# Petrochemistry and Origin of the Raudhamaren Ultramafites, Jotunheimen

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The ultramafites show gradual petrochemical variation and Mg/Fe ratios indicative of crystallisation differentiation from the stratiform type mafic magma series. The country rocks with which they are in primary association, however, have a calc-alkaline trend of evolution, more indicative of affiliation with the alpine type. The ultramafites are essentially spinel peridotites thought to have formed in a dry environment by diapiric upwelling during the basaltic (gabbroic) evolution of the Upper Mantle.

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## Introduction

Ultramafites are rather special rocks because of their extreme femic mineralogy and restricted distribution. Since they are possibly the closest representatives of the Upper Mantle they serve as 'Petrological Windows' to the internal Earth. The traditional classification of ultramafites into alpine and stratiform types has genetic implications in undoubted geological environment, but the catazonal and mesozonal ultramafites cannot be simply attributed to any one of these types.

The ultramafites of Jotunheimen are examples of this, and earlier work by Münster (1884), Rekstad (1904, 1905), Bjørlykke (1905), Goldschmidt (1916), Carstens (1918), Dietrichson (1955, 1958), and Battey (1960, 1965) revealed interesting aspects of these rocks. Carstens (1918) demonstrated that lenses of peridotite occur by the hundreds, possibly by the thousands in the igneous rocks of Jotunheimen, that they are usually surrounded by pyroxenite, and they display gradational contacts towards gabbroic country rocks. Dietrichson (1955, 1958) suggested stratiform magmatic origin for the igneous rocks of Jotunheimen, while Battey (1960) first proposed an intrusive alpine origin for the ultramafites and later (1965) accepted a stratiform origin. This paper is devoted to a study of a single large body, the Raudhamaren ultramafite, and some smaller bodies adjacent to it.

The area in which the ultramafic bodies have been examined is bounded by N latitudes 61°24′ and 61°40′ and E longitudes 8°44′ and 9°00′ on the E30A Sjodalen and E30V Gjende quadrangular topographic maps (Fig. 1). The rocks which belong to the Upper Jotun Nappe, which extends NE–SW for nearly 150 km with a width of about 50 km, are now considered as Precambrian crystallines emplaced during the Caledonian orogeny (Heier et al. 1972).

