

The petrogenesis of charnockitic and granitic migmatites of the high-grade metamorphic Precambrian of Rogaland/Vest-Agder, S.W. Norway – A statistical interpretation of major element rock chemistry

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Received 19 December 1986; accepted in revised form 13 April 1987

Abstract

A charnockitic and granitic rock suite from the high-grade metamorphic Precambrian of southwest Norway was investigated for its geochemical characteristics. Whole rock major element analyses of 37 samples, taken from 8 localities which cover a range of metamorphic grade, were made. Multivariate statistical methods, R-mode and extended Q-mode component analysis, were used to aid the interpretation of the complex data set. Application of these methods resulted in a main division into melanocratic and leucocratic sample groups. A further analysis of the two groups showed that while the melanocratic samples form a homogeneous group, the leucocratic samples display a geochemical variability which is explained here by partial anatexis. Combined geological and geochemical data suggest a primary formation of the rock suite as a series of basic and acid volcanic rocks, that are intercalated with sediments. The charnockitic rock suite (granulite facies) shows no evidence of depletion of magmatophile elements compared to the granitic rock suite (amphibolite-facies).

Introduction

The Precambrian basement of southwest Norway consists of several intrusive masses near the coast (charnockites, granites, anorthosites and the layered lopolith of Bjerkreim-Sokndal, Duchesne et al., 1985) and a surrounding polymetamorphic complex composed mainly of charnockitic and granitic rock series interbedded with Ca- and Al-rich metasediments, augengneisses and some minor basic intrusions (Hermans et al., 1975), see Fig. 1.

The quartzofeldspathic rocks vary in grain size and have a massive to gneissic appearance (see also Table 1). They alternate with dark-coloured layers of (leuco)noritic or amphibolitic composition. This banding is generally regular and more or less con-

tinuous, but agmatitic, nebulitic and ptygmatic structures are observed (Hermans et al., 1975). Based on the paucity of alternating melanocratic layers and also on the presence or absence of a gneissic texture Hermans et al. (1975) recognized 'mainly massive' and 'mainly banded' parts in the charnockitic and granitic rock series. Silica metasomatism is evidenced in the field by the presence of numerous quartz veins, bands and lenses in almost every rocktype of the area.

Isotopic age determinations (Versteeve, 1975; Wielens et al., 1981; Priem & Verschure, 1982; Verschure, 1985; DemaiFFE & Michot, 1985) indicate an oldest, primary or metamorphic, age of about 1500 Ma. This relic age is overprinted by the first definitely recognized metamorphic event

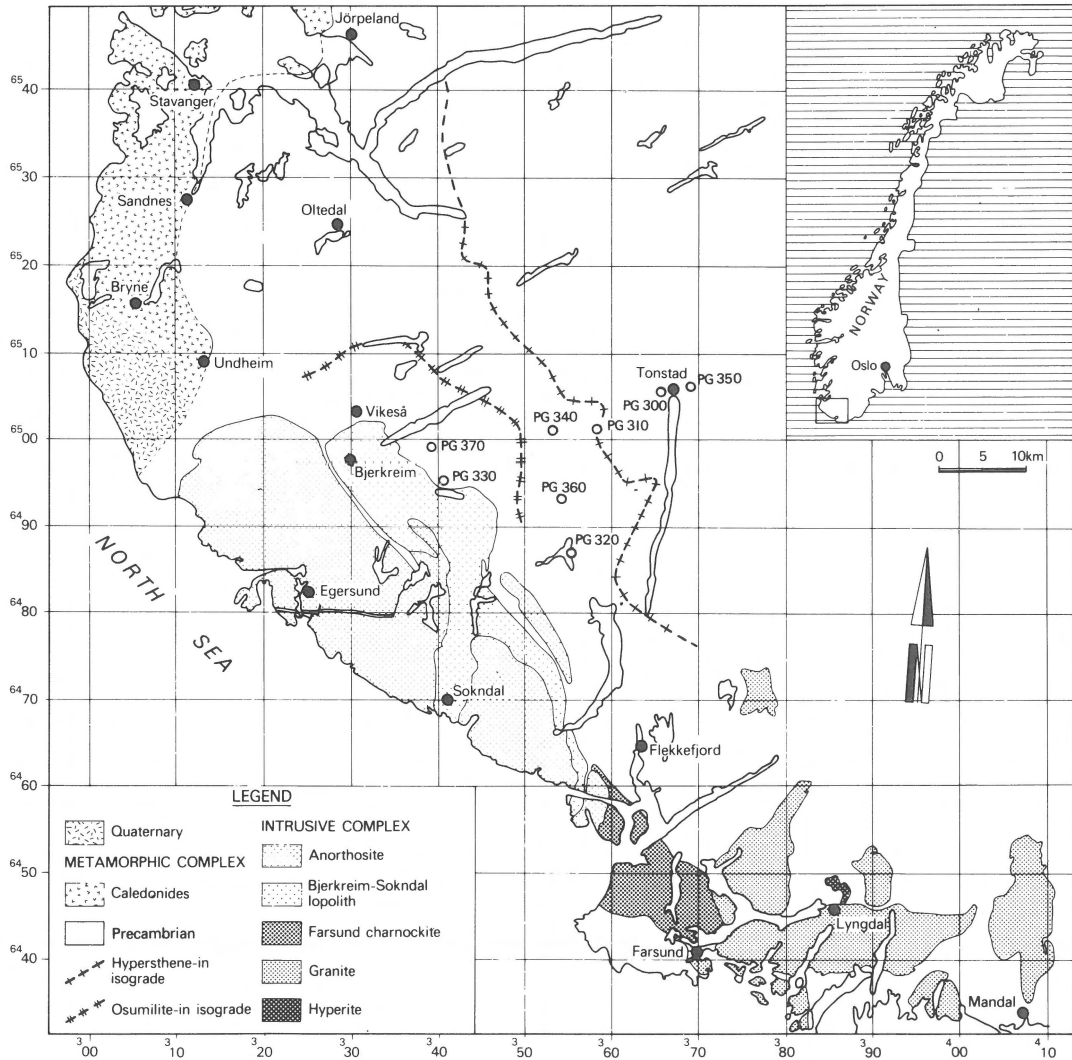


Fig. 1. Simplified geological map of southwestern Norway showing sample locations. Samples 301 to 304 were taken at location PG 300; samples 311 to 316D at location PG 310, etc. The hypersthene isograd marks the boundary between amphibolite facies rocks in the east and granulite facies rocks in the west. After Hermans et al., 1975.

