Polyphase Caledonian metamorphism in the Precambrian basement of Rogaland/ Vest-Agder, Southwest Norway

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In the Sveconorwegian basement of Rogaland/Vest-Agder, SW Norway, two incipient Caledonian metamorphic overprints are assumed on the basis of petrological textures and regional extension of the metamorphic mineral distributions. The inferred M4a is a burial metamorphism mainly in prehnite-pumpellyite facies and the M4b a metamorphism mainly in greenschist facies, restricted to the vicinity of the Caledonides. In order to propose a model sequence of retrograde metamorphic events in the basement of the whole of South Norway the available mineral records of newly formed green biotite, stilpnomelane, prehnite and pumpellyite are integrated with relevant age determinations and other geological information.

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Introduction

The Precambrian basement of Rogaland/Vest-Agder, SW Norway, which is part of the Sveconorwegian of the Baltic Shield, consists mainly of anorthositic masses, the lopolith of Bjerkreim–Sokndal and a polymetamorphic high-grade envelope of charnockitic and granitic migmatites, augen-gneisses and metasupracrustals (Fig. 1; Hermans et al. 1975, Birkeland 1981). The metasupracrustals comprise the garnet-bearing migmatites (Kars et al. 1980, Huijsmans et al. 1981) and the Faurefjell formation, which consists mainly of quartzites, marbles and calc-silicate rocks (Sauter 1981, Sauter 1983).

A synopsis of the apparent ages of the rocks in the basement demonstrates Pre-Sveconorwegian ages of about 1500 Ma for the M0 stage of metamorphism, Sveconorwegian ages of about 1200 Ma for the M1 stage and about 1050 Ma for the granulite facies M2 stage of metamorphism (Versteeve 1975, Pasteels & Michot 1975, Wielens et al. 1981). Late-Sveconorwegian ages

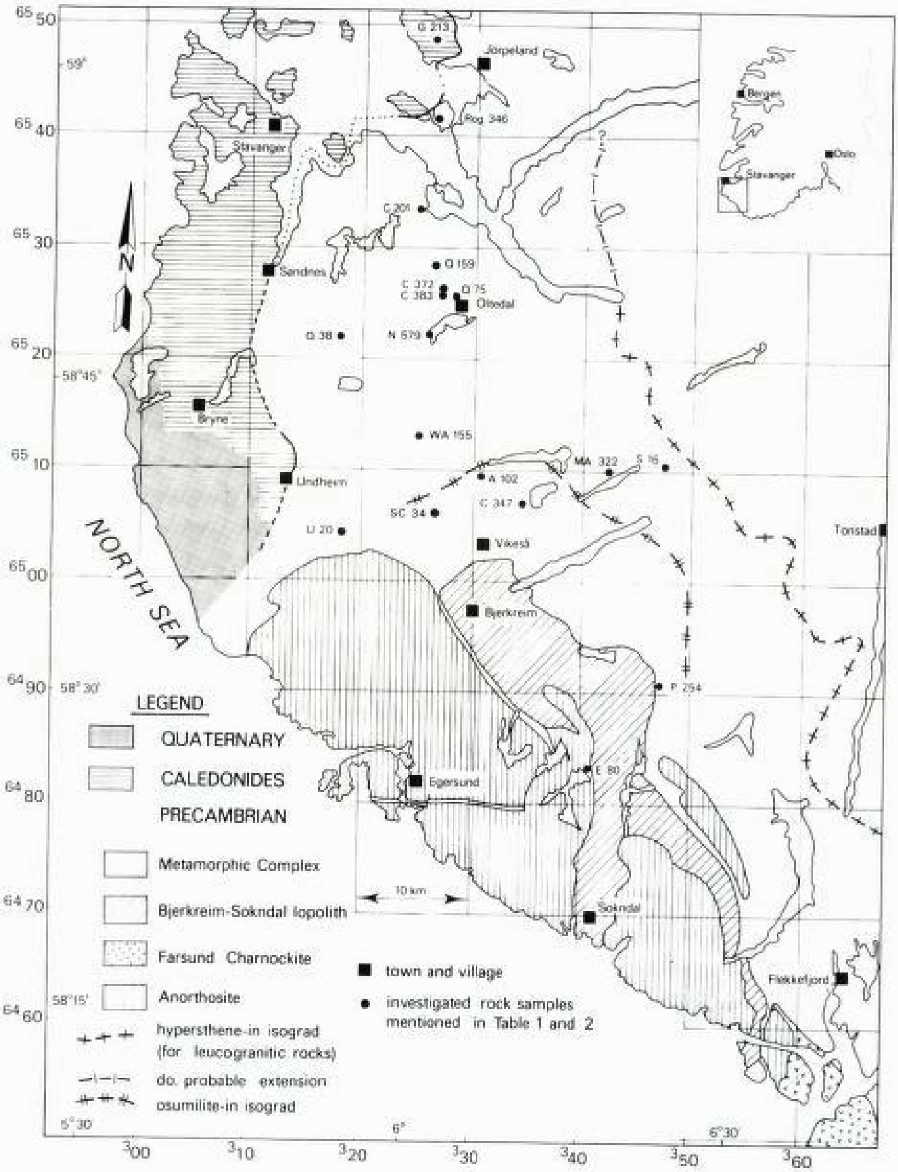

Fig. 1. Outline of the regional geology of Rogaland, SW Norway; with locations of the investigated samples.

