

Geochemistry and Petrology of Dolerite Dykes of Probable Late Caledonian Age from the outer Sunnfjord Region, West Norway

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Major and trace element abundances from dolerite dykes in the outer Sunnfjord region show an overall compositional similarity to continental tholeiites. The dyke rocks exhibit a fractionated nature, especially with respect to a strong enrichment in total Fe and in Ti. The fractionation apparently took place in a deep-seated magma chamber where plagioclase and clinopyroxene were formed as phenocrysts. During ascent of the magma, suspended pyroxene phenocrysts underwent marginal growth and strong resorption of plagioclase primocrysts took place. The PT variation trend during intertelluric crystallization of the Sunnfjord dolerite magmas has been outlined on the basis of textural features and mineral compositions. The geological relationships in the area indicate that the emplacement of the dyke swarm took place in the Lower Devonian and may thus represent the youngest igneous event in the outer Sunnfjord region.

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Introduction

Dolerite dykes in the outer Sunnfjord region were first reported from Kinn by Reusch (1881) and subsequently described both from Kinn and Moldvær by Kolderup (1928). Two more dykes, at Sandvik and Grønevik, were noted by Kildal (1969) and a further dyke has been observed at Haukå by Bryhni (pers. comm. 1979).

The present authors believed that these dykes could be members of an extensive dyke swarm in this region and a systematic search for dolerites was carried out. Thirty dolerite dykes have been sampled from various localities (Fig. 1) and their whole rock and mineral geochemistry investigated.

Geological setting

The Vevring Complex (Fig. 1), which consists of eclogite-bearing amphibolites, gneisses and schists, represents the deepest exposed level in this region and is of Precambrian age (Furnes et al. 1976, Skjerlie & Pringle 1978). It is bounded by major faults with E-W trends (Fig. 1). These faults are considered by Steel (1976) to represent parts of a Devonian graben/wrench fault system. The most complete structural sequence within the graben areas occurs in the southern part of the region. The lowermost unit here is the Askvoll Group which is a parautochthonous sequence of supposed Lower Palaeozoic age (Skjerlie 1969,

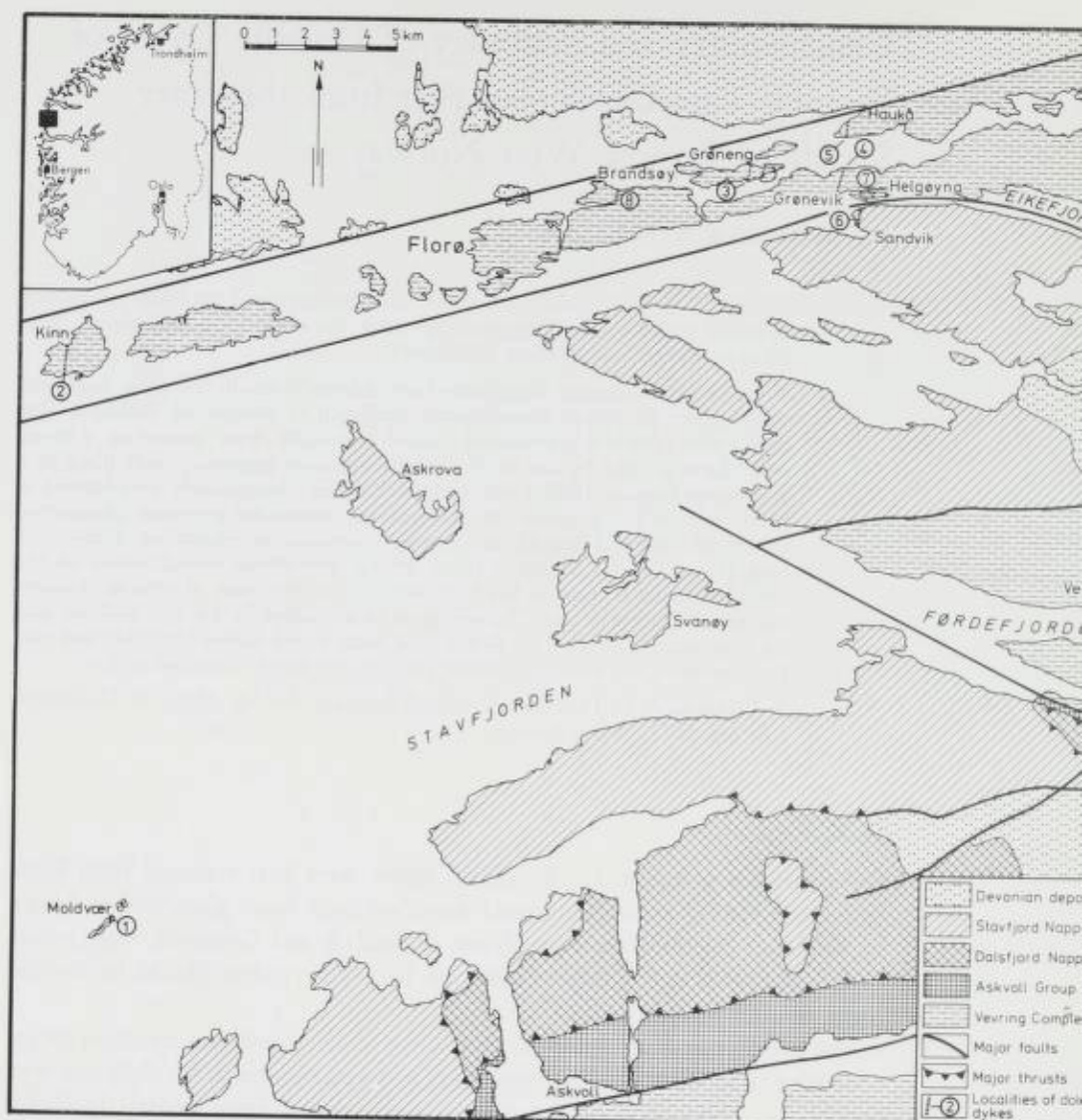


Fig. 1. Simplified geological map of the outer Sunnfjord region showing the locations of the dolerite dykes.

Furnes et al. 1976). This unit is tectonically overlain by the Dalsfjord Nappe which consists of Precambrian charnokitic rocks. The charnokitic rocks are in turn overthrust by the rocks of the Stavfjord Nappe (Skjerlie 1969). The uppermost unit comprises deposits of Devonian age. In the northern part of the region only parts of this succession are present.

Field relationships

The thirty dolerite dykes which have been found to date in the outer Sunnfjord region occur in zones where there is a high incidence of jointing in the host

rocks. Twenty-five of the dykes intrude the Precambrian Vevring Complex and are concentrated in the area between Kinn and Haukå-Helgøyna. Five of the dykes, however, intrude rocks of the Stavfjord Nappe (Fig. 1, localities 1 and 6).

Widths of the dykes range from 10 cm to 10 m, but the majority are from 50 cm to 2 m in thickness. They strike consistently NNE-SSW and are either vertical or dip steeply to the WNW regardless of the structure of the country rocks. The dykes exhibit chilled margins, and apophyses and host rocks xenoliths are rather common.

The dykes at Haukå (Fig. 1, loc. 5) do not extend into the Devonian rocks to the north, nor have dolerite dykes been observed to cut Devonian deposits anywhere else in the outer Sunnfjord region. Some of the dykes on Helgøyna (loc. 7) and on Brandsøy (loc. 8) end abruptly at faults trending parallel to the major dislocations, and the dykes have locally been strongly fractured as a result of movements along these structures. The authors consider that the emplacement of the dolerite dykes pre-dated the major faulting which controlled the deposition of the Middle Devonian sediments (Skjerlie 1971). A further line of evidence for a late Caledonian emplacement is that dykes which cut the rocks of the Stavfjord Nappe, the latter presumably metamorphosed during the Caledonian orogeny, show no signs of metamorphism.