(M1), which is in high temperature amphibolite facies to low granulite facies and is correlated with ages of circa 1200 Ma. Higher temperatures were reached during a second, granulite facies stage (M2), which is probably induced by the emplacement of the intrusive anorthosite complex and is dated at about 1050 Ma. The temperature gradient of this M2 stage is characterized by a systematic change in amphibole properties with distance to the intrusive complex (Dekker, 1978) and by a number of more or less concentric isograds, e.g. a

pigeonite-in and an osumilite-in isograd close to the intrusive complex and a 'hypersthene-line' farther to the east (Hermans et al., 1975; Maijer et al., 1981; Tobi et al., 1985; Fig. 1). The 'hypersthene-line' marks the incoming of orthopyroxene in rocks of leucogranitic composition, i.e. these rocks are mainly orthopyroxene-bearing charnockites west of the hypersthene isograd, while they are mainly orthopyroxene-free granites east of this line. Geothermometric and geobarometric calculations indicate a temperature gradient from 700°C near the

hypersthene isograd to near 1050°C near the intrusive complex at pressures of about 4 kb (Jacques de Dixmude, 1978; Jansen et al., 1985). Ages of 950–870 Ma are ascribed to an M3 metamorphism in the high temperature amphibolite facies to low granulite facies, which possibly represents a period of cooling after the M2 event. The youngest metamorphic event is in the prehnite-pumpellyite facies and is related to the Caledonian orogeny; it is dated at circa 400 Ma (Verschure et al., 1980; Sauter et al., 1983).

At least four phases of deformation are recognized, the main structures (D2) being isoclinal folds which were refolded by asymmetric open folds (D3) (Huijsmans et al., 1981).

The charnockitic and granitic rock suites of Rogaland/Vest-Agder were chosen as the subject of this study because they cover vast parts of the area under investigation by the Utrecht Department of Petrology, but have to date not been studied in detail. Previous work was concentrated on the intrusive masses and metasediments (Rietmeijer, 1979; Kars et al., 1980; Sauter, 1981). One objective of this investigation was to characterize the major element chemistry of the rocks, in order to find indications of their pre-metamorphic origin. The second objective was to evaluate the possible differences in major element rock chemistry that could have been imposed by the high grade regional metamorphism. Some investigators consider granulites to be 'restite' masses depleted in H₂O and magmatophile elements (e.g. Powell, 1983), which supposition predicts – regarding the major elements considered here – granulites to be depleted in Si, K and Na and consequently to be relatively enriched in elements like Fe, Mg and Ti. For quite a number of granulites, however, this theory does not hold (Newton et al., 1980; Barbey & Cuney, 1982; Weaver & Tarney, 1983). Essentially there appear to be two types of granulites: depleted and non-depleted. In the investigated region the M2 metamorphism has left the largest imprint on the mineralogy. The geographic distance to the intrusive complex, to which emplacement this metamorphism is related, was considered a good indicator of the metamorphic grade. Samples from near the Bjerkreim-Sokndal lopolith

(high granulite facies) were compared to samples farther away which probably were not, or much less, heated by the intrusion (amphibolite facies) to test the depletion theory for this M2 granulite facies event in southern Norway.

Sampling

Sampling was concentrated on the 'mainly banded' parts of the charnockitic and granitic rock series. Sample sites were chosen at increasing distances from the Bjerkreim-Sokndal lopolith, to cover the full range of M2 metamorphic grade (Fig. 1). At each locality representative samples of all rock types present (light, dark, coarse, fine, etc.) were collected and their field relations described. Preferentially recent road cuts were sampled to avoid extensive weathering. Large samples (1–3 kg) were collected and the absence of major retrogradation was checked in the field by examination of locally made thin sections.

For comparison with other rock types, two samples of a massive charnockite body with discordant contacts (location PG 370) for which field relations are known in detail (Schreurs, 1982) and some samples of augengneisses (location PG 300) were collected. Comparison was also made with the true intrusive Farsund charnockite and Kleivan granite/charnockite in the south (Petersen, 1980).

Rocks of metasedimentary affinity (the Faurefjell metasediments and the metapelites of the Gyadal formation of Hermans et al. (1975), including the garnet-bearing charnockitic and granitic rocks) were not investigated. However, a sample of a small hedenbergite-bearing lens of probably metasedimentary origin (352), found within a sequence of granitic and amphibolitic rocks at location PG 350, was included in this study.

Petrography

The petrography is summarized in Table 1. The samples (except 352) range from noritic/amphibolitic through charnockitic/granitic to K-feldspar-charnockitic/-granitic.

The melanocratic rocks (314D, 315, 316D, 322, 324, 333, 343, 344, 351 and an alternatingly light-dark, fine-banded sample 355) are fine to medium grained. Grain boundaries are mostly interlobate, sometimes polygonal (terminology of textures after Moore, 1970). They show a (vague) foliation due to the alignment of the dark minerals (orthopyroxene, clinopyroxene, hornblende, biotite, opaques). The anorthite content (An) of the pla-

gioclase is generally about 37%. Samples 315, 333, 344 and especially 351 have more Ca-rich plagioclase (46% and 55% An respectively). The banded sample 355 has An 25%, it is also marked by opaque-associated apatite.

The leucocratic samples have a greater variety in grainsizes, often within one thin section. Coarse quartz, K-feldspar or plagioclase grains occur within fine to medium-grained textures, which may

TABLE 1. Summary of petrographic data.