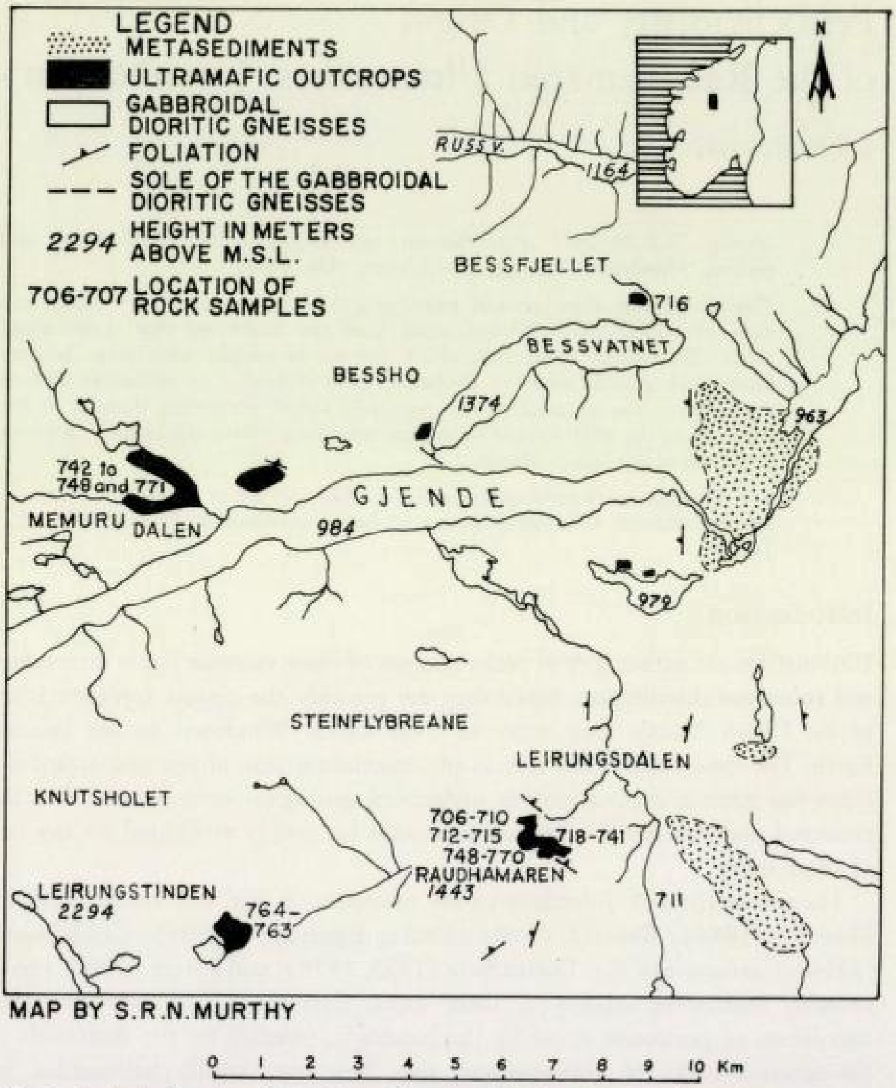


*Fig. 1.* Geological setting of the ultramafic rocks with location of rock samples.

The lithological units and rock types of the examined area are given below:

| Age | Rocks |
|---|---|
| Precambrian igneous rocks of the Caledonian nappes. | Pegmatites and epidote veins; anorthosites, amphibolites and ultramafic rocks; gabbroidal dioritic gneiss, amphibole gabbro gneiss and amphibole biotite gneiss. |
| | Thrust |
| Late Precambrian–lower Palaeozoic metasediments. | Quartz and feldspar veins, phyllites, mica schists, chlorite schists, amphibole schists and amphibole–biotite gneisses. |