Although the geological relationships indicate a possible Lower Devonian emplacement age for the dykes, preliminary age determinations (K/Ar) show a spread of values from 480-990 Ma (Macintyre pers. comm. 1980), and no unequivocal pattern has yet emerged. Obviously the true age of these dykes will be of considerable importance in any geotectonic reconstruction of the area; work is in progress on the geochronology of the dykes by Macintyre (K/Ar) and Råheim (Rb/Sr).

Petrography

The dolerite dykes are fine-grained melanocratic rocks containing plagioclase and pyroxene phenocrysts and glomerocrysts up to 5 mm across. Under the microscope the dykes show a very uniform mineralogy dominated by plagioclase, clinopyroxene and opaques. Reddish-brown biotite and apatite occur as accessories, and quartz has been detected in some of the dykes by microprobe analysis. The ore minerals are essentially titanomagnetite with small amounts of pyrite.

The dykes usually exhibit a glomeroporphyritic texture. Clinopyroxene occurs as phenocrysts in addition to plagioclase. The plagioclase is twinned according to the albite, Carlsbad and pericline laws and the plagioclase phenocrysts commonly show oscillatory zoning. The clinopyroxene is an augite and may exhibit a visible zoning. Both simple and polysynthetic twinning are common in the clinopyroxene phenocrysts.

The cores of the plagioclase phenocrysts show varying degrees of resorption, and may be deeply embayed along their margins and along Carlsbad twin planes (Fig. 2). The less intensely resorbed crystals clearly show that the cores were originally euhedral and tabular. The shapes of the outer zones have, however, been influenced by neighbouring mineral grains during their growth. The margins of the plagioclase phenocrysts also carry poikilitic inclusions of pyroxene. The plagioclase phenocrysts, therefore, appear to have originated during two stages of crystal growth.

Among the groundmass minerals there appears to be some textural evidence that pyroxene began to crystallize before plagioclase. Even though the plagioclase grains are generally elongated in the [001] zone direction, their shape is irregular due to interference with

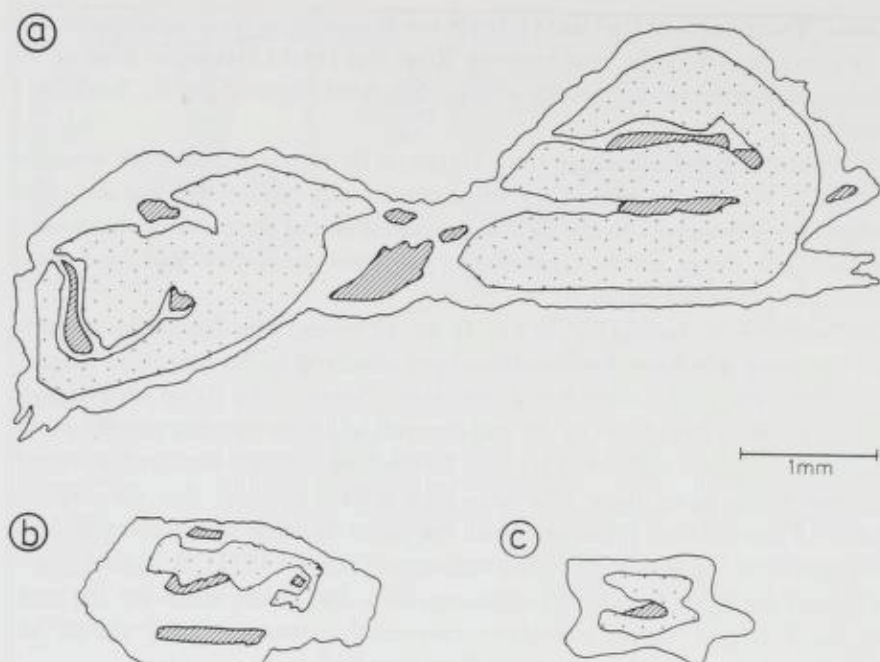


Fig. 2. Plagioclase crystals from the Sunnfjord dolerites. Primocrysts (stippled) have been partly resorbed along their margins and twin planes. Their outer zones carry poikilitic inclusions of clinopyroxene (hatched). a - Plagioclase from dyke 7b; b - Plagioclase from dyke 5d; c - Plagioclase from dyke 8b.

neighbouring pyroxene grains. Poikilitic inclusions of pyroxene in plagioclase also imply that the groundmass pyroxene commenced crystallization before plagioclase.

The titanomagnetite almost certainly commenced crystallization as the last of the major phases and tends to be moulded around the pyroxene and plagioclase grains. Even though there is some suggestion of mutual intergrowth of pyroxene and titanomagnetite, and the plagioclase may have small amounts of titanomagnetite as poikilitic inclusions, the sequence of groundmass crystallization appears to have been pyroxene-plagioclase-titanomagnetite.

The dolerite dykes are as a rule extremely fresh. In a few of the dykes, however, the clinopyroxene is altered to biotite to a minor degree. A weak sericitization of the plagioclase phenocrysts may also be seen in some of the dykes. One of the dykes (6a) exhibits a pervasive sericitization.

Analytical techniques

Major elements were determined by XRF, using glass beads prepared according to the method of Padfield & Gray (1970) except for sodium for which pressed powder pellets were employed. Twenty international standards and the recommended values of Flanagan (1973), refined by least-squares procedures and matrix corrections, were used for calibration. Ferrous iron was determined titrimetrically using potassium dichromate.

The trace elements were determined by XRF using pressed powder pellets. Twelve international standards and the recommended values of Flanagan (1973) refined by least-squares procedures were used for calibration.

The mineral analyses were made with an ARL-SEMO electron microprobe using a series of natural and synthetic standards and ZAF correction procedures.

Fig. 3. $Ol'-Ne'-Q'$ projection of the Sunnfjord dolerites plotted in % cation equivalents based on the cation norm. The heavy solid line is Irvine & Baragar's (1971) dividing line between alkaline and subalkaline series.

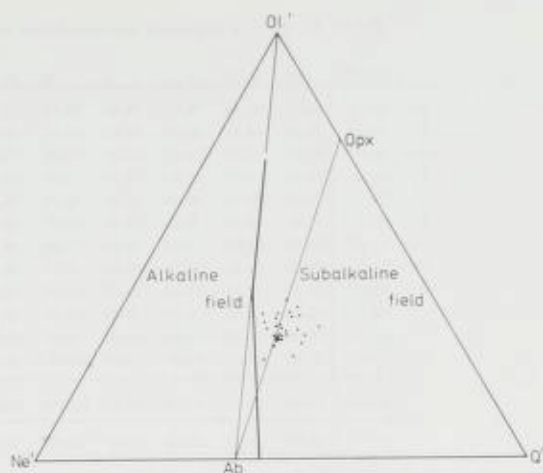
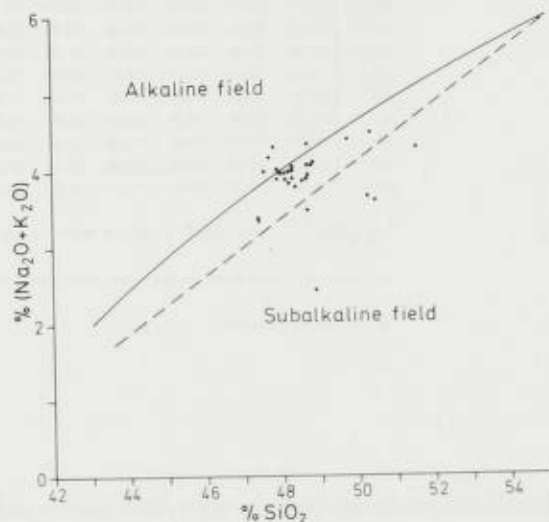


Fig. 4. Alkali-silica plot of the Sunnfjord dolerites. The solid curve is the dividing line after Irvine & Baragar (1971). The dashed line is MacDonald's (1968) dividing line.



