Pyroxenes of the Fen alkaline complex, Norway

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Abstract

Compositional data are presented for pyroxenes from the undersaturated rocks of the Fen alkaline complex. Four groups of pyroxenes are present: (1) Al–Na diopsides rich in $CaAl_2SiO_6$, forming the cores of phenocrysts in damkjernite; (2) Ti–Al salites rich in $CaTiAl_2O_6$, occuring as rims to phenocrysts and as strongly zoned discrete crystals in damkjernite and vibetoite; (3) an acmitic–hedenbergite series found in urtites, ijolites, and silicocarbonatites; (4) an acmitic series characteristic only of the later stages of urtite crystallization. Damkjernites are considered to have evolved at high temperatures over a very wide pressure range and the closely related vibetoites at relatively lower pressures and temperatures under H_2O-rich conditions. Other rocks in the complex formed at low pressures under CO_2-rich conditions, possibly over a range of temperatures. Pyroxene and mica compositions indicate that urtite is not simply related to ijolites by fractional crystallization and that søvites are unlikely to be the end product of extensive crystallization of the ijolite–silicocarbonatite series. The Fen complex is considered to represent the root of an undersaturated volcano and the rocks present are the result of the crystallization under different pressures, temperatures, and volatile conditions of several batches of the same undersaturated (nephelinite or alkali basalt) magma. Thus none of the rocks currently exposed at Fen are related by *in-situ* fractional crystallization of a single batch of magma.

Introduction

The Fen complex of alkaline rocks and carbonatites intrudes Precambrian granite-gneisses just to the west of the Oslo graben, 119 km southwest of Oslo. The geology of the complex (Fig. 1) has been described by Brøgger (1921) and Saether (1957) and is summarized by Barth and Ramberg (1966).

Saether observed that two sequences of intrusion were involved in the formation of the complex. The initial sequence comprised rocks of the ijolite series, silicocarbonatites (hollaite, kåsenite), and carbonatites, dominantly søvite with minor rauhaugite. Intrusion of these rocks was accompanied by intense fenitization of the country rocks. The second sequence of intrusions commenced with damkjernite, a type of lamprophyre, which was subsequently altered and metasomatized in many places by a magnesium-rich carbonatite to rauhaugite and rødberg (hematite carbonatite). Ramberg (1973) has established by means of gravity studies that the carbonatites probably form only a thin veneer over a pipe of dense material (probably damkjernite and/or vibetoite) which

extends to great depths below the complex. Griffin (1973) has shown that spinel lherzolites in the damkjernite equilibrated at pressures of 10–15 kbar at 1200–1250°C, implying a mantle origin for at least the damkjernite.

Mitchell and Brunfelt (1975) have proposed that the Fen complex represents the roots of a nephelinite volcano and that all of the rocks in the complex were derived from a H_2O, CO_2-rich nephelinite. Damkjernites were considered to have formed by crystallization of nephelinite over a wide pressure range at high temperatures. The søvites and ijolites were thought to represent immiscible fractions of nephelinitic liquids formed at low pressures and temperatures. Evolution of the ijolite series was dominated by low-pressure differentiation, with the final liquids being represented by the silicocarbonatites in which residual CO_2 was concentrated. In this petrogenetic scheme the søvites are not the ultimate differentiation products of ijolitic magmas as envisioned by Saether (1957).

Despite the importance of the area in the history of alkaline rock petrogenesis, little information has
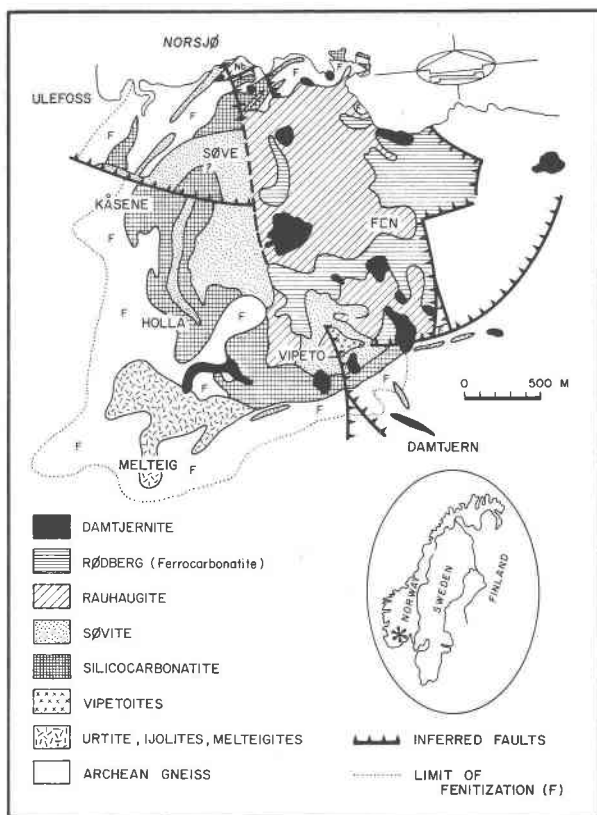
Fig. 1. Geology of the Fen alkaline complex, after Saether (1957) and Ramberg (1972).

been published on the composition of the common rock-forming minerals at Fen, as many previous studies have concentrated upon the exotic minerals associated with the niobium and rare-earth mineralization.

This paper presents compositional data for pyroxenes and uses these data to assess the relationships between the major rock types. The samples studied were from the following localities (Fig. 1): damkjernite—Damtjern; vibetoite—Vipeto farm area; urtite, ijolite, melteigite—Melteig farm area; silicocarbonatites—Holla area; søvites—Søve farm, Hydro and Cappelen quarries.

Mineral compositions were determined at Purdue University on a MAC 500 automated wave-length dispersive microprobe (Finger and Hadidiacos, 1972) with the Bence and Albee (1968) alpha factor data correction method.

Representative analyses of pyroxenes are presented in Tables 1 to 6. In the tables, structural formulae are given, in which all Fe is calculated as FeO. The Fe_2O_3 and FeO contents quoted have been derived by combining all the Na with an equivalent

amount of Fe^{3+} as acmite. This procedure is not unreasonable for pyroxenes from alkaline rocks, as wet-chemical analyses have shown them to be essentially members of the acmite–hedenbergite–diopside series (Tyler and King, 1967). The method provides a reasonable estimate of the acmite content and obviates the problems inherent in estimation of ferric iron by calculation on a stoichiometric basis, e.g. Si analytical errors and possible non-stoichiometry. In Tables 1 to 6 data are recalculated into theoretical end-member components in the sequence: Ti-pyroxene, CaTs, Ac, Wo, Fs, En, as these components most adequately describe the compositional variation. This assignment scheme is least adequate for the Al–

