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Carbonate-orthopyroxenites (sagvandites) from Troms, northern Norway

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Massive carbonate-orthopyroxenites occur in tectonic lenses within narrow zones of high-grade regional metamorphism of the Caledonian mountain belt. Typical country rocks are garnet-kyanite-biotite gneisses, amphibolites, or lime silicate marbles. Some of the pelitic country rocks exhibit water-deficient mineral assemblages, others have endured partial melting. Original peridotites (dunites and, possibly, saxonites) are believed to have reacted with highly CO_2-bearing, SiO_2-enriched gas phases emanating from neighbouring silicate marbles, essentially according to the equations forsterite + CO_2 →enstatite + magnesite, and forsterite + SiO_2 →enstatite. This metasomatism as well as the high-grade metamorphism of the country rocks may have taken place under essentially the same pressure temperature conditions, i.e. under at least 6 kb and 630 °C.

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Rocks consisting predominantly of orthorhombic pyroxene and carbonate magnesite were first found in the Caledonian mountain belt of northern Norway near Lake Sagvandet (Sagelvvatn), Troms, by Pettersen (1883), who defined them as new rock species and named them 'sagvandites'. In accordance with Rosenbusch (1884), Pettersen concluded that they were not of igneous but probably of sedimentary origin. Some forty years later, Barth (1926, 1930) described these same sagvandite occurrences as intrusive dykes and crater-like pods filled by a (ultra-) basic magma, which in turn had been modified through assimilation of dolomites. More recently Reitan & Geul (1958) as well as Randall (1960) working in the Lyngenfjord area, some 60 km northeast of Sagvandet, found very similar sagvandite-like rocks which they reported to be characterized by the occurrence of dolomite instead of magnesite in addition to orthopyroxene and occasionally some olivine. For these rocks the above authors advocate a genesis through metamorphic differentiation and/or metasomatism of carbonate-rich sediments.

Since 1967 the present authors have undertaken field and laboratory studies of the 'classic' sagvandites of the type locality as well as of the related rocks from Lyngen and other more recently discovered localities (Fig. 1). Although these investigations are not completed as yet, it is clear that the results already obtained are incompatible with both a metasomatic/metamorphic origin from carbonate sediments and an intrusive magmatic origin.

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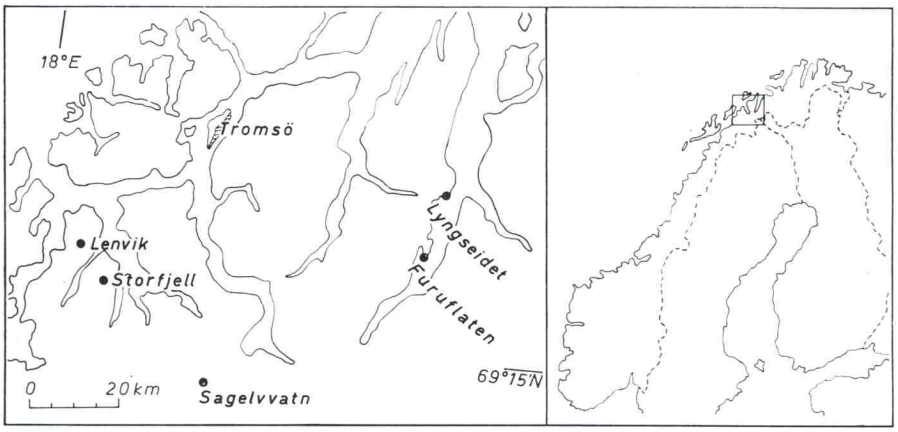

Fig. 1. Sketch map of the Troms area showing (by solid dots) all occurrences of carbonate-orthopyroxenites (sagvandites) known to the authors.

This paper is a first summary of these results thus extending the short abstract by Mannchen et al. (1970). Field and laboratory work has shown that the mineralogy of the sagvandite and its associated rocks is extremely complex. Therefore, it can only be touched upon in the present report which gives the local field relations, the general petrology and some conclusions on the genesis of these unusual rocks. Occurrences of sagvandites elsewhere in the world have been summarized by Barth (1930). Recently sagvandite-type rocks were found in minor amounts at Aaheim, western Norway (Kendel 1970) and in the Swiss Alps (Trommsdorff & Evans 1970), in both cases in close association with peridotites.

Nomenclature

Pettersen's (1883) term 'sagvandite' has priority. It seems preferable, however, to name the rocks after their most prominent and characteristic mineral phases, carbonate-orthopyroxenites. This would mean that the occurrences of both magnesite and dolomite are taken into account. Because assemblages of orthopyroxene with any type of carbonate do not appear in the normal progressive metamorphism of siliceous carbonate rocks (Bowen 1940), the term carbonate-orthopyroxenite is unambiguous.

Field relations

The carbonate-orthopyroxenites of Troms occur within the Caledonian mountain chain, the tectonic style of which is characterized by complicated nappe structures exhibiting overthrusting towards the Precambrian basement of the Baltic Shield (for details see Gustavson 1966, Berthelsen 1967, Landmark 1967). The rocks affected by Caledonian folding and meta-

