The geochemistry of meta-igneous rocks from the amphibolite facies terrain of south Norway

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The field relations, petrography, and geochemistry of a suite of amphibolite facies metamorphic rocks from the Bamble Sector of the Fennoscandian Shield in south Norway are described and discussed. Field and geochemical parameters suggest an igneous origin for the suite, in particular the mineralogical and chemical continuum from acid to basic members, element associations and trends, and the abundance of major constituents. The Na and K contents are consistent with calc-alkaline igneous suites.

Element diffusion trends typical of high-grade metamorphism, particularly those involving K and related elements, contrast with those observed in the meta-igneous rocks, and the metamorphism is considered to be largely isochemical. Therefore the pre-metamorphic chemical characteristics of the area, e.g. high Th concentrations, can be used to assess the metamorphic processes which have affected adjacent granulite and granitic terrains.

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The Songe-Ubergsmoen area of south Norway is in the Bamble Sector of the Fennoscandian Shield. Songe is 250 km south of Oslo, and 40 km north of Arendal (Fig. 1).

The Bamble Sector in the Arendal region consists of high-grade metamorphic rocks of upper amphibolite and granulite facies (Bugge 1943, Touret 1968). The Songe-Ubergsmoen area lies in the upper amphibolite facies terrain. The grade of metamorphism increases southward towards Arendal, where the granulite facies rocks are located (Cooper 1971, Andreae 1974).

The geological history proposed by Starmer (1972) can be applied in general to the Songe-Ubergsmoen area. The main metamorphic episode seen today is the Svenconorwegian orogeny (D3 of Starmer 1972) at an approximate age of 1160–1200 m.y. (O'Nions & Baadsgaard 1971). This was followed by a major period of granitisation, which had a profound effect on the gneisses around Tvedestrand, immediately to the south of the area under discussion (Field 1969).

The Songe-Ubergsmoen has been mapped by the author at a scale of 1:15,000. Four major lithological units occur in the area: metasedimentary gneisses, typified by the presence of sillimanite and graphite (Beeson 1975); the meta-igneous rocks described here; granitic and granodioritic gneisses (Starmer 1969a); and basic rocks of three recognisable ages and varying metamorphism (Starmer 1969b, Elliott 1973). The spatial distribution of these lithologies has been previously described (Beeson 1975).

The meta-igneous rocks and to a lesser extent the metasedimentary gneisses of the Songe-Ubergsmoen area offer an excellent opportunity to study lithologies which have not been extensively affected by the movement of elements during granitisation or K-feldspathisation processes prevalent in adjacent areas. These processes have occured in the area, but detailed mapping has shown that the meta-igneous rocks are only partially affected. This has enabled the sampling of a suite of rocks which offers an indication of the primary nature of the pre-metamorphic lithologies, and the processes active in high-grade metamorphism.

The field relations, petrography and geochemistry of the meta-igneous rocks are discussed, and compared with both metamorphic and igneous rocks suites from elsewhere in the world with which they show affinities.

Field relations

The meta-igneous rocks consist typically of quartz, plagioclase, biotite, and hornblende. The hornblende is normally restricted to the in-

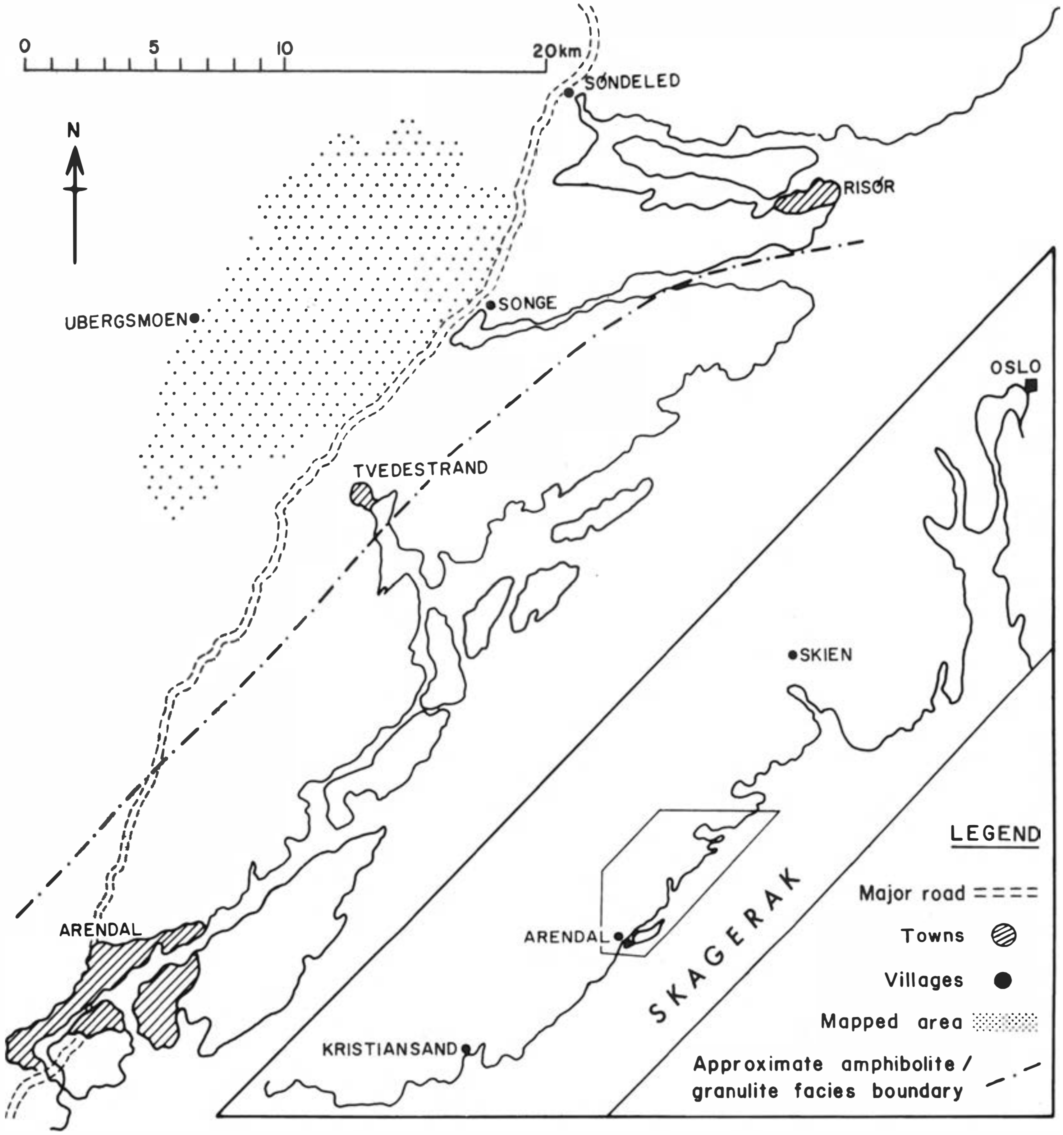

Fig. 1. Location map of the Songe-Ubergsmoen area, south Norway.

termediate and basic varieties of the rock suite. Garnet, when present, is red in colour. K-feldspar is rare in the meta-igneous rocks, but when present the field and petrographic evidence indicates that this mineral replaces plagioclase. This mineralogy contrasts with that of the metasedimentary gneisses in the area, and allows distinction between the two rock groups in the field. The metasedimentary gneisses commonly have sillimanite and graphite in the more acid varieties, and a pale pink garnet in relatively iron-rich varieties. Only rocks with a mineralogy of biotite-quartz-plagioclase are common to both the meta-igneous and metasedimentary lithologies.