Table 1. Representative analyses of pyroxenes from damkjernites

	1	2	3	4	5	6	7	8
SiO_2	51.2	49.6	48.5	49.8	43.8	43.2	39.4	39.2
TiO_2	0.9	1.4	1.6	1.2	2.8	3.6	4.8	5.6
Al_2O_3	7.6	8.5	9.5	7.4	10.0	10.3	12.3	13.1
Cr_2O_3	0.3	0.1	0.2	0.3	0.1	0.0	0.0	0.0
FeO*	4.4	3.8	4.2	4.0	5.9	6.1	6.8	6.6
MnO	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
MgO	16.0	14.5	13.6	14.5	13.0	12.0	12.5	10.3
CaO	19.3	22.6	22.1	22.4	24.2	24.7	23.6	24.2
Na_2O	1.5	0.9	1.0	0.8	0.3	0.1	0.1	0.3
	100.3	101.5	100.8	100.5	100.2	100.1	99.6	99.4
$Fe_2O_3^+$	3.8	2.2	2.4	2.0	0.9	0.3	0.4	0.7
FeO	1.0	1.8	2.0	2.2	5.1	5.8	6.4	6.0

Structural formula based on 6 oxygens

	1	2	3	4	5	6	7	8
Si	1.836	1.788	1.764	1.815	1.640	1.623	1.500	1.497
Ti	0.024	0.038	0.044	0.033	0.079	0.102	0.137	0.161
Al	0.321	0.361	0.407	0.318	0.441	0.456	0.552	0.589
Cr	0.009	0.003	0.006	0.009	0.003	0.000	0.000	0.000
Fe^{2+}	0.132	0.115	0.128	0.122	0.185	0.192	0.217	0.211
Mn	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Mg	0.855	0.779	0.737	0.788	0.726	0.672	0.710	0.386
Ca	0.742	0.873	0.861	0.875	0.971	0.995	0.963	0.990
Na	0.104	0.063	0.071	0.057	0.022	0.007	0.007	0.022

Mol.% end members

	1	2	3	4	5	6	7	8
$CaTiAl_2O_6$	2.5	3.6	4.3	3.4	7.6	10.0	13.2	15.7
$CaAl_2SiO_6$	12.9	14.1	15.8	12.4	7.7	7.9	5.3	8.2
$NaFeSi_2O_6$	10.4	6.0	6.7	5.6	2.4	0.9	1.0	1.9
$Ca_2Si_2O_6$	29.6	34.7	33.2	35.9	35.9	39.6	36.8	36.3
$Fe_2Si_2O_6$	1.5	2.8	3.1	3.3	7.8	8.9	9.7	9.3
$Mg_2Si_2O_6$	43.2	38.9	37.0	39.4	35.1	32.8	34.0	28.7

Recalculated into acmite-hedenbergite-diopside

	1	2	3	4	5	6	7	8
Ac	14.9	8.0	9.2	7.2	2.9	1.1	1.3	2.5
Hd	2.8	6.1	6.9	7.2	17.6	21.2	22.0	23.8
Di	82.3	86.0	83.9	85.6	79.5	77.7	76.7	73.6

1-2, 3-4, cores and margins of colorless to pale green phenocryst cores; 5-8 pale brown to purple-brown Ti-Al salites.
*Total Fe calculated as FeO.+ Fe_2O_3 and FeO calculated by combining all Na_2O as acmite.

Na diopsides of the damkjernites, in which Jd, not acmite, may be the dominant sodium-bearing pyroxene component. However, no attempt has been made to assess Jd contents of these pyroxenes because the low Na content indicates that it is a minor component, with the calculated amount being strongly dependent upon the sequence of assignment of cations between Ti-pyroxene, CaTs, Jd, Ac and possibly calcium ferritschermak's component.

Damkjernite

Damkjernites from the type locality at Damtjern are lamprophyric rocks containing phenocrysts of red-brown titanian phlogopite, yellow-brown titanian pargasite, and clinopyroxene set in a groundmass of brown-green ferropargasite, pyroxene, green phlogopite, manganoan ilmenite, ulvöspinel–magnetite, and calcite. The pyroxene phenocrysts are composed of anhedral pale green cores mantled by anhedral to subhedral overgrowths of purple-brown pyroxenes. Groundmass pyroxenes are euhedral to subhedral pale brown to purple-brown crystals. Olivine is present as anhedral serpentinized crystals and is probably derived by the fragmentation of lherzolite xenoliths (Griffin, 1973). Large nodules (megacrysts) of brown titanian ferropargasite are common.

Table 1 and Figure 2 illustrate that the pyroxenes in the damkjernites are the least-evolved pyroxenes in this complex in terms of their Di/(Di+Hd) ratios. The pale green phenocryst cores are Al–Na diopsides which exhibit a wide range in Al content coupled with a low Ti content (Table 1, anal. 1–4), i.e. the pyroxenes are rich in $CaAl_2SiO_6$ and poor in $CaTiAl_2O_6$. Na_2O and Cr_2O_3 contents of 0–2% and less than 0.5% respectively indicate the presence of minor jadeite and ureyite components. These Al–Na diopsides are complexly zoned with respect to Al_2O_3, which either increases or decreases from core to margin within individual crystals (Table 1, anal. 1–4).

The pyroxenes which mantle the Al–Na diopsides and which form the groundmass pyroxenes are Ti–Al salites, strongly zoned with increasing Ti and Al from core to margin (Table 1, anal. 6–9). This zoning reflects an increase in the $CaTiAl_2O_6$ component at the expense of the $CaAl_2SiO_6$ component. The Ti–Al salites have lower Na_2O (<1%) and Cr_2O_3 (<0.1%) contents and higher FeO contents than the Al–Na diopsides.

Ramberg and Barth (1966) noted that within a 10 km radius of the Fen complex small dikes and plugs of damkjernite are exceedingly abundant and that damkjernite dikes can be found as far as 25 km from
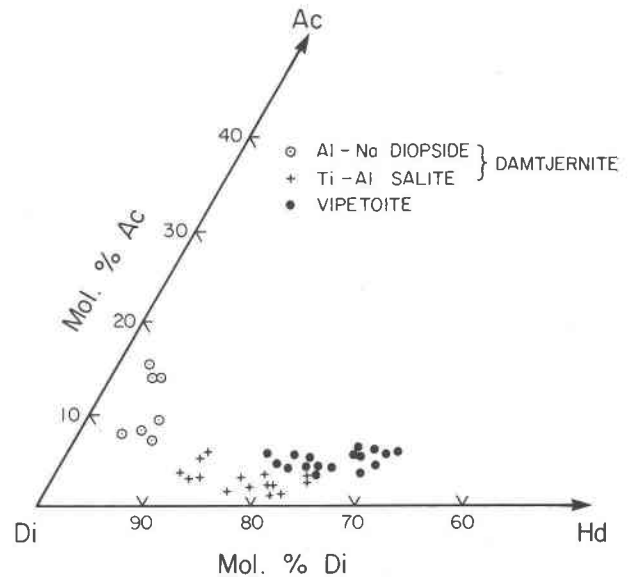

Fig. 2. Compositions of pyroxenes from damkjernites and vibetoites.

the complex. These observations, together with Ramberg's (1973) gravity studies, indicate that damkjernite was one of the most abundant and widely distributed magmas associated with the Fen magmatism. As yet little is known of the extra-complex damkjernites.