of about 950 Ma are related to the M3 stage of metamorphism in the amphibolite facies, which affected most of the intrusive complexes and the envelope, and biotite ages in the range of 900–850 Ma represent the time of a regional cooling in a late M3 stage (Dekker 1978, Wielens et al. 1981). After uplift and erosion, the sub-Cambrian peneplain was formed between 700 and 600 Ma ago and subsequently Palaeozoic and locally even older sediments were deposited (Sigmond 1978, Andresen & Faerseth 1982). The main Caledonian basal thrust-plane must have been situated approximately along or just above the pre-existing peneplain (Sigmond 1978). During the overthrusting the sediments were squeezed out and subsequently metamorphosed together with the upper levels of the bedrock in a greenschist facies metamorphism. The index minerals for this metamorphism in the parautochthonous units and in the basement are green biotite, stilpnomelane, chlorite, actinolite and epidote (Sigmond 1978, Maijer 1980). This metamorphism in Rogaland has been reported as Caledonian in age by Verschure et al. (1980). They dated green biotite from the basement near Stavanger with Rb–Sr methods at about 400 Ma old. The last metamorphic episode in allochthonous rocks in the Sauda area is mentioned by Sigmond (1978) as occurring 410 Ma ago (Andresen et al. 1974). Nevertheless some lower intercept ages of zircons (285–300 Ma) from the basement close to the Caledonian front are given by Pasteels & Michot (1975). Recently Wielens et al. (1981) have reported lower intercept ages in a range from 310 to 410 Ma at a distance of about 50 km east of the Caledonian front. Van den Haute (1977) obtained apatite fission track ages in the basement of Rogaland in the range of 220 to 260 Ma and he interpreted this result as a reflection of an uplift period after a burial of the basement under Cambro–Silurian sediments.

In Rogaland and Vest-Agder many occurrences of retrograde minerals are found and one of the purposes of this study is to elucidate Caledonian incipient metamorphic overprints on the basement. It is also the aim to give an outline of the retrogradation all over southern Norway and to intergrate it with some geological information into a model sequence of low-grade metamorphic events.

Retrograde mineral records in Rogaland

Retrograde alteration of high-grade minerals and rocks can be found all over the map area of Fig. 2, but it varies notably in type and intensity. The retrogradations include the formation of typical metamorphic minerals such as stilpnomelane, green biotite, pumpellyite, prehnite and actinolite-tremolite together with more common alteration minerals. A selection of primary and secondary mineral assemblages of some Precambrian basement rocks of Rogaland is listed in Table 1.

In charnockitic and granitic rocks and in augen-gneisses plagioclase may be altered into sericite, albite or saussurite; orthoclase and sanidine into albite or microcline; biotite into chlorite, titanite and ilmenite; and hypersthene into serpentine, uralite amphibole, chlorite and talc. The garnetiferous migmatites show, in addition to the alterations mentioned, pinite from cordierite and osumilite; and diaspore, magnetite and hematite from hercynite. In mesocratic parts of the migmatites the mafic constituents retrograde to actinolite, chlorite, pumpellyite and prehnite. In marbles of the Faurefjell formation forsterite may be altered into serpentine and partly into clinohumite (Fig. 3A). Diopside shows rims of tremolite. Phlogopite and spinel may alter into Mg-chlorite, and some spinel into hydrotalcite. Locally tremolite, talc, clinohumite and calcite are growing at the expense of serpentine. Hedenbergite-bearing rocks and quartz-diopside gneisses from the same formation show epidote, zoisite, sericite, actinolite and hydrogrossular as retrograde minerals; pumpellyite and prehnite are present. K-feldspar-rich rocks contain albite, microcline and riebeckite as replacement minerals. In the anorthosite complexes An-rich plagioclase is locally altered into kaolinite, prehnite, laumonite and margarite.

Table 1. List of mineral contents of analysed rock samples
(x: mineral content > 10%, o: mineral content < 10% and > 5%, •: mineral content < 5%, _: totally or for the greater part decomposed.
mi: microcline, or: orthoclase, 10: An% plagioclase; 2: hydrogrossular).
The accessory minerals apatite, zircon and opaque are present in most of the samples.

sample		quartz	alkali feldspar	plagioclase	forsterite	orthopyroxene	clinopyroxene	amphibole	phlogopite	brown biotite	spinel	garnet	carbonate	tremolite	actinolite	green biotite	chlorite	serpentine	sericite, talc, sauss.	stilpnomelane	pumpellyite	prehnite	clinohumite	epidote, zoisite	titanite
		primary											retrograde												
A102	leucogranite	x	or	10						$\underline{o}$							o			o					
P254	do	x	mi	29											•		o					•		•	
E00	do	x	or	24				$\underline{o}$		$\underline{o}$									•	o		•			
ROG746	do	x	or	30						$\underline{o}$						o				o				•	•
Q38	garnet granite	x	or	$\underline{x}$						$\underline{x}$		$\underline{x}$					o	o	o		•			•	•
H579	do	x	or	28						o		o	•				o		o		o			•	
S16	garnet granofels	x		10								x	•				•		o			o		•	
MA322	hbl. tonalite	x		$\underline{x}$				$\underline{x}$					o		•		o					o		•	
U20	bi. enderbite	x	mi	18		o				$\underline{o}$			•				o		o		•	o		•	
SC34	norite			$\underline{x}$		$\underline{x}$						•2			o		x		x		o			•	o
WA155	Qu.hedenb.rock	x		$\underline{x}$			x						o		•				o		o	o		o	•
C201	blastomylonite	x	mi										o			x	o		x	x				o	
Q213	do	x	mi	7								o				x			o	o				o	•
C347	di.-fo.rock	o			x		x						o	o											
C372	fo-sp-di marble				x		•		•		o		x				x	•					•		
C387	fo-sp marble				x				•		x		x	o			o	•							
Q75	fo marble				x		o		x				x				o						o		
Q159	di marble				$\underline{x}$		x		$\underline{x}$				x	o			o	•							

