

Major element chemistry of Precambrian dolerite dikes of tholeiitic composition from Rogaland/Vest Agder, SW Norway

G. J. VENHUIS & MICHAEL BARTON

Venhuis, G. J. & Barton, M.: Major element chemistry of Precambrian dolerite dikes of tholeiitic composition from Rogaland/Vest Agder, SW Norway. *Norsk Geologisk Tidsskrift*, Vol. 66, pp. 277–294. Oslo 1986. ISSN 0029-196X.

The Egersund dike swarm was emplaced in the Precambrian terrain of Rogaland/Vest Agder about 790 Ma. The dikes resulted from crystallization of magma of broadly tholeiitic composition. The main phenocrystal and microphenocrystal phases are olivine, plagioclase, augite and magnetite. On the basis of petrography and whole-rock chemistry, three main types of dolerite are recognized: olivine dolerites (abundant olivine phenocrysts, > 6% normative O1), dolerites (abundant augite, 2.1% normative O1–0.6% normative Q) and trachydolerites (presence of K-feldspar and apatite). The dolerites were derived from the olivine dolerites by fractional crystallization but the trachydolerites cannot be related to the other types by this process. The dikes crystallized at 1210–1196°C and P=1 atm–1 kb, and they contained 1 wt.% H₂O on intrusion. This pressure estimate, together with pressure estimates for M3 metamorphism (4.5 kb) allow uplift rates of 0.004–0.022 cm yr⁻¹ to be calculated for the metamorphic complex.

G. J. Venhuis, Department of Petrology, Institute of Earth Sciences, State University of Utrecht, Budapestlaan 4, 3854 CD Utrecht, The Netherlands.

Michael Barton, Department of Geology and Mineralogy, The Ohio State University, Columbus, Ohio 43210, U.S.A.

The Precambrian of SW Norway is dominated by large anorthositic-leuconoritic-noritic intrusive bodies and a high-grade metamorphic complex consisting of charnockitic and granitic migmatites with intercalated augengneisses and garnetiferous migmatites (Fig. 1). Field relationships (Michot & Michot 1969, Hermans et al. 1975) and petrological studies (Kars et al. 1980) indicate a complex intrusive and metamorphic history. Geochronological studies (Versteeve 1975, Priem 1980, Wielens et al. 1981) reveal that this spanned a time period of 1 b.y. Although far from complete, present knowledge indicates the following sequence of events:

- 1.5 Gyr – Intrusion of the Egersund anorthosite (Weis & Duchesne 1983).
- 1.2 Gyr – Regional upper amphibolite-lower granulite facies metamorphism, M1 (Kars et al. 1980; Wielens et al. 1981).
- 1.05–1.03 Gyr – Intrusion of the lower part of the Bjerkreim-Sokndal lopolith and granulite facies metamorphism, M2, of the surrounding metapelites (Maijer et al. 1981;

Wielens et al. 1981). The M2 stage probably represents regional-scale contact metamorphism according to isograd patterns (Fig. 1).

- 1.03–0.85 Gyr – High-grade to low-grade amphibolite facies, M3, metamorphism related to regional cooling of the complex (Maijer et al. 1981). During this period, the mineral assemblages in the intrusives experienced retrograde metamorphism and re-equilibration (Barton & Van Gaans, in preparation; Voncken & Barton, in preparation).
- 0.56–0.44 Gyr – Low-grade (prehnite-pumpellyite facies) metamorphic event related to Caledonian overthrusting (Maijer 1980).

Previous workers have concentrated their efforts on the large igneous bodies or on the metamorphic complex. However, a number of smaller intrusives occur in the region and these are currently being studied in detail by Barton and co-workers. The Hunnedalen dikes and the intru-

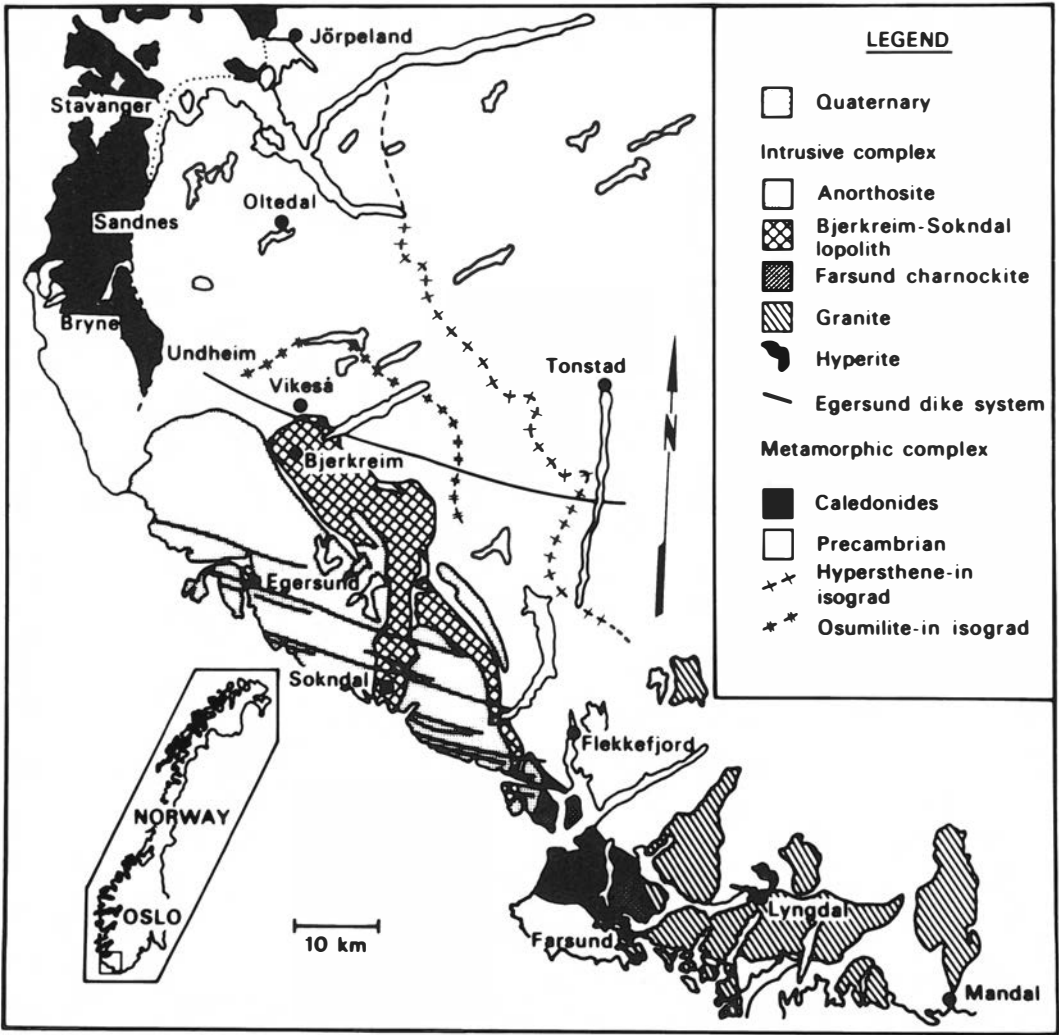


Fig. 1. Geologic map of Rogaland/Vest Agder showing the distribution of the major rock types and the location of some of the Egersund dikes. Other dikes occur but have not been mapped in sufficient detail to be included on the map. The positions of the hypersthene-in and osumilite-in isograds are taken from Hermans *et al.* (1975) and Maijer *et al.* (1981).

sives near Lyngdal are gabbroic-noritic in composition and were probably emplaced during or shortly after the M3 event as they are relatively coarse-grained, implying crystallization at depth, and show evidence of significant interaction with the country rock. Specifically, amphibolitization and retrogressive re-equilibration of mineral assemblages in some of these intrusive rocks indicate that the country rocks were warm at the time of intrusion and that fluids (especially H₂O) gained access shortly after solidification. K-Ar ages for the Hunnedalen dikes are ~ 900 m.y. (Versteve 1975) and support this conclusion.

The Egersund dikes, which are the subject of this paper, seem to have been intruded at a later date as they are relatively fine-grained and have well-defined chilled margins (see also Poorter 1972). Moreover, they are compositionally different from the earlier intrusives and hence appear to represent a significant change in the type of magmatic activity in SW Norway. We present major element whole-rock and mineral chemical data for these dikes and make a preliminary assessment of the conditions of crystallization and of the processes involved in the evolution of the magmas.

Occurrence and age

The distribution of the major dikes of the Egersund swarm was established by Antun (1956) and is shown in Fig. 1. Our field studies indicate that there are many more dikes than shown on Fig. 1, but we do not have sufficient data to plot these accurately on the map.

The dikes in the swarm trend N70°W. The maximum distance over which an individual dike is traceable is 60 km, though as exposures are generally poor, this may be an underestimate. Antun (1956) reports that the thickness of the dikes varies from 2.5 m–30 m, but we have observed some which are only c. 30 cm wide. Usually, the dikes occur in valleys (hence the poor exposure) and were probably emplaced along or parallel to a major fracture system.