The small plug at Sanna (Barth and Ramberg, 1966), 7 km SSW of Fen, shows some similarities to the Fen damkjernites. Here large titanian ferropargasite megacrysts are common and phenocrystal pyroxene cores are Na-salites (Table 2, anal. 1 and 3). However, these cores are mantled by low-Na_2O salites (Table 2, anal. 2–4) with higher MgO contents than the cores. An outer thin discrete rim of apple-green acmitic pyroxene is commonly present on the phenocrysts, and a similar pyroxene (Table 2, anal. 5–7) together with green ferropargasite forms the bulk of the groundmass. Late-stage fluids have crystallized to alkali feldspars, zeolite (?altered nepheline), and calcite. At Sanna the majority of the phenocrysts are euhedral, country-rock xenoliths are uncommon, and spinel lherzolites appear to be absent, indicating that explosive activity was not so intense as at Fen and that the magma cooled relatively slowly. The Sanna "damkjernite" lacks the characteristic red titanian phlogopite and Ti–Al salites found at Fen.

Griffin and Taylor (1975) presented data on dike-facies damkjernites from Brånan and Slåtta. The dikes are petrographically closer to the Fen diatreme

Table 2. Representative analyses of pyroxenes from the Sanna diatreme

	1	2	3	4	5	6	7	8
SiO_6	46.6	45.1	46.8	45.8	52.5	50.3	50.4	50.7
TiO_2	2.4	3.7	2.3	3.2	0.2	0.9	0.4	0.1
Al_2O_3	6.2	8.4	6.4	7.9	0.4	3.2	1.2	0.7
Cr_2O_3	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0
FeO*	10.3	7.4	11.2	6.6	14.2	14.5	19.3	20.7
MnO	0.2	0.1	0.2	0.1	0.5	0.6	0.6	0.0
MgO	10.0	11.5	9.9	12.7	9.8	8.5	5.9	5.0
CaO	21.8	23.6	21.6	23.6	22.0	19.1	17.2	17.1
Na_2O	1.4	0.6	1.6	0.5	1.3	3.0	4.1	4.0
	99.0	100.4	100.1	100.4	100.9	100.1	99.1	98.3
$Fe_2O_3^+$	3.7	1.6	4.0	1.2	3.5	7.8	10.6	10.3
FeO	7.0	6.0	7.6	5.5	11.1	7.5	9.8	11.4

Structural formula based on 6 oxygens

Si	1.788	1.692	1.783	1.710	1.997	1.931	1.998	2.031
Ti	0.069	0.104	0.066	0.089	0.006	0.026	0.012	0.003
Al	0.281	0.372	0.287	0.348	0.018	0.145	0.056	0.033
Cr	0.003	0.000	0.003	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	0.331	0.232	0.357	0.206	0.452	0.466	0.640	0.693
Mn	0.007	0.003	0.006	0.003	0.016	0.020	0.020	0.000
Mg	0.572	0.643	0.562	0.707	0.556	0.486	0.348	0.299
Ca	0.896	0.949	0.882	0.944	0.897	0.786	0.741	0.734
Na	0.105	0.047	0.118	0.036	0.096	0.226	0.315	0.311

Mol.% end members

$CaTiAl_2O_6$	6.9	10.3	6.6	8.9	0.5	2.5	1.2	0.3
$CaAl_2SiO_6$	4.9	5.2	5.2	5.0	0	3.7	0.1	1.3
$NaFeSi_2O_6$	10.6	4.5	11.3	3.4	9.8	22.2	30.9	30.3
$Ca_2Si_2O_6$	38.3	39.1	37.6	39.5	44.5	35.7	35.0	35.0
$Fe_2Si_2O_6$	11.0	9.3	11.9	8.4	17.5	11.9	15.8	18.6
$Mg_2Si_2O_6$	28.2	31.6	27.5	24.9	27.7	24.0	27.0	14.6

Recalculated into acmite-hedenbergite-diopside

Ac	12.2	5.5	13.1	4.1	10.0	23.7	32.0	31.4
Hd	24.7	21.4	26.3	18.6	34.9	25.2	32.8	38.5
Di	63.1	73.1	60.6	77.3	55.2	51.1	35.3	30.2

1,3 clear phenocrysts cores, 2-4 pale green margins to phenocryst cores, 5-7 euhedral green groundmass pyroxenes, 8 phenocryst core from Branan dike (Griffin and Taylor, 1975).
*Total Fe calculated as FeO. $+ Fe_2O_3$ and FeO calculated by combining all Na_2O as acmite.

facies damkjernite than the Sanna rocks, but a notable difference is the occurrence of nepheline phenocrysts and late-stage feldspars. Pyroxene phenocryst cores are again Na-salites, but cores of acmitic hedenbergite (Table 2, anal. 8) identical to the groundmass pyroxenes found at Sanna (Table 2, anal. 7) and similar to pyroxenes in Fen silicocarbonatites also occur (see below). Mantles to all phenocryst cores are richer in MgO and Al_2O_3, as found at Sanna. Groundmass pyroxenes are low Na_2O, low Cr_2O_3 diopsides, similar to the cores of some of the Fen damkjernite phenocrysts. No trends of Ti and Al enrichment are evident. Relationships between the three varieties of damkjernite are discussed below.

Vibetoite

Vibetoites are coarse-grained plutonic rocks, considered by Brøgger (1921) and Saether (1957) to be members of the ijolite series. Mitchell and Brunfelt (1975), on the basis of rare-earth geochemistry, proposed that the rocks are more closely related to damkjernites than to ijolites. Vibetoites consist of anhedral colorless to pale brown pyroxenes overgrown by brown titanian ferropargasite which is in turn mantled by green ferropargasite. The interstices between the pyroxenes are filled by green ferropargasite and green-brown biotite. Apatite is a ubiquitous minor phase. Nepheline and the red titanian phlogopite characteristic of damkjernite are absent.

