2. Garnet-sillimanite and Garnet-spinel Bands in the Layered Gabbro Series in Seiland, North Norway

By

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Introduction

Since the classical study by WAGER and DEER (1939) on the layered Skærgaard intrusion, East Greenland, an ever-increasing number of papers on layered rock series have been published, and new occurrences are constantly being described. By most authors the layering is regarded as a primary banding developed under special conditions during fractional crystallization of a rock magma. Divergent opinions have been voiced but not accepted by the authorities. Few have had other than scorn for the hypothesis of, say, VAN BILJON (1950), by which the Bushveld layered "intrusions" originated by metamorphic transformation of the sedimentary column in place.

Among the many new occurrences of layered gabbroic rocks are those of the Seiland petrographic province, northern Norway. This large province, extending approximately from latitude 70° to 70°30′ N. and from longitude 10°30′ to 12°30′ E. but thus far surveyed only in part, comprises a series of rather unusual deep-seated metamorphites and magmatites. In places layered sequences of gabbroic rocks more than 1000 m thick are conspicuous (BARTH, 1953; KRAUSKOPF, 1954). The present paper is concerned with some peculiar bands in the layered series at Bumannsfjord on the west coast of Seiland.

A schematic diagram of the geology of this area is shown in Fig. 1, and a short profile taken about 10 km S. of Bumannsfjord gives an example of the petrographical nature of the various constituent rock types (Table 1). In the layered complex, predominantly composed of gabbroic rock types, there are some bands of metasediments: diopside-garnet-bearing marbles, and in one place (marked xxx on Fig. 1), a most unusual spinel-sillimanite rock forming a composite band with black selvages and a pinkish grey central part. The metasedimentary bands are strictly parallel to the adjacent gabbroic layers; they form indeed, an integral part of the layered complex.

Description of the Spinel-sillimanite Rock

The aspect of the spinel-sillimanite band is seen from Fig. 2. The border zones are thin, black, symmetrical and composed of spinel, garnet, and albite; the central part is light-colored and composed of garnet, sillimanite, and albite.

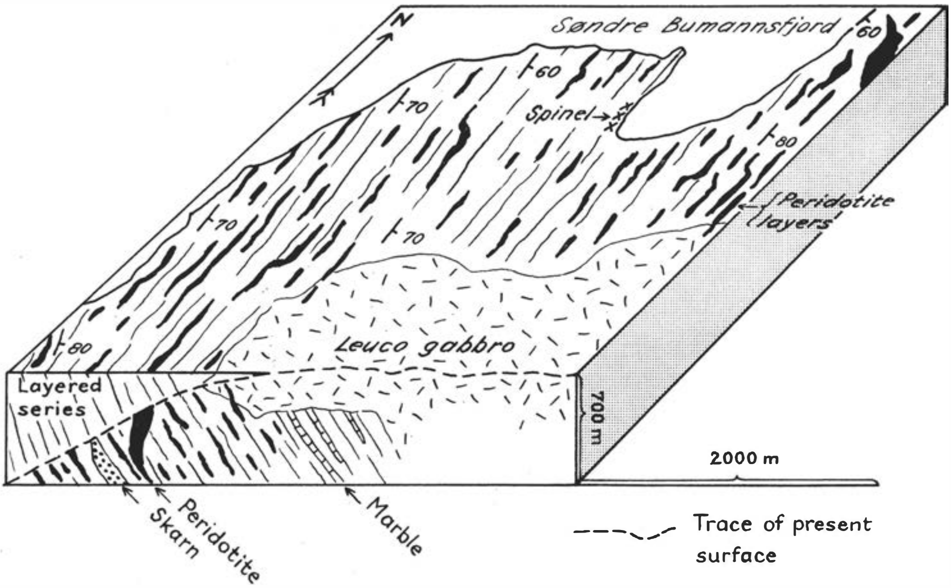

Fig. 1. Schematic block diagram of the geology south of Söndre Bumannsfjord, west coast of Seiland. The peridotites are intruded into the layered series. The layering consists of various bands of gabbroic rocks ranging from dark olivine gabbro to anorthositic types. A short profile chosen at random in the series is listed in Table 1. But here and there are odd layers of skarns or marble, and in one place, marked xxx, is a peculiar layer of spinel-bearing rocks.

