

# MAFIC AND ULTRAMAFIC INCLUSIONS FROM THE INITIAL (CAMBRIAN?) VOLCANISM IN THE CENTRAL TRONDHEIM REGION, NORWAY\*

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A few horizons of metavolcanics occur within the Cambrian Gula Schist Group of the Caledonides of the central Trondheim Region. In spite of a moderate vertical thickness they have a wide lateral extension, being more or less stratabound and associated with bituminous pelitic schists. The metavolcanics consist mostly of mafic assemblages and include clusters or small bodies of alpine-type ultramafics which in places grade into gabbroic varieties. A polyphase deformation and metamorphism has affected the original mineral assemblages and the ultramafics appear mostly as hornblendites, actinolite–chlorite rocks, talc–chlorite schists and serpentinites. Petrochemical investigations reveal a fractionation pattern following a progressive Fenner-trend. The Cr/Ni ratio is nearly constant throughout the series and the Cr + Ni-content is closely related to the magnesia content of the rocks. A cognate, cumulate origin of the inclusions is suggested.

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The evidence for volcanic events preceding the well known Lower Ordovician volcanic sequence within the Trondheim Region (Støren Group) has briefly been touched upon in the literature concerning the Cambro–Silurian succession in this part of the Norwegian Caledonides. In the inverted Lower Palaeozoic sequence of the central Trondheim Region the Gula Schist Group constitutes the lowermost Eocambrian/Cambrian member which pre-dates the volcanic Støren-Group (Bugge 1954, Wolff 1967, Roberts et al. 1970, Rui 1972, Rohr-Torp 1973).

Psammitic mica schists make up the major part of the Gula schists, which include some horizons of bituminous phyllites and quartzites. Tørnebohm (1896) included the latter in his 'Brek-skiffer gruppe' (a sub-division of the Gula Schist Group) and was among the first who recognized the green-schists associated with them. They were later recognized by Bugge (1910) and C. W. Carstens (1920) in the central Gula schist area. Vogt (1947) included the western train of Gula metabasites in his survey map of the Trondheim Region but correlated and coupled them with the Støren Group in the Selbu and Innset districts.

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Amphibolites of a possible Gula-schist age occur intercalated within the lowermost strata ('Røros schists') in the Surnadal syncline (Hernes 1956) and in the Snåsa syncline (Peacy 1964).

Recent investigations in the southern Trondheim Region have revealed the wide lateral extension of the stratabound Gula amphibolites. In the Røros district they occur near the border between the psammitic schists and graphite phyllite of the Gula Schist Group, more or less continuously from Tynset to Haltdalen (Rui 1972). They have also been recorded by Mosson & Quesnel (1970), Berthomier & Maillot (1971), Berthomier et al. (1971), Mosson et al. (1972), Guezou et al. (1972) and Pinna (1973) within black schist horizons of the Gula schists in the Savalen-Folldal-Dovre region. They have been mapped in connection with investigations of the sulphide ore deposits in the Røstvangen-Kvikne-Innset area by Lindberg (1971), Nilsen & Mukherjee (1972) and Rui (1973). An initial Upper Cambrian basaltic volcanism now seems to be generally accepted (Carstens 1960, Roberts et al. 1970, Gale & Roberts 1972).

The great number of sulphide deposits which are confined to the Gula amphibolites (Nilsen & Mukherjee 1972: 152) induced a detailed mapping of the apparently insignificant amphibolite horizons in connection with sulphide ore studies in the central Caledonides.

The Gula metavolcanics can be grouped into three different components, viz. fine-grained amphibolites, hornblende porphyrites and ultramafics. The fine-grained amphibolites make up the major part of the metavolcanics and the ultramafic to gabbroic components occur sparsely as smaller inclusions or bodies adjacent to the main amphibolite horizons.

The present paper gives an account of the petrology and geochemistry of the Gula metabasites in an area of approximately 2,500 km<sup>2</sup> within the southern, central Trondheim Region (Fig. 1). Emphasis will be laid on the ultramafic and gabbroic inclusions and their petrogenetical significance will be discussed. A number of type-localities will be described. In the text they will be referred to with a number in parentheses to the maps (Figs. 1 and 2).

## The amphibolites

The Gula amphibolites occur as more or less continuous trains in the central and western parts of the Gula-schist area. Their discontinuous appearance

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Fig. 1. Map of the central and western Gula schist area, southern Trondheim Region. Black: The Gula metabasites. Ruled: The Lower Ordovician 'Støren Group' and younger formations. Grey: Caledonian intrusives (trondhjemite, opdalite). Localities of mafic and ultramafic bodies described in the text:

- |                               |                                   |
|-------------------------------|-----------------------------------|
| 1. Gråhø serpentinite quarry  | 5. Bjerkenås (at the river Hauka) |
| 2. Kaltberget mine and quarry | 6. Plassbekken quarry, Gauldalen  |
| 3. Vakkerlien prospect        | A. Kletten metaperidotite body    |
| 4. Undal gabbro complex       | B. Haukfjellet gabbro complex     |

The inset frames A and B refer to the maps in Fig. 2.

and variable thickness, which is in the range 1–50 m, are partly due to tectonic disruption by slip folding. This can be demonstrated in the Soknedal–Budal area, where two phases of folding, viz.  $F_1$  in a NNE–SSW direction interferes with a dominant  $F_2$ -direction (NW–SE), thereby displaying a pinch-and-swell pattern in the volcanic horizons. In the southern areas the  $F_1$ -phase is the most dominant and some horizons have been traced along the strike for several km.

The stratigraphical position of the metabasites within the Gula schists has been a problem. In the eastern part they clearly occur near the border between the psammitic and the younger bituminous pelitic parts of the succession. This is in accordance with the observations of Rui (1972) from the Røros district. In the central part of the Gula-schist area they are similarly mostly confined to black schists and quartzites, but the isoclinal and poly-phase deformation of the strata makes it difficult to delineate their exact stratigraphical position.

The different lithologies of the Gula Schist Group have been metamorphosed to mineral assemblages characteristic of the greenschist facies and the middle amphibolite facies in the area. Metamorphism of the lower intensity is restricted to the Soknedal–Budal area, while the Kvikne area is representative of the higher facies.

The metavolcanics occur as fine-grained schistose amphibolites of a dark green to greenish-grey colour. The amphibolites of the Budal–Soknedal region generally have a more fine-grained texture and a lighter, less schistose appearance. It is pertinent to mention that no intermediate to acid varieties are found within the metavolcanics, in contrast to the younger Støren volcanic suite which has quartz-dacitic to rhyolitic affinities.

A banding, usually present in the mm to cm scale, is due to variable relative proportions of plagioclase and hornblende, which are the main constituents of the rocks. This banding is always conformable with the prominent schistosity of the rock. Locally, thicker (1–3 cm) bands and lenses of coarse-grained calcite marble occur – usually accompanied by clinozoisite, plagioclase and quartz in the southern areas.