sample nr.	structure	grainsize	quartz	K-feldspar	plagioclase An%	orthopyroxene	clinopyroxene	amphibole	biotite	garnet	corundum	apatite	monazite/xenotime	zircon	opaque	titanite	sericite*	chlorite*	epidote*	carbonate*	rockname
PG301	sia	c	2	4	3	2		0	0			a	x	a	0	0					granitic augengneiss
PG302	sii	f-m	3	3	3	2		1	0			a	x	a	0	0	a				granitic augengneiss
PG303	sia	m	2	4	3	2		1	0			0	x	a	0	0	a				granitic augengneiss
PG304	gia	c	2	4	3	2			0			a			a	2	0	a			granite
PG3111	gii	c	2	5	3	3	0		0			0	x		a			a	a		K-feldspar charnockite
d	gii	c	0	0		9			a		0										hypersthentite
PG312	gia	f-m	5	3	1	3	a		0			a		0	0	0	0				charnockite
PG313	goa	m	3	3	3	2				a			x		a	2	a				garnet granite
PG314L	gia	m-c	2	1	7	3	0	0	0			a			a	1	a	a			enderbite
PG314D	gii	f		4	4	1		1	1		0		a	2			a				norite
PG315	sii	f		4	5			4	2					0		1					gneissic amphibolite
PG316L1	gia	f-m	5	a	5	3	0		a			a	a			1	0				enderbite
d	gip	f-m		6	4	1		0	3			a	a	0							norite
PG316Dd	gii	f-m		4	4	1	2	0	0			a		2							norite
l	gia	f-m	6	3	4	0	0	a					a	0		1					enderbite
PG321	gia	f-c	4	0	5	4	a							a		1	a				enderbite
PG322d	gii	f-m		0	6	3	2	0				a			1						norite
l	gia	m-c	7		1	2	1				0		a	a		1	1				quartzite
PG323	gia	f-c		6	3	3	0					a			0		1	1			hypersthene monzonite
PG324	gii	f-m			5	4	2	2	0	0					2						enderbite
PG331	gia	c	6	0	3	3	0						a	a		1	2				enderbite
PG332	gia	f	0	2	6	2	2					a		a	0	0					monzo-norite
PG333	gia	f-m			3	5	2	1	2	1					1		1				hornblende norite
PG334	gia	f-c	3	3	3	3	1						a	0			1				charnockite
PG341	gii	m	2	2	4	4	2			a						0					charno-enderbite
PG342	gia	c	5	2	2	4	1			a				a		2	1				charnockite
PG343L	gia	c	4	5	a									a		2	1				K-feldspar charnockite
PG343D	gia	m	1	7	4	1			0					a	0	1					leuco-norite
PG344d	gia	f-m	0	1	6	5	2							a	0	0					leuco-norite
l	gia	c	7	2	1	3	a							a			a	a	a		quartzite
PG345	gia	f-c	3	3	3	3	a							a		2	0				leuco-charnockite
PG351	gip	f-m		4	6				a							1					amphibolite
PG352	gii	f-m		1	4		8	a				0		a	1	0	1	0			hedenbergite rock
PG353	gia	c	3	5	2	3						a		a		1	a				leuco-granite
PG354	gia	f-m	3	3	2	3			2		x	0		a	0	0	1	0			biotite granite
PG355	gia	m	2	0	3	2		1	2	1		0			1	a	1	0			amphibolitic tonalite
PG356	gii	f-c	4	4	2	2			0					a	0	a	1	a			leuco-granite
PG361	gii	m-c	4		5	3										1	0	0	a		leuco-enderbite
PG362	gia	m	2	1	4	3	2			1				a		0					melano-enderbite
PG363	gii	m	1	9			a							a	a	2	0			a	K-feldspar syenite
PG371	gia	f-m	4	5	1	2			0					a	a	0	2	2	0		granite
PG372	goa	f-m	4	4	2	2			0					a	a	a	1	1	a		granite

Abbreviations:

sample nr.: L = Light sample, D = Dark sample (separated by sawing); l = light part of thin section*, d = dark part of thin section* (major part is mentioned first).

structure: 1) s = gneissic, g = granulitic; 2) i = inequigranular, O = seriate;

3) a = amoeboid, i = interlobate, p = polygonal. (Modified after Moore, 1970).

grainsize: f = fine, m = medium, c = coarse

modes, An%: a = 0-1%, 0 = 1-5%, 1 = 6-15%, 2 = 16-25%, 3 = 26-35%, 4 = 36-45%, 5 = 46-55%, 6 = 56-65%, 7 = 66-76%, 8 = 76-85%, 9 = 86-100%, x = probably present. Modes are estimated.

* Thin sections were mostly made of the, sometimes slightly altered, margins of the samples.

For chemical analysis these margins were removed before crushing. Thin sections of samples which were separated by sawing were sometimes made near the interface.

Altered plagioclase, pyroxene, etc. is taken as sericite, chlorite and so on, but is also included in the modes of the respective original minerals.

evidence recrystallization. Grain boundaries are interlobate to amoeboid (Moore, 1970). K-feldspar is generally perthitic, plagioclase sometimes anti-perthitic; occasionally myrmekitic textures are observed. The anorthite content ranges from 25% to 38%. Streaks of dark minerals (hornblende, biotite, orthopyroxene, opaques) or a platy quartz texture may define a foliation. The leucocratic samples generally show more evidence of retrogradation than the melanocratic samples, in the form of minor chloritization of orthopyroxene and sericitization of plagioclase.

Rock names in Table 1 are according to Streck-eisen (1974) but are not considered to have any genetic meaning, nor to be implicative of metamorphic grade.

Analytical techniques

Weathered outer surfaces of the samples were removed with a hydraulic crusher. After crushing and milling the samples to less than 0.2 mm, whole rock analyses were made according to the method of Shapiro (1967). For Si, Ti, Al, P and Fe(TOT), i.e. total iron, a Perkin-Elmer 550S spectrophotometer was used; Mn, Mg, Ca, Na and K were measured with a Perkin-Elmer 460 Atomic Absorption Spectrometer. Fe⁽²⁺⁾ was measured separately (sample decomposition with H₂SO₄/HF and oxidation-reduction titration with K-dichromate) and Fe⁽³⁺⁾ was computed as the difference of Fe(TOT) and Fe⁽²⁺⁾. The volatile elements were measured as the loss on