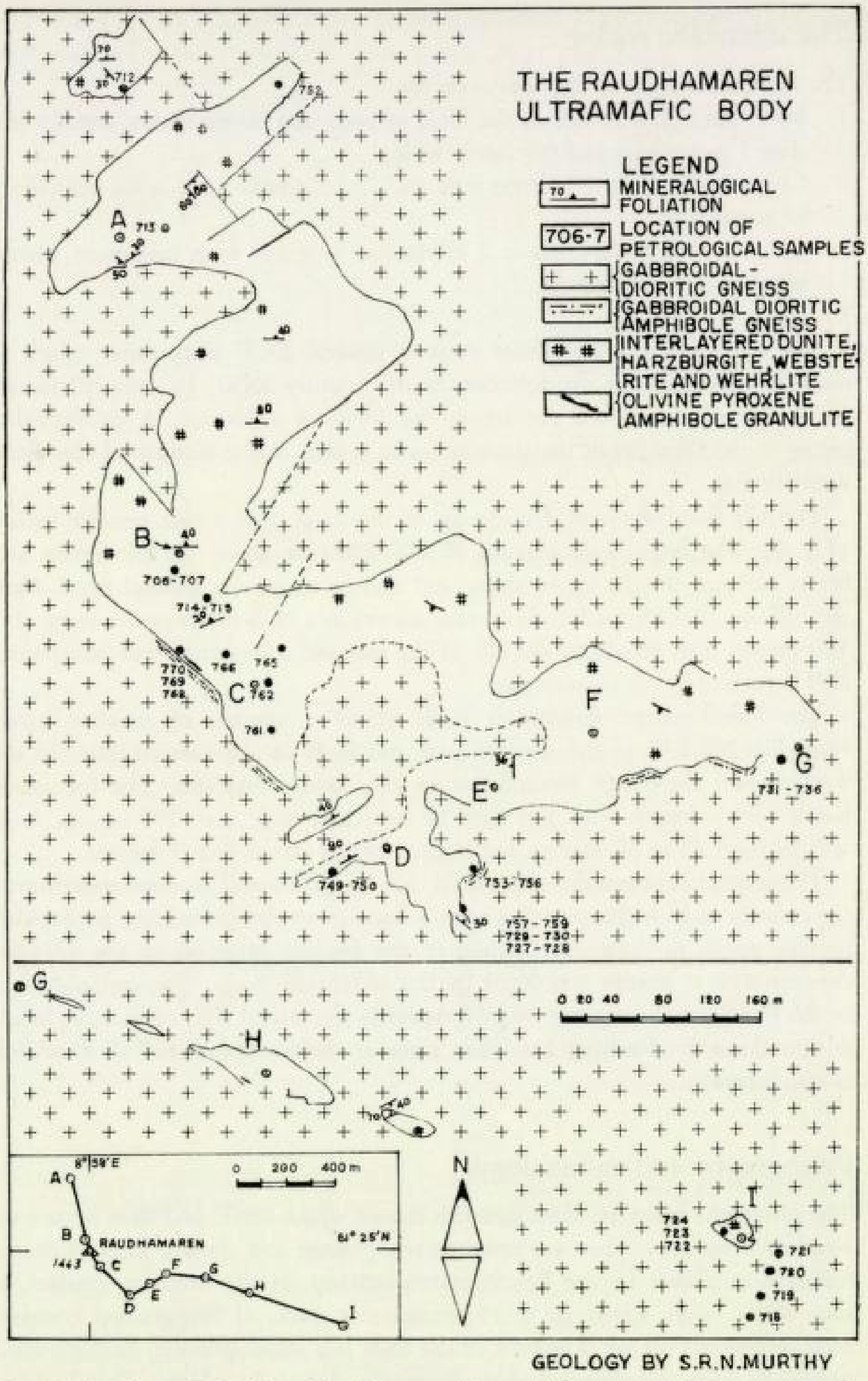


*Fig. 2.* The ultramafic bodies at Raudhamaren. Upper and lower part of the map are to be joined orthogonally at points G.

## The ultramafic rocks

The ultramafic rocks in the area occur as;

1. Small individual bodies in the form of pods and minor lenses, usually less than 1 metre long and 0.5 metre wide;
2. Larger bodies, 5 to 10 metres long and 1 to 3 metres wide, with a tendency to group; and
3. Large lensoid bodies, nearly 2 kilometres long and with maximum widths of more than 500 metres.

The outcrops of ultramafites show a general E–W disposition which is usually at an angle to the foliation of the country rocks, but the ultramafic rocks themselves do not cut across the foliation anywhere. A conformable swing in the foliation of the country rocks is seen in the vicinity of the ultramafic bodies.

The hill Raudhamaren is made up of one large and a few smaller bodies (Fig. 2). The large body extends WNW–ESE for about 1.5 kilometres and forms elevated terrain up to about 500 metres above the general level. Near the hill top, it outcrops for about 600 metres in a N–S direction. A steep cliff 300 metres high occurs to the NE of the top and a less steep but continuous cliff is present in the eastern part.

The Raudhamaren outcrop is made up of a number of massive bands extending NE–SW in the western part and E–W in the eastern part. In the western part the bands succeed one another northwestwards. The individual bands vary in length from less than 10 metres to more than 500 metres, with widths from 20 to 30 metres and thicknesses of about 2 to 3 metres.

The contact between the ultramafite and the gabbroidal gneisses constituting the country rocks is sharp with a narrow band of amphibole-bearing gabbroidal-dioritic gneiss in between. Folding of the gneissic foliation in the adjacent country rock is always simulated by the ultramafic body. The apparent fold in the Raudhamaren outcrop largely expresses the lateral shift of massive bands within the body. Faulting has taken place at various places and slickensiding is also common.

## Petrography and mineralogy

The ultramafic rocks are dark greenish brown where fresh, and dark brown on weathered surfaces. They are rather coarse-grained and show a kind of coarse foliation in places. In the Raudhamaren outcrop, at the southern contact, is seen a thin band, about 10 to 15 centimetres thick, of fine-grained compact rock of greenish colour. The bulk of the body is a coarse-grained, dark greenish peridotite with interbanded dark brownish dunite in places. The body is transected by dunite veins, with coarse metamorphic foliation, which may be mistaken for igneous layering.