Whole rock chemistry

MAJOR ELEMENTS

Major element analyses of the dykes together with cation norms are given in Table 1. The norm calculations were made after adjustments of the analytical data as recommended by Irvine & Baragar (1971): (1) Fe_2O_3 was limited according to the equation $\% Fe_2O_3 = \% TiO_2 + 1.5$, the excess being converted to FeO ; (2) the analyses were recalculated to 100% volatile free. The cation norm was obtained from the CIPW norm using the conversion factors calculated by Hutchinson (1975).

Although neither orthopyroxene nor pigeonite has been identified in the thin-sections, and all the modal pyroxene appears to be augite, the dyke rocks

Table 1. Major element composition and cation norms of dykes in the outer Sunnfjord region

Dyke No.	1a	1b	1c	2	3	4a	4b	4c	4d	4e	4f	4g	5a	5b
SiO ₂	51.07	48.64	49.07	49.40	49.87	47.42	48.02	47.94	48.24	47.54	48.13	47.41	47.93	46.89
Al ₂ O ₃	13.12	14.46	14.03	12.65	13.15	12.94	13.45	13.21	12.85	13.01	13.36	12.84	13.28	12.03
TiO ₂	2.70	2.72	2.66	3.19	3.26	3.30	3.35	3.28	3.29	3.34	3.19	3.28	3.26	3.28
Fe ₂ O ₃	5.57	2.77	3.13	3.93	5.52	5.61	5.04	5.49	5.39	5.37	5.21	3.92	5.22	3.14
FeO	9.09	10.82	10.67	11.76	10.05	10.62	11.32	11.42	11.42	11.02	11.32	12.77	11.32	13.14
MgO	4.60	5.59	4.99	4.48	5.25	5.34	5.14	4.91	4.99	5.04	4.94	5.12	5.29	5.07
CaO	8.24	7.89	7.95	8.26	7.84	8.56	8.85	8.49	8.46	8.61	8.72	8.76	8.60	8.88
Na ₂ O	3.00	2.92	2.86	2.74	2.59	2.85	2.21	3.09	2.78	2.88	2.54	2.84	3.05	2.85
K ₂ O	1.27	1.41	1.53	0.78	1.06	0.88	0.21	0.90	1.11	1.11	0.91	0.96	0.91	1.39
MnO	0.22	0.23	0.21	0.24	0.33	0.22	0.18	0.21	0.21	0.19	0.18	0.19	0.18	0.18
P ₂ O ₅	0.38	0.39	0.41	0.46	0.47	0.44	0.40	0.43	0.43	0.44	0.48	0.44	0.73	0.40
H ₂ O	0.42	1.47	1.67	0.94	1.35	1.50	2.32	1.20	1.22	1.88	1.47	1.54	1.20	1.31
TOTAL	99.68	99.31	99.18	98.83	100.74	99.68	100.49	100.57	100.39	100.43	100.45	100.07	100.97	99.48
FM ¹	75.69	70.78	73.30	77.62	74.51	74.85	75.73	77.14	76.76	76.09	76.62	76.31	75.38	76.11
Cation Norms														
Q	4.22	-----	0.84	5.02	5.40	1.22	6.62	0.46	1.82	0.79	3.07	-----	0.61	-----
Or	7.77	8.67	9.49	4.90	6.54	5.49	1.29	5.56	6.86	6.90	5.84	5.92	5.88	8.64
Ne	27.98	27.29	26.91	26.07	24.24	26.98	21.03	28.86	26.05	27.10	25.94	26.74	26.35	26.83
An	19.28	23.14	21.96	21.06	21.98	20.92	27.74	20.29	20.21	20.28	23.44	20.42	20.54	19.57
Mc	4.55	3.02	3.42	4.34	5.18	5.27	5.37	5.20	5.23	5.30	5.13	4.30	5.15	3.44
Ti	3.90	3.94	3.89	4.71	4.73	4.83	4.94	4.75	4.79	4.88	4.65	4.80	4.70	4.68
Ap	0.81	0.86	0.90	1.02	1.01	0.97	0.89	0.93	0.95	0.97	1.06	0.97	1.58	0.89
Qpx	16.45	11.97	13.27	15.34	12.27	16.61	12.83	16.50	16.56	17.21	14.85	17.70	14.91	19.16
Qpx	15.04	18.54	19.32	17.54	18.65	17.71	19.29	17.45	17.53	16.60	18.22	18.43	18.61	7.83
Ol	-----	2.57	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.72	-----	8.96

$${}^1\text{FM} = (\text{FeO}^* + \text{MnO})/(\text{FeO}^* + \text{MnO} + \text{MgO}) \times 100$$

M: Mean of thirty dykes in the outer Sunnfjord region

S: Standard deviation

are all comparatively high in opx in their norm and commonly also have Q (21 dykes). This is typical for subalkaline rocks, and in the Ol'-Ne'-Q' projection (Irvine & Baragar 1971) all the dykes plot within the subalkaline field (Fig. 3). In the alkali-silica diagram (Fig. 4), however, only five of the dykes plot in the subalkaline field of MacDonald (1968); the others lie within the alkaline field. Using the dividing line of Irvine & Baragar (1971) twenty-five of the dykes plot in the subalkaline field, the majority of them, however, plotting very close to the dividing line. From the alkali-silica diagram alone we might draw the conclusion that the dyke rocks have neither typical subalkaline nor alkaline compositions; i.e. they are transitional rocks. We must bear in mind, however, that interstitial silica has been detected in some dykes by microprobe analysis, and that all the dyke rocks are comparatively high in opx in their norm and commonly also have small amounts of Q. The conclusion must be, therefore, that the dolerite dykes are saturated and of subalkaline affinity.

The major element chemistry (Table 1) demonstrates that the dyke rocks

	5a	5f	6a	6f	7a	7b	7c	7d	8a	8b	8c	8d	8e	8f	9	10
67	46.80	47.14	48.33	47.69	48.30	47.71	48.06	48.22	46.12	47.19	47.51	47.65	46.48	47.86	47.94	0.98
67	12.88	13.17	13.08	13.28	13.29	13.24	13.16	13.36	12.24	12.41	12.50	13.09	12.09	13.02	13.09	0.46
70	3.23	3.22	3.23	3.22	3.21	3.30	3.15	3.17	3.26	3.25	3.36	3.23	3.27	3.27	3.20	0.18
70	1.82	4.89	5.96	6.56	4.73	5.94	5.29	4.21	4.50	5.51	5.07	4.21	5.27	6.78	4.93	0.96
95	12.91	11.47	9.70	9.92	11.84	10.48	10.84	12.14	11.84	11.50	11.80	10.80	11.76	10.28	11.25	0.93
94	5.07	4.95	5.46	5.27	5.11	5.00	5.04	5.05	6.43	5.98	5.82	5.89	6.77	5.74	5.28	0.50
79	8.74	8.84	8.38	7.36	8.57	8.91	8.34	8.04	9.01	8.73	8.71	8.50	8.51	8.45	8.49	0.37
81	2.99	2.84	2.99	3.38	2.76	3.02	2.18	2.23	2.84	3.18	2.86	2.30	2.48	2.98	2.77	0.28
100	1.10	0.95	1.09	1.59	1.10	0.94	2.12	1.82	0.46	0.76	1.02	1.56	0.79	0.99	1.09	0.38
100	0.19	0.19	0.27	0.20	0.20	0.19	0.28	0.22	0.25	0.25	0.26	0.25	0.25	0.25	0.22	0.04
54	0.42	0.42	0.64	0.43	0.43	0.38	0.42	0.61	0.45	0.45	0.44	0.46	0.44	0.45	0.46	0.08
23	1.48	1.72	1.40	2.54	1.81	1.47	1.36	1.37	1.40	0.90	1.20	1.30	1.20	0.90	1.38	0.38
76	99.63	99.80	100.53	100.45	100.55	100.58	100.24	100.44	98.80	100.21	100.57	99.24	99.32	100.97	100.10	
47	76.54	76.44	73.74	75.25	76.13	76.21	75.91	76.18	71.51	73.64	74.06	71.59	71.22	74.34		
---	---	0.60	1.33	2.35	1.43	0.29	1.40	2.00	---	---	---	1.29	0.03	---	1.37	
10	6.83	5.92	6.69	5.97	6.78	5.79	13.10	11.27	2.80	4.68	6.28	9.68	4.94	6.03	6.71	
100	28.26	26.91	27.92	22.78	25.73	28.27	20.56	20.95	26.44	29.66	26.70	21.74	23.45	27.59	26.06	
76	19.39	21.45	19.80	22.01	21.43	20.65	20.84	22.07	19.95	17.88	18.94	21.87	20.52	19.07	20.39	
99	4.20	5.20	5.13	5.23	5.11	5.23	5.10	4.60	4.87	5.15	5.29	4.63	5.24	5.15	5.15	
72	4.72	4.72	4.67	4.74	4.65	4.79	4.60	4.62	4.70	4.70	4.86	4.74	4.79	4.70	4.66	
17	0.93	0.83	1.40	0.95	0.93	0.82	0.92	1.33	0.97	0.97	0.95	0.99	0.97	0.97	0.99	
66	18.64	17.52	15.22	10.94	15.87	18.30	15.78	12.46	18.62	19.18	18.40	15.52	16.70	16.29	15.99	
19	10.51	16.25	17.82	21.03	18.07	15.86	17.70	20.70	19.01	12.52	17.82	19.54	23.36	18.12	18.10	
25	6.52	---	---	---	---	---	---	---	2.64	5.16	0.76	---	---	1.28	---	

