

The Torsvik sagvandite body, North Norway

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A large ultramafic body crops out on the coast of Nordland at Torsvik just north of Ørnes. It is surrounded by amphibolite facies rocks of the Meløy Group. The main rock-types are (olivine) – carbonate-orthopyroxenites, tremolite-orthopyroxenites and tremolite rocks. Detailed petrological and chemical studies of both whole-rocks and minerals indicate that the major rock groups are identical to those of the type sagvanditic associations in Troms. Other bodies from adjacent areas appear to be similar. The Torsvik sagvandite represents the best exposed body of its type so far described from Norway.

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An ultramafic body crops out on the west coast of Nordland near the farm Torsvik about 5 km north of Ørnes and 60 km south of Bodø (Fig. 1). The occurrence was first mapped and described by Holmsen (1932), is represented on the 1:1,000,000 geological map of Norway (Holte-dahl 1960), and a brief description of one outcrop appears in Holmes (1960). Recent construction work on the coastal road has produced a section of about 750 m through the body. When the cliffs below the road are taken into account the section has a maximum height of 50 m. It was along this section that the various rock-types and their relationships were studied in detail by Cribb (1979). Detailed mapping on enlarged aerial photographs showed that the body is roughly triangular with the apex inland to the east (Fig. 2).

Mode of occurrence, rock-types and mineral chemistry

The boundaries of the mass are very rarely seen, being covered by drift at the coast and dense vegetation inland. The body lies at the boundary between kyanite-schists of the Meløy Group and the Ørnes Dioritic Gneisses (Holmes 1960, 1966) both of which have been respectively correlated with kyanite-schists and the Hornblendic-rocks of the Sørfinset area further north (Wells & Bradshaw 1970, Cribb 1979). Recent geochronological data (Cribb 1979, 1981) indicate that the kyanite-schists show evidence of a Precambrian

isotopic homogenisation event (1360–1038 my) which occurred before the maximum estimated age of the precursors of the Hornblendic-rock and the Ørnes Dioritic Gneisses (758 my). Consequently the boundary was interpreted as a major tectonic break within the Meløy Group.

The ultramafic body is made up of several rock-types, of which the first two described are areally most important.

(Olivine) – carbonate – orthopyroxenite

This is the dominant rock-type; it is massive and unfoliated. The rocks are grey in colour when fresh, but weather to a characteristic yellow-brown, the latter being an important diagnostic feature when mapping inland. The main phases are orthopyroxene and carbonate together with varying proportions (0–3 %) of olivine. Mesoscopically the most notable features are rosettes of orthopyroxene prisms up to 15 cm in length, whilst the other minerals are medium-grained and interstitial. The olivine grains, which are unserpentinised, represent the relics of much larger crystals now partially replaced by orthopyroxene and/or carbonate. The main accessory minerals are opaques up to 1 mm in diameter scattered throughout the rock together with a small amount of fibrous amphibole and talc. There are rare veins, 2–3 cm in width, of asbestiform anthophyllite associated with talc and chlorite.

The means of microprobe analyses of several grains of orthopyroxene (12 analyses), olivine (3 analyses) and opaque (3 analyses) from a typical

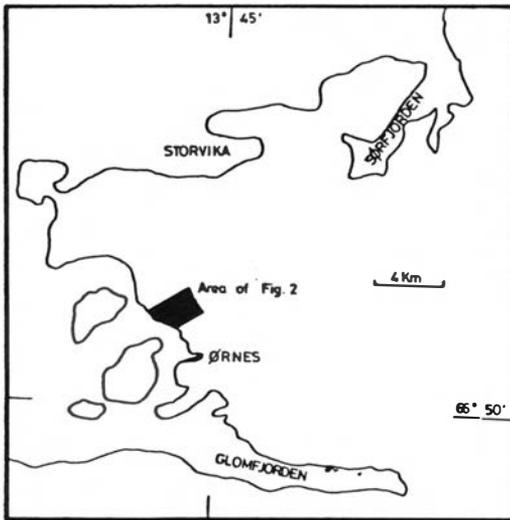


Fig. 1. Regional map showing location of the Torsvik body.

olivine-carbonate-orthopyroxenite are given in Table 1.