Pyroxene compositions are illustrated in Figure 2 and representative analyses are given in Table 3. The

Table 3. Representative analyses of pyroxenes from vibetoites

	1	2	3	4	5	6
SiO_2	48.7	44.1	46.4	43.1	48.1	44.5
TiO_2	1.3	2.9	2.4	2.9	1.5	2.6
Al_2O_3	4.9	9.1	7.9	9.6	5.2	8.5
Cr_2O_3	0.0	0.0	0.0	0.0	0.0	0.0
FeO*	7.8	9.3	9.3	9.2	7.8	9.2
MnO	0.3	0.2	0.3	0.3	0.3	0.2
MgO	12.8	10.6	11.1	9.9	12.0	10.7
CaO	24.6	24.0	24.2	23.3	24.6	23.9
Na_2O	0.5	0.7	0.5	0.7	0.7	0.7
	100.9	100.9	101.7	99.0	100.2	100.3
$Fe_2O_3^+$	1.4	1.8	1.2	1.8	1.8	1.7
FeO	6.5	7.7	8.2	7.6	6.2	7.7

Structural formula based on 6 oxygens

Si	1.818	1.666	1.725	1.659	1.811	1.689
Ti	0.036	0.082	0.067	0.084	0.042	0.074
Al	0.216	0.406	0.346	0.436	0.231	0.380
Cr	0.000	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	0.243	0.294	0.289	0.296	0.246	0.292
Mn	0.009	0.006	0.009	0.010	0.010	0.006
Mg	0.712	0.597	0.615	0.568	0.673	0.605
Ca	0.984	0.971	0.964	0.961	0.992	0.972
Na	0.036	0.051	0.036	0.052	0.051	0.052

Mol.% end members

$CaTiAl_2O_6$	3.6	7.9	5.6	8.2	4.2	7.2
$CaAl_2SiO_6$	2.8	6.2	7.3	8.3	3.4	6.0
$NaFeSi_2O_6$	3.8	5.1	3.2	5.1	4.9	4.7
$Ca_2Si_2O_6$	45.0	40.1	41.1	38.7	44.9	40.7
$Fe_2Si_2O_6$	10.0	11.8	12.6	12.0	9.6	11.9
$Mg_2Si_2O_6$	34.8	29.0	30.3	27.8	33.0	29.5

Recalculated into acmite-hedenbergite-diopside

Ac	4.1	5.9	3.8	6.2	5.4	5.5
Hd	21.4	27.2	28.3	28.3	21.3	27.2
Di	74.5	66.9	68.0	65.5	73.3	67.3

1,3,5 and 2,4,6, are cores and margins of light brown pyroxenes respectively.
*Total Fe calculated as FeO. $+ Fe_2O_3$ and FeO calculated by combining all Na_2O as acmite.

pyroxenes are low-Na aluminous salites zoned towards increasing FeO, TiO_2, and Al_2O_3 from core to margin. No discrete cores of Al–Na diopside are present. The pyroxene compositions and evolutionary trends are similar to those of the Ti–Al salites of the damkjernites; however, the Ti and Al enrichment trend is quickly terminated in vibetoite by the crystallization of ferropargasite. No trend of Na enrichment is found.

Urtite

Urtites at Fen contain 70–90% nepheline. Pyroxene occurs as prismatic and anhedral crystals interstitial to anhedral nephelines. Accessory minerals include apatite, calcite, and cancrinite. The nephelines have compositions $Ne_{74}Ks_{25}Qz_1$, within the Morozewicz–Buerger convergence field of plutonic nephelines

Fig. 3. Compositions of pyroxenes from urtites. Pyroxenes zoned along the acmitic trend indicated by solid lines.

Table 4. Representative analyses of pyroxenes from urtites

	1	2	3	4	5	6	7	8	9
SiO_2	48.5	44.8	52.5	53.5	53.1	48.2	50.1	50.1	51.7
Al_2O_3	1.5	2.8	0.4	0.2	0.3	1.7	0.8	0.6	0.4
Al_2O_3	4.7	7.3	1.5	1.1	1.2	4.5	2.6	2.1	1.2
Cr_2O_3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FeO*	7.7	8.9	9.9	11.3	13.4	9.6	12.0	13.8	17.2
MnO	0.2	0.2	0.3	0.5	0.4	0.3	0.6	0.7	0.6
MgO	12.5	10.9	12.6	11.2	8.3	11.3	10.3	8.7	7.1
CaO	23.8	23.5	22.4	19.7	17.8	23.3	21.8	19.8	17.9
Na_2O	0.5	0.8	1.5	2.9	4.6	1.1	1.4	2.7	4.4
	99.4	99.2	101.1	100.4	99.1	100.0	99.6	98.5	100.5
$Fe_2O_3^+$	1.4	2.1	3.7	7.5	11.9	2.8	3.6	6.9	11.3
FeO	6.4	7.1	6.6	4.6	3.0	7.1	8.8	7.6	7.0
Structural formula based on 6 oxygens									
Si	1.832	1.717	1.956	2.009	2.036	1.829	1.919	1.955	2.000
Ti	0.043	0.081	0.011	0.006	0.009	0.049	0.023	0.018	0.012
Al	0.209	0.330	0.066	0.048	0.054	0.201	0.117	0.097	0.055
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	0.243	0.285	0.309	0.355	0.439	0.305	0.384	0.450	0.557
Mn	0.006	0.006	0.009	0.016	0.013	0.010	0.019	0.023	0.019
Mg	0.704	0.623	0.699	0.627	0.474	0.639	0.588	0.506	0.409
Ca	0.964	0.965	0.894	0.793	0.731	0.948	0.894	0.828	0.742
Na	0.037	0.059	0.108	0.212	0.342	0.081	0.104	0.204	0.330
Mol.% end members									
$CaTiAl_2O_6$	4.3	7.9	1.1	0.6	0.8	4.7	2.3	1.8	1.0
$CaAl_2SiO_6$	3.4	3.6	0.5	1.5	0.8	2.0	1.8	1.8	0.2
$NaFeSi_2O_6$	3.9	5.8	10.3	21.1	34.2	7.7	10.4	20.1	32.0
$Ca_2Si_2O_6$	43.7	41.2	43.4	38.4	35.7	43.1	42.2	39.1	35.6
$Fe_2Si_2O_6$	10.0	11.1	10.2	7.2	4.8	11.0	14.0	12.1	11.1
$Mg_2Si_2O_6$	34.8	30.4	34.5	31.2	23.7	31.5	29.2	25.2	20.1
Recalculated into acmite-hedenbergite-diopside									
Ac	4.3	6.6	10.5	21.6	37.5	8.4	11.0	21.3	22.9
Hd	21.4	25.0	20.3	14.8	10.5	23.8	28.8	25.8	23.5
Di	74.3	68.4	69.1	63.6	52.0	67.9	60.2	52.9	42.6