Green hornblende is the predominant constituent and occurs as helicitic shattered prisms, 0.3–1 mm in length, usually with a preferred orientation parallel to the foliation. Pleochroism is weak, but distinct:  $\alpha$  – light yellowish-grey,  $\beta$  – light olive green,  $\gamma$  – light greyish-green. In the Soknedal–Budal area the amphibole is more randomly oriented in the amphibolites as tangled masses of pale, greenish-grey prisms.

Plagioclase occurs as an interstitial, fine-grained mosaic (0.05–0.3 mm) between the amphiboles and as coarser-grained aggregates together with quartz and calcite. Clinozoisite and chlorite are common within the ground-mass of the Budal–Soknedal amphibolites. Biotite, rutile and sphene are common accessory constituents, while opaque ores are rare.

In the Kvikne region the amphibolites display a zonal character. Towards the enclosing metasediments the amphibolites become more coarse-grained

and massive. Quartz and porphyroblasts of garnet, often several mm across, appear at the expense of the calcic constituents of the rock such as plagioclase, calcite or clinozoisite. The change is transitional and the border zone usually contains pyrrhotite-impregnated, coarse-grained cummingtonite/hornblende-bearing garnet quartzites. These boundary relations are described in more detail by Nilsen & Mukherjee (1972) from the Kvikne mines. This characteristic development of the contact-zone, which involves a depletion of lime, is, namely, restricted to areas of high grade metamorphism, i.e. the Kvikne-Innset area, and are not found within the low grade chlorite zone in the Budal-Soknedal areas. The enrichment of Mg, Fe and partly Al of the rocks may be a primary geochemical feature of the border facies of the metavolcanics. This may be difficult to distinguish in the field in the low-grade areas, but may be accentuated in the high-grade areas by the specific mineral assemblages. However, the coarse-grained texture, which tends to a monomineralic, pegmatitic development of the border zones, suggests a metamorphic/metasomatic origin of a reaction-seam type. The mineral transformations of the metavolcanics, which undoubtedly for the greater part are related to the different metamorphic conditions subjected to them, need more investigations and are not considered further in this paper.

### The inclusions

The mafic and ultramafic nodules occur included in or closely adjacent to the Gula metabasites. Their dimensions are small. The largest outcrops at Kletten and at Haukfjellet are presented in Fig. 2, A and B, respectively, with reference to the map (Fig. 1).

Their size and shape vary from ellipsoidal and elongate bodies, clearly distinguishable from the amphibolitic host rocks, to less well-defined clusters or sheets within the amphibolite. Usually the inclusions occur near the border between the metavolcanics and the enclosing mica schists. In the Kvikne area some ultramafic bodies occur well separated from the metavolcanics, e.g. at Kaltberget (2) and Vakkerlien (3).

The inclusions have been subjected to metamorphism together with the host amphibolite and alteration, deformation and recrystallization have taken place to a considerable degree which unfortunately has obscured the original geochemical, petrological and morphological field relations. In the high-grade metamorphic terrains the inclusions are readily overlooked because of their strong mineralogical similarity to and structural concordance with the amphibolites. However, the inclusions are easier to distinguish in the low-grade areas due to the more distinctive mineral parageneses developed there (such as chlorite, talc and colourless amphibole) and their different texture as compared with the host amphibolites.

Roughly one can discern two petrologically different types of inclusions, viz. the metagabbroic and metaperidotitic inclusions, of which the former appears to be the most frequent member. However, more or less gradual

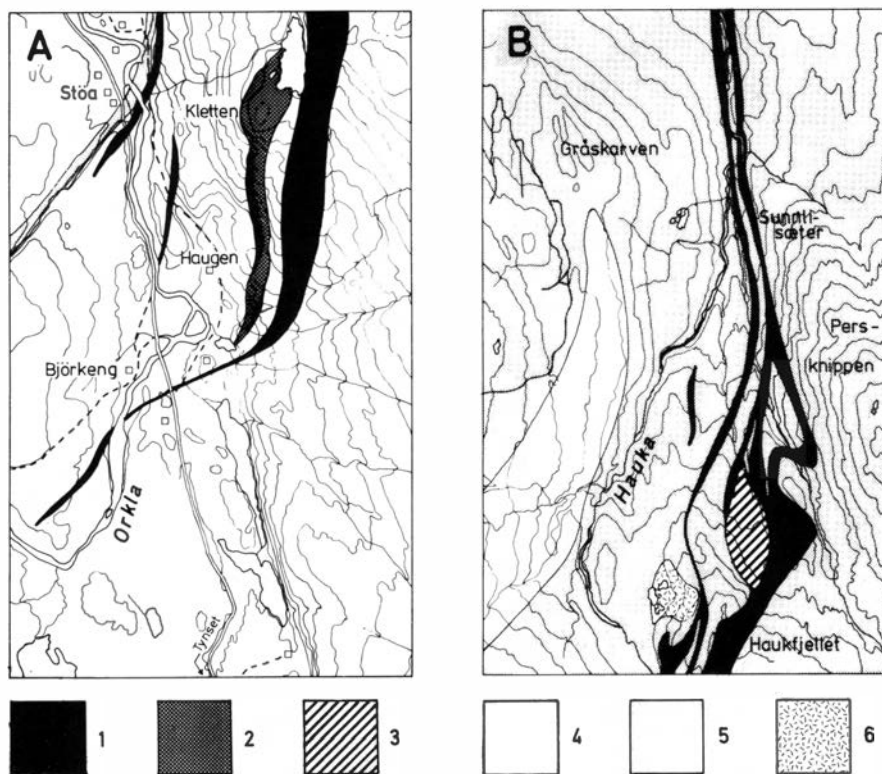


Fig. 2. A: Map of the Kletten metaperidotite body. B: Map of the Haukfjellet gabbro complex. Scale: 1:50 000. Legend: 1: Amphibolite. 2: Cortlandtite and hornblendite. 3: Porphyritic hornblende gabbro. 4: Calciferous biotite-quartz schist. 5: Graphite schist and -quartzite. 6: Trondhjemite.

transitions exist in the field the petrological significance of which will be discussed later.

#### *Gabbroic and composite inclusions*

The gabbroic varieties occur chiefly as massive, fine- to medium-grained hornblende porphyrites. Two larger bodies occur in the field – at Undal (Fig. 1 (4)) and at Haukfjellet (Fig. 1 (B) and Fig. 2 (B)) – but usually they appear as lenticular sheets within the Gula metabasites. Their mineralogical composition is close to the latter, but they differ with respect to texture and the absence of carbonate minerals.

