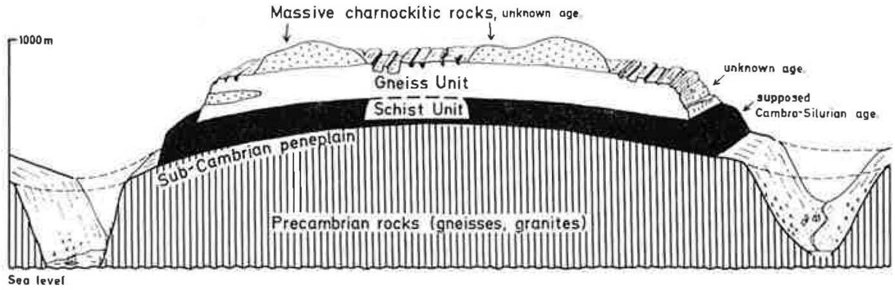


Fig. 2. Simplified sketch-section of the geology of the Suldal area (vertical scale greatly exaggerated).

The age and origin of the overlying gneisses have been a long debated problem in Norwegian geology. For the last decades, however, it has been generally considered that the phyllites and quartz-mica schists are (para-)autochthonous Cambro–Silurian rocks, and that the overlying gneisses are allochthonous. This theory is based mainly on work carried out in Central Southern Norway, where well-marked thrust-planes are present and where differences in the petrographic constitution or sedimentary facies and/or in the metamorphic grade of rocks below and above the thrust-plane are established facts. The theory has also been applied to the Hardangervidda–Ryfylke area despite the fact that the geologists who have worked there (Brøgger 1893, Kaldhol 1909), for various reasons found the theory to be rather doubtful. Kildal (1967) found that the boundary between pelitic and gneissic rocks probably did not represent a major tectonic break, and proposed that either parts of the gneisses must be recrystallized Cambro–Silurian rocks, or rocks considered to be para-autochthonous Cambro–Silurian schists must be part of the nappe. In the Stavanger area Müller & Wurm (1969, 1970) consider the gneisses to be Cambro–Silurian autochthonous rocks.

The main results relevant to this problem from the author's general work in the mapped area (Fig. 1) are as follows:

1. There is no marked thrust-plane between the two Units; thrust-planes and mylonite zones may be found from place to place at any level within the Units.
2. There is no marked difference in metamorphic grade between the rocks above and below the boundary separating the two Units. Most of the rocks within both Units belong to the same metamorphic facies, the middle and upper greenschist facies (B. 1.2–B. 1.3 of Winkler 1967).

   Exceptions to this general rule are found in:

   a. Gneisses close to the charnockitic rocks – these gneisses are in lower amphibolite facies (B. 2.1 or B. 2.2 of Winkler 1967). This could be a result of a type of contact metamorphism.
   b. The charnockitic rocks, indicating the lower granulite facies.
   c. Some of the phyllitic rocks in the lower greenschist facies (B. 1.1), resulting from retrograde metamorphism connected with the latest tectonic phase.

The metamorphic facies of the rocks thus provides no clear support for the theory that the boundary between the Schist Unit and the Gneiss Unit represents a major tectonic break.

Meta-andesites occur as layers in the Schist Unit, and thin layers of rocks with the appearance of gneissified meta-andesites may be recognized at all levels within the Gneiss Unit (west of the boundary line drawn on Fig. 1). These field observations indicated that detailed investigation of these rocks might yield significant information leading to a better understanding of the 'Gneiss problem'.

In this study these volcanites will be described, and the following relevant questions discussed:

1. Are the meta-andesites sills or lavas?
2. Are the meta-andesites in the Schist Unit and the meta-andesites in the Gneiss Unit related in space and time?

In addition, the petrographic and chemical analyses necessary in answering these questions also provide data suited to a comparison of these rocks with other andesitic rocks in the world, and allow a grouping according to the different classification systems of volcanic rock-suites.

For the sake of brevity, the meta-andesites in the Schist Unit and those occurring in the Gneiss Unit will henceforth be termed 'andesites' and 'meta-andesites' respectively.

Andesites in the Schist Unit

The andesites of this Unit cover an area of about 120 km^2 (Fig. 1). They are generally found in the upper part of the Schist Unit, interlayered with quartz-mica schist, and thin beds of phyllite and tuffite. One or two thin andesite zones (1–5 m) are also found in the lower part of the Unit (west of Rossheinibbo and NW and SE of Skorpehei). The maximum thickness of any one andesite layer is about 40 metres, and the observed maximum thickness of the rock-pile between a bottom layer and a top layer of andesite/meta-andesite is about 350 m. The small-scale folding and cleavage typical of the neighbouring quartz-mica schist are seldom observed in the andesites. During deformation the andesites have reacted as a competent rock, and this fact may explain the survival of possible primary structures in the andesites at Skorpehei. Most of the andesites are massive; a few are faintly layered.

Generally, the boundary between the andesites and the neighbouring rocks is sharp, and in places where a primary layering is traceable the boundary is parallel to the layering. At a few places, however, a transitional boundary has been observed; there the quartz-mica schist contains an increasing number of plagioclase grains towards the boundary. Cross-cutting dykes of andesite have never been observed.

The modes of the rocks and the anorthite content of the plagioclases are listed in Table 1, the chemical composition in Table 2, and the C.I.P.W. norms with the calculated normative plagioclases are listed in Table 3.

Table 1. Modal compositions. Sample localities are indicated on the map, Fig. 1

	Andesites in the Schist Unit									Meta-andesites in the Gneiss Unit				
Specimen No.	476A	289	267	363	475	392	388	390	391	366	483	389	520	498
Quartz and plag. in matrix	46.3	21.5	24.9	27.0	33.6	47.9	46.7	42.4	38.7	40.2	50.4	31.8	44.0	57.2
plag. phenocrysts.	23.6	14.0	13.7	22.5	17.4	15.7	29.6	5.6	37.6	13.3	9.9	14.0	6.5	7.7
clinoz. (epidote*)	6.9	13.1	18.0	15.0	19.3	5.6	2.0	10.0	2.2	8.7	14.9	13.5	20.2	10.0
biotite	22.5	23.0	15.4	20.0	21.0	15.5	0.1	15.5	0.2	37.2	22.8	23.2	26.2	22.8
hornblende			0.7	7.0	4.6	10.0	10.6	16.0	10.2	tr.		0.2		
muscovite	0.2	2.3	0.5		0.6		2.4		0.3				0.7	1.7
chlorite	tr.	17.5	22.5	7.6	3.0	3.6	8.5	10.0	10.4	0.2	tr.	16.2	0.1	
sphene	tr.	2.7	1.7	0.9	0.4	1.5	tr.	0.5	0.5	0.4	0.6	tr.	2.6	1.5
calcite		2.1	2.8				tr.							
ore-min.	tr.	1.8	0.2	tr.	tr.		0.1	tr.		tr.	tr.	0.9	0.1	
apatite	tr.	1.8	tr.	tr.	tr.		tr.	0.1	0.1	tr.	0.3	tr.	0.1	tr.
allanite	tr.				tr.	tr.	tr.	tr.		tr.				
zircon	0.2	1.8	tr.		0.1	tr.	0.1		0.1	tr.	0.1	tr.	tr.	tr.
tourmaline	0.6					0.2	tr.		tr.					
garnet													0.3	
percentage dark minerals	30.2	66	60	50	48	36	22	53	24	47	39	54	50	34
An.-content in plag. (measured)	37	35-40	28-38	25-52			31-33	31-39	23-37	45-50				

The andesites are dark grey-green in colour. They are fine-grained with evenly dispersed phenocrysts of plagioclase (length 1 mm–5 mm). The texture is porphyritic to blastoporphyritic, and in some of the andesites at Skorpehei a possible fluidal texture has been observed (Fig. 5). The matrix consists mainly of quartz, plagioclase, clinozoisite, biotite, and chlorite.