1–3 Al-salites, acmitic hedenbergite trend; 4–6 acmite trend, 7–10, acmitic hedenbergite to acmite trend.
*Total Fe calculated as FeO. + Fe_2O_3 and FeO calculated by combining all Na_2O as acmite.
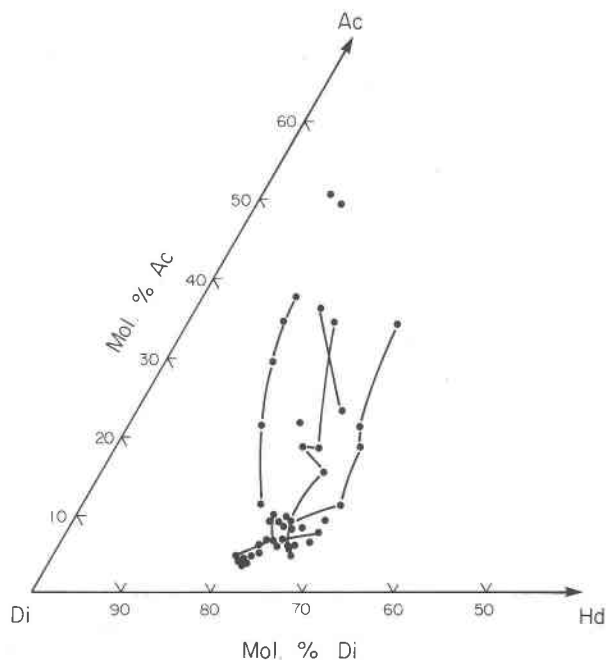
(Tilley, 1954), indicating low temperatures of crystallization or equilibration. Pyroxenes are continuously zoned from pale brown cores to green margins. The cores of the crystals are Al-salites (Table 4, anal. 1–3), similar to the Al-salites in vibetoite and damkjernite. These Al-salites show an initial minor zoning trend towards Ti and Al enrichment, but this trend is quickly reversed and the bulk of the crystals are poor in Ti and Al. Two compositional trends are evident in these low-Al pyroxenes. Representative analyses are given in Table 4.

Trend 1. Rapid decrease in Ti and Al coupled with increase in Fe and Na. The compositional trend is across Figure 3 towards the acmite–hedenbergite join, *i.e.* an acmitic hedenbergite trend. This trend extends from $Di_{80}Hd_{15}Ac_5$ to $Di_{60}Hd_{30}Ac_{10}$, but individual pyroxenes do not show zoning over the whole range. Each pyroxene follows this trend over a short segment of the trend and then undergoes rapid Na enrichment along trend 2 (Table 4, anal. 7–9).

Trend 2. This trend is characterized by strong Na and Fe enrichment towards the acmite apex of Figure 3. Hedenbergite contents remain approximately constant or decrease slightly. Individual pyroxenes follow parallel acmite enrichment trends, each trend originating at a different point along the acmitic hedenbergite trend 1 (Fig. 3), *e.g.* $Di_{69}Hd_{21}Ac_{10}$ to $Di_{41}Hd_9Ac_{50}$ or $Di_{69}Hd_{26}Ac_5$ to $Di_{49}Hd_{16}Ac_{35}$.

Table 5. Representative analyses of pyroxenes from ijolites and melanite–ijolites

	1	2	3	4	5	6	7	8	9
SiO_2	51.1	51.2	52.3	51.2	51.5	50.6	47.0	50.5	50.5
TiO_2	0.7	0.5	0.6	0.3	0.5	0.5	2.5	0.3	0.5
Al_2O_3	1.8	1.4	1.7	1.6	1.4	1.8	5.9	1.1	1.3
Cr_2O_3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$FeO*$	9.8	14.1	11.4	16.1	12.8	15.9	7.8	17.9	17.5
MnO	0.3	0.5	0.4	0.7	0.5	0.7	0.1	0.7	0.7
MgO	12.8	9.6	11.1	7.8	10.2	8.2	12.7	6.9	7.0
CaO	23.2	19.9	21.6	19.0	21.7	20.4	23.4	17.6	21.1
Na_2O	1.3	2.8	1.9	3.1	1.7	1.8	0.5	3.5	1.8
	101.0	100.0	101.0	99.8	100.3	99.9	99.9	98.6	100.4
Fe_2O_3	3.4	7.1	5.0	8.0	4.3	4.6	1.3	9.3	4.7
FeO	6.7	7.7	6.9	8.9	8.9	11.8	6.6	9.5	13.3
Structural formula based on 6 oxygens									
Si	1.915	1.967	1.971	1.985	1.962	1.961	1.770	1.942	1.967
Ti	0.019	0.014	0.017	0.009	0.014	0.015	0.071	0.009	0.015
Al	0.079	0.063	0.058	0.073	0.063	0.082	0.262	0.163	0.060
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	0.307	0.453	0.359	0.522	0.408	0.515	0.246	0.576	0.570
Mn	0.009	0.016	0.013	0.023	0.016	0.023	0.003	0.023	0.023
Mg	0.715	0.550	0.623	0.451	0.579	0.474	0.713	0.395	0.400
Ca	0.932	0.819	0.872	0.789	0.886	0.847	0.944	0.727	0.880
Na	0.054	0.208	0.139	0.233	0.126	0.135	0.037	0.268	0.135
Mol.% end members									
$CaTiAl_2O_6$	1.9	1.3	1.6	1.0	1.5	1.4	7.1	0.8	1.4
$CaAl_2SiO_6$	0.0	0.0	1.5	1.8	0.5	1.9	2.4	0.6	0.4
$NaFeSi_2O_6$	9.2	20.2	14.0	23.1	12.1	13.4	3.6	27.1	13.7
$Ca_2Si_2O_6$	44.2	39.4	41.5	37.6	43.0	40.6	41.7	36.1	42.7
$Fe_2Si_2O_6$	10.2	12.2	10.7	14.3	14.1	19.0	10.2	15.5	21.6
$Mg_2Si_2O_6$	34.6	26.9	30.7	22.2	28.8	23.7	35.0	19.9	20.3
Recalculated into acmite-hedenbergite-diopside									
Ac	9.5	20.5	14.5	24.0	12.4	14.2	4.1	27.7	14.1
Hd	20.6	24.8	22.2	29.8	28.7	38.2	21.6	31.6	44.2
Di	70.0	54.7	63.3	46.2	58.9	47.6	74.3	40.7	41.7

1–2, 3–4, 5–6, cores and rims of acmite hedenbergite trend pyroxenes in ijolite; 7–8 core and rim of strongly zoned pyroxene and 9 unzoned pyroxene in melanite-ijolite.
*Total Fe calculated as FeO. + Fe_2O_3 and FeO calculated by combining all Na_2O as acmite.

Pyroxene crystallization is terminated by the crystallization of minor green biotite or edenitic hornblende.

Ijolite

Ijolites and melteigites (mela-ijolites) consist of euhedral prismatic crystals of clinopyroxene and apatite set in a matrix of nepheline and minor calcite. Sphene and strongly zoned (5–12% TiO_2) melanite are common accessories. The nepheline is similar in composition to that in the urtites. Pyroxenes are pleochroic in shades of light yellow-green to apple-green. Colorless to light brown cores of Al-salite (Table 5, anal. 1) can be found, but the bulk of the pyroxenes are low Ti, low Al, Na-rich salites. The

compositional zoning is one of Na and Fe enrichment along an acmitic–hedenbergite trend (Fig. 4) similar to that determined for the urtite pyroxenes, e.g. $Di_{70}Hd_{20}Ac_{10}$ to $Di_{40}Hd_{40}Ac_{20}$. Figure 4 shows that overlap with urtite pyroxene compositions occurs, but that in general ijolite pyroxenes are richer in Fe. Pyroxenes from ijolites which contain melanite are richer in Na and Fe on average than pyroxenes from rocks which lack melanite (Table 5). The green acmitic hedenbergites from Sanna and the Brånan dike-facies damkjernites are similar to the most evolved ijolite pyroxenes (cf. Table 2, anal. 5–8; Table 5, anal. 8–9).