exhibit a fractionated nature especially with respect to an enrichment in total Fe and Ti. In classifying the fractionated tholeiitic suite of eastern Iceland, Wood (1978) used a combination of phenocryst assemblages and a chemical parameter, the FM ratio, where:

$$FM = \frac{FeO^* + MnO}{FeO^* + MnO + MgO} \times 100$$

All oxides are in wt. pr. cent and FeO* refers to total Fe expressed as FeO.

The FM ratio of the dolerite dykes (Table 1) classifies the majority of them as ferrobasalt (FM = 74 to 77) and a few of them fall within the range of low magnesia basalt (FM = 66 to 73). The dyke rocks have been plotted in the MgO versus FeO* diagram of Wood (1978). The Sunnfjord dykes are relatively enriched in Fe compared to the aphyric Thingmuli lavas (Carmichael 1964) (Fig. 5).

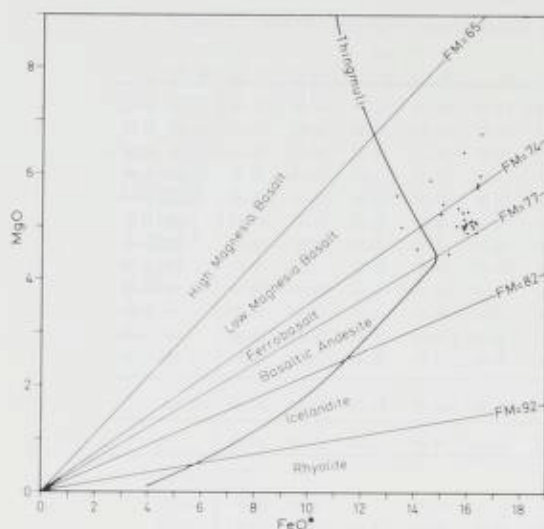


Fig. 5. MgO versus FeO* for the Sunnfjord dolerites. Oxides as wt %, total iron as FeO*. The field boundaries separating different volcanic rocks are after Wood (1978). The trend defined by the aphyric lavas of the Thingmuli complex is included (Carmichael 1964).

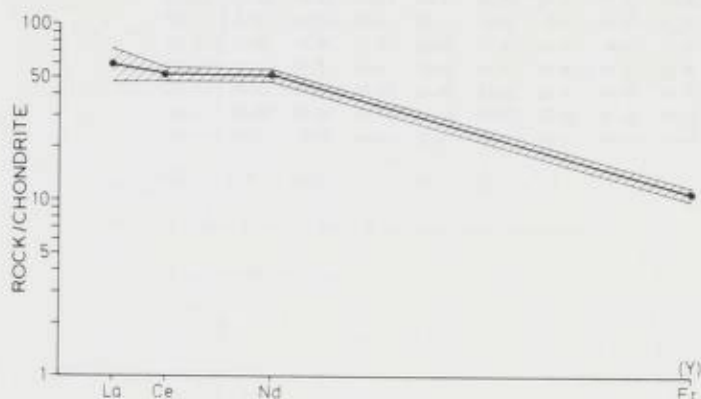


Fig. 6. Mean chondrite-normalized rare-earth distribution for 30 dolerites from Sunnfjord (chondrite data from Frey et al. 1968). Hatched field is 2 standard deviations wide.

TRACE ELEMENTS

Trace element analyses and selected element ratios of the Sunnfjord dolerite are given in Table 2.

According to Pearce and Cann (1973) Y/Nb ratios for within-plate basalts are less than 1.0 for alkalic rocks and greater than 2.0 for tholeiitic rocks. The Y/Nb ratios for the Sunnfjord dolerites vary between 1.0 and 1.53 (mean 1.24) and thus suggest a transitional nature. Yet continental basaltic rocks having a typical tholeiitic geochemistry, e.g. the Karroo dolerites (Cox et al. 1967), exhibit the same range in Y/Nb ratios as do the Sunnfjord dolerites, and the tholeiitic Vestfjella dolerite dykes in Antarctica have an average Y/Nb ratio of 1.28 (Furnes, pers. comm. 1980).

The elements La, Ce, Nd and Y (the latter proxying for Er) have been taken as representative members of the rare earth series. The REE distribution pattern

Table 2. Trace element concentrations (ppm) of dykes in the outer Sunnfjord region

Dyke No.	Rb	Sr	Ba	Y	Zr	Nb	La	Co	Ni	Y/Sr	K/Rb	Ba/Sr	Co/Sr	Sr/Zn	K/Sr	Rb/Sr	K/Ba
1a	36	240	326	20	140	20	19	50	36	1.0	292	9	245	0.74	44	0.15	32
1b	52	241	417	23	108	23	17	50	36	1.0	225	8	234	0.58	49	0.22	28
1c	53	232	443	23	143	22	15	45	35	1.05	225	8	245	0.52	55	0.25	29
2	19	297	460	22	134	17	19	47	34	1.29	337	24	199	0.65	22	0.06	14
3	27	163	355	20	135	16	18	46	32	1.25	326	13	344	0.45	54	0.17	25
4a	28	260	386	20	138	17	21	44	28	1.18	263	14	235	0.67	28	0.11	19
4b	3	193	301	20	139	17	20	42	30	1.18	567	100	328	0.64	9	0.02	6
4c	12	197	464	21	160	16	26	48	32	1.31	625	38	308	0.42	38	0.06	18
4d	20	186	474	20	139	14	21	56	38	1.25	440	24	322	0.40	49	0.11	19
4e	18	184	456	20	140	16	25	48	31	1.25	511	25	335	0.40	50	0.10	20
4f	20	184	344	21	137	16	23	48	31	1.31	375	17	339	0.53	41	0.11	22
4g	14	199	415	20	138	16	22	52	35	1.25	571	30	315	0.48	40	0.07	19
5a	11	204	422	20	139	17	29	46	33	1.18	682	38	301	0.48	37	0.05	18
5b	26	190	432	19	132	16	20	50	28	1.19	442	17	334	0.44	60	0.14	26
5c	10	212	441	20	139	16	26	50	37	1.25	740	44	298	0.48	35	0.05	17
5d	12	211	471	21	137	16	29	50	37	1.31	691	39	298	0.45	39	0.06	18
5e	17	211	401	21	136	15	21	47	33	1.40	535	24	296	0.53	43	0.08	23
5f	16	208	377	20	137	17	20	40	32	1.18	494	23	304	0.55	38	0.08	21
6a	30	231	403	21	137	16	18	45	30	1.31	300	14	259	0.55	39	0.13	21
6b	31	198	440	21	139	17	17	50	29	1.24	426	14	266	0.45	66	0.16	30
7a	13	191	445	20	139	16	19	57	33	1.25	700	34	321	0.43	47	0.07	20
7b	13	198	359	20	134	16	20	42	27	1.25	600	27	321	0.55	40	0.07	22
7c	45	190	424	22	137	17	12	40	27	1.29	391	9	313	0.45	93	0.24	41
7d	26	190	656	21	138	16	23	41	39	1.31	580	25	302	0.29	80	0.14	23
8a	8	201	356	26	136	17	19	39	27	1.53	475	45	320	0.56	18	0.04	11
8b	14	202	395	20	134	17	15	39	24	1.18	573	36	309	0.51	31	0.05	16
8c	25	212	390	25	134	17	16	39	25	1.47	340	16	294	0.53	40	0.12	21
8d	45	226	451	20	145	18	16	37	24	1.11	287	10	283	0.50	57	0.20	29
8e	21	182	319	30	139	17	18	37	29	1.38	314	9	334	0.57	36	0.12	16
8f	26	197	379	20	140	17	16	44	26	1.18	315	15	306	0.52	42	0.13	22
8	23	207	414	21	138	17	20	46	31	1.24	455	25	296	0.51	44	0.11	22
9	13	27	66	1	3	2	4	5	4	0.11	153	18	36	0.09	17	0.08	7