Stilpnomelane commonly occurs as small fibrous aggregates in cracks and cleavages of altered plagioclase (Fig. 3B), or as small crystals around dark minerals. Mostly it is associated with chlorite and albite. This stilpnomelane is found all over Rogaland and the adjacent parts of Vest-Agder. The proportion and crystal size of the stilpnomelane increase from SE towards NW. Especially in the mylonitic rocks, which are related to the Caledonian front, the stilpnomelane occurs as large radiating, euhedral postkinematic crystals (Fig. 3C). Mostly it is associated with calcite, white mica and chlorite but it is evidently younger than the synkinematic green biotite, white mica and chlorite. Locally in some mylonitic rocks of the basement, in some parautochthonous phyllites and rarely in allochthonous Precambrian rocks within the Caledonides the stilpnomelane is also observed to be oriented together with green biotite, white mica and chlorite along the plane of the schistosity.

A new generation of green biotite is formed in the Sveconorwegian basement in an approximately 15 km wide zone along the Caledonian front (Fig. 2). The proportion of this biotite increases toward that front (Verschure et al. 1980). Northwest of the green biotite-in isograd it becomes a common constituent, just as brown, titanium-rich biotite is in fresh basement rocks outside the zone. Towards the Caledonian front the brown biotite is progres-

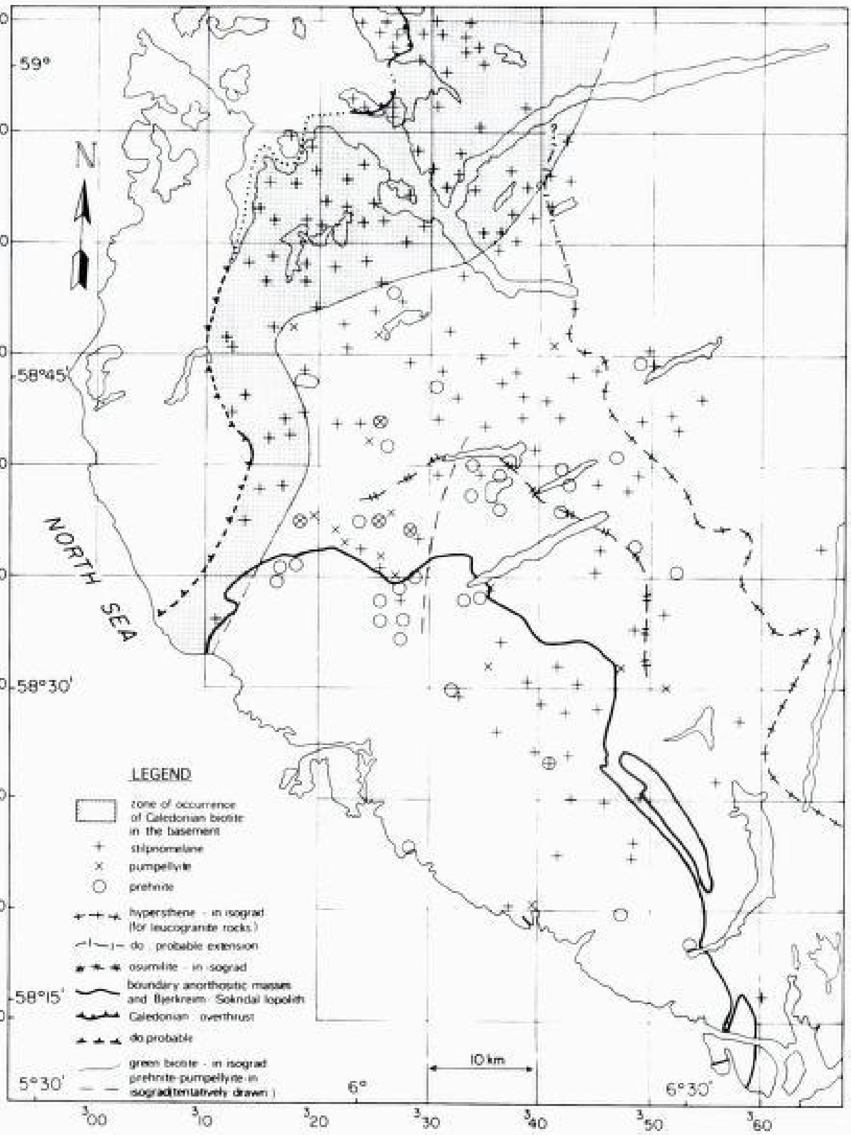

Fig. 2. Regional distribution of the minerals stilpnomelane, green biotite, pumpellyite and prehnite in Rogaland/Vest-Agder, SW Norway.

sively more decomposed and within the zone mentioned above, small granules of titanite appear with simultaneous discoloration and chloritization (Verschure et al. 1980). Close to the front most brown biotites have been replaced by pseudomorphs consisting of a mixture of green biotite, chlorite and titanite, locally with albite and white mica. Green biotite forms fine-grained aggregates of Ti-poor flakes also at the expense of amphibole and opaques. In mylonitic rocks in the basement and in phyllites of the Caledonides, for example near Jörpeland, the green biotite occurs mainly as minute flakes parallel to the foliation.