*Table 1.* Modal composition (vol%) of ultramafites from Raudhamaren

| Minerals | Ol | Opx | Cpx | Amph & Bi | Sp & Ore | nd | Carb | Nomenclature |
|---|---|---|---|---|---|---|---|---|
| Sample No. | | | | | | | | |
| 758 | 96 | | | | 1 | 2 | 1 | Dunite |
| 731 | 52 | 15 | 29 | 1 | 1 | | 2 | Websterite |
| 733 | 62 | 11 | 26 | | 1 | | | Wehrlite |
| 735 | 85 | 10 | 5 | | | | | Ol. Harzburgite |
| 736 | 58 | 16 | 25 | | 1 | | | Websterite |
| 737 | 83 | 10 | 1 | | 4 | | 2 | Ol. Harzburgite |
| 739 | 40 | 9 | 47 | | 4 | | | Wehrlite |
| 761 | 50 | 19 | 16 | | 3 | 11 | 1 | Websterite |
| 762 | 34 | 22 | 36 | | 3 | 5 | | Websterite |
| 764 | 40 | 17 | 39 | | 4 | | | Wehrlite |

The rock samples are registered at the Mineralogisk–Geologisk Museum, Oslo.

Olivine, clinopyroxene, orthopyroxene and green spinel make up the peridotite varieties while the compact greenish rock at the southern contact contains much amphibole, chlorite and some carbonate. Modal composition of ten samples demonstrates that the Raudhamaren body contains dunite, olivine harzburgite, websterite and wehrlite (Table 1). (Classified according to a scheme adopted from Malakhov 1964.) The peridotitic varieties are difficult to recognise by visual examination alone, but the dunite veins and the compact greenish rock at the base of the outcrop can be distinguished by their habit and compactness respectively.

Olivine ($Fo_{80}$–$Fo_{92}$) is the main constituent of the peridotites and its composition was determined by microprobe to be $Fo_{80}$ in three samples (Table 2). The grains are euhedral to subhedral, varying from 1 to 4 mm but commonly 1 to 2 mm wide with pale yellow serpentine filling cracks at places. Simple twinning and a characteristic ribbon banding formed by minute inclusions of green spinel and opaque ores can sometimes be seen. Olivines enclosed in tabular grains of pyroxene show effects of resorption and colour zoning. Extremely fractured olivine grains make up the veined dunite, and show preferred orientation by which the coarse foliation of this rock is defined.

Pyroxenes, similar in grain size to the olivines, show well developed (100) and (010) cleavages and distinct partings. Simple lamellar twinning, intergrowth between ortho and clino varieties are present. Olivine, green spinel, some wasps of amphibole and opaque ores are present as inclusions. Orthopyroxene occurs as a coloured variety with pleochroism: X = pink, Y = pale greenish brown and Z = pale green and En content around 70, and as a colourless variety with En about 88–92. Partial microprobe analyses of pyroxenes and their associated olivine are given in Table 2. An interesting point is that the clinopyroxenes are chemically zoned with decreasing alumina outwards.

The amphiboles, occurring as inclusions and forming the greenish compact rock, are secondary tremolite–actinolite varieties. Their formation from

*Table 2.* Chemical composition and structural formula of minerals from the Raudhamaren ultramafites

| Sample No. | 750 | | | 766 | | | 769 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Minerals | Cpx | Opx (Col) | Ol | Cpx | Opx (Col) | Ol | Cpx core | Cpx mantle | Cpx rim | Opx (Col) | Ol |
| Oxides | | | | | | | | | | | |
| $SiO_2$ | 55.5 | | | 53.4 | | | 50.4 | 50.2 | 51.3 | | |
| $TiO_2$ | 0.1 | | | 0.1 | | | 0.1 | 0.1 | 0.1 | | |
| $Al_2O_3$ | 2.9 | 3.2 | | 3.2 | 2.9 | | 3.4 | 2.4 | 2.0 | 3.2 | |
| FeO (tot) | 4.5 | 12.5 | 18.4 | 4.4 | 13.0 | 18.4 | 4.4 | 4.5 | 4.3 | 12.4 | 18.6 |
| MgO | 16.1 | | | 16.2 | | | 16.4 | 16.7 | 16.5 | | |
| CaO | 24.0 | | | 22.7 | | | 23.9 | 24.3 | 24.2 | | |
| Total | 103.1 | | | 100.3 | | | 98.9 | 98.2 | 98.4 | | |