Silicocarbonatites

Silicocarbonatites, termed pyroxene søvites by Saether (1957) and hollaites or kåsenites by Brøgger (1921), consist of euhedral prisms of pyroxene, apatite, and sphene set in a groundmass of anhedral interlocking crystals of calcite. The pyroxenes are pleochroic in shades of light yellow-green to apple-green and appear similar to the green pyroxene rims richest in Na found in the ijolites. Rarely the pyroxenes are mantled by light yellow-green biotites. Unlike pyroxenes found in all the other rocks at Fen, the silicocarbonatite pyroxenes are only weakly zoned and show little grain-to-grain compositional variation. Compositions range from $Di_{47}Hd_{35}Ac_{18}$ to $Di_{44}Hd_{29}Ac_{27}$ (Table 6) and overlap the Na-rich por-
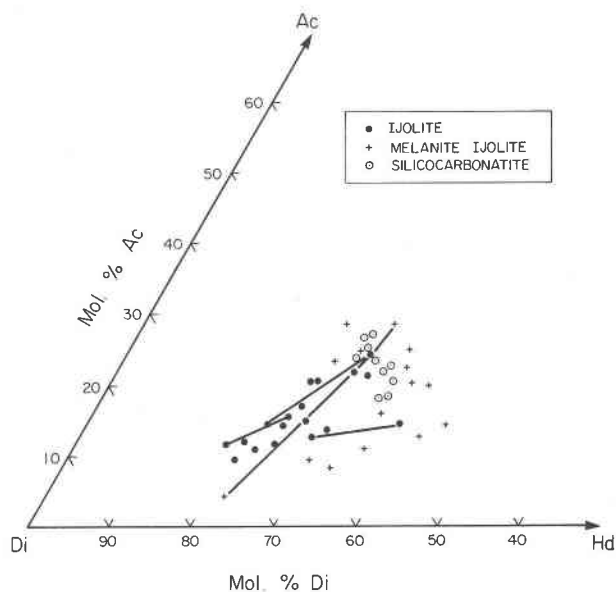

Fig. 4. Compositions of pyroxenes from ijolites, melanite ijolites, and silicocarbonatites. Zonation trends indicated by solid lines.

tion of the ijolite acmitic hedenbergite trend (Fig. 4). They differ from these latter pyroxenes, however, in being richer in MnO (0.8–1.0%) and poorer in Al_2O_3(1.0–1.2%).

Summary and comparison of pyroxene compositional trends

Four groups of pyroxenes are present in the Fen rocks:

(1) *Al–Na diopsides* which form the cores of phenocrysts in damkjernite. These pyroxenes are rich in $CaAl_2SiO_6$ and are similar to megacryst and phenocryst pyroxenes described from a wide variety of alkali basalts, *e.g.* Tenerife, Canary Isles (Scott, 1976); SE Australia (Irving, 1974). Pyroxenes with high $CaAl_2SiO_6$ contents are commonly considered to form at high temperatures (>1000°C) at 10–20 kbar pressure (Thompson, 1974; Irving, 1974). The occurrence of such pyroxenes in association with mantle-derived spinel lherzolite supports a high-pressure origin for these phenocryst cores. The clinopyroxenes in the lherzolites are compositionally different to the phenocrysts in being poorer in Ti and Fe (Griffin, 1973).

(2) *Ti–Al salites* with compositional trends towards increasing Ti and Al content are found in damkjernites and vibetoites. Pyroxenes with similar evolutionary trends of $CaTiAl_2O_6$ enrichment are found only in undersaturated volcanic rocks, *e.g.* alkali basalts from Tenerife (Scott, 1976), basanites, Massif Central, France (Magonthier and Velde, 1976), nephelinites, Bathurst Island, Canada (Mitchell and Platt, unpublished data), and possibly nephelinites of the Eastern Rift of Africa (King and Sutherland, 1966). The development of $CaTiAl_2O_6$-rich pyroxenes appears to be confined to environments of low pressure, low silica activity, and high temperature.

(3) *Acmitic hedenbergite* pyroxenes are found in the urtites, ijolites, and silicocarbonatites. Figure 5 indicates that the compositional trends of the Fen pyroxenes follow the trends characteristic of pyroxenes from undersaturated miascitic plutonic alkaline rocks. The Fen trend is directly comparable with and similar to trends defined by pyroxenes from ijolite-series rocks from Iron Hill (Nash, 1972) and Napak (Tyler and King, 1967), the other trends in Figure 5 being for feldspar-bearing rocks. The acmitic hedenbergite trend is one developed at relatively low temperatures under low H_2O pressures (Nash, 1972; Kogarko, 1977).

(4) *The acmitic trend* is present only within the urtites. Similar trends are known only from søvites at

Table 6. Representative analyses of pyroxenes from silicocarbonatites

	1	2	3	4	5
SiO_2	50.7	52.1	51.9	51.3	51.9
TiO_2	0.5	0.3	0.2	0.4	0.3
Al_2O_3	1.2	1.2	1.0	1.0	1.2
Cr_2O_3	0.0	0.0	0.0	0.0	0.0
$FeO*$	16.3	16.4	15.6	15.8	16.3
MnO	0.9	0.9	0.8	0.9	0.9
MgO	8.1	7.7	8.1	7.4	7.3
CaO	20.2	19.9	19.2	18.5	18.5
Na_2O	2.4	2.6	3.1	3.3	3.4
	100.3	101.1	99.9	98.6	99.8
$Fe_2O_3^+$	6.2	6.7	7.9	8.4	8.7
FeO	10.7	10.4	8.5	8.2	8.5

Structural formula based on 6 oxygens.