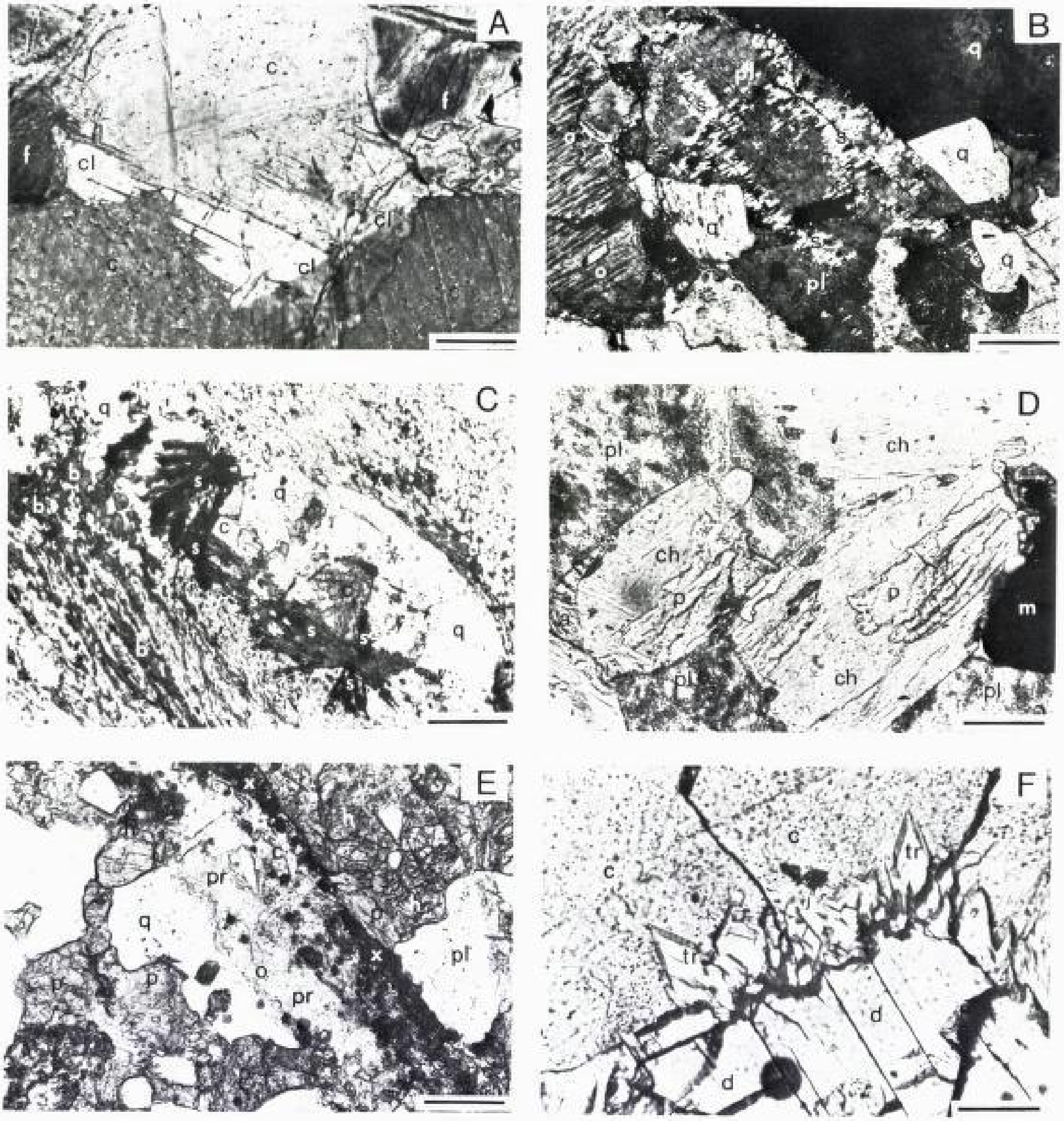

Fig. 3 (A) Clinohumite (cl) with lamellar twins in forsterite (f) marble; sample Q75, scale bar: 0.1 mm.

(B) Flakes of stilpnomelane (s) in cracks and cleavages through plagioclase (pl); sample E80, scale bar: 0.2 mm.

(C) Postkinematic stilpnomelane (s) in mylonitic rock; sample C201, scale bar: 0.2 mm.

(D) Pyroxene totally altered into chlorite (ch) and pumpellyite (p) with rims of actinolite (a); plagioclase (pl) is saussuritic; sample SC34, scale bar: 0.1 mm.

(E) Vein of prehnite (pr) with an aggregate of pumpellyite, epidote and titanite (x); hedenbergite (h) is partly also altered into pumpellyite (p); sample WA155, scale bar: 0.2 mm.

(F) Tremolite (tr) rims in diopside (d) marble; sample Q159, scale bar: 0.04 mm. (o = orthoclase, q = quartz; c = calcite; b = green biotite; m = magnetite; t = titanite).

Pumpellyite is rarely found. It occurs only in ca. 20 out of several thousands of samples. It mainly replaces plagioclase and pyroxene, and forms small anhedral aggregates in the matrix of saussuritic plagioclase. Brown biotite may also be replaced by pumpellyite, chlorite, epidote and titanite. In more mafic rocks hypersthene can be completely altered into chlorite aggregates in which pumpellyite and titanite are observed, while along the margins of the chlorite crystals new actinolite is developed (Fig. 3D).

Prehnite is observed in about 40 thin-sections. While pumpellyite is mostly an alteration product, the prehnite fills cracks and veinlets. Where these veinlets intersect altered clinopyroxene or plagioclase the prehnite may be attended by epidote, chlorite, pumpellyite and titanite (Fig. 3E). In some samples located SE of the green biotite–in isograd the coexistence of prehnite and pumpellyite is observed, and tentatively a prehnite–pumpellyite–in isograd is drawn in Fig. 2. Neither pumpellyite nor prehnite is found in the zone of green biotite, which is due to the fact that they require lower grade metamorphic conditions. Although the occurrence of stilpnomelane overlaps the area where prehnite and pumpellyite are found, the pumpellyite is not, and the prehnite only once, observed in association with stilpnomelane. This phenomenon presumably is due to differences in appropriate rock chemistry.

