Metamorphic petrology of the Froland corundum-bearing rocks: the cooling and uplift history of the Bamble Sector, South Norway

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Corundum-bearing rocks from Kleggåsen, Froland, preserve metamorphic textures which reflect the cooling and uplift path of the Bamble Sector. The P-T path may be correlated with a T-t path constructed from published ages. The P-T path starts at the thermal climax of prograde metamorphism, M I (c. 750°C, 7 kb), characterized by Sil, Pl, Bt, Rt and Crn. Subsequent near-isobaric cooling results in M II, characterized by Ky + Ms ± Chl veinlets (600-700°C, 7 kb). This marks the onset of rehydration. M III assemblages of Mrg ± Crn formed around 500-570°C and 3-7 Kb, and are followed by M IV (c. 400°C, 2-4 kb) characterized by Ms, Bt and Ep. The trajectory from M II via M III to M IV is believed to reflect the uplift of the area in response to Sveconorwegian upthrusting. The uplift was completed before c. 940 Ma, which is the age of post-tectonic granites and K-Ar biotite cooling ages. The latest episode recorded by the Froland rocks, M V (175-280°C, 2-3 kb), is characterized by Prh, Pmp, Scp and Tur, indicating local influx of B- and Cl-bearing hydrous fluids. M V is interpreted as adaption to upper crustal conditions between c. 920 and 760 Ma.

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Introduction

The Bamble Sector (Fig. 1) is part of the Southwest Scandinavian Domain of the Fennoscandian Shield (Gaál & Gorbatschev 1987). It is composed of a Proterozoic supracrustal suite that was metamorphosed and intruded by acidic and basic magmas during the Gothian (1750-1500 Ma) and Sveconorwegian (1250-950 Ma) orogenies. For a detailed description of the lithologies and structural geology of the area, the reader is referred to Starmer (1985, 1991).

In the Nelaug-Froland-Arendal area (Fig. 1), the grade of metamorphism ranges from upper-amphibolite facies in the north up to granulite facies in the area around Arendal in the south (Bugge 1940, Touret 1971, Lamb et al. 1986). P-T estimates range from c. 836°C, 7.7 kb in the core of the granulite facies area to c. 752°, 7.1 kb in the amphibolite facies area (Nijland & Maijer 1992).

Corundum-bearing rocks occur at Kleggåsen, Froland, 11 km northwest of Arendal, and were first described by Oftedahl (1963). The rocks have been interpreted as metamorphosed kaolinite-bauxite weathering crusts (Serdyuchenko 1968). They are leucocratic, and gneissic in their biotite-rich parts. The rocks are composed mainly of plagioclase, corundum, biotite and sillimanite, and cut by veinlets of green mica and kyanite. They occur in a 2 m-wide, concordant lens, which is separated from steeply dipping banded and granitic gneisses by a 20 cm-thick biotitite. A small, intensively altered part of the outcrop features large brown tourmaline and a rare chromian montmorillonite, volkonskoite (Nilssen & Raade 1973). The rocks provide information about the successive stages of post-peak metamorphism and have been studied to unravel the cooling and uplift history of the Bamble Sector.

Petrography

Oldest mineral assemblage (M I)

The oldest assemblage, M Ia, consists of plagioclase, biotite, fibrolitic and euhedral sillimanite, and rutile, with accessory zircon, allanite and apatite (Table 1). Microfolds of fibrolite are enclosed by large plagioclase crystals. Plagioclase is in some cases antiperthitic. Large subhedral brown biotites, which commonly contain small sagenite needles, constitute the foliation together with fibrolite. Younger euhedral sillimanite generally also follows this