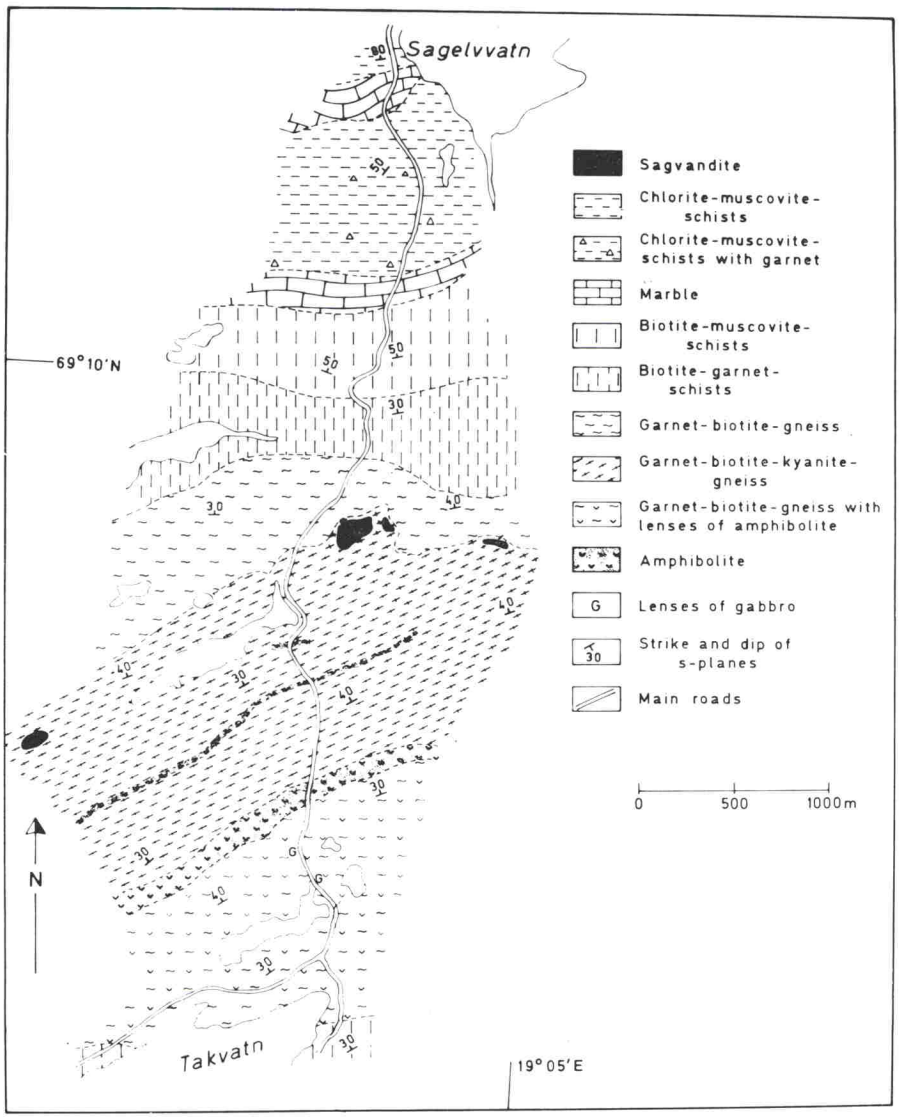

Fig. 2. Simplified geological map of the region south of Sagelvvatn revealing field relations around the 'classic' sagvandite locality (centre). Note that two new sagvandite occurrences were discovered along the strike to the south-west and east of the original locality. Topographical basis: Sheet 1533 III, Takvatnet, 1:50000, AMS Series of Norway.

morphism range from low-grade greenschists to high-grade amphibolites and gneisses. A survey of rock types encountered is provided by Landmark (1959) in his geological map (1:100000) of Målselv (Gradteig O7) which contains the 'classic' occurrence of the sagvandites at Sagelvvatn. During his field work in the Troms region, Landmark (pers. comm. 1967) also detected new occurrences of these rocks in other areas; the new occurrences were visited by the present authors and are taken into consideration in the



Fig. 3. Massive carbonate-orthopyroxenite (sagvandite) concordantly overlying strongly banded and schistose biotite gneisses. Note that schistosity follows the curved surface of the carbonate-orthopyroxenite body. Peninsula 3 km ENE of Lyngseidet near Kviteberg.

general description following. All occurrences known up to the present time are shown schematically in Fig. 1.

The carbonate-orthopyroxenites occur *exclusively in high-grade metamorphic terranes*. They were never found in greenschists or phyllites etc. Typical country rocks are coarse-grained, pelitic garnet–kyanite–biotite gneisses, dark amphibolites with or without garnets, and often, but *not necessarily*, lime silicate-bearing marbles. In the pelitic gneisses occasional granitoid schlieren indicative of partial melting may be observed. In some pelitic gneisses, instead of muscovite + quartz, the assemblage kyanite + K-feldspar, which is indicative of water-deficiency, was encountered. These high-grade metamorphic country rocks are usually confined to relatively narrow zones (some kilometres) which show relatively *rapid transitions into the lower-grade schists* thus probably implying steep temperature gradients during metamorphism. The area south of Sagelvvatn mapped in the course of the present study provides a good example (Fig. 2).

The contacts of the carbonate-orthopyroxenite bodies against their country rocks are, according to our observations, never of the discordant, intrusive type which one would expect for transgressive dykes filled by igneous material (Barth 1926). Detailed mapping has revealed that these bodies are essentially *lenses* of varying thickness (3–50 m) the contacts of which, in all cases, are *concordant* (Fig. 3) with the direction of the schistosity in the neighbouring metamorphic rocks (see also Barth 1926, Fig. 4 and Reitan & Geul 1958, Fig. 5). Usually several lenses are grouped together as shown

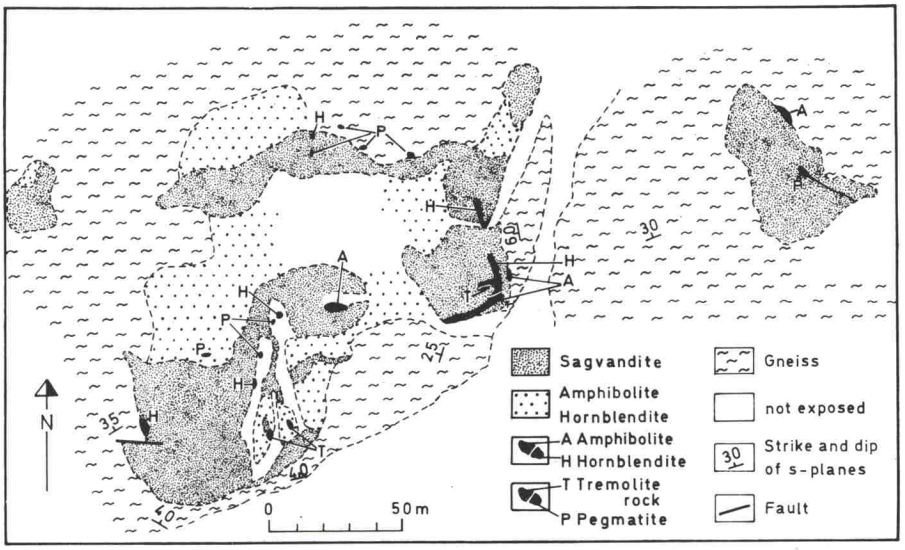

Fig. 4. Geological map of the type locality of the 'classic' sagvandite about 2 km south of Sagelvvatn showing in some detail the spatial relationships of the carbonate-orthopyroxenites (sagvandites) with associated other rock types which are predominantly massive like sagvandite and thus in textural contrast to the gneiss country rock occurring around the composite lenses.

in the detailed geological map of the 'classic' occurrence south of Sagelvvatn (Fig. 4).

Contrary to their gneissose country rocks the carbonate-orthopyroxenites are *massive* (Fig. 3), and are of considerably coarser grain size, only exceptionally exhibiting diffuse compositional banding. The carbonate-orthopyroxenites are spatially associated in a variety of ways with other rock types not to be regarded as country rocks (Fig. 4). Some of these associated rocks are simply rootless inclusions within the carbonate-orthopyroxenite lenses; others extend beyond the borders of the carbonate-orthopyroxenites and form a kind of matrix between different portions of composite lenses; finally there are cross-cutting veinlets of later origin occurring within the carbonate-orthopyroxenites. Due to limited exposure the spatial relationship cannot always be determined.