Actinolite and tremolite are more or less frequently found as secondary minerals, particularly in marbles and diopside gneisses. A few samples in the pumpellyite-prehnite zone contain actinolite with pumpellyite, chlorite and carbonate (Fig. 3D). The actinolite is not found in association with stilpnomelane or green biotite. Actinolite rims around brown or deep green amphiboles are mostly related to the M3-cooling stage (Dekker 1978), while newly formed actinolite needles replacing chlorite and serpentine are assumed to be very late. Tremolite is in particular observed together with talc, newly formed at the expense of serpentine, or as rims around diopside (Fig. 3F).

The increase in size and proportion of the metamorphic minerals stilpnomelane and green biotite in a NW direction towards the Caledonian front are considered to bear some relation to the Caledonian orogenic belt. The regional temperature of retrograde metamorphism in Rogaland may have ranged from about 400°C for the green biotite-in isograd (Verschure et al. 1980) to about 300°C for the prehnite-pumpellyite-in isograd (Liou 1971), while the pumpellyite-actinolite assemblages point to a cover thickness of several kilometres (Nitsch 1971, Coombs et al. 1976). The Caledonian origin of metamorphism is also supported by the parallelism of the metamorphic zonation in the Precambrian basement along the present front of the Caledonian nappe system. Due to the fact that the metamorphic minerals involved are found in the basement as well as in the Caledonian units, especially in the parautochthonous Lower Palaeozoic sediments, at least a part of the formation of these minerals post-dates the Caledonian thrusting. However, it is questionable if all the Caledonian retrogradations in the basement of SW Norway are developed subsequent to the thrusting.

Table 2. Electron microprobe analyses [1)]

	Pumpellyite			Prehnite			Stilpnomelane			Clino-zoisite
	N 579	SC 34	U 20	P 254	S 16	U 20	E 80	C 201	G 213	N 579
SiO_2	38.3	37.5	38.1	44.7	43.35	45.6	45.25	47.6	45.6	39.6
Al_2O_3	24.5	21.7	22.7	20.3	24.9	24.55	7.9	6.7	7.25	30.2
TiO_2	b.d.	0.1	0.4	-	-	-	0.1	-	b.d.	b.d.
Fe_2O_3	4.9	6.7	5.3	3.8	2.3	0.1	32.3	33.5	35.2	1.8
MnO	b.d.	0.1	0.1	-	0.05	b.d.	0.2	1.0	1.7	-
MgO	1.5	3.7	3.2	-	2.5	b.d.	6.1	3.65	1.6	-
CaO	23.0	22.4	22.8	25.85	21.8	26.1	0.5	b.d.	0.1	24.3
Na_2O	0.25	0.1	0.2	0.2	0.5	b.d.	0.1	0.35	0.6	0.2
K_2O	b.d.	b.d.	b.d.	0.9	b.d.	b.d.	1.5	0.9	1.5	b.d.
Total	92.45	92.3	9[illegible].8	95.75	95.4	96.35	93.95	93.7	93.55	96.1

	Tremolite		Green-biotite	Chlorite			Serpentine		Clinohumite	
	C 347	Q 159	Rog 346	P 254	C 372	C 383	C 372	C 372	Q 75	C 372
SiO_2	57.94	56.47	35.4	30.3	28.72	29.07	35.89	39.30	38.32	37.48
Al_2O_3	0.14	0.28	15.4	18.6	20.86	20.17	7.70	1.87	b.d.	b.d.
TiO_2	b.d.	b.d.	1.2	b.d.	0.06	0.12	b.d.	0.12	b.d.	3.24
FeO	2.91	1.17	28.3	22.3	1.74	2.23	1.71	1.79	4.73	2.24
MnO	0.26	0.16	0.21	0.1	-	-	0.08	0.17	0.42	1.41
MgO	22.46	22.82	5.8	15.0	32.64	33.41	38.33	39.88	53.77	51.86
CaO	13.09	13.84	b.d.	0.9	-	-	-	-	-	-
Na_2O	0.11	0.10	b.d.	0.2	b.d.	b.d.	-	-	-	-
K_2O	0.13	0.08	9.3	0.8	b.d.	b.d.	-	-	-	-
Total	97.04	94.95	95.6	88.2	84.02	85.00	83.71	83.13	97.24	96.23

1) The analyses were performed at the Instituut voor Aardwetenschappen of the Rijksuniversiteit Utrecht, and that of the Vrije Universiteit Amsterdam. Both institutes were provided with financial and personnel support by ZWO-WACOM (Research group for analytical chemistry of minerals and rocks, subsidized by the Netherlands Organisation for the Advancement of Pure Research).

b.d.: below detection limit.

CHEMISTRY OF SOME RETROGRADE MINERALS

To illustrate the composition of the retrograde minerals, some microprobe analyses are listed in Table 2. Pumpellyite contains significant amounts of ferric iron. The pleochroic colours of pumpellyite, ranging from almost colourless to deep-green, seem to be related to this Fe^{3+} content. Prehnite too contains Fe^{3+}, up to about 11 mol% of the Fe^{3+} end-member. Relatively high Mg contents and low Ca contents in sample S16 suggest a substitution of Ca by Mg. The stilpnomelanes mainly show a compositional variation in Fe, Mg and Mn, suggesting substitution of Fe+Mn by Mg. The brown colour of the stilpnomelanes indicates an appreciable amount of Fe^{3+} present. No compositional differences have been found between stilpnomelane associated with Caledonian mylonitization and those in the Precambrian basement. The green biotite is rather Fe-rich and Ti-poor. Chlorite, as a secondary product in plagioclase (P254), is iron-rich. Chlorites and other secondary minerals in the marbles have a composition close to their Mg end-members.