Both the orthopyroxenes and olivines are highly magnesian: En_{86-91} (enstatite-bronzite) and Fo_{88-89} (forsterite-chrysolite) respectively. The Fe^{3+}/Fe^{2+} ratios of the opaques were calculated on a charge-balance basis and the analyses were recast in terms of hercynite-spinel-chromite-picrochromite end-members (Simpson 1921, Bevan & Rogers 1977). All analyses fall within the chromite field. The carbonate phase was not probed but the major element analyses of this rock-type (Table 4) show very low CaO (1.0%) and high MgO. Consequently it is likely that the carbonate phase is magnesite ($MgCO_3$) and/or breunnerite ($Mg_9Fe(CO_3)_{10}$). The latter has been identified as the main carbonate phase in similar rocks from the Troms area of North Norway (Rosenbusch 1923).

Rocks similar to the ones described above were first found near Sagvandet (Sagelvvatn), Troms by Pettersen (1883), who suggested the name sagvandite.

Dyke-like bodies and related rocks

In the south and east of the mass, in particular, dyke-like pods of amphibole-rich rocks occur within the sagvandite. The pods are particularly well seen in cutting 1 (Fig. 2), where the dominant rock-type is composed solely of pale-green to colourless amphibole prisms with parallel ori-

Table 1. Means of microprobe analyses of orthopyroxenes, olivines and opaques from a typical olivine-carbonate-orthopyroxenite from the Torsvik body. n = number of analyses. tr = <0.50 %

	Orthopyroxene (n = 12)		Amphibole (n = 3)		Opaque (n = 3)	
	\bar{x}	σ	\bar{x}	σ	\bar{x}	σ
SiO ₂	58.08	0.56	41.03	0.15	tr(3)	
Al ₂ O ₃		tr(1)		—	1.87	0.13
TiO ₂		—		—	tr(3)	
FeO ^o	7.47	0.69	10.88	0.55	58.47	2.73
MgO	34.26	0.62	48.26	0.40	2.52	0.21
Na ₂ O		tr(1)		—		—
MnO		tr(3)		—		—
Cr ₂ O ₃		tr(1)		—	31.95	1.96
NiO ₂		—		tr(3)		tr(1)

entation defining a strong lineation. At the eastern end of the cutting, the zoned contact between a pod and the enclosing sagvandite is well exposed. The inner part of the pod comprises pale-green to colourless amphibole laths up to 2 cm in length together with fine-grained opaques and accessory carbonate. This is surrounded by a fine-grained black rock made up of green to brown amphibole and epidote, in part massive and in places heavily weathered with a clinker-like aspect. The contact zone between the pod and the surrounding sagvandite is marked by up to 20 cm of a coarse-grained biotite-carbonate rock with green spinel and euhedral opaques.

A close study of the contacts on the main face of cutting 1 (Fig. 2) shows that a similar zonation is recognisable, though in these cases the hornblende-epidote rocks are not so well developed. Similar dyke-like bodies were noted in cutting 2, where the pale-green amphibole rocks are not visible and the rock-type is a coarse-grained hornblende-epidote variety. A biotite-carbonate outer zone is also present. It is suggested that these bodies represent pods similar to those in cutting 1 but with only the outer zones exposed.

There is a further occurrence of black, cindery amphibole rock at the seaward end of the peninsula, 100 m to the south of Torsvik farmhouse (Fig. 2) where two isolated pods outcrop within coarse-grained sagvandite. These bodies are made up almost entirely of medium-grained dark-green amphibole with large euhedral opaques. Epidote is lacking. Both bodies show the development of a biotite-carbonate margin. It is thought that these bodies represent the tips of larger zoned pods such as have been described