TABLE 2. Chemical analyses in weight percent

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI*	Fe _{TOT}	Total	n*
PG301	69.16	.41	15.15	.88	1.48	.02	.88	.27	4.01	4.83	.15	.48	2.52	99.72	2
302	75.18	.05	13.48	.38	.51	.02	.10	.34	3.54	4.68	.01	.36	.95	99.65	2
303	68.35	.44	15.02	.88	1.88	.04	1.14	.60	4.04	4.34	.15	.49	2.97	99.37	2
304	74.04	.05	14.16	.23	.44	.01	.14	.33	3.64	5.36	.02	.23	.72	99.65	2
PG311	67.45	.05	15.41	.01	3.03	.08	1.65	.24	3.87	4.87	.21	.52	3.15	99.39	2
312	76.55	.20	12.30	.83	.95	.03	.22	.17	3.28	4.35	.03	.30	1.89	100.21	2
313	73.55	.01	14.48	.18	.55	.10	.05	.82	4.44	5.01	.02	.40	.79	99.61	2
314L	76.15	.02	12.74	.37	.80	.03	.52	.45	3.79	1.69	.07	.35	1.26	98.98	1
314D	42.66	4.68	14.44	6.20	12.25	.28	5.23	.09	3.32	.90	.92	1.08	19.81	99.05	1
315	46.15	1.85	15.75	4.30	8.52	.20	7.20	.16	3.36	1.54	.25	1.28	13.77	99.56	1
316L	77.61	.13	11.71	.05	.85	.01	.20	.37	2.79	3.77	.02	.34	.99	98.85	1
316D	47.11	2.47	15.14	5.31	9.65	.24	6.07	.50	3.63	1.22	.40	1.08	16.03	99.82	1
PG321	74.81	.05	14.07	.09	.32	.02	.19	.05	3.02	5.02	.01	.37	.45	100.02	1
322	49.52	2.01	14.49	5.94	7.89	.31	6.17	.02	3.43	.67	.26	1.14	14.71	100.85	1
323	61.71	.31	17.90	.47	1.36	.04	.84	.49	2.87	9.86	.72	.85	1.98	99.42	2
324	48.88	2.11	14.36	6.15	8.10	.30	5.96	.70	3.31	.85	.27	.97	15.15	99.96	1
PG331	79.23	.31	10.60	.01	1.74	.03	.41	.19	3.08	1.01	.03	.49	1.80	99.13	1
332	63.94	.72	15.99	.43	5.65	.06	2.05	.62	4.48	2.03	.19	.68	6.71	99.84	1
333	49.36	1.19	15.66	2.80	8.57	.19	6.72	.51	2.95	1.28	.15	1.22	12.55	99.60	2
334	70.95	.47	13.60	.19	2.83	.05	.65	.83	3.32	4.28	.13	.67	3.33	98.97	1
PG341	67.00	.50	15.91	.28	3.96	.07	1.62	.10	3.75	2.34	.10	.53	4.68	100.16	1
342	73.66	.11	13.85	.08	.75	.01	.28	.00	2.42	6.80	.02	.52	.91	99.50	1
343L	72.06	.05	14.90	.07	.52	.01	.17	.61	2.30	8.77	.02	.57	.65	100.05	1
343D	67.14	.51	15.03	.23	4.09	.01	1.72	.76	3.59	2.11	.06	.60	4.77	98.85	1
344	64.26	.56	15.96	.51	4.74	.04	2.52	.36	3.14	1.76	.11	.63	5.78	99.59	1
345	71.10	.07	15.16	.41	.49	.02	.35	.20	2.89	6.25	.40	.41	.95	99.75	1
PG351	48.72	1.49	15.02	2.92	7.08	.22	8.11	.80	3.38	1.43	.17	1.88	10.79	100.22	1
352	42.96	1.28	20.78	7.92	3.73	.20	1.75	.15	2.15	2.21	.45	3.01	12.06	99.59	2
353	70.94	.23	14.68	.73	.97	.01	.49	.11	3.62	5.79	.08	.77	1.81	99.42	1
354	68.43	.40	15.21	1.17	1.78	.05	.89	.62	4.07	4.82	.15	1.51	3.15	100.10	1
355	55.72	1.77	15.33	4.65	5.94	.21	2.71	.14	4.88	1.06	.43	1.11	11.25	99.95	1
356	69.87	.43	14.71	.92	1.35	.04	.50	.45	3.60	5.18	.10	.82	2.42	98.97	1
PG361	74.62	.12	14.32	.12	.40	.03	.21	.37	3.77	4.43	.03	.83	.56	100.25	1
362	64.26	.52	15.66	.01	4.64	.03	2.79	.59	4.04	1.79	.09	1.36	4.88	98.95	1
363	61.79	.38	17.31	.55	2.71	.03	1.48	.34	4.89	5.53	.10	2.98	3.56	100.09	2
PG371	71.26	.37	14.58	.39	1.28	.03	.44	.67	3.91	4.44	.09	1.17	1.81	99.63	1
372	71.42	.32	14.48	.43	1.26	.02	.43	.75	3.39	4.87	.07	.91	1.83	99.25	1
pooled st.dev. of repeat	.44	.05	.19	.12	.03*	.02	.06	.10	.06	.06	.02	*	.13		

*Values are the mean of n measurements. FeO and LOI for samples and LOI for standards are only measured once (see also Table III). Standard deviations are computed from duplicate analyses of samples and standards.

ignition (LOI). Accuracy and precision of the measurements were controlled by the use of standards and by duplicate analyses. Except for LOI, an estimate of the standard deviation for all elements could be made. The results of the chemical analyses together with the pooled standard deviation of duplicate analyses are given in Table 2. An estimate of the accuracy is obtained from the totals and from the comparison of standards in Table 3. Accuracy and precision are both adequate.

Factor analysis

Introduction

A chemical data-set, such as that presented in Table 2, is difficult to interpret. Petrogenetic modeling, however, asks for the grouping of data in subsets, trends, etc. As no obvious primary model exists for the Rogaland charnockitic and granitic rock series, any model for these rocks should preferentially be based upon all available data.

Factor analysis, or more precisely – as it is used here – component analysis, is one method of detecting the inherent systematics in a group of data and can greatly facilitate petrogenetic modelling. It creates a reduced, optimum set of variables (components or factors), which describe the original data-structure to a close approximation. Because factor analysis makes use of essentially all data and their interrelationships and does not depend on a-priori models or assumptions, it should be able to detect more or less ‘hidden’ features that otherwise would be unnoticed or to which the data would be considered relatively insensitive. In real factor analysis the variance of the original parameters is split into a part that depends on a number of common features (common variance) and a part not related to the common features (unique variance). Real factor analysis is aimed at the elucidation of the common features or processes only and is therefore covariance-orientated (Jöreskog et al., 1976). Component analysis does not make this distinction (or the unique variance for all parameters is considered to be zero) and is thus more variance-

Table 3. Comparison of standards.

	GS-N		BN 01		GN 02		GRAN-1	
	*)	this study (n = 1)	**) (n = 108)	this study (n = 6)	**) (n = 80)	this study (n = 6)	**) (n = 36)	this study (n = 4)
SiO ₂	65.98	65.66	44.57	44.55	70.32	70.28	71.3	70.93
TiO ₂	.68	.60	3.00	3.08	.34	.32	.30	.29
Al ₂ O ₃	14.71	14.65	15.38	15.20	14.58	14.53	14.2	14.03
Fe ₂ O ₃	1.93	n.a.	3.86	3.66	1.20	1.24	.99	n.a.
FeO	1.65	n.a.	7.90	8.02	1.16	1.09	1.19	n.a.
MnO	.06	.01	.19	.18	.09	.06	.07	.06
MgO	2.31	2.27	6.81	6.86	.85	.90	.47	.54
CaO	2.51	2.50	10.60	10.47	2.13	2.21	1.43	1.58
Na ₂ O	3.78	3.86	3.22	3.37	3.44	3.56	3.38	3.52
K ₂ O	4.64	4.52	1.63	1.65	4.22	4.21	5.3	5.26
P ₂ O ₅	.28	.28	.79	.76	.13	.13	.08	.09
LOI (n = 1)	1.57	n.a.	2.19	2.48	1.03	1.09	.45	.45
Fe _{TOT}	3.75	3.51	12.60	12.54	2.50	2.45	2.31	2.32
TOTAL	100.10	(99.43)	100.14	100.28	99.49	99.62	99.2	(99.07)

*) International standard (Abbey, 1977).