	1	2	3	4	5
Si	1.966	1.997	2.005	2.012	2.012
Ti	0.015	0.009	0.006	0.012	0.009
Al	0.055	0.054	0.046	0.046	0.055
Cr	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	0.529	0.526	0.504	0.518	0.528
Mn	0.029	0.029	0.026	0.030	0.029
Mg	0.468	0.440	0.467	0.432	0.422
Ca	0.839	0.817	0.795	0.777	0.768
Na	0.180	0.193	0.232	0.251	0.256

Mol.% end members

	1	2	3	4	5
$CaTiAl_2O_6$	1.4	0.9	0.5	1.1	0.9
$CaAl_2SiO_6$	0	1.7	1.2	0.7	1.4
$NaFeSi_2O_6$	17.8	19.3	22.9	24.9	25.4
$Ca_2Si_2O_6$	40.8	39.7	38.7	38.1	37.4
$Fe_2Si_2O_6$	17.1	16.6	13.6	13.5	13.8
$Mg_2Si_2O_6$	23.0	21.9	23.1	21.7	21.1

Recalculated into acmite-hedenbergite-diopside

	1	2	3	4	5
Ac	18.1	20.0	23.8	26.1	26.7
Hd	34.9	34.5	28.3	28.4	29.0
Di	47.0	45.5	50.9	45.5	44.3

*Total Fe calculated as FeO. + Fe_2O_3 and FeO calculated by combining all Na_2O as acmite.

Iron Hill (Nash, 1972), from mela-nepheline syenites at Turja (Fig. 5; Mitchell, unpublished data), and from syenites at South Qôroq (Stephenson, 1972); Stephenson, however, interprets this example as being due to recrystallization. No evidence of such an origin is seen in the Fen, Turja, and Iron Hill pyroxenes, and all are considered to have crystallized directly from the magma. The different acmitic trends (Fig. 3) for individual pyroxenes in the Fen urtites indicate that the residual liquids in these rocks were not of uniform composition and that the pore spaces between the nephelines were not connected.

The following conclusions can be drawn from the pyroxene composition trends:

(1) Damkjernite and the ijolite series are unlikely to be related by any simple process of fractional crystallization.
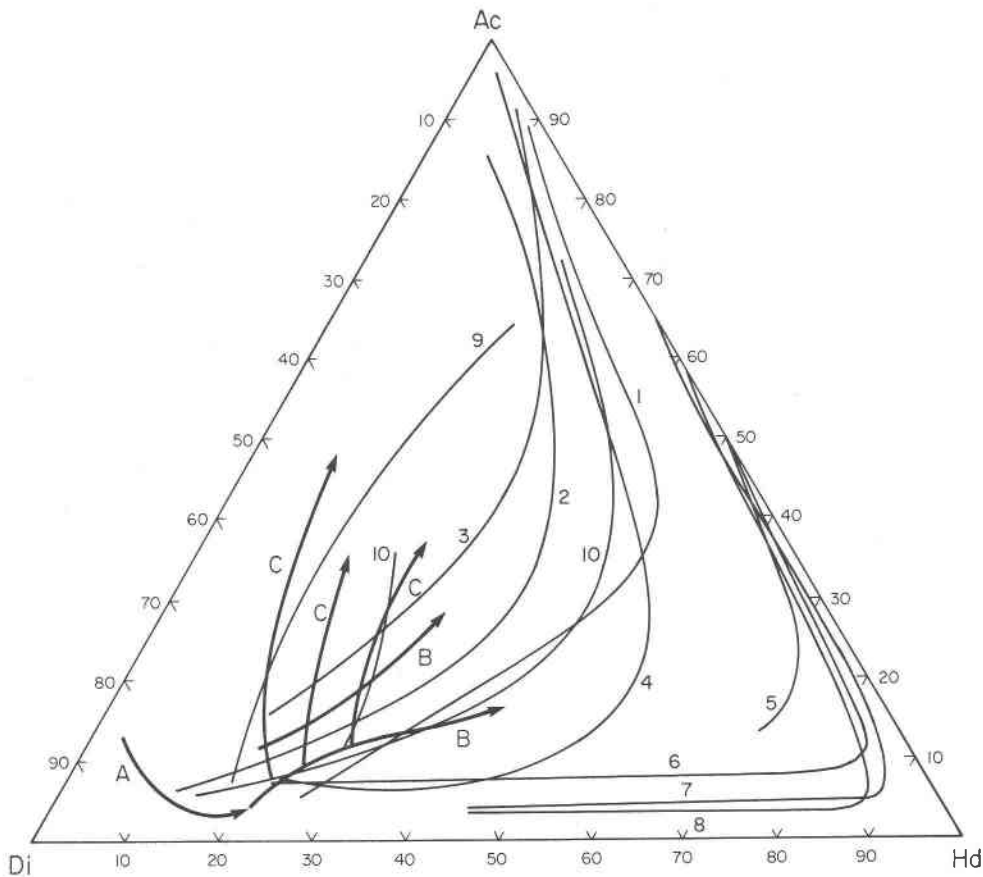
Fig. 5. Composition of pyroxenes from Fen compared with pyroxene compositional trends of other alkaline rocks. A, Fen, damkjernite–vibetoite trend; B, Fen, acmitic hedenbergite trend; C, Fen, acmitic trend; 1, Morotu (Yagi, 1953); 2, Uganda (Tyler and King, 1967); 3, Itapirapua (Gomes *et al.,* 1970); 4, South Qôroq (Stephenson, 1972); 5, pantellerite (Nicholls and Carmichael, 1969); 6, Nandewar (Abbott, 1969); 7, Ilimaussaq (Larsen, 1976); 8, Coldwell (Mitchell and Platt, 1978); 9, Turja (Mitchell, unpublished data); 10, Iron Hill (Nash, 1972).

(2) Vibetoites are more closely related to damkjernites than to ijolites, but their pyroxenes exhibit features characteristic of both series.

(3) Rocks of the ijolite series formed in the sequence ijolite, melanite mela-ijolite, silicocarbonatite, if the extent of Na and Fe enrichment along the acmitic hedenbergite trend is an indicator of the degree of evolution of the parent magma.

(4) Urtites are not related to ijolites by fractional crystallization of the same batch of magma.

Søvites

Saether (1957) mentions that acmite occurs rarely near the margins of the søvites and apparently considers it to be of minor importance. In this study no pyroxenes were found in over 30 thin sections of søvites from the main søvite outcrops at the Cappelen and Hydro quarries and in the Hatveit area. The characteristic mafic mineral of the søvites is mica, the composition of which has some bearing on the relationships of the søvites to the other Fen rocks. In the søvites, micas are euhedral to anhedral pale turquoise phlogopites mantled by bright red tetraferriphlogopites (Table 7, anal. 3–4). These latter micas also occur as discrete crystals. The only other Fen rock which contains phlogopite is damkjernite, in which it occurs as yellow to orange-red phenocrysts. This phlogopite is different from the søvite phlogopite optically and chemically, being richer in TiO_2 (Table 7, anal. 1). In damkjernite and all other Fen rocks except søvite, the final mafic mineral crystallizing from residual fluids is a yellow-green Fe-rich biotite (Table 7, anal. 5–7). The occurrence of such biotite in the silicocarbonatites is considered to be evidence in favor of the hypothesis that the søvites cannot be residua of those rocks.

Petrogenesis

The presence of the titanian pyroxene compositional trend, characteristic of undersaturated volcanic rocks, in damkjernite supports Mitchell and Brunfelt's (1975) contention that the Fen complex represents the root zone of a nephelinitic or alkali basalt volcano. Individual rock units probably reflect the crystallization of different batches of such magmas under different pressure, temperature, and volatile conditions.