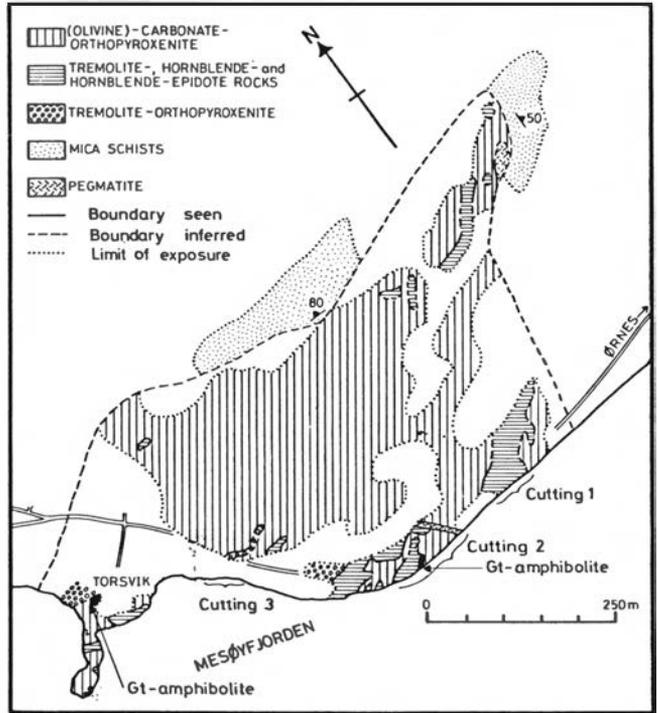


Fig. 2. Geological map of the ultramafic body near Torsvik showing the cuttings described in the text.

previously. Microprobe analytical data from amphiboles (mean of 5 analyses) and opaques (3 analyses) from one of the bodies are presented in Table 2.

The amphiboles are magnesio-hornblendes (Leake 1978). The analyses of three opaque grains indicate that there is a wide variation in composition even within a single sample of rock. Two grains (83, 84) are members of the ulvöspinel-magnetite series and the third (82) contains an excess of titanium over iron which may be indicative of the presence of rutile exsolved within ilmenite (Buddington & Lindsley 1964).

Tremolite-orthopyroxenites

An apparently transitional rock-type is present in three areas of the coastal outcrop of the body. Orthopyroxene and pale-green amphibole are the major phases with which are associated minor amounts of carbonate, opaques and talc. The pale-green amphibole replaces the orthopyroxene, and there is a wide range of rock-types from orthopyroxene-dominant to amphibole-dominant. The means of the results of microprobe analysis of orthopyroxenes (6 analyses), amphi-

boles (5 analyses) and opaques (4 analyses) from a typical sample are presented in Table 3.

The orthopyroxenes are highly magnesian ($En_{88.0-87.2}$) and fall within the bronzite field. The pale-green amphiboles are magnesium-rich calcic amphiboles and plot within the tremolite field of Leake (1978). If the amphiboles are recalculated, using the method of Leake, there is still a charge deficit, even if all iron is calculated

Table 2. Mean of microprobe analyses of amphiboles and analyses of three opaques from one of the dyke-like pods in the Torsvik body. n = number of analyses. tr = < 0.50 %

	Amphibole n = 5		Opaque		
	\bar{x}	σ	83	84	82
SiO ₂	46.82	1.48	0.74	0.35	0.95
Al ₂ O ₃	9.43	1.62	0.32	1.01	0.51
TiO ₂	tr(5)		29.40	-	52.32
FeO°	9.75	0.15	62.38	86.47	41.47
MgO	15.62	0.69	0.80	-	1.40
CaO	12.34	0.04	-	-	0.12
Na ₂ O	1.35	0.29	-	-	-
K ₂ O	tr(5)		-	-	-
MnO	tr(1)		0.54	-	0.94
Cr ₂ O ₃	tr(2)		-	4.27	-

Table 3. Means of microprobe analyses of orthopyroxenes, amphiboles and opaques from a typical tremolite-orthopyroxenite from the Torsvik body. n = number of analyses. tr = <0.50 %

	Orthopyroxene n = 6		Amphibole n = 5		Opaque n = 4	
	\bar{x}	σ	\bar{x}	σ	\bar{x}	σ
SiO ₂	57.79	0.44	57.47	0.15	tr(3)	
Al ₂ O ₃	-	-	0.89	0.39	4.47	1.20
TiO ₂	-	-	-	-	tr(4)	
FeO ^o	8.43	0.22	2.85	0.11	63.39	4.84
MgO	33.56	0.17	22.91	0.14	2.72	0.29
CaO	-	-	12.65	0.12	-	-
Na ₂ O	tr(1)		-	-	-	-
MnO	tr(3)		-	-	-	-
Cr ₂ O ₃	-	-	tr(1)		24.99	3.56
NiO	-	-	-	-	tr(1)	

as ferric iron. It is probable that the number of oxygens to which the cations are ratioed should be greater than 23 but less than 24 (Leake 1979, pers. comm.). The opaques are chromites (Simpson 1921).

