THE ORTHOAMPHIBOLE-BEARING ROCKS OF THE SØNDELED-TVEDESTRAND AREA, AUST-AGDER, SOUTH NORWAY

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Five orthoamphibole-bearing assemblages are recognised in the Søndeled-Tvedestrand area of the Precambrian basement: quartzorthoamphibole gneisses, gedridites, cordierite-anthophyllite rocks, orthopyroxene-bearing rocks, and actinolite gneisses. Quartz-orthoamphibole gneisses and gedridites are largely restricted to the metasedimentary sequence. Cordierite-anthophyllite assemblages are the most common of orthoamphibole-bearing rocks in this region and can locally be seen in the field and petrographically to form from the actinolite gneisses. The formation of anthopyllite from actinolite is controlled by a deficiency of Na and a high Mg/Fe ratio. The presence of orthoamphibole-bearing rocks within the metasedimentary sequence is considered to result from the metamorphic segregation of mafic and felsic parts.

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The orthoamphibole-bearing rocks of the Søndeled-Tvedestrand area of the Bamble Sector are a lithology with a restricted distribution, but their form and origin are indicative of local metamorphic processes. This distinctive lithology is typified by the presence of an orthorhombic amphibole (anthophyllite or gedrite), frequently accompanied by cordierite, and commonly reflecting a high magnesium content of the rocks. The most comprehensive survey to date is given by Bugge (1943), although several, more recent, local studies have provided additional comment (Starmer 1967, Rodwell 1968, Field 1969, Morton et al. 1970).

Orthoamphibole-bearing rocks have a world-wide distribution in numerous metamorphic environments, and are attributed to a variety of origins. However, from the limited analytical data available for this lithology, few localities show the extreme enrichment of Mg found in the Bamble Sector, both in absolute concentration and relative to ferrous iron.

This paper discusses the field relations, and the petrographical and geochemical nature of the lithology. Two origins are proposed for the occurrence of the orthoamphibole-bearing rocks of the Søndeled-Tvedestrand area, and other origins applied to this and other areas are discussed.

Data tables of modal and chemical analyses, cation percent and Niggli numbers, and details of analytical techniques used are recorded in the author's Ph.D. thesis (Beeson 1972).

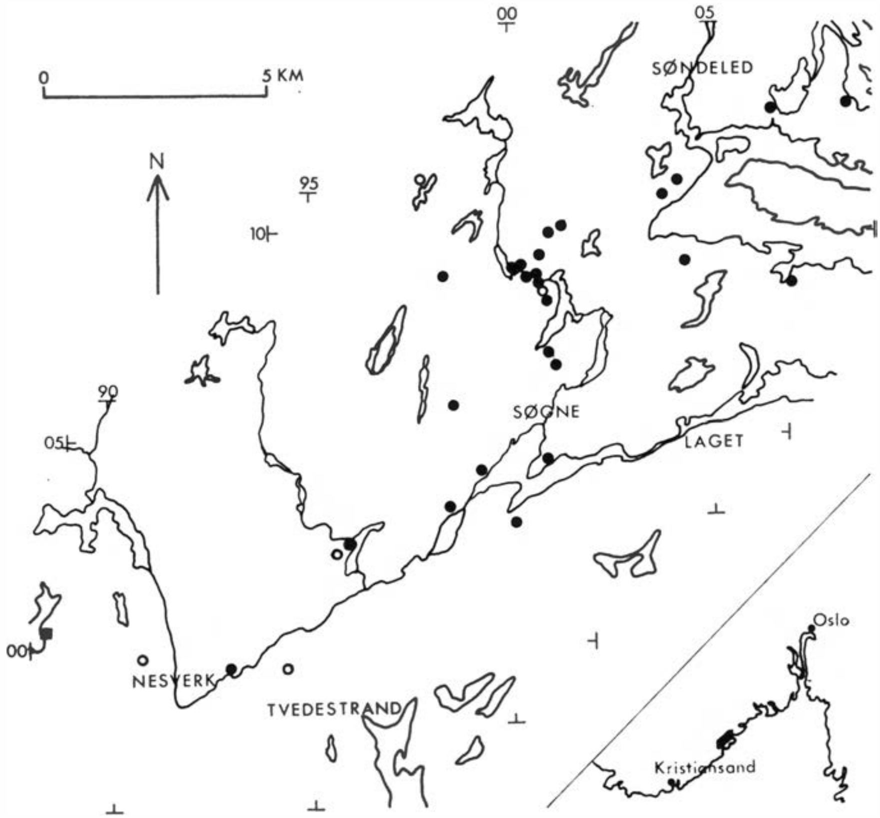

Fig. 1. Location of orthoamphibole-bearing rocks (solid circles) in the Søndeled-Tvedestrand area, including orthopyroxene-bearing rocks (open circles) and garnet-bearing cordierite-anthophyllite rocks (square).

Map references are taken from 1: 50 000 scale AMS standard series. The classification of orthoamphiboles used is after Deer et al. (1963).

Field relations

The orthoamphibole-bearing rocks of the Søndeled-Tvedestrand area occur in thin layers and lenses elongate parallel to the strike of the foliation. These rarely exceed 50 m × 10 m in size and are frequently much smaller. Five forms are recognised on the basis of field relations and petrography.

