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The petrography and geochemistry of corona-bearing dolerites from the Jotun Nappe, central southern Norway

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ABSTRACT. The petrography and geochemistry of a suite of dolerite dykes emplaced into orthogneisses of the Jotun Nappe, central southern Norway, are described. The dolerites, which appear to be tholeiitic in character, show well-developed ophitic and doleritic textures and are not foliated. They contain corona structures of six types which represent the various stages of reaction between olivine or clinopyroxene and plagioclase, and oxide grains and plagioclase. Corona growth always proceeds after the plagioclase has become clouded with numerous extremely fine opaque particles, and reaches its fullest development in rocks with the most heavily clouded plagioclase. Garnet grows in coronas only in rocks with $Fe_2O_3/(Fe_2O_3+FeO) = 0.20$ to 0.27. The ratio $MgO/MgO+Fe_2O_3+FeO)$ is of lesser importance in controlling the growth of this mineral. The role of water in corona-forming reactions, and the preservation of original igneous textures indicates that the coronas are a product of post-solidification deuterism, possibly active at high pressures and temperatures, rather than of prograde metamorphism.

THE Jotun Nappe of central southern Norway is composed of a suite of variably metamorphosed orthogneisses, gabbros, and granites of Precambrian age (Battey and McRitchie, 1973; Schärer, 1980) which are unconformably overlain by Eocambrian and Lower Palaeozoic sediments (Sturt and Thon, 1978). Prior to the formation of the nappe (during the Caledonian Orogeny), the Precambrian rocks were intruded by a suite of dolerite dykes which, although not numerous, are of wide geographical distribution (fig. 1). They are found around Lake Gjende (Emmett, 1980), east and north-east of Tyin (Battey and McRitchie, 1973), south of Bygdin (Hossack, 1976), and along the north-west margin of the nappe (Twist, 1979). The dykes are of interest because they contain corona structures around olivine, clinopyroxene, oxide grains, and biotite. This account describes the dolerites which occur in the central part of the Jotun Nappe, around the west end of Gjende, and comparisons will be drawn with the examples described by Battey and his co-workers.

The structure of the Jotun Nappe between Tyin and Gjende is dominated by the large north-east-trending Tyin–Gjende Fault (Battey, 1965). To the north-west of this fault lies a massif of intermediate pressure granulite facies meta-igneous tectonites (Battey and McRitchie, 1975; Emmett, in prep., and fig. 1) which appear to represent the metamorphosed intermediate levels of a large igneous intrusion (Emmett, 1980). To the south-east of the fault are a series of thrust sheets which are believed to contain the upper levels of this intrusion, and the grade of metamorphism within these is correspondingly lower. It was from these thrust sheets east of Tyin that McRitchie (1965) reported the discovery of nine dolerite dykes, the first known examples from this area. Battey *et al.* (1979) subsequently described a peculiar garnet-pseudomorph phenomenon from a dyke discovered on the mountain Storegut. Following a detailed study of the area around the west end of Gjende, the author discovered another dyke south-east of the fault and four to the north-west (fig. 1*c*). The dykes from the north-west area, the uppermost and the lowermost thrust sheets, trend just east of north, whilst those from the intermediate sheets strike somewhat more northeasterly (Battey and McRitchie, 1973; Emmett, 1980).

Petrography. All the dolerite dykes studied are unfoliated and cut across the fabric of the host gneisses. The locations of the dykes studied are shown in fig. 1 and all are sub-vertical with the thickest 10 m wide. Medium grained ophitic textures are apparent in hand specimen, but where country rock–dyke contacts are exposed, fine grained chilled marginal zones are developed. The petrography of the various dolerites is similar, the

