THE PETROGRAPHY AND POSSIBLE REGIONAL SIGNIFICANCE OF THE HJELMKONA ULTRAMAFIC BODY (SAGVANDITE), NORDMØRE, NORWAY

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The Hjelmkona ultramafic body crops out in upper amphibolite facies rocks of the Basal Gneiss Complex of western Norway, dated at 1,700 m.y., and it consists dominantly of carbonate-bearing harzburgites (sagvandites) with associated chromitites. The earliest recognisable mineral assemblages (olivine plus orthopyroxene) are metamorphic in origin and have undergone late stage CO_2-metasomatism. Similar rocks are found in high-grade metamorphic gneisses elsewhere in west Norway. The proposal is made that these distinctive types of ultramafic rocks are characteristic of much of the Basal Gneiss Complex and may provide a basis for correlation.

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The Hjelmkona ultramafic body crops out near the peak of Hjelmkona (846 m above sea level) between Valsøyfjorden and Hamnesfjorden in Nordmøre. It is one of a number of pod-like ultramafic bodies found in the Basal Gneiss Complex of Nordmøre, east of Kristiansund N (Fig. 1A). The gneisses form a high-grade metamorphic sequence (almandine-amphibolite facies), including some minor marble and calc-silicate horizons, and have been dated at about 1,700 m.y. (Pidgeon & Råheim 1972, Råheim 1974). These carbonate-bearing ultramafic rocks have been termed sagvandites (Pettersen 1883). The Hjelkkona ultramafic body contains chromitite pods and attempts were made to mine these in the early part of the century. It is referred to by Foslie (1925) as Hjelmen Grube.

Petrography and mineralogy

The Hjelmkona body forms an elongate mass, approximately 150 m by 75 m in plan, and is concordant with the surrounding gneisses. It forms two lobes in the form of an open antiform (Fig. 1B) with the lobes separated by a narrow strip of gneiss. This gneiss has a marked vertical schistosity parallel to northwest trending joints and may reflect a sequence 'nipped in' between the more competent ultramafic rocks at an early stage in the deformation (e.g. Ramsay 1967, fig. 7–44). This quartzo-feldspathic biotite gneiss also contains garnet (5 %) and hornblende (20 %) which occur as discrete

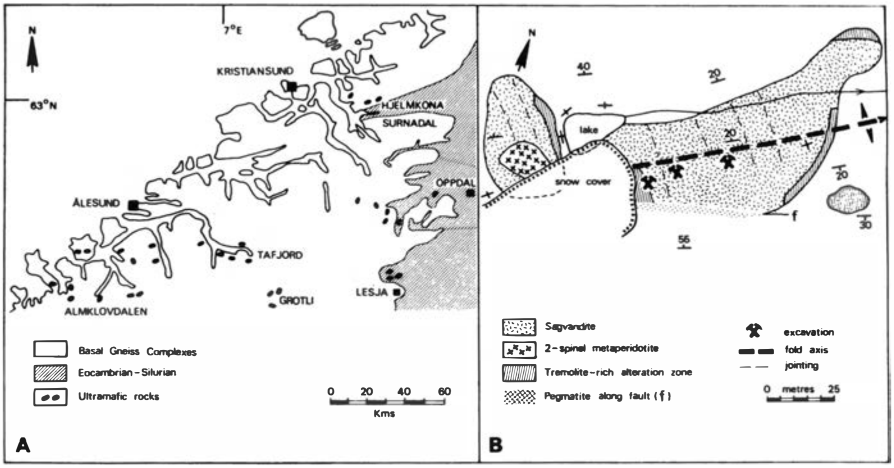

Fig. 1A. Locality map of the Hjelmkona ultramafic body in Nordmøre.
1B. Sketch map of the Hjelmkona ultramafic body.

grains and as rims around relic orthopyroxene and clinopyroxene. The ultramafic rocks are generally massive and coarse-grained although schistosity is locally well-developed and a compositional banding is found. Within the ultramafic rocks three S-surfaces are recognised. The first is a penetrative schistosity (S_1) which outlines the antiformal structure of the body. Where the compositional banding is recognised this is also parallel to S_1, as is the dominant schistosity of the surrounding gneisses. It is the direction of easiest parting of the rocks and is most strongly developed at the western and eastern extremities. The second (S_2) is a weak, vertical, penetrative schistosity parallel to the fold-axial plane and is best seen in exposures near the fold axis. The third (S_3) is a vertical jointing, striking northwest, which corresponds to the orientation of the axial planes of small, late-stage open folds seen in the surrounding gneisses.