The phenocrysts of plagioclase show many distinctive features. Some are hypidiomorphic, other are somewhat rounded due to corrosion, and others seem to be fragments or corroded parts of larger hypidiomorphic crystals. The anorthite content shows remarkable variability, not only within one layer, or thin section, but also within any one crystal. This variability has been observed in the thin sections of all these andesites and is thus one of the distinctive characteristics of the rocks. In one and the same thin section all degrees of saussuritization can be observed, from clear crystals free of inclusions to heavily saussuritized phenocrysts. Some phenocrysts are clear in one half of the crystal and heavily saussuritized in the other half (Fig. 3). In other plagioclases, saussuritization is arranged in zones (indicating a primary zoning) or in spots or rosettes. The saussurite consists almost entirely of clinozoisite, epidote is rare, and sericite is lacking in these plagioclases. The measured anorthite content of the plagioclases varies between 25% and 52% and the calculated anorthite content of the normative plagioclase varies between 38% and 51%. The plagioclase phenocrysts are saussuritized and must originally have been much more basic. Thus the original An-content of the phenocrysts must have varied within limits

Table 2. Chemical analyses

	Andesites in the Schist Unit									Meta-andesites in the Gneiss Unit							
Specimen No.	476A	289	267	363	475	392	388	390	391	366	483	389	520	501	498	Average total — 476A and 366	Average total
SiO_2	67.53	61.00	58.24	61.89	58.94	61.82	61.09	60.39	59.19	66.81	62.83	61.95	59.61	59.89	62.22	60.70	61.56
TiO_2	0.64	0.82	0.61	0.50	0.62	0.50	0.56	0.54	0.56	0.45	0.60	0.73	1.08	0.80	0.56	0.65	0.64
Al_2O_3	16.80	15.59	17.72	16.64	18.81	16.40	17.51	17.56	17.86	16.54	17.76	17.22	15.93	17.81	18.30	17.31	17.23
Fe_2O_3	0.67	2.08	0.36	1.31	0.16	1.78	0.36	1.16	0.33	1.29	0.60	0.31	2.57	1.59	1.64	1.10	1.09
FeO	2.78	5.24	4.84	4.28	4.57	4.05	5.04	4.90	4.85	2.36	3.19	4.54	5.24	3.61	2.88	4.40	4.16
MnO	0.11	0.09	0.13	0.08	0.12	0.09	0.11	0.09	0.06	0.07	0.05	0.06	0.07	0.05	0.08	0.08	0.08
MgO	1.54	2.77	3.61	3.15	3.30	3.26	3.76	3.62	4.17	1.39	2.41	3.66	2.18	2.61	1.88	2.86	2.70
CaO	3.83	3.92	6.52	5.57	6.02	5.10	4.28	4.76	5.69	4.08	5.14	4.90	6.17	6.26	5.20	5.35	5.16
Na_2O	3.28	3.28	3.28	3.40	3.29	4.09	4.01	3.59	4.20	4.73	3.89	3.29	2.64	3.56	4.46	3.61	3.67
K_2O	1.45	2.07	1.25	1.64	1.49	1.57	1.59	1.30	1.11	1.47	2.05	1.59	2.28	2.09	1.83	1.68	1.65
H_2O-	0.05	0.13	0.06	0.08	0.09	0.02	0.08	0.05	0.08	0.05	0.09	0.06	0.06	0.05	0.05	0.07	0.07
H_2O+	0.98	2.17	1.95	1.25	2.28	1.17	1.56	1.65	1.62	0.78	0.85	1.94	1.56	1.12	0.89	1.54	1.45
CO_2	0.05	0.29	0.89	0.02	0.08	0.10	0.12	0.05	0.15	0.06	0.05	0.03	0.05	0.07	0.05	0.15	0.14
P_2O_5	0.11	0.10	0.12	0.10	0.09	0.07	0.13	0.10	0.07	0.10	0.11	0.04	0.15	0.19	0.12	0.11	0.11
Total	99.82	99.55	99.58	99.91	99.86	100.02	100.20	99.76	99.94	100.18	99.62	100.32	99.59	99.70	100.16		

Analyst: Per Reidar Graff, Norges geologiske undersøkelse, Trondheim

Table 3. C.I.P.W. norms

	Andesites in the Schist Unit									Meta-andesites in the Gneiss Unit							
Specimen No.	476A	289	267	363	475	392	388	390	391	366	483	389	520	501	498	Average — 476A and 366	Average total
Quartz	30.68	18.45	13.75	16.76	12.07	14.49	13.83	15.60	8.82	21.78	15.71	16.42	17.14	12.81	14.08	14.61	16.15
orthoclase	8.57	12.23	7.39	9.69	8.80	9.28	9.40	7.68	6.56	8.69	12.11	9.40	13.47	12.35	10.81	9.93	9.76
albite	27.73	27.73	27.73	28.75	27.82	34.58	33.91	30.35	35.51	39.99	32.89	27.82	22.32	30.10	37.71	30.55	30.99
anorthite	18.09	17.13	26.09	25.13	28.92	21.59	19.77	22.78	26.94	19.33	24.61	23.96	24.72	26.27	24.33	24.01	23.11
corundum	3.15	1.63	1.35	–	1.12	–	1.89	1.84		–	–	1.25	–				
wollastonite	–	–	–	0.79		1.15	–	–	0.23	–	–	–	2.00	1.39	0.23		
enstatite	3.85	6.93	9.03	7.88	8.26	8.15	9.41	9.06	10.43	3.48	6.03	9.16	5.45	6.53	4.70	7.77	7.22
hypersthene	4.75	8.06	8.82	6.91	8.47	6.12	8.23	8.19	8.73	3.39	5.45	8.18	7.61	5.40	4.01	7.24	6.82
ilmenite	1.20	1.53	1.15	0.94	1.16	0.94	1.05	1.01	1.05	0.85	1.13	1.37	2.03	1.50	1.05	1.22	1.19
magnetite	0.97	3.02	0.52	2.02	0.23	2.58	0.52	1.68	0.48	1.87	0.87	0.45	3.73	2.31	2.38	1.59	1.57
apatite	0.24	0.22	0.26	0.22	0.20	0.15	0.28	0.22	0.15	0.22	0.24	0.87	0.32	0.42	0.26	0.29	0.28
calcite	0.11	0.66	2.02	0.05	0.18	0.23	0.27	0.11	0.34	0.14	0.11	0.07	0.11	0.16	0.11	0.34	0.31
H_2O+ + H_2O-	1.03	2.30	2.01	1.33	2.37	1.19	1.63	1.70	1.70	0.83	0.94	2.00	1.62	1.17	0.94	1.60	1.45
Anorthite content in plagioclase (calculated)	39	38	48	47	51	38	37	43	43	32	43	46	53	47	39	44	43

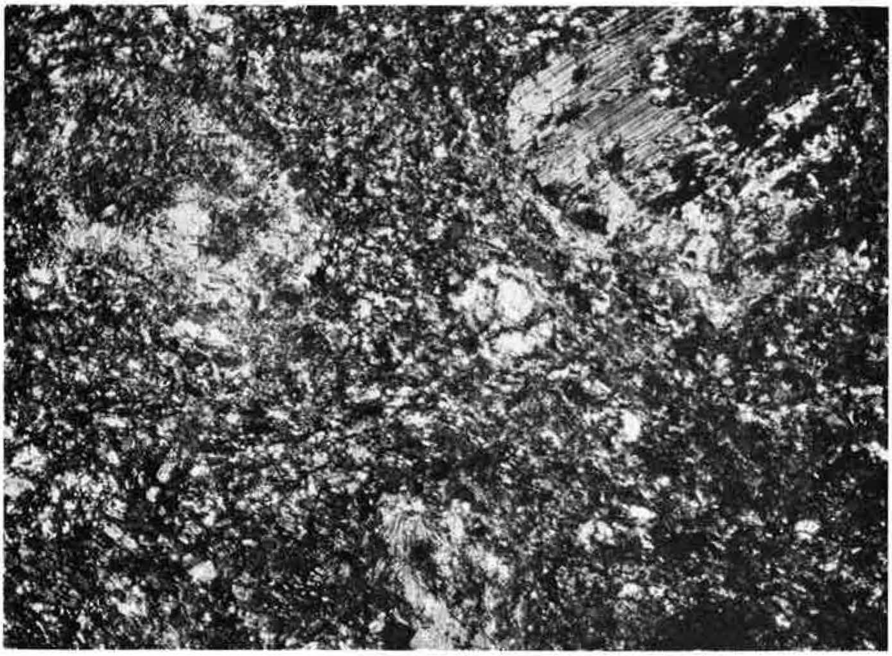


Fig. 3. Andesite from the Schist Unit. Note the variable saussuritization in the hypidiomorphic phenocryst, upper right corner. (Skorpehei, sample 267, × Nicols.)

somewhat higher than those of the calculated An-content of the normative plagioclase. This is, however, in accordance with observations from other areas. Larsen & Cross (1956, p. 261) in describing the relation between the measured and the calculated anorthite content from the San Juan lavas, note that 'The phenocrysts of a rock commonly contain about 20 per cent more anorthite than the normative plagioclase.'