Most of the associated rock types such as garnet amphibolites, greenish tremolite rocks, and spinel-corundum veinlets are also massive, and thus in sharp textural contrast to the rocks outside the composite lenses, that is within the country rock series. The only rock types exhibiting strong schistosity despite their occurrence inside the lenses are later cross-cutting pegmatites and aplites, more properly termed *metapegmatites* and *metaaplites*, that contain biotite and occasionally corundum.

A characteristic and significant feature of all occurrences of carbonate-orthopyroxenites is the *blastomylonitization of their country rocks*. It shows that the high-grade metamorphic rocks occurring in narrow zones were

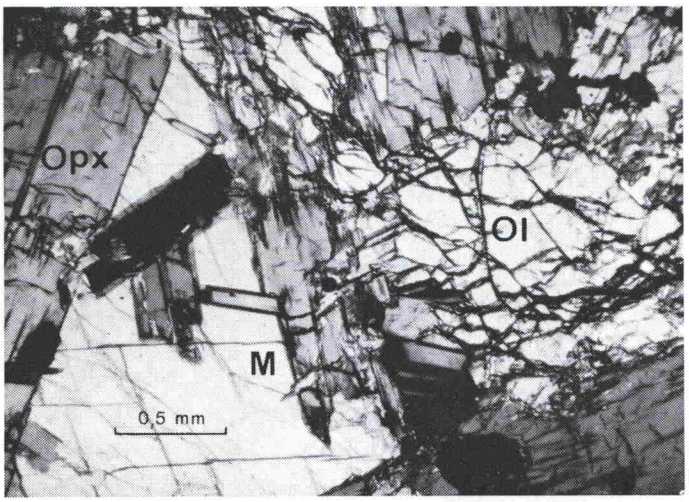

Fig. 5. Thin section photomicrograph showing corroded relic of olivine (Ol) surrounded by large crystals of orthopyroxene (Opx) and magnesite (M). Olivine-bearing carbonate-orthopyroxenite, 2 km south of Sagelvvatn.

affected at a late stage by intense shearing resulting in mylonitization, cataclasis of all high-grade minerals, and formation of densely distributed shear planes exhibiting partial recrystallization of quartz and minute biotite flakes. The newly formed shear planes are essentially concordant with the earlier schistosity and, consequently, also follow the borders against the composite lenses containing the carbonate-orthopyroxenites. It is clear that the metapegmatites and -aplites which intruded these lenses were also subjected to the late blastomylonitic deformation. This indicates that even the lenses themselves must have been affected by the late penetrative movements although to a much lesser extent due to their massive nature and competent behaviour. However, in some places narrow shear zones of cm widths exhibiting pronounced schistosity and containing talc and fibrous anthophyllite (asbestos) can be observed even macroscopically within the lenses.

Petrography

Only the more common and genetically significant rock types found in the carbonate-orthopyroxenite lenses will be described here.

Magnesite-orthopyroxenites represent, as a sub-group of carbonate-orthopyroxenites, the 'classic sagvandites' of the type locality. These coarse-grained greyish to brownish rocks contain 70–90% of enstatite/bronzite often forming rosettes of prisms up to 12 cm long, and 10–30% magnesite/breunnerite filling the interstices. Small amounts of corroded olivine grains (about $forsterite_{90}fayalite_{10}$) may be observed occasionally (Fig. 5). Accessories are phlogopite, chlorite, chromite-rich spinel, pentlandite, and pyrite. Small amounts of talc (and anthophyllite) formed at the expense of enstatite

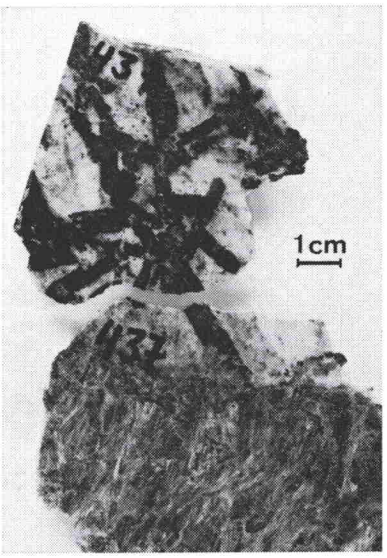

Fig. 6. Photograph showing, in the lower portion, the contact between carbonate-orthopyroxenite and olivine-magnesite rock. The upper portion displays the olivine-magnesite rock in some more detail. Note the corrosion of the formerly euhedral olivine crystals through partial replacement by magnesite. 2 km south of Sagelvvatn.

may or may not be related to the blastomylonitic deformation. Serpentine is the result of the latest retrograde alteration.

Tremolite-carbonate-orthopyroxenites may be the best term for the 'sagvandite-like' material occurring in the Lyngenfjord area. In addition to the coarse enstatite/bronzite (up to 80–90%) these rocks contain macroscopically visible light green crystals of Cr-bearing tremolite and usually both magnesite and dolomite. The total carbonate contents are generally smaller than in the magnesite-orthopyroxenites. Olivine may be completely absent, but, in some cases, has been found in large subhedral prisms intergrown with orthopyroxene. The accessories are identical with those mentioned for the magnesite-orthopyroxenites.

Olivine-magnesite rocks form schlieren in the magnesite-orthopyroxenites and are the prime reason for the diffuse compositional banding mentioned previously. A contact of olivine-magnesite rock versus magnesite-orthopyroxenite is shown in Fig. 6. The most important feature of the olivine-magnesite rocks is the predominance of carbonate over silicate which is opposite to the relationship found in the carbonate-orthopyroxenites. Thus the carbonate constitutes a kind of groundmass around the isolated large, formerly euhedral prisms of olivine ($forsterite_{90}fayalite_{10}$).