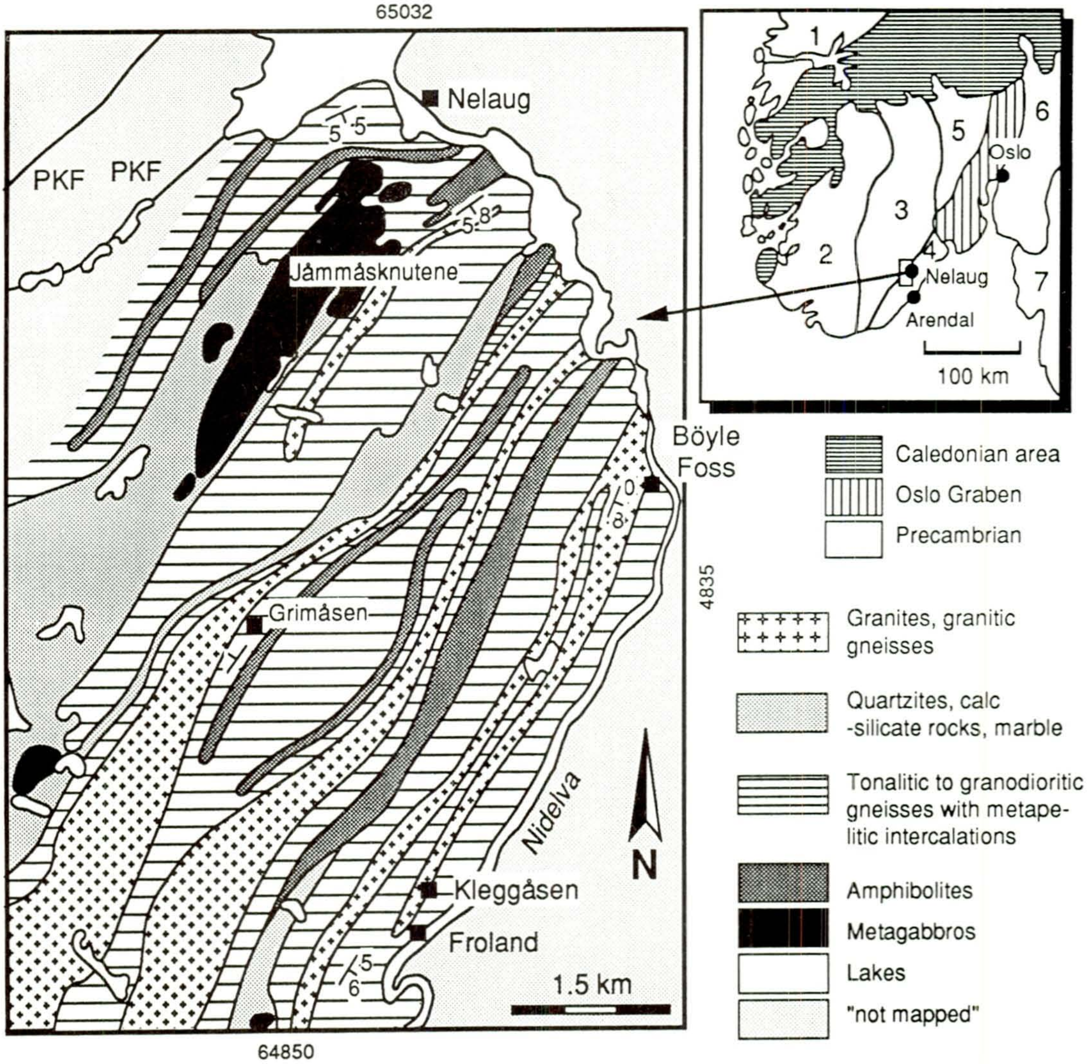

Fig. 1. Geological sketch map of the Froland area west of the Nidelva river with relevant localities (modified after Visser & Senior 1990). Coordinates along the margins of the map are according to the grid of Norges geografiske oppmåling. PKF = Porsgrunn-Kristiansand Fault, which is the boundary between the Bamble and Telemark Sectors. Inset: Division of the Southwest Scandinavian Domain (modified after Verschure 1985). Numbers denote: 1 - Western Gneiss Region, 2 - Rogaland / Vest-Agder Sector, 3 - Telemark Sector, 4 - Bamble Sector, 5 - Kongsberg Sector, 6 - Østfold Sector, 7 - Stora Le-Marstrand Belt.

foliation, but its crystal faces truncate the fibrolite (Fig. 2). Large bronze rutile occurs intergrown with euhedral sillimanite. Rutile shows lamellar twinning and is commonly concentrated within the hinges of microfolds.

Large colourless to pink, pleochroic, corundum crystals enclose both fibrolite and euhedral sillimanite, biotite, rutile and plagioclase, and is therefore denoted as M Ib. Boundaries between corundum and the other minerals are usually sharp, and show no signs of reaction; only sillimanite bottle-neck textures are sporadically observed, i.e. the thinning of sillimanite prisms at the place where they are overgrown by corundum. The M Ib corundum occurs in two different microstructures: either as large subhedral to euhedral crystals (up to several cm) grown in the centre of sigmoidal thickenings of the fibrolite foliation, or as large archipelago-like crystals (Fig. 3). Corundum shows lamellar twinning, and displays slight colour zoning with a bluish tinge, especially along the margins and according to crystallographic planes; the blue colour becomes more intense along altered margins.

	M I										M II			M III		M IV						M V			
	Sil	Fib	Pl	Bt	Crn	Rt	Zrn	All	Ap	Tur	Ky	Ms	Chl	Mrg	Crn	Pl	Bt	Ms	Chl	Cal	Ep	Prh	Pmp	Scp	Tur
TN75	x	x	x	x	x	x	x			x		x						x	x		x	x			
TN76	x	x	x	x	x	x	x					x	x					x	x	x	x				
TN77	x	x	x	x	x	x	x	x	x		x	x	x	x	x		x	x		x		x	x	x	x
TN78	x	x	x	x	x	x		x	x		x	x	x	x	x			x	x	x	x				
TN79		x	x			x	x							x				x		x		x			x
TN81	x	x	x	x	x	x	x					x					x	x	x			x			
TN82	x	x	x	x		x					x	x						x	x	x		x		x	
TN83	x	x	x	x	x	x	x					x						x		x					
TN84	x	x	x	x	x	x					x	x						x							
MA993	x	x	x	x	x	x	x				x	x	x	x			x	x							
FL143			x	x	x	x					x	x	x				x	x	x	x					
FL144			x		x	x	x				x	x	x	x	x	x	x	x	x		x				
FL145	x	x	x	x	x	x			x									x			x				
FL146	x	x	x	x	x	x					x	x	x	x				x		x				x	
FL147	x	x	x	x	x	x	x										x	x							
FL148			x	x		x					x	x	x	x			x	x	x	x	x				
FL149	x	x	x	x	x	x	x				x	x	x	x	x		x	x	x						
FL150	x	x	x	x	x	x					x	x	x	x	x	x	x	x		x	x				
FL151		x	x			x	x	x						x				x			x	x			x

Table 1. Distribution of the successive metamorphic assemblages in the different samples. Mineral abbreviations according to Kretz (1983), except Fib - fibrolite.

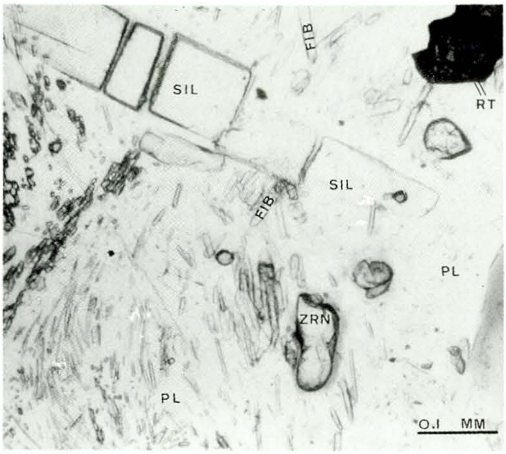

Fig. 2. M Ia fibrolite truncated by M Ia euhedral sillimanite. Photomicrograph of sample TN84.

Kyanite-bearing veinlets (M II)

Veinlets of kyanite and muscovite with minor chlorite cut through the M I assemblages (Fig. 4). Kyanite occurs in the centre of the veinlets, and is weakly bluish pleochroic and twinned. Muscovite and chlorite occur along the margins of the veinlets. Both display a pale green pleochroism. They form relatively large subhedral grains. Rare relics of biotite and fibrolite occur in the veinlets. Although M II minerals are mainly restricted to veinlets, green muscovite and chlorite also occur dispersed throughout the rocks. Here too, they form relatively large, subhedral grains, in contrast to M IV muscovite and chlorite which usually occur as rims and fine-grained aggregates around older phases. M II Muscovite outside the veinlets has been found to enclose microfolds of fibrolite.

Margaritization reactions (M III)

In the host rock (M I assemblage), aggregates of sheaf-like bundles of margarite locally replaced M Ia plagioclase. These aggregates are usually present in the vicinity of M Ib corundum crystals, but the grain boundaries of corundum are virtually unaffected. Sporadically, small corundum grains occur in the margarite aggregates; these may represent relics. Rutile and biotite occur unaffected in these aggregates.