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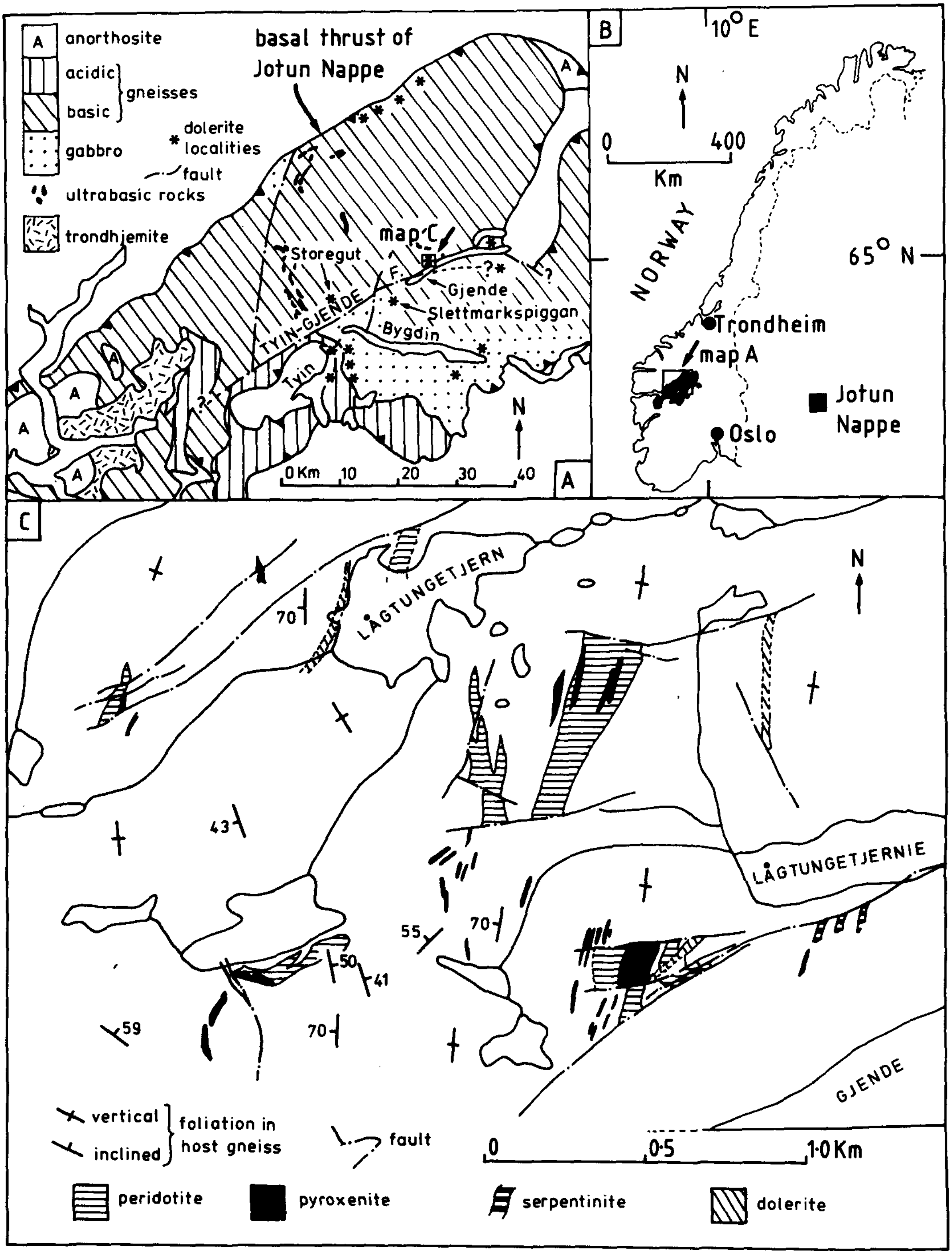

FIG. 1. Sketch maps showing (*a*) simplified geology of the Jotun Nappe (after Emmett, 1980), with dyke localities marked by asterisks, (*b*) the location of the Jotun Nappe, and (*c*) a sketch map of a central portion of the nappe, showing the field relations of the newly discovered dykes.

rock being composed essentially of laths of plagioclase with interstitial clinopyroxene and some olivine and amphibole (fig. 3). Typical grain sizes are: plagioclase phenocrysts 1100 × 200 μm, ophitic plagioclase 500 × 100 μm, ophitic clinopyroxene up to 2000 μm across, interstitial clinopyroxene and olivine about 300 μm across. Common accessory minerals are opaque oxide phases (mainly ilmenite), apatite, and greenish spinel (very rare). However, there are detailed differences, especially in the nature and form of the ubiquitous corona stuctures, and these are summarized in Table I.