Greyish-green hornblende phenocrysts appear as stout prisms, 1–20 mm in length, commonly clustered together in glomeroporphyritic groups and scattered through an intersertal groundmass of plagioclase ( $An_{30-40}$ ), sphene and occasional clinozoisite. The groundmass is usually granular and fine-grained, often fracturing and splintering the hornblende phenocrysts, but ophitic, equigranular varieties are also found. The porphyritic gabbros may grade into coarse-grained, nearly monomineralic hornblendites or dense

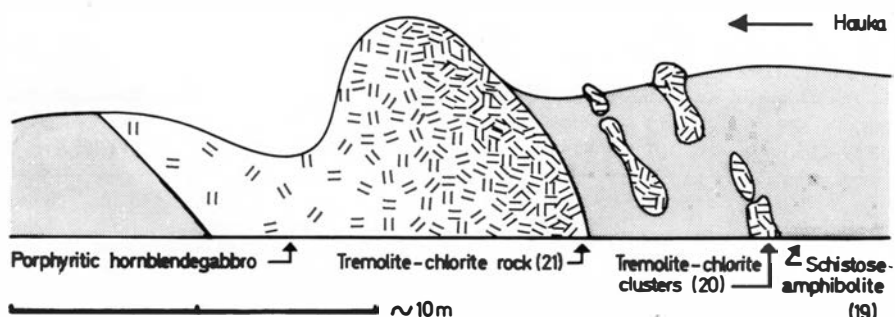


Fig. 3. The section at the river Hauka near Bjerkenås (Fig. 1 (5)). The numbers in parentheses refer to the analyses listed in Table 1.

tremolite-chlorite rocks, but usually an abrupt transition into the equigranular, fine-grained host amphibolite occurs.

The relationship between amphibolite host rock and the mafic nodules is best seen in a river section at Hauka, near Bjerkenås (Fig. 1 (5)). A composite cluster of metabasites is exposed within a homogeneous succession of foliated, fine-grained greyish-green amphibolites (Fig. 3). Small irregular discs, 10–15 cm in thickness, of a more massive fine-grained amphibole-chlorite rock are included in the schistose amphibolite. At first glance they resemble relict pillow-structures (Fig. 4). The discs, however, are clearly related to a larger composite body, 3–7 m in thickness, included below. The 'upper' part of the body consists of the same massive actinolite-chlorite rock. The amphibole occurs as phenocrysts, 0.3–1 mm in length, within a



Fig. 4. A cluster of massive tremolite-chlorite rock within the schistose amphibolite at Bjerkenås (Fig. 1 (5)).

Table 1. Chemical analyses, norms and specific gravity of Gula metabasites. Analyses nos. 6–10 from Rui (1973), nos. 11–13 from Berthomier & Maillot (1971) and nos. 14–16 from Lindberg (1971).

Sample No. UTM Grid ref.	1 707274	2 811358	3 800307	4 696621	5 699253	6 784117	7 785115	8 663195	9 782195	10 719179
SiO <sub>2</sub>	47.30	47.59	46.03	43.84	45.39	46.39	48.62	48.66	50.23	47.32
TiO <sub>2</sub>	0.69	0.90	1.03	1.53	0.99	0.94	1.03	1.46	1.16	1.02
Al <sub>2</sub> O <sub>3</sub>	12.63	14.70	14.04	15.63	13.83	14.50	14.69	14.29	15.04	14.29
Fe <sub>2</sub> O <sub>3</sub>	1.86	1.75	1.50	0.91	1.87	3.26	2.83	1.49	2.84	1.79
FeO	7.40	6.18	8.20	10.43	11.61	5.46	6.51	8.98	5.29	6.67
MnO	0.30	0.14	0.16	0.14	0.46	0.14	0.13	0.00	0.00	0.00
MgO	15.14	8.26	7.40	9.53	8.41	9.21	7.06	9.42	11.15	11.15
CaO	11.28	13.58	12.30	12.66	10.23	13.96	10.70	11.60	10.75	10.45
Na <sub>2</sub> O	1.32	2.73	2.92	2.11	1.68	2.35	2.94	2.76	2.54	3.45
K <sub>2</sub> O	0.14	0.06	0.23	0.73	0.17	0.15	0.13	0.12	0.11	0.17
P <sub>2</sub> O <sub>5</sub>	0.07	0.08	0.08	0.17	0.12	0.11	0.10	0.13	0.15	0.16
CO <sub>2</sub> + H <sub>2</sub> O	2.85	3.53	4.37	3.84	3.35	3.75	1.79	2.71	1.99	2.30
	100.99	99.49	98.27	99.10	99.28	99.42	99.68	99.26	99.52	98.77
Ni (ppm)	640	210	70	175	280	500	400	45	180	350
Cr (ppm)	950	400	200	400	600	400	800	200	450	850
g	3.07	3.00	2.98	3.04	3.08	3.07	3.02	3.01	2.98	2.98
Q	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0
Or	0.82	0.37	1.44	4.55	1.06	0.92	0.79	0.74	0.98	1.02
Ab	11.81	22.21	21.86	11.36	15.86	20.07	27.01	25.78	30.36	24.96
An	28.03	28.61	26.05	32.77	31.24	29.78	27.13	27.32	24.56	23.29
Ne	0	1.87	3.59	5.19	0	1.15	0	0	0	3.83
Hy	14.65	0	0	0	16.12	0	9.26	10.59	2.99	0
Di	21.81	32.37	30.55	25.90	17.05	33.29	21.21	25.33	20.18	22.49
Ol	19.83	11.21	13.16	16.59	14.91	9.64	9.89	6.22	16.11	20.75
Mt	1.94	1.89	1.66	1.00	2.06	3.55	3.03	1.62	2.91	1.89
He	0	0	0	0	0	0	0	0	0	0
Il	0.96	1.30	1.52	2.25	1.45	1.36	1.47	2.12	1.58	1.44
Ap	0.15	0.17	0.18	0.38	0.26	0.24	0.21	0.28	0.33	0.34

- 1: Dark amphibolite, Orkelbogen.
- 2: Fine-grained amphibolite, Rundhaugen.
- 3: Schistose amphibolite, Magnilsæter.
- 4: Fine-grained amphibolite, Budal.
- 5: Coarse-grained amphibolite, Gråhø.
- 6: Amphibolite, Savalen.
- 7: Amphibolite, Savalen.
- 8: Amphibolite, Børsjøhø.
- 9: Amphibolite, Knausen.
- 10: Amphibolite, Røstvangen.

fine-grained, felty mass of colourless chlorite (clinocllore). Downwards the body grades into plagioclase-bearing varieties, semi-porphyritic to porphyritic in texture. The plagioclase (An<sub>27-32</sub>) clearly intersects the amphibole phenocrysts along cracks and crystal faces as a fine granular groundmass. Zoning of the amphibole is characterized by a deepening in colour and a decrease in birefringence towards the ragged margins of the phenocrysts.

It is likely, as revealed from other localities, that the transition between the

Table 1. (cont.)