In the M II veinlets, kyanite is partially replaced by fine-grained aggregates and rosettes of margarite. This replacement has preferentially taken place along cracks, cleavage planes and grain boundaries. The margarite is usually accompanied by small cloudy grains of co-

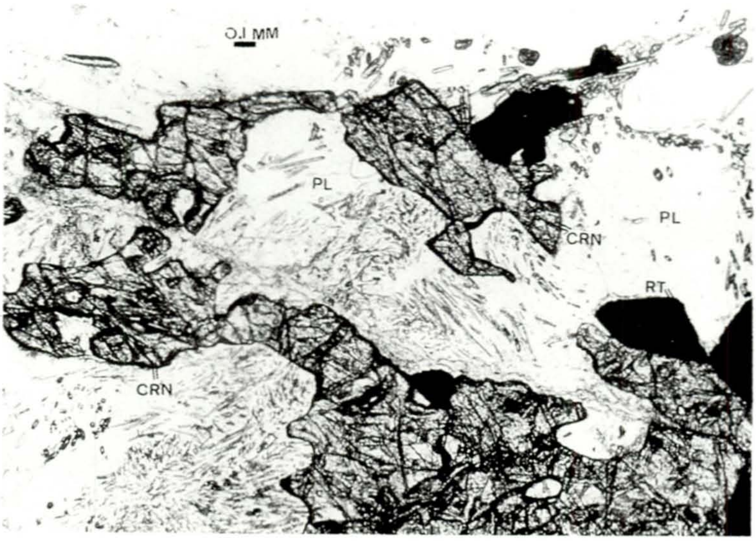

Fig. 3. Archipelago crystal of M Ib corundum enclosed by plagioclase. Photomicrograph of sample TN81.

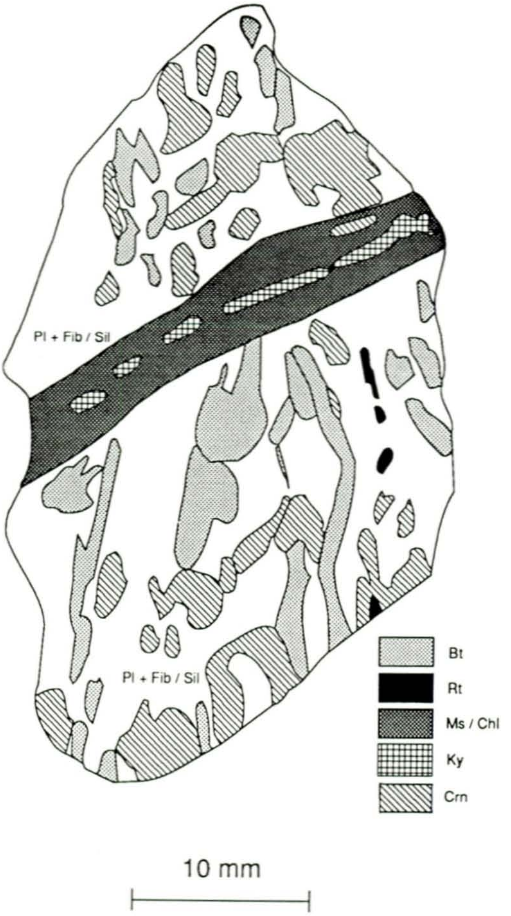

Fig. 4. M II veinlet of muscovite and chlorite, with kyanite in the centre, cutting the M I assemblage and foliation. Drawn from a thin-section of sample MA993.

rundum (Fig. 5), which are situated in the centre of the cracks. Traces of muscovite occur in the margarite aggregates.

Low-grade assemblages (M IV)

Several low-grade minerals developed after the margaritization reactions. A rim of anorthite-rich plagioclase is locally present around both M Ib and M III corundum. Small M III corundum is in places entirely replaced by aggregates of anorthite-rich plagioclase and micas. Anorthite-rich plagioclase and M Ia matrix plagioclase have never been observed in contact. Former grain boundaries and characteristic cleavage planes of M Ib corundum can be retraced in the anorthite-rich plagioclase. Plagioclase, biotite and aluminium silicates are locally altered to sericite / muscovite ± calcite. Some pseudomorphs of fine-grained muscovite after kyanite occur. Margarite is in some cases altered to chlorite and calcite. Fine-grained brown biotite occurs in small veinlets. Epidote occurs as a few isolated grains.

Both anorthite-rich plagioclase and the other phases are grouped in M IV because they clearly postdate M III and predate even lower grade phases. Their mutual relationships are unclear, but anorthite-rich plagioclase is likely to be slightly older, as it has locally been altered to sericite.

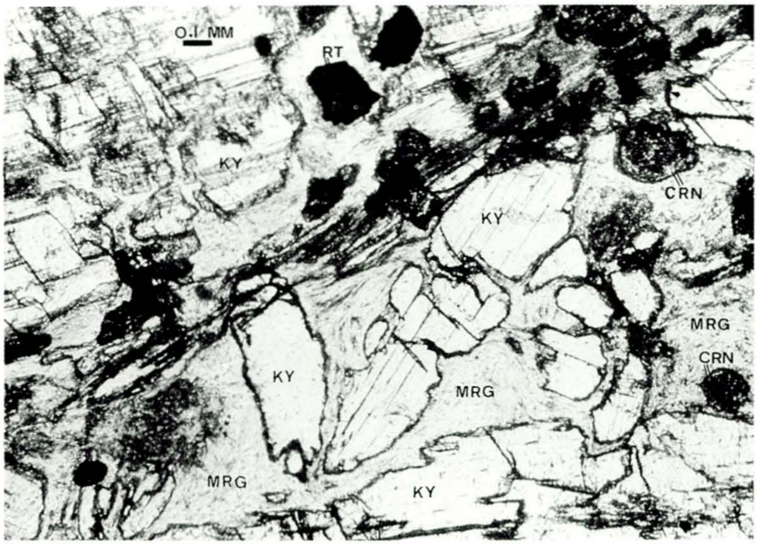

Fig. 5. Replacement of M II kyanite by M III margarite and corundum. Photomicrograph of sample TN77.

Lowest grade alteration (M V)

Prehnite and potash feldspar occur together with chlorite as small lenses along the cleavage planes of biotite. Scapolite with a birefringence of 0.020, has replaced plagioclase in a patchy way, and encloses M II kyanite and M IV pseudomorphs of muscovite after kyanite. Rare pumpellyite occurs, but not in the same aggregates as prehnite. In the intensively altered part of the outcrop (cf. Nilssen & Raade 1973), the main replacing mineral is euhedral prehnite. Prehnite encloses fibrolite, margarite, rutile and fine-grained white mica pseudomorphs after kyanite. It occurs together with large olive-green to blue-green zoned tourmaline. Beryl, which was reported by Oftedahl (1963), has not been found in our samples.