Plagioclase may occur as phenocrysts or as part of the matrix, and is commonly about An_{55}, though in the Slettmarkspiggan dyke it is more sodic, An_{46}. The plagioclase may show weak zoning. Plagioclase phenocrysts in chilled margins are often flow-aligned, and they show much evidence of corrosion by the matrix. It is a notable feature of the dykes studied that the plagioclase is invariably clouded with numerous fine opaque particles which impart a reddish tinge to the crystals. The clouding is variable in intensity, being affected by such features as zoning and twinning (cf. McLelland and Whitney, 1980). The rocks with the most intensely clouded plagioclase (e.g. as from the dyke at the west end of Lågtungetjern, fig. 1*c*) have the most fully developed corona structures. Chilled margins usually do not show good coronas and have only faintly clouded plagioclase. However, the margin of the dyke north of Lågtungetjernie contains shapeless spongy porphyroblasts growing in a matrix dominated by heavily uralitized clinopyroxene and green amphibole.

Fig. 2 presents a schematic summary of the types of corona encountered in this study, and their nomenclature. The distribution of the various types is shown in Table I. The coronas are developed between mafic silicates or opaque oxide phases and plagioclase, with preferential development around olivine (fig. 3). By careful observation of the coronas in thin section, it is possible to determine the order of mineral development. In general, garnet grows at the expense of green amphibole and plagioclase, and granular garnet develops only from garnetiferous symplectites. Coronas grow after the clouding of plagioclase. Other general observations are that the amphibole in coronas is pale green whereas the primary igneous amphibole is brown, and also that garnet or garnetiferous symplectite is not ubiquitous, but most common in association with biotite. Two types of biotite are recognized in coronas. Biotite I is the earlier formed of the two, usually the coarser grained, and pleochroic from pale straw to dark red-brown. Biotite II, which only occurs in coronas of type 6 (see fig. 2), forms finely granular rims to biotite I and is much paler and yellower than the earlier biotite.

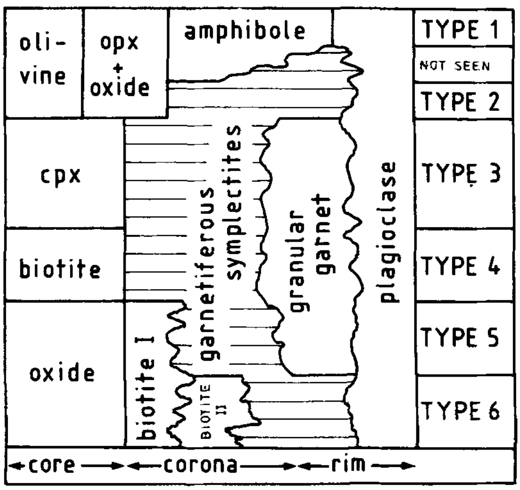

FIG. 2. Schematic representation of the six types of corona discussed in this paper.

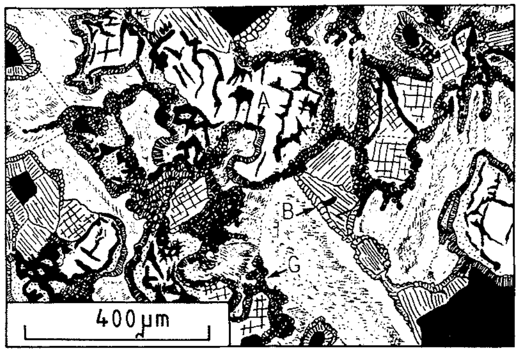

FIG. 3. A sketch from a photomicrograph of a portion of the Slettmarkspiggan dyke. Laths of plagioclase (light cross-hatching representing clouding) are corroded by coronas developed around olivine (with skeletal opaques), clinopyroxene (coarse cross-hatching), and opaques (black). Orthopyroxene is shown in light stipple, biotite I by a coarse line ornament. Biotite II (arrowed 'B') grows around biotite I. Amphibole of type 1 coronas is arrowed 'A', whilst garnet or garnetiferous symplectite is shown by a curly ornament (arrowed 'G'). The view is atypical in so far as clinopyroxene is usually more common than olivine, the reverse being true in the sketch.