Contacts against the surrounding gneisses are not everywhere exposed but those at the eastern end show an alteration zone of green tremolite schist varying from 10 cm to 2 m width. Similar rocks are also found irregularly developed near the gneiss between the two lobes. A pinnacle-shaped outlier of tremolite-rich rock occurs to the southeast (Fig. 1B) and this, together with the general form of the body, suggests that it forms a concordant sheet-like mass.

Eastern lobe

The majority of rocks in the eastern lobe are best described as carbonate-harzburgites, where the term harzburgite is used for ultramafic rocks consisting essentially of olivine and orthopyroxene and has no genetic implications. Variations in the proportions of the major minerals present cause a discontinuous banding which is nearly horizontal or dips at shallow angles, and rock types vary from harzburgite to chromitite, depending on

Fig. 2. Textures of the Hjelmkona ultramafic rocks. To the left is the olivine-rich variety, with large olivine laths and interstitial talc and carbonate. To the right are interlocking laths of pyroxene, some forming radiating clusters with interstition carbonate. The scale is 30 cms lang and is parallel to S_1.

the scale of the sample. Contacts between bands may be sharp (Fig. 2) or diffuse. The most abundant rock type is carbonate-harzburgite consisting of orthopyroxene (10–30 %), olivine (5–70 %), phlogopite (0–20 %), and carbonate (5–60 %) with lesser amounts of tremolite (0–15 %), talc (0–30 %), chlorite (0–10 %), chromite ($<$ 1–3 %), and serpentine ($<$ 1 %). Where chromite becomes abundant ($>$ 30 %) it forms chromitite bands and lenses which are discontinuous and rarely exceed 5 cm in width or 3 m in length. The chromite grains form clusters of several crystals, some euhedral, separated by carbonate, phlogopite, or altered pyroxene and olivine.

The margins of the body show partial or complete alteration to green tremolite, with minor relic orthopyroxene, some chlorite, carbonate, and oxide minerals. The tremolite laths produce a strong lineate schistosity parallel to the contacts with the gneisses.

The textures and grain-size of the carbonate-harzburgites are best seen on weathered surfaces (Fig. 2), especially where talc and carbonate are major components. The grain-size is characteristically coarse (single pyroxene crystals up to 20 cm long have been measured), but variable. The textures are very characteristic and are of two types. In one, large laths of olivine, or less commonly orthopyroxene, in random orientation are