M: Mean of thirty dykes in the outer Sunnfjord region

S: Standard deviation

for the dyke swarm shows significant enrichment in light over heavy REE (Fig. 6). The slope of the light REE is similar to those of the Grande Ronde (Reidel 1978), the Ice Harbor flows (Helz et al. 1974), Deccan trap basalts (Alexander & Gibson 1977) and the Vestfjella dolerites (Furnes pers. comm. 1980) and, therefore, appears to be common for continental tholeiites.

The K/Rb ratios for the Sunnfjord dolerites lie within the range 225–700, averaging 455. This is distinctly higher than that observed for tholeiitic dolerites from Tasmania and Antarctica (Compston et al. 1968) and is somewhat higher than for most of the basalts of the Columbia River Group (McDougall 1976)

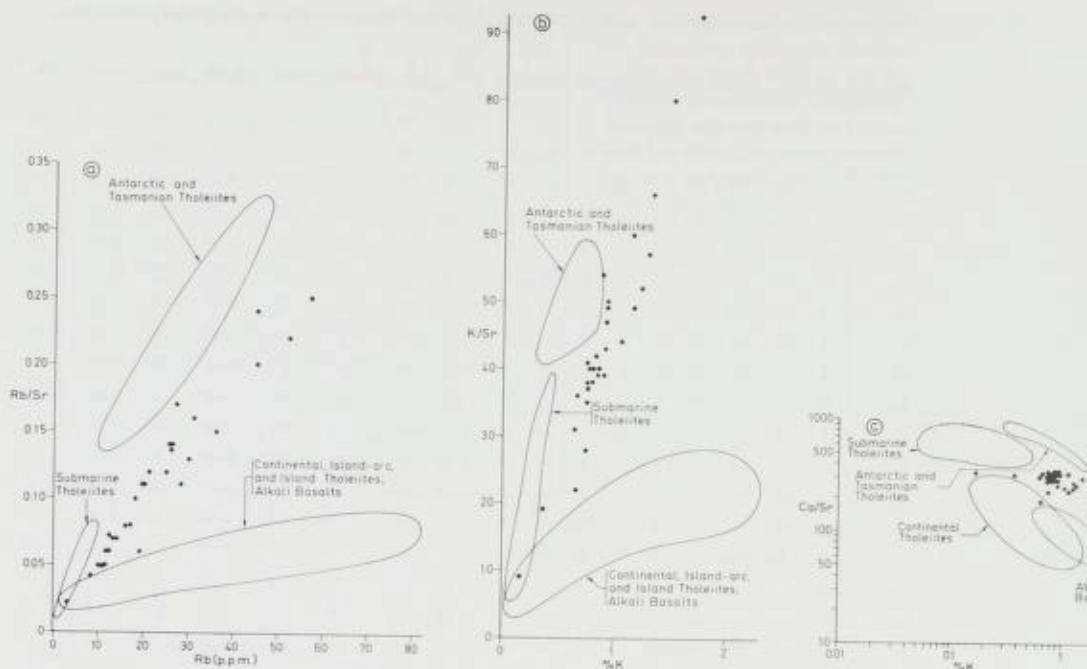


Fig. 7. Rb/Sr-Rb, K/Sr-K, and Ca/Sr-K scattergrams for the Sunnfjord dolerites, with field boundaries after Condie et al. (1969).

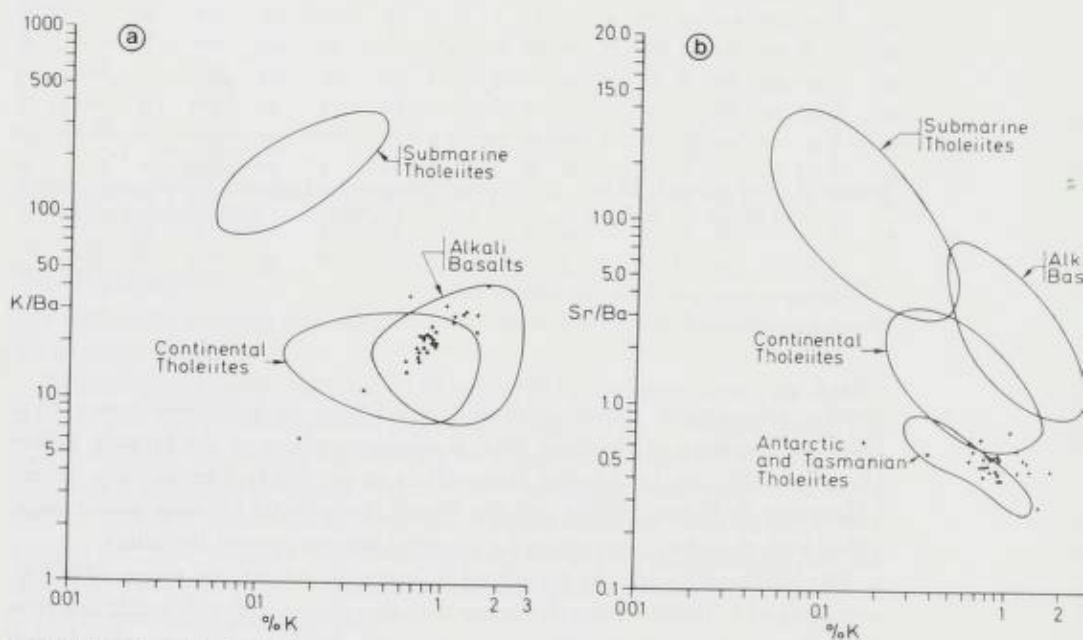


Fig. 8. K/Ba-K and Sr/Ba-K scattergrams for the Sunnfjord dolerites, with field boundaries after Condie et al. (1969).

except for the Picture George Basalt which shows higher K/Rb ratios than those of the Sunnfjord dykes. The Karroo dolerites, however, have K/Rb ratios in the range 303–609, and the average of 465 (Erlank & Hofmeyer 1966) is nearly the same as that of the Sunnfjord dolerites. An average K/Rb ratio of 465 is also observed for the tholeiitic Vestfjella dykes from Antarctica (Furnes, pers. comm. 1980).