Number of ions on the basis of 6 oxygens

| | 750 Cpx | 766 Cpx | 769 Cpx core | 769 Cpx mantle | 769 Cpx rim |
|---|---|---|---|---|---|
| Si | 1.963 | 1.943 | 1.881 | 1.890 | 1.921 |
| Al | 0.037 | 0.057 | 0.119 | 0.107 | 0.079 |
| (Si + Al) | = 2.000 | = 2.000 | = 2.000 | = 1.997 | = 2.000 |
| Ti | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 |
| Al | 0.084 | 0.080 | 0.031 | | 0.009 |
| Fe | 0.133 | 0.143 | 0.147 | 0.142 | 0.135 |
| Mn | | | | | |
| Mg | 0.849 | 0.879 | 0.912 | 0.937 | 0.921 |
| Ca | 0.910 | 0.885 | 0.955 | 0.980 | 0.971 |
| (Ti–Ca) | = 1.979 | = 1.990 | = 2.248 | = 2.062 | = 2.039 |

Electron probe analyses by B. Griffin and I. Bryhni. Formula obtained on a computer programme.

pyroxene in the compact green rock suggests effects of local water pressure in an otherwise essentially dry environment.

Opaque ores, generally magnetite, and green spinel occur as accessories in these rocks.

The essential mineralogical assemblages are:

1. Olivine–orthopyroxene–spinel,
2. Olivine–orthopyroxene–clinopyroxene–spinel, and
3. Olivine–clinopyroxene–spinel.

## Chemistry

Major and selected trace element analyses of 36 rock samples have been analysed out of which 30 are from the Raudhamaren outcrop. The samples from Raudhamaren are from four 'profiles', two in the eastern part, one from the central and one from the western part. Since the base of the nappe is to the SE of the area, it is contended that sampling from SE to NW along the western profile would show variation, if any, in a singular mass from bottom to top of some 150 m thickness, subject to lateral variation due to shifting of bands.

The chemical analyses were carried out by the writer at the Mineralogisk–Geologisk Museum using a Phillips X-ray fluorescence spectrograph. Sample

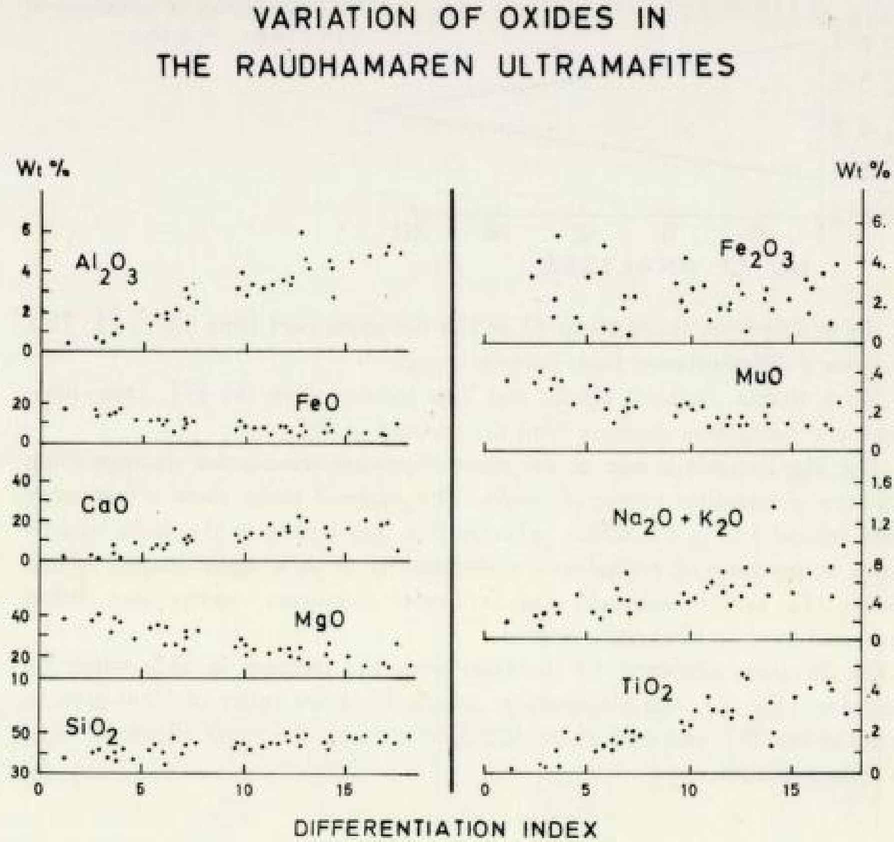


*Fig. 3.* Major oxides plotted against the differentiation index (D.I.).