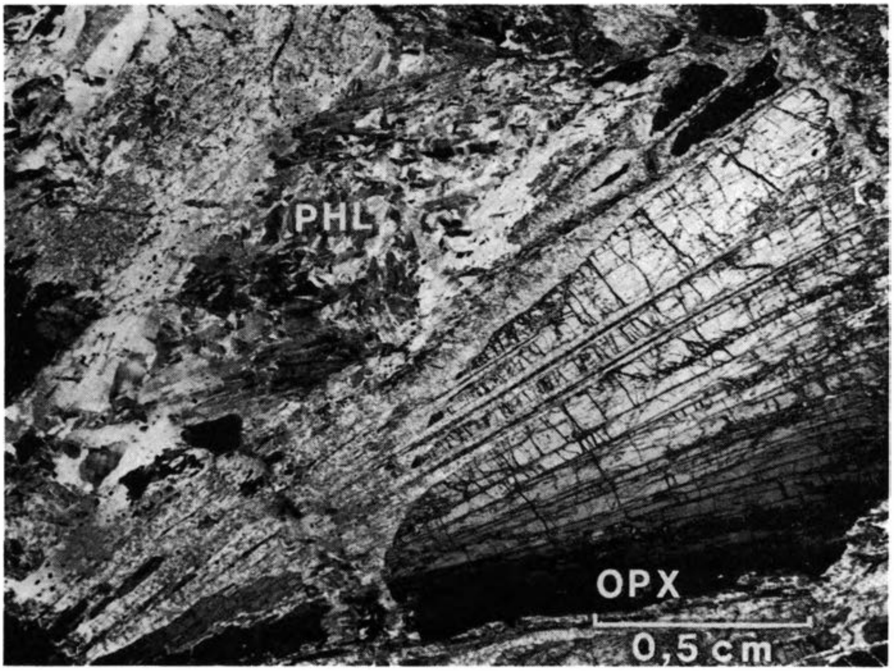

Fig. 3. Photomicrograph of a large cluster of radiating orthopyroxene crystals (OPX) with interstitial phlogopite (PHL). The pyroxene is partially replaced along grain boundaries and cleavages by carbonate and talc. Carbonate has preferentially replaced the pyroxene along the cleavage and the talc occurs on either side of it with irregular contacts against the pyroxene.

separated by interstitial carbonate and talc with or without tremolite. In the other, large crystals of pyroxene are intergrown to form radiating clusters (spherules) or interpenetrant laths and olivine, as equidimensional or highly elongate crystals, together with the later-stage minerals such as talc, carbonate and amphibole, which also commonly form radiating fibre-like crystals, if found interstitially. In both types the opaque minerals occur as equidimensional, evenly disseminated grains.

The textures of many samples of rock from Hjelmkona are identical to those illustrated by Ohnmacht (1974), in particular pls. 1c and 2c, except that in the Hjelmkona rocks the elongate olivine crystals are relatively unaltered and are separated by talc, carbonate, and amphibole. In olivine-rich varieties the olivines may be elongate parallel to *c*, a feature also found in sagvandites in the Troms area (Schreyer et al. 1972, fig. 6, Ohnmacht 1974, pl. 2). It is a habit characteristic of metamorphic olivine in ultramafic hornfelses (Matthes 1971) and is probably likely to develop in regionally metamorphosed ultramafics, such as the Hjelmkona body, where the internal structure of the body remains essentially massive. The orthopyroxenes occur as anhedral laths or as large radiating or intergrown groups of crystals, some of which are in excess of 10 cm in diameter. Fig. 3 illustrates the characteristic radiating form of the pyroxenes as well as the later replacement by talc and carbonate. Such radiating groups of crystals are also found in the sagvandites of the Troms area (Schreyer et al. 1972: 350 and pers. observ.) and are also characteristic of orthopyroxenes which have grown during metamorphism (Matthes 1971, figs. 6 and 7).

Apart from interstitial chlorite, chromite, and phlogopite, which locally may become major mineral components, all other minerals show replacement textures with respect to the olivine and orthopyroxene. Irregular crystals of carbonate, often with talc and amphibole associated, and acicular tremolite crystals are the most common replacement minerals. The amphibole may also form radiating clusters which penetrate olivine.

Western lobe

The mineralogy and textures of rocks of the western lobe are identical to those of the eastern, except for an area of metaperidotite which has a very well-developed S_1 schistosity and is readily distinguished in the field by its more brownish weathered surface compared with the reddish-brown of the other ultramafic rocks. The metaperidotite is distinguished from the other rocks by distinct mineralogical differences. It consists essentially of equigranular polygonal olivine (50 %), orthopyroxene (20 %), both as large crystals and as polygonal grains, and amphibole (approximately 15 % tremolite and 5 % anthophyllite). Carbonate occurs in only small amounts (approx. 5 %) interstitially. There is neither mica nor talc and the opaque minerals (5 %) consist of both green spinel and chrome-magnetite. These are intimately associated with spinel occurring as exsolution lamellae in, and as anhedral grains intergrown with, the chrome-magnetite. Some analyses are given in Table 1. The metaperidotite is coarse-grained and has