Sample No. UTM Grid ref.	11 493107	12 498200	13 636069	14 548700	15 543665	16 528658	17 741766	18 741766	19 679780	20 679780
SiO <sub>2</sub>	44.60	45.90	49.30	47.55	52.62	53.66	48.89	47.35	47.98	46.51
TiO <sub>2</sub>	1.22	1.00	0.86	1.93	2.37	2.71	1.52	0.73	1.34	1.09
Al <sub>2</sub> O <sub>3</sub>	12.60	16.20	15.80	15.55	15.28	14.54	16.76	9.65	16.98	13.71
Fe <sub>2</sub> O <sub>3</sub>				1.76	3.71		2.76	1.22	2.30	1.51
FeO	11.51*	10.21*	7.67*	9.91	11.82	10.14*	7.79	9.30	8.00	8.67
MnO	0.19	0.16	0.13	0.33	0.21	0.12	0.16	0.22	0.13	0.16
MgO	14.53	9.38	9.26	7.65	8.34	4.31	8.33	18.71	8.65	14.16
CaO	9.64	10.46	10.44	7.29	2.58	7.71	10.92	9.57	11.00	8.86
Na <sub>2</sub> O	1.64	2.76	2.61	2.76	1.82	4.03	2.22	0.26	3.30	1.88
K <sub>2</sub> O	0.09	0.19	0.24	0.29	0.09	0.37	0.31	0.21	0.50	0.50
P <sub>2</sub> O <sub>5</sub>				0.18	0.22	0.64	0.10	0.05	0.13	0.11
CO <sub>2</sub> + H <sub>2</sub> O	3.12	1.27	1.49	5.23	2.58	2.43	1.36	4.35	1.95	3.84
Ni (ppm)	100.42	98.67	98.65	100.44	101.65	100.66	101.11	101.63	102.25	101.00
Cr (ppm)				90	95	25	90	570	270	570
g				250	300	50	300	1050	550	1150
							3.05	3.00	3.03	2.98
Q	0	0	0	0	16.74	3.85	0	0	0	0
C	0	0	0	0	9.07	0	0	0	0	0
Or	0.54	1.15	1.45	1.81	0.55	2.25	1.84	1.25	2.92	2.98
Ab	15.08	23.40	24.00	26.23	16.92	37.24	20.04	2.35	23.09	17.04
An	27.41	32.09	31.44	30.90	11.76	21.10	35.05	24.75	29.68	27.76
Ne	0	1.22	0	0	0	0	0	0	3.70	0
Hy	8.50	0	16.83	27.84	37.05	19.14	19.50	36.14	0	11.68
Di	17.26	16.94	17.28	4.90	0	11.17	15.00	18.22	18.69	12.70
Ol	27.25	21.54	5.55	3.12	0	0	3.33	14.86	17.44	24.48
Mt	2.23	2.23	2.23	1.95	4.01	0	2.90	1.29	2.37	1.59
He	0	0	0	0	0	0	0	0	0	0
Il	1.74	1.43	1.23	2.85	3.42	3.89	2.13	1.03	1.84	1.53
Ap	0	0	0	0.40	0.48	1.38	0.21	0.11	0.27	0.23

11: Amphibolite, Døllibru.

12: Amphibolite, Digerkampen.

13: Amphibolite, Digerkletten.

14: Greenstone massive, Undal.

15: Pillow-lava, Undal.

16: Schistose amphibolite, Undal.

17: Dark amphibolite, Svardal.

18: Light coloured amphibolite, Svardal.

19: Schistose amphibolite, Bjerkenås.

20: Tremolite-chlorite cluster, Bjerkenås.

\* Total iron as FeO

ultramafic and the mafic inclusions in general is gradual when they appear together. However, the gabbroic clusters seem to occur most frequently without, or less associated with, ultramafics.

### *Ultramafic inclusions*

The ultramafic inclusions are more conspicuous in appearance in their dif-

Table 1. (cont.)

Sample No. UTM Grid ref.	21 679780	22 688227	23 721305	24 711351	25 704880	26 529624	27 698596	28 568532	29 526637
SiO <sub>2</sub>	43.50	37.94	49.73	51.28	45.45	47.23	50.62	51.74	57.92
TiO <sub>2</sub>	0.88	0.34	0.67	0.47	0.43	1.96	1.12	1.88	0.51
Al <sub>2</sub> O <sub>3</sub>	11.01	4.21	7.46	6.20	7.47	9.48	15.42	15.62	16.04
Fe <sub>2</sub> O <sub>3</sub>	1.48	3.06	2.16	1.13	1.84	1.96	1.10	2.45	1.02
FeO	8.85	6.63	6.67	6.74	7.45	8.89	8.06	9.57	4.64
MnO	0.18	0.15	0.17	0.15	0.17	0.00	0.00	0.19	0.00
MgO	21.47	31.47	18.33	22.00	23.50	16.86	9.09	5.65	5.15
CaO	7.64	2.49	10.56	8.86	7.14	9.00	11.14	6.79	8.05
Na <sub>2</sub> O	0.49	0.00	1.32	1.18	0.48	0.91	2.54	4.49	4.16
K <sub>2</sub> O	0.03	0.22	1.70	0.20	0.00	2.42	0.65	0.20	0.26
P <sub>2</sub> O <sub>5</sub>	0.08	0.04	0.07	0.03	0.05	0.01	0.05	0.26	0.08
CO <sub>2</sub> + H <sub>2</sub> O	6.45	12.90	2.53	3.77	7.89	3.30	1.52	1.90	2.50
	102.07	99.75	101.36	102.02	101.87	102.01	101.31	100.75	100.32
Ni (ppm)	800	1700	350	450	800	450	120		40
Cr (ppm)	1800	2700	1400	1950	1900	850	300		350
q	2.95	2.75	3.05	3.00	2.91				
Q	0	0	0	0	0	0	0	0	7.65
C	0	0	0	0	0	0	0	0	0
Or	0.18	1.38	9.88	1.16	0	14.24	3.82	1.20	1.56
Ab	4.44	0	11.66	10.36	4.39	8.14	22.70	40.89	37.83
An	28.00	11.55	9.26	10.79	18.58	14.58	28.63	22.20	24.65
Ne	0	0	0	0	0	0	0	0	0
Hy	23.36	23.42	6.68	34.00	34.41	5.41	10.80	18.78	14.14
Di	7.76	2.33	33.45	25.60	13.74	23.85	20.84	8.20	12.21
Ol	33.30	57.31	25.80	16.23	26.21	29.00	10.41	2.93	0
Mt	1.56	3.41	2.22	1.15	1.96	2.04	1.14	2.60	1.08
He	0	0	0	0	0	0	0	0	0
Il	1.24	0.50	0.92	0.64	0.61	2.72	1.55	2.66	0.72
Ap	0.17	0.09	0.14	0.06	0.11	0.02	0.10	0.55	0.17

21: Tremolite-chlorite body, Bjerkenås.

22: Serpentine, Gråhø.

23: Meta-peridotite, Kletten.

24: Meta-peridotite, Kaltberget.

25: Chlorite-talc schist, Plassbekken.

26: Dark hornblende gabbro, Undal.

27: Porphyritic gabbro, Haukfjellet.

28: Porphyritic gabbro, Næverdalen.

29: Porphyritic gabbro, Undal.