Rock chemistry. Table II lists rock analyses of the dolerites of this study and, for comparative purposes, an analysis of the Storegut dyke (Battey *et al.*, 1979). The Storegut dyke is very similar in composition to the Slettmarkspiggan dyke, but compared to these two the other analyses are poorer in K_2O and TiO_2 and richer in MgO, CaO,

TABLE I. *Summary of dyke petrography*

	1a	1b	2	3a	3b
plag	An_{55}	$*An_{55}$	An_{56}	An_{46}	An_{45}
cpx	x	x	x	x	x
brown amph.	x				
olv	x			x	r
coronas	1,6	**	3,4,6	1,2,3,6	

x present. r rare.
* phenocrysts and matrix.
** no coronas, but garnet porphyroblasts present.

TABLE II. *Analyses of dolerites*

	1a	1b	2	3a/b	4b
SiO_2	46.7	47.2	47.6	46.3	45.5
Al_2O_3	16.72	16.42	13.13	15.70	14.5
Fe_2O_3	2.73	1.10	2.91	3.97	4.6
FeO	8.99	10.31	13.54	12.31	12.8
MgO	8.26	8.27	5.69	5.54	5.01
CaO	9.99	10.11	9.41	7.72	8.58
Na_2O	2.29	2.62	2.55	3.07	2.93
K_2O	0.48	0.51	0.84	1.40	1.22
TiO_2	1.37	1.39	2.65	2.55	3.88
MnO	0.16	0.16	0.25	0.21	0.23
P_2O_5	0.14	0.14	0.27	0.55	0.57
H_2O^+	0.07	0.05	0.18	0.46	0.45
H_2O^-	0.12	0.05	0.11	0.24	0.05
(CO_2)	1.00	1.14	0.90	0.83	—
Total	97.66	98.33	99.13	99.74	99.92
Cr	226	254	84	53	
Li	8	5	5	5	
Ni	171	156	64	74	
Co	74	72	84	88	
Zn	103	100	155	150	
Cu	101	79	181	51	
Sr	350	333	265	325	
Pb	5	15	5	11	
Rb	9	14	16	20	

TABLE III. *Geochemical ratios*

	*1a	1b	*2	*3a/b	4a	*4b
K/Rb	443	302	436	609	—	—
mg	0.42	0.42	0.26	0.23	0.23	0.23
ox	0.21	0.10	0.20	0.25	0.42	0.27
mg in garnet	—	—	0.15	—	—	0.16

* Contains garnetiferous coronas.
$mg = MgO/(MgO + Fe_2O_3 + FeO)$
$ox = Fe_2O_3/(Fe_2O_3 + FeO)$

TABLE IV. *Mineral analyses*

	A	B	C	D
SiO_2	0.2	55.8	64.2	38.5
Al_2O_3	0.07	28.49	19.28	17.88
FeO*	48.46	0.31	0.10	24.36
MgO	0.97	0.13	—	6.68
CaO	0.04	9.37	1.28	10.24
Na_2O	—	5.88	1.31	—
K_2O	—	0.28	14.74	—
MnO	0.34	—	—	1.41
TiO_2	48.58	—	—	0.36
Total	98.66	100.26	100.91	99.43
		Structural formulae		
Si	0.11	5.01	5.88	3.05
Al^{iv}	—	0.99	0.12	—
Al^{vi}	—	2.02	1.97	1.67
Fe	1.05	0.02	0.01	1.61
Mg	0.04	0.02	—	0.77
Ca	—	0.90	0.13	0.87
Na	—	1.02	0.23	—
K	—	0.03	1.72	—
Mn	0.01	—	—	0.09
Ti	0.95	—	—	0.02
O	3	16	16	12
		or 2%	86%	alm 48%
		ab 67%	11%	pyr 23%
		an 31%	3%	gro 26%
				spes 3%

FeO* = total iron as FeO.

The following explanations apply to Tables I to IV.

1. Lågtungetjernie dyke (a, centre; b, margin).
2. Lågtungetjern dyke.
3. Slettmarkspiggan dyke (a, centre; b, margin; a/b, average).
4. Storegut dyke (a, margin; b, centre). From Battey *et al.* (1979).