In the present rocks, normal zoning (Core An_{37}, rim An_{23}) and simple reverse zoning (Core An_{25}, rim An_{32}) are observed, and the zonary arrangement of saussurite in some crystals indicates that oscillatory zoning may have been present. This, however, is not unusual as the zoning and the general variation in anorthite content are found to be widespread and general features of andesitic lavas (Turner & Verhoogen 1960, p. 276, Yoder 1969).

Many of the phenocrysts are twinned, with albite, pericline, and Carlsbad twins being most common. Other types of twin have been observed, but not identified.

Some phenocrysts have a rim of calcite or muscovite. The rim of muscovite might possibly be an alteration product of alkali feldspar, and according to Moorhouse (1959, p. 191): 'Rims of sanidine or orthoclase around plagioclase phenocrysts are more common than phenocrysts of the alkali feldspar'.

Two of the phenocrysts contain inclusions of biotite with sag nite.

Idiomorphic crystals of *green hornblende* are found in some of the layers of andesite. The idiomorphic shape indicates that they may be meta-phenocrysts. Larsen et al. (1937, p. 894) discuss the conditions favouring the formation of

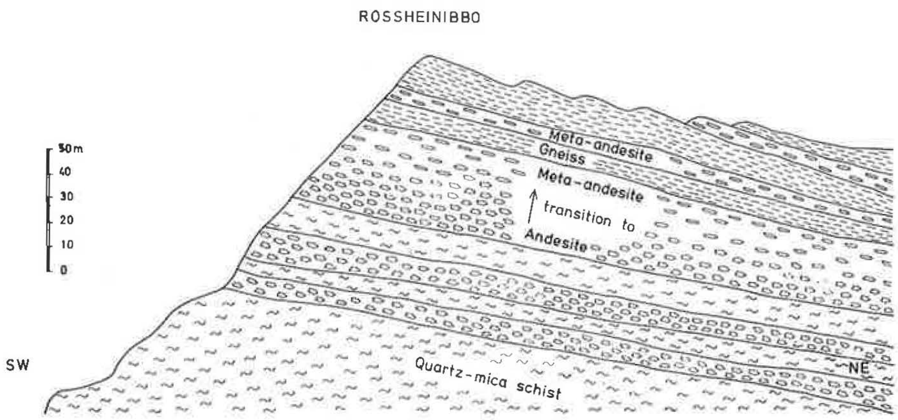


Fig. 4. Profile from Rossheinibbo, illustrating the transitional boundary between andesites (with traces of primary texture) interlayered with quartz-mica schists, and gneissified *meta-andesites* interlayered with quartz-feldspar gneisses.

green hornblende instead of basaltic hornblende. They found that basaltic hornblende differs from the other only by containing little H_2O and most of its iron in the ferric state. The Suldal volcanites have exceptionally low Fe_2O_3/FeO ratios – conditions favourable for the formation of phenocrysts of green hornblende.

The large areal distribution, and the fact that no cross-cutting relations have been observed indicate that these rocks are *supracrustals*. Most layers are rather massive with an even distribution of the phenocrysts; these rocks are most probably meta-lavas. The faintly layered andesites with transitional boundaries towards quartz-mica schists – with plagioclase crystals that seem to be fragments of larger hypidiomorphic crystals – could also be tuffs or tuffites.

Additional facts in favour of a supracrustal origin for the andesites is that grains of plagioclase (showing the same special type of saussuritization found in the andesites) occur in an underlying tuff/tuffite. This rock is clearly supracrustal; it is thin-bedded and occurs in alternation with thin layers of phyllite. This indicates either that this tuff/tuffite is a pyroclastic rock genetically connected with the andesites, or that the andesites have been exposed to erosion.

Further the numerous fine-grained leptite layers of supracrustal non-pelitic rocks in the Schist Unit are characterized by a low quartz content and the dominance of plagioclase (especially in the upper part of the Schist Unit). These rocks are either pyroclastic (andesitic) sediments, or epiclastic sediments where the detrital material is derived from a plagioclase-dominant source rock (which cannot be the quartz-rich, microcline-dominant Precambrian granites, migmatites, and gneisses). Thus the general lithology of the (epiclastic) rocks in the Schist Unit points to the presence of an andesitic volcanism contemporary with the sedimentation.

The data listed in Tables 1, 2, and 3 indicate that these rocks should be grouped as andesites. One of the rocks (476 A) could be termed a quartz-andesite.

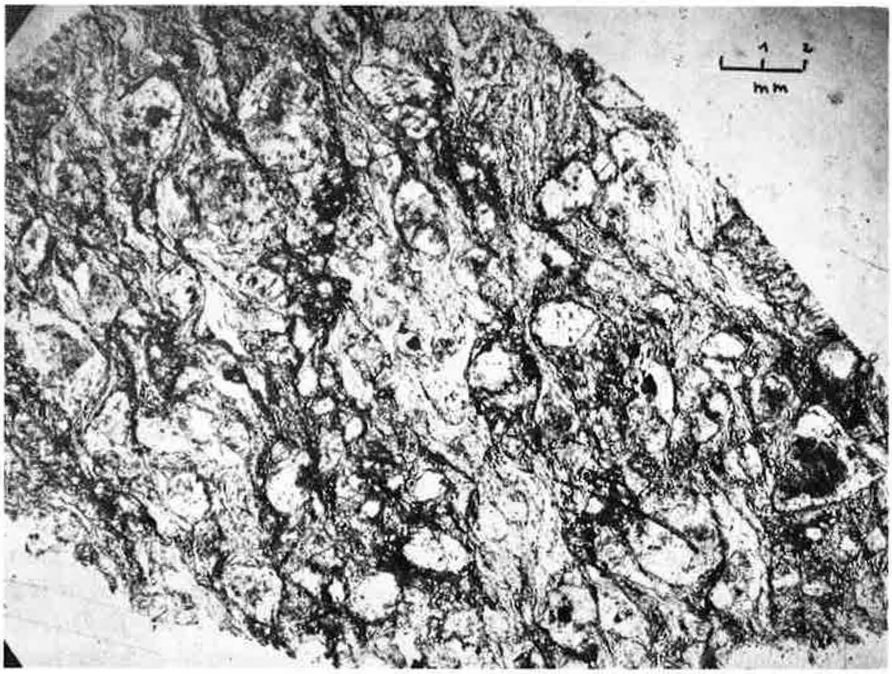


Fig. 5. Andesite from the Schist Unit with phenocrysts of plagioclase. Note the typical saussuritization and the possible primary fluidal texture, now formed by bands of clinozoisite and sphene (Skorpehei, plane polarized light).

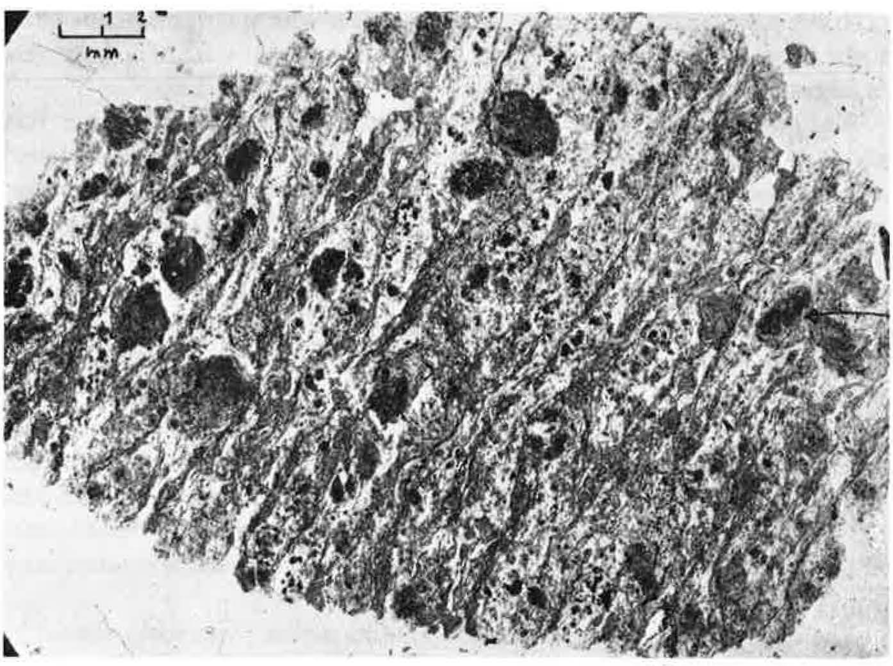


Fig. 6. Andesite from the Schist Unit with heavily saussuritized plagioclases. (Froa, sample 388, plane polarized light.)