The average Sr content in the Sunnfjord dykes is distinctly lower than the average (428 ppm) for continental tholeiites in general (Condie et al. 1969), yet higher than for Antarctic tholeiites (Compston et al. 1968) and some of the Karroo dolerites (Cox et al. 1967, Woolley et al. 1979). The Rb/Sr ratios of the Sunnfjord dolerites lie within the range 0.02–0.25; the average of 0.11 is distinctly lower than that observed for tholeiitic dolerites from Antarctica and Tasmania (Compston et al. *op. cit.*) but shows greater similarity with the Columbia River Group, especially the Yakima Basalt (McDougall *op. cit.*).

In Fig. 7 the Rb/Sr ratios are plotted as a function of Rb, and the K/Sr and Ca/Sr ratios as functions of K. The fields occupied by the major basalt types are after Condie et al. (1969). The Rb/Sr ratios increase linearly with Rb (Fig. 7a) and the K/Sr ratios increase linearly with K (Fig. 7b), features which indicate that K, Rb and Sr cannot have been affected by alteration to any significant extent. The rate of increase in Rb/Sr with Rb and K/Sr with K follows the Sr-depletion fractionation trend typical of submarine tholeiites and Sr-depleted continental tholeiites (Condie et al. 1969). The Ca/Sr ratios which occupy the area between continental tholeiites and Antarctic and Tasmanian tholeiites (Fig. 7c), follow the same trend; i.e. depleted in Sr relative to Ca compared to continental tholeiites.

The K/Ba ratios plotted as a function of K illustrate the similarity of the Sunnfjord dolerites to continental tholeiites as well as to alkali basalt (Fig. 8a). However, in the Sr/Ba versus K diagram all analyses plot exclusively in the field of continental tholeiites, showing in particular similarities with Antarctic and Tasmanian tholeiites (Fig. 8b).

Mineral chemistry

PLAGIOCLASE

Microprobe analyses of phenocryst and groundmass plagioclase are given in Table 3. The margins of the plagioclase phenocrysts display pronounced normal zoning. The cores, which show varying degrees of resorption (Fig. 2), are relatively homogeneous with An contents between 63 and 64 per cent. The innermost parts of the marginal zones vary between 55 and 59% An whilst the outermost parts of the phenocrysts have compositions varying between An 41 and 52.

The groundmass plagioclase also show normal zoning. The cores have An contents of 54 to 59 whilst the margins vary from An 41 to 52 per cent. The compositional variations of the groundmass plagioclase correspond, therefore, with those of the margins of the plagioclase phenocrysts. The groundmass

Table 3. Representative microprobe analyses of plagioclase from dykes in the outer Sunnfjord region

Dyke No.	4a					5c					
	Phenocrysts			Matrix		Phenocrysts			Matrix		
	P	Mp	R	Mc	R	P	Mp	R	Mc	R	Mc
CaO	12.52	11.36	9.75	11.73	9.61	12.30	11.66	9.90	11.67	9.80	11.42
Na ₂ O	3.82	4.42	5.41	4.43	5.27	3.85	4.68	5.15	4.80	5.22	4.63
K ₂ O	0.27	0.53	0.29	0.29	0.36	0.12	0.00	0.06	0.20	0.50	0.20
SiO ₂	54.53	56.95	56.61	55.24	57.49	53.79	54.35	58.21	55.02	56.55	56.16
Al ₂ O ₃	27.71	26.98	26.13	26.97	26.33	28.79	27.34	26.23	26.95	26.99	25.68
TOTAL	98.85	100.24	98.19	98.66	99.06	98.85	98.23	99.75	98.64	99.06	98.09

Number of ions on the basis of 24 oxygens

Ca	1.83	1.64	1.43	1.72	1.39	1.80	1.72	1.43	1.72	1.42	1.68
Na	1.01	1.15	1.44	1.18	1.36	1.02	1.25	1.34	1.27	1.37	1.23
K	0.05	0.09	0.05	0.05	0.06	0.02	0.03	0.04	0.03	0.08	0.03
Si	7.46	7.66	7.75	7.56	7.79	7.36	7.45	7.82	7.55	7.68	7.72
Al	4.47	4.28	4.22	4.35	4.20	4.64	4.44	4.16	4.36	4.32	4.16

Mol Proportions

An	63.16	56.87	49.04	58.04	48.94	63.39	57.26	50.71	56.68	49.40	57.04
Ab	34.86	40.00	49.23	39.68	48.58	35.88	41.59	47.70	42.15	47.63	41.79
Or	1.98	3.13	1.73	2.28	2.48	0.73	1.15	1.59	1.17	2.97	1.17

- Abbreviations: P: Cores of partly resorbed phenocrysts
 Mp: Innermost marginal zone of the phenocrysts
 Mc: Core of the matrix plagioclase
 R: Rim of the phenocrysts and the matrix plagioclase.

plagioclase may also have small cores of irregular shape with compositions from 63 to 64% An. These cores probably represent strongly resorbed phenocrysts which have acted as nuclei during the later crystallization of the groundmass plagioclase.

The plagioclase appears to have crystallized in two different magmatic environments. The phenocryst cores were formed as phenocrysts suspended in a slowly cooling magma, and the phenocrysts suffered subsequent resorption though prior to the growth of the rims. The margins of the phenocrysts, on the other hand, formed simultaneously with the groundmass plagioclase after the emplacement of the magma as dykes.

CLINOPYROXENE

Microprobe analyses from four samples (5c, 6a, 7a, 8b) show that the single

7a							8b							
Phenocrysts			Matrix				Phenocrysts			Matrix				
P	Mp	R	Mc	R	Mc	R	P	Mp	R	P	Mc	R	Mc	R
8.84	11.27	8.22	10.71	8.43	10.65	8.53	12.75	12.35	10.60	12.70	11.56	10.73	11.84	10.61
9.90	4.99	6.09	4.82	6.29	4.77	5.87	3.92	4.46	5.23	3.85	4.25	5.18	4.60	5.16
1.15	0.27	0.54	0.28	0.31	0.20	0.40	0.20	0.25	0.22	0.21	0.14	0.31	0.19	0.26
50.01	56.78	59.59	56.67	58.66	57.04	58.38	54.92	55.22	57.33	55.18	55.95	57.72	55.11	56.36
2.41	27.35	23.69	26.50	24.67	26.21	26.27	28.01	27.61	25.97	27.44	28.07	26.74	27.76	25.93
9.31	100.66	98.13	98.98	98.36	98.89	99.45	99.80	99.89	99.35	99.38	99.97	100.68	99.50	98.32

1.90	1.62	1.20	1.56	1.23	1.55	1.22	1.85	1.79	1.54	1.85	1.67	1.54	1.72	1.56
1.04	1.30	1.61	1.27	1.66	1.26	1.52	1.03	1.17	1.37	1.02	1.11	1.34	1.21	1.37
0.02	0.05	0.09	0.05	0.05	0.03	0.07	0.04	0.04	0.04	0.04	0.02	0.05	0.03	0.05
7.44	7.61	8.12	7.70	7.99	7.75	7.81	7.45	7.49	7.77	7.51	7.54	7.72	7.49	7.73
4.45	4.32	3.81	4.25	3.96	4.20	4.14	4.48	4.41	4.15	4.40	4.46	4.21	4.45	4.19

5.96	54.67	41.37	54.18	41.78	54.57	43.50	63.48	59.61	52.13	63.29	59.56	52.39	58.07	52.38
5.04	43.76	55.39	44.16	56.42	44.23	54.10	35.32	38.97	46.56	34.72	39.59	45.81	40.82	46.07
1.10	1.57	3.24	1.66	1.80	1.20	2.40	1.20	1.42	1.31	1.99	0.85	1.80	1.11	1.55