The tremolite-orthopyroxenite bodies are easily identifiable in fresh outcrops but very difficult to define weathered. Consequently there may be further occurrences of this rock-type inland.

Garnet-amphibolites and associated rocks

To the north-west of the farmhouse at Torsvik there is a small outcrop of garnet-amphibolite within the sagvandite. This rock has the assemblage pink garnet – green to yellow amphibole – quartz – plagioclase. Unfortunately no boundaries are visible.

A complex zoned body 3 m in height and 5 m in width is well exposed in the cliffs below the road by cutting 2. The body lies along the boundary between sagvandite to the east and tremolite-rock to the west. The body, which is described in detail elsewhere (Cribb 1979), is mainly garnet-amphibole-biotite rock, but the unique feature is the development of pods and selvages of alumina-rich assemblages comprising green and brown spinels, corundum and epidote.

Pegmatites

A pegmatite dyke, up to 2 m in width and striking north-west to south-east, cuts across the ultramafic body at the eastern end of cutting 2. The

rock is made up almost entirely of large plagioclases which are extensively saussuritised. Muscovite is present in accessory amounts. Despite an intensive search it was impossible to trace the dyke inland.

A much larger pegmatite mass forms part of the large cliff-face at the north-eastern end of the body. The outcrop proved inaccessible but the rock appears to be similar to that described from cutting 2. The mass lies along the boundary between the ultramafic rocks and the surrounding schists and can be seen to be intrusive into the latter. It is apparent that the pegmatites are late-stage phenomena and are in no way genetically related to the ultramafic body.

Whole-rock chemistry

Twenty-eight samples of the major rock-types were analysed, and for the sake of brevity during the following discussion the various rock-types have been given letters as follows:

A – (Olivine) – carbonate-orthopyroxenites.

B – Tremolite rocks

C – Tremolite-orthopyroxenites. Essentially a transitional rock-type between A and B showing a wide range of variation from orthopyroxene-dominant to amphibole-dominant.

Full individual analyses are presented in Cribb (1979), but major element means and trace element ranges for each of the above groups are listed in Table 4.

Over 96 % of the composition of type A rocks is attributable to the components SiO₂, MgO, (FeO + Fe₂O₃) and CO₂. There is little variation in the amounts of these components in the eleven samples that were analysed. Previous authors (Moore 1977, Ohnmacht 1974, Schreyer et al. 1972), when dealing with similar rocks, quoted total iron as ferrous iron, and for consistency this convention has been continued. Ohnmacht (1974) found that the ratio 100 MgO/(FeO^o + MgO) was constant in all phases in the Troms sagvandites and consequently assumed that MgO and FeO^o could be treated as a single component. The Torsvik Sagvandite mineral analyses (Table 1) indicate that, at least as far as the olivines and orthopyroxenes are concerned, a similar constancy is found. The 100 MgO/(FeO^o + MgO) ratio of ten of the whole-rock analyses of type A varies between 86.3 and 91.4; the eleventh has a value of 96.5.

Table 4. Means of major-element analyses and trace-element ranges (in parts per million) of ultramafics from Torsvik and Troms. BDL – below detection limit, ND – not determined.

Type A: (Olivine) – carbonate-orthopyroxenites, Torsvik.

Type B: Tremolite rocks, Torsvik.

Type C: Tremolite-orthopyroxenites, Torsvik.

TROMS: (Olivine) – carbonate-orthopyroxenites from Sagelvatn, Lyngseidet, Furufalten and Rossfjord. (Ohnmacht 1974).