Fig. 7. Meta-andesite from the Gneiss Unit with blastoporphyritic texture. The rock is recrystallized, the only primary character still remaining being the granulated saussuritized plagioclase. Compared with the plagioclase grains in the Schist Unit (Figs. 3, 5 and 6) they are now reduced in size and number. Note also the porphyroblasts of oligoclase (x). (Rossheinibbo, sample 366 A, plane polarized light.)

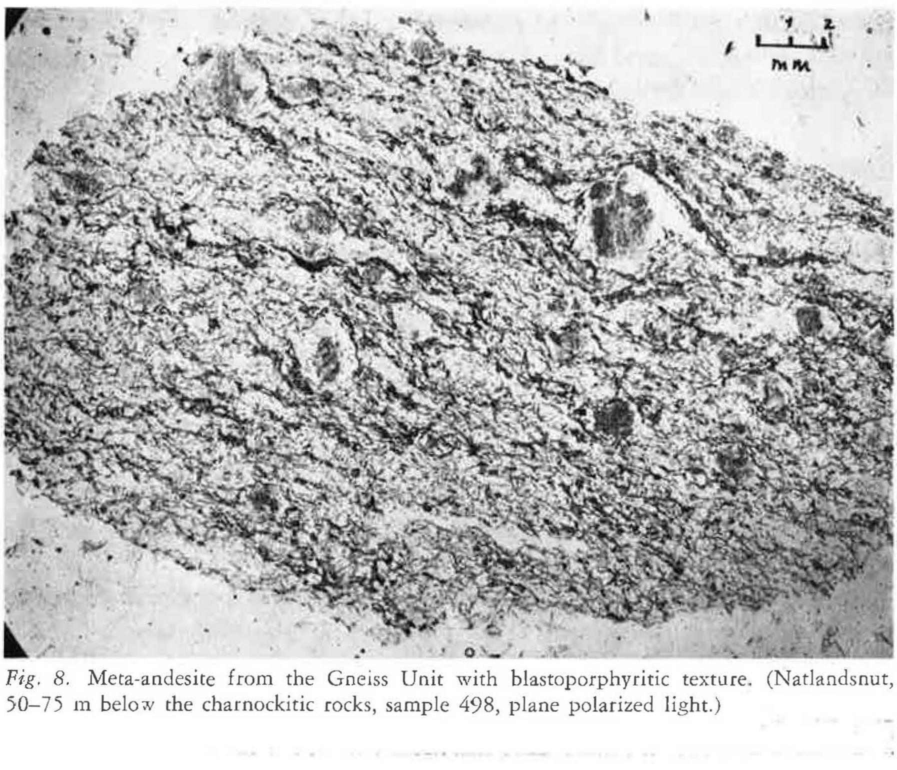


Fig. 8. Meta-andesite from the Gneiss Unit with blastoporphyritic texture. (Natlandsnut, 50–75 m below the charnockitic rocks, sample 498, plane polarized light.)

Meta-andesites in the Gneiss Unit

Thin layers of gneissified meta-andesites are found at all levels in the Gneiss Unit, the 'highest' layer being the one sampled at Natlandsnut. Near the boundary between the two Units, the layers of meta-andesite are somewhat thicker and much more numerous than those farther away from the boundary ('higher' up in the Gneiss Unit). The section from Rossheinibbo (Fig. 4) shows the transitional boundary between dark-coloured *andesites* and *meta-andesites*; they are interlayered with light-coloured quartz-mica schists and gneisses respectively.

The blastoporphyritic texture of the meta-andesites and the characteristic saussuritization of the plagioclase grains indicate that these rocks are closely related to the andesites of the Schist Unit (Figs. 5–8). However, the two rock-types differ in the size and shape of their constituent minerals. The content of quartz + plagioclase in the matrix, clinozoisite (epidote) and biotite is higher in the meta-andesites than in the andesites, while the content of plagioclase phenocrysts is lower. Chlorite (with one exception) and hornblende are absent in the meta-andesites (Table 2). The matrix minerals in the meta-andesites are more coarse-grained than those in the andesites, and the rock is free of the tiny inclusions which gives the andesite its dusty appearance. Porphyroblasts of younger oligoclase are also present in the meta-andesites (Fig. 7).

All transitional stages from the andesites in which primary textures are retained, to the most recrystallized blastoporphyritic plagioclase-biotite gneiss, can be observed. Thus, the study of these rocks in the field (the section of Rossheinibbo is especially informative) and in thin section, indicates that the meta-andesites are recrystallized andesites, and that their observed differences are most probably due to an isochemical recrystallization. The main purpose of carrying out the chemical analyses was to check this relationship.

Comparison between the andesites and the meta-andesites

Fig. 9 is a schematic presentation of the chemical analyses (Table 2) which facilitates the comparison between the above-mentioned rocks. It is seen that the weight percentages of the oxides of the meta-andesites vary within the same limits as those of the andesites. The Larsen diagram (Larsen 1938) is well suited to check if two groups of igneous rocks belong to the same petrographic province. Normative quartz, feldspar, and femic minerals are recalculated to 100% and plotted against the recalculated normative feldspars, and the respective plots are joined by a line. The length, slope, and position of the lines are characteristic of any one province.

The diagram Fig. 10 indicates that *the andesites and the meta-andesites are comagmatic rocks.*

Further, there is no recognizable chemical trend from basaltic andesites to quartz andesites (or vice versa) when passing from a bottom andesite layer in the Schist Unit to a top meta-andesite layer in the Gneiss Unit. In the next