Large (up to 1 cm) phenocrysts of plagioclase are commonly observed in the centres of the dikes, whereas the margins are mostly extremely fine-grained (aphyric) and make well defined, sharp contacts with the country rocks. Relatively large phenocrysts are found in the centres of even the thinnest dikes which suggests that crystallization was initiated prior to intrusion at the presently exposed erosion levels. Phenocryst phases other than plagioclase have not been observed in hand specimen, though spherical patches of sulfides occur in dikes to the south-east of Sokndal. In general, crustal xenoliths are rare in the swarm as a whole, but they are abundant in exposures of the 60 km long dike between Vikeså and Undheim; here, they comprise 30–50% of individual exposures.

Previous workers have suggested a late Precambrian age for the dikes based upon paleomagnetic (Storetvedt & Gidskehaug 1968, Poorter 1972) or K-Ar (Verstevee 1975) data. The latter worker reported a single age determination of 663 m.y. As noted by Barton & Van Bergen (1984), the dikes cut all other Precambrian formations, implying an age < 850 m.y., but have been affected by the Caledonian metamorphic event. Some previously unpublished K-Ar age determinations by F. J. Fitch have been kindly made available to us recently by Dr. K. M. Storetvedt. Ages range from 572 ± 7 m.y. to 792 ± 19 m.y. and correlate with the degree of alteration observed petrographically. The oldest age is the closest estimate of the true age of intrusion because it was obtained from a fresh sample.

Petrography

The dikes can be divided into three main groups on the basis of petrography:

1. Those rich in olivine phenocrysts
2. Those with rare or with no olivine phenocrysts
3. Those relatively rich in apatite and which contain K-feldspar

Hereafter, these groups will be referred to as olivine dolerites, dolerites and trachydolerites respectively (cf. Antun 1956).

The *olivine dolerites* contain euhedral to subhedral phenocrysts of olivine (up to 2 mm) and plagioclase (up to 1 cm) set in a finer-grained matrix which contains augite, plagioclase, olivine, Fe-Ti oxides and minor apatite. The augite and plagioclase form sub-ophitic intergrowths whereas the Fe-Ti oxides commonly, though not exclusively, occur as small (< 100 μ m) skeletal crystals. Olivine, plagioclase and augite are zoned and the latter mineral, in particular, may show complex zoning patterns with oscillatory zoning superimposed upon normal concentric zoning. Towards the margins of the dikes, the matrix becomes progressively finer-grained until at the margin euhedral microphenocrysts of olivine and plagioclase (\pm rare augite) are set in a microcrystalline or cryptocrystalline groundmass. In rare cases, the microphenocrysts are set in a clear, brown-colored glass. Olivine microphenocrysts with a hopper morphology are not uncommon in the chilled margins.

The *dolerites* differ from the olivine dolerites in that olivine is rare or absent and augite is more abundant. In the centres of the dikes, both plagioclase and augite (\pm olivine) occur as phenocrysts and these minerals occur in the matrix together with microphenocrysts and skeletal crystals of magnetite and minor apatite. Quartz occurs sporadically as an interstitial phase. In the chilled margins, plagioclase, augite, magnetite and rare olivine form euhedral microphenocrysts in a cryptocrystalline or glassy groundmass. The augite in these rocks (commonly also in the olivine dolerites) is slightly pleochroic in shades of purple implying a significant Ti-content. The augite microphenocrysts in the chilled margins occasionally show sector zoning.

The *trachydolerites* contain, in addition to the minerals mentioned above, interstitial K-feldspar

Table 1. Summary of main petrographic characteristics of the Egersund dikes.

Rock-type	Olivine-dolerite	Dolerite	Trachydolerite
Olivine	P	(P)	P
Plagioclase	P	P	P
Augite	(P)	P	P
Ti-magnetite ilmenite	G	G	P
K-feldspar	—	—	G
Apatite	—	—	G

P – phenocryst phase; G – groundmass/microphenocryst phase; Parentheses indicate a phase is present sporadically or is not abundant.

and small flakes of biotite. Needles of apatite are abundant in the matrix in the centres of the dikes.

The major petrographic characteristics of the dikes are summarized in Table 1. Other minerals, which were clearly out of equilibrium with the host magmas at the time of intrusion, also occur and are interpreted to be xenocrysts or to result from interaction of the melt and entrained xenoliths.

Xenocrysts of *quartz*, *albitic plagioclase*, *K-feldspar*, *apatite* and *zircon* are inevitably strongly resorbed and are clearly derived from disaggregated xenoliths or from the wall rocks; they are most abundant in the chilled margins or in the vicinity of xenoliths. The cores of relatively *calcic plagioclase* megacrysts show resorption effects but are mantled by unresorbed plagioclase and are interpreted to have formed during a stage of high-pressure crystallization. To date, we have found no petrographic or mineralogic evidence for magma mixing, such as was described by Barton et al. (1982).

The xenoliths have the mineralogy of *charnockitic* and *granitic granulites*. The dolerites show a change in petrographic character in their vicinity. Amphibole becomes abundant, the amount of olivine decreases, and quartz and hypersthene occur in the matrix. Mineral grains (xenocrysts) have been liberated from the margins of the xenoliths and melt from the dolerite has penetrated along grain boundaries etc., into the xenoliths.

An unusual feature of the dike-swarm is the presence of spherical aggregates of grains of carbonate or carbonate and quartz. In the latter case, the quartz always occurs at the centre of the aggregate (Fig. 2a). There is a tendency for the aggregates to be partially surrounded by tangentially arranged laths of plagioclase (Fig. 2b). Carbonates also occur in irregularly shaped patches

between the augite and plagioclase in the matrix. At first sight, the spherical aggregates appear to be similar to the ocelli commonly observed in alkaline igneous rocks (lamprophyres, kimberlites, damtjernites, etc.) which have in some cases been interpreted to represent quenched droplets of immiscible carbonate melt. We argue in a later

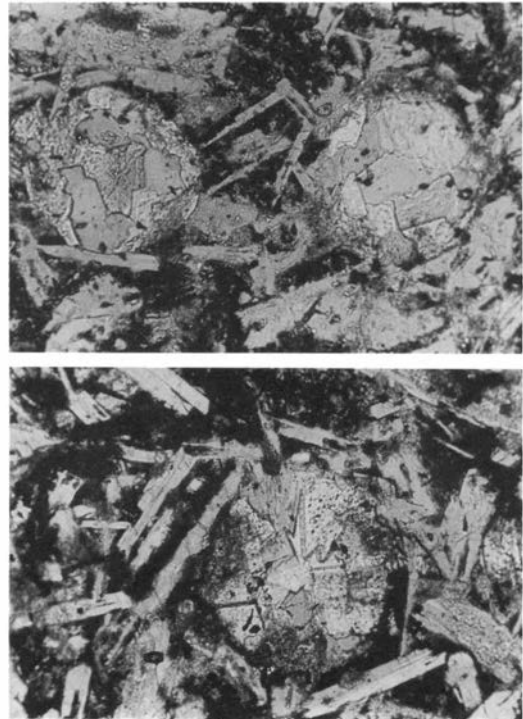


Fig. 2. a: Spherical aggregates of carbonate (mainly calcite) and quartz. Width of aggregates-0.3 mm. Note also the skeletal opaques (Fe-Ti oxides). b: Approximately spherical aggregate of carbonate (dolomite-ankerite) and quartz partially surrounded by tangentially arranged laths of plagioclase. Width of aggregate – 0.6 mm.

section of the paper, however, that the spherical aggregates in the Egersund dikes are secondary and do not represent carbonate melt.

Most dikes have been affected to a greater or lesser extent by hydrothermal alteration. The effects have been described in some detail by Barton & Van Bergen (1984) and only a brief summary is given here. Olivines are commonly partially, or even completely (especially in the dolerites), pseudomorphed by serpentine, iddingsite, cummingtonite and carbonate. Plagioclase shows varying degrees of alteration to sericite, ilmenite

to leucoxene and magnetite to fine-grained, indeterminate opaque material. Augite may be partially or completely replaced by actinolite. Other minerals which are ascribed to hydrothermal alteration include chlorite, green mica, prehnite and epidote. The latter two minerals occur only in the vicinity of veins which transect the dike/country-rock contact and contain also carbonate and quartz. Textural data suggest that the sulfides, which form spherical aggregates, are secondary as is the relatively rare mineral, ilvaite (Barton & Van Bergen 1984).

Table 2. Whole-rock chemical analyses and CIPW norms of representative samples of Egersund dikes.