Quartz-orthoamphibole gneiss. – The most acidic of the orthoamphibole-bearing rocks, this variety normally has felsic layers of quartz-cordierite or quartz-plagioclase separated by orthoamphibole layers 0.5–5.0 cm apart. The orthoamphibole may be lineated (930994), randomly oriented in two dimensions (993041), or radiating (Starmer 1967).

Gedridite. – Gedrite normally occurs in the Søndeled-Tvedestrand area in monomineralic or high modal gedrite rocks, as its abundance of alumina corresponds to whole rock compositions. Anthophyllite, however, being Al-poor, requires the presence of cordierite to balance the rock chemistry. Spinel occurs in rocks depleted in silica, e.g. 000028. Gedridites are most commonly found in Mg-rich metasediments which may be cordierite-bearing

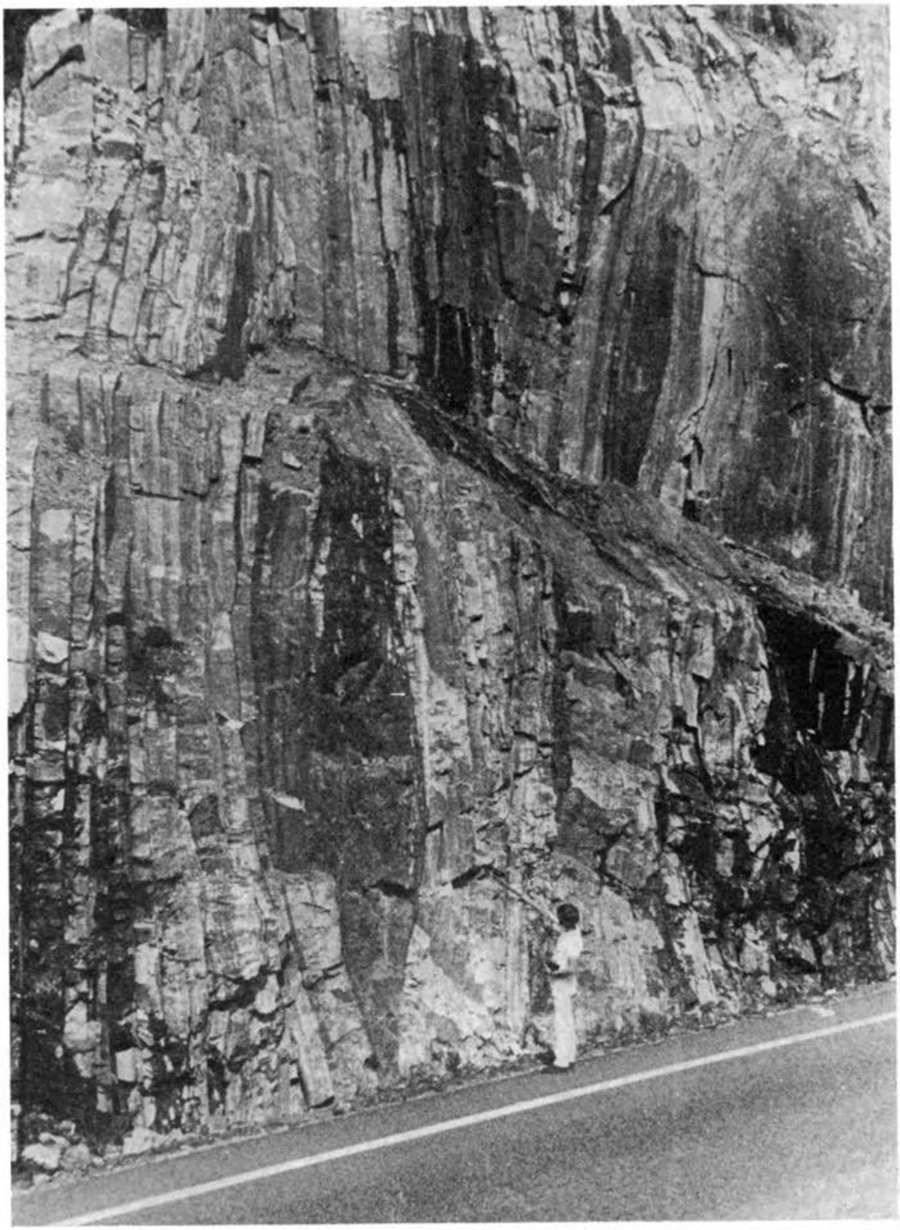

Fig. 2. Gedridite lens in cordierite-bearing metasediments, Sundsvalen (984033).

(Fig. 2). The gedridites form thin horizons often in association with amphibole (984033). Graphite occurs in the gedridites at this locality.

Cordierite-anthophyllite rock. – At least half of the orthoamphibole-bearing rocks in the area are of this type. The rocks are made up of variable proportions of pink or lilac anthophyllite with subsidiary cordierite. Phlogopite is a common additional mineral, although it is frequently secondary. This type is associated with metasedimentary gneisses, biotite schists, and actinolite gneisses.

Orthopyroxene-bearing rock. – This type is commonly associated with acid metasediments, particularly quartzites and sillimanite gneisses. Orthopyroxenes are preserved in Amphibolite facies rocks where subsequent metamorphism has not caused retrogression.