Table 1. Silicate minerals from the western lobe metaperidotite

	1	2	3	4	5	6	7	8	9
SiO_2	57.22	56.36	57.80	57.22	57.41	56.87	51.65	41.07	40.98
Al_2O_3	1.04	1.33	0.51	0.36	0.64	0.58	0.57	0.12	0.15
TiO_2	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.00
MgO	37.91	37.68	38.61	38.34	24.91	24.45	42.70	53.91	54.12
FeO*	3.48	3.74	3.41	3.43	1.02	1.07	3.63	4.79	4.47
MnO	0.19	0.13	0.15	0.14	0.03	0.01	0.17	0.00	0.06
CaO	0.01	0.00	0.00	0.00	12.98	12.99	0.00	0.00	0.00
Sum	99.85	99.25	100.48	99.49	97.00	95.97	98.73	99.89	99.78

FeO*: total iron as FeO

1, 2 Orthopyroxene within masses of polygonal olivine; they contain no inclusions.
3, 4 Porphyroblastic orthopyroxene containing trails of inclusions.
5, 6 Tremolite laths.
7 Anhedral, porphyroblastic anthophyllite with inclusions of olivine.
8 Olivine within polygonal aggregates, interstitial to larger pyroxenes.
9 Rounded olivine inclusions within porphyroblastic pyroxene.

For these analyses Na_2O, K_2O and Cr_2O_3 were below detection limits except for analysis 5 where a value of 0.03 % Na_2O was obtained.

large orthopyroxene porphyroblasts (up to 5 cm), some of which form radiating clusters, in the equigranular olivine matrix (average grain-size about 0.5 mm). It also contains porphyroblastic amphiboles. The tremolite occurs as laths and acicular crystals interstitial to other phases, but anthophyllite forms equidimensional anhedral grains containing inclusions of other minerals and is very difficult to distinguish from orthopyroxene in thin section. Some of the larger orthopyroxene and anthophyllite porphyroblasts contain trains of rounded inclusions (olivine and spinel) which have no optical preferred orientation, but, as groups, are parallel to the schistosity.

Some electron microprobe analyses have been carried out on a reconnaissance basis so that the composition of some of the minerals from both lobes are known (Tables 1–3). The olivines are homogeneous and highly magnesian. Those from the metaperidotite in the western lobe are more magnesian (Fo_{95}) than those in the sagvandites of the eastern lobe (Fo_{90}). In the metaperidotite the aggregates of equigranular, polygonal olivines have an identical composition to the rounded olivines which occur as inclusions in the porphyroblastic pyroxene and anthophyllite. The radiating pyroxenes are also magnesian (En_{95}) with low Al_2O_3 contents, while smaller polygonal pyroxenes associated with the olivine aggregates and without inclusions are slightly less magnesian (En_{90}) and have distinctly higher Al_2O_3 contents (Table 1). The sagvandites contain Fe- and Al-rich chromites which are distinctly zoned (Table 3) whereas the spinels in the metaperidotite are chrome-rich magnetite and green Cr-rich spinel. The compositions of spinel exsolution lamellae in the magnetite and of discrete spinel crystals associated with the magnetite are the same, suggesting a common origin, i.e. by exsolution from the magnetite. This indicates a two-phase field between spinel and magnetic similar to that recognised by Muir & Naldrett

Table 2. Spinels from the western lobe metaperidotite

	10	11	12
SiO_2	0.09	0.02	0.00
Al_2O_3	1.37	56.43	56.23
TiO_2	0.02	0.00	0.02
Fe_2O_3	62.16	5.43	7.18
MgO	3.63	22.09	24.24
FeO	24.97	6.96	3.25
MnO	0.29	0.00	0.01
CaO	0.49	0.00	0.52
Cr_2O_3	6.72	8.98	9.10
NiO	0.94	0.11	0.01
Sum	100.68	100.02	100.56

Fe^{2+}/Fe^{3+} calculated on the basis of charge balance after calculation of a structural formula on the basis of 24 cations.

10 Chrome-magnetite with associated green spinels.
11 Green spinel – discrete grain.
12 Exsolution lamella of green spinel in the magnetite (10)

Table 3. Minerals from the eastern lobe sagvandite

	13	14	15	16	17
SiO_2	41.58	41.52	0.29	0.59	0.20
Al_2O_3	0.00	14.99	9.02	14.83	0.44
TiO_2	0.00	0.09	0.11	0.07	0.00
Fe_2O_3	–	–	10.79	10.71	–
MgO	49.56	26.14	6.11	7.18	20.66
FeO*	8.60	2.46	23.45	23.51	0.62
MnO	0.19	0.00	0.64	0.54	0.00
CaO	0.12	0.08	0.06	0.03	26.95
Na_2O	0.00	0.51	0.00	0.00	0.00
K_2O	0.00	9.66	na	na	na
Cr_2O_3	0.01	0.82	48.94	42.98	0.00
Sum	100.06	96.27	99.41	100.44	48.87

For silicates FeO* is total iron as FeO. For chromites FeO* gives the FeO value after calculation of Fe^{2+}/Fe^{3+} to achieve charge balance using a structural formula based on 24 cations.