Retrograde mineral distribution in South Norway

The regional extension of stilpnomelane, green biotite, pumpellyite and prehnite in the basement of South Norway, observed in our samples and encountered in the literature, is given in Fig. 4. The widespread occurrences

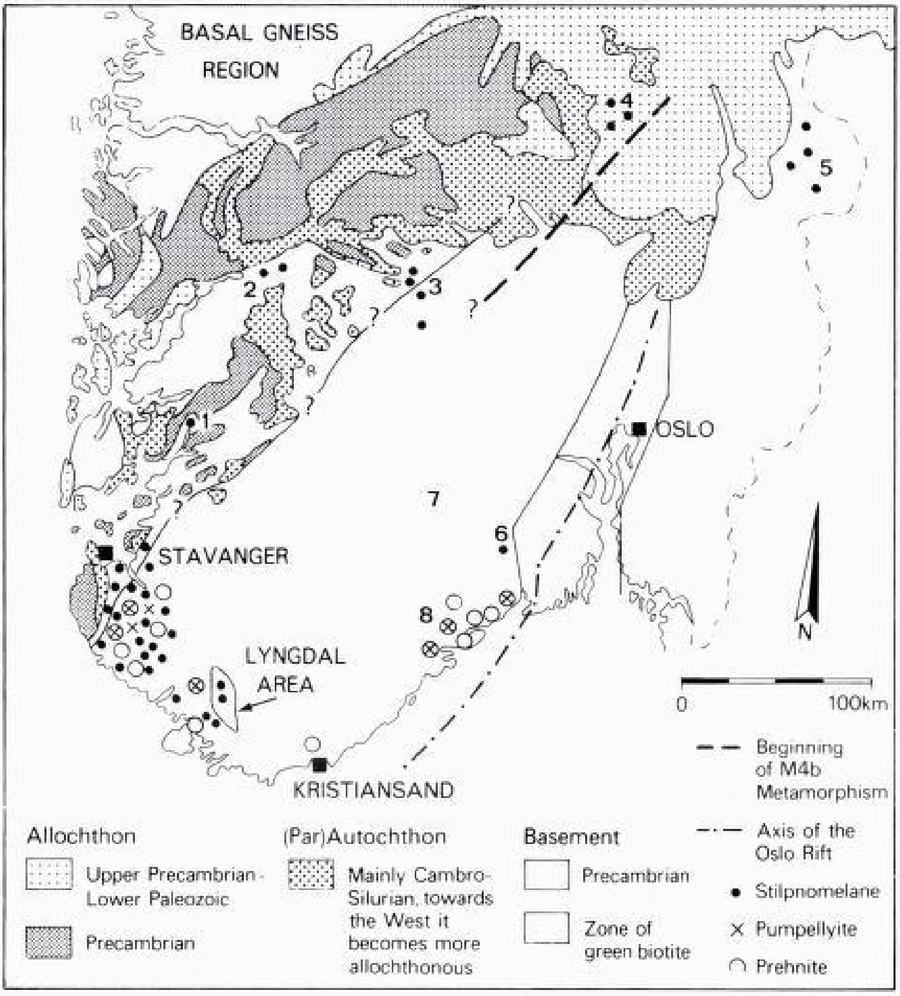

Fig. 4. Schematized distribution of low-grade metamorphic minerals in South Norway; geology after Reymer (1979). Axis of the Oslo Rift after Huseby & Ramberg (1978). Beginning of M4b metamorphism interpreted after Bryhni & Brastad (1980). 1: Sauda area; 2: Eidfjord area; 3: Geilo area; 4: Vinstra area; 5: E Hedmark; 6: Fen area; 7: E Telemark; 8: Bamble area.

in the Precambrian of South Norway are records of metamorphic overprinting, but they cannot all be attributed to the influence of the Caledonian nappe system.

The stilpnomelane distribution in the basement is largely restricted to the vicinity of the Caledonian orogenic belt. Most occurrences in the basement near Stavanger (this paper), in the Sauda area (Sigmond 1978), in the Eidfjord granite (Priem et al. 1976), in the neighbourhood of Geilo (Priem et al. 1972) and, of course, those in the lower units of the Caledonides NNW of Oslo, near Vinstra (Englund 1973) and in Rogaland (this paper) may be attributed to the Caledonian metamorphism, post-dating the main thrusting. This metamorphism, so far called M4 in Rogaland, will be referred to as M4b. The formation of stilpnomelane in the sparagmites near Vinstra seems to indicate the beginning of this Caledonian metamorphism towards the NW, while the SE part of these allochthonous units is practically unmetamorphosed (Englund 1973, Bryhni & Brastad 1980). Priem et al. (1970) reported stilpnomelane in sub-Jotnian rocks of the basement of eastern Hedmark, NNE of Oslo, beneath unmetamorphosed allochthonous sparagmites. These occurrences are restricted to mylonitic rocks and they are presumably strain-induced and related to the Caledonian thrusting events. In the Dala region, being the eastward continuation of this basement in Sweden, a burial metamorphism has been recorded with an increasing grade from prehnite-pumpellyite facies via pumpellyite-actinolite facies to greenschist facies towards the east (Nyström & Levi 1980, Nyström 1982). These authors assume that this burial metamorphism took place before 1220 Ma, but biotites of this basement in east Hedmark, Norway, yield Sveconorwegian K-Ar and Rb-Sr ages of around 925 Ma with a youngest age of 842 Ma (Priem et al. 1970). Whole-rock K-Ar ages as low as 605 Ma in the sub-Jotnian porphyries in the Dala region are interpreted as a function of argon leakage due to mild Caledonian events (Priem et al. 1968). Verschure (1981) therefore suggested that this burial, retrograde metamorphism is likewise related to the Caledonian orogeny. The distribution of the metamorphic grade, however, shows no clear relation with the present position of the Caledonian front. This fact, and the considerable distance between the Caledonian nappe system and the greenschist facies zone, suggests that the basement underwent the burial metamorphism before the Caledonian overthrusting. The stilpnomelane in the Fen area belongs to a late stage of the fenitization, while the carbonatite itself is dated as about 600 Ma old (Verschure et al. 1983). The occurrences of stilpnomelane in the Lyngdal area and most of the occurrences in Rogaland are not related to mylonitization. Although the original southeastward extent of the Caledonian nappe system some 400 Ma ago is unknown, it is unlikely that these stilpnomelane occurrences are induced by Caledonian thrusting or by Caledonian M4b metamorphism, in view of the long distance to the present front position.