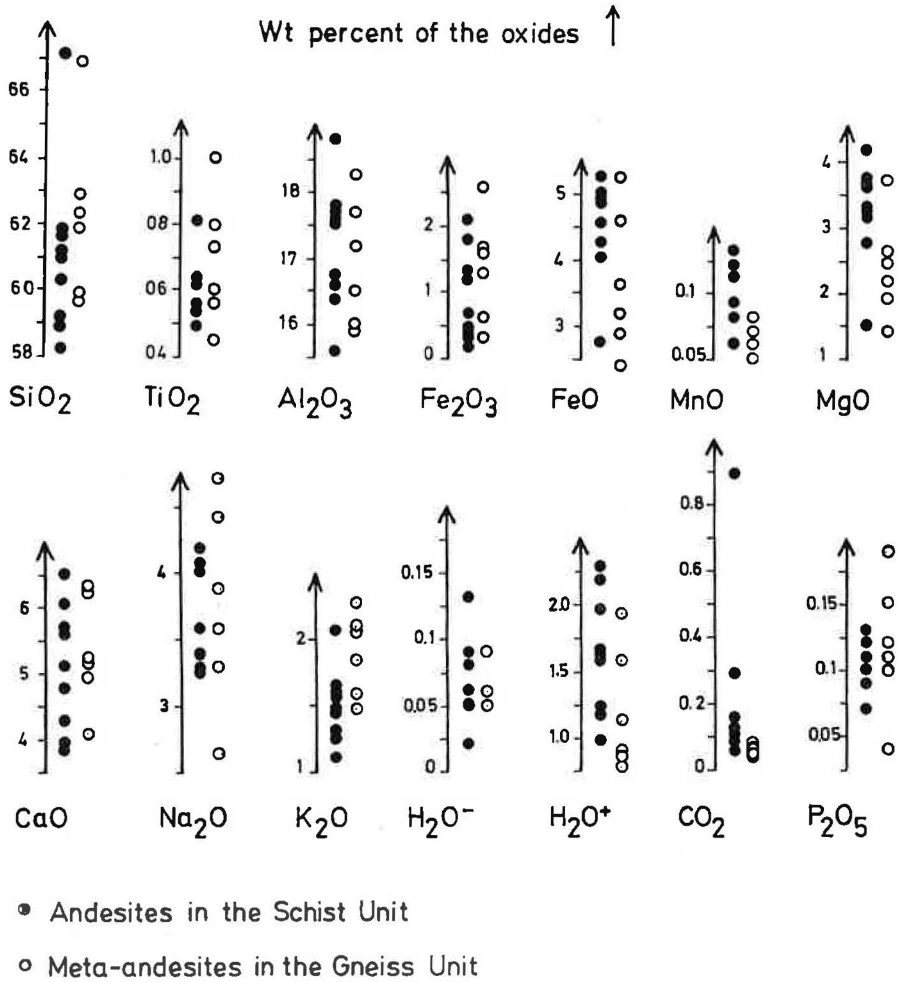


Fig. 9. Schematic presentation of the chemical analyses of andesites and meta-andesites. (A point may represent more than one analyses.) The weight percent of each oxide in the meta-andesites varies between the same limits as those of the andesites.

chapter the present rocks are compared with andesites from other parts of the world. The andesites and dacites of Mount Pelée (Martinique) have a chemical composition almost identical to that of the Suldal andesites. The magmatic evolution also shows considerable similarities. Lacroix (1904, pp. 644–646) states that there has been no regular change in the composition with time, and that actual volcanoes at Martinique may have their equivalent rocks: 'ni dans celles que fournit aujourd' hui la Montagne Pelée, mais dans des types beaucoup plus anciens'.

Field-observations, petrographical investigations and the study of chemical analyses thus indicate that:

1. The andesites in the Schist Unit and the meta-andesites in the Gneiss Unit

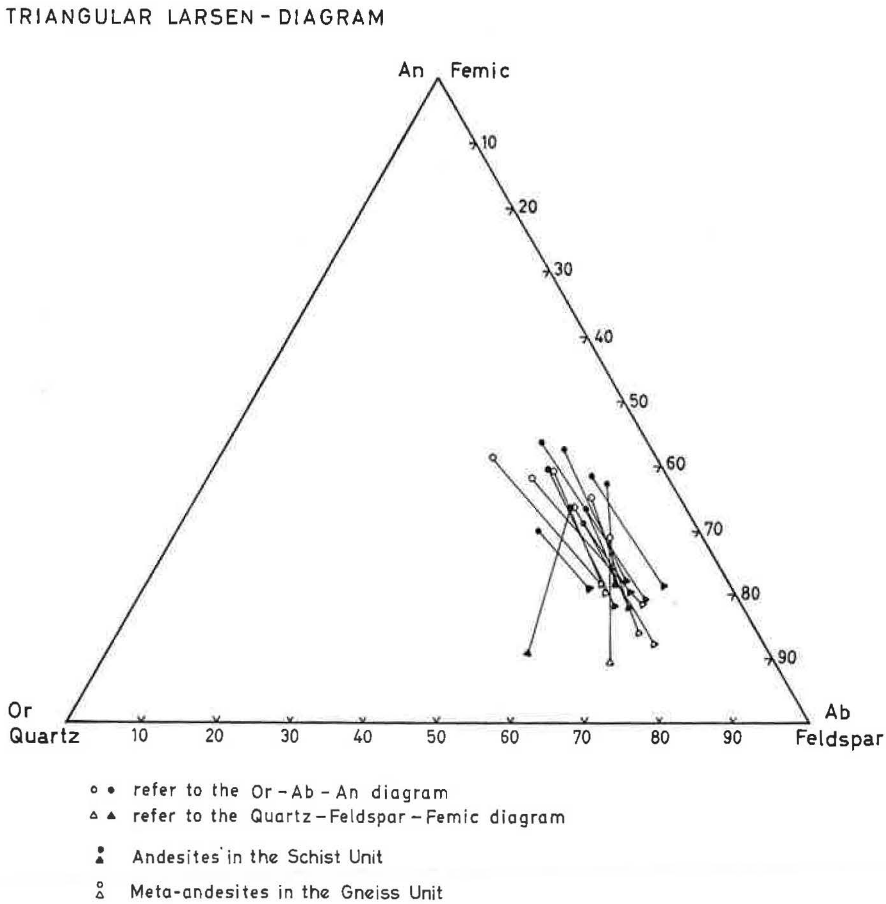


Fig. 10. Normative feldspars are plotted against the normative quartz, feldspar, and femic minerals, and the respective plots are joined by a line. The lenght, slope, and position of the lines are the same for the andesites in the Schist Unit and for the meta-andesites in the Gneiss Unit, thus indicating that the andesites and the meta-andesites belong to the same petrographic province (Larsen 1938).

are comagmatic, and thus related in space and time.

2. The metamorphic processes which the rocks have undergone were essentially isochemical.
3. The chemical composition of the volcanites does not seem to have varied with *time* in a regular manner.

COMPARISON WITH OTHER ANDESITIC ROCKS

In the forthcoming discussion the andesites in the Schist Unit and the meta-andesites in the Gneiss Unit will be treated as one group, and will be termed the Suldal andesites (or volcanites).

The chemistry of the Suldal andesites indicates that they belong to the basalt-andesite-rhyolite association (Turner & Verhoogen 1960, p. 272), the alkali-calcic classes of Peacock (1931) (Fig. 11) and the strong Pacific suite of

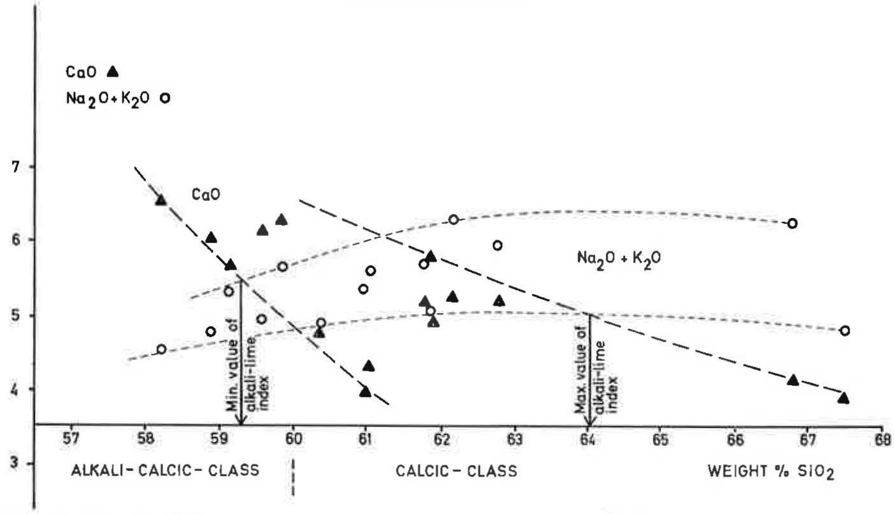


Fig. 11. The alkali-lime index (Peacock 1931) of the Suldal andesites.

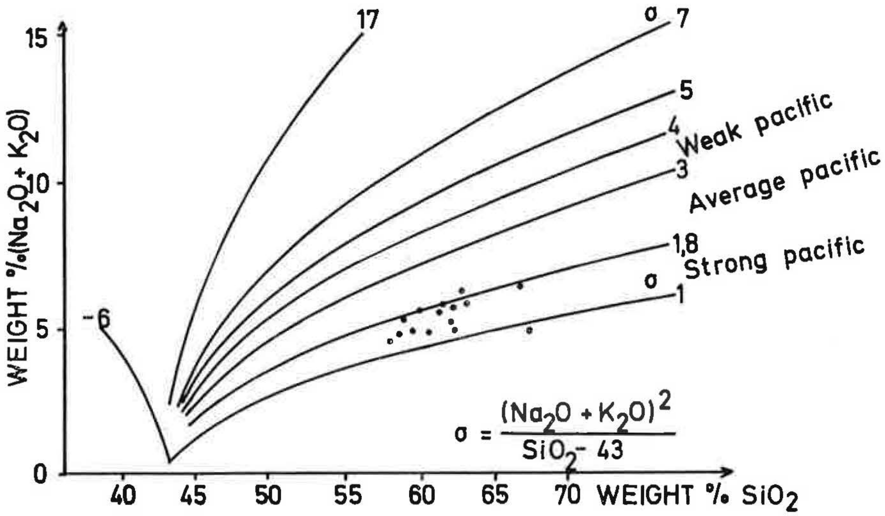


Fig. 12. Oxides of the Suldal andesites plotted in the volcanic rock-suite diagram of Rittman (1962 p. 109).