The rock suite normally has a well-developed gneissic texture, but it is locally massive. It varies from leucocratic quartz-plagioclase gneisses with minor contents of biotite to amphibolites consisting of only plagioclase and hornblende. Banding of leucocratic and melanocratic layers occurs, commonly with a pre-

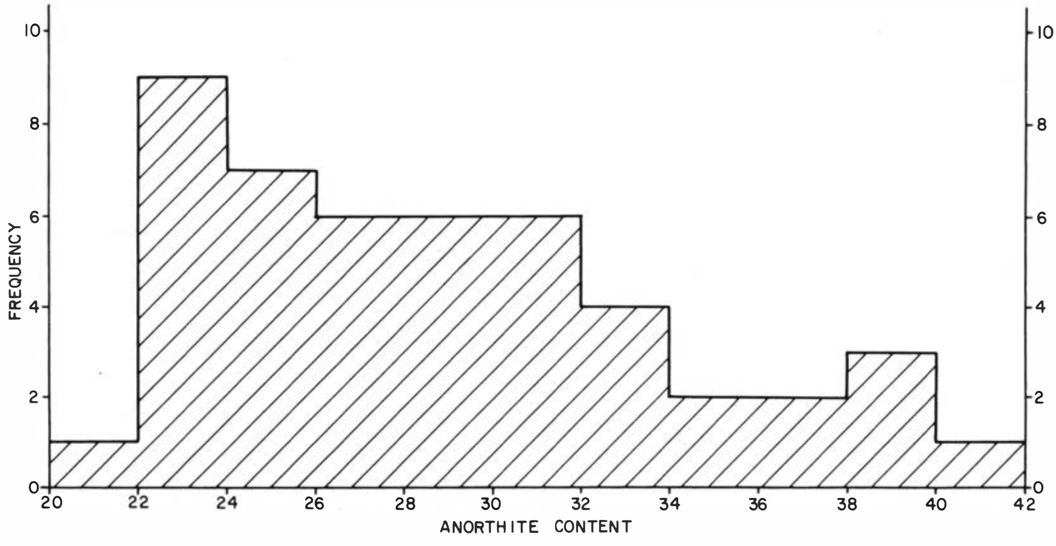

Fig. 2. Frequency distribution of the anorthite content of plagioclase in the meta-igneous rocks.

dominance of the former. The individual layers vary from 1 centimetre to several metres in width. The amphibolite horizons within the quartz-plagioclase-biotite gneisses (± hornblende) can be much wider than these banded gneisses, being tens or hundreds of metres in width. These amphibolite horizons can extend for more than a kilometre along strike.

Metasedimentary gneisses rarely occur as thin intercalations within the meta-igneous rocks, but are commonly at least 50 m in width. However, the reverse is not true, and thin intercalations of the meta-igneous rocks are not found in the metasedimentary gneisses. Units of the meta-igneous rocks can be extremely persistent, one 500 m wide unit continuing for 15 km throughout the area.

Petrography

The petrographic description tendered here is a generalised summary of the features of the meta-igneous rocks as a whole.

Two main varieties of quartz (3–59%) are present. The first occurs as sub-rounded grains (0.1–5 mm) with a non- or partially-undulose extinction and curved or lobate margins. The second variety has an irregular shape, frequently displays sutured margins, and undulose extinction. The latter may occasionally contain trains of inclusions parallel to the foliation. These are considered to have formed during two metamorphic stages, i.e. syn- and post- the main metamorphic episode (Beeson 1975).

Plagioclase (2–82 %) is normally present as equidimensional grains (≤3 mm), although slightly elongate, coarser varieties (≤7 mm) are present. The grain shape can be rounded, angular or irregular. Plagioclase composition shows a continuous increase in Ab content with silica in this rock type (Fig. 2). The plagioclase is occasionally antiperthitic. In such cases the antiperthitic types are patch, flame and rod forms.

Biotite (0–69 %) is predominantly pleochroic pale to dark brown (X, Y) or brown (Z), although pale phlogopitic micas and iron-rich medium-brown to black varieties are represented. Primary mica varies from stubby, shortened grains to thin, platelike crystals (0.5–4 mm). Mica defines the foliation plane, particularly when abundant, but the foliation can be distorted by either the growth of garnet or quartz veinlets. Biotite commonly replaces hornblende, both in the presence and absence of K-feldspar. Two replacement forms are recognised: distinct stubby or elongate laths cutting across the hornblende grains, or a felted mosaic of fine-grained mica. The biotite also replaces garnet and rarely epidote. Minerals occuring as inclusions in the biotite are zircon, apatite, and opaque minerals. The biotite alters to chlorite and prehnite.

The hornblende (0–33 %) is exclusively green in colour, commonly with X, Y pleochroic pale

Table 1. Meta-igneous rocks, Songe-Ubergsmoen area: summary statistics. Major elements in oxide percentages, trace elements in ppm (n = 50)

Element	Mean	Standard deviation	Maximum	Minimum	Crustal average
SiO_2	66.12	7.87	78.19	47.62	60.3
Al_2O_3	14.63	2.15	21.32	10.51	15.6
TiO_2	0.73	0.44	2.13	0.17	1.0
Fe_2O_3	2.50	2.02	8.20	0.29	7.2
FeO	2.67	1.85	8.97	0.43	
MgO	2.40	2.47	13.14	0.14	3.9
CaO	3.99	1.85	8.17	0.21	5.8
Na_2O	3.72	1.50	8.46	0.30	3.2
K_2O	1.83	1.19	5.62	0.14	2.5
MnO	0.07	0.07	0.20	0.01	0.10
P_2O_5	0.17	0.12	0.52	0.02	0.11
S	292	458	3011	7	260
Cl	358	318	1302	25	130
Sc	14	9	45	2	22
V	127	85	523	13	135
Cr	27	35	149	0*	100
Co	20	12	53	0*	25
Ni	17	23	86	0*	75
Cu	25	30	198	1	55
Zn	76	47	216	6	70
Ga	21	4	34	12	15
Rb	65	45	215	0*	90
Sr	254	138	587	13	375
Y	35	38	188	0*	33
Zr	294	197	1754	70	165
Sn	1	4	23	0*	2
Ba	860	335	1886	276	425
La	29	24	100	1	30
Ce	88	53	261	24	60
Pr	21	11	45	1*	8
Nd	26	15	74	7	28
Sm	11	6	28	3*	6
Pb	14	10	52	3*	13
Th	9	9	35	0*	10
U	1	1	4	0*	3

(1) From Taylor (1964)
* indicates value below the direction limit

green to medium green-brown or emerald green and Z pale to dark green-brown. Grain size is variable, and increases proportionally with the hornblende content of the rock. Commonly the hornblende is xenoblastic or elongate xenoblastic, although it is also often prismatic. Quartz, plagioclase, apatite and opaque minerals occur as inclusions in the hornblende.

The garnet (0–15%) is present as large poikiloblastic grains (≤15 mm) which are irregular, angular, rounded or elongate in shape. Included minerals are quartz, opaques, apatite, and altered plagioclase. Elongate grains commonly form in bands parallel to the foliation or rarely as individual grains cutting across the foliation.

Other minerals occurring in the meta-igneous rocks are K-feldspar, cordierite, and epidote. Accessory minerals present include opaque minerals (magnetite and pyrite), zircon, and apatite.

Geochemistry

50 samples of the meta-igneous rocks have been analysed for 11 major and 24 trace elements. Sample collection was based on 2 principles. To establish a representative collection of the rock group, samples were taken at 100 m intervals along road traverses perpendicular to the strike of the foliation. In addition samples were collected in all parts of the mapped area to establish the regional variation.

Only the summary statistics of the data are presented here (Table 1). The individual analyses , Niggli values, cation percentages, modal analyses and katanorms have been presented elsewhere (Beeson 1972).