Hornblendites and *amphibolites* are closely associated with the carbonate-orthopyroxenites. They may be massive or schistose depending on whether they occur inside or peripheral to the composite carbonate-orthopyroxenite lenses, respectively. Whereas hornblendites consist almost entirely of greenish-brown hornblende, the amphibolites contain appreciable amounts of intermediate plagioclase. In addition, diopsidic augites may be present. Furthermore these rocks are often modified by the occurrence of small or

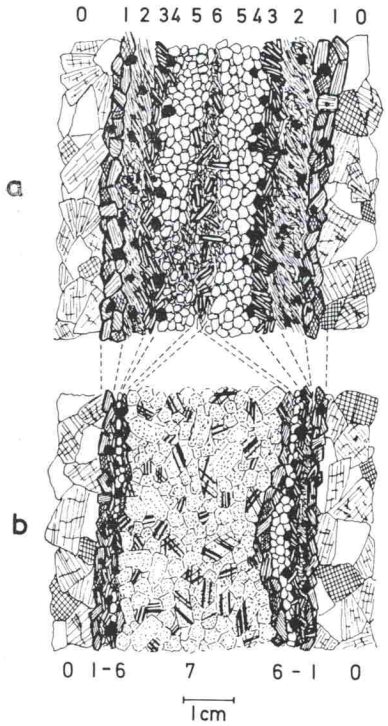

Fig. 7. Zoning of spinel veinlet (a) and corundum veinlet (b):
0 = carbonate-orthopyroxenite; 1 = tremolite zone; 2 = outer phlogopite zone; 3 = outer chlorite zone; 4 = zone of chromite enrichment; 5 = spinel zone; 6 = inner phlogopite zone with bulky chlorite crystals and/or clinoamphibole; 7 = corundum zone. The corundum crystals are often twinned and contain zonal inclusions as indicated in the drawing. Locality for (a) Lyngseidet, for (b) Furuflaten (cf. Fig. 1).

large porphyroblasts (up to 8 cm in diameter) of garnet (grandite-almandine-pyrope). As in the famous occurrence at Gore Mountain, New York (Bartholomé 1958), the garnets of the amphibolites are surrounded by a zone of hornblendite. Some varieties of amphibolite show scapolite replacing plagioclase.

Tremolite rocks consisting almost entirely of this mineral occur as greenish, dyke-like bodies within the carbonate-orthopyroxenites; they are, however, usually related in space to massive amphibolites or hornblendites (Fig. 4). A genetic relationship between the tremolite rocks and the carbonate-orthopyroxenites is evident from the occurrence of transitional *tremolite-enstatite rocks* as well as from accessory chromite crystals appearing in all three rock types. On the other hand, monomineralic tremolite rocks were also found as thin layers in marbles forming the country rock of some Lyngen carbonate-orthopyroxenites.

Spinel- and corundum veinlets have been found exclusively in the tremolite-carbonate-orthopyroxenites of the Lyngen area, where they attain widths of some 5 cm. In these unusual, if not unique rocks, either spinel or corundum is commonly the dominant aluminous phase present. Macroscopically, corundum forms white, spinel blue, equidimensional, interlocking grains, which are concentrated in a central zone of the veinlet amounting to up to 90% of its total width. The spinels are colourless or bluish-green to green

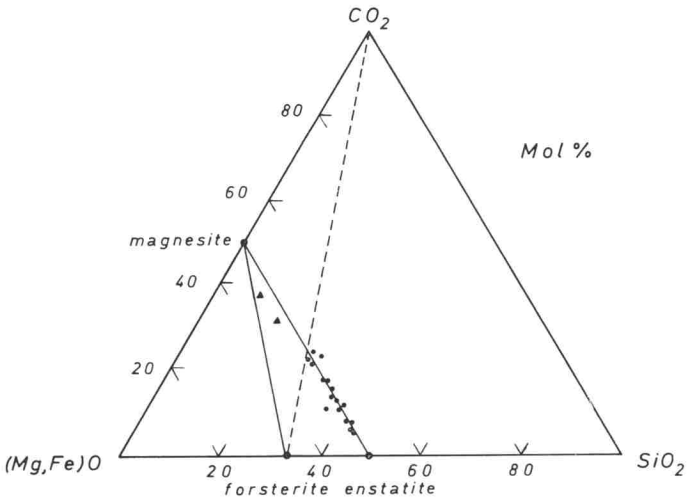

Fig. 8. Triangular plot (Mg, Fe) O–SiO_2–CO_2 showing projection points of chemical analyses of 16 carbonate-orthopyroxenites (small solid circles) and 2 olivine-magnesite rocks (solid triangles) from the locality south of Sagelvvatn. The solid tie line enstatite-magnesite is stable only at relatively low temperatures; the dashed one from forsterite to CO_2 develops at higher temperatures (cf. Fig. 9).

in thin section and represent various intermediate members of the series $MgAl_2O_4$–$FeAl_2O_4$. Some of the spinels contain smaller grains of chromite-rich spinel which is also an accessory mineral in the adjacent carbonate-orthopyroxenites. The spinel and corundum crystals within the vein are separated from the carbonate-orthopyroxenite by zoned selvages of MgAl-rich chlorite, phlogopite, and tremolite arranged in the order depicted in Fig. 7.

Spinel-olivine-amphibole rocks were found as inclusions within or as contact zones against the carbonate-orthopyroxenites of Lyngen. The amphiboles comprise green and brown varieties as well as orthorhombic and monoclinic members. Preliminary microprobe analyses indicate Na-rich gedrites and Ca-rich hornblendes. Spinel is green in thin section and has a composition along the join $MgAl_2O_4$–$FeAl_2O_4$. Olivine is often intergrown with large porphyroblastic crystals of MgAl-chlorite. Accessory phases include phlogopite and carbonates.

Garnet-amphibole rocks occurring in a contact zone around the Lyngseidet carbonate-orthopyroxenite body must be distinguished from the garnet hornblendites and garnet amphibolites mentioned earlier because of the coexistence of two amphiboles: The orthorhombic and monoclinic members are similar to those of the spinel-olivine-amphibole rocks mentioned above. These amphiboles may vary in amount from a few percent — so that the rock is a garnetite — to nearly one hundred percent. The garnet is rich in the pyrope component. Additional phases are green spinel and some corundum.

Pegmatites and *aplites* crosscutting the carbonate-orthopyroxenites, but also occurring as schlieren and dykes in the directly adjacent country rocks, are often schistose *metapegmatites* and *metaaplites*. Their predominant mineral is zoned plagioclase (An_{23} to An_{32}). Some metapegmatites contain additional quartz, biotite, and K-feldspar, in others corundum appears. The latter rocks might be called '*plumasites*' .

Chemistry

A total of 26 wet chemical analyses was made of various types of carbonate-orthopyroxenites from Troms using the methods described by Langer (1971). The composition of 16 samples from Sagelvvatn is shown diagrammatically in terms of (MgO, FeO), SiO_2, and CO_2 in Fig. 8 (small solid dots). Table 1 lists the analytical data for 4 carbonate-orthopyroxenites from two localities considered characteristic for the range of compositions covered by this unusual rock type. Total iron is given as FeO; H_2O has not been determined, but must be below 1% because of the small amounts of hydrous minerals observed. The two carbonate-orthopyroxenite analyses exhibiting the highest CO_2 values were also recalculated on a CO_2-free basis. For comparison analyses of ultramafic, non-carbonate-bearing rocks taken from the literature and recalculated on a H_2O-free basis are included.