Table 1. Profile at Lille Kufjord, Seiland.

Abbreviations: Plag. = plagioclase, aug. = augite, hy. = hypersthene, ol. = olivine, hbl. = hornblende.

Top	
?	
5.4 m	Peridotite: Ol., less than 10% each plag., aug., hy., hbl., ore.
8.0 m	Pyroxenite; Aug., less than 10% each plag., ol., hy., hbl., ore, spinel.
8.2 m	Peridotite: Ol., less than 10% each plag., aug., hy., hbl., ore, spinel.
8.4 m	Gabbro: Plag., aug., ol., hbl., ore, spinel.
18.7 m	covered.
4.8 m	Pyroxenite: Aug., hbl., ore.
1.5 m	Pyroxenite: Aug., hbl. (ol.), (ore).
4.4 m	Peridotite: Aug., ol., hbl., ore, spinel.
2.0 m	Pyroxenite: Aug., less than 10% each hbl., ol., hy., plag., ore, spinel.
9.2 m	Olivine gabbro: Plag., ol., aug., hy., hbl., ore, spinel.
7.0 m	Gabbro: Plag., aug., hbl., ore, spinel, trace of ol. and hy.
2.6 m	Peridotite: Ol., aug., hy., hbl., ore, spinel, 10% plag.
6.0 m	Olivine Gabbro: Plag., ol., aug., hy., hbl., spinel.
6.0 m	Gabbro: Plag., aug., hy., hbl., spinel, ore.
?	
Bottom.	

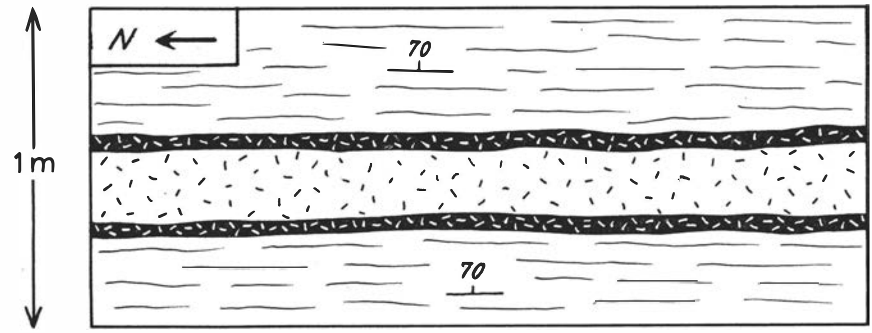

Fig. 2. Sketch of the composite layer with borders of spinel–garnet–albite rock and core of garnet–sillimanite–albite rock.

The border zone (Fig. 3) is fine-grained, very dense and hard, and composed of small garnet crystals, colorless in thin sections, usually forming speckled clusters about 5 mm large; irregular shapeless grains of dark green *spinel* up to 1 mm large; some odd elongate grains of *hypersthene*, 0.1–1 mm long, very faintly pleochroic in pale greenish-grey hues. There is a sort of matrix of *albite* in angular equidimensional crystals about 30 μ across, either untwinned or with simple repeat of thin albite twin lamellae.

The following physical constants were determined: garnet, $a_0 = 11.498$ Å, $n = 1.775$, corresponding to 60 almandine, 40 pyrope; spinel, $a_0 = 8.122$ Å, corresponding to 60 % of hercynite; hypersthene, $\gamma = 1.707$, $\alpha = 1.698$, corresponding to 35 Fs.; and albite, $\gamma = 1.539$–1.541, corresponding to pure albite.

The central part (Fig. 4) is also fine-grained and dense, and composed of about 50 per cent of *garnet* (colourless in thin sections but imparting to the rock a pale pink tinge) each crystal equidimensional and only about 50 μ across, but segregated into a continuous system of irregular splotches. *Sillimanite* and *albite* form ragged laciniated patches in the garnet areas; in places sillimanite forms sheaf-like bundles of very thin needles, just several μ thick; albite forms angular grains, about 30 μ across, and is untwinned, or with extremely narrow, almost sub-microscopically small, albite-twin lamellae. Rare grains of a light green spinel can be seen. Garnet is in its physical properties identical with that of the border zone.