Rittman (1962 p. 109), (Fig. 12). This association (class, suite), according to Turner (1960 p. 272), is '. . . confined to continental sectors of the earth's surface, and its most typical development is in connection with moderate to strong orogenic movements . . .'

The origin of the calc-alkali series has been a long-debated problem. Wilkinson (in Hess & Poldervaart 1967, p. 169) gives a resumé of the controversy:

'Thus some petrologists (e.g. Bowen 1928, Osborn 1962) consider that fractional crystallization of basaltic (tholeiitic) magma alone may produce the calc-alkali series; others (e.g. Tilley 1950, Kuno 1950) consider that sialic or

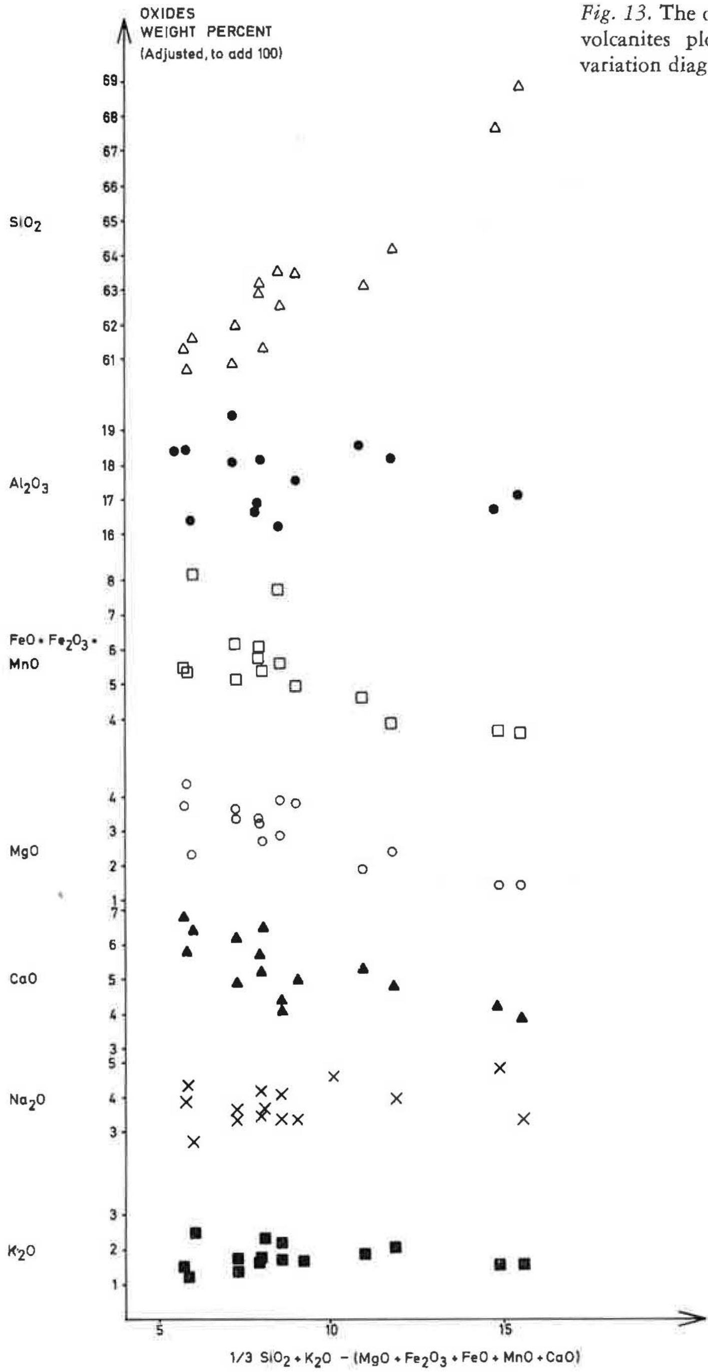
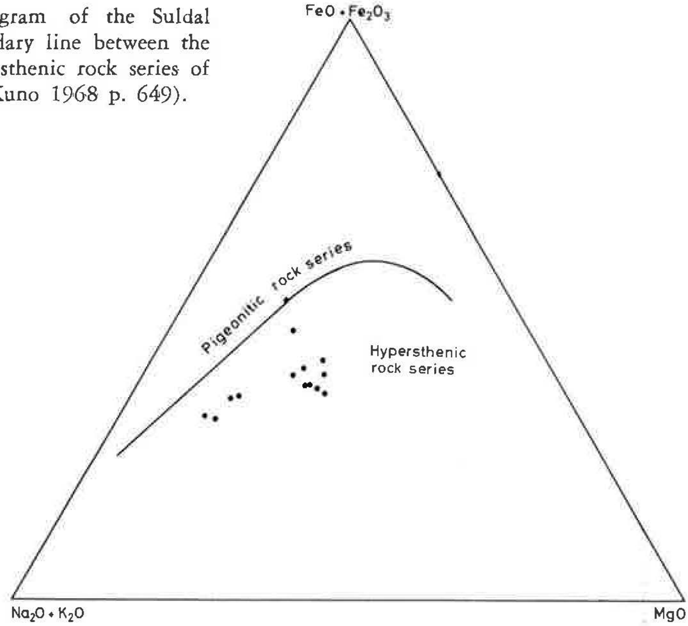


Fig. 13. The oxides of the Suldal volcanites plotted in a Larsen variation diagram (Larsen 1938).

granitic contamination of basaltic magma is prerequisite (followed by fractional crystallization) to the generation of the more evolved calc-alkali member.'

(Turner 1960, p. 287) takes into consideration all the anomalies of andesites and proposes that these phenomena must be due to differential fusion of crustal rocks.

Fig. 14. AMF diagram of the Suldal andesites. The boundary line between the pigeonitic and hypersthenic rock series of Japan is included (Kuno 1968 p. 649).



As to the Suldal andesites, it seems most reasonable that the anomalies of these rocks (the variable An-content, the complex zoning in the plagioclase phenocrysts) are a result of complicated conditions during the crystallization, not of 'mechanical' mixing of magma and surrounding rocks. This follows from the fact that the rocks are remarkably homogeneous and that the character of the plagioclase phenocrysts, and to a certain extent also their size and number, remain constant. This is so even though the rocks cover a large area, and have been extruded over an interval of time. Furthermore a plot of the chemical analyses (Fig. 13) in a Larsen variation diagram (Larsen 1938) shows a regular covariation between the oxides, indicating that these volcanites have evolved by fractional crystallization or partial melting from similar sources (Green & Ringwood 1968), and are probably unaffected by heavy crustal contamination (Figs. 10, 13). This is in accordance with the latest data concerning andesite genesis; these data appear to deny the participation of continental crust in the magma genesis (Dickinson 1970).