Sample No.	Olivine dolerite		Dolerite		Trachydolerite	
	800526	800548	800589	800515	800517	800519
SiO ₂	48.02	47.10	48.40	49.86	45.32	46.13
Al ₂ O ₃	16.66	17.71	15.59	15.50	13.98	14.26
TiO ₂	2.03	1.51	2.42	2.01	3.16	3.08
Fe ₂ O ₃	1.78	1.51	2.02	1.83	2.22	2.45
FeO	9.08	7.71	10.31	9.35	11.31	12.51
MnO	0.16	0.07	0.12	0.12	0.17	0.17
MgO	7.63	7.40	6.09	5.79	4.29	4.59
CaO	10.24	10.54	9.67	8.98	7.29	8.03
Na ₂ O	2.64	2.60	2.85	2.86	3.55	3.60
K ₂ O	0.51	0.46	0.58	0.86	2.17	1.94
P ₂ O ₅	0.25	0.27	0.39	0.34	2.66	2.58
CO ₂	n.a.	0.78	0.25	0.85	1.42	0.21
H ₂ O ⁺	n.a.	1.58	1.34	1.03	0.65	0.51
Total	99.00	99.24	100.03	99.38	98.19	100.03
Mg#	0.56	0.59	0.47	0.49	0.37	0.36
Q	—	—	—	0.6	—	—
or	3.0	2.8	3.5	5.2	13.3	11.5
ab	22.6	22.7	24.5	24.8	31.3	30.7
an	32.4	36.4	28.5	27.6	16.4	17.1
di-wo	7.2	6.6	7.4	6.6	1.3	2.5
di-en	4.2	4.0	3.8	3.4	0.6	1.0
di-fs	2.7	2.3	3.4	3.0	0.7	1.5
hy-en	6.5	5.1	8.6	11.4	3.8	2.2
hy-fs	4.2	2.9	7.7	9.9	5.0	3.2
ol-fo	6.0	7.0	2.1	—	4.7	5.8
ol-fa	4.2	4.4	2.1	—	6.9	9.0
mt	2.6	2.3	3.0	2.7	3.3	3.6
il	3.9	3.0	4.7	3.9	6.2	5.9
ap	0.6	0.7	0.9	0.8	6.6	6.2
Total	100.1	100.2	100.2	99.9	100.1	100.2

Footnotes:

- 1) All analyses performed by classical wet-chemical techniques except 800526 (XRF).
- 2) Fe₂O₃ = 0.15 FeOT.
- 3) Mg # = Mg/(Mg + ΣFe²⁺).
- 4) CIPW norms calculated on a volatile-free basis.

Table 3. Calculated and measured Fe₂O₃ and FeO contents of the dolerites.

Sample No.	800548	800589	800515	800517	800519
FeO total	9.07	12.27	11.10	13.29	14.70
Fe ₂ O ₃ calc.	1.51	2.02	1.83	2.22	2.45
FeO calc.	7.71	10.31	9.35	11.31	12.51
Fe ₂ O ₃ Meas.	1.74	2.85	2.28	4.38	3.22
FeO Meas.	7.54	9.57	8.95	9.36	11.82

Footnotes:
 Fe₂O₃ and FeO calculated from the relationship.
 Fe₂O₃ = 0.15 FeO (Total) (Brooks 1976).

Whole-rock analyses

Whole-rock samples were analysed by classical wet chemical techniques with the exception of one sample which was analysed by XRF. A representative set of analyses, together with CIPW norms, is presented in Table 2. These analyses were chosen to show the complete range of variation displayed by the Egersund dike swarm. CIPW norms were calculated on a volatile-free basis with Fe₂O₃ normalized to 0.15 FeO total (see Brooks, 1976), but in many cases measured Fe₂O₃ contents are very similar to the calculated Fe₂O₃ contents (Table 3) suggesting minimal post-emplacement oxidation. This is surprising in view of the high H₂O and CO₂ contents relative to MORB and evidence for minor but important hydrothermal alteration (Barton & Van Bergen 1984; also see later discussion on the origin of the carbonates in the dikes).

SiO₂ varies from 45.3–49.9 wt.%, indicating the basaltic character of the dikes. Hermans et al. (1975) considered that the dikes crystallized from alkali-basaltic magmas on the basis of comparison of Antun's (1956) analyses with the total alkalis versus SiO₂ classification scheme of Kuno (1966). This scheme, and others based upon similar plots, is singularly unsuitable for the classification of non-orogenic magmas. Indeed, all of the Egersund dikes are hy-normative and, following the definition of Shand (1922), they are thus sub-alkaline, or tholeiitic (Fig. 3). The analyses clearly plot in the tholeiitic field in the AFM diagram (Fig. 4).

The three types of dolerite distinguished on the basis of petrographic observations can also be identified from normative mineralogy. The olivine dolerites contain > 6% OI, the dolerites contain 2.1% OI–0.6% Q and the trachydolerites contain > 11% K-spar and ~ 5% Ap. In terms of Mg/(Mg + ΣFe²⁺) – total iron calculated as FeO –

the olivine dolerites represent the least evolved, and the trachydolerites the most evolved magmas. However, the relatively low Mg/(Mg + ΣFe²⁺) ratios of the dolerites (<0.59) indicate that none represent a primary, upper mantle derived magma.

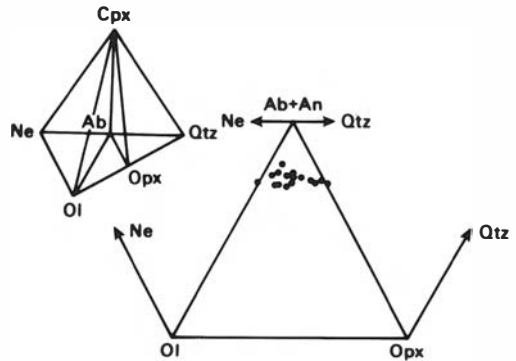


Fig. 3. CIPW normative compositions of the dikes projected from clinopyroxene onto the basal plane of the basalt tetrahedron (Yoder & Tilley 1962). The analysis plotting just in the triangle Ne-OI-Plag is from Antun (1956) and is of a trachydolerite.

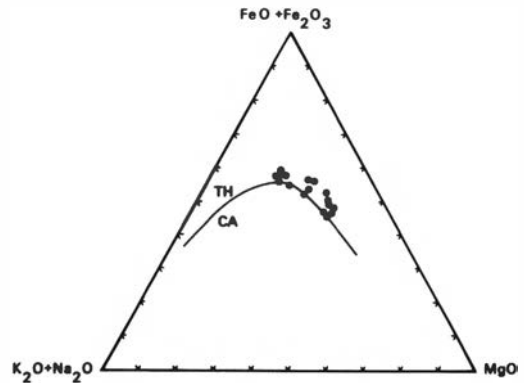


Fig. 4. Chemical compositions of the dikes plotted on an AFM diagram.

The relatively high CO₂ and H₂O contents can be ascribed to the effects of alteration (cf Barton & Van Bergen 1984). The similarity in the composition of the centre and margin of a single dike suggests, however, that other major oxides have not been significantly affected by the alteration process.

Mineral chemistry

The minerals were analyzed by electron microprobe using the techniques described by Huijsmans et al. (1982). Representative analyses are presented in Tables 4 to 7. Analyses of actinolite, cummingtonite, chlorite, biotite, epidote, prehnite, ilvaite and carbonate have been presented by Barton & Van Bergen (1984), and are not considered further here.

Plagioclase shows a wide range of composition (An₈₀-An₃₄). Phenocryst phases in individual dikes show both normal and oscillatory zoning, and there is a general tendency for the average anorthite contents of the phenocrysts to decrease with decreasing Mg/(Mg + ΣFe²⁺) ratio of the host

rock. K₂O contents are mostly low (<1.7 wt.%), as shown in Fig. 5.

Olivine shows limited zoning (Fo₈₃-Fo₇₅) and a relatively restricted range of composition in the dike system as a whole (Fo₈₃Fo₅₈). NiO, CaO and MnO contents are low.

The *augites* show significant variations in Mg/(Mg + ΣFe²⁺) (Fig. 6) and these correlate, in general, with whole-rock composition. They contain substantial amounts of TiO₂ (0.2-2.7 wt.%) and Al₂O₃ (1.2-5.9 wt.%), characteristics usually associated with clinopyroxenes in alkaline lavas rather than tholeiites (Carmichael et al. 1974). We attribute the high Ti and Al contents to relatively fast cooling rates. Walker et al. (1976) and Gamble & Taylor (1980) have shown that more Ti and Al are incorporated into augites crystallized from sub-alkaline magmas at relatively high cooling rates, and evidence for rapid cooling of the Egersund dikes is afforded by a) the presence of chilled margins which may contain glass; b) the occurrence of skeletal crystals of opaque and c) the occurrence of sector zoning in the augites. Na₂O and Fe₂O₃ (calculated by assuming that S cations = 4.000 on a 6 oxygen basis) contents are low (< 0.7 and < 2.0 wt.% respectively).

Table 4. Representative microprobe analyses of plagioclase.

Sample No.	800526			800589			800517		
	Core	Rim	Micro	Core	Rim	Micro	Core	Rim	Micro
SiO ₂	47.70	49.95	53.65	52.30	53.30	55.48	54.62	56.27	59.65
Al ₂ O ₃	32.45	31.05	27.85	29.15	28.05	27.25	28.43	26.80	24.30
Fe ₂ O ₃	0.40	0.45	0.85	0.49	0.88	0.68	0.45	0.57	0.69
MgO	0.15	0.20	0.29	-	-	-	-	-	-
CaO	16.59	14.89	11.30	12.65	11.50	10.50	10.89	9.68	7.23
Na ₂ O	2.25	2.89	5.05	4.10	4.75	5.55	4.82	5.49	6.20
K ₂ O	0.05	0.10	0.25	0.25	0.29	0.40	0.67	0.88	1.66
Total	99.59	99.53	99.24	98.94	98.77	99.86	99.88	99.69	99.73
Si	2.200	2.341	2.451	2.399	2.446	2.510	2.472	2.545	2.675
Al	1.764	1.715	1.500	1.576	1.517	1.453	1.517	1.429	1.284
Fe ³⁺	0.014	0.016	0.029	0.017	0.031	0.024	0.015	0.020	0.023
Mg	0.010	0.016	0.020	-	-	-	-	-	-
Ca	0.820	0.568	0.553	0.662	0.565	0.508	0.527	0.470	0.348
Na	0.201	0.262	0.447	0.365	0.425	0.489	0.424	0.484	0.587
K	0.003	0.015	0.015	0.015	0.017	0.022	0.038	0.049	0.097
Total	5.012	4.933	5.015	5.034	5.001	5.006	4.993	4.997	5.014
An	0.801	0.672	0.545	0.635	0.561	0.499	0.533	0.469	0.337
Ab	0.196	0.310	0.440	0.350	0.422	0.480	0.429	0.483	0.569
Or	0.003	0.018	0.015	0.014	0.017	0.022	0.038	0.049	0.094

*Total iron as Fe₂O₃

Core = core of phenocryst; Rim = rim of phenocryst; micro = microphenocryst.