pellets (pressed pellets and fused pellets) were prepared in duplicate. Fused pellets were prepared by fusing finely powdered, homogenised sample material with sodium tetraborate in 1:9 dilution. All the major elements (excepting $Na_2O$, $K_2O$ and FeO) and the trace elements were determined utilising International Geochemical Rock Standards. Counting times were chosen to keep the relative standard deviation of the counting statistics well below 1%. FeO was determined by wet analyses. $Na_2O$ and $K_2O$ were determined by flame photometric techniques, using standard solutions.

The petrochemical variations within the analysed rock samples are illustrated in Fig. 3. The oxides are plotted against the total wt% of normative salic minerals quartz, orthoclase, albite, anorthite, leucite, nepheline, and kaliophilite, a parameter only slightly different from the differentiation index (D.I.) of Thornton & Tuttle (1960). The illustration demonstrates clearly that there is almost a gradual passage from the most salic to the most femic rock types. The differentiation trend in these rocks is almost linear and the D.I. varies from 3 to 18. The Raudhamaren outcrop shows an overall – although internally inconsistent – increase in the D.I. from southeast to northwest. In the lower southeast part the body shows D.I.s varying from 3 to 7.

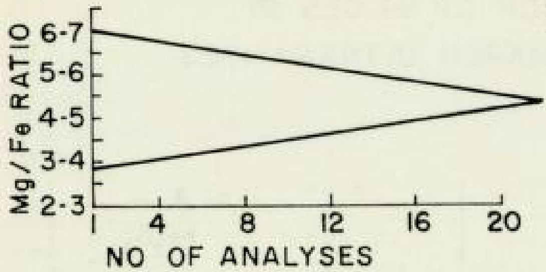


*Fig. 4.* Frequency of occurrence of Mg/Fe ratios (36 analyses).

in the middle from about 10 to 12 and in the upper part from 14 to 18. This suggests a differentiation from bottom to top.

Silica, titania, alumina, alkalis and lime increase with the D.I. Iron, magnesia and manganese decrease with the increase in D.I.

The Mg/Fe ratio is one of the most important criteria for distinguishing between ultramafites of varied origin. The analysed rocks show a frequency peak around 5 (Fig. 4), which indicates that they belong to the mafic magma series as products of crystallisation differentiation of a mafic magma (Hess 1938) like in the Bushveld and Stillwater complexes, rather than being produced from an ultramafic magma.

Of the trace elements, Cr increases with the increase in D.I. while Ni decreases (Fig. 5). The ultramafites contain Ni of the order of 1000 ppm in rocks of low D.I. and only about 300 ppm in rocks of a more advanced stage of differentiation.

## Petrogenesis

Occurrence of the ultramafites in gabbroidal dioritic gneisses, massive banding and coarse foliation (pseudomagmatic), gradual petrochemical variation and almost a lack of serpentinisation as well as the frequency peak of Mg/Fe ratio around 5 are strong evidence suggesting a stratiform origin. Habit and distribution, apparent xenolithic relationship characteristic of 'root zone' ultramafites (Den Tex 1969) are equally strong items of evidence suggesting an alpine origin for these rocks. However, the analyses of known alpine type intrusives suggest a magnesian differentiation trend that crosses the A–F–M triangle nearer to the typical calc–alkaline trend than the Skaergaard trend (Thayer 1967). By this criteria the Jotunheimen ultramafites are certainly 'Alpine type' (Fig. 6). The variation diagram (Dietrichson 1958) shows that the alkali-lime index of the Upper Jotun Nappe rocks is around 57.

Carstens (1918) observed that;

1. Peridotite lenses are generally surrounded by pyroxenite which displays gradational contacts to gabbro and peridotites.
2. Sharp contacts between the lithological units are rare.
3. Transecting relations serve to define the intrusion sequence peridotite–pyroxenite–gabbroic and granitic rocks.