Chemistry of the Spinel-sillimanite Rocks

Chemical analyses of these rocks are listed in Table 2. Remarkable is the almost complete absence of calcium; otherwise the compositions compare closely with certain types of hornfelses (see TILLEY, 1924). The relations between the border and the center of the layer are interesting: chemically the

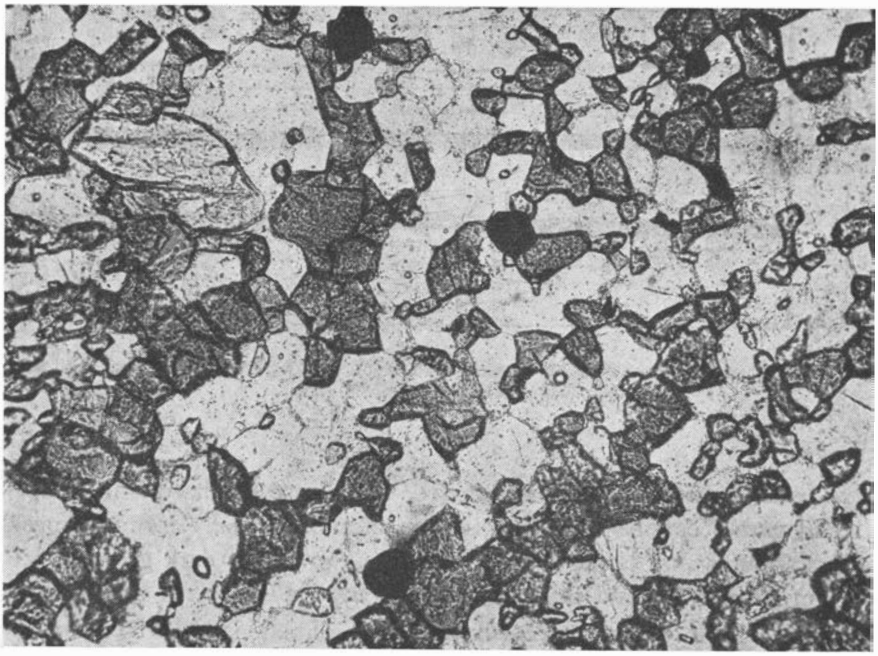

Fig. 3. Border facies of the composite layer. The microphotograph is 0.6 mm across.

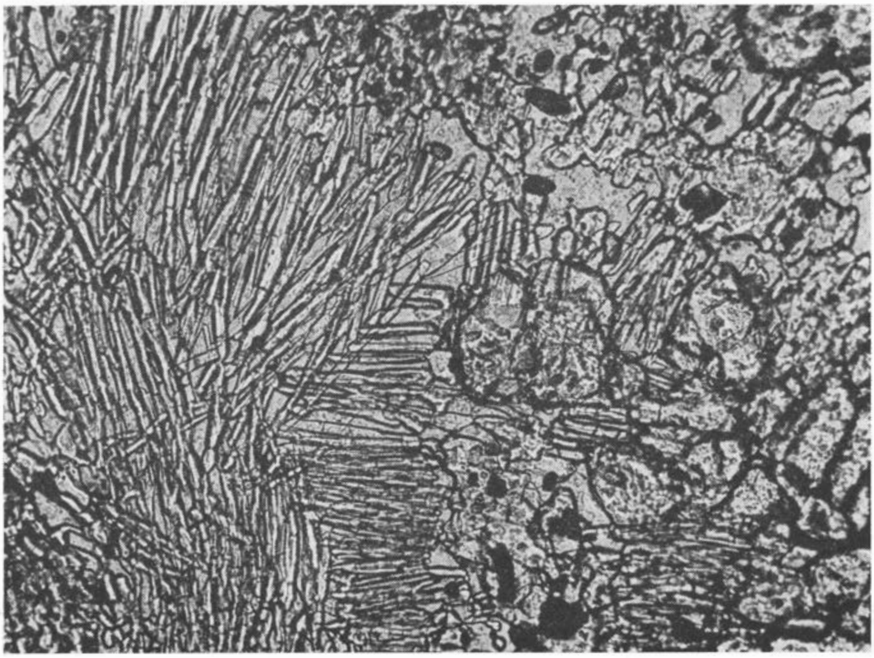

Fig. 4. Main central facies of the composite layer. The microphotograph is 0.6 mm across.