Table 5. Representative microprobe analyses of olivine.

Sample No.	Core	800526 Rim	Micro	800589 *	Core	800517 Rim**
SiO ₂	39.40	39.25	38.19	38.00	36.93	35.94
FeO	16.55	18.80	21.28	22.64	31.98	35.50
MnO	0.20	0.20	0.29	0.25	0.50	0.60
MgO	43.75	41.85	39.90	38.85	30.73	27.94
NiO	0.15	0.11	0.10	—	—	—
CaO	0.25	0.25	0.25	0.25	0.29	0.28
Total	100.30	100.46	100.01	99.99	100.43	100.26
Si	0.995	0.999	0.991	0.991	1.004	0.998
Fe ²⁺	0.350	0.401	0.461	0.494	0.727	0.824
Mn	0.004	0.005	0.006	0.006	0.011	0.013
Mg	1.647	1.588	1.543	1.511	1.245	1.157
Ni	0.003	0.002	0.002	—	—	—
Ca	0.007	0.006	0.006	0.006	0.008	0.008
Total	3.006	3.001	3.009	3.008	2.995	3.000
Mol%						
Fo	0.825	0.798	0.770	0.754	0.631	0.584
Fa	0.175	0.202	0.230	0.246	0.369	0.416

* Phenocrysts usually altered. No significant zoning observed.

** Range encompasses the composition of the microphenocrysts. Other abbreviations as in Table 4.

Nearly all dikes contain both *ilmenite* and *magnetite*. Textural features suggest that these minerals for the most part crystallized relatively late, after the primary silicate minerals. Magnetite contains 1.8–3.0 wt.% Al₂O₃ and up to 1.2% ZnO. Reconnaissance studies of the *sulfides* indicate that in most cases they are close to pyrite in composition though a considerable amount (~ 1 wt.%) Co was found in a few samples.

Effects of alteration

As noted above, alteration has affected the centres of many of the Egersund dikes but appears to have had no effect on major oxide chemistry apart from addition of H₂O and CO₂ (see also below). In general, alteration does not seem to have affected the chemistry of the primary (i.e. magmatic) silicate and oxide minerals inasmuch as the compositions of these remain the same within a single dike regardless of the degree of alteration. This is true even though the augite and plagioclase crystals in contact with obviously secondary minerals such as ilvaite are corroded (Barton & Van Bergen 1984). Furthermore, augites which are partially replaced by ferroactino-

lite are identical in composition to fresh augites in the same rock and partial replacement of olivine by serpentine or cummingtonite/magnesian-cummingtonite has not been accompanied by a change in olivine composition. We thus conclude that the compositions of the olivines, plagioclases, augites and Fe-Ti oxides faithfully represent those of the minerals precipitated from the

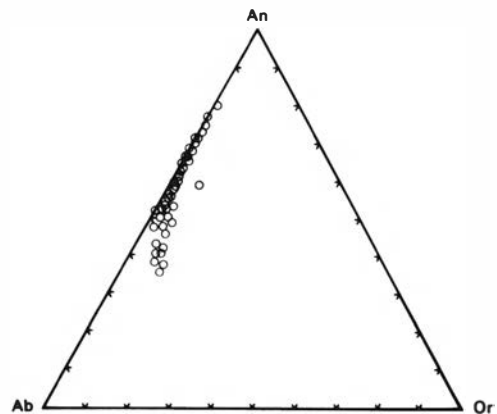


Fig. 5. Microprobe analyses of plagioclase plotted in terms of Ab-An-Or.

Table 6. Representative microprobe analyses of clinopyroxene.

Sample No.	800526		800589		800517	
	Core	Rim	Core	Rim	Core	Rim
SiO ₂	46.55	48.25	48.70	48.25	50.08	51.51
Al ₂ O ₃	5.85	4.63	5.11	4.65	2.71	1.15
TiO ₂	2.65	1.85	1.85	1.95	1.53	0.21
FeO*	11.80	10.30	10.28	12.95	14.82	18.16
MnO	0.20	0.21	0.21	0.25	0.42	0.48
MgO	12.01	14.25	13.65	13.10	10.80	11.04
CaO	20.32	19.08	18.95	18.65	19.18	17.18
Na ₂ O	0.49	0.33	0.41	0.50	0.62	0.66
Total	99.86	98.90	99.16	100.30	100.16	100.39
Si	1.772	1.830	1.837	1.824	1.910	1.975
Al	0.262	0.207	0.227	0.207	0.122	0.052
Ti	0.076	0.052	0.052	0.037	0.044	0.006
Fe ²⁺	0.375	0.326	0.324	0.409	0.477	0.583
Mn	0.007	0.007	0.007	0.009	0.014	0.016
Mg	0.682	0.806	0.769	0.738	0.614	0.631
Ca	0.828	0.775	0.766	0.756	0.784	0.705
Na	0.037	0.023	0.032	0.036	0.046	0.054
Total	4.039	4.020	4.014	4.016	4.011	4.019
Wo	0.439	0.406	0.412	0.397	0.418	0.367
En	0.362	0.423	0.414	0.388	0.327	0.329
Fs	0.199	0.171	0.174	0.215	0.254	0.304

* Total iron as FeO.

Table 7. Representative microprobe analyses of Fe-Ti oxides.

Sample No.	800526		800589		800517	
	Core	Rim	Core	Rim	Core	Rim
SiO ₂	0.10	0.31	—	—	—	—
Al ₂ O ₃	2.85	—	1.76	—	2.20	0.58
TiO ₂	19.70	42.93	20.50	46.70	11.17	44.28
V ₂ O ₃	0.60	0.47	0.42	0.21	0.24	—
FeO	71.30	55.42	71.26	49.95	80.69	53.10
MnO	0.35	0.36	0.78	1.65	0.35	0.89
MgO	0.50	—	—	—	0.37	0.28
ZnO	0.30	—	0.52	—	—	—
Total	95.70	99.49	95.24	98.71	95.02	99.13
Calculated						
Fe ₂ O ₃	25.40	19.53	25.23	10.46	44.40	16.37
FeO	48.40	37.84	48.56	40.32	40.74	38.37
Total	98.20	101.44	97.76	99.54	99.47	100.77
Mol. % ulvospinel	56.5	—	58.9	—	31.7	—
Mol. % R ₂ O ₃	—	19.0	—	10.3	—	16.5

Fe₂O₃, FeO, mol. % ulvospinel and mol. % R₂O₃ calculated following the method of Carmichael (1967).

magma at the time of intrusion. At this point it should be emphasized that, as far as possible, only the freshest samples were selected for whole-rock analysis.

Origin of the carbonates

Despite the similarity in the appearance of the spherical patches of carbonate and the ocelli in lamprophyres etc., several lines of evidence indicate that the carbonate is secondary and formed during hydrothermal alteration.

- a) The dolerites are tholeiitic, not alkaline. Observational and experimental evidence suggests that carbonate-rich melts (usually Narich) show an immiscibility relation only with strongly alkaline magmas.
- b) Carbonates also occur in veins which transect the dike-country-rock contact and which are clearly secondary. Note the association, in these veins, of carbonate, prehnite and epidote.
- c) Corrosion of augites, in particular, in the vicinity of carbonate in the matrix strongly suggests that carbonate replaces clinopyroxene.
- d) The spherical patches of carbonate are identical in appearance to spherical aggregates of actinolite. The latter formed by subsolidus replacement of augite as demonstrated by textural relationships.
- e) In some dikes, carbonate and actinolite are most abundant in the vicinity of the veins described above.
- f) $^{18}\text{O}/^{16}\text{O}$ and $^{13}\text{C}/^{12}\text{C}$ isotope ratios measured for the carbonates by G. Konert range from +9 to +12‰ and -4 to -5.4‰ respectively and are thus incompatible with a primary magmatic origin. Similar values were found for carbonates in or near hydrothermal veins and stringers which provides strong support for the proposed sub-solidus origin of the carbonates.