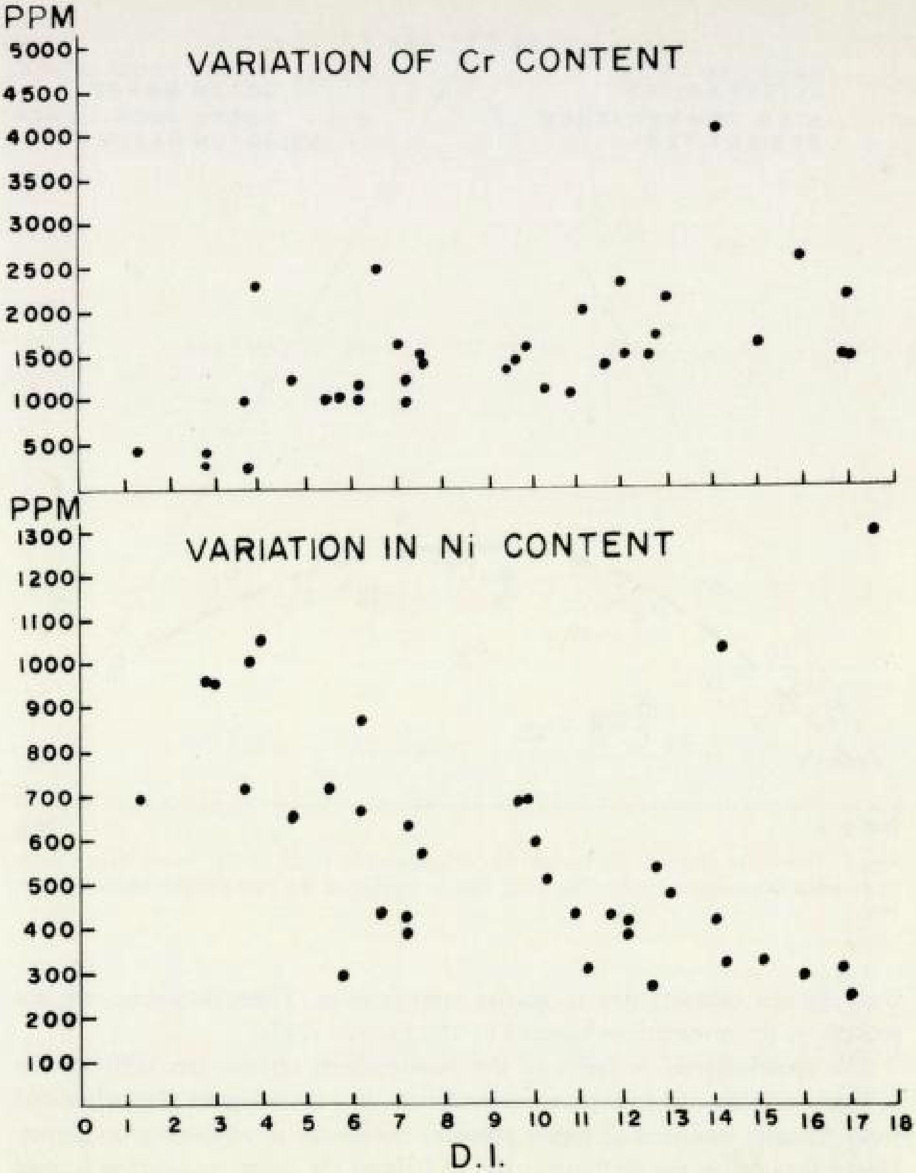


*Fig. 5.* Chromium and nickel contents plotted against the differentiation index (D.I.).

4. Lithological sequence could be explained in terms of in situ concentration of the first crystallised minerals from the parental magma.

The present study has not confirmed observations 1, 2 and 3, but the mineralogical paragenesis confirms the intrusion sequence given by Carstens. Absence of chilled contacts between the individual rock types does not support the intrusive sequence. The in situ concentration of the first crystallised minerals from the parental magma in the order mentioned by Carstens (1918) would produce reaction and cumulate textures and in large bodies also layering