The total amount of CaO is calculated as silicate and phosphate norms; hence calcite is not included in the norms.

ferent colour and mode of weathering. Some of them are associated with the gabbroic varieties as previously described, but many appear as small isolated sheets and discs within or adjacent to the Gula metavolcanics.

In the valley of Gauldalen a few soapstone quarries are confined to the Gula metabasites. They were exploited at the beginning of this century for restoring the cathedral in Trondheim (Helland 1893, C. W. Carstens 1929).

A petrographical description of the rock from one of the quarries has been given by Kjerulf (1892). The soapstone quarry at Plassbekken (Fig. 1 (6)) is a trench 70 m in length with a width of about 5 m. The ultrabasic apparently has the shape of a sheet with relatively sharp and conformable boundaries to the enclosing host amphibolite, carrying small schlieren of porphyritic amphibolite.

The soapstone is weakly foliated and contains small, sparsely distributed and shattered tremolite needles and is intensively replaced by felty chlorite. Talc occurs as flaky aggregates that are usually oriented across the foliation of the rock, which is defined by parallel oriented trains of chlorite. Dolomite, rutile, chalcopyrite, pyrrhotite and pentlandite are accessory constituents.

Smaller soapstone inclusions (talc-chlorite schists) are commonly included in the amphibolites of the northern part of the valley of the river Hauka, but their field relations are obscured by heavy covering.

In the southern areas, separate small bodies of ultrabasics occur adjacent to the amphibolite horizons between Røstvangen and Kvikne. With the exception of the Kletten ultrabasic (Fig. 1 (A)), the single outcrops cover only a few hundred square metres.

A zonal arrangement of a metamorphosed ultrabasic can be found at the peak of Kletten (Fig. 1 (A) and Fig. 2 (A)), which is the biggest exposure of ultrabasics in the Kvikne-Budal area. Its central parts consist of a massive, coarse- to medium-grained hornblende-metaperidotite (cortlandtite) with relics of olivine and pyroxenes. Olivine and diopside occur in the less altered varieties as rounded blebs, 0.1–0.3 mm across, poikilitically included in the amphiboles, which are the chief mineral component of the rocks. These occur as stout prisms several cm in length with a weak, olive-green to yellowish-grey pleochroism. A zonal bleaching of the amphibole along the crystal faces and across the prism zones is often accompanied by carbonate mineralization.

Otherwise the amphibole is replaced by serpentine (chrysotile) along grain boundaries and cracks. The olivine inclusions are usually rimmed by a felty mass of serpentine and magnetite. Orthopyroxene (bronzite) occurs as anhedral laths and contains similar rounded inclusions of olivine and clinopyroxene. Analyses of two orthopyroxenes, one clinopyroxene and one olivine are given in Table 2.

Pyrite, pyrrhotite and pentlandite, which are common accessory constituents of the rock, give lepidochrosite and goethite as alteration products.

Transitions to phlogopite-bearing actinolite rocks take place towards the margins of the Kletten body. The same veined and bleached zonal structure of the amphibole is present, but the poikilitic inclusions are lacking. Phlogopite overgrows the amphibole in large flakes, randomly orientated.

A recent excavation has revealed numerous chlorite veins through the body as well as an envelope of talc schist.

The Kletten body gives the only evidence for an original lherzolitic composition of one ultramafic inclusion within the Gula metabasites.

Table 2. Analyses of pyroxenes and olivine from cortlandtite, Kletten. I-II: Orthopyroxenes. III: Clinopyroxene. IV: Olivine.

	I	II	III	IV
SiO <sub>2</sub>	55.4	54.6	53.3	40.7
TiO <sub>2</sub>	0.07	0.25	0.28	—
Al <sub>2</sub> O <sub>3</sub>	1.1	2.4	1.9	—
FeO	9.7	9.6	4.4	14.1
MgO	31.6	30.9	17.2	45.2
CaO	1.0	1.0	21.5	—
Na <sub>2</sub> O	0.04	0.03	0.37	—
	98.91	98.78	98.95	100.00

Analyst: W. L. Griffin.

The ultramafics at Kaltberget (Fig. 1 (2)) were described in connection with the sulphide deposit associated with them by Nilsen & Mukherjee (1972) and will be briefly described below. They occur as three small knolls composed of a coarse-grained actinolite rock quite similar to the marginal parts of the Kletten body. In the old days these rocks were exploited for the manufacture of pots and vessels (Helland 1893, Helland 1902, Skjølsvold 1961). The border facies of the ultramafics are feldspathic, phlogopite-bearing and sheared – usually impregnated with chalcopyrite, pyrrhotite and pentlandite.

At Gråhø (Fig. 1 (1)) a small body of serpentinite is exposed. Recent archaeological investigations there have revealed traces of an extensive soapstone industry dating back to the pre-Roman Iron Age (Skjølsvold 1969). The serpentinite has yielded excellent material for pots and vessels (Fig. 5) and a great number of moulds and cavities are visible on the rock surface. In this century the old quarry has furnished the cathedral in Trondheim with raw material for its restoration.

The rock is massive and fine-grained and has a beautiful bluish-green colour. It is composed of serpentine (antigorite), chlorite and talc with accessory dolomite, sphene, ilmenite, magnetite, pyrrhotite, pentlandite and chalcopyrite. The serpentine occurs as flaky aggregates ('books'), slightly rounded and with a six-sided outline – a typical bastite texture which is rimmed with opaque dust of oxide ore or penetrated parallel (001) with the sulphides. Chlorite and talc occur interstitially – the latter also replacing the antigorite pseudomorphs.

At Vakkerlien (Fig. 1 (3)) a small nickeliferous metagabbro/peridotite cluster is exposed in a heavily covered area. Exploration for copper ore started around 1870 and was taken up again in the period 1910–1920. The workings have revealed a rock quite similar to the ore-bearing metabasite at Kaltberget. The rock is fine-grained and consists chiefly of pale greyish amphibole (actinolite) and minor plagioclase (An<sub>55-65</sub>) in varying proportions, exhibiting a granoblastic texture. The border zone is brecciated and phlogopite-bearing. Zoning and veining of the amphibole by a colourless amphibole



Fig. 5. Moulds and cavities from the Iron Age pot production at the Gråhø serpentinite (Fig. 1 (1)).

is likewise present here, and the growth of phlogopite is seen to accompany the veining of the mineral. Separate crystals of the colourless amphibole often display a multiple (010)-twinning which might indicate an alteration to cummingtonite. However, the birefringence and refractive indices point to a tremolite composition. The twinning may thus be interpreted as a strain phenomenon induced by the brecciation of the rock (Tröger 1969: 441).

### Petrogenetical considerations

As revealed by the petrology and field relations of the mafic and ultramafic rocks, they can be considered as being of an 'alpine type' in the sense of Thayer (1960). The term does not however, imply an unambiguous origin and mode of emplacement of alpine bodies. In this case we are apparently dealing with syn-volcanic peridotitic nodules which are frequently recorded from recent basalts as well as from many pre-Cenozoic metavolcanics (Challis & Lauder 1966, Dudek & Kopecký 1966, Forbes & Kuno 1967, Naldrett 1970, Pamić et al. 1973).