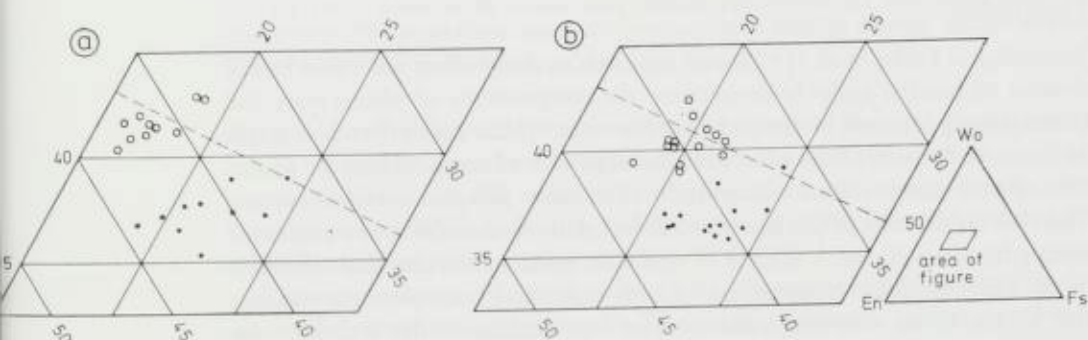


Fig. 9. Plots of clinopyroxenes from Table 4 expressed in terms of the molecular end members enstatite (En: $Mg_2Si_2O_6$), ferrosilite (Fs: $Fe_2Si_2O_6$), and wollastonite (Wo: $Ca_2Si_2O_6$). The dashed line separates pyroxenes from alkaline (above) and subalkaline volcanic rocks (below) (Le Bas 1962). *a* - Clinopyroxene phenocrysts; circles—core; dots—rim. *b* - Groundmass clinopyroxene: circles—core; dots—rim.

pyroxene present in the dykes is an augite. Representative analyses from cores and rims of phenocryst and groundmass pyroxenes are given in Table 4.

The phenocrysts are characterized by relatively homogeneous cores constituting the larger parts of the grains, and strongly zoned margins. The compositional zoning in the phenocrysts consists of Fe increasing and Ca decreasing from core to rim (Fig. 9a), and Al and Ti increasing in the same direction (Fig. 10 a-b).

The cores of the groundmass pyroxenes are somewhat richer in Fe and poorer in Ca than the cores of the phenocrysts, but the compositional zoning follows the same trend with respect to these elements, Fe increasing and Ca decreasing from core to rim (Fig. 9b). Unlike the phenocrysts, however, the compositional zoning of the groundmass pyroxene shows that Al and Ti decrease from core to rim (Fig. 10c-d). The difference between the rims of the phenocrysts and the cores of the groundmass pyroxenes is, therefore, that the latter are richer in Ca and poorer in Fe (Fig. 9a-b). On the other hand there are no significant differences between the groundmass pyroxene cores and the rims of the phenocrysts with respect to the content of Al and Ti (Fig. 10a-d).

Kushiro (1960) and Le Bas (1962) showed that the amounts of Al and Ti which enter clinopyroxene depend on the degree of alkalinity of the parent magma, and that the Al and Ti contents in clinopyroxene could be used to distinguish between alkaline and non-alkaline magmas. Barberi et al. (1971) considered, however, that the physical conditions under which the pyroxene crystallized are at least of the same importance as the composition of the parent magma, and hence the pyroxene cannot be regarded as diagnostic of parental magma type. This view is substantiated by Fig. 10a-d; in these plots the cores of the phenocrysts lie within the non-alkaline field and the margins within the alkaline field of Le Bas (1962). The groundmass pyroxenes show the opposite trend, their cores falling within the alkaline and their rims within the non-alkaline fields.

Discussion

According to Fodor et al. (1975) one approach to deciphering the liquid line of descent of basaltic rocks is to compare the compositions of phenocrysts and groundmass pyroxenes in one and the same rock. These will reflect two stages in the crystallization of the melt, provided that mineral compositions are a function of melt compositions and crystallization takes place in a closed system. The bulk chemistries of the Sunnfjord dolerites show that the dykes originated from a fractionated basalt magma of tholeiitic affinity. The chemical similarity of the different dykes with respect to both major and trace elements suggests that all the dykes were emplaced more or less simultaneously, and from the same source. The compositional zoning of the phenocryst and groundmass pyroxenes might, therefore, provide a record of the nature of the crystallization of the melts both before and after emplacement of the dykes.

It appears reasonable to suppose that the melts which produced the Sunn-

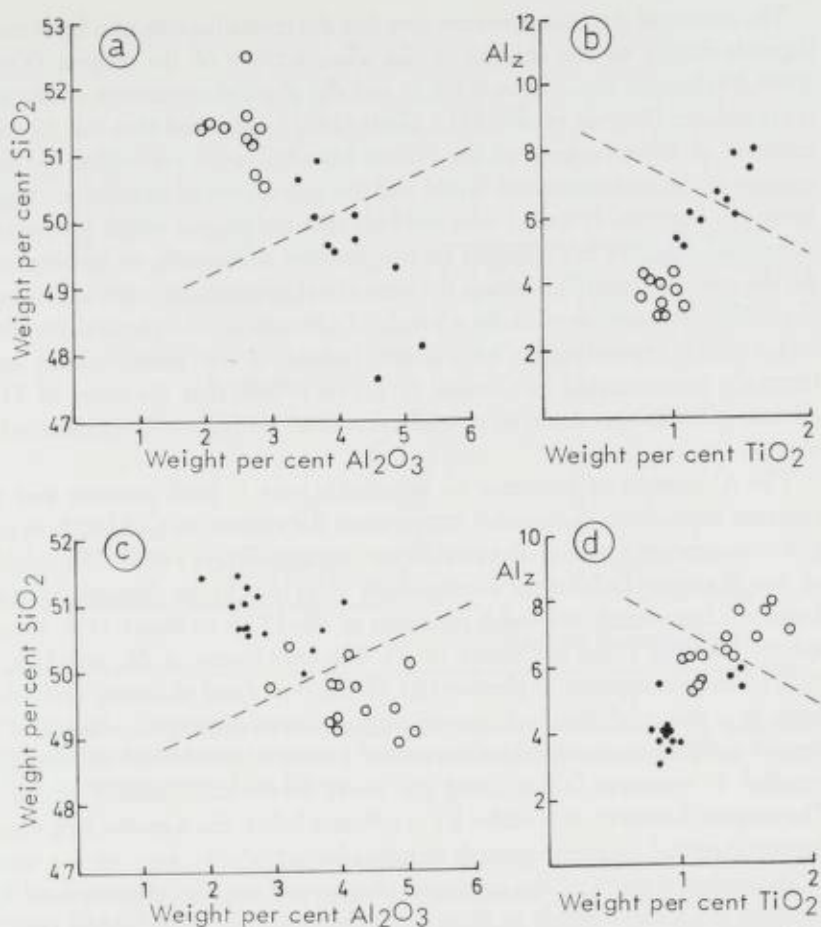


Fig. 10. Plots of clinopyroxene compositions from Table 4. Symbols as in Fig. 9. *a* and *c*: SiO₂ versus Al₂O₃ plots of phenocrysts and groundmass pyroxene, respectively. The dashed line separates pyroxenes from subalkaline (above) and alkaline volcanic rocks (below) (Le Bas 1962). *b* and *d*: Al_z versus TiO₂ plots of phenocrysts and groundmass pyroxene, respectively. The dashed line separates pyroxenes from alkaline (above) and subalkaline volcanics (below) (Le Bas 1962).

fjord dolerites originated by fractionation of a primitive tholeiitic parent magma which occupied a deep-seated magma chamber. At a certain stage in the fractionation history of this magma, both plagioclase and clinopyroxene were liquidus phases. Plagioclase with a composition from An 63 to 64 commenced crystallization before clinopyroxene (Wo 40.4–42.7).