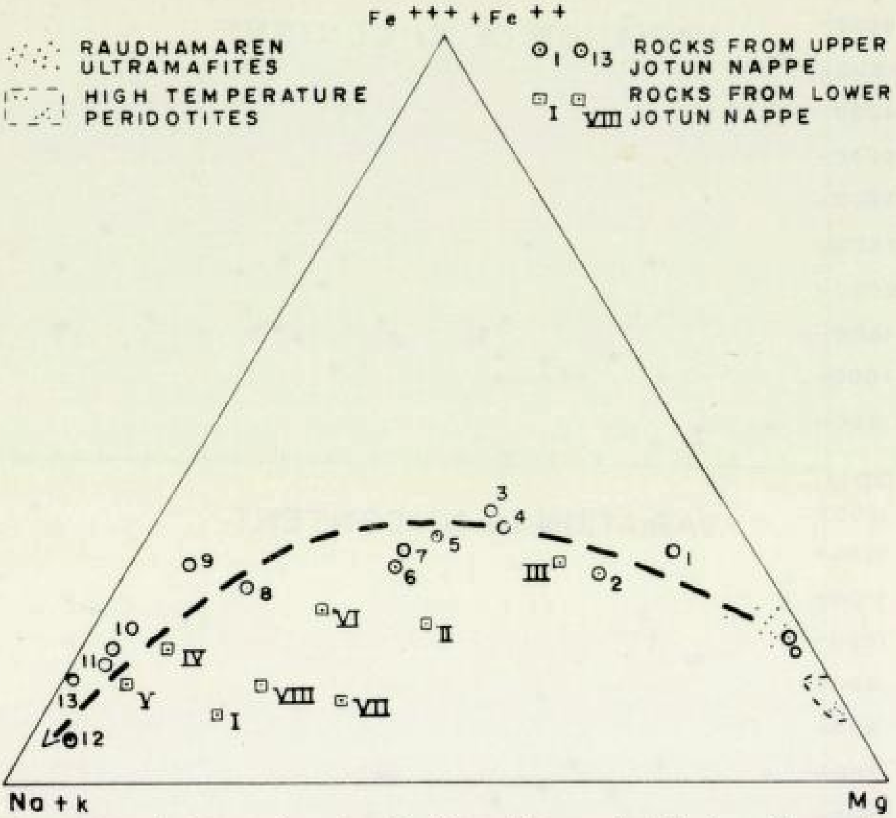


*Fig. 6.* Triangular diagram illustrating the differentiation trend of the Jotun Nappe rocks (data from Dietrichson 1958). The trend line is typical of the calc-alkaline series (Thayer 1967).

with distinct contacts due to gravity stratification. These, however, are not present in the ultramafites covered by the present study.

The spinel–lherzolite facies of the Jotunheimen ultramafites differs from Seiland subfacies of lower pressure conditions in containing no plagioclase and from Ariegite subfacies of higher pressure conditions in containing no garnet. Hence they define the restricted stability field of the spinel–peridotites formed under high temperature and moderately high pressure conditions (MacGregor 1967).

The origin of alpine ultramafite–gabbro association was explained by Thayer (1963) as due to gravity stratification of peridotite and gabbro in the upper mantle and their emplacement into shallower levels. Such a gravity-stratified intrusive hypothesis is difficult to reconcile with the origin and emplacement of the Jotunheimen ultramafites because undoubted gravity strata are not seen there. The Jotunheimen ultramafites rather occur as numerous xenoliths and podiform bodies of limited dimensions. Reaction and cumulate textures, cryptic layering, etc. characteristic of stratiform bodies are absent in this area.

High pressure ultramafic mineralogy has shown (Green & Ringwood 1967) that plagioclase disappears between 13.5 and 15.7 kb pressure at 1200°C temperature, and that garnet will disappear from pyrolite composition at about 21 kb pressure around 1300°C temperature. In the light of these data the absence of plagioclase and garnet in the Jotunheimen ultramafites indicates load pressure between 13.5 and 21 kb at magmatic temperatures (1200° to 1300°C).

The origin of the calc-alkaline magma is uncertain (O'Hara 1968). Spinel peridotites have been correlated with the Upper Mantle composition (MacGregor 1967) and it is now believed that the low velocity zone of the Upper Mantle can cause basaltic magmatism by diapiric upwelling (Green 1970). Hence, the alpine peridotite-gabbro association appears to be due to the Upper Mantle evolution of basalts due to diapiric upwelling in orogenic zones and segregation of gabbro or basalt leaving residual peridotite. The anhydrous differentiation of ultramafites is complementary to the segregation of gabbro and basalt magma, the evolutionary trend of which possibly depends upon the level of partial fusion and the local composition of the mantle on fusion.

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