The majority of elements in this lithology are typified by a lognormal distribution with a positive skew (Table 1). Only SiO_2, Al_2O_3, and Ga have normal distributions. The distributions of CaO, Na_2O, Zr, and Th are irregular, which may indicate the presence of sub-populations.

Only limited data are available for amphibolite grade metamorphic rocks from other areas but there are similarities in chemistry between the meta-igneous rocks from the Songe-Ubergsmoen area and elsewhere. The major-element composition of the meta-igneous rocks can be compared with the sub-acid and intermediate rocks from Brazil (Sighinolfi 1971), and with amphibolite facies rocks from northern Norway (Heier & Thoresen 1971). However, trace-element compositions, particularly the elements associated with K, are less related to other areas.

Cluster analysis is used in this study to summarise element associations. Cluster analysis is based on all inter-element correlations, and hence identifies groups of related elements. The degree of correlation between the groups can also be identified. The results of the clustering are shown as a dendrogram, which is a simplification of the multi-dimensional correlations in two dimensional form (Fig. 3). This gives the following associations: Mg, V, Co, Cr and Ni; Fe, Ti, Mn, Sc, P and Zn; K, Rb and Ba; Zr, Y,

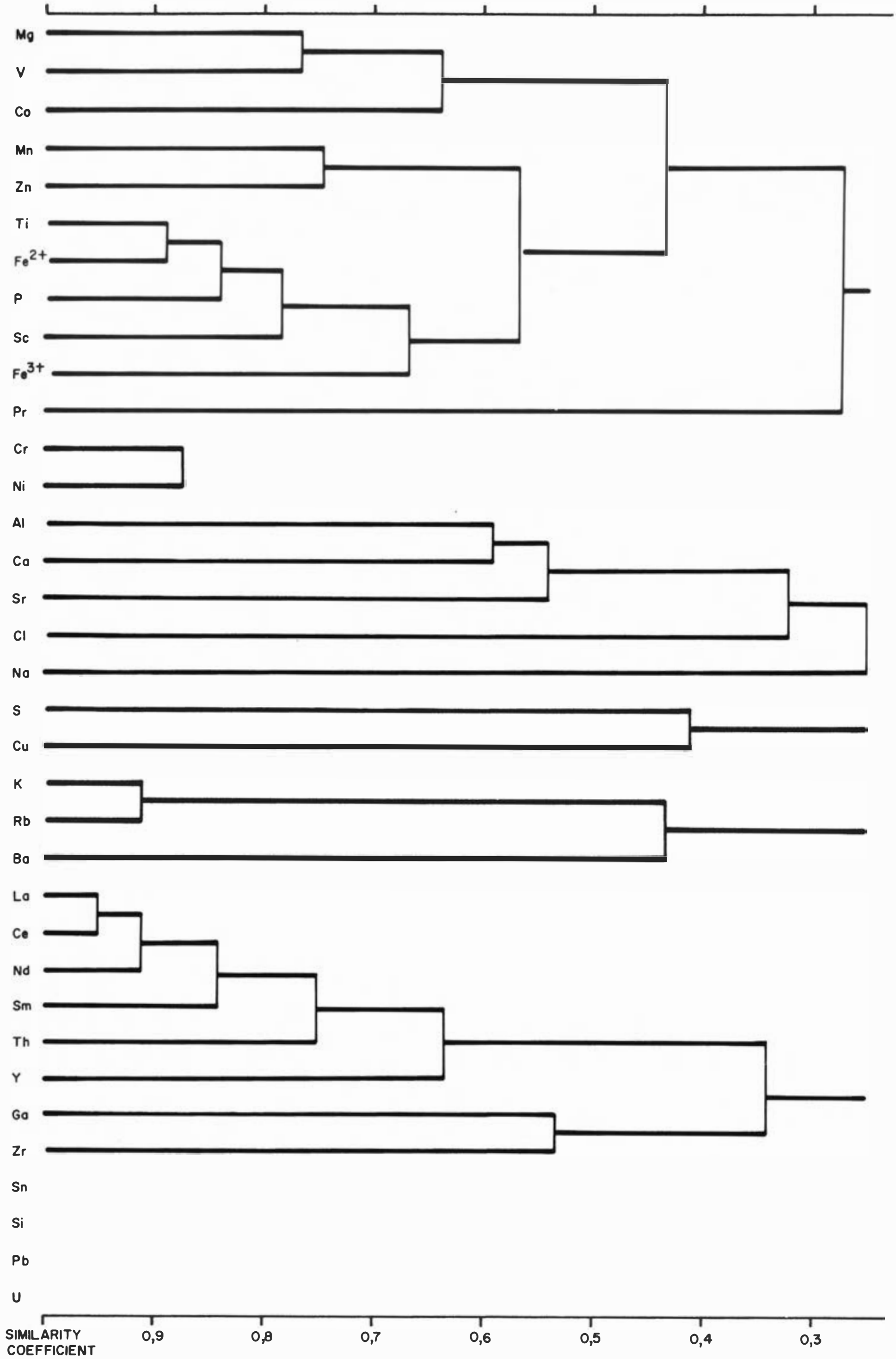

Fig. 3. The R-mode dendrogram for the cluster analysis of elements in the meta-igneous rocks. Clustering terminated at the 95% confidence level (0.25).