Lenses of serpentinite and related rocks occur mostly outside the greenstone areas in the Norwegian Caledonides and their origin and mode of emplacement have been a problem to most of the workers on the Caledonian mountain chain.

They have recently been described either adjacent to or separated from metabasites of Gula schist age in the Sparbu region, Nord-Trøndelag by Mortenson (1973). Their cognate genetic association with the Støren green-

stone suite was already emphasized by Goldschmidt (1915) but little has yet been published on these inclusions. However, Foslie (1955) noticed the entirely different field appearance of soapstones included in the Støren greenstone of Hardanger in comparison with the apparently exotic nodules within the mountain chain and he suggested a cognate (paleopicritic) origin of these sheet-like soapstone inclusions.

As for the Gula inclusions, from their strata-bound nature it is evident that most of them have been emplaced as nodules together with the greenstones – either within shallow intrusions within the Gula schists or as effusive volcanics. The origin of the more isolated but adjacent bodies may be of the same kind, either displaced by a tectonic breakup of a parent body or synchronously emplaced as satellite intrusions. However, the extensive metamorphic recrystallization has obliterated the field evidence for a possible intrusive origin of these bodies.

The biggest inclusions within the Gula greenstone have a tendency to occur within, or closely adjacent to, the thicker parts of the metavolcanics. At Haukfjell, the greenstone horizon swells around the gabbroic body, thinning out northwards. This relationship is also demonstrated at Undal and Kletten. Oftedahl (1968) has referred the same relationship within the Støren volcanism to old intrusion channels or effusion conduits. It is reasonable that the mafic and ultramafic constituents will deposit near the conduits of the greenstone whatever their physical nature.

The origin of the mafic and ultramafic nodules within basaltic rocks has been a controversial topic for a long time. Generally speaking, three different models have been proposed for their origin: They may represent accidentally incorporated material from the upper mantle (Ross et al. 1954, Kutolin & Frolova 1970), or xenoliths from the mantle from which a certain quantity of elements was removed when the basalts were formed (a cognate partial melting residua) (Kleeman & Cooper 1970, Reid & Frey 1971, Stull & McMillan 1973), or cognate accumulations of a basalt magma, temporarily trapped in an intracrustal magma chamber (Richter & Murata 1961, Challis & Lauder 1966, Forbes & Kuno 1967, Potts 1972). No reliable criteria have yet been established which can distinguish between the different models, but field evidence, together with the following petrochemical considerations, may discriminate between a cumulate versus an exotic origin of the inclusions of the Gula greenstone.

## Petrochemistry

18 whole rocks from the Gula metabasites have been analysed for their major elements by means of XRF (Siemens SRS1) using fused powder + Li-tetraborate (1:9). FeO was determined by potassium dichromate titration. In addition, five analyses from Rui (1973), three from Lindberg (1971) and three from Berthomier & Maillot (1971) are listed in Table 1, together with their CIPW-norms. With the exception of Berthomier & Maillot's samples,

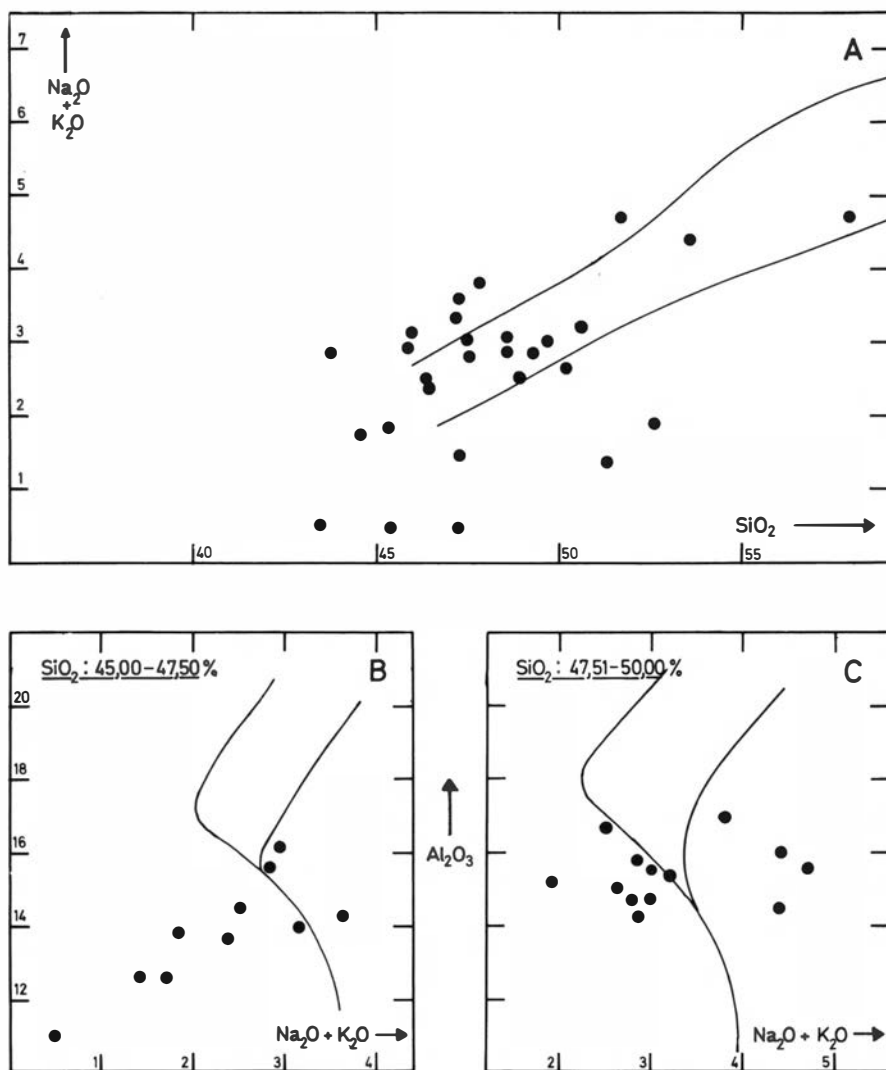


Fig. 6. A:  $\text{SiO}_2$  vs.  $(\text{Na}_2\text{O} + \text{K}_2\text{O})$  of the Gula metabasites. B & C: Alkali-alumina diagram of the Gula metabasites. Boundary lines separate the fields for tholeiitic basalts, high alumina basalts and alkali basalts, after Kuno (1968).

their Cr and Ni contents were determined by XRF, using rock powder pellets. Their analytical error is  $\pm 10\%$ . The compositional variations of the inclusions, as well as their host rocks, are presented in the diagrams (Figs. 6, 7 and 8).

Microprobe analyses of minerals from the cortlandtite of Kletten are presented in Table 2. They were done with an ARL-EMX probe using a series of natural and synthetic standards and the correction procedures of Bence & Albee (1968).