**) House standard, Service Laboratory IVA.

n.a. = not analyzed.

Totals in brackets for incomplete analyses.

orientated. It may be considered as a projection of the data cloud in a space of smaller dimension.

R- and Q-mode analysis differ in their way of scaling of the original data and in the similarity measure used in the computation of the factors. R-mode analysis looks upon the cases or samples in the space spanned by the variables – in our case chemical elements – (variable space), Q-mode analysis is concerned with the representation of the variables in the space described by the samples (object space).

From factor or component analysis the minimum number of new variables needed to describe the (co-)variance in the original data can be estimated. Once this number is decided upon, a set of factors, the factor loading matrix, can be computed in terms of the original parameters (variables for R-mode, objects for Q-mode). Different approaches exist for the choice of factors with reference to the original parameters. Principal component (PCOM) and Varimax rotated factors (VRMX) are mostly used. They are both orthogonal sets of factors. PCOM factors are aligned with the major axes of the data cloud, describing directions of largest variance. The Varimax rotation is such that each original parameter is described as much as possible by one new factor only. The coordinates of the objects in the R-mode (variable) factor-space or of the variables in the Q-mode (object) factor-space are expressed in the factor scores matrix. The original data matrix is now approximated by the multiplication of the factor scores matrix with the factor loading matrix.

In 'extended' Q-mode analysis (Miesch, 1976b) an attempt is made to conform the factor scores, which are then called composition scores, to the original samples by imposing upon them the same constant row sum (here 100%). The VRMX composition scores can then be thought of as approaching (hypothetical) endmembers of the data set.

For a detailed treatment of factor analysis, the interested reader is referred to Jöreskog et al. (1976), Klován (1975), Klován & Miesch (1976) and Miesch (1976a, 1976b). Le Maitre (1982) gives a good survey of the various types of factor analysis applied in petrology, including extended Q-mode analysis. The computer programs used in this study

were that of Miesch (1976b) for Q-mode and the SPSS program (Nie et al., 1975) for R-mode. R-mode component analysis was applied to the data-set to gain insight in the inter-element association pattern, which is indicative of the various processes that formed or modified the rocks. Extended Q-mode analysis, especially meant for constant row-sum matrices like petrological data-sets, was used to reveal the underlying structure in the sample set.

All samples, R-mode

Data were normalized to units standard deviation. The Pearson correlation coefficients were used as the similarity measure. The system (LOI excluded because it showed no correlation with any other element) is adequately described by a three factor model, which explains 85.8% of the original variance in the data set. VRMX factors for this model are given in Table 4. In Fig. 2 the original variables are plotted against the new reference axes. It can be seen from this figure that VRMX1 represents the positive association of Si with K, and their negative association with Fe, Mg, Ti, Mn, and Ca which are preferentially retained in refractory, mafic minerals. This latter group will further be referred to as the mafic elements. Leucocratic samples will plot to the negative side of VRMX1, melanocratic (mafic) samples to the positive side. VRMX2 is mainly defined by Al, to a lesser extent by P and negatively by Si. Possibly Fe⁽³⁺⁾, Ca, K and the remaining mafic elements have a slight positive association to this factor. VRMX3 is close to the original variable Na, thus obviously Na is not strongly related to any other element. In Fig. 3 the samples are plotted against the different combinations of the reference factors. Two groups of samples can be seen in the plots with VRMX1, which separates melanocratic, amphibolitic/noritic samples from the more leucocratic samples. The melanocratic samples have a narrow compositional range, whereas the sample cloud defined by the leucocratic samples shows a much greater chemical variability. From these diagrams, samples 323, 331, 352 and also 355 and 314D appear to have deviating compositions.

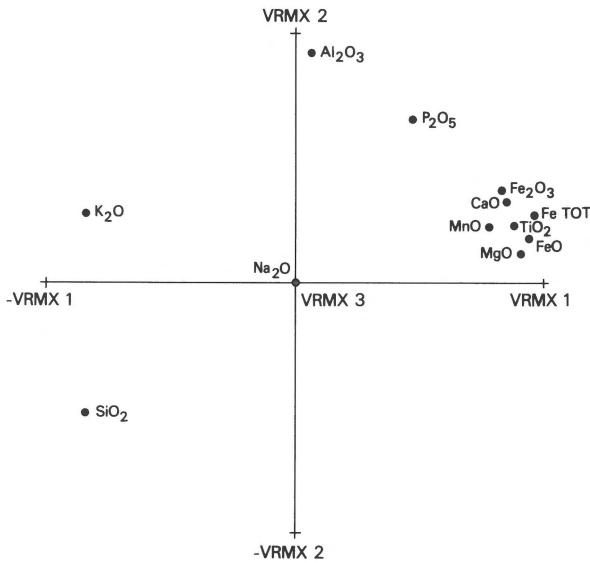


Fig. 2. R-mode, three factor model. The original variables are plotted against the first two VRMX axes.

All samples, extended Q-mode

After normalization to 100% (LOI and Fe(TOT) excluded) the data-matrix (Table 2) was standardized column-wise to range from zero for the minimum value to one for the maximum. The covariance matrix of the standardized data was used as

Table 4. R-mode, all samples, VRMX factor loading matrix. The figures in the table indicate the strength of association between the original variables and the factors.

	VRMX 1	VRMX 2	VRMX 3
SiO ₂	-.84	-.51	.05
TiO ₂	.88	.23	-.03
Al ₂ O ₃	.08	.92	.06
Fe ₂ O ₃	.83	.37	-.17
FeO	.94	.18	.07
MnO	.80	.24	.02
MgO	.91	.12	-.02
CaO	.85	.33	-.18
Na ₂ O	.00	-.00	.99
K ₂ O	-.84	.28	-.22
P ₂ O ₅	.47	.66	-.12
Fe _{TOT}	.96	.27	-.03

the similarity measure. 93.8% of the total variance in the data set is described by a three factor model. Only for Al and Na this model explains less than 50% of the original variability (a coefficient of determination of less than 0.5). Table 5 lists the VRMX composition scores matrix. VRMX1 represents a leucocratic endmember, VRMX2 noritic/amphibolitic rocks. VRMX3 is high in K, Al and Fe⁽³⁺⁾, low in Si and even negative in Fe⁽²⁺⁾, Na and Mg. The negative values, non-realistic for a true endmember composition, are due to the constraint of orthogonality of the factors. VRMX3 may represent mobility of K, Na and Si and oxidation of Fe in a metasomatic or weathering event. Al may remain constant in absolute sense but be relatively increased.