This conclusion may also apply to some carbonates in ocelli in some alkaline lavas. For example, carbonates from ocelli in damtjernites from the Fen Complex, which have been interpreted in terms of liquid immiscibility, have $\delta^{18}\text{O} = 11.5\%$ and $\delta^{13}\text{C} = 5\%$ (unpublished data), indicating that they are not simply magmatic in origin (see Griffin & Taylor (1975) for a discussion of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the lavas of the Fen Complex, and

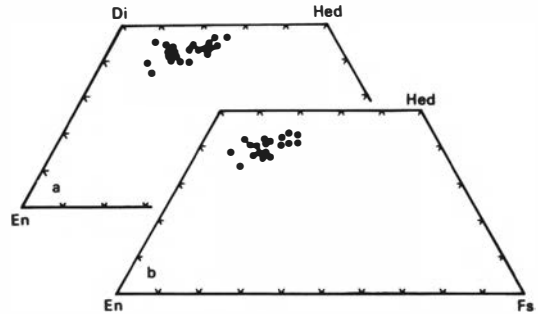


Fig. 6. Clinopyroxene compositions plotted in the conventional Ca-Mg-(Fe + Mn) quadrilateral. a: Analyses uncorrected for the presence of additional components (CaTs etc.). b: Analyses corrected for the presence of additional components.

Andersen (1984) for a discussion of the role of oxidizing fluids in the alteration of the Fen Complex carbonatites).

Barton & Van Bergen (1984) argued that the carbonates formed as replacement products of augite. They concluded that alteration of the Egersund dike system was accomplished by fluids rich in CO_2 and H_2O and that initial fluids were relatively rich in CO_2 . The fluids probably penetrated along fractures parallel to the dike swarm and some of the dikes may even have acted as channelways for fluid migration/circulation. Alteration of the dikes was related to Caledonian over-thrusting. Mineral assemblages are indicative of prehnite-pumpellyite facies conditions during the alteration.

Relationships of the different types of dolerite

The major oxide chemical and petrographic characteristics of the three main groups of dolerites are qualitatively consistent with the hypothesis that the magmas evolved via fractional crystallization. Taking olivine tholeiite to be the parental magma, it would be expected that the amount of olivine would decrease and the amount of pyroxene would increase during fractionation, as is observed in the olivine dolerites and dolerites. Incompatible oxides such as K_2O and P_2O_5 would be expected to become enriched in residual liquids as is found for the trachydolerites.

The presence of olivine phenocrysts and interstitial quartz in the same rock suggests rapid cooling of the magma (cf. petrography and mineral chemistry) and extreme fractionation on the scale

of a thin section. This has been described also for basalts from the Oceanographer Fracture Zone (Walker et al. 1979). The absence of abundant pigeonite (or hypersthene), which would be expected to develop as a result of the predicted reaction between olivine and tholeiitic magma, in the dikes is another feature in common with many abyssal tholeiites (Walker & DeLong 1982). We interpret this to indicate rapid cooling and the failure of low-Ca pyroxene to nucleate in abundance. Support for this proposal is provided by the occurrence of low-Ca pyroxene in more slowly cooled gabbroic xenoliths found in abyssal tholeiites (Walker & DeLong op. cit.). We thus do not feel justified in attributing the absence of low-Ca pyroxene phenocrysts to poorly constrained processes such as Soret separation and, interestingly, Grove & Bryan (1983) have also recently suggested that the absence of augite-pigeonite pairs in FAMOUS glasses could result from a kinetic effect imposed by rapid cooling. Evidence for rapid cooling in the case of the Egersund dikes includes the high Ti and Al contents of the augites, sector zoning of the augites, the occurrence of hopper crystals of olivine (cf. Donaldson 1976) and the presence of skeletal crystals of Fe-Ti oxide. However, the effects of cooling rate on the nucleation of low-Ca pyroxene need to be investigated in more detail.

Major oxide, least squares, mass balance tech-

niques (Bryan et al. 1969) may be used to test quantitatively the hypothesis that the different groups of dolerite are related to one another via fractional crystallization processes. The results of two sets of calculations are reported in Table 8. The first calculation demonstrates that removal of olivine, plagioclase and augite (analysed phenocryst phases) from the olivine dolerites could yield magmas with compositions corresponding to those of the dolerites. Adjustment of the compositions of the phenocrysts used in the calculation might yield a better fit between the observed and calculated residual liquid composition (note that the phenocrysts are zoned and that there is thus substantial leeway in the input parameters), but in view of the age of the dikes and the fact that they have been affected by minor hydrothermal alteration, the degree of misfit reported in Table 8 (0.1972) is believed to be entirely satisfactory. Indeed, it is well within total analytical uncertainty so that attempts to reduce the degree of misfit are of uncertain significance.

The second calculation indicates that the trachydolerites cannot be produced from the dolerites by fractional crystallization alone. The poor fit between the observed and calculated residual liquid composition cannot be ascribed to analytical errors or uncertainties and proves beyond doubt that processes other than fractional crystallization were involved in the genesis of the tra-

Table 8. Results of major oxide, least-squares, mass balance calculations.

Example 1:	Parent-800526 Daughter-800589 Phases - 01, aug, plag.	Example 2:	Parent-800589 Daughter-800517 Phases - 01, aug, plag*
	Calc. - obs. comp. of daughter		Calc. - obs. comp. of daughter
SiO ₂	-0.0873		-0.0379
TiO ₂	-0.1022		-0.1545
Al ₂ O ₃	0.1134		-0.0824
Fe ₂ O ₃	-0.2056		-0.3185
FeO	0.3233		-0.5029
MnO	-0.0488		0.0371
MgO	-0.0472		0.3287
CaO	0.0353		0.1891
Na ₂ O	-0.0983		0.4723
K ₂ O	-0.0036		0.8381
P ₂ O ₅	-0.0628		1.3134
	r ² = 0.1972		r ² = 3.1820
Proportion of daughter	= 0.7747		
olivine	= 0.0597		
augite	= 0.0254		
plagioclase	= 0.1397		

* The results of this calculation are not significantly improved if Fe-Ti oxides are included in the crystal extract.

chydolerites. It should also be noted that the fits for K_2O and P_2O_5 are especially poor, and contribute much to the misfit for the calculation as a whole.

Recent work has shown that the compositions of tholeiitic magmas may result from the interplay of several processes. In the case of some abyssal tholeiites, magma mixing (Walker et al. 1979) may operate in the subvolcanic plumbing system and could preferentially enrich hybrid magmas in incompatible elements such as K and P (O'Hara 1977, O'Hara & Matthews 1981). There is also evidence that significant chemical variations exist in the parental magmas which rise into the near-surface magma chambers (see Grove & Bryan 1983 for a summary of the evidence). These variations may reflect the effects of variable degrees of partial melting in the upper mantle or result from different amounts of high-pressure fractionation. Yet another process may be important in the determination of the chemistry of continental tholeiites: assimilation of crustal material (see, for example, Thompson et al. 1983).

A detailed discussion of the relative importance of each of these processes is beyond the scope of this paper and, in any case, must await the results of trace element and additional petrological studies which are in progress. Nevertheless, the data presented in this paper allow the following conclusions to be reached with regard to the petrogenesis of the Egersund dikes:

1. There is, as previously noted, no petrographic or mineralogic evidence for magma mixing. Comparison of the $Mg/(Mg + SFe^{2+})$ ratios, K and P contents of the different groups of dikes provides compelling evidence that the high K and P contents of the trachydolerites are not the result of mixing of the olivine dolerites and the dolerites. Although the possibility of mixing between olivine dolerite and an (as yet) unidentified end-member cannot be entirely discounted, we feel that the absence of mineralogic evidence strongly mitigates against this possibility.
2. The presence of disaggregated xenoliths of crustal material supports the hypothesis that the trachydolerites have assimilated crustal material. Studies of the mineralogic changes in the dolerites in the vicinity of the granulite xenoliths demonstrate the potency of assimilation in changing the composition of the magmas. The abundance of amphibole, in particular, indicates that volatiles may be added to the magma by assimilation (see also Henderson et al. 1984) and this may alter the course of crystallization significantly (Osborn 1959). As emphasized by Bowen (1928), assimilation will, in general, be accompanied by crystallization and the effects of these combined processes may be relatively complex. Experimental and petrological studies (Watson 1982, Van Bergen & Barton 1984) reveal that selective assimilation may be *exceedingly* complex, to the extent that the effects may be completely unpredictable in terms of conventional phase equilibria studies. It is thus impossible to disregard the potential role of assimilation in the genesis of the trachydolerites. However, the high P_2O_5 contents of these rocks are difficult to explain in terms of assimilation. The P_2O_5 contents of crustal rocks are not particularly high (cf. Thompson et al. 1983) so that assimilation, even combined with fractionation, is unlikely to be responsible for the high P_2O_5 and K_2O contents of the trachydolerites. It is noteworthy that the P_2O_5 contents are uniform throughout the trachydolerites (i.e. in the centres and margins), suggesting that the magma was uniformly enriched in P_2O_5 . It is further noteworthy that the amount of apatite in these dolerites does not increase in the vicinity of the entrained xenoliths despite the occurrence of resorbed apatite in the latter.
3. It appears, therefore, that assimilation (even if selective) cannot account for the high P_2O_5 contents of the trachydolerites, and it should be emphasized in this context that previous studies of assimilation provide no evidence for selective enrichment in P_2O_5 (Maury & Bizourd 1974, Kays et al. 1981, Harris & Bell 1982, Van Bergen & Barton 1984). Although selective assimilation of country rocks unusually enriched in P_2O_5 cannot be ruled out, it seems more likely that the high K_2O and P_2O_5 content of the trachydolerites is a primary feature and is unrelated to intracrustal processes such as magma mixing and assimilation.
3. Based upon the preceding discussion, it is probable that the trachydolerites were derived from different parental magmas than the dolerites. The required differences in parental magma composition could result from two processes – high pressure (or polybaric) fractional crystallization and partial melting in the upper mantle. High-pressure fractionation

may well involve different crystalline phases than low-pressure fractionation. If the crystalline assemblage removed at high pressures is close to the liquid in composition (as is the case with eclogite fractionation), then the incompatible elements may become strongly enriched while other major elements show relatively little change in composition (see O'Hara & Yoder 1967). Alternatively, magmas produced by low degrees of fusion will be substantially richer in incompatible elements and oxides than those formed by higher degrees of fusion. If melting occurs at the natural equivalent of an invariant point (i.e. pseudo-eutectic or pseudo-peritectic), then the degree of melting has minor influence upon the major oxide composition of the liquid.