Even on a CO_2-free basis, the carbonate-orthopyroxenites display a considerable variation in SiO_2 (42 to 55 wt %). This indicates that these rocks can by no means all be grouped with the ultrabasic rock suite as defined by Wyllie (1967) with $SiO_2 < 45\%$. On the basis of the comparative analyses shown in Table 1 it may be concluded that some carbonate-orthopyroxenites have an overall chemical composition (disregarding CO_2) close to that of dunitic peridotites, whereas others approach the chemistry of true orthopyroxenites. Characteristic in all cases are the relatively high amounts of Cr_2O_3 and NiO.

Petrogenetic discussion

On the basis of their field relations the carbonate-orthopyroxenites ('sagvandites' in a wide sense) cannot be considered as primary, unaltered, *in situ* crystallization products of an intruded magma. Undoubtedly the rocks have undergone periods of metamorphism which are at least partly identical with those endured by their primarily metasedimentary country rocks. However, on the basis of their mineralogical and chemical composition it is also extremely improbable that these rocks represent modified metasediments themselves: The occurrence of chromite-rich spinel and pentlandite, and the high concentrations of Ni and Cr (Table 1) as well as of Pt (Barth 1926) place them with a high degree of certainty among the series of peridotitic to pyroxenitic rocks of magmatic and /or mantle origin. The only component unusual in high amounts for the chemistry of such rocks is CO_2.

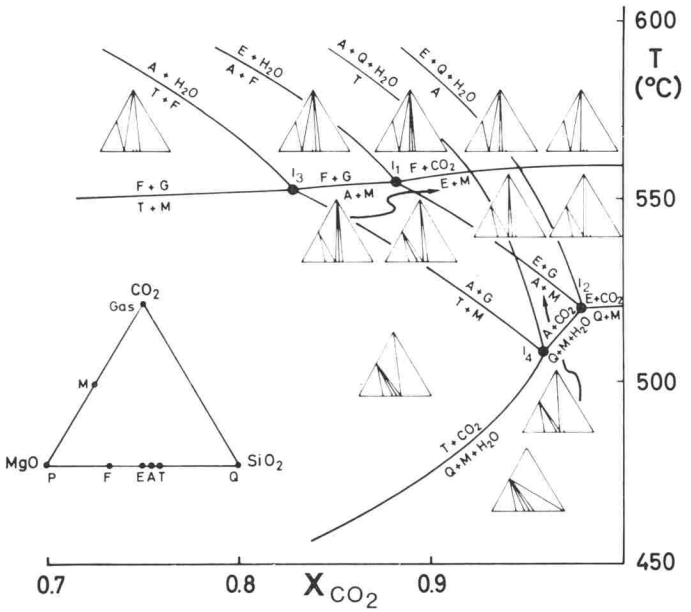

Fig. 9. Partial TX_{CO_2}-diagram for the system MgO–SiO_2–CO_2–H_2O at P_{fluid} = 2 kb showing the stability fields of mineral assemblages coexisting with a CO_2-rich gas phase; redrawn after Johannes (1969). P = periclase, F = forsterite, E = enstatite, A = Mg-anthophyllite, T = talc, Q = quartz, M = magnesite, G = gas. Solid circles with symbols I_1–I_4: Isobaric invariant points. The compatibility triangles represent projections from the H_2O apex onto the water-free base. Therefore, the extent of the gas-deficient region and its subdivision as a function of T cannot be shown adequately. Note, however, that according to the phase rule four solid phases may coexist in the absence of a gas phase. Note also that the three phases enstatite, forsterite, and magnesite with or without a fourth solid phase represent a gas-deficient assemblage at temperatures below some 550 °C.

It thus seems plausible that the carbonate-orthopyroxenites represent ultrabasic to basic material modified through the introduction of CO_2.

It is significant that olivine crystals have been found as corroded relics within the carbonate-orthopyroxenites described (Fig. 5). Whereas in some cases the replacing assemblage can be shown to be orthopyroxene + magnesite, it is only orthopyroxene in others. These observations together with chemical reasoning (see later) seem to suggest two reactions:

$$\underset{\text{Olivine}}{(Mg, Fe^{+2})_2SiO_4} + CO_2 \rightarrow \underset{\text{Orthopyroxene}}{(Mg, Fe^{+2})SiO_3} + \underset{\text{Magnesite/Breunnerite}}{(Mg, Fe^{+2})CO_3} \quad (1)$$

$$\underset{\text{Olivine}}{(Mg, Fe^{+2})_2SiO_4} + SiO_2 \rightarrow 2\underset{\text{Orthopyroxene}}{(Mg, Fe^{+2})SiO_3} \quad (2)$$

Since the left side of equation (2) represents an obvious case of disequilibrium, the reacting SiO_2 must have been introduced at the time of the reaction itself, probably together with the CO_2 necessary to initiate reaction (1). Whereas the production of orthopyroxene by means of reaction (2) is possible throughout the stability field of orthopyroxene, the question remains as to

Table 1. Wet chemical analyses of four carbonate-orthopyroxenites and two other ultramafic rocks.

Sample	124	129	274	384	274**	384**	H**	675**
SiO_2	54.6	52.4	33.6	47.7	42.0	52.4	42.8	56.1
TiO_2	<0.05	0.05	0.1	0.1	0.1	0.1	0.01	0.4
Al_2O_3	1.4	1.0	0.9	1.0	1.1	1.1	1.5	2.1
Cr_2O_3	1.1	0.8	0.8	0.4	1.0	0.4	0.26	
FeO*	6.5	6.2	7.3	7.2	9.1	7.9	7.6	9.9
MnO	0.15	0.13	0.22	0.09	0.28	0.10	0.17	
NiO	0.20	0.18	0.24	0.30	0.30	0.33	0.27	
MgO	31.3	31.1	36.6	34.1	45.8	37.4	45.2	29.7
CaO	1.5	4.2	0.2	0.2	0.3	0.2	2.2	1.7
Na_2O	0.1	0.1	<0.05	n.d.	<0.06	n.d.		
K_2O	0.2	0.05	0.05	<0.05	0.06	<0.05		
P_2O_5	<0.01	<0.01	n.d.	<0.01	n.d.	<0.01		
CO_2	0.9	2.7	19.0	6.6				
	98.0	98.9	99.0	97.7	100.1	100.0	100.0	100.0

* Total iron as FeO; Fe_2O_3 contents of H** and 675** were recalculated to FeO.
** These analyses were recalculated on a CO_2- and H_2O-free basis. n.d. = not detected.
124 and 129: Tremolite-carbonate-orthopyroxenites (containing both magnesite and dolomite), ENE of Lyngseidet, Troms, Norway. Lab. No. 125 and 128.
274 and 384: Carbonate-orthopyroxenites (with magnesite only), S of Sagelvvatn, Troms, Norway. Lab. No. 140 and 148.
H**: Peridotite, Klet, Czechoslovakia (Rost 1966, Tables 14 and 15, analysis H).
675**: Bronzitite, Marico District, West Transvaal (Tröger 1935, No. 675).