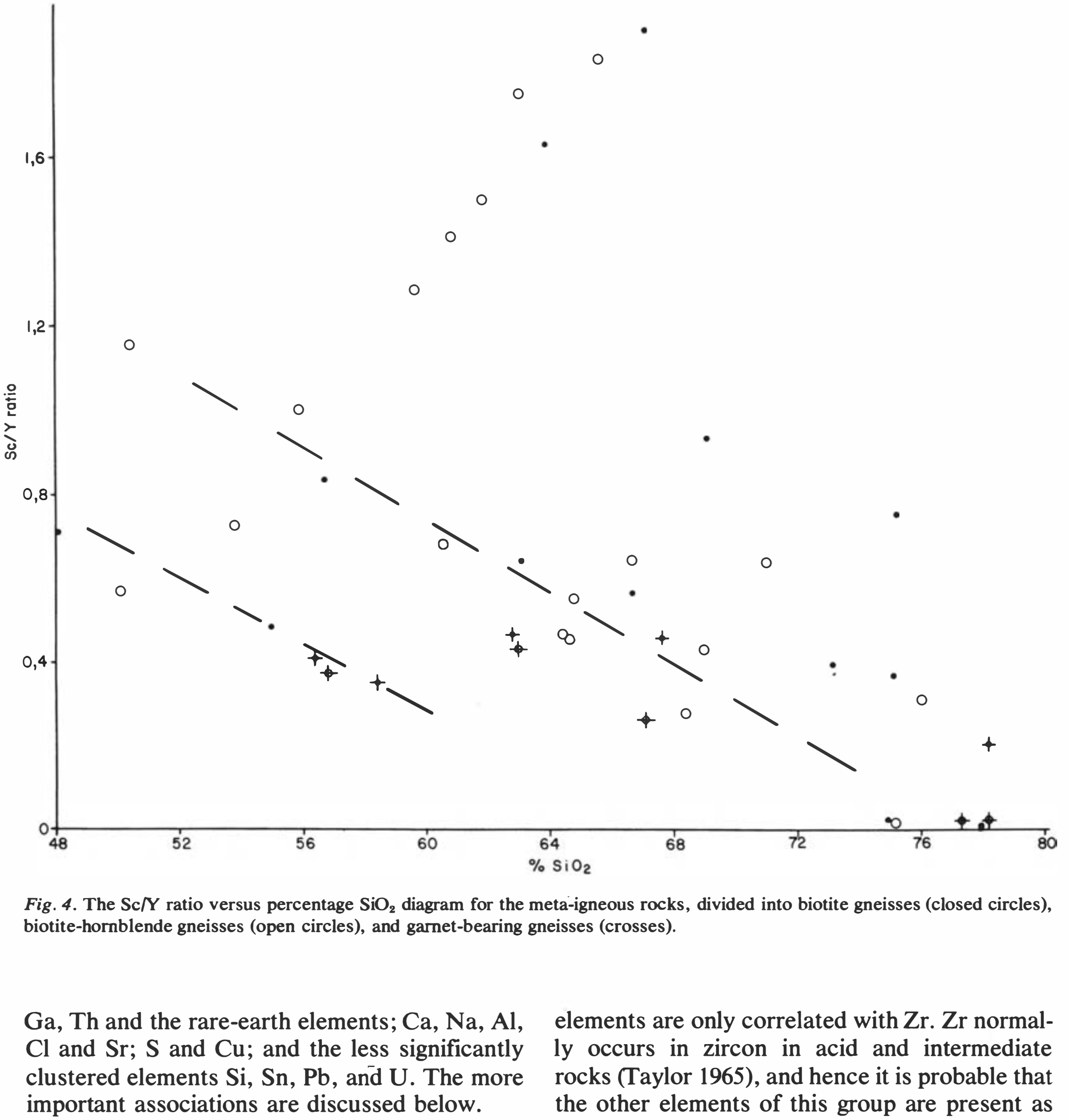

Fig. 4. The Sc/Y ratio versus percentage SiO_2 diagram for the meta-igneous rocks, divided into biotite gneisses (closed circles), biotite-hornblende gneisses (open circles), and garnet-bearing gneisses (crosses).

Ga, Th and the rare-earth elements; Ca, Na, Al, Cl and Sr; S and Cu; and the less significantly clustered elements Si, Sn, Pb, and U. The more important associations are discussed below.

Silicon has a wide range of values (47–78 %); this gives it strong negative correlations with the 15 elements which are most abundant in basic rocks because of the closed percentage system.

Zirconium group (Zr, Y, Th, and the rare-earth elements): Zr is clustered with Y, Th and the rare-earth elements in both the metasedimentary and meta-igneous rocks of the Songe-Ubergsmoen area, but a correlation with Na in the former lithology suggests that at least a proportion of these elements is located in plagioclase (Beeson 1975). In the meta-igneous rocks the elements are only correlated with Zr. Zr normally occurs in zircon in acid and intermediate rocks (Taylor 1965), and hence it is probable that the other elements of this group are present as isomorphous inclusions in the zircon structure in the meta-igneous rocks (Vlassov 1966).

All elements of this association excepting Y are positively correlated with Si, although only La, Ce, Sm, and Th are correlated at the 99 % confidence level. Y decreases with Niggli Si, and hence has positive correlations with both the mafic elements and Zr. A strong, positive correlation between Zr and Ga exists, particularly at high concentrations of both elements, but this correlation cannot be explained.

Taylor (1965) suggests that the Sc/Y ratio is a guide to igneous fractionation. The Sc/Y ratio shows two individual and distinct decreasing trends with increasing SiO_2 (Fig. 4), excepting seven high values of the ratio. This suggests that this lithology has an igneous origin.

Fig. 4 also indicates that garnet only occurs in rocks with a Sc/Y ratio of less than 0.5. As Sc is strongly correlated with Fe^{2+} in these rocks, the high Sc/Y ratios would normally be expected in garnet-bearing rocks.

Potassium group (K, Rb and Ba): K-feldspar constitutes over 1 % of the mode in only 20 % of the meta-igneous rocks, and hence K and Rb are normally located in biotite. In K-feldspar-bearing rocks the K content is markedly increased. When present, K-feldspar replaces plagioclase in this lithology, and consequently both K and Rb show a negative correlation with Ca and Na. The negative correlation between the latter two elements and Ba is less pronounced than that of K and Rb, and hence it is considered that at least part of the Ba abundance is present in the plagioclase.

The mean K/Rb ratio (292) is higher in the meta-igneous rocks than crustal average estimates (e.g. Taylor 1965, table II). However, it has a wide range of values (138–1200), and the relatively high mean is caused by the high ratios in rocks deficient in K and Rb, where the mean is 739 for rocks with less than 0.5 % K. The median value for the meta-igneous rocks is consequently lower (238).

Comparative data in the Bamble Sector are currently only available for metabasites from the area of the granulite facies transition south of the Songe-Ubergsmoen area (Field & Clough 1976), and the charnockitic gneisses from the granulite facies (Cooper & Field 1977). Although a similar mean K/Rb ratio is obtained for the metabasites from amphibolite facies samples (378), both the granulite facies metabasites (mean 567) and particularly the charnockitic gneisses (mean 1323) show the Rb depletion typical of many high grade metamorphic terrains (e.g. Sighinolfi 1969, 1971). Consequently the linear trend exhibited by the metabasites and the field of the charnockitic gneisses are both on the K-rich side of the regression lines calculated by Shaw (1968) for igneous rock suites, and have an atypical orientation (Fig. 5). In contrast the field of the meta-igneous rocks falls well within that of examples given by Shaw, and have similar K/Rb ratios to several unmetamorphosed rock suites, e.g. the hornblende dacites from the western USA and the andesites and dacites from the

Table 2. Mean K/Rb and K/Ba ratios for the meta-igneous rocks and metamorphic rocks from elsewhere in the world.

	1	2	3	4	5	6	7	8	9	10
K/Rb	292	378	1330	240	217	258	688	232	297	539
K/Ba	19	18	20	40	28	48	13	–	–	–

1. Meta-igneous rocks, Songe-Ubergsmoen area.
2. Amphibolites, Sogne-Ubergsmoen area.
3. Charnockitic gneisses (Cooper & Field 1977).
4. Granitic gneisses, Arendal area (Cooper 1971).
5. Sub-acid gneisses, Musgrave Range, Australia (Lambert & Heier 1968).
6. Acid gneisses, Musgrave Range, Australia (Lambert & Heier 1968).
7. Basic rocks, Musgrave Range, Australia (Lambert & Heier 1968).
8. Crustal average (Taylor 1964).
9, 10. Amphibolite facies rocks, northern Norway (Heier & Thoresen 1971).

Solomon Islands (Jakes & White 1970). The meta-igneous trend is also not markedly divergent from the Lewis & Spooner (1973) granulite trend, although Field & Clough (1976) indicate that this is for a composite sample and not necessarily typical of observed individual trends. Six meta-igneous rocks with below 15 ppm Rb do not conform to the regular trend of the remainder of the rock suite. These samples are deficient in K-bearing minerals, having no K-feldspar and biotite being absent or less than 1 % of the mode.

Although K/Ba ratios in the meta-igneous rocks are similar to those recorded in the amphibolite facies terrains of Australia (Lambert & Heier 1968, table II), and the adjacent granulite facies rocks (Cooper & Field 1977), the Ba values (mean 860 ppm) are considerably higher than the estimates for the average of the continental crust (e.g. Taylor 1965, 425 ppm).

Comparison of the K, Th and U concentrations of the meta-igneous rocks with a range of rock types from elsewhere in the world indicates that Th is relatively enriched (Table 3). This results in high values of the Th/U and Th/K ratios in comparison with granitic rocks (Heier & Rojers 1963). Granitic rocks from the Songe-Ubergsmoen area are similar in respect of these elements to those reported by Killeen & Heier (1974) for gneisses from elsewhere in the Bamble Sector.