Relations between scapolite and prehnite, pumpellyite and tourmaline could not be established. As they are the youngest minerals present in the samples, they are grouped in the same metamorphic phase.

Mineral chemistry

Analyses were performed using a Jeol JXA 8600 Superprobe and an automated TPD microprobe at the Dept. of Geochemistry, Utrecht. Operating conditions were 15 keV, 10 nA, and 40 keV, 15 nA for the Jeol and TPD, respectively. Analyses were corrected using Tracor Northern PROZA and ZAF correction programs, respectively. Selected analyses are presented in Table 2. A more comprehensive list of analyses may be obtained upon request from the first author.

$7Table 2. Selected analyses. Fib, Sil, Ky normalized to O=5, Bt, Mrg, Ms to O=22, Chl to O=28, Pl to O=8, Crn to O=3, rt to O=2, Scp to Si+Al = 12.

Phase M	Fib Ia	Sil Ia	Pl Ia	Bt Ia	Rt Ia	Crn Ib	Ky II
SiO_2	36.48	36.84	57.70	36.97	.	.	37.01
TiO_2	.	.	.	1.82	97.86	.	.12
Al_2O_3	62.66	61.67	25.98	20.03	.	98.22	61.82
Cr_2O_3	.69	.64	.04	.82	.91	.99	.66
FeO	.	.32	.	9.71	.	.	.
MnO	.03	.	.	.13	.01	.	.01
MgO	.18	.	.	15.06	.	.	.
CaO	.	.	8.26	.	.	.	.
Na_2O	.	.	6.96	.36	.01	.	.
K_2O	.08	.	.16	9.11	.	.	.
P_2O_5	.	.	.	.	.32	.	.
SO_3	nd	nd	nd	nd	nd	nd	nd
Cl	.01	.	.02	.12	.01	.	.
F	.	.	.	.32	.	.	.
Total	100.13	99.47	99.12	94.45	99.12	99.21	99.70
Si	.99	1.00	2.61	5.43	.	.	1.00
Ti	.	.	.	.20	.99	.	.00
Al	2.00	1.98	1.38	3.46	.	1.99	1.98
Cr	.02	.01	.00	.09	.01	.01	.01
Fe	.	.01	.	1.19	.	.	.
Mn	.00	.	.	.02	.00	.	.00
Mg	.01	.	.	3.30	.	.	.
Ca	.	.	.40	.	.	.	.00
Na	.	.	.61	.11	.00	.	.
K	.00	.	.01	1.71	.	.	.
P	.	.	.	.	.00	.	.
S	.	.	.	.	.	.	.
Cl	.00	.	.00	.03	.00	.	.
F	.	.	.	.15	.	.	.

Table 2. Continued.

Phase	Chl	Ms	Mrg	Crn	Ms	Pl	Scp
M	II	II	III	III	IV	IV	V
SiO_2	26.38	45.55	32.60	.	44.82	55.70	51.82
TiO_2	.05	.98	.15	.	.85	.	.
Al_2O_3	21.90	35.20	47.94	97.93	34.82	28.86	24.94
Cr_2O_3	nd	.47	.18	.88	.89	nd	nd
FeO	16.61	.44	.37	.26	1.10	.	.
MnO	.06	.	.	.	.	.	.
MgO	20.78	.48	.71	.	.89	.	.
CaO	.	.	8.94	.	.	10.47	11.22
Na_2O	.	1.12	1.93	.	1.25	5.89	6.81
K_2O	.	9.71	.69	.	9.55	.	.28
P_2O_5	.	.	.	.	nd	.	.
SO_3	.	nd	nd	nd	nd	.	.42
Cl	.03	.01	.01	.	nd	.	2.07
F	.07	.	.	.	nd	.	.
Total	85.88	93.96	93.52	99.07	94.17	100.82	97.56
Si	5.41	6.12	4.38	.	6.05	2.48	7.66
Ti	.01	.10	.02	.	.09	.	.
Al	5.29	5.58	7.60	1.98	5.54	1.52	4.34
Cr	.	.05	.02	.01	.10	.	.
Fe	2.85	.05	.04	.00	.13	.	.
Mn	.01	.	.	.	.	.	.
Mg	6.34	.10	.15	.	.18	.	.
Ca	.	.	1.28	.	.	.50	1.78
Na	.	.29	.50	.	.33	.51	1.95
K	.	1.66	.11	.	1.64	.	.05
P	.	.	.	.	.	.	.
S	.	.	.	.	.	.	.05
Cl	.01	.00	.00	.	.	.	.52
F	.04	.	.	.	.	.	.

Aluminium silicates

All aluminium silicates have a near ideal stoichiometrical composition. Fe is present in minor amounts only, but Cr contents are high. M Ia fibrolite contains 0.72 ± 0.05 wt.% Cr_2O_3 (mean ± 1σ), M Ia euhedral sillimanite 0.69 ± 0.07 wt.%, and M II kyanite 0.70 ± 0.09 wt.% in samples TN77, 78, 84 and FL144. The Cr content of the aluminium silicates is much lower in sample MA993: Kyanites contain only 0.24 ± 0.07 wt% Cr_2O_3 and sillimanites 0.50 ± 0.04 wt%. No systematic difference in Cr_2O_3 content is shown by aluminium silicates from the successive metamorphic phases. The Cr contents of Froland sillimanite and kyanite are high for metapelites, which both typically contains less than 0.20 wt.% Cr_2O_3 (Kerrick 1991, and references therein).

Corundum

Both M Ib and M III corundum contain small amounts of Fe and Cr. In spite of its colour zoning, M Ia corundum does not show any detectable chemical zoning. M III corundum has a lower Cr_2O_3 content than the M Ib corundum, respectively 0.78 ± 0.28 wt.% and 1.07 ± 0.10 wt.%.

Biotite

Only M I biotites have been analysed. X_{Mg}, defined as Mg/(Fe+Mn+Mg), ranges from 0.69 to 0.73. TiO_2 is present in the range 1.80-2.55 wt.%. Ti shows negative correlations with Al^{IV} and X_{Mg}. The biotites contain 0.64 to 0.99 wt.% Cr_2O_3. The Cr content of biotites from MA993 is much lower (0.30-0.42 wt%). The biotites contain trace amounts of Cl ($\leqq$ 0.04 at O=22), whereas F ranges from 0 to 0.15 atoms per 22 oxygens ($\leqq$ 0.32 wt.%). The F-content of the biotites increases towards their core.