In Fig. 4 the original samples are plotted in an extended triangle with the three VRMX factors at the apices. The separation into two groups of samples, corresponding to leucocratic samples near VRMX1 and melanocratic samples near VRMX2, is obvious. The third factor (metasomatism, weathering?) seems to be equally effective for light and dark samples. The melanocratic samples distinguished in this plot conform with the results of the R-mode analysis. Again samples 323, 352 and 314D are deviating. The banded sample 355 is recognized as an intermediate rock type.

Table 5. Q-mode, all samples, VRMX composition scores matrix. The composition scores approach endmembers of the data set. Negative values are due to the constraint of orthogonality of the factors.

	VRMX 1	VRMX 2	VRMX 3
SiO ₂	78.9	36.0	24.7
TiO ₂	-.12	2.88	.11
Al ₂ O ₃	13.6	17.7	32.8
Fe ₂ O ₃	-.77	6.62	9.66
FeO	.30	12.2	-10.6
MnO	-.01	.34	.16
MgO	-.42	8.41	-3.22
CaO	.36	12.6	3.92
Na ₂ O	3.78	3.85	-7.42
K ₂ O	4.41	-1.10	47.6
P ₂ O ₅	-.01	.49	2.23

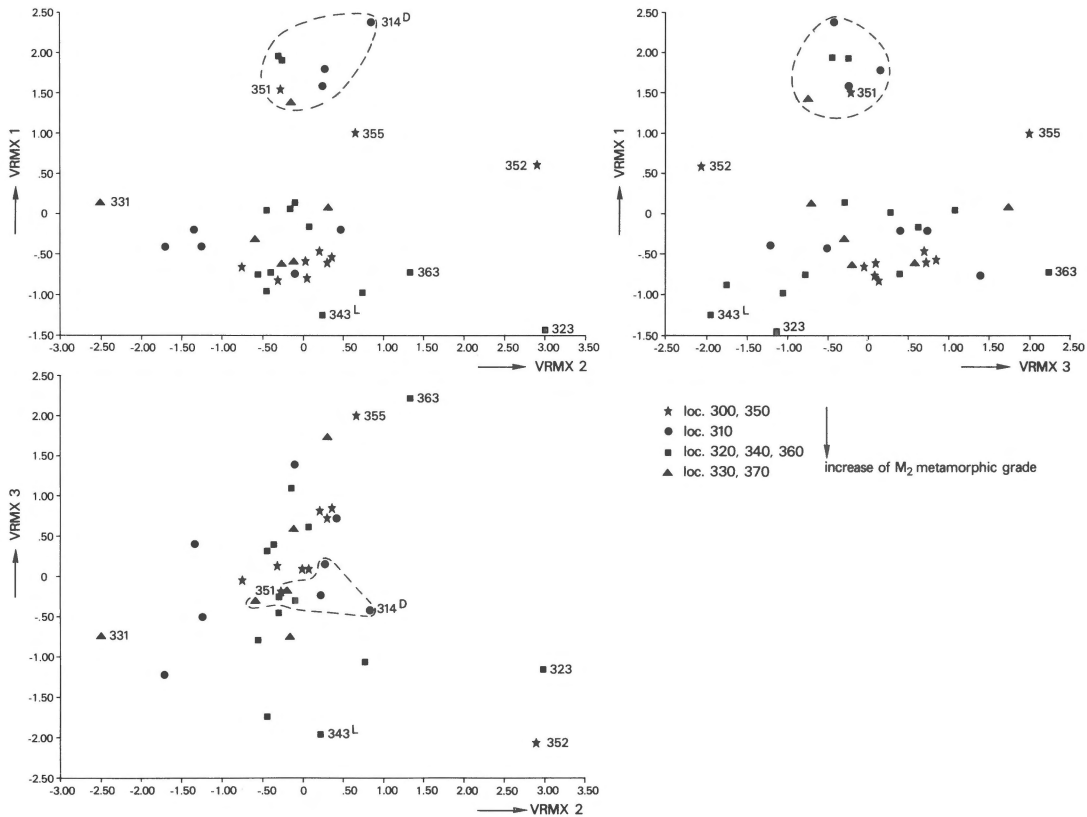


Fig. 3. R-mode, three factor model. The samples are plotted against the different combinations of the VRMX axes. The dashed boundary outlines the field of the melanocratic samples.

Melanocratic samples

Eight melanocratic, amphibolitic/noritic samples (314D, 315, 316D, 322, 324, 333, 351, and the meta-sedimentary hedenbergite-bearing 352) are unequivocally recognized through R- and extended Q-mode component analysis. Samples 343 and 344, which were petrographically classified as melanocratic samples, chemically belong to the leucocratic group of samples. The results of both types of factor analysis show that the melanocratic samples are rather constant in composition. This is supported by their basic statistics, summarized in Table 6.

Leucocratic samples

Table 7 summarizes the basic statistics of the leuco-

cratic samples. This group of samples is clearly less homogeneous than the melanocratic group (Figs. 3 and 4). A Q-mode three factor model (extended Q-mode, same standardization and similarity measure as for all samples) satisfactorily describes this subset of the data, accounting for 90.8% of the variance. Mn, Na and Fe⁽³⁺⁾ are only for a small part included in the model. The variation in Mn, however, for this group of samples, equals its analytical precision (as shown in Table 2) and is therefore of no significance for the petrogenetic interpretation.