The present data do not allow us to confidently discriminate between these two alternatives, and we therefore conclude that the major oxide chemistry of the Egersund dikes reflects the operation of low-pressure fractionation and either high-pressure fractionation or variable degrees of melting in the upper mantle. This proposal obviously requires further testing and, as noted above, the requisite trace element studies are in progress.

Conditions of crystallization

The conditions of crystallization may be estimated using olivine-liquid (Roeder & Emslie 1970, Roeder 1974, Bender et al. 1978) and plagioclase-liquid (Ghiorso & Carmichael 1980) equilibria. We have carried out calculations for only one sample (No. 800526), an olivine dolerite, because we have sufficient mineralogical data for this sample (note: the results are strongly dependent upon the input phenocryst compositions). As this sample represents one of the most primitive magmas intruded in the dike system, the calculated P-conditions of equilibration are almost certainly valid for the more evolved magmas which crystallized to form other dikes (intrusion temperatures for the latter will necessarily be lower). In addition, field evidence indicates that crystallization occurred prior to intrusion, so that estimated pressures may represent *maximum* values.

Before calculating equilibration temperatures, it is important to establish, as far as is possible,

that the olivine and plagioclase phenocrysts were in equilibrium with the magma, represented in this case by the whole rock.

Roeder & Emslie (1970) showed that the distribution of Mg and Fe²⁺ between olivine and liquid obeys the equation

$$K_D^{\text{Fe-Mg}} = \frac{X_{\text{Fe}}^{\text{ol}}}{X_{\text{Fe}}^{\text{liq}}} \cdot \frac{X_{\text{Mg}}^{\text{liq}}}{X_{\text{Mg}}^{\text{ol}}} = 0.30 \pm 0.03$$

and this has been confirmed by subsequent studies (Roeder 1974, Bender et al. 1978). Values of $K_D^{\text{Fe-Mg}}$ calculated for olivine phenocrysts and wholerock compositions for the Egersund dikes fall in the range 0.27–0.33 and, specifically, are 0.28–0.29 for sample No. 800526, indicating that the olivine phenocrysts crystallized in equilibrium with the initial magma.

The distribution of Ca and Na between plagioclase and liquid is difficult to establish experimentally because of the slowness of diffusion in feldspar crystals. Nevertheless, work by Drake (1976), Shibata et al. (1979) and Gerlach & Grove (1982) suggests that

$$K_D^{\text{Ca-Na}} = \frac{X_{\text{Ca}}^{\text{plag}}}{X_{\text{Na}}^{\text{plag}}} \cdot \frac{X_{\text{Na}}^{\text{liq}}}{X_{\text{Ca}}^{\text{liq}}} = 0.9-1.2$$

and values of K_D computed from the compositions of the cores of plagioclase phenocrysts and the whole-rock composition for sample No. 800526 fall within this range (actual values 0.96–1.0), once more indicating attainment of equilibrium.

Temperatures calculated from olivine-liquid equilibria are reported in Table 9 and range from 1210°C to 1196°C, with an average of 1204°C, which agrees well with 1-atmosphere liquidus temperatures measured experimentally for abyssal tholeiites (Walker et al. 1979, Grove & Bryan 1983). This fact, together with the multiply-saturated condition of the magmas suggests evolution at low-pressure (near surface) conditions (cf. O'Hara 1965, 1968). This conclusion is confirmed by the results of calculations based upon plagioclase-liquid equilibria. The temperature of equilibration of plagioclase and melt is strongly dependent upon pressure and water content of the magma (Ghiorso & Carmichael 1980). By making the (reasonable) assumption, based upon petrographic observations, that the plagioclase and olivine phenocrysts grew simultaneously from the magma, comparison of calculated oli-

Table 9. Calculated conditions of crystallization for sample 800526.

	T°C	P kb.	$C_{H_2O}^{liq}$ (wt.%)	fO_2 (atm.)
01-liq ¹	1210	—	—	—
01-liq ²	1207	—	—	—
01-liq ³	1196	—	—	—
01-liq ⁴	1204	—	—	—
Plag-liq ⁵	1198–1188	0.001–1	1.0–.01	—
Fe-Ti oxides ⁶	1150	—	—	10 ^{-8.2}

¹ – Roeder and Emslie (1970).

² – Roeder (1974).

³ – Bender et al. (1978).

⁴ – Average of 1–3.

⁵ – Ghiorso and Carmichael (1980).

⁶ – Spencer and Lindsley (1981).

vine-liquid and plagioclase-liquid temperatures allows P_{total} and the water content of the melt to be estimated. The results are 1 atm – 1 kb and ≤ 1 wt% H_2O (see Table 9), suggesting relatively low pressure crystallization of a volatile-rich tholeiitic magma.

The occurrence of coexisting magnetite_{ss} and ilmenite_{ss} allows calculation of temperature and fO_2 during cooling following the method of Spencer & Lindsley (1981). Calculated conditions are $T = 1150^\circ C$, $fO_2 = 10^{-8.2}$ bars and $T = 1100^\circ C$, $fO_2 = 10^{-8.8}$ bars, the range of T and fO_2 resulting from variations in the compositions of the oxide phase in the dike. The temperatures are lower than those obtained from olivine-liquid and plagioclase-liquid equilibria, as would be expected since the oxides clearly crystallized later than plagioclase and olivine. These results thus suggest a crystallization interval of 50–100°C, which is not unreasonable in comparison with experimental studies of Mid-Ocean Ridge Basalts (Bender et al. 1978, Grove & Bryan 1983). The calculated fugacity of oxygen lies slightly higher than, but within 1 log unit of, the QFM buffer (Myers & Eugster 1983) and is thus comparable to values which typically prevailed during the crystallization of most non-orogenic basalts (Carmichael et al. 1974).

Implications for the geological evolution of SW Norway

Proterozoic magmatic activity in SW Norway was dominated by emplacement of anorthositic-noritic-high-Al gabbroic intrusives. The latest theories for the origin of these rock-types envisage derivation from parental tholeiitic magmas via high-pressure fractional crystallization (Emslie

1978, Morse 1982). There are serious problems with this hypothesis (Drent et al. 1983), but it is nevertheless clear that intrusion of the Egersund dikes represents a significant departure from previous magmatic activity in Rogaland/Vest Agder. The tectonic significance of this is not, however, clear. Given estimates of the conditions of crystallization of the Egersund dikes and the conditions of the M3 metamorphic episode, then the rate of uplift of the metamorphic complex may be calculated and constraints may be placed upon cooling rates during uplift.

As noted previously, M3 metamorphism occurred between 1.03 and 0.85 Gyr ago. However, the conditions of metamorphism are poorly constrained. Most workers agree that the M3 event represents regional cooling after the M2 event and that the latter was induced by intrusion of the leuconoritic phase of the Bjerkreim-Sokndal lopolith. Pressures during M2 metamorphism were estimated as 3–6 kb by Hermans et al. (1976), and Swanenberg (1980) has suggested that subsequent cooling was essentially isobaric. Huijsmans et al. (1982) have estimated that Fe-rich granodiorite in a pegmatite formed at $P \leq 4$ kb, $T < 750^\circ C$ during M3 metamorphism. Barton & Drent (in preparation) conclude that the noritic magmas of the syn-M3 Hunnedalen dike system were emplaced at (i.e. crystallized at) a pressure of ~ 4.5 kb. Studies of the pyroxenes in the Bjerkreim-Sokndal lopolith, Hydra anorthosite massif, the hyperites of the Lyngdal region and the Hunnedalen dikes reveal that the original magmatic pyroxenes re-equilibrated at temperatures of 750–700°C (Barton and co-workers, work in progress). These data appear to indicate temperatures of 750–700°C for the M3 event and substantiate the hypothesis of essentially isobaric

cooling. However, it seems likely that the ambient temperatures were substantially lower than 750–700°C during at least part of the M3 event. Some of the Hunnedalen dikes were metamorphosed under amphibolite facies conditions immediately after they solidified, implying temperatures of 670–450°C (Turner 1968). The blocking temperatures for and Rb-Sr diffusion in osumilite, biotite and amphibole combined with K-Ar isotopic ages indicate temperatures of 550°C–400°C between 990 and 850 Ma (Rietmeijer 1984). The temperatures of pyroxene re-equilibration obtained for the Hunnedalen dikes (900 Ma) are thus probably those at which diffusion rates for Ca, Mg and Fe became so low that further compositional adjustment during cooling was inhibited.