The apparent polyphase metamorphism, which in varying degrees has affected the Gula Schist Group, has undoubtedly involved chemical adjust-

ments within the different lithologies. These processes have probably brought about mineral transformations and an obliteration of the original geochemical character of the rocks. Appreciable quantities of water were necessarily added during the formation of actinolite, chlorite and serpentine minerals and the effect of an influx of lime ('rodingitization'), silica and alkalies cannot be overlooked. Thus the narrow ranges of geochemical parameters which characterize recent alkali-olivine basalts and tholeiites were not found within the Gula metabasites. The total amount of alkalis versus silica or alumina varies for instance to a large degree and the samples plot in the fields of alkali-olivine basalts as well as within the fields of the tholeiitic suite of basaltic rocks (Kuno 1968) (Fig. 6).

However, in the AFM-diagram (Fig. 7) the samples lie close to the olivine-tholeiites of Shido et al. (1971) and MacDonald & Katsura (1964) but have a tendency to plot near the Mg-corner of the diagram. In this respect their resemblance to the high Mg-basalts or komatiites from the Archaean of South Africa (Viljoen & Viljoen 1969) and Australia (Hallberg & Williams 1972, McCall 1973) is striking.

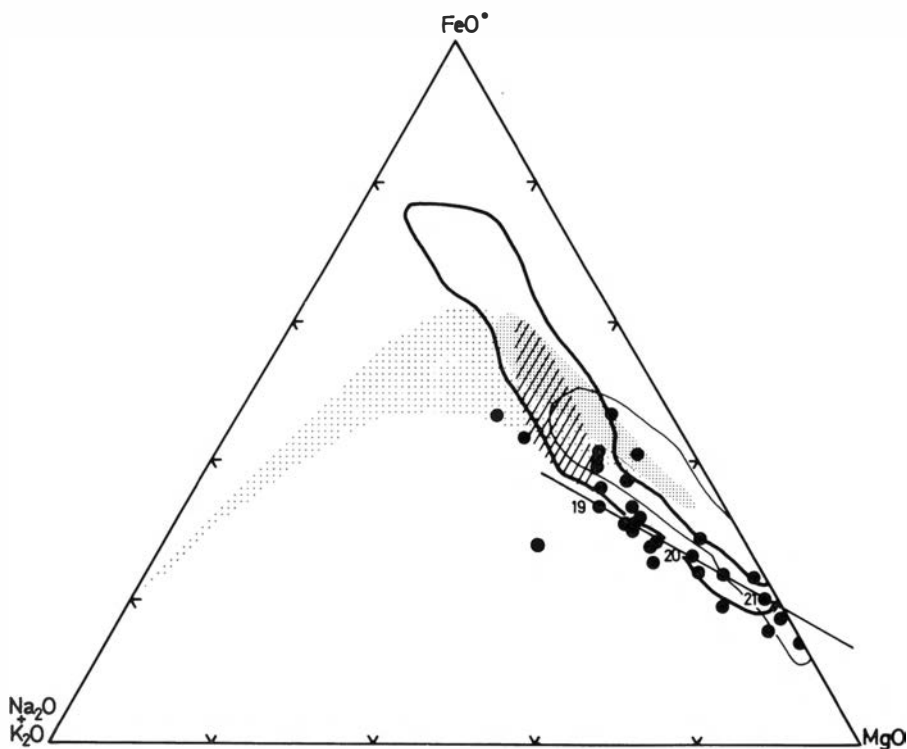


Fig. 7. AFM-diagram of the Gula metabasites. The relative distribution of Hawaiian rocks belonging to the tholeiitic (dark grey) and alkalic (light grey) fields are indicated after MacDonald & Katsura (1964). Closely ruled area indicates the field of olivine-tholeiites of Shido et al. (1971). The heavy solid line field and the thin line field include the high Mg-basalts and ultramafics from the Eastern Goldfields region, W. Australia from McCall (1973) resp. Hallberg & Williams (1972). The straight line passes through analyses nos. 19, 20 & 21 of Table 1. (The Bjerkenås loc.)

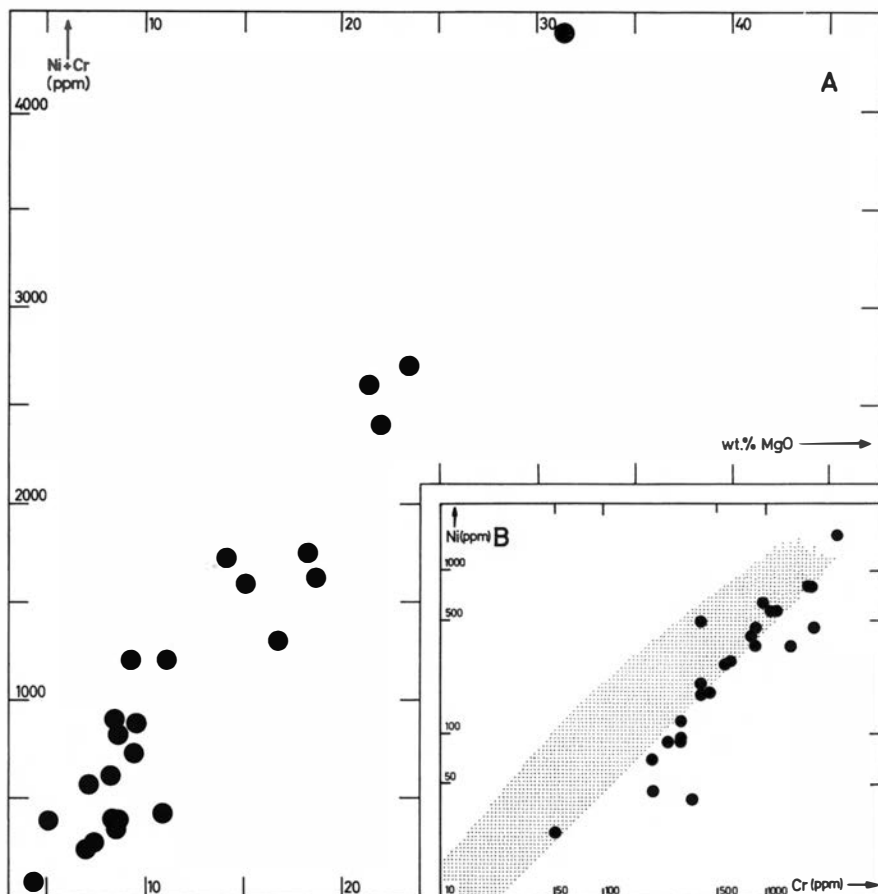


Fig. 8. A: (Cr + Ni) vs. MgO of the Gula metabasites. B: Cr vs. Ni of the Gula metabasites. Stippled area represents the Cr/Ni-relationship of basalts from a world-wide sampling (Turekian 1963).

Taking the spatial ultramafic-mafic association of the Archaean komatiites and their wide variation in chemical composition (which partly overlaps the fields for tholeiitic basalts and ultramafics) into account, the similarity between these high Mg-basalts and the suite of Gula metabasites becomes more evident.