The actinolite gneiss. – These represent a parent lithology of cordierite-anthophyllite rocks. At several localities in the Moland area (e.g. 010100), elongate prisms of anthophyllite (10 cm length) are growing in actinolite segregations as a replacement of the latter mineral. In certain horizons the replacement is complete and lenses of cordierite-anthophyllite rock now occur (see below). The original stuctures of actinolite gneisses, e.g. tight isoclinal folding and semi-rotated blocks of more competent material, are now completely replaced by cordierite-anthophyllite assemblages (002091). The actinolite gneisses are a sub-group of the biotite-actinolite gneisses which form a mappable unit in the area around Aklandstjern (0009).

Quartz-orthoamphibole gneisses are intergradational with quartz-cordierite gneisses in this area. Both of these lithologies can contain lenses of gedridite or rarely cordierite-anthophyllite rock. Gedridites are largely restricted to this environment.

Cordierite-anthophyllite rocks are also preferentially located in certain horizons, either sillimanite-bearing metasediments, or the actinolite gneisses. A single, garnet-bearing cordierite-anthophyllite rock occurs in the northwest of this area (882003). Orthopyroxene-bearing rocks are not associated with other subgroups.

The main metamorphic episode to affect the Søndeled-Tvedestrand area was the Sveconorwegian regeneration of approximately 1200 m.y. (Starmer 1972). Locally this regeneration was of Amphibolite facies grade, with granulite facies to the south. It can now be observed as the main foliation, and as isoclinical folding and associated lineations.

Four of the five lithological types outlined above took their present form during this episode. Examples of features relating to this period are the presence of orthopyroxene in some localities, the boudinage form of many gedridites (e.g. Fig. 2), and the layering of the quartz-orthoamphibole gneisses.

In contrast, the cordierite-anthophylite rocks originated subsequently to the folding associated with the main phase of the Sveconorwegian regeneration. The mineralogical components cut fold structures of this episode within the actinolite gneisses. In addition the anthophyllite has a coarse grain size atypical of this period of mineral formation, and it is not necessarily aligned parallel to the main foliation. As the cordierite-anthophyllite rocks appear to undergo alteration in the period of K-feldspathisation in the later stages of the Sveconorwegian regeneration (see p. 130), it is probably tha they originated immediately after the main metamorphism.

Petrography

Orthoamphibole occurs as subidioblastic to xenoblastic prisms. The mineral grains are elongate parallel to their C axes, particularly in the sub-radiating forms. Birefringence is low, commonly ≤ 0.008. Grain margins are always ragged on basal surfaces when in contact with cordierite, whilst other faces are normally straight. Orthoamphibole and orthopyroxene are rarely a stable assemblage, the former normally replacing the latter. Two replacement forms are present: subidioblastic orthoamphibole cutting original orthopyroxene grains, and pseudomorphs of earlier orthopyroxene poikiloblasts (Fig. 3). Large anthophyllite prisms also replace actinolite. Orthoamphibole

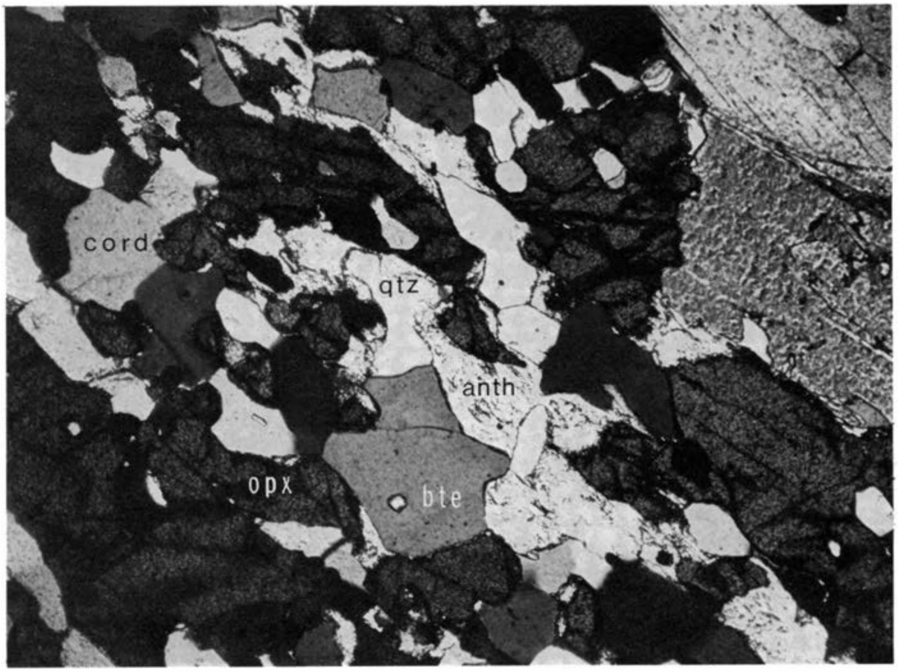

Fig. 3. Pale orthoamphibole pseudomorphing dark orthopyroxene poikiloblasts in quartz-orthopyroxene-phlogopite gneiss, Tvedestrand (947996). Polarised light, × 38.

itself can be replaced by cordierite, the latter forming corona structures around the orthoamphibole grains. This cordierite appears to be related in origin to a second growth of mica, possibly from the potash metasomatism of an original cordierite-anthophyllite rock. In this case, the excess Mg from the breakdown of orthoamphibole has formed the second generation of cordierite (981112). Pale phlogopitic mica is the common alteration product of orthoamphibole, occurring first within the cleavage, and secondly, when more abundant, sub-parallel to the foliation. This has been previously recorded in similar rocks adjacent to pegmatitic dykes (Lal & Moorhouse 1969).