A. Ilmenite. B. Plagioclase (rim). C. Interstitial orthoclase. D. Granular garnet. A–D from the Lågtungetjern dyke.

Mineral analyses by EPMA, rock analyses by AAS and colorimetric methods. Full analytical techniques described in Emmett (1980). (CO_2) is a nominal figure which represents all volatiles (determined by ignition at 850 °C by 2 hours) other than water (H_2O^+ and H_2O^- determined separately).

All analyses by the author.

Cr, and Ni. All these analyses bear close comparison to the 'average' composition of dolerites from the southern Norwegian coast (Brøgger, 1935) and Sunnmøre (Gjelsvik, 1952). In spite of the presence of modal olivine in some of the dolerites, all are quartz-normative, and the analyses are close to that of the 'average' dolerite as determined by Le Maitre

(1976). Though there are not enough individual analyses to determine a trend, the analyses all plot in that part of the MgO-total Fe-total alkali diagram assigned by Irvine and Baragar (1971) to the tholeiitic rocks.

Many authors have pointed out that chemical environment is as important as P–T conditions in delimiting the stability field of garnet in rocks, and this view is supported by experimental studies (e.g. Hsu, 1968). Leake (1972) emphasized the roles of mg, i.e. $Mg/(Mg+Fe+Mn)$, MnO and oxidation ratio in controlling the first appearance of garnet. In general, garnet forms first in rocks of low mg, i.e. generally iron-rich rocks (Battey *et al.*, 1979). In the dolerites of this study, the oxidation ratio, $Fe_2O_3/(Fe_2O_3+FeO)$, seems more critical, with garnet only developing where the oxidation ratio lies between 0.20 and 0.27. If the ratio lies outside these limits (Table III), amphibole or chlorite, or both, are developed instead of garnet.

The corona-forming reactions. Microprobe analysis of the mineral components of some coronas are listed in Table IV. Good analyses were obtained from ilmenites and granular garnets in a type 5 corona, a clinopyroxene (from a type 3), and plagioclase. Phases within symplectites gave poorly reproducible results with bad totals: these unusable results are attributed to interference from adjacent grains due to the extremely small grain size and intimate nature of the intergrowths. The garnet is rich in almandine and pyrope components, but is low in Ti. Compositionally, it is not uniform but the zoning is weak and erratically distributed. The ilmenite is relatively pure, with Mg the only significant trace element. The clinopyroxene is augitic and shows weak oscillatory zoning (variation from $Ca_{41}Mg_{36}Fe_{23}$ to $Ca_{31}Mg_{39}Fe_{30}$). The plagioclase immediately adjacent to the granular garnet of a type 3 corona was found to be somewhat more sodic (An_{25}–An_{30}) than the overall composition of the crystal (determined optically as approximately An_{55}). It may be that the growth of grossular-rich garnet has impoverished the immediately adjacent plagioclase in Ca (cf. Whitney and McLelland, 1973), but it may equally well represent an original igneous feature. McLelland and Whitney (1980) were similarly undecided about closely related phenomena in metagabbros from the Adirondacks.

The mineral analyses and the petrographic data already presented place constraints on the processes of corona formation. The petrographic evidence requires that the growth of coronas does not totally disrupt the original igneous texture of the rock. This point cannot be ignored since a large proportion of all coronas are constructed out of minerals which are denser than the presumed reactants. Accordingly, if the growth of coronas is to occur without the collapse of the rock fabric, there must be a net addition of material during corona development. Battey *et al.* (1979) noted that the most mobile elements appear to have been Fe, Mg, and O (additions), and possibly Na (removed). Though the textural constraints in the Storegut dyke are tighter than in our case, simple calculations show that the same elements have been mobile to form the coronas of this study. Another important 'addition' must be hydroxyl ions, since amphibole is a common constituent of coronas. The growth of amphibole from olivine and plagioclase requires a greater number of mobile elements than the subsequent growth of garnet from amphibole. It may well be that the presence of amphibole 'buffers' (or stabilizes) the oxidation state of the immediate micro-environment and therefore promotes the development of garnet. Biotite may perform a similar function in coronas of types 5 and 6.