The sodium group (Na, Ca, Sr, Al and Cl): the elements of this association are variably located

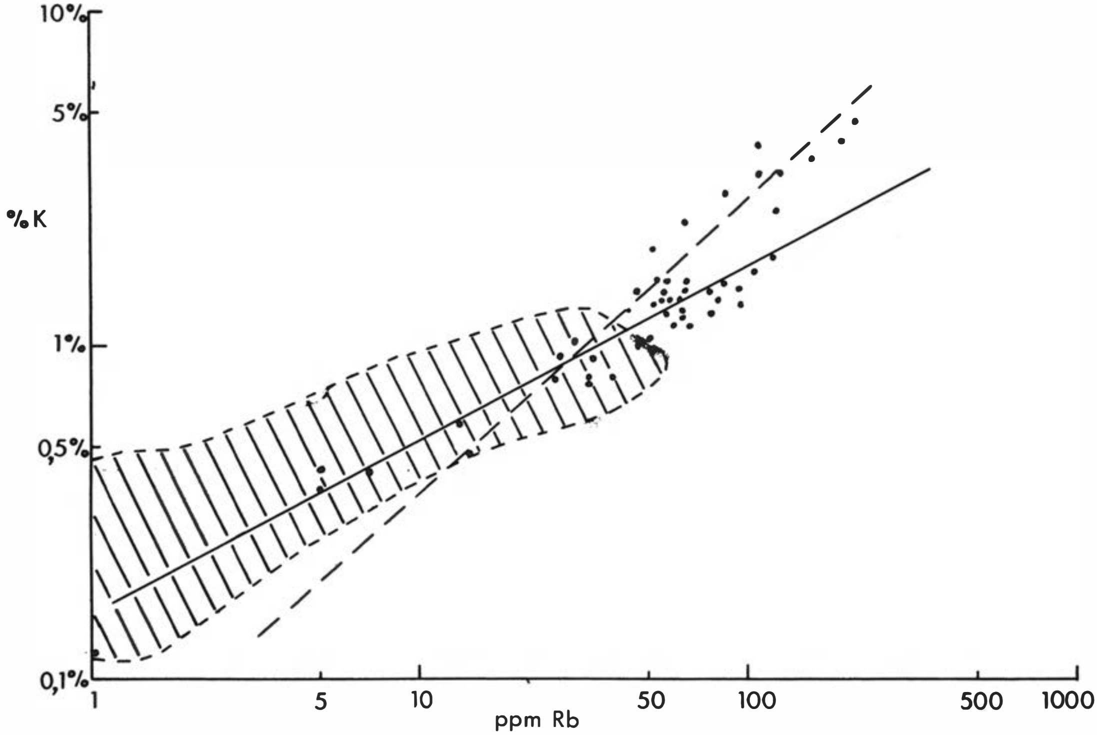

Fig. 5. K versus Rb for the meta-igneous rocks. The dashed line represents the ratio calculated by Lewis & Spooner (1973) for granulites, the continuous line the regression calculated for metabasites (Field & Clough 1976), and the hatched area is the upper part of the charnockitic gneiss field (Cooper & Field 1977).

in plagioclase and hornblende in the meta-igneous rocks. The Na is largely restricted to the former, and it displays a reasonable correlation with the plagioclase content (Fig. 6). The relatively limited range of anorthite contents of the plagioclase (Fig. 2) is not sufficient to disturb this relationship markedly. Ca is contained

Table 3. Mean values ofTh, U, K and ratios for metamorphic and granitic rocks.

	1	2	3	4	5
Th	9	21	20	10	17
U	1	3	5	2	5
K	1.52	3.17	3.09	2.58	3.79
Th/U	5.86	9.05	5.2		3.5
Th/k (E4)	6.06	8.55	6.7		3.9
U/K (E4)	1.00	1.45	1.5	0.95	1.2

1. Meta-igneous rocks, this study
2. Granitic gneisses, this study.
3. Levang gneisses, Killeen & Heier (1974).
4. Canadian Shield, Shaw et al. (1967).
5. Granitic rocks, Heier & Rogers (1963).

within both hornblende and plagioclase. The latter normally constitutes 30–65 % of the mode of these rocks, and no systematic variation between Ca and modal abundance was observed (Fig. 7a). However, it is evident that Ca concentrations above 3 % are directly related to the abundance of modal hornblende (Fig. 7b). Only two samples which contain less than 3 % Ca also contain hornblende. At the higher abundances of Ca (>9 %) and modal hornblende (>40 %), plagioclase and hornblende are the main constituents and their linear relationship noted above is disturbed.

Sr correlates with both CaO and Na_2O at the 99 % significance level, and shows a similar relationship as Na in respect of modal plagioclase. Hence it can be assumed that Sr substitutes for both Na and Ca in that mineral.

The association between Ca and modal hornblende causes strong positive correlations between the former and the elements of the Fe and Mg associations. Al has a similar behaviour pattern to both Ca and Na, giving correlations at

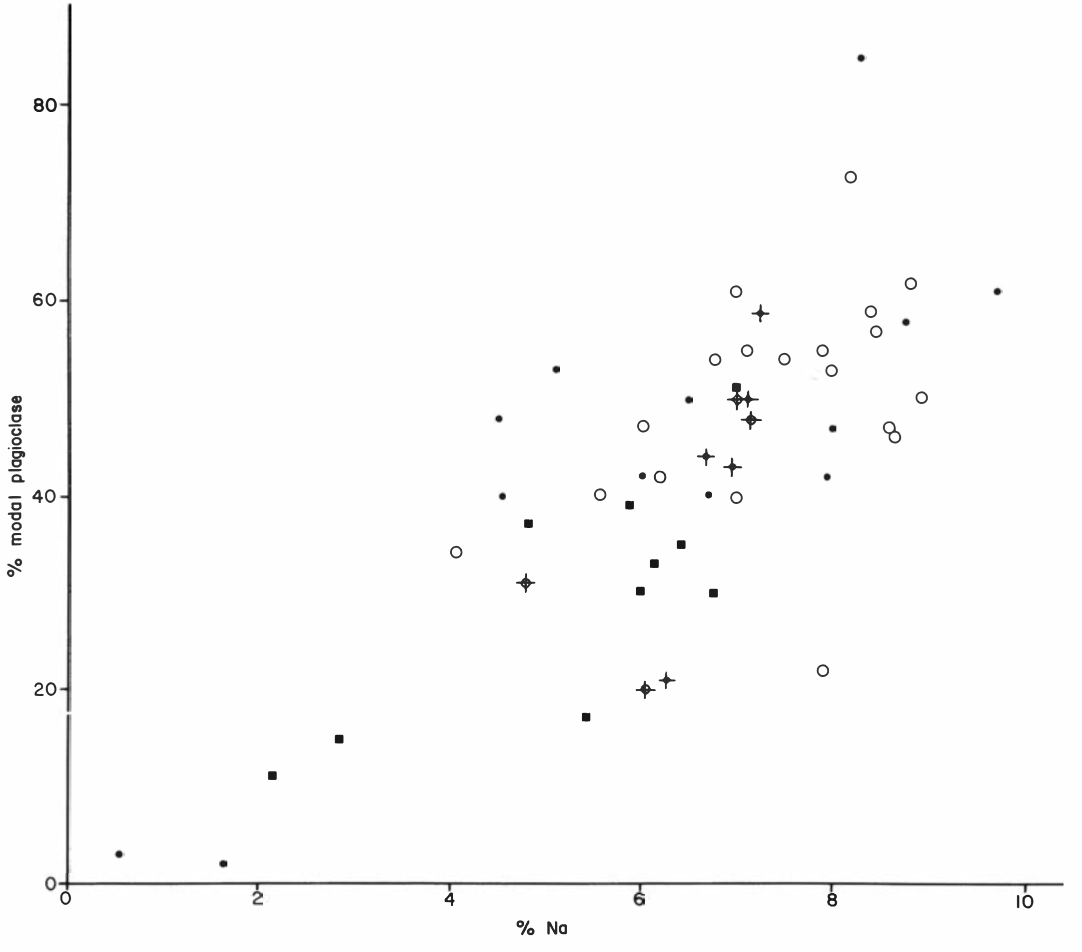

Fig. 6. Modal plagioclase versus percentage Na for the meta-igneous rocks. Key as for Fig. 4, plus amphibolites (squares).

the 99 % significance level with Ca and at the 95 % level with Na, indicating the major element association in plagioclase and hornblende. Cl would normally be expected to associate with the elements in mica, and its presence in this grouping cannot be readily explained.