Cordierite normally forms sub-equant, slightly pinitised grains with curved or embayed margins, but may be elongate ($\leq$ 10 cm) parallel to a coarse orthoamphibole growth. A polygonal texture may be present in cordierite-rich segregations. One relatively iron-rich cordierite has a faint grey colour in this sections, whereas all others are colourless. Poorly developed polysynthetic twinning is moderately common, whilst sector twinning is rare or absent. South Norwegian cordierite is typified by an abundance of very fine, opaque inclusions. Larger inclusions of quartz, phlogopite, rutile or apatite may be present, dependent on the type of growth. Cordierite is normally the last mineral to form in the genesis of cordierite-anthophyllite rocks. It replaces calcic plagioclase (bytownite) in the actinolite gneisses as

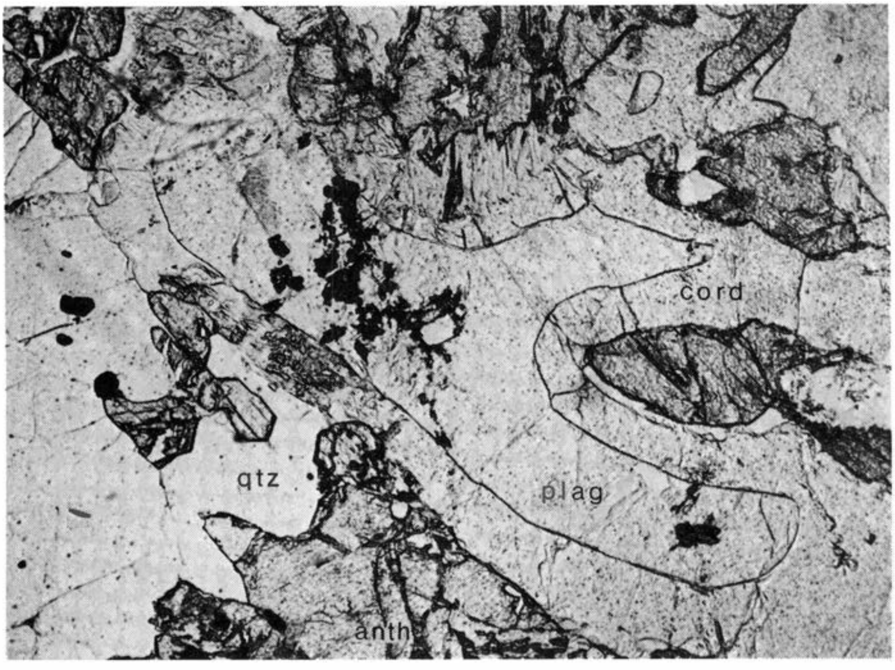

Fig. 4. Corona of cordierite replacing bytownite in actinolite gneiss, Moland (016104) × 38.

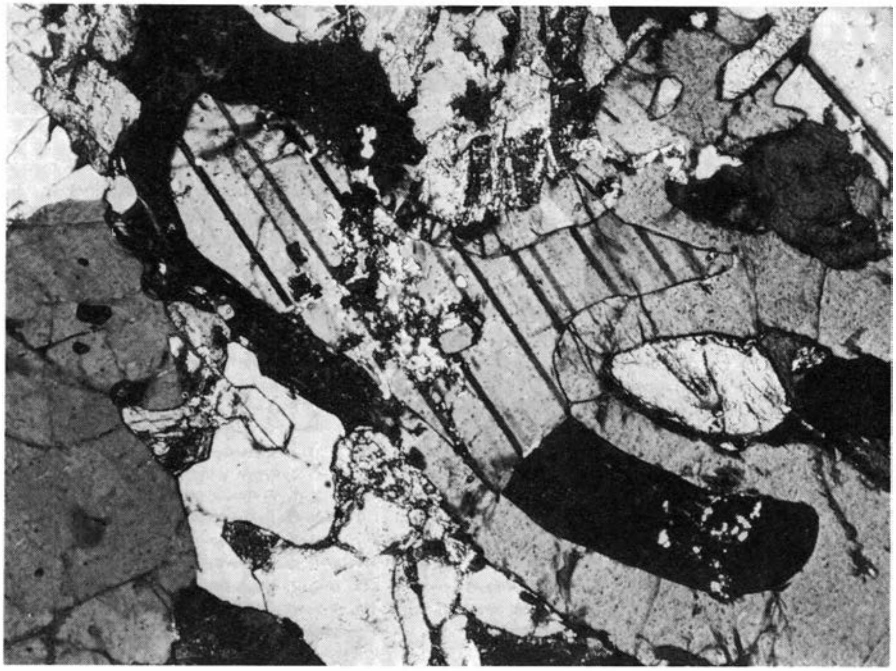

Fig. 5. The same as Fig. 4 in polarised light, × 38.

a corona growth (Figs. 4, 5), when recrystallisation of actinolite to anthophyllite has reached an advanced stage.

Phlogopite is both primary and secondary in the orthoamphibole-bearing rocks. Its form varies from lepidoblastic plates to equidimensional secondary prisms or fine-grained alteration in cracks.