Table 2. Chemical analyses of spinel rocks, Seiland.

Weight per cent				Cation per cent		
	B (Border)	C (Center)	B + 25 % SiO_2		Border	Center
SiO_2	30.85	44.81	44.8	Si	28.1	41.2
TiO_2	1.36	1.50	1.1	Ti	0.9	1.0
Al_2O_3	37.14	32.92	29.8	Al	39.6	35.6
Cr_2O_3	0.03	n.d.	—			
Fe_2O_3	2.49	1.66	2.0	$Fe^{\cdot\cdot\cdot}$	1.7	1.1
FeO	15.08	10.40	12.1	Fe	11.6	8.0
MnO	0.19	n.d.	0.16			
MgO	8.50	5.94	6.8	Mg	11.5	8.1
CaO	0.05	0.04	0.04			
Na_2O	3.41	2.57	2.7	Na	6.0	4.6
K_2O	0.50	0.34	0.4	K	0.6	0.4
P_2O_5	0.12	0.10	0.1			
$H_2O\div$	0.47	n.d.	—			
Total	100.19	100.29	100.0		100.0	100.0

central rock corresponds to the border rock plus 25 per cent silica (see Table 2).

If the albite contents are subtracted from the analyses, the remaining oxides form a pseudo-ternary system: $(MgO + FeO) - (Al_2O_3 + Fe_2O_3) - SiO_2$.

Discussion of the Mineral Assemblages

The melting phenomena of the systems Al_2O_3–SiO_2 with FeO and MgO have been investigated (see SHAIRER, 1952 and 1954) and the primary phases of crystallization have been determined (see Fig. 5). If the Seiland rocks had crystallized from a magma, the mineral association would have been olivine,

Table 3. Calculated mineral composition.

Molecular per cent.

	Border	Center
Spinel	45	—
Garnet	20	44
Sillimanite	—	30
Hypersthene	2	—
Cordierite	—	—
Albite	33	25

Table 4.

	B minus albite	C minus albite	Recalculated to 100 %	
			B′	C′
Si	8.2	26.0	12	35
Al′ = Al	33.0	30.6	53	43
Fe···	1.7	1.1		
Mg = Fe··	11.6	8.0	35	22
Mg	11.5	8.1		
	66.0	73.8	100	100

cordierite, and spinel in addition to albite. Actually a garnet (of the almandite–pyrope series) has formed; it is unstable at the liquidus. This makes cordierite unstable in contact both with olivine and with spinel:

$$11 \text{ Co} + 12 \text{ Ol} = 3 \text{ Sp} + 8 \text{ Gr} + 12 \text{ Hy} \quad (1)$$

and

$$11 \text{ Co} + 3 \text{ Sp} = 8 \text{ Gr} + 6 \text{ Sill} \quad (2)$$

The quaternary system $MgO–Al_2O_3–SiO_2–H_2O$ has been investigated by YODER (1952). At pressures of 15,000 psi and with excess of water vapor a series of various stable assemblages exists in the range 400°–990°C, but none of them contain garnet (pyrope). This YODER explains by the fact that there is a region in the quaternary system which was not accessible by means of his experimental methods. He has called this region the water-deficient region, since all compositions within the region are incapable of stable coexistence with water vapor at the conditions of the experiments. It is within this region that garnet lies.

Thus we conclude that the recrystallization of the Seiland layered sequence took place in a water-deficient region. It is furthermore worthy of note that the phase assemblages actually observed (Fig. 5) are different from any of those indicated on YODER's Fig. 14 in the water-deficient region at ca. 600°, the main difference being that pyrope actually is in contact with sillimanite, whereas YODER assumes that pyrope is separated from sillimanite by the cordierite–spinel join. See equation 2 above.