13 Equidimensional olivine grain in sagvandite (chromite and phlogopite-rich).
14 Interstitial phlogopite in chromite plus mica-rich sagvandite.
15 Core zone of altered chromite.
16 Margin of the same grain as 15. na = not analysed
17 Interstitial dolomite.

Analyses in Tables 1–3 were carried out on an ARL-EMX microprobe at Sentralinstitutt for Industriell Forskning, Oslo, using 15 Kv accelerating voltage and between 0.05 μ amp and 0.025 μ amp sample current. Natural mineral standards were used for calibration and the usual corrections made for matrix effects.

(1973) for hercynite and magnetite. In both cases there is a strong fractionation of Ti and Ni into the magnetite.

The amphiboles both in the metaperidotite and in the sagvandite as well as those in the alteration zones are dominantly tremolite. Until now, only those in the metaperidotite have been analysed but these have the same optical properties as those in the other rocks. Anthophyllite porphyroblasts have been analysed in the metaperidotite (Table 1) where they occur in small quantities. Anthophyllite has not been recognised elsewhere but is very difficult to recognise under the microscope because, in these rocks, it looks very similar to the orthopyroxene. The carbonates in the eastern lobe sagvandites are dolomite and, on the basis of optical properties and staining, it seems likely that the carbonates found elsewhere in the Hjelmkona body are also dolomite. Both magnesite and dolomite (breunnerite) have been reported from the sagvandites of the Troms district (Schreyer et al. 1972, Ohnmacht 1974).

Possible significance of the Hjelmkona body

Until further work has been completed some problems must remain unanswered: for example, the relationship of the metaperiodotite to the sagvandites and the presence of the chrome-rich spinels in the metaperidotite rather than chromite, although this may be caused by an original lower chrome content. However, even at this stage some important inferences may be drawn.

Firstly, the 'primary' assemblage of the sagvandites (olivine, bronzite with or without phlogopite and chlorite) is metamorphic, not igneous as implied by previous workers (e.g. Ohnmacht 1974), although Lappin (1967) recognised the metamorphic nature of the olivines in the somewhat different dunites from Almklovdalen. This conclusion is based essentially on the distinctive texture, particularly the radiating pyroxenes and highly elongate olivines. In the metaperidotite, porphyroblastic pyroxene has enclosed pre-existing olivine and spinel, indicating that it continued to grow after the peak of metamorphism, thus entrapping trails of inclusions which are parallel to the S_1 schistosity. This early metamorphic assemblage is partially replaced by the talc, tremolite, and carbonate assemblage (Fig. 3), although anthophyllite probably predates these minerals. At this stage no attempt is made to relate the mineral assemblages to fixed pressure and temperature conditions. The development of the sagvandites is almost certainly related to late metamorphic CO_2 metasomatism as suggested by Schreyer et al. (1972) and Ohnmacht (1974).

Secondly, the sagvandite-type assemblages are distinctive both mineralogically and texturally and are found only in ultramafic rocks within high-grade metamorphic terrains. There may be marble horizons in the immediate neighbourhood which could be a source of CO_2 but this is not essential, as can be shown for the Hjelmkona area, and the high CO_2 activity may be a regional rather than a local effect. The sagvandites should be clearly distinguished from other ultramafic rocks of the Basal Gneiss Complex where some alteration to talc-carbonate assemblages may, and commonly does, take place along contacts and fractures (e.g. Kendel 1970). In these the major type of alteration is to serpentine minerals, and carbonate minerals are limited. By contrast the sagvandites have undergone penetrative carbonatization with very little development of serpentine. Where serpentine is found in minor amounts it is along fractures in olivine and may even be a weathering feature. The carbonate minerals show ambiguous relationships towards the silicates; some appear in textural equilibrium whereas others have a distinct replacement relationship. It is probable that, at an early stage in the metamorphic development of these rocks, carbonate and silicate crystallized in equilibrium, suppressing the development of serpentine, and later reduction in the temperature and P_{CO_2} (or increase in P_{H_2O}) allowed for reaction between the carbonate and orthopyroxene to produce talc plus more carbonate (Ohnmacht 1974).