Margarite

M III margarites contain substantial quantities of Na_2O (Table 2). In some margarites, Si is higher than the ideal stoichiometric 4 atoms, suggesting that the presence of Na is due to the plagioclase substitution $NaSiCa_{-1}Al_{-1}$ (Frey et al. 1982), giving paragonite solid solution. In other margarites, the number of Ca atoms is low, but Si normal, as has been observed at other localities where margarite has grown out of aluminium silicates (e.g. Guidotti & Cheney 1976, Gibson 1979, Baltatzis & Katagas 1981). Froland margarites have Ca/(Ca+Na) ratios between 0.72 and 0.79. Ca/(Ca+Na) ratios in margarite are considerably higher than those of coexisting plagioclase (0.38-0.43), as is commonly observed (Ackermand & Morteani 1973, Gibson 1979, Frey et al. 1982). The amount of K_2O in the margarites shows a weak positive correlation with the amount of Na_2O.

Cr_2O_3 contents ($\leqq$ 0.59 wt.%) are higher than usual, and even higher than in the Cr-rich margarites reported by Morand (1990) from New South Wales, Australia, which contain up to 0.37 wt.%. The highest Cr contents ($\leqq$ 1.93 wt.%) recorded in retrograde margarites are from the New Zealand Alps (Cooper 1980). The Cr_2O_3 contents in the Froland margarites reflect the whole rock composition, and are lower for MA993 margarites than those from other samples. The FeO content ($\leqq$ 0.45 wt.%) is normal for margarites. TiO_2 in the Froland margarites is less than 0.35 wt.%. Only traces of Mg, Cl and F have been detected.

Muscovite s.l.

Chemically, no distinction could be made between M II and M IV muscovites. The muscovites show limited solid solution with paragonite, and minor Ca substitution. All muscovites contain FeO (0.37-1.29 wt.%), Cr_2O_3 ($\leqq$ 0.90 wt.%) and TiO2 (0.30-1.42 wt.%). The muscovites contain no Cl and only traces of F ($\leqq$ 0.13 wt.%).

Plagioclase and scapolite

Both M Ia and M IV plagioclase are almost orthoclase free. M Ia plagioclase has an anorthite content of 38-43 %. M IV anorthite-rich plagioclase has 48-51 %An. The scapolites are Cl-rich (1.78-2.10 wt.%) and SO_3-poor ($\leqq$ 0.42 wt.%), with trace amounts of fluorine ($\leqq$ 0.14 wt.%). The meionite percentage ranges from 45 to 47%.

Rutile

Cr is the only element substituting significantly in rutile. Cr_2O_3 is present in moderately high amounts (0.70-1.05 wt.%).

Chlorite

X_{Mg} of the chlorites ranges from 0.64 to 0.70. Al^{IV} varies between 1.85 and 2.72. TiO_2 occurs in considerable amounts, up to 1.02 wt.%, and traces of Mn, Ca, Na, K, and S may be present.

Reaction history and P-T path

Thermal climax (M I)

The oldest mineral assemblage, M Ia, is represented by plagioclase, sillimanite, biotite and rutile. The observed textures do not directly reveal the relationship between fibrolite and the euhedral sillimanite. However, the euhedral sillimanite truncates the fibrolite foliation (Fig. 2). This is interpreted as evidence that euhedral sillimanite replaces the fibrolite (cf. Vernon 1987).

M Ib corundum encloses both types of sillimanite, but mainly grew at expense of the fibrolite, as indicated by the occurrence of large corundum crystals in the centres of fibrolite aggregates. This may be explained by the larger effective reaction surface of the fibrolite aggregates with respect to the euhedral sillimanite, whereas removal of silica will have been much easier along the grain boundary networks in fibrolite aggregates than from massive euhedral sillimanite. Contacts between corundum and the euhedral sillimanite are usually sharp crystal faces. However, bottle-neck textures involving this sillimanite indicate that it was also partially consumed by corundum. Neither quartz nor other silica-bearing reactions products are present. Therefore, the growth of corundum must have involved removal of silica by a fluid phase:

$$(1) Al_2SiO_5\,(Sil) + 2\,H_2O \rightarrow Al_2O_3\,(Crn) + Si(OH)_4$$

This reaction is not restricted to a narrow P-T space, but mainly depends on the activity of SiO_2 in the coexisting fluid, and may have occurred at temperatures higher than c. 450-500°C (cf. Hemley et al. 1980) for the pressures recorded in the Bamble Sector (7-8 kb).

With exception of the replacement of fibrolite by euhedral sillimanite, no trace of the prograde P-T history has been found in the Froland rocks. Neither early mineral inclusions nor chemical zonations have been observed. Nevertheless, M I is interpreted to represent the thermal climax of metamorphism, because sillimanite is the ubiquitous aluminium silicate present in the Bamble Sector (Starmer 1976, Touret & Falkum 1987). From the M I assemblage, it is impossible to estimate peak metamorphic P-T conditions. However, as M I phases sillimanite, biotite and plagioclase are peak metamorphic minerals in this part of the Bamble Sector, we will adopt the peak metamorphic P-T estimates for the Froland area. Nijland & Maijer (1992) estimated P-T conditions at 752 ± 34°C and 7.1 ± 0.4 kb based on mineral pairs in amphibolites. Visser & Senior (1990) obtained nearly identical results of 740 ± 60°C, 7 kb, from aluminous enclaves in cordierite-orthoamphibole rocks.