	Type A (n = 11)		Type B (n = 5)		Type C (n = 12)		TROMS (n = 20)	
	\bar{x}	σ	\bar{x}	σ	\bar{x}	σ	\bar{x}	σ
SiO ₂	46.03	2.92	51.10	0.97	51.68	1.57	43.59	6.64
Al ₂ O ₃	1.04	0.48	1.75	0.49	1.48	1.04	0.88	0.39
TiO ₂	0.02	0.01	0.04	0.00	0.02	0.02	< 0.10	
Fe ₂ O ₃	2.66	1.09	2.14	0.99	1.55	0.58		
FeO	6.46	1.24	3.43	0.54	4.13	0.65	6.42°	1.20°
MgO	38.51	1.73	21.07	0.50	28.18	3.15	35.97	1.47
CaO	0.29	0.17	14.83	1.34	8.21	2.42	0.22	0.13
Na ₂ O	0.05	0.04	0.19	0.09	0.18	0.13		< 0.05
K ₂ O	0.07	0.17		BDL		BDL		< 0.05
MnO	0.13	0.01	0.14	0.01	0.15	0.05	0.11	0.03
P ₂ O ₅	0.10	0.07	0.09	0.08	0.08	0.07		< 0.01
H ₂ O	0.76	0.31	1.98	0.13	1.50	0.51		ND
CO ₂	2.69	1.16	2.76	0.57	2.19	0.88	9.12	5.64
Cr ₂ O ₅	0.66	0.41	0.27	0.05	0.45	0.16	0.43	0.15
NiO ₂	0.20	0.06	0.04	0.00	0.09	0.04	0.27	0.04
	ppm		ppm		ppm			
Ba	17– 42		18–26		14–37			
Co	85–151		53–63		58–95			
Rb	0– 52		0– 4		0– 3			
Sr	BDL		4–14		3–16			
Zn	37– 64		26–34		26–64			

When type B rocks are compared with type A (Table 4) it is seen that the major chemical differences are an increase in CaO from 0.5 % to 15 % and a decrease of MgO from 39 % to 21 %. The FeO° values mirror the drop in MgO and thus the ratio 100 MgO/(FeO° + MgO) remains constant. SiO₂ and H₂O content increase slightly, but the amount of CO₂ remains constant between 2.5 % and 3.0 %.

The suggestion that type C rocks are transitional between types A and B appears to be valid in terms of chemical composition. The values for specific oxides are between those for types A and B and show quite a large degree of variation.

Major-element analyses of carbonate-orthopyroxenites from various localities in the Troms area are tabulated in Ohnmacht (1974) and the mean of twenty analyses is given in Table 4. Three of Ohnmacht's analyses (276,301,444) were described as being totally altered and were not used in the calculation of the mean. Torsvik type A rocks are very similar to the Troms sagvandites with the exception that the CO₂ content of the latter is much more variable and generally substantially higher. Schreyer et al. (1972) men-

tion the occurrence of rocks from the Troms area similar to types B and C but present no chemical analyses.

The Torsvik rocks were analysed for the trace elements Ba, Ce, Co, Cr, Ga, La, Nd, Ni, Rb, Sr, Y and Zn. Chromium and nickel occur in quantities large enough to be quoted as oxides and are listed as major elements (Table 4). The values for Ce, Ga, La, Nd and Y generally proved to be below their respective detection limits and are not discussed further. Data for the remainder are tabulated individually in Cribb (1979), but the ranges for each major rock-type are given in Table 4. The generation of a correlation matrix proved useful in the identification of inter-relationships between trace and major elements. The usual relationship between nickel and cobalt (Burns & Burns 1974) was confirmed by their strong positive correlations with each other. Both elements also showed a positive correlation with ferrous iron and magnesium and to a lesser extent zinc and chromium. Taylor (1965) stated that nickel and cobalt preferentially enter the olivine structure replacing ferrous iron and magnesium. This seems reasonable in the present