Rietmeijer (1984) has estimated cooling rates of 7–4.4°C Ma⁻¹ between 1050 and 990 Ma and a cooling rate of 1.6°C Ma⁻¹ between 990 and 850 Ma on the basis of pyroxene re-equilibration data, isotopic age data and the closure temperatures for isotopic systems. However, assuming that the ambient temperatures were 450°C at the time of intrusion of the Hunnedalen dikes, which is consistent with a cooling rate of 1.6°C Ma⁻¹, and 100°C at the time of intrusion of the Egersund dikes (signifying a slightly higher than average continental geothermal gradient, Bott 1982) then either the cooling rate must have been closer to 3°C Ma⁻¹, or the reported age of the Egersund dikes is in error. An intrusion age of 670–650 Ma for the latter is more in accord with a cooling rate of 1.6°C Ma⁻¹, and surface temperatures would be reached at 616 Ma. This agrees with the data of Sigmond (1978) and Andresen & Faereth (1982) which indicate that the sub-Cambrian peneplain was reached between 700 and 600 Ma. Nevertheless, despite the possibility that the K-Ar ages for the Egersund dikes may be in error, we are reluctant to accept this evidence unreservedly since it is unlikely that cooling rates are linear over long periods of time. This is especially true if a metamorphic complex cools towards temperatures appropriate for an ambient continental geothermal gradient under isobaric conditions; initial cooling rates will be greater, because of the larger discrepancy between the actual temperature and the final temperature. The evidence discussed above could thus be interpreted to indicate initial cooling rates of 4.4–7°C/Ma⁻¹ declining to values of 3°C Ma⁻¹ during M3, and, finally, very low cooling rates of 0.8–0.4°C Ma⁻¹ after intrusion of the Egersund dikes and

prior to peneplanation. It is noteworthy that ambient temperatures during intrusion of the Hunnedalen dikes at 900 Ma were almost certainly significantly higher than those expected to occur at a depth equivalent to 4.5 kb along even a slightly higher than 'normal' continental geotherm.

The cooling history of Rogaland/Vest Agder in the period of 900 Ma – 600 Ma is complicated by the fact that uplift and erosion must also have occurred. Calculated rates of uplift are 0.004–0.022 cm yr⁻¹ and are sufficiently low so that uplift should not have been accompanied by significant departure from the temperatures appropriate for the regional geothermal gradient (note: cooling rates discussed above). Values for the latter during uplift may be calculated assuming that the density of the average crustal rocks is 2.7–2.9 gms cm⁻³ and range from 21.2–23.4°C km⁻¹. These are high by comparison with normal or even slightly abnormal continental geothermal gradients; this supports the conclusion reached above that during the M3 event the metamorphic complex was cooling towards temperatures appropriate for a normal geothermal gradient. The latter probably would not exceed a value of 15°C km⁻¹ at a depth of 17 km (Bott 1982), which is the depth at which M3 metamorphism occurred. We tentatively suggest, as long as cooling was isobaric during the later stages of M3, that temperatures corresponding to values found along continental geothermal gradients were established around 840–820 Ma.

Conclusions

The main conclusions of this paper are:

1. The Egersund dikes are olivine dolerites, dolerites and trachydolerites which formed by intrusion of magma of broadly tholeiitic composition.
2. Many of the dikes have been affected by prehnite-pumpellyite facies metamorphism (especially, formation of carbonates, serpentine, chlorite, mica, actinolite, cummingtonite, prehnite and epidote) and this was related to Caledonian overthrusting. Alteration is localized, however, and does not appear to have affected either the whole-rock major oxide chemistry or the compositions of the primary (i.e. magmatic) minerals.
3. Major-oxide compositional differences between the olivine dolerites and dolerites can

- be quantitatively explained in terms of fractional crystallization involving removal of olivine, plagioclase and augite. Rapid cooling during crystallization is suggested by the presence of both olivine and quartz, and the absence of low-Ca pyroxene, in the same rock; by the occurrence of hopper olivines and skeletal opaques; and by the relatively high Al and Ti contents of the augite phenocrysts.
4. The trachydolerites cannot be related to the olivine dolerites and dolerites via fractional crystallization involving removal of the observed phenocryst phases. Although there is petrographic evidence for assimilation, it is unlikely that the high P_2O_5 and K_2O contents of the trachydolerites is the result of assimilation combined with fractionation, and it is thus more likely that the observed compositional differences reflect polybaric fractionation or melting events in the upper mantle.
 5. The magmas crystallized at a pressure of 1 atm to 1 kb. The olivine dolerites crystallized at 1204–1150°C and contained ~ 1 wt. % H_2O .
 6. Combining the results for the Egersund dikes with published and unpublished data for other rocks from SW Norway indicates that regional cooling rates between 1050 Ma and 600 Ma may have varied between $7^\circ C Ma^{-1}$ and $0.4^\circ C Ma^{-1}$. Between 850 Ma and 790 Ma, the region was uplifted at a rate of $0.004\text{--}0.022\text{ cm yr}^{-1}$, and the calculated geothermal gradient was $21\text{--}23^\circ C km^{-1}$ which is slightly high compared with generally accepted geothermal gradients for continental regions. If cooling rates decreased with time, then temperatures corresponding to values found along 'normal' continental geothermal gradients were reached 840–820 Ma.

Acknowledgements – We wish to thank C. Kieft and W. Lustenhauer (Free University of Amsterdam) and M. J. van Bergen (State University of Utrecht) for assistance with the microprobe analyses, V. J. M. Salters for the whole-rock XRF analysis, G. Konert for carrying out the stable isotope analyses, and Dr. Karsten Storetvedt for allowing us to use the unpublished K-Ar data for the Egersund dikes. We are also grateful to the State University of Utrecht for financial support for fieldwork in S.W. Norway and the Netherlands Foundation for Pure Research (ZWO-WACOM) for support to the microprobe facilities at Utrecht and Amsterdam.

Manuscript received October 1985

References

- Andersen, T. 1984: Secondary processes in carbonatites: petrology of 'rodberg' (hematite-calcite-dolomite carbonate) in the Fen central complex, Telemark (South Norway). *Lithos* 17, 227–245.
- Andresen, A. & Faereth, R. 1982: An evolutionary model for the southwest Norwegian Caledonides. *Am. J. Sci.* 282, 756–782.
- Antun, P. 1956: *Géologie et pétrologie des dolérites de la région d'Egersund (Norvège Méridionale)*. Ph.D. thesis, Université de Liège.
- Barton, M. & Van Bergen, M. J. 1984: Secondary ilvaite in a dolerite dyke from Rogaland, SW Norway. *Mineral. mag.* 48, 449–456.
- Barton, M., Varekamp, J. C. & Van Bergen, M. J. 1982: Complex zoning of clinopyroxenes in the lavas of Vulsini, Latium, Italy: evidence for magma mixing. *J. Volc. Geotherm. Res.* 14, 361–388.
- Bender, J. F., Hodges, F. N. & Bence, A. E. 1978: Petrogenesis of basalts from the Project Famous Area: Experimental study from 0 to 15 kbars. *Earth Planet. Sci. Lett.* 41, 277–302.
- Bott, M. H. P. 1982: *The Interior of the Earth: Its Structure, Constitution and Evolution*, 2nd ed., Edward Arnold Ltd., London. 403 pp.
- Bowen, N. L. 1928: *The Evolution of the Igneous Rocks*. University Press, Princeton, N. J. 332 pp.
- Brooks, C. K. 1976: The Fe_2O_3/FeO ratio of basalt analyses: an appeal for a standardized procedure. *Bull. Geol. Soc. Denmark*, 25, 117–120.
- Bryan, W. B., Finger, L. W. & Chayes, F. 1969: Estimating proportions in petrographic mixing equations by least-squares approximation. *Science*, 163, 926–927.
- Carmichael, I. S. E. 1967: The iron-titanium oxides of salic volcanic rocks and their associated ferromagnesian silicates. *Contrib. Mineral. Petrol.* 14, 36–64.
- Carmichael, I. S. E., Turner, F. J. & Verhoogan, J. 1974: *Igneous Petrology*, McGraw-Hill Inc., New York. 739 pp.
- Donaldson, C. H. 1976: An experimental investigation of olivine morphology. *Contrib. Mineral. Petrol.* 57, 187–213.
- Drent, H. P., Barton, M. & Tobi, A. C. 1983: Parental magmas of massif-type anorthosites: late-stage fractionation products of tholeiites? *XVIII General Assembly, IUGG (IAVCEI)*, 98, 98.
- Drake, M. J. 1976: Plagioclase-melt equilibria. *Geochim. Cosmochim. Acta*, 40, 457–465.
- Emslie, R. F. 1978: Anorthosite massifs, rapakivi granites, and late Proterozoic rifting of North America. *Precambrian Research*, 7, 61–98.
- Gamble, R. P. & Taylor, L. A. 1980: Crystal/liquid partitioning in augite; effects of cooling rate. *Earth Planet. Sci. Lett.* 47, 21–33.
- Gerlach, D. C. & Grove, T. L. 1982: Petrology of Medicine Lake Highland Volcanics: characterization of endmembers of magma mixing. *Contrib. Mineral. Petrol.* 80, 147–159.
- Ghiorso, M. S. & Carmichael, I. S. E. 1980: A regular solution model for metaluminous silicate liquids: applications to geothermometry, immiscibility and the source region of basic magmas. *Contrib. Mineral. Petrol.* 71, 323–343.
- Griffin, W. L. & Taylor, P. N. 1975: The Fen damtjernite: petrology of a 'central complex kimberlite'. *Phys. Chem. Earth*, 9, 163–177.
- Grove, T. L. & Bryan, W. L. 1983: Fractionation of pyroxene-phyric MORB at low pressure: an experimental study. *Contrib. Mineral. Petrol.* 84, 293–309.