the specific pressure temperature conditions under which magnesite can coexist with the orthopyroxene. This problem has recently been studied both theoretically and experimentally by Greenwood (1967) and Johannes (1969, 1970) working independently within the model system MgO–SiO_2–CO_2–H_2O. The resulting phase relations for 2 kb fluid pressure (= total pressure) are reproduced in the TX_{CO_2}-diagram of Fig. 9. The assemblage enstatite + magnesite + gas is confined both to a relatively narrow temperature range (520–560 °C) and X_{CO_2}-range ($\sim$0.87–1.0). Thus, for the pressure considered, this assemblage can only form if the coexisting gas phase is very rich in CO_2 and poor in H_2O. Only slightly higher H_2O contents would lead to the replacement of enstatite by anthophyllite coexisting with magnesite at approximately the same temperature. At temperatures exceeding some 550–560 °C the assemblage enstatite-magnesite breaks down to form forsterite that is compatible with free CO_2 following reaction (1) in the reverse direction.

On the basis of the phase relations depicted in Fig. 9 and the microscopic observations it seems most plausible that the carbonate-orthopyroxenites described were *formed from formerly olivine-bearing ultramafic rocks through the introduction of* CO_2, while temperatures were decreasing and/or while X_{CO_2} was increasing. Under the provision that only CO_2 was introduced and none of the silicates were lost, the resulting rocks should contain the newly formed silicate and carbonate minerals in fixed amounts, that is, in the 1:1

molar ratio derived for equation (1). However, the ratios orthopyroxene/carbonate observed microscopically and determined through chemical analyses (Fig. 8) differ drastically from this value in many cases with orthopyroxene strongly predominating. The authors interpret this fact, which is also reflected in the high SiO_2-values of some of the analyses of carbonate-orthopyroxenites (cf. Table 1), as additional evidence for the introduction of SiO_2 concomitantly with CO_2. An alternative hypothesis that the ultramafic starting materials did not consist of olivine only (as dunites), but contained variable amounts of primary orthopyroxene (as saxonites) may hold in some cases, where relic saxonitic portions enclosed within the carbonate-orthopyroxenites were found.

In Fig. 8 two analyses of *olivine-magnesite rocks* interlayered with magnesite-orthopyroxenites are also plotted. In addition this diagram shows the tie lines between coexisting phases valid for the PTX_{CO_2}-conditions necessary for the formation of the assemblage enstatite–magnesite–gas (cf. Fig. 9). Under these conditions, the assemblage olivine-magnesite is only stable in the absence of a CO_2-rich gas phase. However, Fig. 9 reveals that this assemblage would coexist with a gas phase if the equilibrium conditions for reaction (1) were surpassed for example by a local increase in temperature. A further difficulty in unravelling the petrogenesis of the olivine-magnesite rocks stems from the large amounts of magnesite present (Fig. 8). If one recalculates these analyses on a CO_2-free basis, i.e. projects them in Fig. 8 from the CO_2 corner onto the (Mg, Fe)O–SiO_2 side of triangle, they plot between olivine and periclase. Since, with the exception of the geochemically unique carbonatites, no primary ultrabasic rocks of such high silica-deficiency are known, the olivine-magnesite rocks cannot be explained through the sole introduction of CO_2, but a concomitant *loss* of SiO_2 or, alternatively, *gain* of MgO has to be assumed in addition. As a further alternative the possibility has been considered that these olivine-magnesite schlieren represent locations within the magnesite-orthopyroxenites, where magnesite has been concentrated in a mechanical fashion, i.e. through plastic flow of the mobile carbonate relative to the more rigid orthopyroxene. However, this hypothesis does not explain the occurrence of large olivine crystals and their apparent replacement by magnesite (cf. Fig. 6).

The explanation of the occurrence of *tremolite and dolomite* in addition to enstatite and magnesite within the Lyngen carbonate-orthopyroxenites is also somewhat ambiguous. No doubt these two additional mineral phases are the result of generally more Ca-rich bulk compositions of the Lyngen rocks versus those found in the 'classic' occurrences of the Sagelvvatn area (cf. Table 1). The question remains open, however, as to whether this Ca was already present in the ultramafic starting materials, e.g. as diopside in lherzolites, or whether it had also been introduced together with CO_2 and SiO_2.

Despite some uncertainties discussed above, the conclusion is that the carbonate-orthopyroxenites are *metasomatically modified* ultramafic, perido-

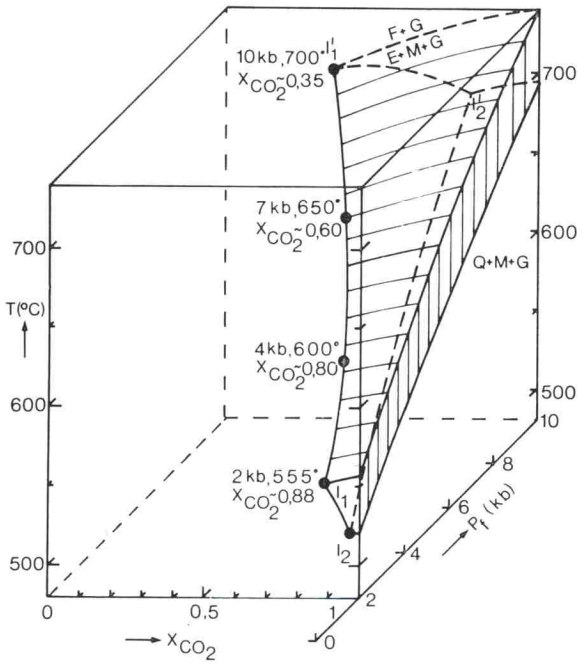

Fig. 10. Three-dimensional P–T–X_{CO_2}-diagram for the conditions $P_{fluid} = P_{total}$ showing the stability volume of the assemblage enstatite + magnesite + gas. Abbreviations as in Fig. 9. The solid dots accompanied by values for P, T, and X_{CO_2} represent locations of the isobaric invariant point I_1 (cf. Fig. 9) at higher pressures ($\rightarrow I_1'$) according to Johannes (1970). The line I_2–I_2' limiting the stability volume towards lower temperatures is based on an estimate by Johannes (pers. comm. 1971). The high-temperature limit of the stability volume is given by the curve valid for the reaction enstatite + magnesite = forsterite + CO_2 at $X_{CO_2} = 1$. The temperature chosen (740 °C at 10 kb) is in agreement with Johannes's (1970) estimate. Note that the curve I_1'–I_2' exhibits a temperature maximum at $X_{CO_2} = 0.5$.

titic rocks. Therefore, in this petrogenetic discussion three more problems related to their specific occurrences in the Troms region will have to be included:

1. What are the relations between the physical conditions necessary for the metasomatic reaction (1) and the metamorphic grade prevailing in the country rocks of the carbonate-orthopyroxenites?
2. What was the mechanical state of the ultramafic rocks during metasomatism?
3. What are the sources from which the components introduced into the primary ultramafic rock can be derived?