Kuno (1960, 1968) believes that the calc-alkali series may be formed from any of his three main types of basaltic magma (tholeiitic-, high-alumina- and alkali basalt magma) by addition of water; this may or may not be accompanied by assimilation of granitic or sedimentary rocks. Kuno proposes that the term 'calc-alkali' rock series should be used only for the hypersthenic rock series and that this series is formed from low-temperature water-rich magmas (Kuno 1968, p. 643). The difference between the series is based on mineralogical and chemical criteria. Because the original mineralogy of the matrix of the Suldal andesites is uncertain, the following comparison with the rocks from Japan, Korea, and Manchuria (which form the basis of the classification of Kuno) is necessarily based on chemical criteria. The plots of the Suldal andesite (Figs. 14, 15) indicate that they, even in the strict sense of Kuno, might belong to the calc-

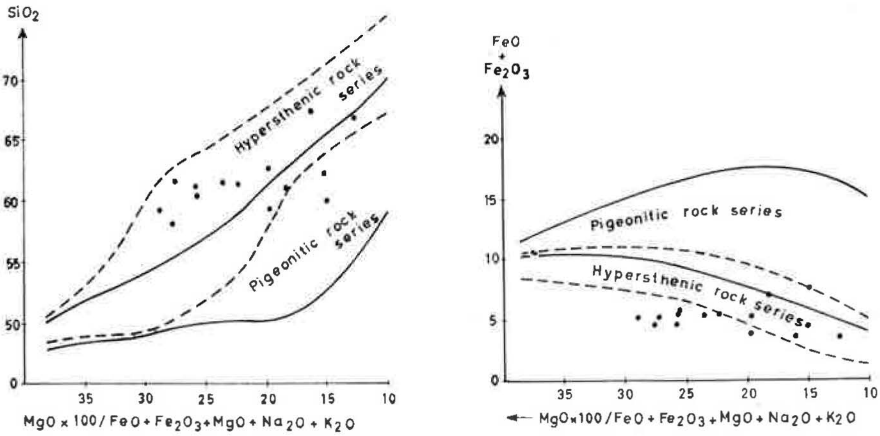


Fig. 15. SiO_2 and $FeO+Fe_2O_3$ of the Suldal andesites plotted against the solidification index SI ($SI=Mg \times 100/MgO+Fe_2O_3+FeO+Na_2O+K_2O$). The boundary lines of the fields of the pigeonitic and hypersthenic rock series from Japan are reproduced (Kuno 1968 p. 651).

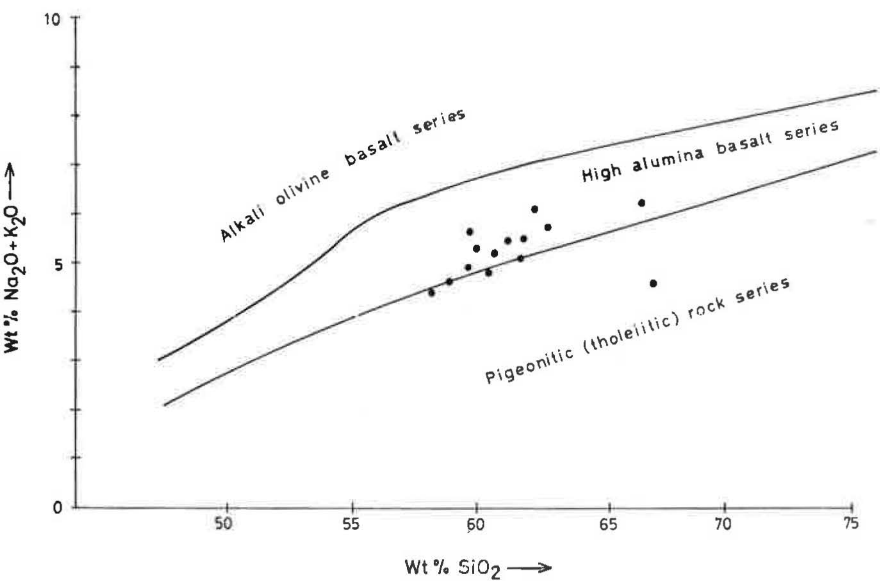


Fig. 16. Alkali-silica diagram of the Suldal volcanites. The boundary lines between the fields of the three types of basalt drawn by Kuno (1968 p. 627) are reproduced.

alkali series (hypersthenic rock series). Hornblende and biotite may occur as phenocrysts in this series, and the presence of possible primary hornblende phenocrysts in the Suldal andesites thus supports this conclusion.

The plots in Fig. 16 indicate that the Suldal volcanites might have been derived from a high-alumina basalt magma. This, however, is somewhat uncertain as the rocks are highly porphyritic and thus might have been derived from a tholeiitic magma where plagioclase phenocrysts accumulated.

Osborn (1959, 1962) advocates that the rocks of the calc-alkali series might be a product of fractional crystallization of a basaltic magma at constant (or

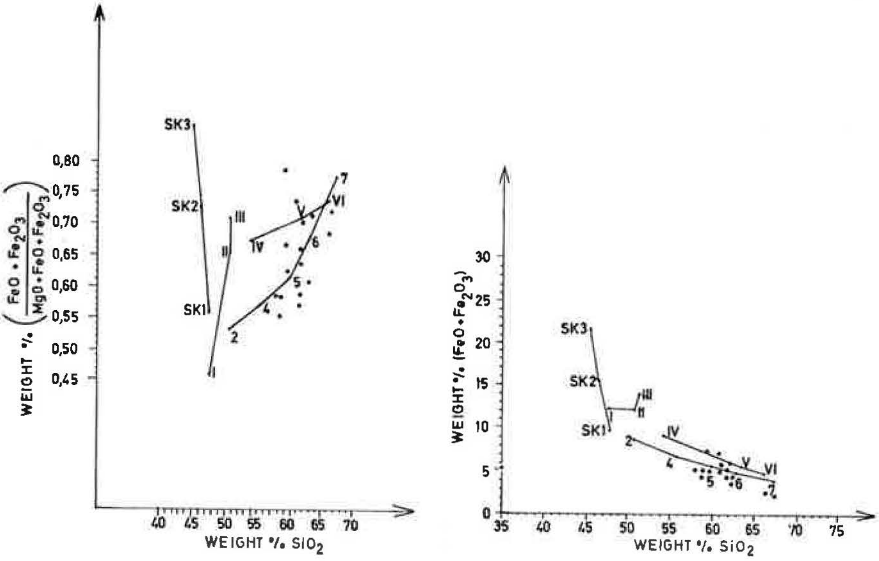


Fig. 17. Oxides of the Suldal andesites plotted in the magma series diagram of Osborn 1959 p. 634).

increasing) oxygen partial pressure (P_{O_2}). His curves for different magma series are reproduced in Fig. 17. The series Sk_1–Sk_3 and I–III are thought to represent crystallization under constant total pressure (decreasing P_{O_2}), the series IV–VI and 2–7 having crystallized under constant or increasing P_{O_2}. The corresponding values for the Suldal andesites are plotted in the same diagram.

The plots show that if the andesitic magma is formed from a basaltic magma by fractional crystallization, the magma has crystallized under constant or increasing oxygen pressure. Following this, it is now generally assumed that the high oxygen partial pressure is caused and maintained by absorption of water (Goldschmidt 1958, p. 658, Hess & Poldervaart 1967, 1968). The normal result of this absorption would be a general oxidation, precipitation of magnetite, lowering of the total iron content, and oxidation of the iron.

Looking at the Suldal andesites the total iron content is relatively low, and thus in accordance with the general picture outlined by Osborne and others. The Fe_2O_3/FeO ratio, however, is of particular interest, as it is generally accepted that the degree of oxidation of iron in a rock undergoes practically no change during ordinary regional metamorphism (James & Howland 1955, Yoder 1957, Chinner 1960, Mueller 1967). The Fe_2O_3/FeO ratio should therefore give information of the oxidation stage in the magma at the time of eruption, and/or the eruptional environment. A comparison with 100 andesite analyses with a SiO_2 content ranging from 57% to 67%, (Washington 1917), shows that 96 of the tabulated andesites had a higher Fe_2O_3/FeO ratio than the Suldal andesites. In Table 4 other important ratios are also tabulated. It is seen that all the others ratios of the Suldal andesites are comparatively 'normal', while the Fe_2O_3/FeO ratio is exceptionally low. (0.03–0.57). (Goldschmidt (1958,

Table 4. SiO_2 weight percentages and various oxide ratios in andesites/dacites from several regions