Orthopyroxene normally forms large xenoblastic poikiloblasts which may in part be aggregates of optically aligned grains. Inclusions are abundant and can total up to 80 % of the orthopyroxene grains. At one locality the orthopyroxene is aligned in a foliation at an angle to a later, coarse-grained, orthoamphibole growth. The orthopyroxene forms an apparently stable assemblage with cordierite in this layer (981112).

Garnet occurs as large poikiloblasts in segregations with quartz parallel to the foliation, with other ferromagnesian minerals appearing in equilibrium. There is a slight alteration of garnet to a fine-grained, white mica.

Rutile is the commonest accessory mineral and is normally evenly distributed throughout the rock. Starmer (1967) attributes this to the lack of a mineral phase that can accommodate TiO_2 in its structure. The generally low Fe/Mg ratio of the whole rock normally restricts the development of ilmenite or ilmenomagnetite.

Table 1. Orthoamphibole-bearing rocks from the Søndeled-Tvedestrand area, summary statistics ($n = 32$). Oxides in percent, trace elements in ppm.

	Median	Mean	Standard deviation	Relative skew	Maximum	Minimum
SiO_2	55.10	55.24	7.9	0.78	80.26	40.73
Al_2O_3	14.67	14.36	3.1	−0.50	19.82	5.54
TiO_2	1.28	1.45	0.8	0.91	3.53	0.10
Fe_2O_3	1.32	1.83	1.7	3.13	9.67	0.20
FeO	4.27	5.15	2.9	0.42	11.02	0.78
MgO	15.08	15.31	4.8	−0.68	22.28	3.48
CaO	1.07	2.31	2.7	1.95	11.01	0.06
Na_2O	0.63	1.02	1.0	1.92	3.70	0.29
K_2O	0.50	0.86	0.9	1.37	3.39	0.02
MnO	0.03	0.06	0.0	1.09	0.17	0.01
P_2O_5	0.20	0.22	0.1	0.27	0.47	0.01
H_2O	1.59	2.00	1.8	3.03	9.72	0.62
S	101	146	111	1.98	484	59
Cl	137	176	146	1.70	617	29
Sc	24	26	14	1.70	72	2
V	163	228	203	2.09	1037	9
Cr	59	73	51	1.91	258	8
Co	27	27	13	0.10	51	3+
Ni	58	67	48	0.66	173	0+
Cu	17	22	16	2.40	81	9
Zn	33	66	85	3.19	427	20
Ga	22	23	4.9	0.06	32	12
Rb	19	35	38	1.32	140	0+
Sr	17	34	41	1.86	153	5
Y	30	39	20	0.88	92	3
Zr	203	198	64	−0.01	341	89
Ba	121	185	148	2.42	786	62
La	5	18	50	5.01	286	0+
Ce	41	65	104	4.92	620	12
Pr	17	21	17	1.94	88	0+
Nd	15	21	27	4.55	159	3+
Sm	9	9	6.1	1.84	34	0+

\+ indicates values below the detection limit.

Geochemistry

32 orthoamphibole-bearing rocks have been analysed for 12 major and 20 trace elements. The summary statistics of this data are given here (Table 1), with a survey of the important aspects of the geochemistry, in particular the element associations. These associations are selected by correlation, cluster analysis, and factor analysis, and are representative of the population as a whole and not individual sub-groups. Only the associations of direct significance to the form and origin of these rocks are described here. The wide variation of form recognised in the field relations of this lithology is reflected in the extended ranges of element concentration given in Table 1. Hence, as with the petrography, the description below applies to the population as a whole.