Initial cooling (M II)

The M I assemblage is replaced by M II kyanite, muscovite and minor chlorite along veinlets. As relics of biotite and sillimanite are still present in these veinlets, the replacement probably took place by the generalized reaction:

$$\begin{aligned}
&(2)\ K_{1.7}Na_{0.1}Mg_{3.3}Fe_{1.2}Ti_{0.2}\\
&Cr_{0.1}Al_{3.5}Si_{5.5}O_{20}(OH)_4\ (Bt)\\
&+ 3\ Al_2Mg_{0.01}Si_{1.0}O_5\ (Fib)\ +\\
&0.5\ Ca_{0.4}Na_{0.6}Al_{1.4}Si_{2.6}O_8\ (Pl)\\
&+ 4\ H_2O + 0.25\ Fe^{2+}\\
&\rightarrow K_{1.7}Na_{0.3}Mg_{0.1}Ti_{0.1}\\
&Cr_{0.1}Al_{5.6}Si_{6.1}O_{20}(OH)_4\\
&(Ms) + 0.5\ Mg_{6.3}Fe_{2.9}Al_{5.3}Si_{5.4}O_{20}(OH)_{16}\\
&(Chl) + Al_{2.0}Si_{1.0}O_5\ (Ky) + 0.1\ Ti^{4+}\\
&+ 0.08\ Mg^{2+} + 0.2\ Ca^{2+} + 0.1\ Na^{+}
\end{aligned}$$

As in many terrains, the occurrence of the M II assemblage in veinlets shows that kyanite developed not directly from sillimanite, but by a 'transport reaction', i.e. by means of an intermediary fluid phase. The development of the M II assemblage is the first response of the rocks to re-introduction of hydrous fluids after the metamorphic climax. A small drop in temperature at nearly constant pressure might have been sufficient to effectuate the growth of kyanite and hydrous phyllosilicates. M II is constrained by the kyanite-sillimanite phase boundary and reaction (3) which marks the dawn of M III. This implies that M II took place at temperatures of about 600-700°C (Fig. 6a), or slightly lower (See below).

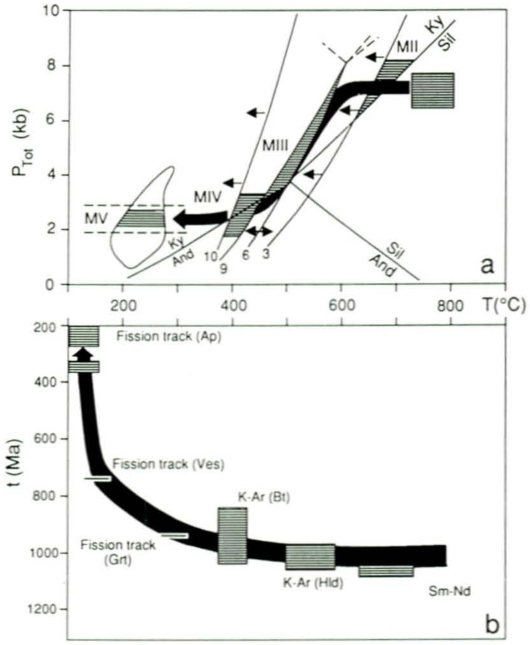

Fig. 6. The cooling and uplift history of the Bamble Sector. (a) The P-T path as deduced from the Froland rocks. Mineral abbreviations are after Kretz (1983). Indicated are: the aluminum silicates after Holdaway (1971), the peak metamorphic P-T box after Nijland & Maijer (1992), the fields of metamorphic episodes M I-V, relevant reaction lines 3, 6, 9, and 10 as discussed in the text, the prehnite-pumpellyite facies field of Frey et al. (1991) with 2 and 3 kb. isobars (See text).

(b) The T-t path as constructed from separately published mineral ages. The T-t path was constructed with the mean ± one sigma of the following published mineral ages (All data recalculated to current decay constants): Sm-Nd - Mineral ages of Kullerud & Dahlgren (1992). K-Ar (Hbl) - O'Nions et al. (1969). K-Ar (Bt) - Kulp & Neumann (1961), O'Nions et al. (1969), de Haas et al. (1992c). Fission tracks (Grt) and (Ves) - Haack (1975). Fission tracks (Ap) - Van Haren & Röhrman (1988). The following closure temperatures were used:Sm-Nd (Grt) - Mezger et al. (1992). K-Ar (Hbl) - Harrison (1981). K-Ar (Bt) - Verschure et al. (1980). Fission tracks (Grt) and (Ves) - Haack (1977). Fission tracks (Ap) - Sharma et al. (1980).

Uplift and further cooling (M III)

Rehydration progressed by the margaritization of plagioclase and kyanite during M III. As outlined above, margarite formed both in the host rock and in the M II kyanite-bearing veinlets. Textural relations of margarite with respect to corundum are different in both environments. In the host rock (M I assemblage), corundum remains unaffected or occurs as reaction relics within margarite aggregates. In the M II veinlets, corundum occurs, and was most likely formed together with margarite in cracks in kyanite. We will first discuss the reactions in the host rock (reactions 3-4), and subsequently consider the M II veinlets (reactions 5-8).

In the host rock, margarite may have been produced by the following reaction:

(3) $CaAl_2Si_2O_8$ (An) + Al_2O_3 (Crn) + $H_2O \rightarrow CaAl_4Si_2O_{10}(OH)_2$ (Mrg)

(Gibson 1979, Dymek 1983). This reaction has been calibrated experimentally, and provides an upper temperature limit of c. 650°C at 7 kb (Chatterjee et al. 1984). However, in case of $P_{H2O} < P_{Total}$, reaction (3) will be shifted to lower temperatures. The addition of Na to the CASH system will stabilize plagioclase over margarite (as indicated by Ca/(Ca+Na) ratios) and consequently also shift reaction (3) to lower temperatures. Cr is likely to favour corundum. Concluding, reaction (3) will in reality be situated at somewhat lower temperatures than its ideal position in the CASH system (Fig. 6a).

Another possible reaction resulting in the growth of margarite in the Froland rocks, which involves the consumption of plagioclase with fibrolite inclusions (which were already metastable as the rocks had passed into the kyanite field), may be reaction (4):

(4) $CaAl_2Si_2O_8$ (An) + Al_2SiO_5 (Fib) + 3 $H_2O \rightarrow$ $CaAl_4Si_2O_{10}(OH)_2$ (Mrg) + $Si(OH)_4$

In this reaction, silica again has to be removed by a fluid phase. In a silica-saturated environment, the reaction would occur between 3 and 7 kb ($P_{Total} = P_{H2O}$) and in the temperature range 500-570°C (Chatterjee et al. 1984). Fibrolite is already metastable, which enhances the growth of margarite. The undersaturation of silica will also favour margarite, and shifts the reaction (4) to higher temperatures. This will be opposed, however, by the effect of Na (see above).