Damkjernite from Damtjern commenced crystallization at high pressures and temperatures, as shown by the $CaAl_2SiO_6$-rich phenocrysts and mantle-derived xenoliths. Subsequent crystallization as shown by strongly zoned pyroxenes was probably rapid and occurred at high temperature and low pressures as the magma ascended. The abundance of amphibole and biotite indicates H_2O-rich conditions.

Other "damkjernitic" magmas, however, crystallized under different conditions. At Sanna, titanian pyroxene is absent and the pyroxenes are similar to those of plutonic rocks in other alkaline complexes. Crystallization probably occurred at low pressures and low temperatures under relatively H_2O-poor conditions. Rocks similar to the Sanna rocks have probably formed throughout the Fen region, and fragmentation of such rocks by later intrusions has led to the occurrence of acmitic hedenbergite as nucleation sites for pyroxene phenocrysts in the Brånan dikes. The amphibole megacrysts and large phlogopite phenocrysts common in damkjernite probably were derived by fragmentation of pooled batches of magma by later pulses of the same magma. Thus damkjernites can be considered to be mixed rocks which incorporate, as megacrysts, the products of earlier episodes of crystallization of magmas of similar composition.

Vibetoites are coarse-grained plutonic rocks whose pyroxenes show similarities to those of damkjernite and urtite. Vibetoite probably commenced crystallization at lower pressures and temperatures than damkjernites, under H_2O-rich conditions. The magma was similar in composition to that which produced damkjernites, but the trend towards titanian pyroxenes was halted by slow cooling and the crystallization of abundant amphibole and biotite. Urtites, in contrast to vibetoites, are "dry" rocks (Kogarko, 1977) containing only minor amounts of hydrous phases. The characteristic minerals cancrinite and calcite indicate that CO_2 was probably the dominant volatile species during urtite crystallization. The similarities between the earliest pyroxenes in urtites and those of vibetoite might indicate that, if

Table 7. Representative analyses of micas

	1	2	3	4	5	6	7
SiO_2	37.1	37.2	42.6	41.3	37.3	37.5	36.6
TiO_2	4.5	1.2	0.1	0.1	2.4	2.3	3.3
Al_2O_3	17.3	18.0	10.7	4.1	13.4	13.1	11.8
FeO*	5.5	5.0	5.1	13.4	17.2	24.8	24.4
MnO	0.1	0.1	0.1	0.1	0.5	0.6	0.4
MgO	20.0	25.1	27.3	26.0	15.4	9.3	9.8
CaO	0.1	0.2	0.0	0.2	0.0	0.1	0.1
Na_2O	0.5	1.5	0.4	0.4	0.4	0.2	0.2
K_2O	8.9	6.8	10.2	9.7	9.2	8.8	9.2
	94.3	95.1	96.6	95.6	95.4	96.7	95.9

Structural formula based on 22 oxygens

	1	2	3	4	5	6	7
Si	5.358	5.256	5.995	6.188	5.603	5.783	5.729
Ti	0.489	0.128	0.005	0.011	0.271	0.267	0.388
Al	2.945	2.998	1.775	0.724	2.373	2.381	2.177
Fe^{2+}	0.664	0.591	0.600	1.679	2.161	3.198	3.194
Mn	0.012	0.012	0.012	0.013	0.063	0.078	0.053
Mg	4.305	5.285	5.775	5.806	3.448	2.138	2.286
Ca	0.015	0.030	0.000	0.032	0.000	0.017	0.017
Na	0.140	0.411	0.109	0.116	0.117	0.060	0.061
K	1.640	1.226	1.831	1.854	1.859	1.731	1.837

*Total Fe expressed as FeO. 1-2 orange-red core and green rim of phenocryst in damtjernite, 3 turquoise phlogopite in søvite, 4, red tetraferriphlogopite in søvite, 5,6, and 7 yellow green biotites from urtite, melteigite and silicocarbonatite respectively.

vibetoite had not retained water, then the magma might have crystallized pyroxenes along the acmitic hedenbergite trend.

The relationship between the urtites and ijolites is not a simple one. The first mineral to crystallize in urtite is nepheline, whilst in ijolite it is pyroxene. The rocks are not simple modal variants related by fractional crystallization, and moreover the pyroxenes evolve along different evolutionary trends. Thus urtite cannot be regarded as a leuco-ijolite in a genetic sense. Kogarko (1977) has discussed the formation of urtite and ijolite with reference to her studies of the system apatite–nepheline–diopside, and has noted that the early crystallization of pyroxene is favored by high pressures (and temperatures) and/or H_2O-rich conditions, whilst early nepheline is favored by low pressures and CO_2-rich conditions. The lack of $CaTiAl_2O_6$- and $CaAl_2SiO_6$-rich pyroxenes and the presence of the acmitic hedenbergite trend indicate crystallization of both urtite and ijolite under low pressures at low temperatures relative to damkjernites and vibetoites. The two rocks might conceivably represent crystallization of different batches of magma of the same composition under different volatile conditions, but the more evolved nature of the pyroxenes in ijolites and the large number of crystallization paths possible in "ijolite liquids" (Kogarko, 1977) may preclude such a simple explanation of their relationship. It is however improbable that

they represent different fractions of the same batch of magma.

Ijolites, melteigites, and melanite melteigites are demonstrably related by low-pressure fractional crystallization, on the basis of petrographic and geochemical evidence (Mitchell and Brunfelt, 1975), and could represent fractions of the same batch of magma, with the silicocarbonatites representing the CO_2-rich residua remaining after fractional crystallization.

The søvites are difficult to place in any petrogenetic scheme. They are, on the evidence of La/Yb ratios (Mitchell and Brunfelt, 1975) and mica compositions, unlikely to be residual fractions of ijolitic magmas; the highly magnesian nature of the mica indicates rather a relationship to less evolved magmas. Mitchell and Brunfelt (1975) suggested that søvites represent an immiscible fraction of a carbonated nephelinite or alkali basalt. This hypothesis is supported by the occurrence of carbonate ocelli in the Brånan–Slåtta type damkjernites (Griffin and Taylor, 1975), and the widespread occurrence of liquid immiscibility in CO_2-rich alkaline basic liquids (Ferguson and Currie, 1971).

In summary, the pyroxene data indicate a complex evolutionary history for the Fen area. It is unlikely that any of the rocks currently exposed are related to each other by simple in-situ fractionation of a single batch of magma, with perhaps the exception of the ijolite–silicocarbonatite series. The complex is the result of the crystallization and fractionation of many batches of the same undersaturated basic magma under different pressure, temperature, and volatile conditions, and has formed over the life span of an undersaturated volcano rather than being a single or double episode of alkaline magmatism.

Acknowledgments

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