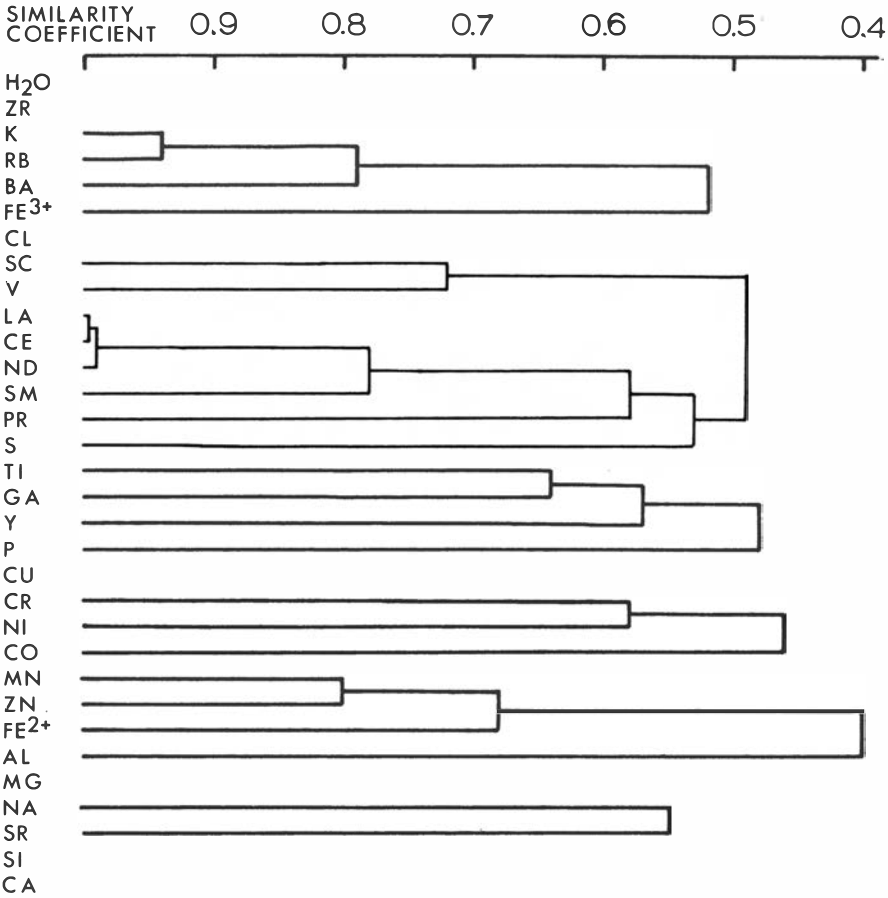

Fig. 6. Cluster analysis of orthoamphibole-bearing rocks from the Søndeled-Tvedestrand area (R-mode dendrogram). Clustering terminated at the 95 % confidence limit.

The description of the geachemistry below is based on the R-mode cluster analysis (Fig. 6). Explanations of the statistical techniques used here are to be found in Krumbein & Graybill (1965).

The range of silica values in the orthoamphibole-bearing rocks, with 90 % falling in the range 45–67 % SiO_2, is sufficient to give strong negative correlations with many granitophobe elements, particularly Mg, Co, and Ni. This represents the overall acid-basic whole rock variation within the samples and not necessarily an inverse relationship with silica.

Potassium, Rubidium, Barium, Ferric Iron and Chlorine. – These elements are correlated and clustered together. Mica is the only K-enriched phase in the orthoamphibole-bearing rocks, and consequently all elements of this association are considered to be largely partitioned in that mineral.

Scandium and Vanadium. – Sc and V are closely correlated and thought to occur in similar phase. No substitution is envisaged as physical dissimilarities

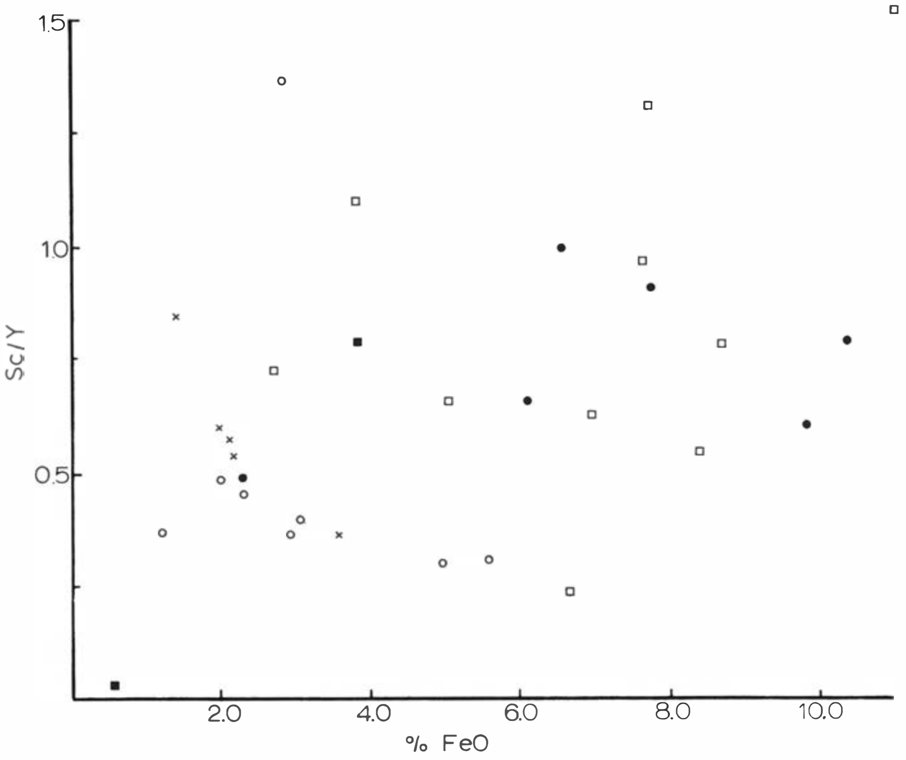

Fig. 7. Variation diagram of ferrous iron versus the ratio Sc/Y for cordierite-anthophyllite rocks (open circles), gedridites (open squares), quartz-orthoamphibole gneiss (solid squares), orthopyroxene-bearing rocks (solid circles), and actinolite gneisses (crosses).

are large. Sc is also correlated with Y, and the Sc/Y ratio, normally a useful fractionation index, separates the individual samples into three fields when plotted against FeO: one actinolite gneiss/cordierite-anthophyllite rock field, and two orthopyroxene-bearing rock/gedridite fields (Fig. 7).

Titanium, Phisphorous, Gallium and Yttrium. – These elements are significantly correlated and clustered. Ti is restricted to rutile in this lithology. The sympathetic variation indicates that the element concentrations are related, and the excess of each not accommodated in the essential minerals of this rock type is now seen as rutile and apatite. Y may substitute for Ca in apatite (Vlassov 1966).