Magnesium and associated elements (Mg, V, Co, Cr, Ni): the meta-igneous rocks are divided into two associations centred on Mg and Fe. Although correlations between the two groups are commonly above the 99 % significance level for individual elements, V, Cr, Co, and Ni have a more close association with Mg. Cluster analysis (Fig. 3) displays these two associations, although it shows that Cr and Ni have no direct relationship with Co and V except through Mg.

The Co/Mg and V/Mg ratios show no variation with an increase in the Niggli value Si. Cr and Ni have a sympathetic relationship with each other (Fig. 8) and with Mg except in samples with particularly high Mg values. Hornblende-bearing rocks have both high and low values of Cr and Ni (Fig. 8). The Ni/Cr ratio does not vary with increasing silica and, as stated by Taylor (1965), is not a good indicator of fractionation.

The Cr/FeO ratio splits the meta-igneous rocks into two distinct fields which are not related to any contrasts in modal abundances.

Iron and the associated elements (Ti, Mn, Sc, Zn): this forms the closest association found within the meta-igneous rocks, except that between the individual rare-earth elements. This relationship of elements has been previously noted by Sighinolfi (1971) in granulite facies

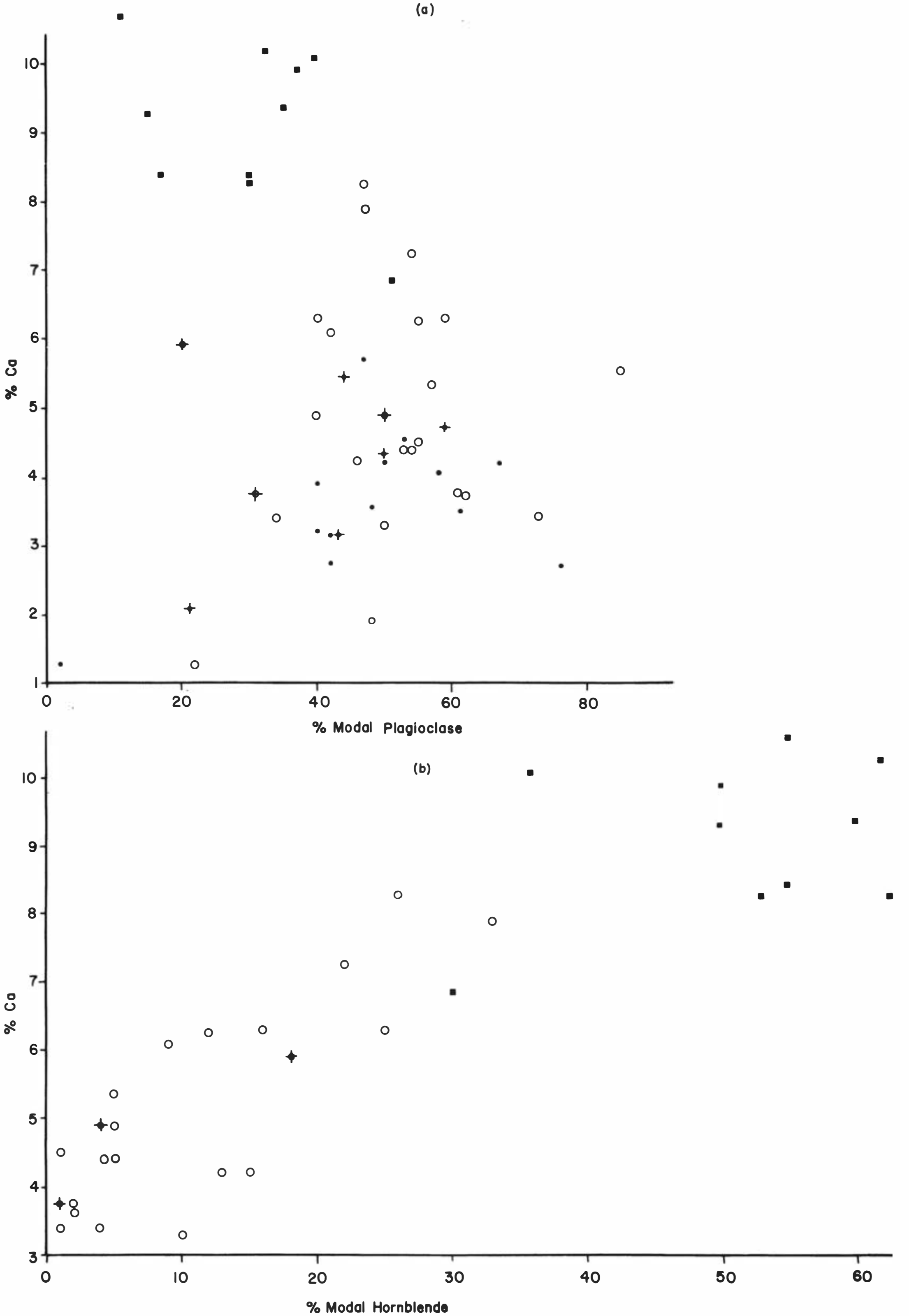

Fig. 7. Percentage Ca versus modal plagioclase (7a) and modal hornblende (7b) for the meta-igneous rocks. Key as for Fig. 4.

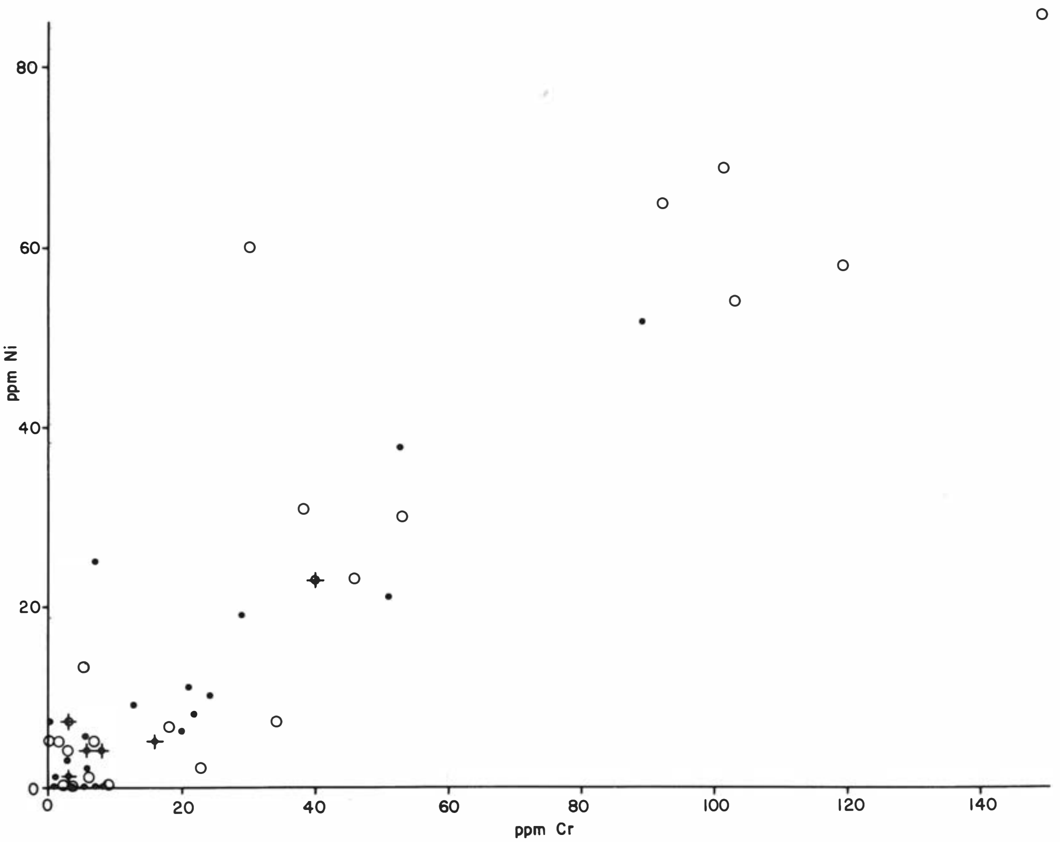

Fig. 8. Cr versus Ni for the meta-igneous rocks. Key as for Fig. 4.

metamorphic rocks in Brazil, and is common in both igneous (e.g. Gruza 1965) and sedimentary rocks (e.g. Condie 1967). Both Mn and Zn are closely correlated with Fe^{2+}, and appear to substitute for that element.