Having recognised the distinctive characteristics of these rocks, as exemplified by those at Hjelmkona, it can be shown that similar rocks are found in the south, at Sjømæling, from near Hornindal, Nordfjord, and from localities near Grotli and Skjåk (specimens in the collections of Mineralogisk-geologisk museum, Oslo). Ultramafic rocks in the Basal Gneiss Complex south of Hjelmkona are more commonly carbonate-free and consist of olivine, pyroxene, and chlorite. They may contain amphibole and have serpentinised margins with minor talc-carbonate development (Bryhni 1966, Carswell 1968). Rocks almost identical to those at Hjelmkona are found in the high-grade metamorphic gneisses of 'uncertain age' (Holtedahl & Dons 1960) near Svartisen, particularly in Hollandsfjorden-Glomfjorden area (Sørensen 1967), near Misvær and the islands off the north Helgeland coast (e.g. Rødøya, Hestmona, pers. observ.), and in the Lesja area (pers. observ.). Identical rocks occur at the well-described sagvandite localities of the Troms district (Schreyer et al. 1972). The rocks in the Troms and Lesja areas are regarded as being within metamorphosed Cambro-Silurian metasedimentary and metavolcanic sequences affected by the Caledonian orogeny. However, the rocks enclosing the ultramafics are high-grade metamorphic gneisses and, in the case of the Troms area, Schreyer et al. (1972) emphasise this type of association (i.e. sagvandite in high-grade metamorphic gneisses) and they also emphasise the rapid transition from high-grade gneisses to lower-grade schists in which sagvandites are not found. Recently Binns (1975 and pers. comm.) has shown that the Troms sagvandites, including a new one discovered at Båtsfjellet, confirm the suggestion made by Landmark (1973) that these ultramafic rocks lie along strike in one tectonostratigraphic horizon. Binns interprets this horizon as a nappe of Cambro-Silurian rocks which is termed the Skibotn nappe.

The Hjelmkona ultramafic, with its distinctive mineralogy and textures, occurs within Basal Gneisses, dated at 1,700 m.y. and is considered to be representative of the type of ultramafic body found in much of the Basal Gneiss Complex, excluding the Sunnmøre area (i.e. that area marked 'Gneiss. Gneiss-granite (including quartz-dioritic rocks)') on the geological map of Norway (Holtedahl & Dons 1960), where carbonate-free metaperidotites, often with associated eclogites, are the predominant type of ultramafic rock occurrence. The sagvandites are characteristic of high-grade metamorphism (almandine amphibolite facies) and high P_{CO_2}, which allows for the production of carbonate and prevents serpentinization. By comparison with the Hjelmkona ultramafic, where the surrounding gneisses have been dated (Råheim 1974), it is suggested that the occurrences of similar ultramafics (i.e. sagvandites) elsewhere in Norway are also in Basal Gneiss which may be of similar age. It is possible that similar metamorphic conditions could have developed locally in the Cambro-Silurian metasedimentary and metavolcanic sequences during the Caledonian orogeny, but this is considered a less likely possibility in view of the relative rarity of these types of ultramafic rocks and because where ultramafic rocks are found in metamorphic rocks of undisputed Cambro-Silurian age they are serpentinites. If this interpretation is correct then those gneisses with associated sagvandites in the Helgeland islands and around Svartisen, those in the Lesja area and in the Skibotn nappe, Troms, are Basal Gneisses and could give ages of 1,700 m.y., although some younger ages may emerge because of the influence of the Caledonian orogeny (e.g. Carswell 1968, Pidgeon & Råheim 1972). The Skibotn nappe would then be interpreted as a thrust slice of Basal Gneisses.

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