Table 8 gives the VRMX composition scores matrix; in Fig. 5 the model is graphically represented. VRMX3 seems to be mainly composed of silica and feldspar components, it represents a granitic end-member. VRMX2 clearly represents a more melanocratic sample with less Si, more Fe⁽²⁺⁾, Mg, Ca and Ti. VRMX1 is very rich in K and Al and

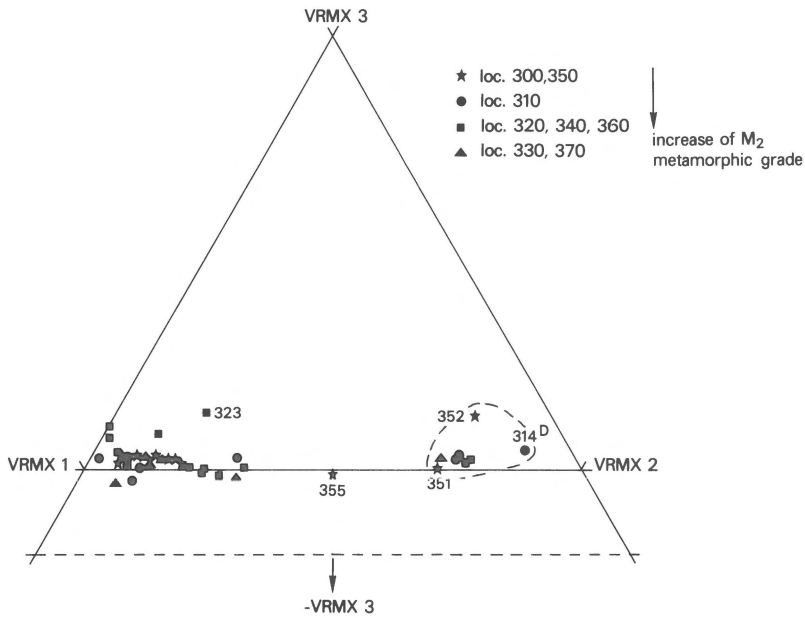


Fig. 4. Q-mode, all samples, three factor model. The samples are plotted in an extended triangle with the three VRMX composition scores at the apices. The dashed boundary outlines the field of the melanocratic samples.

could represent a K-feldspar-granitic sample or be the result of K-metasomatism. It also reflects oxidation by the relatively high $\text{Fe}^{(3+)}$ value and negative $\text{Fe}^{(2+)}$. All samples cluster near the granitic VRMX3, the cluster stretching mainly in the direction of the melanocratic VRMX2 (Fig. 5). Apart from possibly sample 323, the samples show a con-

tinuous trend and no obvious division into subgroups is visible. The compositional trend is not related to the variation in distance from the Bjerkreim-Sokndal lopolith; it is present at almost every sample location, independent of metamorphic grade.

Table 6. Basic statistics for the melanocratic samples, 352 excluded (in weight percent). Average values of tholeiitic basalts are given for comparison (Wedepohl, 1969).

	Mean	Standard deviation	Range	Tholeiitic basalt
SiO_2	47.5	2.5	42.7–49.5	50.83
TiO_2	2.26	1.15	1.19–4.68	2.03
Al_2O_3	15.0	.58	14.4–15.8	14.07
Fe_2O_3	4.80	1.48	2.80–6.20	2.88
FeO	8.87	1.68	7.08–12.3	9.00
MnO	.25	.05	.19–.31	.18
MgO	6.50	0.94	5.23–8.11	6.34
CaO	8.68	1.02	7.10–9.80	10.42
Na_2O	3.34	.20	2.95–3.63	2.23
K_2O	1.13	.32	.67–1.54	.82
P_2O_5	.35	.27	.15–.92	.23
LOI	1.24	.30	.97–1.88	.91 (H_2O)

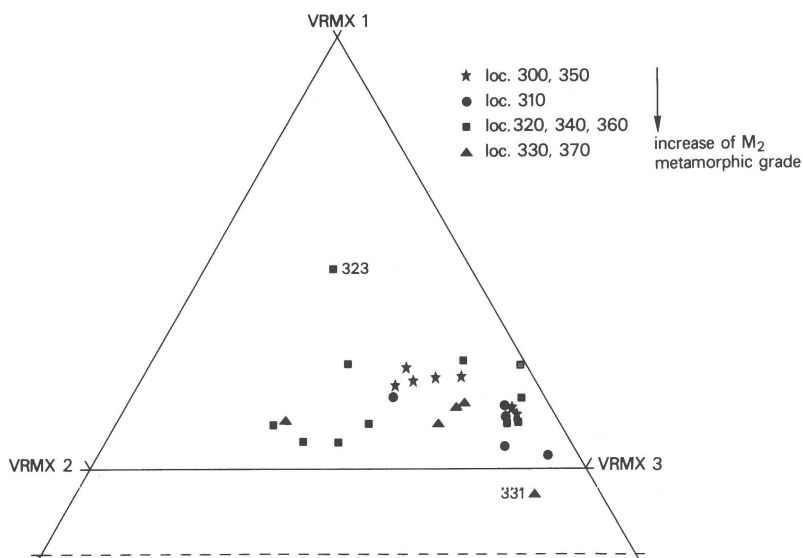


Fig. 5. Q-mode, leucocratic samples, three factor model. The samples are plotted in an extended triangle with the three VRMX composition scores at the apices.

Discussion and interpretation

Petrographic and structural evidence of anatexis is observed in the field. Indeed migmatization may explain the compositional trend in the leucocratic samples. Anatexis provides melts enriched in magmatophile elements (leucocratic samples-VRMX3) and residues enriched in mafic elements, restites being enderbitic/tonalitic in most cases

Table 7. Basic statistics for the leucocratic samples (in weight percent).

	Mean	Standard deviation	Range
SiO ₂	70.6	4.7	61.7–79.2
TiO ₂	.28	.20	.01–.72
Al ₂ O ₃	14.6	1.5	10.6–17.9
Fe ₂ O ₃	.39	.32	.01–1.17
FeO	1.83	1.53	.32–5.65
MnO	.03	.02	.01–.10
MgO	.82	.77	.05–2.79
CaO	2.13	1.10	.61–5.36
Na ₂ O	3.56	.61	2.30–4.89
K ₂ O	4.50	2.04	1.01–9.86
P ₂ O ₅	.11	.15	.01–.72
LOI	.72	.54	.23–2.98

(leucocratic samples-VRMX2), alkalifeldspar-charnockitic/-granitic in some cases (leucocratic samples-VRMX1). Rocks which have a near-minimum melt composition are likely to melt first. Samples 371 and 372, of a homogeneous, massif charnockite body (Schreurs, 1981) appear to have this composition as they plot in the centre of Winkler's (1979) field (in the Qz-Ab-Or diagram) of experimentally produced anatectic melts. An origin as a

Table 8. Q-mode, leucocratic samples, VRMX composition scores matrix. The composition scores approach endmembers of the data set. Negative values are due to the constraint of orthogonality of the factors.