Green biotites, which are newly formed in the basement rocks, can be distinguished in three different areas: –

1) In the Basal Gneis Region (fig. 4) it occurs as a secondary mineral in the greenschist facies overprint with epidote, actinolite, white mica, chlorite, albite, microcline and often titanite or ilmenite.
   Priem et al. (1973), for example, described this greenschist facies assemblage as an overprint on the Sveconorwegian Hestbrepiggan granite, which contains relict brown biotite with reset K-Ar and Rb-Sr ages of about 390 Ma. The effects of greenschist facies metamorphism were also reported by Bryhni et al. (1971) in the mineral content of their samples used for dating work. No pumpellyite, prehnite or stilpnomelane is known from this region.

2) In the area between and just southeast of the Caledonides the green biotite is not associated with actinolite, but it frequently occurs with stil-

pnomelane. The same holds for the green biotite occurrences in the lower nappe units of the Caledonides in Rogaland. These assemblages are indicative for a lower grade part of the greenschist facies than those of the Basal Gneiss Region.

3) In the Lyngdal area the secondary green biotite is associated with actinolite, stilpnomelane, chlorite, epidote, white mica, albite and microcline. In this area the metamorphic grade seems to be a bit higher than in Rogaland. This is supported by the occurrences of retrograde corundum instead of diaspore as an alteration pruduct of hercynite (Pieters, pers. comm.).
   As already stated for the stilpnomelane findings in this area, these green biotites are not developed during the M4b metamorphism. They are evidently later than the relict, olive-green biotites which are supposed to be Sveconorwegian.

The prehnite and pumpellyite occurrences in South Norway are scarce. In Rogaland the pumpellyite and prehnite-pumpellyite assemblages are observed SE of the green biotite isograd. Only a few prehnite-pumpellyite assemblages are observed in the Lyngdal area and they are probably also formed outside the green biotite zone (Fig. 4). The latter assemblages and the prehnite occurrences in the Lyngdal area and near Kristiansand, Vest-Agder (Falkum 1966), are in fact situated about a hundred kilometres away from the present Caledonian front. Therefore, these occurrences and presumably also the southeasterly occurrences in Rogaland do not belong to the M4b metamorphism. It is practically impossible, for the same reason, that the occurrences of prehnite and pumpellyite reported from SE Norway (Mitchell 1967, Field & Rodwell 1968, O'Nions et al. 1969) have originated during the M4b metamorphism. Due to the continuation of the axis of the Oslo rift valley along the Norwegian coast in a southwestward direction (Husebye & Ramberg 1978), the basement in this area may have been affected by a Permian event which may be responsible for the low-grade metamorphic effects (Fig. 4). The Permian thermal influence can also be recognized in K-Ar ages of 260 Ma on whole-rock samples of pre-Sveconorwegian rhyolites in eastern Telemark (Priem et. al., 1967) and in lower intercept ages of 260 Ma on zircons and sphenes from the Bamble region (O'Nions & Baadsgaard 1971).

Discussion

A large part of the retrograde metamorphism in the Precambrian basement of SW Norway is clearly attributed to the Caledonian orogeny. This is supported by Caledonian ages of green biotite (Verschure et al. 1980) and of lower intercepts of zircons (Pasteels & Michot 1975, Corfu 1978, 1979, Schärer 1980, Wielens et al. 1981).

Petrological textures in the basement of Rogaland are suggestive of a polyphase retrograde metamorphism. Indications are, for instance, the growth of green biotite at the expence of chlorite, which is pseudomorphous after brown biotite, the occurrence of synkinematic and postkinematic generations of stilpnomelane, green biotite, chlorite and white mica and the development of tremolite, clinohumite and talc at the expense of serpentine, which is an alteration product of forsterite or diopside. In addition, the geographical distribution of the retrogradations in the basement of Southern Norway in relation to the present position of the Caledonian front also suggests that not all retrogradations can be fitted into only one phase of Caledonian incipient metamorphism.

The occurrences of stilpnomelane, green biotite and prehnite + pumpellyite in the Precambrian basement close to the Caledonian front are assumed to be the expression of a Caledonian M4b metamorphism. In Rogaland the distribution of these minerals seems to suggest an inversed thermal gradient. Metamorphism showing inversed gradients is well known in the Scandinavian Caledonides (e.g. Andréasson & Gorbatschev 1980, Andréasson & Lagerblad 1980). In allochthonous units this inversion can be caused by a telescoping effect of superposed nappes, but in the autochthonous basement mainly by a downwards directed heat flow from relatively hot nappes. As a result of intense Caledonian mylonitisation the retrograde overprint may locally be strain-induced (Andréasson & Gorbatschev 1980). Generally, such zones are relatively thin. In Rogaland pure strain-induced retrogradation may be excluded. Although stilpnomelane growth may be favoured in mylonitic zones, it also occurs in undeformed rocks throughout the mapped area (Fig. 2). The green biotite is not particularly related to deformation.