With increasing silica the ratios Mn/Fe^{2+} and Zn/Fe^{2+} exhibit no change, but the ratios Ti/Fe^{2+} and Sc/Fe^{2+} both decrease. The Mn/Fe^{2+} ratio is normally constant during igneous fractionation (e.g. Putman & Burnham 1963) and appears to remain so in the meta-igneous rocks. The Zn/Fe^{2+} ratio, however, decreases in the later stages of igneous fractionation (e.g. Papezik 1965).

Ti/Mg, Fe^{2+}/Mg, and Zn/Mg ratios show no variation with increasing silica, whereas the Sc/Mg ratio decreases. The Co/Fe^{2+} ratio decreases sharply with increasing Fe^{2+}, despite the strong correlation between the two elements. The Ti/Zr ratio, an indicator of fractionation (Taylor 1965), decreases with increasing silica content (Fig. 9).

The close association of Fe and related elements is considered to be a primary, igneous feature, particularly as there is a contrast with the element ratio behaviour in the meta-sedimentary gneisses of this area (Beeson 1975). The clear distinction of two groups of mafic elements in the meta-igneous rocks is difficult to explain for certain elements, particularly V. This element occurs chiefly as V^{3+} and should enter Fe^{3+} position in the later stages of igneous fractionation in igneous rocks, but V and Fe^{3+} are barely correlated here. This is the converse of the findings of Field & Elliott (1974), who established a complimentary increase of these two elements in the amphibolitisation of basic rocks in the southern Bamble Sector. Cr and V have similar characteristics except in their ionic radii, normally resulting in Cr fractionating in

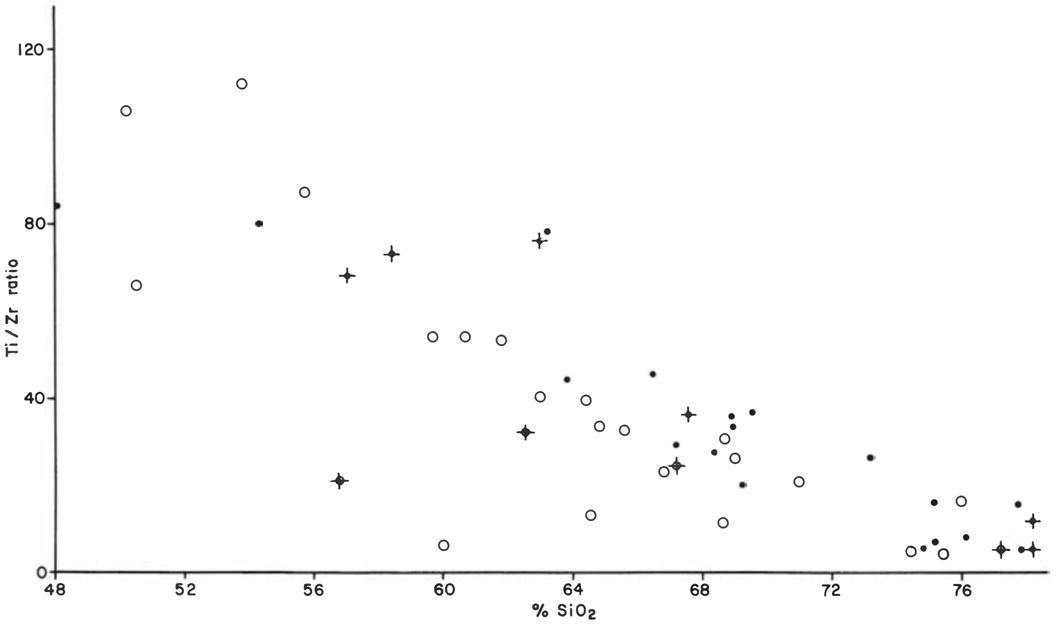

Fig. 9. The Ti/Zr ratio versus percentage SiO_2 for the meta)igneous rocks. Key as for Fig. 4.

the more basic rocks. In view of their similar distributions here, this may explain the Mg-Cr-V association in the meta-igneous rocks.

Discussion

Igneous characteristics of the meta-igneous rocks

Several features combine to justify the classification of the above described lithology as being meta-igneous. It is an individual rock suite which can be recognised in the field, and contrasted with other lithologies of previously determined origin, e.g. the metasedimentary gneisses which contain meta-graywackes, -pelites, and -quartzites (Beeson 1975). The individual members of the meta-igneous rocks have sharp contacts with other lithologies which are parallel to the foliation.

The lithology constitutes a chemical continuum from basic 'amphibolitic' rocks to rocks containing up to 78 % silica. The continuum is reflected in the observed mineralogy, in which the four essential minerals – quartz, plagioclase, biotite and hornblende – all have a wide variation in modal abundance which is controlled by the major element chemistry (see above).

The mean values of the major elements in the meta-igneous rocks are comparable with those of intermediate and acid rocks compiled by Nockolds (1954). As the meta-igneous rocks have a wide compositional range it is difficult to make direct comparisons, but dacites and quartz-diorites have similar compositions (Table 4). The $Na_2O + K_2O$ contents of meta-igneous rocks are similar in relation to SiO_2 for the majority of acid and intermediate volcanic rocks (Fig. 10).

In contrast, metasedimentary gneisses from the Songe-Ubergsmoen area have values dissimilar to igneous rocks, particularly for MgO, CaO and Na_2O (Table 4). In addition, major and trace elements show fractionation trends characteristic of known igneous models, e.g. $Na_2O + K_2O$, Sc/Y, Ti/Zr, Cr/Fe^{2+}, Ti/Fe^{2+} and Mn/Fe^{2+}.

Affinities of the meta-igneous rocks

The geochemistry of the meta-igneous rocks suggests that the element concentrations have undergone little modification during the high-grade metamorphism. Consequently comparisons can be made with modern equivalents with some confidence. The meta-igneous rocks display close affinities with several tholeitic rock suites, e.g. the Scottish Tertiary Province (Kuno 1968) Fig. 10. Some high silica rocks do not fit directly onto the tholeitic trend, and it is suggested that these are clastic rocks of which a proportion of the material was derived from an igneous source. An example of such sedimentary lithologies has been recorded by Kuno (1968), and given in Fig. 10.

Significance of this study to the Bamble Sector

The southern Bamble Sector is an excellent region for the study of metamorphic processes. Detailed geological mapping has defined the nature of the amphibolite and granulite facies metamorphism and a transitional zone with intense K-feldspathisation. The meta-igneous rocks of the Songe-Ubergsmoen area lie adjacent to the zone of K-feldspathisation and are apparently little affected by this process. Consequently this lithology exhibits igneous characteristics which have not been substantially modified by subsequent metamorphism, and provides a reference against which the rocks of adjacent areas can be compared to determine high-grade metamorphic processes.