Problem 1: Physical conditions of metasomatism. Whereas the TX_{CO_2}-diagram of Fig. 9 is valid only for 2 kb, a recent paper by Johannes (1970) gives an estimate on the stability relations of the enstatite-magnesite assemblages at higher total pressures. The T- and X_{CO_2}-values for the locations of the isobaric invariant point I_1 (Fig. 9) as a function of pressure as given by Johannes (1970) allow the construction of the three-dimensional PTX_{CO_2}-

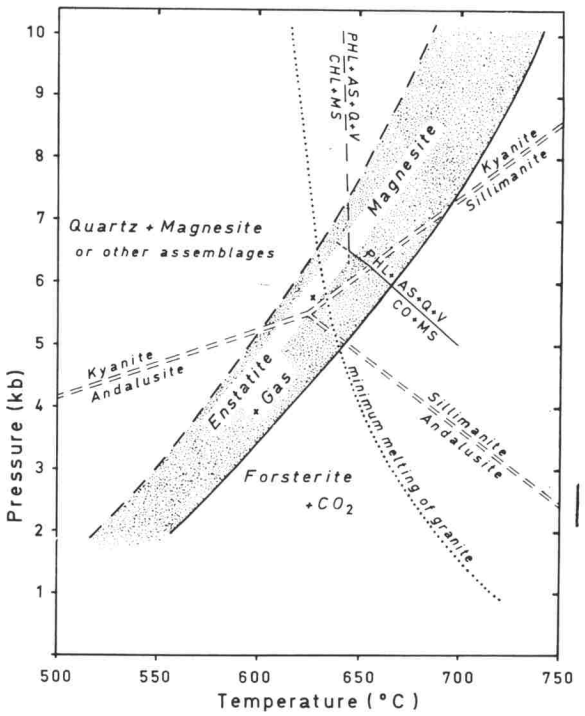

Fig. 11. Pressure-temperature plot for the conditions $P_{fluid} = P_{tot}$ displaying the estimated stability range for the assemblage enstatite + magnesite as deduced through projection of Fig. 10. For geothermometric and geobarometric comparisons the stability fields of the Al_2SiO_5 polymorphs and of the assemblage phlogopite + Al_2SiO_5 + quartz as well as the minimum melting curve of granite have been added. For discussion and references see text. Abbreviations: AS = Al_2SiO_5, CHL = chlorite, CO = cordierite, MS = muscovite, PHL = phlogopite, Q = quartz, V = vapor.

diagram of Fig. 10, which shows an enstatite–magnesite–gas volume of considerable size the more so the higher the pressure and the temperature. Thus with increasing pressures the limiting CO_2-content of the gas phase necessary for the formation of the enstatite-magnesite assemblage will decrease towards fairly low values.

Provided Johannes's (1970) extrapolations are valid, Fig. 10 can also be used as the basis for estimating a total pressure-temperature stability range for enstatite-magnesite rocks. Fig. 11 presents such an estimate, which assumes for the whole pressure temperature band a similar width in temperature as that determined by Johannes (Fig. 9) for 2 kb total pressure. For all pressure/temperature conditions inside the band it is assumed that the X_{CO_2} values are high enough in order to maintain the enstatite–magnesite–gas assemblage in stable equilibrium. At higher temperatures and/or lower pressures than those included within the band enstatite and magnesite react to form forsterite + CO_2; at lower temperatures and/or higher pressures they break down into other assemblages such as quartz + magnesite or talc + magnesite depending on X_{CO_2} (cf. Fig. 9).

It is interesting to compare this pressure/temperature stability field for enstatite-magnesite rocks with stability data for mineral assemblages present in the neighbouring country rocks of the Troms carbonate-orthopyroxenites. In this context only one example is selected, namely, the assemblage of kyanite with biotite and quartz often occurring in pelitic compositions. It can be seen from Fig. 11 that the lower pressure stability limit for kyanite alone (Richardson et al. 1969) intersects the enstatite-magnesite band at pressures and temperatures near the Al_2SiO_5 triple point. The coexistence of kyanite with biotite and quartz places additional restrictions on the pressure temperature conditions under which the country rocks formed. As a limiting case the stability range for the assemblage kyanite-pure Mg–phlogopite–quartz as shown by Schreyer & Seifert (1969) and more recently verified experimentally by Bird (pers. comm. 1971) has been outlined in Fig. 11. The influence of iron resulting in the formation of normal biotite will undoubtedly shift the lower temperature stability limit of that assemblage to somewhat lower temperatures. Yet the granitoid schlieren occasionally found in the pelitic country rocks suggest that pressure temperature conditions above the granitic minimum as determined by Luth et al. (1964) were prevailing (cf. Fig. 11). Thus metamorphic conditions of at least some 630 °C and 6 kb may be estimated. In the case of water deficiency during partial melting the minimum values would be increased (Brown & Fyfe 1970).

On these grounds the following general conclusion of importance for the genesis and history of the carbonate-orthopyroxenites of Troms seems to be justified: In principle, the rocks may have reacted to develop their present mineralogy *in close juxtaposition and simultaneously with their present country rocks under essentially identical conditions of total pressure and temperature.* The only constraint on the origin of the carbonate-orthopyroxenites is, depending on total pressure, the relatively high partial pressure of CO_2 versus that of H_2O (i.e. high X_{CO_2}). It seems possible that high X_{CO_2} also prevailed locally in the pelitic country rocks; this would help to explain the occasional water-deficiency of these rocks as indicated by the assemblage kyanite–K–feldspar, which is probably totally unstable in the presence of excess water (Lambert et al. 1969). In this connection it may be of interest to note that Touret (1971) has found high CO_2 fractions in fluid inclusions of the granulite rocks of southern Norway.

Problem 2: Mechanical state during metasomatism. This problem is related in a general way to the much discussed question of emplacement of peridotitic rocks as a whole. According to present petrological knowledge such rocks can either form as crystal accumulates from a liquid at the base of layered basic intrusions or they may represent largely solid fragments of the earth's upper mantle transported tectonically into crustal environments. A more detailed discussion has been given by Seifert & Schreyer (1968). However, based on experimental evidence, those authors submitted the additional possibility that rocks largely consisting of olivine may also have

intruded as low temperature crystal mushes provided small amounts of K_2O and H_2O had been present which escaped later.