No trace of sapphirine ($Mg_4Al_{10}Si_2O_{23}$) has been found in the Seiland rocks. It is known to exist as a phase at the solidus (KEITH and SCHAIRER, 1952) and as a metamorphic mineral in contact with hornblende, phlogopite, spinel, sillimanite, cordierite (VOGT, 1947; RAMBERG 1948), and, in one locality (Cortlandt, N.Y.) with a garnet that is very similar to the present Seiland garnet (FRIEDMAN, 1954). Its appearance at the solidus of synthetic melts and in the Cortlandt rocks, which are inclusions in norite, suggests a high temperature of stability; similarly both VOGT and RAMBERG place it in a metamorphic facies of somewhat higher temperature and pressure than the amphibolite facies. The absence of sapphirine in the present assemblage of spinel–garnet–sillimanite indicates a lower temperature range for the Seiland rocks. Unfortunately we know too

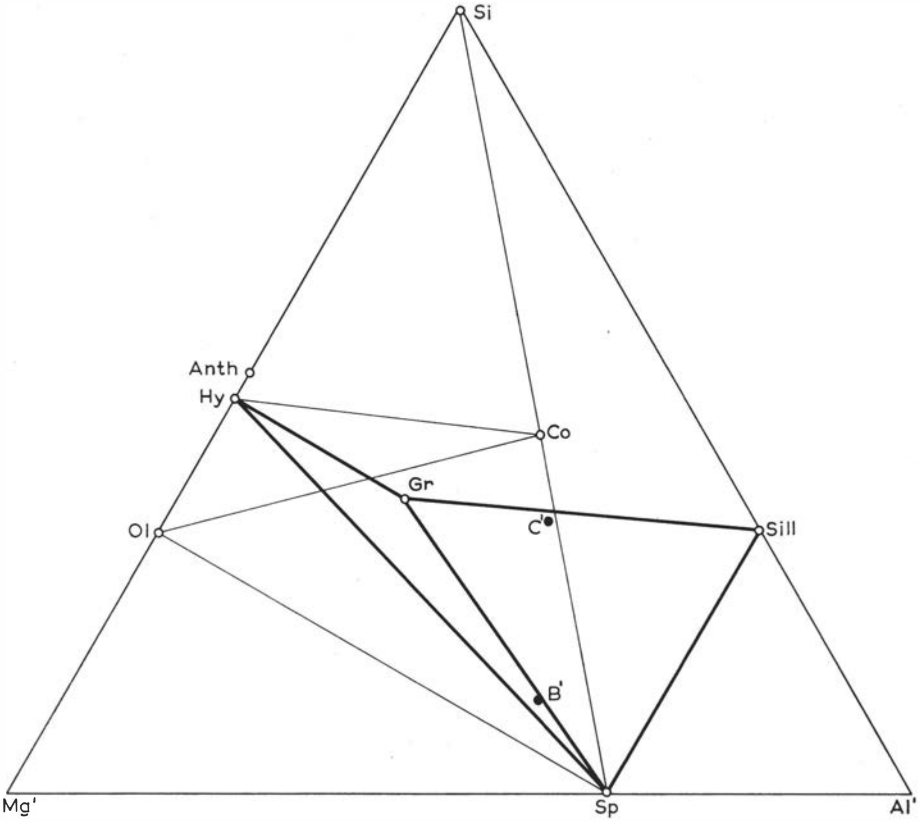

Fig. 5. Phase assemblages in the system $MgO'-Al_2O_3'-SiO_2$. Thin lines correspond to phases at the solidus in the system $MgO-Al_2O_3-SiO_2$. Sapphirine has been omitted for simplicity; its projection point is on the line Co–Sp, well inside the triangle Sp–Gr–Sill. Heavy lines indicate the mineral assemblages observed in the composite layer of Seiland. B′ and C′ are the projection points of the border rock and the central rock respectively of the Seiland composite layer. Ol = olivine, Hy = hypersthene, Anth = anthophyllite, Gr = garnet, Co = cordierite, Sill = sillimanite, Sp = spinel.

little about the assemblage to estimate the temperature more closely. We can only say that it clearly belongs to a sub-solidus region.

It is significant that this rock layer together with the various layers of skarn rocks are metasediments. For this reason the adjacent gabbroic layers, although petrographically they are undistinguishable from igneous plutonic rocks, would seem to derive from either original basic lavas or sills or from other supracrustal rocks which have been basified under plutonic conditions (see Tilley, 1925, and Harry, 1952). This hypothesis is supported by a study of the contacts of the layered complex. In contradistinction to the layered gabbro of the Skaergaard intrusion, the present layered series has no definite side walls, but seems to extend without a clear break into the contiguous and analogously layered amphibolite–gneiss complex. A complete survey of the region is in progress.

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