Chromium, Cobalt and Nickel. – These elements are closely correlated individually, and Ni is the only element to have significant correlation with Mg. However, the ratios of Mg/Ni and Mg/Cr are respectively 3x and 9x as large as in other rock-type of this area, illustrating the extreme Mg enrichment. This contrasts with the abundances of Cr, Co and Ni which are similar to other rocks of this silica content.

Ferrous Iron, Manganese and Zinc. – This association occurs in all lithologies examined in the region to date. In only one locality does FeO exceed MgO in absolute abundance in the orthoamphibole-bearing rocks.

Aluminium. – The absolute abundance of Al is comparable with other lithologies of similar silica content in the Søndeled-Tvedestrand area, although cordierite is an essential phase. This contrasts with similar rocks in Colorado (Gable & Sims 1969), which have higher values of alumina (mean 17.52 %, cf. Table 1).

Magnesium. – Mg geochemistry in the orthoamphibole-bearing rocks is characterised by its high concentration and the absence of corresponding concentrations in any trace element. The latter indicates that the present abundance of Mg is not related to a primary, igneous origin.

Sodium and Strontium. – Both Na and Sr are depleted in the orthoamphibole-bearing rocks (Table 1). Na substitutes for Al in orthoamphibole (Beeson 1972), but is not related to that element in other minerals. Both elements are situated in plagioclase when this is present.

Calcium. – Ca, like Na, is depleted, and is only abundant in the actinolite gneisses.

The origins of the orthoamphibole-bearing rocks

The differing nature and location of the orthoamphibole-bearing rocks both in the Bamble Sector and elsewhere indicate that a polyphyletic origin is probable, and each locality must be considered individually.

In spite of the varied composition noted in metasedimentary rocks from the area (Beeson 1975), no lithologies with a chemistry comparable with the orthoamphibole-bearing rocks occur in recent sediments (e.g. Wedepohl 1969). Hence any origin proposed must involve the subsequent alteration of an original lithology.

Field, petrographic, and geochemical evidence suggests that the orthoamphibole-bearing rocks have formed at two separate periods in the Søndeled-Tvedestrand area. In addition a separate process of formation has taken place in each period.

Metamorphic segregation. – Stable orthoamphibole occurs in quartz-orthoamphibole gneisses in which both CaO and Na_2O exceed 3.0 % and where hornblende would be normally expected to form. (Ca, Na) and (Mg, Fe^{2+}) have partitioned into quartz-plagioclase and orthoamphibole-mica layers respectively at the main phase of metamorphism. Although these small scale segregations rarely exceed 3 cm in width at this locality (993042), they

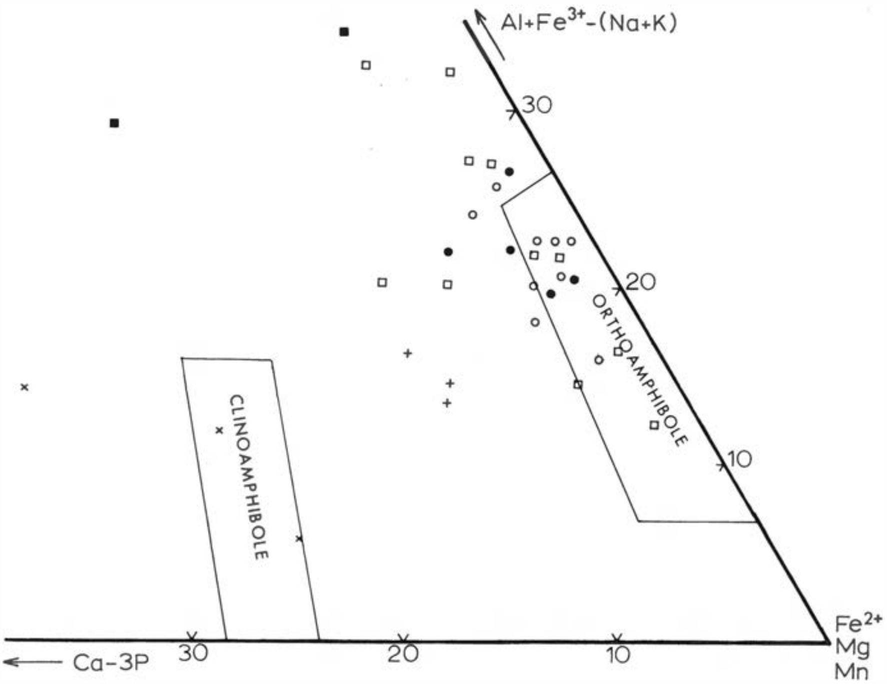

Fig. 8. ACF diagram of orthoamphibole-bearing rocks from the Søndeled-Tvedestrand area. Symbols as for Fig. 3, excepting actinolite gneisses which are divided into orthoamphibole-bearing (vertical crosses) and orthoamphibole-free (inclined crosses).

may be able to occur on a larger scale, particularly in metasedimentary gneisses deficient in Ca and Na. As no elements are added or removed from the system, the abundance of trace elements will not exceed that of adjacent amphibolites. The cause of the segregation cannot be determined, whether it be the result of a form of metasomatism (Orville 1969), local metamorphic gradients (Dietrich 1963, Sørbye 1964), or other means. The occurrence of segregation of both small and large scales is indicative that this hypothesis may have a widespread application.