Low-grade to very low-grade metamorphism at greater distances from the Caledonian front can clearly not be related to the Caledonian overthrust. Therefore it is assumed that these metamorphic effects are related to a burial type of metamorphism (M4a), possibly prior to Caledonian thrusting, as a result of a burden of sediments in late Precambrian or early Palaeozoic times. Thick late Precambrian sediments are known from the sparagmite region in central south Norway (Bjørlykke 1978), and Lower Palaeozoic sediments in the parautochthonous (Vidda group) and allochthonous (Holmasjö allochthon) units at the base of the Caledonian nappe pile in SW Norway (Andresen & Faerseth 1982). Evidence from central Norway and Sweden shows that sediment thicknesses vary laterally but they may amount to several kilometres (Bjørlykke 1978, Gee & Zachrisson 1979).

The absolute timing of the Caledonian retrograde metamorphic events in Rogaland is uncertain. Generally in the Caledonian orogen a Finmarkian and a Scandian phase are recognized, dated to late Cambrian to early Ordovician time and Middle to late Silurian time, respectively (Roberts & Sturt 1980, Bryhni & Brastad 1980). In the Caledonides of SW Norway both phases are recognized (Roberts & Gale 1978). The only isotopically dated retrograde mineral from the basement in Rogaland close to the front is green biotite, yielding K-Ar ages of 557 Ma and 469 – 444 Ma and Rb-Sr ages from

421 to 397 Ma (Verschure et al. 1980). The ages around 400 Ma evidently refer to the Scandian phase which is the most commonly reported deformation event in the Caledonides of SW Norway (Sturt & Thon 1978, Roberts & Sturt 1980, Roddick & Jorde 1981). Tentatively, the high K-Ar ages can be attributed to the Finnmarkian phase, although Verschure et al. (1980) suggest incorporation of excess argon as the cause of the high ages. Most of the relict biotites in the basement SE of the Caledonian front in southern Norway remain Sveconorwegian (900–850 Ma) in age (O'Nions et al. 1969, Priem et al. 1970, Brueckner 1972, Priem et al. 1972, Versteeve 1975, Verschure et al. 1980, Wielens et al. 1981); only a few brown biotites just beneath the Caledonian thrust front near Stavanger form an exception in showing reset K-Ar and Rb-Sr ages down to 700 Ma (Verschure et al. 1980). In the Basal Gneiss Region, where most biotites show reset Caledonian ages in contrast to biotites from the basement SE of the Caledonian front, the K-Ar mineral datings are also higher than the Rb-Sr datings. Brueckner (1972) ascribed this feature to a more ready reequilibration of Sr than to the idea that Ar is expelled from the mineral. This could mean that some of the K-Ar mineral datings are a real reflection of the Finnmarkian event. Bryhni et al. (1971) reported three $^{39}Ar/^{40}Ar$ ages of 524, 488 and 405 Ma in the Basal Gneiss Region. Further indications for an early Caledonian event in SW Norway possibly may be found in a date of about 540 Ma on the parautochthonous phyllites in the Jæren district, south of Stavanger (Roddick & Jorde 1981) and in a lower intercept age of zircons of about 540 Ma in autochthonous basement near Undheim (Pasteels & Michot 1975). Whole-rock K-Ar ages, as low as 564 Ma in Sveconorwegian dike systems in Rogaland and Vest-Agder, sampled about 50 km east from the Caledonian nappe front, seem to reflect argon leakage due to post-Sveconorwegian thermal events (Versteeve 1975). Thus, in the basement of SW Norway there are isotopic indications for two Caledonian events.

Based on the above reasoning we assume a Finnmarkian metamorphism (M4a), mainly in the prehnite-pumpellyite facies, affecting the basement in SW Norway. This weak, up to now radiometrically not definitely dated event, was a regional burial metamorphism. Because of the interference of the M4a and M4b metamorphic phases in the basement the mineral records of the M4a in Rogaland were formerly ascribed to the M4b phase, which was induced about 400 Ma ago by the Caledonian nappe system (Maijer 1980, Verschure et al. 1980, Verschure 1981). The retrograde metamorphic events in the basement of southern Norway may be summarized in the following model sequence:

M3 – The regional Sveconorwegian cooling stage is reported in K-Ar ages on amphiboles and biotites over the whole of South Norway and it lasted to about 850 Ma. Low-grade retrogradation may have been operative. After denudation, Upper Precambrian and Palaeozoic sediments were deposited on the peneplain.

M4a – A burial Finnmarkian metamorphism took place, mainly in prehnite–

pumpellyite facies. Locally, where the sediment pile was thicker, it may have produced a higher metamorphic grade. It may have been active in several periods. Probably this metamorphism extended over a great part of the Baltic Shield.

M4b -This Scandian metamorphic phase in the basement is restricted to the vicinity of the Caledonides. It mostly developed with an inversed gradient and it was locally strain-induced in specific mylonitic zones. It is about 400 Ma old and waning towards the southeast from greenschist facies near the Caledonian front into prehnite-pumpellyite facies. Late M4b thermal reequilibration lasted to about 300 Ma ago.

M5 – The Permian reheating of about 250 Ma ago was active in the basement only in a zone marginal to the Oslo Rift valley and along Permian dike systems. Its conditions reached prehnite-pumpellyite facies. Erosion of the basement started again and at least 220 Ma ago the Sveconorwegian basement, as it is exposed at the present day, passed through the 100°C isograd.

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