case because the olivine analyses quoted in Table 1 include up to 0.38% NiO, whereas none is present in the coexisting enstatites. Zinc shows its strongest correlation with cobalt and nickel and thus most probably occurs within the olivines. However, between 26 ppm and 34 ppm is present in the tremolite-rocks, which do not contain olivine, indicating an amount of substitution into ferrous iron and magnesium sites within the amphiboles. Chromium shows a weak positive correlation with ferrous iron, nickel and cobalt and a stronger negative correlation with silicon. Most of the chromium is present in chromite and there is only limited substitution into silicate lattices. Rubidium and strontium were detected in only 50% of the Torsvik samples and occur in the rocks with higher potassium and calcium contents respectively. Puchelt (1972) stated that barium may follow either potassium or calcium, and, although no significant correlation was noted in the Torsvik analyses, the concentrations are in general agreement with the values he quotes of 25 ppm in peridotites and 23 ppm in pyroxenites.

Petrogenesis

Considering the previously described field relationships it seems highly unlikely that the present carbonate-orthopyroxene assemblage is the result of crystallisation from an ultramafic magma. The Torsvik body lies within high-grade (upper amphibolite facies) metamorphic rocks and has probably been subjected to some if not all of the events which have affected the surrounding metasediments. Sørensen (1955) studied similar rocks from the Holandsfjord area (30 km south of Torsvik) and interpreted the assemblages as the result of the regional metamorphism of siliceous dolomites, a hypothesis which is in conflict with the high concentrations of chromium and nickel and low levels of phosphorous and titanium found in other sagvandites. The petrochemical studies of the Troms sagvandites (*sensu stricto*) presented by Schreyer et al. (1972) and Ohnmacht (1974) demonstrate that the major-element chemistry of sagvanditic rocks is similar to that of typical peridotites and orthopyroxenites with the exception that the CO₂ content is unusually high. The general similarity may be confirmed by comparison with the mean peridotite and pyroxenite analyses quoted by Le Maitre (1976).

Schreyer et al. (1972) and Ohnmacht (1974) noted that, as in the Torsvik sagvandites, most olivines were present as relicts replaced either by orthopyroxene and magnesite or orthopyroxene alone. Their studies of the P-T-X_{CO₂} stabilities of the assemblages olivine-CO₂-enstatite-magnesite and olivine-quartz-enstatite indicated that the minimum conditions for the genesis of carbonate-orthopyroxenites lay near 5 Kb and 600°C. At pressures of 7 Kb, temperatures of about 650° were indicated. Specific X_{CO₂} conditions were not identified for the stability of the above assemblages, but the general conclusion was that high values, in relation to X_{H₂O}, were necessary in order to suppress reactions which would form anthophyllite and serpentine. They concluded that the carbonate-orthopyroxenites were the result of CO₂-H₂O-SiO₂ metasomatism of primary ultramafic material of peridotitic and/or orthopyroxenitic composition, and furthermore that the rocks achieved their present mineralogy *in close juxtaposition and simultaneously with their present country rocks under essentially identical conditions of total pressure and temperature*.

The CO₂-rich metasomatising fluid was considered to have been derived from limestones and siliceous dolomites which surrounded the ultramafic body. The latter may have been the case at Lyngen but sagvandites do also occur in areas that are not in close proximity to carbonate rocks. Moore (1977) studied the Hjelmkona sagvandite and concluded that the high CO₂ partial pressures were a regional rather than a local effect. No carbonate horizons are present in the rocks surrounding the Torsvik body though there are marbles within the Meløy Group as a whole (Holmes 1960, 1966, Walton 1959, Wells & Bradshaw 1970). However, the likelihood that the Torsvik body was emplaced along a major tectonic boundary suggests that the body achieved its present mineralogy elsewhere and arrived at its present position at a tectonically late stage.

The occurrence of tremolite-carbonate-orthopyroxenites and tremolite-rocks has been noted by several authors, though their chemistry and petrogenetic significance have never been discussed. Sørensen (1955) and Moore (1977) found that the tremolite rocks formed an outer zone between the sagvandites and the country rocks. In addition, Sørensen noted the presence of an extreme outer zone of green or black hornblende rock. Although these rock-types are found at

Torsvik their disposition, as dyke-like bodies, clearly differs from those described by Sørensen and Moore. Ohnmacht (1974) proposed a genetic relationship between the tremolite-rocks and the sagvandites because of the occurrence of the transitional tremolite-carbonate-orthopyroxenites. At Torsvik the transitional rocks are developed in close proximity to the dyke-like pods and consequently it is suggested that these rocks are the result of progressive transference of calcium and water from the pods into the surrounding sagvandite. The pods themselves may originally have been mafic dykes.