In the M II veinlets, margarite formed within cracks in kyanite. Retrograde reactions (5) (Guidotti et al. 1979, Cooper 1980, Feenstra 1985) and (6) (Yardley and Baltatzis 1985) have been proposed to explain the growth of margarite at the expense of kyanite in other rocks:

(5) $2\ Al_2SiO_5$ (Ky) + Ca^{2+} + H_2O + $^1/_2\ O_2 \rightharpoonup$ $CaAl_4Si_2O_{10}(OH)_2$ (Mrg)

(6) Al_2SiO_5 (Ky) + $CaAl_2Si_2O_8$ (An) + $3\ H_2O \rightharpoonup$ $CaAl_4Si_2O_{10}(OH)_2$ (Mrg) + $Si(OH)_4$

Quartz is not present in any of the Froland samples, which excludes the possibility of reaction (6), unless all silica has been removed by a fluid phase. Reaction (5) may have proceeded in the Froland rocks, but does not account for the occurrence of small grains of corundum in the centre of the margarite-filled cracks in kyanite. The latter also holds for (6). Therefore, other reactions have to be considered for the margaritization of kyanite. A possible reaction, involving the consumption of anorthite, is:

(7) $2\ Al_2SiO_5$ (Ky) + $CaAl_2Si_2O_8$ (An) + $5\ H_2O \rightharpoonup$ $CaAl_4Si_2O_{10}(OH)_2$ (Mrg) + Al_2O_3 (Crn)
+ $2\ Si(OH)_4$

However, there is no textural evidence in the Froland rocks for the involvement of plagioclase in the breakdown of kyanite. Kyanite and plagioclase have not been found in contact with each other, but late scapolite (probably replacing plagioclase) has been found enclosing kyanite. This indicates that plagioclase and kyanite may have coexisted in the M II veins. The reaction may also have taken place by a fluid phase:

(8) $3\ Al_2SiO_5$ (Ky) + Ca^{2+} + $3\ H_2O$ + $^1/_2\ O_2 \rightharpoonup$ $CaAl_4Si_2O_{10}(OH)_2$ (Mrg) + Al_2O_3 (Crn) + $Si(OH)_4$

To our knowledge, reactions producing margarite plus corundum from aluminium silicates have not been reported until now. The only reaction published so far resulting in the growth of both minerals is: 8 Dsp + Prl + 2 Cal = 2 Mrg + Crn + 2 CO_2 + 3 H_2O, occurring prograde in marbles (Okrusch et al. 1976).

Rosing et al. (1987) calculated equilibria between aqueous solutions and minerals in the CASH and NCFASH systems. Their log $(a_{Ca2+}/a_{H+}{}^2)$ vs. temperature and $\log(a_{SiO2(aq)})$ vs. temperature diagrams show that margarite and corundum are stable with respect to anorthite and corundum below a maximum temperature of 583°C at $P_{Total} = P_{H2O} = 5$ kb, provided that the silica activity in the coexisting fluid is lower than 0.1. This temperature is in fair agreement with conditions for reaction (6) in the silica saturated system (Chatterjee et al. 1984). The stability of margarite plus corundum with respect to aluminium silicates depends entirely on the silica and lime saturation of the coexisting fluid. Moderately low $\log(a_{SiO2(aq)})$ and relatively high log $(a_{Ca2+}/a_{H+}{}^2)$ stabilize the assemblage margarite plus corundum, whereas lower silica and higher Ca^{2+} activities favour the forming of clinozoisite / epidote plus corundum. Addition of Na and Fe to the systems tends to narrow the stability field of margarite plus corundum in favour of epidote plus corundum.

Margarite and an epidote group mineral have not been observed together, indicating that reaction (9) did not take place.

(9) $5\ CaAl_2Si_2O_8$ (An) + $2\ H_2O \rightharpoonup$ $CaAl_4Si_2O_{10}(OH)_2$ (Mrg) + $2\ Ca_2Al_3Si_3O_{12}(OH)$ (Zo) + $2\ SiO_2$

(Chatterjee et al. 1984). This constrains the lower temperature side of M III. The reaction line may slightly deviate from its ideal position. Addition of Na will stabilize plagioclase; regarding the anorthite-content of M I plagioclase (38-48%), this will inevitably have occurred. $P_{H2O} < P_{Total}$ will have the same effect. Addition of Fe to the CASH system will favour zoisite + margarite, and, under silica-undersaturated conditions zoisite (epidote) over margarite.

Late-stage cooling (M IV & M V)

The growth of M IV minerals, i.e. muscovite, new biotite, epidote, etc., indicates adaption to greenschist facies conditions. No mineral reactions could be deduced, so M IV is not well constrained. However, its P-T conditions are indicated by the following: (1) The new growth of biotite, indicating that the rocks were still in the biotite stability field; (2) The absence of diaspore; and (3) The nearby occurrence of late andalusite.

The absence of diaspore indicates that reaction (10) did not occur:

(10) Al_2O_3 (Crn) + $H_2O \rightharpoonup 2\ AlO(OH)$ (Dsp)

This constrains the lower temperature limit to 400°C. At $P_{H2O} < P_{Total}$, reaction (10) will be shifted to lower temperatures.

Metapelites at Grimåsen (Fig. 1), in the direct vicinity of the Froland locality (c. 4.5 km) contain late blasts of andalusite and staurolite, which overgrow the old biotite foliation. Cordierite-orthoamphibole rocks from the nearby Böylefoss locality (Fig. 1) contain both late-stage andalusite and kyanite (Visser & Senior 1990). This indicates equilibration at or below the andalusite-kyanite cotectic line.

M V is constrained by the coexistence of prehnite and pumpellyite (Fig. 6a), which limits the temperature to 175-280°C and pressure from 0.5 to 4.5 kb (Frey et al. 1991). Pressure is more narrowly constrained to 2-3 kb by the fluid inclusion data of Touret & Olsen (1985), who observed that H2O-rich inclusions were spatially associated with prehnite and pumpellyite. Growth of M V hydrous minerals like prehnite, pumpellyite, Cl-rich scapolite and tourmaline record the local influx of Cl- and B-bearing hydrous fluids.

Retrograde P-T path

The cooling and uplift path of the Froland rocks starts at M I, for which we adopt P-T estimates from the same area (Fig. 6a). To form the M II veinlets, while anorthite + corundum + vapour remain stable, limited cooling must have occurred. As discussed above, addition of Na and Cr to the CASH system will shift reaction (3) to lower temperatures than indicated in Fig. 6a. The field of M II will have been larger, and the rocks may have experienced a slight uplift.

The formation of margarite from M II kyanite implicates that the rocks passed reaction line (6), which constrains the upper limit of M III. The lower temperature limit of M III is less well constrained. Reaction (9) has not been observed in the Froland rocks, but may be situated at slightly lower temperatures than indicated in Fig. 6a.