Of particular interest to the Bamble Sector is the marked similarity for the majority of elements between the meta-igneous rocks and the charnockitic gneisses of the adjacent granulite

Table 4. Comparison of the major-element compositions of meta-igneous rocks (1) and metasedimentary gneisses (2) of the Songe-Ubergsmoen area with charnockitic gneisses (3, Cooper & Field 1977), and averages for dacites (4) and quartz-diorites (5, Nockolds 1954).

	1	2	3	4	5
SiO_2	66.12	70.05	68.35	63.58	66.15
Al_2O_3	14.63	13.07	13.83	16.67	15.56
TiO_2	0.73	0.74	0.53	0.64	0.62
Fe_2O_3	2.50	1.37	6.01	2.24	1.36
FeO	2.67	3.61		3.00	3.42
MgO	2.40	2.72	1.90	2.12	1.94
CaO	3.99	2.44	3.64	5.53	4.65
Na_2O	3.72	2.03	4.67	3.98	3.90
K_2O	1.83	2.57	0.47	1.40	1.42
MnO	0.07	0.06	0.09	0.11	0.08
P_2O_5	0.17	0.15	0.12	0.17	0.21

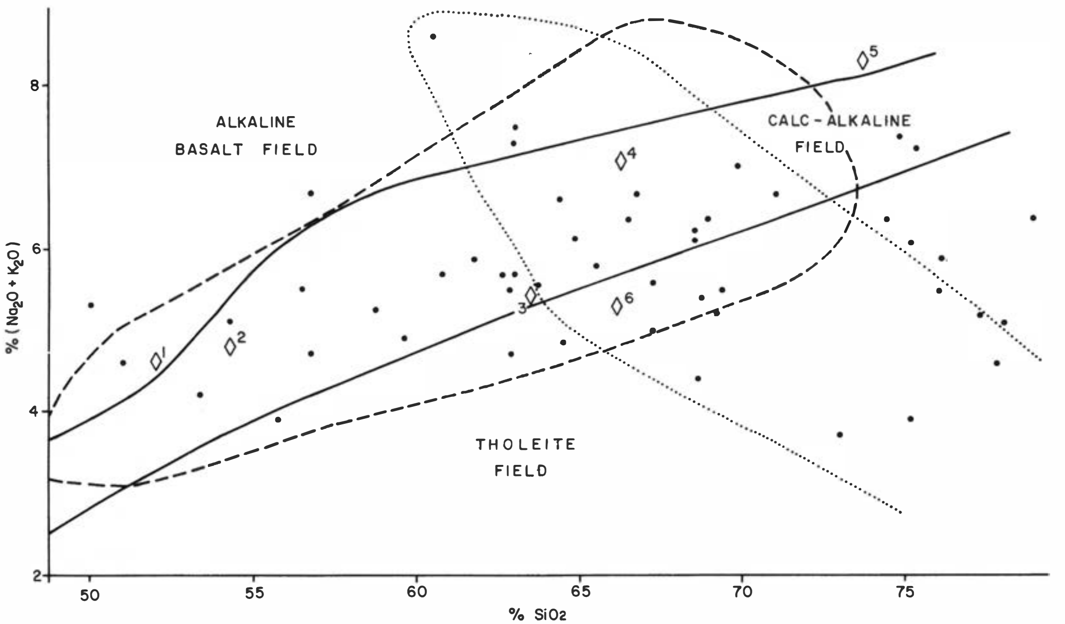

Fig. 10. Percentage ($Na_2O + K_2O$) versus SiO_2 for the meta-igneous rocks (after Kuno 1968). Represented are the fields of the tholeitic series of the Scottish Tertiary Province (dashed line) and geosynclinal deposits from Japan (dotted line). The mean values for the igneous rock types compiled by Nockolds (1954) are given as diamonds: 1 – diorite, 2 – andesite, 3 – dacite, 4 – rhyodacite, 5 – rhyolite, 6 – quartz diorite.

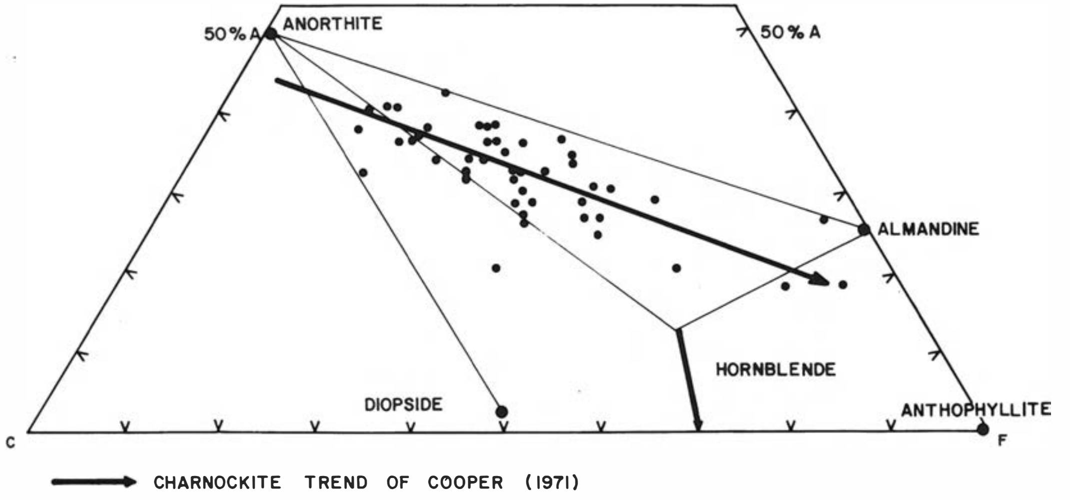

Fig. 11. ACF diagram for the amphibolite facies showing the composition of the meta-igneous rocks (after Winkler 1967).

facies. This is well illustrated by the ACF diagram (Fig. 11), in which the fields of both rocks are identical. Consequently both rock types may well have had the same parentage, and subsequent metamorphic processes have not affected the abundances of Al, Ca, Mg, Fe, and other elements.

Comparisons are drawn by Cooper & Field (1977) between the charnockitic gneisses and Fe-rich rapakivi suites of the Archaean in the northern hemisphere. However, the rapakivi intrusives are Rb-rich with relatively low K/Rb ratios, whereas the charnockitic gneisses and the meta-igneous rocks are predominantly poor in Rb. Consequently this comparison may not be valid.

Relationship to other metamorphic terrains

The evidence given above substantiates a model of isochemical metamorphism for the meta-igneous rocks, and hence the geochemical parameters are original. The majority of elements have similar concentrations to that of estimates of the earth's crust. However, Rb and U, two elements important to the study of high grade metamorphic terrains, are depleted in relation to associated elements. As both metasedimentary and meta-igneous rocks have high K/Rb ratios, it can only be concluded that this is an original characteristic of the Bamble Sector in this area.

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Appendix

1. *Optical determinations*

The modal analyses were made by the point counting method covering the whole of the thin section on a $0{,}3 \times 0{,}6$ mm grid. This totalled approximately 1500 counts per section.

Plagioclase compositions were determined using the Michel-Levy technique on random grains, making 6 determinations per thin section.

2. *Analytical methods*

Major and trace elements were determined by X-ray fluorescence spectrometry using a Philips PW 1212 spectrograph. Major-element analysis was carried out on fused glass discs according to the method described by Harvey et al (1973).

Trace-element analysis was carried out on pressed powder pellets and was based on the ratio technique. The calibration and corrections are made according to the method described by Field & Elliott (1974). The USGS standard AGV. 1 was used as a control standard on a daily basis.

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