	VRMX 1	VRMX 2	VRMX 3
SiO ₂	51.5	56.8	81.2
TiO ₂	-.15	1.40	.03
Al ₂ O ₃	24.9	17.6	11.4
Fe ₂ O ₃	1.85	.59	.01
FeO	-2.95	9.72	.22
MnO	.02	.13	.02
MgO	-.35	4.21	-.16
CaO	-1.52	7.45	1.16
Na ₂ O	3.13	5.46	3.10
K ₂ O	22.8	-3.64	3.09
P ₂ O ₅	.78	.22	-.08

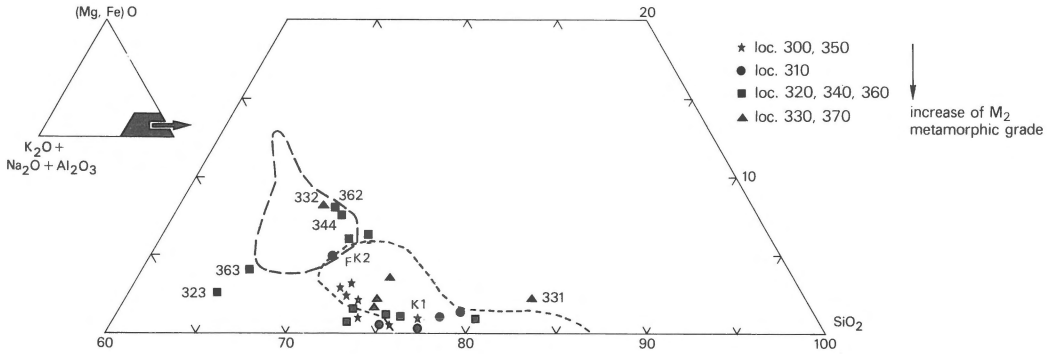


Fig. 6. The leucocratic sample plotted in a SiO_2 versus $(\text{FeO} + \text{MgO})$ versus $(\text{K}_2\text{O} + \text{Na}_2\text{O} + \text{Al}_2\text{O}_3)$ triangle. The dashed boundaries outline an upper-left charnockite field and a lower-right granite field after Wendlandt (1981). K1, K2 and F indicate the composition of the intrusive Kleivan biotite-granite, Kleivan hornblende/pyroxene-granite and Farsund charnockite respectively (after Petersen, 1980).

mobilised melt is thus likely. However, it is important to note that the anatectic trend is observed within the leucocratic samples of nearly each individual sampled outcrop. This defines the scale of the anatectic redistribution. The relative immobility of the melts is also evidenced by the in situ, only semi-intrusive character of the charnockite body of location PG 370.

The investigated leucocratic granulite facies rocks show no significant evidence of depletion with reference to their major element chemistry. The results of factor analysis do not indicate any difference in chemistry between the amphibolite facies leucocratic rocks (granites s.l.) and the granulite facies leucocratic rocks (charnockites s.l.). Compared to Wendlandt (1981), who distinguished granites from charnockites in a SiO_2 vs. $\text{MgO} + \text{FeO}$ vs. $\text{K}_2\text{O} + \text{Na}_2\text{O} + \text{Al}_2\text{O}_3$ triangle, both amphibolite facies and granulite facies rocks from this investigation plot mainly in his 'granite' field (Fig. 6). Also in this figure no general trend related to metamorphic grade is indicated. Only a few enderbitic/leuco-noritic samples, which were interpreted as being restites, plot within the 'charnockite' field (Fig. 6).

Samples 371 and 372 of the semi-intrusive charnockite body plot almost in the centre of the 'granite' field, near the position of the intrusive Kleivan biotite-granite (Petersen, 1980). The intrusive Farsund charnockite and Kleivan hornblende- and pyroxene-granite plot near the transition of the

'granite' to the 'charnockite' field. The analogy with these intrusive rocks further supports an anatectic origin for the investigated charnockitic and granitic rocks and is also not in favour of depletion of magmatophile elements.

Chemical differences between locations appear either to be primary, or to result from processes other than migmatization, such as metasomatism which apparently followed or accompanied migmatization. The effects of silica metasomatism can be observed in the field and several R- and Q-mode factors point to a (re)distribution of elements as a result of Si, K and/or Na-metasomatism. Some K-feldspar-rich samples are coarse-grained (311L, 343L, 353) which is not in favour of an origin as a restite. Coarse microcline crystals also appear in the deviating sample 323. These rocks might result from progressive melting of originally K-feldspar-rich rocks or, in the light of the various VRMX factors, have a metasomatic or pegmatite-like origin. No systematics, relating metasomatism to metamorphic grade or otherwise to the spatial distribution of the outcrops, could be detected.

The differences between the sample locations are generally small. The individual outcrops cannot readily be distinguished on the basis of the chemistry of the leucocratic samples. Even augengneisses (location PG 300) show no significant deviation.

The amphibolitic/noritic samples are a chemically quite distinct and homogeneous group. They are not regarded as restites for several reasons.

Chemically the melanocratic samples show no evidence of anatexis. A continuous trend from light to dark samples rather than a sharp separation into two groups might be expected (Price, 1983). Also a greater restite variability for samples coming from such a large area is more probable. The formation of restites with such a homogeneous basic composition is only possible by subtraction of high and equal amounts of melt of a similar rock in the whole region, which is quite unlikely. Furthermore, no hydrous minerals would be left in a restite, as all the H₂O would be used for anatexis. In fact biotite and amphibole are still present. Most probably these rocks still have primary compositions. The similarity with basaltic compositions (Table 6) is noteworthy.

Conclusions

In accordance with field and petrological evidence, the sample set is divided into melanocratic (amphibolitic/noritic) and leucocratic samples. The melanocratic samples resemble basalts chemically. An origin as restites is considered unlikely. There is textural and chemical evidence of anatexis in the leucocratic group. Component analysis applied to this group of samples provides an enderbitic/tonalitic factor corresponding to melt residues and a granitic factor corresponding to a molten fraction. Anatexis was restricted to the leucocratic rocks.

Regarding the intimate association of the amphibolitic/noritic rocks (basaltic composition) with the leucocratic granitic/charnockitic rocks and the presence of interbedded meta-pelites and -marbles, the rock sequence is best explained by assuming a supracrustal origin as a volcanic-sedimentary series. The leucocratic rocks could represent metamorphosed and migmatized acid volcanic rocks (e.g. tuffs, rhyolites). A sedimentary origin of the rocks, however, cannot be excluded on the basis of the present data.

Comparison of the amphibolite facies rocks in the east with the granulite facies rocks in the west does not reveal significant differences in major element chemistry. No systematic relation of major element chemistry to metamorphic grade (distance

to the lopolith of Bjerkreim-Sokndal) was found. The chemical variability is virtually the same for each individual outcrop. The major element chemistry provides evidence against depletion of the granulite facies region.

Acknowledgements

Our thanks are due to N. Willemsen for his cooperation in the field and the laboratory. A. T. Miesch is thanked for his kind supply of the computer program and relevant literature. M. Barton is sincerely thanked for critically reviewing earlier versions of this manuscript.

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