Although massive and schistose lenses of amphibolite and garnet-amphibolite are a common feature of the Troms bodies (Schreyer et al. 1972), the development of alumina-rich assemblages similar to those at Torsvik has not been noted. However, Schreyer et al. (1972) do describe the occurrence of alumina-rich veinlets up to 5 cm in width within the tremolite-carbonate-orthopyroxenites of the Lyngen area. The veinlets are composed of varying proportions of corundum and colourless to green spinel (spinel-hercynite series) and are separated from the carbonate-orthopyroxenites by zoned selvages of MgAl-rich chlorite, phlogopite and tremolite. It is probable that the amphibolite bodies were formed by the metamorphism of calcareous pelites or basic igneous rocks which were either primary or tectonic inclusions within the ultramafic body. The alumina-rich assemblages are the result of extreme desilication of the margins of the bodies directly in contact with ultramafic material.

Other bodies in north Rana

Sagvandite associations were originally considered to be rare and of restricted occurrence. However, since the detailed descriptive work of Schreyer et al. (1972), Ohnmacht (1974) and Moore & Qvale (1977) the recognition of such bodies has been greatly facilitated. There is no doubt that the ultramafics described by Sørensen (1955a, b) from the Holandsfjord area are of this type. Wells & Bradshaw (1970) show the position of a small (50 m by 50 m) ultramafic body on the slopes of Middagshaugen but present no description. The author visited this body and found that the dominant rock-types are olivine-carbonate-orthopyroxenites and tremolite-rock pods identical to those of Torsvik. Brad-

shaw (pers. comm.) noted the development of chlorite-schists at the contacts between this body and the surrounding metasediments. The body occurs within rocks of the Meløy Group and is spatially related to the biotite-hornblende gneisses, which have been shown to be equivalent to the Ørnes dioritic gneisses that occur on the eastern margin of the Torsvik mass (Cribb 1979). Ultramafic bodies which occur at the base of the Venset gneisses in the Skjerstad region have enstatite-carbonate assemblages (Farrow 1974 and pers. comm.). It is probable therefore that the Skjerstad bodies are similar to the previously described sagvanditic associations. Tragheim (pers. comm.) discovered ultramafic bodies in the area north of Straumen (to the north of Saltfjord) within which carbonate-orthopyroxenites and tremolite-rocks are present. Moore & Qvale (1977) suggested that the metasediments in which sagvanditic bodies occur are of Precambrian and not of Cambro-Ordovician age – a suggestion that, in the case of the Torsvik body, is confirmed by Cribb (1979, 1981).

In summary it is clear that most, if not all, of the ultramafic bodies in Meløy and adjacent areas are similar to the sagvandite bodies of the type area in Troms. Furthermore, as all the other bodies are only a few tens of metres in diameter, the Torsvik mass is the largest and best-exposed example of this type so far described from this part of Norway.

Analytical methods

Samples between 2 and 6 kg in weight were collected from roadside cuttings where freshly blasted material was available. Whole-rock and trace-element analyses were determined by X-ray fluorescence using the Siemens SRS 200 fully automatic spectrometer at the University of Bristol. Sodium and the trace-elements were determined on pressed powder pellets (Leake 1969) whilst the other major-element analyses utilised fused beads (Harvey et al. 1973). FeO was determined by the method of Riley (1958) and CO₂ by a modified acid-base titration method after Grimaldi et al. (1966). H₂O was calculated after heating 0.5 g of powder in a nitrogen atmosphere and collecting the water driven off in a previously weighed magnesium perchlorate absorption tube.

Major-element analysis of mineral phases was undertaken at the University of Manchester uti-

lising a Link Systems Model 290-2KX energy dispersive spectrometer attached to a Cambridge Instruments Geoscan utilising methods described by Dunham & Wilkinson (1978).

Further details of analytical techniques are presented in Cribb (1979).

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