The mode of emplacement of the premetasomatic ultramafic rocks later leading to the carbonate-orthopyroxenites of Troms is, of course, practically impossible to reconstruct, although the occurrence of phlogopite in these rocks attests the presence of K_2O and H_2O. On the other hand, it is likely from the tectonic pattern of the carbonate-orthopyroxenites in relation to their country rocks, that these ultramafic materials were *in the solid state* during most of the metasomatic reactions and afterwards, i.e. they behaved as rigid, competent masses against their country rocks thus producing lens-shaped bodies surrounded concordantly by the more plastic metasedimentary material exhibiting partial melting (Fig. 3). This deduction is in agreement with the experimental results of Johannes (1969) who concluded for the K-free system that the assemblage enstatite–magnesite–gas cannot exist 'at the high temperatures which would be expected for a "sagvandite magma" '.

Thus the massive fabric of the carbonate-orthopyroxenites not exhibiting preferred orientation cannot be explained by crystallization from a liquid. It is likely to be the result of metasomatically induced mineral reactions in already rigid, unsheared bodies under locally hydrostatic conditions enhanced by the metasomatizing gas phase (fluid).

Problem 3: Derivation of the metasomatizing fluid. Although Si, and possibly Ca, may have been introduced into the carbonate-orthopyroxenites described, by far the most prominent component to be added to the ultramafic starting material is CO_2. It is highly probable that this mobile component was derived from metasedimentary carbonate rocks (impure limestones, etc.) that were in juxtaposition, or close proximity, to the ultramafic, peridotitic lenses. This can be demonstrated for all carbonate-orthopyroxenite occurrences in the Lyngen area, which are closely associated with strongly metamorphosed tremolite- and diopside-bearing marbles. A brief survey of mineral reactions taking place in siliceous dolomites and other carbonaceous sediments during progressive metamorphism (e.g. Bowen 1940, Metz & Trommsdorf 1968) reveals that they release CO_2 in nearly all cases, whereas dehydration takes place in a more subordinate manner. Thus progressive metamorphism of metasedimentary impure carbonate rocks will produce highly CO_2-rich, water-bearing fluids which are also likely to carry minor amounts of Si and Ca.

Provided this mechanism is correct, the difficulty remains that at the 'classical' occurrence of 'sagvandite' at Sagelvvatn and several other localities of carbonate-orthopyroxenites shown in Fig. 1, no neighbouring metasedimentary carbonate rocks were found. At Sagelvvatn the nearest marble outcrop is some 1.5 km away and, moreover, represents a very low degree of metamorphism (cf. Fig. 2). A common feature of all carbonate-orthopyroxenites in Troms is their occurrence in blastomylonitic shear zones that

were active even after the emplacement and metasomatic changes of the ultramafic lenses themselves. It is, therefore, possible that tectonic transport of carbonate-orthopyroxenite lenses along shear planes has continued even beyond the processes of metasomatism and thus effectively separated the metasomatized rocks from their earlier carbonate-bearing country rocks. An alternative or even additional mechanism might be that the CO_2-rich fluids emanating from the carbonaceous sediments found channels leading into shallower crustal levels preferentially along such shear planes, where they caused the metasomatism of ultramafic rocks.

Under these circumstances one major prerequisite for the development of carbonate-orthopyroxenites from peridotitic materials in orogenetic belts would be a high frequency of marbles within the metasedimentary sequence. This condition is generally fulfilled in the Caledonian rock suites of the Troms region as shown in Fig. 1 (e.g. Landmark 1959). The fact remains to be explained, however, that ultramafic lenses occurring in *low-grade* metamorphic areas of this region (e.g. the serpentinites of Fiskelausvatn, Landmark 1959) exhibit mineral assemblages (e.g. serpentine-magnesite) which are indicative of very low CO_2- and high H_2O-contents in the coexisting gas phase (cf. Johannes 1969, 1970). It is most likely that the low X_{CO_2} values governing the mineralogy of these rocks are due mainly to the low grade of metamorphism itself in which the carbonate-releasing reactions within adjoining impure marbles have not yet taken place.

Conclusions bearing on the geological history

The carbonate-orthopyroxenites ('sagvandites' in a wide sense) of the Troms region represent metasomatically modified peridotitic ultramafic rocks that may be part of an 'ophiolitic' sequence including so-called 'alpine type peridotites'. The premetasomatic rocks may or may not have been of mantle origin. It is possible, but not proven that the rocks have gone through a serpentinite stage before or during their emplacement and before metasomatism. Typical olivine deformation fabrics of alpine type peridotites (cf. den Tex 1969) have never been observed as relic structures within the carbonate-orthopyroxenites. On the other hand, some rare very coarse-grained olivine-orthopyroxene rocks (saxonites) without magnesite indicate that CO_2-metasomatism can affect an anhydrous, non-serpentine-bearing ultramafic rock. Thus, if serpentine was present at an earlier stage of the geologic history of the carbonate-orthopyroxenites, it must have broken down prior to the introduction of CO_2 to form the carbonates. A former serpentinite stage could partly explain the relatively high SiO_2 contents found for the carbonate-orthopyroxenites.

The stability relations summarized in Fig. 11 suggest that the carbonate-producing reaction in the ultramafic rock took place within the lower parts of the earth's crust during a regional metamorphism that required (under lithostatic conditions) an overburden of some 20–25 km. The amphibolites

and hornblendites associated with the carbonate-orthopyroxenites were formed from either calcareous pelites or basic igneous rocks during this metamorphism.

At a later stage, but still during high-grade metamorphism, granitic and pegmatitic liquids and fluids mobilized within the pelitic country rocks must have percolated along fissures through the carbonate-orthopyroxenites. These liquids and fluids crystallized as either normal quartz-bearing pegmatites or — through reaction with the ultramafic material — as desilicated pegmatites with corundum. Extreme cases of desilication are probably the veinlets of spinel and/or corundum, their assumed origin being supported by the occasional occurrence of zircon and uraninite within them.

Whereas the high-grade metamorphism including the CO_2-metasomatism as well as the pegmatitic penetration may have taken place during a period of relative tectonic quiescence, the latest pre-weathering events in the geological history of the carbonate-orthopyroxenites are intensive shearing, deformation, and blastomylonitization occurring primarily within their country rocks. It is likely that during these events at least some of the carbonate-orthopyroxenite lenses were dislocated and transported tectonically along shear zones. On the other hand, the regional tectonic significance of the zones of blastomylonitization, their strange coincidence with the narrow zones of high-grade regional metamorphism, and their possible relationships to major nappe structures within the Caledonian mountain belt are open problems. They can only be attacked in collaboration with geologists working on a regional scale.

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