Examination of fig. 2 indicates that the six corona types observed represent different stages of just two separate reactions. The first, represented by corona types 1, 2, and 3, involves the reaction of mafic silicate (olivine and clinopyroxene) with plagioclase to form garnet, with orthopyroxene, an opaque phase, and green amphibole as intermediate products. The reaction can be represented by a series of partial equations, as follows:

$$\text{olivine or clinopyroxene} + H_2O \rightarrow \text{orthopyroxene} + (Fe,Mg)^{2+} + (OH)^- \quad \text{(i)}$$

$$(Fe,Mg)^{2+} + (OH)^- + \text{plagioclase} \rightarrow \text{amphibole} + SiO_2 \quad \text{(ii)}$$

$$\text{amphibole} \rightarrow \text{garnet} + Na^+ + (OH)^- \quad \text{(iii)}$$

Reactions (i) and (ii) combine to produce coronas of type 1 (McRitchie, 1965). Further reaction along the lines of reaction (iii) produces coronas of types 2 and 3.

Coronas of types 4, 5, and 6 represent reaction between oxide and, or, biotite and clouded plagioclase to form a secondary biotite and garnet. Like the reactions considered previously, it is not possible to write precise equations since analyses of the phases involved, especially biotite, are not available. However, following Griffin and Heier (1969), qualitative reactions may be written as follows:

$$\text{oxide} + \text{plagioclase} + (OH)^- + K^+ \rightarrow \text{biotite I} \quad \text{(iv)}$$

$$\text{biotite I} + \text{plagioclase} + \text{oxide} + O^{2-} \rightarrow \text{biotite II} + \text{garnet} \quad \text{(v)}$$

Coronas of type 4 require only the involvement of reaction (v), with presumably original igneous biotite replacing biotite I.

Discussion and conclusions. The clouding of plagioclase and, to a lesser extent, clinopyroxene (probably with iron oxide and, or, spinel), preceded the formation of the coronas, and it is clear that the degree of development of coronas is greatest when the plagioclase and clinopyroxene are most intensely clouded. Poldervaart and Gilkey (1954) regarded such clouding phenomena as being due to the preferential alteration of sub-microscopically unmixed plagioclase by iron-rich fluids. A similar alteration model was proposed by Whitney (1972) and, after a detailed critique, Smith (1974, section 205) also adopted this view. McRitchie (1965) states that clouding probably takes place at between 500 °C and 600 °C, and this suggests that the alteration is deuteric. In support of the conclusion that corona formation is deuteric, it may be observed that coronas are absent or only poorly developed in the chilled margins of dykes. The presumed rapid cooling would prevent their heat energy being used to drive the corona-forming reactions.

As noted previously, water has an important role to play in the generation of the coronas. Water would not be available from the host gneisses since these are essentially unaltered rocks composed predominantly of anhydrous mineral phases (Emmett, 1980). The absence of coronas from chilled margins, and the possibility that the chilled margins may have acted as gaskets to seal in the centres of the dykes, suggests that the source of the water was hydrothermal or deuteric solutions migrating along the central parts of the dykes themselves (cf. Esbensen, 1978). Simple deuterism is not a sufficient process to account for the coronas since not all tholeiite dykes possess them. However, such coronas are typical of the dykes intruded into the high-grade gneisses of southern and western Norway (the 'hyperites' of Brøgger, 1935). Possible explanations for the production of coronas include crystallization and subsequent cooling at elevated pressure and, or, maintenance of high sub-solidus temperatures after initial consolidation. The fact that the enclosing rocks are relatively impermeable and that therefore late magmatic fluids would be concentrated in the dykes may also be important. Battey *et al.* (1979) suggested that the Storegut dyke was intruded at, and cooled at, rather high pressures, so it seems that coronas are produced in tholeiite dykes intruded at depth in the crust. The coexistence of olivine and plagioclase as primary igneous minerals indicates that the pressure must never have exceeded about 7 kb (Presnall *et al.*, 1978).

The conclusions of this study are as follows. The dolerite dykes of central Jotunheimen show tholeiitic tendencies and are essentially unmetamorphosed, the coronas within them being due to processes acting during post-magmatic cooling in the presence of internally-derived hydrous fluids. High pressure (up to 7 kb) and possibly the maintenance of high sub-solidus temperatures during deuterism are also required. Garnet is developed in the coronas only if the oxidation ratio of the host rock falls within a specific range, with the Mg/Fe ratio of the host rock being of secondary importance.

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