Formation of cordierite-anthophyllite rocks. – Actinolite, a mineral normally restricted to the lower metamorphic facies, is locally preserved in lithologies of unusual chemistry in the Bamble Sector. Its retention is controlled by the lack of sufficient Na to permit the formation of hornblende, and/or the instability of Mg-hornblende in this metamorphic environment where the MgO/FeO ratio is extremely high (approximately 6.0 in the actinolite gneisses). Anthophyllite alone of Mg-amphiboles is Na-deficient, and hence is presumed to replace actinolite if the local P/T or geochemical conditions make the latter unstable after the main phase of the Sveconorwegian regeneration. Tracing this process on the ACF diagram (Fig. 8), the actinolite gneisses on the actinolite-plagioclase tie-line will move directly away from the Ca end member to the position of the orthoamphibole-bearing actinolite gneisses. This can be observed petrographically in the growth of anthophyllite at the expense of actinolite, and the subsequent formation of cordierite from bytownite as further Ca is removed. It is presumed that Ca is removed in solution into the surrounding actinolite gneisses. Neither Mg nor Fe^{2+} is added in this process, as the values of Niggli Mg are identical in both the cordierite-anthophyllite rocks from the area of the actinolite gneisses and the gneisses themselves.

Other hypotheses. – Previous workers in the Bamble Sector have attributed the formation of orthoamphibole-bearing rocks to a form of Mg-metasomatism, with the introduction of Mg from the amphibolitisation of olivine-rich gabbros, or the leaching of Mg in the migmatisation of gabbros and amphibolites (Starmer 1969, Bugge 1943). This theory cannot have widespread application in this area as there is little spatial relationship with amphibolites and gabbros, there is no change in Mg concentration during the amphibolitisation of gabbros (Field 1969, Elliott 1972), and there is no evidence of dilution of element concentrations with increasing Mg.

The incongruent melting of acid gneisses has been put forward as the origin of similar rocks in Ontario (Lal & Moorhouse 1969). It has a sound basis in terms of phase equilibria (Grant 1968), from which it can be demonstrated that the removal of a partial melt from a wide range of acid parent

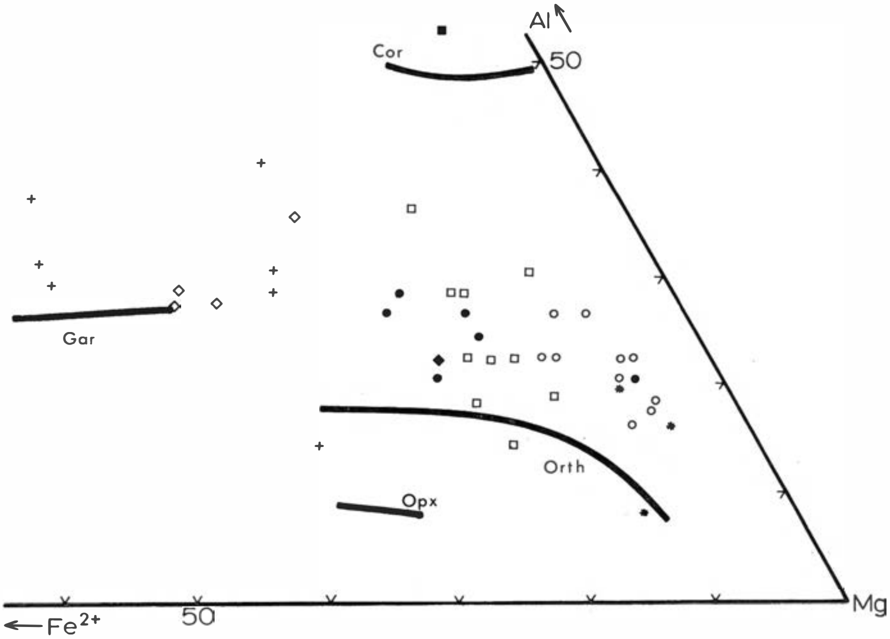

Fig. 9. AFM diagram of orthoamphibole-bearing rocks from differing geologic terrains. Symbols as for Fig. 3, plus garnet-bearing rocks (Gable & Sims 1969, diamonds), rocks of thermal metamorphism (crosses), and actinolite gneisses (asterisks).

lithologies, e.g. Ca-deficient sillimanite gneisses, would give a Mg-enriched residuum. The chemical investigation discards this hypothesis as the elements enriched by the removal of partial melts – Al, Ti, Fe, Mg, V, Cr, Co, Ni and Ga (Evans 1964) – do not, excepting Mg, have this characteristic in the orthoamphibole-bearing rocks.

The thermal or low grade regional metamorphism of previously altered lithologies can give orthoamphibole-bearing rocks, e.g. Vallence (1967), Tilley & Flett (1930). However, the stability of almandine garnet at the Amphibolite facies grade of metamorphism markedly reduces the field of orthoamphibole stability. All examples given of the lower grade assemblages will have either co-existing almandine and orthoamphibole or only the former at higher grades of metamorphism (Fig. 9).

Conclusions

The classical interpretation of the orthoamphibole-bearing rocks of the Bamble Sector as the products of Mg-metasomatism may be applicable in a limited number of instances in the Søndeled-Tvedestrand area. However, the majority of these rocks are considered to result either from the segregation of mafic elements or from the metamorphism of originally Mg-, Ca-rich, Na-deficient lithologies at the Amphibolite or Hornblende Granulite facies.

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