The M IV stability field must have been along the andalusite-kyanite reaction line (Fig. 6a). Its upper temperature limit is constrained by the lower limit of M III. The M V stability fields are well constrained by the occurrence of prehnite + pumpellyite (Fig. 6a). However, rocks from the alteration zone contain an overwhelming amount of prehnite with respect to pumpellyite. Therefore, it is likely that M V started at slightly higher temperatures than those of the prehnite-pumpellyite facies.

Summarizing, the retrograde P-T path (Fig. 6a) starts with near-isobaric cooling (M I-II), followed by near-isothermal decompression (M III), and is concluded by slight decompression during cooling from greenschist to prehnite-pumpellyite facies conditions (M IV-V). From the discussion above, however, it appears that especially the latest stages indicate sliding changes rather than discrete episodes.

The first part of the deduced retrograde P-T path (Fig. 6a) essentially confirms the paths proposed by Touret & Olsen (1985) and Visser & Senior (1990). However, the stability fields of the margarite-bearing assemblages require a P_{H2O} considerably higher than the $^1/_2 P_{Total}$ suggested by Visser & Senior (1990) for the same metamorphic stage (their M4). The retrograde P-T path of the Froland rocks also agrees with the cooling path of the Modum Complex of the Kongsberg Sector (Munz 1990), which at that time may have constituted one continuous terrain with the Bamble Sector (Bugge 1936, Starmer 1985). A small increase in pressure between M I and M II, as suggested in the Modum Complex, is not found in the Bamble Sector.

Time constraints

M I in the Froland rocks is most likely equivalent to the M 3b of Visser & Senior (1990), which is the thermal climax of their prograde P-T path, and the sole sillimanite-producing stage in their rocks. These authors considered this stage to be related to Gothian continental collision. This interpretation may be supported by the fact that sillimanite occurs in the foliation cut by the basic intrusions of the Jåmmåsknutene Gabbro (Fig. 1), which have been dated at 1766 ± 190 Ma (Sm-Nd whole rock, de Haas et al. 1992a).

However, Kullerud & Dahlgren (1992) recently obtained Sm-Nd mineral ages between 1068 and 1107 Ma for granulite facies assemblages near Arendal. Sm-Nd mineral isotopic systems are still poorly understood, and blocking temperatures not defined for most minerals. Recently, Mezger et al. (1992) concluded that the blocking temperature of granulite facies garnets is ca. 600 ± 30°C for the Sm-Nd system. This is ca. 150°C below our peak metamorphic conditions, and would reflect M II rather than M I temperatures. Consequently, M I will have occurred during or before the Early Sveconorwegian.

Early Sveconorwegian gabbroic intrusions in the Froland area (1.2 ± 0.1 Ga, Sm-Nd whole rock + minerals; de Haas et al. 1992c) still enjoyed amphibolite facies metamorphism (de Haas et al. 1992b). Garnet-hornblende thermometry yields temperatures of ca. 720°C for this metamorphism (G.J.L.M. de Haas pers. comm. 1991), indicating that high-temperature conditions prevailed at this time. Therefore, the onset of cooling is likely to be Early to Mid Sveconorwegian (Fig. 6b). The end of uplift (Fig. 6b) is constrained by K-Ar biotite cooling ages that average 940 Ma (Kulp & Neumann 1961, O'Nions et al. 1969, de Haas et al. 1992c).

The timing of the latest metamorphic phase, M V, is less evident. Prehnite, pumpellyite and scapolite are also present in several post-tectonic microdolerite dykes in the area, and have been reported from other rocks as well (e.g. Field & Rodwell 1968). The dykes are generally considered to be of Permian age, but may partly be contemporaneous with basic dyke swarms in the Rogaland Sector, that were dated by Sundvoll (1990) as Late Proterozoic. Preliminary results from radiometric studies in the Arendal area seem to confirm this (M.M. Moree pers. comm. 1992). Correlation of M V with Caledonian activity (Verschure 1982) is unlikely because of the large distance from the Caledonian front. Sauter et al. (1983) suggest that the growth of prehnite was due to Permian thermal disturbance. Available fission-track ages from the Bamble Sector are illustrated in Fig. 6b. Apatite fission-track ages of c. 240 Ma (van Haren & Röhrman 1988) indicate that temperatures were too low to produce prehnite and pumpellyite during the Permian. Haack (1975) obtained fission-track ages on garnet (924 Ma) and vesuvianite (761 Ma) from the Arendal skarns. Andriessen (pers. comm. 1991) obtained slightly younger ages for garnet (c. 900 Ma) and slightly older ages for vesuvianite. Both mineral ages suffer from not well established annealing temperatures (P. A.M. Andriessen pers. comm. 1991). Haack (1977) estimated annealing temperatures of 135-155°C and 280-300°C for vesuvianite and garnet, respectively, although the latter may actually be a little too low. This indicates that M V, which equilibrated between 175 and 280°C, should have equilibrated between c. 760 and 920 Ma.

Tectonic history

The combined P-T and T-t paths show that after 1150 Ma the Sveconorwegian was dominantly a cooling and uplift event. The slow uplift points to prolonged residence at lower crustal levels after M I, and indicates a crust thickened by overthrusting, probably with magmatic addition and slow erosion. Evidence for magmatic addition is provided by the evolution of gabbroic intrusions perforating this crust (Frost et al. 1989, de Haas et al. 1992ab).

The drop in pressure after initial cooling, reflected by the M III and M IV, represents upthrusting of the Bamble Sector, probably accompanied by erosion or tectonic unroofing. The intrusion of undeformed granites between 990-950 Ma throughout the Southwest Scandinavian Domain (Priem et al. 1973, Pedersen & Maaløe 1990, Kullerud & Machado 1991; among others) and slightly younger K-Ar biotite cooling ages of 940 Ma (Kulp & Neumann 1961, O'Nions et al. 1969, de Haas et al. 1992c) indicate that the process of upthrusting was completed before this time. Sveconorwegian upward movement is likely to have occurred along deeply penetrating, low-angle shear zones. The imbricated structure of the Sveconorwegian terrain in southern Norway is not as clearly demonstrated as in SW Sweden (Eugeno-S Working Group 1988, Park et al. 1991), but the deep, gently dipping, seismic reflectors cutting the Moho below southern Norway and the Skagerrak (Husebye et al. 1988, Lie et al. 1990, Pedersen et al. 19990, Kinck et al. 1991) may be remnants of the zones along which upthrusting occurred. After upthrusting, the formerly lower crustal rocks adapted to their new upper crustal environment. Therefore, M V was probably not related to a separate thermal event, but just reflects the adaption of lower crustal rocks to their new upper crustal environment.

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