- Harris, C. & Bell, J. D. 1982: Natural partial melting of syenite blocks from Ascension Island. *Contrib. Mineral. Petrol.* 79, 107–113.
- Henderson, C. M. B., Barton, M. & Wyers, G. P. 1984: The transition from alkaline to sub-alkaline lavas in the low-P environment: the role of volatiles. *Trans. Am. Geophys. Union*, 65, 1153.
- Hermans, G. A. E. M., Tobi, A. C., Poorter, R. P. E. & Maijer, C. 1975: The high-grade metamorphic Precambrian of the Sirdal-Orsdal area, Rogaland/Vest Agder, south-west Norway. *Nor. geol. unders.* 318, 51–74.
- Hermans, G. A. E. M., Hakstege, A. L., Jansen, J. B. H. & Poorter, R. P. E. 1976: Sapphirine occurrence near Vikeså in Rogaland, southwestern Norway. *Nor. Geol. Tidsskr.* 56, 397–412.
- Huijsmans, J. P. P., Barton, M. & Van Bergen, M. J. 1982: A pegmatite containing Fe-rich grandierite, Ti-rich dumortierite and tourmaline from the Precambrian, high-grade metamorphic complex of Rogaland, S.W. Norway. *N. Jb. Miner. Abh.* 143, 249–261.
- Kars, H., Jansen, J. B. H., Tobi, A. C. & Poorter, R. P. E. 1980: Mineral relations in metapelites of SW Norway. Part II. Mineral relations between cordierite, hercynite and magnetite within the osumilite-in isograd. *Contrib. Mineral. Petrol.* 74, 235–244.
- Kays, M. A., McBirney, A. R. & Goles, G. G. 1981: Xenoliths of gneisses and the conformable, clotted-like granophyres in the marginal border group, Skaergaard Intrusion, East Greenland. *Contrib. Mineral. Petrol.* 76, 265–284.
- Kuno, H. 1966: Lateral variation of basalt magma type across continental margins and island arcs. *Bull. Volc.* 29, 195–222.
- Maijer, C. 1980: Caledonian metamorphism of the Precambrian of Rogaland/Vest Agder, SW Norway. *Internat. Colloquium on the high-grade metamorphic precambrian and its intrusive masses, SW Norway, Abstract No. 4, Utrecht.*
- Maijer, C., Andriessen, P. A. M., Hebeda, E. H., Jansen, J. B. H. & Verschure, R. H. 1981: Osumilite, an approximately 970 Ma old high-temperature index mineral of the granulite-facies metamorphism in Rogaland, SW Norway. *Geol. & Mijnbouw* 60, 267–272.
- Maury, R. C. & Bizouard, H. 1974: Melting of acid xenoliths into a basanite: an approach to the possible mechanisms of crustal contamination. *Contrib. Mineral. Petrol.* 48, 275–286.
- Michot, J. & Michot, P. 1969: The problem of anorthosites: the South Rogaland igneous complex, southwestern Norway. In: *Origin of Anorthosite and Related Rocks*, Y. W. Isachsen (ed.), *New York State Museum Sci. Ser., Mem.* 18, 399–410.
- Morse, S. A. 1982: A partisan review of Proterozoic anorthosites. *Am. Mineral.* 67, 1087–1100.
- Myers, J. R. Eugster, H. P. 1983: The system Fe-Si-O: oxygen buffer calibrations to 1,500K. *Contrib. Mineral. Petrol.* 82, 75–90.
- O'Hara, M. J. 1965: Primary magmas and the origin of basalts. *Scott. J. Geol.* 1, 19–40.
- O'Hara, M. J. 1968: The bearing of phase equilibria studies in synthetic and natural systems on the origin and evolution of basic and ultrabasic rocks. *Earth Sci. Rev.* 4, 69–133.
- O'Hara, M. J. 1977: Geochemical evolution during fractional crystallization of a periodically refilled magma chamber. *Nature* 266, 503–507.
- O'Hara, M. J. & Yoder, H. S. 1967: Formation and fractionation of basic magmas at high pressures. *Scott. J. Geol.* 3, 67–117.
- O'Hara, M. J. & Matthews, R. E. 1981: Geochemical evolution in an advancing, periodically replenished, periodically tapped, continuously fractionated magma chamber. *J. Geol. Soc. London* 138, 237–277.
- Osborn, E. F. 1959: Role of oxygen pressure in the crystallization and differentiation of basaltic magma. *Am. J. Sci.* 257, 609–647.
- Poorter, R. P. E. 1972: Paleomagnetism of the Rogaland Precambrian (southwestern Norway). *Phys. Earth Planet. Interiors* 5, 167–176.
- Priem, H. N. A. 1980: Isotope geochronology of the high-grade metamorphic Precambrian of SW Norway. *Internat. Colloquium on the high-grade metamorphic Precambrian and its intrusive masses, SW Norway, Abstract No. 6, Utrecht.*
- Rietmeijer, F. J. M. 1984: Pyroxene (re-) equilibration in the Precambrian terrain of SW Norway between 1030–990 Ma and reinterpretation of events during regional cooling (M3 stage). *Nor. Geol. Tidsskr.* 64, 7–20.
- Roeder, P. L. 1974: Activity of iron and olivine solubility in basaltic liquids. *Earth Planet. Sci. Lett.* 23, 397–410.
- Roeder, P. L. & Emslie, R. F. 1970: Olivine-liquid equilibrium. *Contrib. Mineral. Petrol.* 29, 275–289.
- Sigmond, E. M. O. 1978: Beskrivelse til det berggrunnsgeologiske kartbladet Sauda 1:250,000. *Nor. geol. unders.* 341, 1–94.
- Shand, S. J. 1922: The alkaline rocks of the Transport Line, Pretoria District. *Geol. Soc. S. Africa Trans.* 25, 85.
- Shibata, T., DeLong, S. E. & Walker, D., 1979: Abyssal tholeiites from the Oceanographer Fracture Zone. I. Petrology and fractionation. *Contrib. Mineral. Petrol.* 70, 89–102.
- Spencer, K. J. & Lindsley, D. H. 1981: A solution model for coexisting iron-titanium oxides. *Am. Mineral.* 66, 1189–1201.
- Storetvedt, K. M. & Gidskehaug, A. 1968: Palaeomagnetism and the origin of the Egersund dolerites, S. Norway. *Nor. Geol. Tidsskr.* 48, 121–124.
- Swanenberg, H. E. C. 1980: *Fluid inclusions in high-grade metamorphic rocks from S.W. Norway*. Ph.D. thesis, University of Utrecht.
- Thompson, R. N., Morrison, M. A., Dickin, A. P. & Hendy, G. L. 1983: continental flood basalts.. arachnids rule OK? In: *Continental basalts and mantle xenoliths*, C. J. Hawkesworth and M. J. Norry (eds.), *Shiva Publishing Ltd., Cheshire*, 158–185.
- Turner, F. J. 1968: *Metamorphic Petrology: Mineralogical and Field Aspects*, McGraw-Hill Inc., New York. 403 pp.
- Van Bergen, M. J. & Barton, M. 1984: Complex interaction of aluminous metasedimentary xenoliths and siliceous magma; an example from Mt. Amiata (Central Italy). *Contrib. Mineral. Petrol.* 86, 374–385.
- Verstevee, A. J. 1975: Isotope geochronology in the high-grade metamorphic Precambrian of SW Norway. *Nor. geol. unders.* 318, 1–50.
- Walker, D. & DeLong, S. E. 1982: Soret separation of Mid-Ocean Ridge basalt magma. *Contrib. Mineral. Petrol.* 79, 231–240.
- Walker, D., Kirkpatrick, R. J., Longhi, J. & Hays, J. F. 1976: Crystallization history of lunar pyrite basalt sample 12002: phase equilibria and cooling-rate studies. *Geol. Soc. Am. Bull.* 87, 646–656.
- Walker, D., Shibata, T. & DeLong, S. E. 1979: Abyssal tholeiites from the Oceanographer Fracture Zone II. Phase equilibria and mixing. *Contrib. Mineral. Petrol.* 70, 111–125.

- Watson, E. B. 1982: Basalt contamination by continental crust: some experiments and models. *Contrib. Mineral. Petrol.* 80, 73–87.
- Weis, D. & Duchesne, J. C. 1983: Pb isotopic compositions in the Egersund-Ogna anorthosite (SW Norway): an indication of a Gothian magmatic event? *Terra Cognita*, 3, 140.
- Wielens, J. B. W., Andriessen, P. A. M., Boelrijk, N. A. I. M., Hebeda, E. H., Priem, H. N. A., Verdurmen, E. A. Th. & Verschure, R. H. 1981: Isotope geochronology in the high-grade metamorphic Precambrian of southwestern Norway: new data and reinterpretations. *Nor. geol. unders.* 359, 1–30.
- Yoder, H. S., Jr. & Tilley, C. E. 1962: Origin of basalt magmas; an experimental study of natural and synthetic rock systems. *J. Petrol.* 3, 342–532.