The variation in the high Mg-basalts from Australia is explained as a result of fractional crystallization, largely of olivine (Williams 1972). Fractional crystallization may have brought about the apparently regular Fenner-trend of the Gula suite displayed in the AFM-diagram (Fig. 7). The trend is consistent with the line passing through analyses 19, 20 and 21 indicated in the diagram. The three analyses are from the Bjerkenås locality previously described (Fig. 3) and show a progressive iron enrichment from the ultrabasic cluster (21) via the sparsely distributed, light coloured nodules (20) within the schistose, fine-grained matrix (19). This consistency suggests a general cognate relationship of the mafic inclusions with their metabasaltic

host rocks. Hence the apparent fractionation trend as revealed by the AFM-plots from the entire suite of Gula metabasites is consistent with a local petrochemical gradation of ultramafic and mafic fractions once separated from the basaltic host magma. This may have been brought about by a temporary crystal settling in an intracrustal magma reservoir before the ejection of the material.

As shown by Green (1964) early formed pyroxenes in well documented differentiated basaltic intrusions have  $\text{Al}_2\text{O}_3$  contents between 1.5 % and 2.0 % in contrast to accidental nodules with  $\text{Al}_2\text{O}_3$  contents ranging from 2.17 % to 5.32 %. Thus the composition of the pyroxenes from the Kletten cortlandtite (Table 2) may support the evidence of an original intracrustal cumulate origin of the ultramafics.

It is tempting to cite the similar conclusions reached by Thompson (1916) (as referred to by Wilshire & Binns 1961: 203) on the consanguinity between basalts and inclusions from the Antarctic: 'The fact that the inclusions themselves form a differentiation series comparable with that which would have been expected had the various basic volcanic rocks enclosing them consolidated under plutonic conditions suggests that they are actually fragments from such a series which has arisen from the differentiation in depth of a portion of the primary basic magma.'

#### *The petrochemistry of Cr and Ni*

Throughout the series the Cr and Ni contents of the Gula metabasites show certain regularities which may have a certain petrogenetic significance. As seen from Fig. 8B their Cr/Ni-ratios have an approximate constant value (average 2.7) lying close to the average ratio for basaltic rocks from all over the world (Turekian 1963). The nearly constant ratio of chromium to nickel in the ultramafics and metabasalts lends support to the statements put forward by Turekian (1963) and Mercy & O'Hara (1967) that the ratio in basalts is probably derived from the mantle rather than generated by processes operating in the crust and that fractional crystallization of a basaltic magma does not result in significant alteration of this Cr/Ni-ratio.

As seen from the figure the Cr + Ni content is strongly correlated with the magnesia content of the metabasites. The rocks being nearly devoid of opaque ore, the nickel and chromium must be fixed in the femic constituents. Nickel is known to replace  $\text{Mg}^{++}$  and  $\text{Fe}^{++}$  in the olivine lattice, while chromium tends to replace  $\text{Al}^{+++}$  in the pyroxenes (e.g. chrome-diopside) (Wedepohl 1963, Mercy & O'Hara 1967). However, a Ni-content much above 2000 ppm cannot be derived from olivine alone (Wedepohl 1963) and a sulphide phase has to be expected. Pentlandite is thus recorded in some of the ultrabasics with the highest Ni-content (Plassbekken, Gråhø) as accessory constituents. In a few cases, e.g. at Vakkerlien and Kaltberget, nickel ore has been mined together with copper ore.

The nickel enrichment of these ultramafics may have been brought about either by metamorphic modifications of primary sulphide cumulates (Kilburn

et al. 1969, Marmo 1955) or by sulphurization of the original Ni-bearing silicates contemporaneous with or followed by serpentinization and tectogene concentration processes (Naldrett 1966, Kullerud & Yoder 1965, Ashley 1973).

The sulphides apparently replace the gangue minerals along grain boundaries and crystal faces, and in contrast to the gangue, they do not show any effect of metamorphism or deformation. This might point to a post-amphibolitization/serpentinization mineralization, but as demonstrated by Kilburn et al. (1969) the textures can be metamorphic, a crystallization of primary sulphides postdating the primary silicate crystallization. By recrystallization and redistribution of silicate and sulphide, the latter component tends to fill interstices between the silicates. The presence of exsolution textures between pentlandite and pyrrhotite in the ores of Vakkerlien and Kaltberget mines indicates that the pentlandite was formed below 610°C and round about 550°C (Kullerud 1963). As flames of pentlandite within accessory pyrrhotite are found within the low-grade talc-chlorite schist at Plassbekken as well as within the high-grade cordierites of Kletten and Kaltberget, these exsolution textures may be derived by exsolution from an orthomagmatic pyrrhotite-phase or formed by recrystallization under high amphibolite-facies conditions. However, exsolution textures do not exist between pentlandite and pyrrhotite in the Gråhø serpentinite. There pentlandite is developed as discrete flakes, intergrown parallel to (001) of the pyrrhotite, which again is parallel to (001) of the antigorite. Thus it is likely that the original textural relationship between pyrrhotite and pentlandite has been destroyed during the serpentinization of the rock.

Chromite has not yet been found within the Gula metabasites. The chromium content should therefore be fixed in hornblende or chlorite and within the antigorite and magnetite at Gråhø. In general the Gula ultramafics differ from the Caledonian serpentinites of the Røros region in being devoid of chromite.

## Conclusions

The mafic and ultramafic inclusions within the Gula metavolcanics comprise a special group of alpine-type ultramafics. From the nearly constant association of the ultramafic rocks with these metavolcanics and their chemical affinities, it is reasonable to suppose that they are genetically related. Thus they reflect an oceanic (ensimatic) environment as exemplified by Chidester & Cady (1972) from the greenstone belt of northern Newfoundland and from the Scottish Highlands by Garson & Plant (1973). In view of their intimate association with the gabbroic rocks it seems unreasonable to consider the ultramafic nodules as possible refractory residues of an extended partial melting. The metabasalts and the inclusions are suggested to be products of a magma fractionated according to a Fenner-trend. The Ni and Cr distribution in the rocks is consistent with that of a magma having

both basic and ultrabasic affinities. The sympathetic variation of Cr and Ni with the magnesia contents of the metabasites is moreover in accordance with the general fractionation trend obtained during differentiation of a tholeiite magma (e.g. Greenland & Lovering 1966, Danchin & Ferguson 1970, Thompson et al. 1972).

The inclusions may represent intracrustal cumulates from a normal basalt magma, temporarily trapped in reservoirs and later injected as shallow intrusions or extruded on the sea floor as proposed by Richter & Murata (1961), McCall (1970) and Sagredo (1973).

The assemblages have undergone at least three different phases of metamorphism and deformation as revealed by microtextures, recrystallization and associated neomineralization. During folding and penetrative movements of the strata some clusters have probably been removed from larger magmatic bodies and brought into new environments.

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September 1973

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