The enrichment of Al_z in the rims of the clinopyroxene phenocrysts is undoubtedly related to an increase in Ti content (Table 4). Verhoogen (1962) showed on the basis of thermodynamic considerations, that the entry of Ti into clinopyroxene is favoured by high temperature and is directly controlled by silica activity. The compositions of clinopyroxenes from volcanic rocks are consistent with this interpretation (Le Bas 1962).

The nature of the clinopyroxene trend in the crystallization of a basic magma depends mainly on the changes in the silica activity of the magma (Kushiro 1960, Verhoogen 1962, Brown 1967) and the physical conditions under which it crystallizes (Barberi et al. 1971). Gibb (1972) suggested that the Al and Ti contents of clinopyroxene of the Shiant Isles Sill were controlled by the Ti content of the undersaturated liquid and the appearance of titaniferous magnetite on the liquidus. It would seem unlikely that the magma which produced the Sunnfjord dolerites has changed its composition sufficiently to be responsible for the compositional differences between the clinopyroxene cores and margins; the differences are more likely a result of changes in the physical conditions under which crystallization took place. Indeed, it has recently been experimentally demonstrated by Gamble & Taylor (1980) that the entry of Ti and Al into the clinopyroxene is strongly favoured by high cooling rates of the magma.

The Al content of pyroxene in subsolidus runs is both pressure and temperature dependent; at constant temperature the content of $\text{CaAl}_2\text{SiO}_6$ in clinopyroxene reaches a maximum at moderate pressures (Hays 1967). The solubility of the titanium Tschermack's component ($\text{CaTiAl}_2\text{O}_6$) in diopside increases, however, from nearly nil under pressures of 10–25 kb to about 11% at atmospheric pressure (Yagi & Onuma 1967). The enrichment of Al₂ and Ti in the rims of the clinopyroxene phenocrysts of the Sunnfjord dolerites may, therefore, be a result of marginal growth during ascent of magma. Ascent of the magma carrying suspended phenocrysts of basic plagioclase and clinopyroxene resulted in pressures falling along the trend drawn schematically in Fig. 11. The magma, however, was under PT conditions below the liquidus long enough for the marginal pyroxene growth to take place.

The marginal parts of the pyroxene phenocrysts are also characterized by a decrease in Ca and increase in Fe towards the rim. This is probably a result of depletion of the magma in Ca due to simultaneous crystallization of plagioclase. The growth of the zoned margins of the pyroxene phenocrysts, therefore, probably took place under decreasing pressure and mainly under PT conditions within the stability field of Pl + Cpx + L, with the exception of the outermost rims (Fig. 11). By a further fall in pressure, plagioclase was no longer a liquidus phase and resorption of plagioclase phenocrysts took place.

There exists an unquestionable relationship between water pressure ($p\text{H}_2\text{O}$) and the order of appearance of the mineral phases in basaltic magmas (Yoder & Tilley 1962, Nesbitt & Hamilton 1970). The sequence of groundmass crystallization in the Sunnfjord dolerites, which appears to have been pyroxene–plagioclase–titanomagnetite, probably took place under relatively high $p\text{H}_2\text{O}$; under these conditions pyroxene will crystallize before plagioclase.

Fodor et al. (1975) established that the ratio $\text{FeO}/(\text{FeO} + \text{MgO} + \text{CaO})$ for groundmass clinopyroxenes in Hawaiian tholeiitic rocks is dependent on the same ratio in the liquid by the onset of the pyroxene crystallization. The strong resorption of plagioclase phenocrysts which took place prior to the crystallization of the groundmass clinopyroxene within the Sunnfjord dolerites led to a

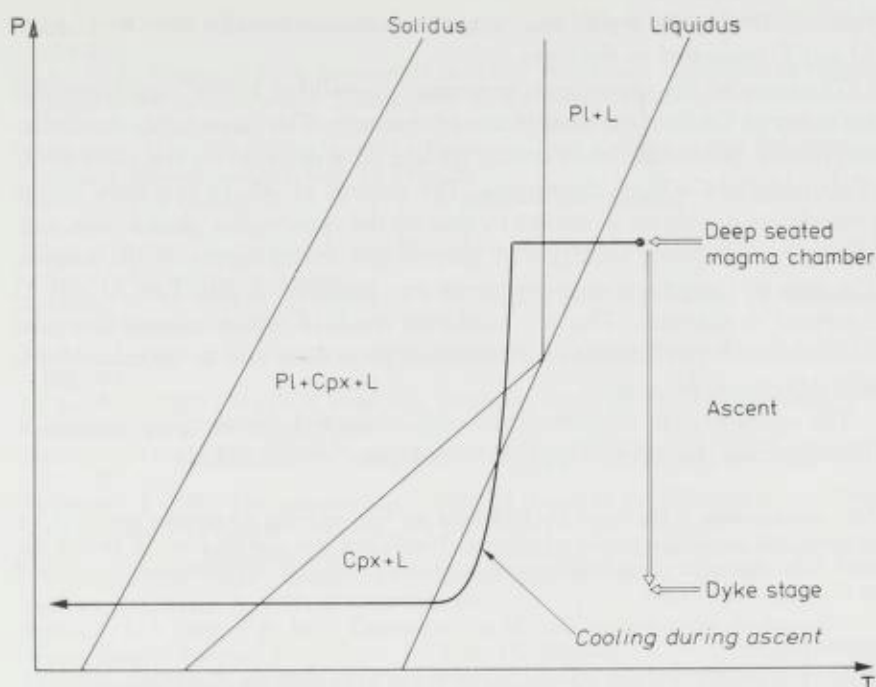


Fig. 11. Hypothetical PT diagram (S. Maaloe pers. comm. 1979) showing the suggested evolution of phenocrysts based on textural features and mineral compositions. Pl — plagioclase; Cpx — clinopyroxene; L — liquid.

decrease in the ratio $\text{FeO}/(\text{FeO} + \text{MgO} + \text{CaO})$ in the magma; hence the groundmass pyroxene cores were richer in Ca than the rims of the phenocrysts. The high content of Al_2 in the groundmass pyroxene clearly demonstrates that the magma temperature at which their cores commenced crystallization was of the same order as during the growth of the margins of the pyroxene phenocrysts (Verhooogen 1962, Boyd & England 1964, Akela & Boyd 1973). The decrease in the Al_2 content in the marginal part of the groundmass pyroxene was a function of falling temperatures, the simultaneous crystallization of groundmass plagioclase and an increase in the activity of SiO_2 consequent upon titanomagnetite crystallization.

Summary and conclusion

The major part of the investigated dolerite dykes from Sunnfjord are sub-alkaline, strongly fractionated ferrobasalts that show many geochemical similarities with continental tholeiitic basalts. Textural and mineralogical compositions of plagioclase and clinopyroxene phenocrysts suggest that crystal fractionation started at relatively high pressure. During ascent of the plagioclase- and clinopyroxene-phyric magma, plagioclase was partially resorbed, a phenomenon ascribed to rapid decrease in pressure without any significant reduction in tem-

perature. During the evolutionary stage the pyroxene margins were enriched in Al and Ti compared to the cores.

The cores of the groundmass pyroxenes crystallized before plagioclase and are richer in Ca than the rims of the phenocrysts. This is probably due to resorption of plagioclase phenocrysts, leading to a decrease in the ratio $\text{FeO}/(\text{FeO} + \text{MgO} + \text{CaO})$ of the magma. The content of Al_2 in the cores of the groundmass pyroxenes is similar to that of the rims of the phenocrysts, suggesting no significant reduction in temperature during ascent of the magma. The rims of the groundmass pyroxenes are, however, depleted in Al and Ti compared to the cores. This is a combined result of falling temperatures, the simultaneous crystallization of groundmass plagioclase and an increase in the SiO_2 activity of the magma.

The crystallization of groundmass plagioclase and the marginal growth of the plagioclase phenocrysts apparently took place simultaneously.

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