	Number of analyses	SiO_2 Wt%	Na_2O/CaO	FeO/MgO	SiO_2/MgO	K_2O/CaO	Fe_2O_3/FeO
Dacites, Daly (1933)	30	66.91	1.26	1.09	51.9	0.76	1.83
Dacites Nockolds (1954)	50	63.58	0.72	1.41	29.9	0.25	0.74
Andesites Mont Pelée (Lacroix 1904 p. 527)	8	61.88	0.5	1.59	22.8	0.17	0.45
Andesites Suldal	15	61.56	0.71	1.54	22.8	0.32	0.26
Andesites Daly (1933)	87	59.59	0.66	0.14	21.6	0.35	1.06
Andesites Nockolds (1954)	49	54.20	0.46	1.26	12.4	0.14	0.63

p. 657) states that this ratio increases from about 0.2 to about 20 in the course of magmatic evolution.) It is therefore reasonable to consider if the low ratio could be caused by secondary (pre-metamorphic) reducing processes. Contact with, or assimilation of carbonaceous matter, or if the eruption took place in environments characterized by stagnant bottom water, might result in reduction of the lavas. As no carbonaceous matter is found in the lavas or in the surrounding rocks, and sulphides are rare, this does not seem to be a plausible explanation. The andesites have the same Fe_2O_3/FeO ratio whether they are adjacent to quartz-mica schist or gneisses, or whether they are located in the Schist Unit or in the Gneiss Unit. The Mont Pelée andesites have almost the same chemistry as the Suldal andesites, including also an exceptionally low Fe_2O_3/FeO ratio. This at least indicates that recent andesites *may* have low primary oxidation ratios. Thus it is not *necessary* to postulate special environmental conditions, and the low oxidation ratio could be inherited from the magma.

However, in order to check the oxidation ratio of the surrounding rocks, 5 different rocks from the Schist Unit and the Gneiss Unit were analysed for FeO and Fe_2O_3 (Table 5). All of them had exceptionally low Fe_2O_3/FeO ratios (0.04–0.32). These results indicate that not only the andesites, but maybe most of (or all) the rocks in the two Units are in a reduced state. When such a particular ratio is common for chemically and genetically different rocks this could reasonably be caused by:

1. A generally reducing environment during deposition or eruption, i.e. an anoxic atmosphere. If so, the rocks must be surprisingly old – more than about 2300 m.y. (Fairbairn et al. 1969, Roscoe 1969). Age determinations from Hardangerjøkulen (Priem 1968) of a gneiss in a geological situation

Table 5. Weight percentages of FeO and Fe_2O_3, and Fe_2O_3/FeO ratios of non-volcanic rocks from the Schist Unit and the Gneiss Unit

Rock type. Locality	Main minerals	Unit	Fe_2O_3	FeO	Fe_2O_3/FeO
17. Kyanite–chloritoid Schist. North of Rossheinibbo	Quartz, kyanite chloritoid	Schist Unit	0.36	9.49	0.04
392. Quartz-mica Schist. m Gullingenut	Quartz, chl., musc., ep., ga.	Schist Unit	0.62	5.78	0.11
481. Gneiss. NNW of Urdanut	Quartz, plag., k.feldsp., bi.	On the boundary between the Units	0.38	1.54	0.25
486. Gneiss. Between Urdanut and Rossheinibbo	Quartz, plag., k.feldsp., musc., bi., clinoz.	Gneiss Unit	0.54	1.67	0.32
496. Gneiss. NW of Natlandsnut	Quartz, micr., plag., bi., ep., ga., sph.	Gneiss Unit	0.26	3.60	0.07

much like the rocks of the Gneiss Unit gave a Rb–Sr whole-rock isochron age of 1550 + 100 m.y. From the Stavanger area determinations of gneisses in a similiar situation gave a whole rock Rb–Sr isochron date of about 1160 m.y. (Heier, Naterstad & Bryhni, in press). However, as these authors interpret the last age to be the age of metamorphism, this determination does not exclude that the rocks might have such a high age of formation.

2. Later processes influencing all the rocks, i.e. the regional metamorphism. If so, this implies that the degree of oxidation of iron *may* change during regional metamorphism, a hypothesis which is in some contrast with the assumption stated by Mueller and others (p. 45). Many authors (Engel & Engel 1962, Buddington, Fahey & Vlisidis 1963, Schwarcz 1966) find that reduction has apparently taken place during metamorphism.

Age determinations and more extensive investigations are necessary in order to solve this special problem.

Summary and conclusions

Andesites interlayered with quartz-mica schists, phyllites, and tuffites (traditionally thought to be of Cambro-Silurian age) cover an area of about 120 km² in the Suldal area, Ryfylke. Layers of gneissified recrystallized meta-andesites are also found in the overlying Gneiss Unit. Petrographical studies and chemical analyses indicate that all these (meta-)andesites are comagmatic, and that the metamorphic processes which the meta-andesites have undergone were essentially isochemical.

A comparison with other andesitic rocks in the world indicates that the Suldal andesites belong to the basalt-rhyolite association of Turner & Verhoogen, the alkali-calcic or calcic classes of Peacock, the strong Pacific suite of Rittman, and the hypersthenic rock series (derived possibly from a high-alumina basalt magma) of Kuno.

The Fe_2O_3/FeO ratios of the Suldal andesites are exceptionally low (0.03–0.57). Analyses of 5 of the surrounding schists and gneisses also showed the same low ratios (0.04–0.32). This points to the possibility that in most (or all) of the rocks in the Schist Unit and the Gneiss Unit iron is highly reduced.

This is due either to:

1. Reducing environment during emplacement, i.e. an anoxic atmosphere, which implies that the rocks are more than about 2300 m.y. old,
   or
2. Reducing processes in the course of metamorphism.

Over the last 20–30 years it has been generally considered that the gneisses overlying the Cambro-Silurian rocks in Ryfylke are allochthonous. Müller & Wurm (1969, 1970) consider these gneisses to be autochthonous or para-autochthonous Cambro-Silurian rocks.

The main relevant results from the author's general geological mapping of the Suldal area and the present study of the Suldal andesites are:

1. There is no marked thrust-plane at the boundary between the Schist Unit and the Gneiss Unit; thrust-planes and mylonite zones may from place to place be found at any level within the Units.
2. There is no difference in metamorphic grade in the rocks below and above the boundary.
3. There is a transitional development observed in the field and under the microscope from rather massive andesites in the Schist Unit to recrystallized, gneissified meta-andesites in the Gneiss Unit.
4. The andesites in the Schist Unit and the meta-andesites in the Gneiss Unit are comagmatic, and thus related in space and time.

These results, together, indicate that *the main parts of the Schist Unit and the Gneiss Unit are one tectono-stratigraphic Unit.*

We then have two possibilities:

1) *Both Units are in allochthonous position*

   In this case the thrust plane of this allochthonous Schist-Gneiss Unit must be found at some level between the Sub-Cambrian peneplain and the lowest situated andesite, i.e. in the lower part of the Schist Unit. Some places the thrust plane must be situated near, or at, the peneplain itself – in other places it must be found within the phyllites and mica-schists, separating autochthonous and allochthonous metamorphic pelitic rocks of probably highly different age.

   The fossiliferous shale at Ritland (Henningsmoen 1952) must then be considered as autochthonous and preserved from destruction because of its position in pockets in the Sub-Cambrian peneplain.

2) *Both Units are in a para-autochthonous position*

It is difficult to find conclusive arguments favouring one of the possibilities to the absolute exclusion of the other, but the new age determinations (Priem 1968, Heier, Naterstad & Bryhni, in press) seem to favour the first possibility. If so, the present investigation indicates that the thrust plane is generally not to be found between the metamorphic pelites and the gneisses, but within the pelitic rocks itself.

Whichever the case may be, an explanation still remains to be found for the upward increase in recrystallization of the andesites. Further, one must explain why this change takes place at about the level where the enclosing rocks change from quartz-mica schists to gneisses. The present investigation shows that such a change in the degree of recrystallization cannot reasonably be ascribed to major differences in age or environment of formation of the andesitic rocks. This change in degree of recrystallization thus cannot represent a major tectonic break or an (inverted) basement-to-cover contact.

The results presented above for the Gneiss Unit should not be applied generally for all the gneisses overlying phyllites and mica schist elsewhere. The author's investigations north and east of Suldal area and investigations in the Haukeliseter–Røldal area by Naterstad, Andresen & Jorde (personal communication) have shown that other additional and different gneiss complexes are present. This is also the case in the Stavanger area.

This indicates that the gneisses overlying the metamorphic pelitic rocks in the Hardangervidda–Stavanger area can be composed of rock units of highly different age and with a different tectonic and metamorphic history.

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