

## Zoned pyroxenes and amphiboles from camptonites near Gran, Oslo region, Norway

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### SYNOPSIS

CAMPTONITE sills of Permian age, intruded into Cambrosilurian sediments, are present in the northern part of the Oslo region, immediately to the north of Gran, Hadeland. They have been considered, along with associated dykes of camptonite and other minor intrusions of maenaite, to be related to the predominantly gabbroic rocks comprising the Oslo-essexite plugs (Brögger, 1894). Porphyritic varieties of camptonite are the most common, containing phenocrysts of concentrically zoned clinopyroxene and concentrically zoned brown amphibole; but, aphyric varieties with abundant brown amphibole also occur. A second amphibole (actinolite) forms thin, patchy, green overgrowths to some phenocryst or matrix brown amphiboles.

The pyroxenes range in composition from diopside to sahlite. They contain up to 0.7% Cr<sub>2</sub>O<sub>3</sub> in the most Mg-rich zones and up to 0.6% Na<sub>2</sub>O in the most Fe-rich zones. TiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> are in the ranges 0.5-3.8% and 3.0-9.2% respectively. These compositions are similar to pyroxenes from other camptonites and alkali basaltic and alkali gabbroic rocks. 'Normal' zoned phenocrysts, in which an outer pinkish zone surrounds a colourless core in thin section, have more Fe, Ti, and Al, and less Mg and Si in the outer zone. In 'reversed' zoned crystals, the slightly pinkish core contains more Fe, Ti, and Al, and less Mg and Si. Oscillatory zoning, restricted to three concentric zones (pinkish-colourless-pinkish) show the same chemical changes with colour variation. In terms of end-member molecules, substitutions involving CaTiAl<sub>2</sub>O<sub>6</sub>, CaAl<sub>2</sub>SiO<sub>6</sub> plus CaFeSi<sub>2</sub>O<sub>6</sub> replacing CaMgSi<sub>2</sub>O<sub>6</sub> are responsible for the zoning.

The majority of the zoned brown amphiboles are kaersutite following the criteria of Leake (1978). Those zones with Ti < 0.5 atoms per formula unit

range from titanian pargasite and titanian ferroan pargasite to titanian ferro-pargasite. These compositions are similar to kaersutites crystallizing from other camptonites and as inclusions, or as megacrysts and phenocrysts in alkali basalts and derivative rocks. A simple concentric zoning with more Fe and less Mg in the outer zones occurs; but, an oscillatory zoning pattern, with an intermediate lighter brown zone (containing more Mg and less Fe) between two concentric darker zones, is more common. Other elements do not show consistent variations between zones, but Ti generally increases with increase in Al<sup>iv</sup>.

It is postulated that the earliest pyroxene zones crystallized from an alkali basalt magma at approximately 20 km depth. Crystallization of the remainder of the pyroxene phenocrysts and the kaersutite took place at high temperatures (> 940 °C) and at probably greater depths (7-15 km) than crystallization of nearby exposed gabbroic plugs (Oslo essexites). A mechanism of alternate crystallization of pyroxene and kaersutite in response to changes in P<sub>H<sub>2</sub>O</sub>, with some partial resorption of the non-crystallizing phase, is suggested to account for the observed petrographic features and oscillatory zoning in both minerals. The actinolite is a product of late-stage metasomatic activity.

### REFERENCES

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## ZONED PYROXENES AND AMPHIBOLES FROM CAMPTONITES NEAR GRAN,

## OSLO REGION, NORWAY.

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Permian sills and dykes of camptonite intruded into Cambrosilurian sediments are a common occurrence in the northern part of the Oslo rift valley. They have been considered to be related to the predominantly gabbroic rocks comprising the Oslo-esselite plugs (Brøgger, 1894). Many camptonite sills, up to 5 m thick, and associated felsitic rocks (nostonites or masanites of Brøgger, 1894; 1935) are present in a small area to the north of Gran, Hadeland. Samples from this area were used in the present study. Individual pyroxene and amphibole crystals in the porphyritic camptonites exhibit distinctive optical and chemical zoning. Chemical analyses of mineral separates and electron microprobe analyses of individual zones have been carried out to determine the variation in chemistry between zones and the range of composition of the pyroxenes and amphiboles. This data has then been used to determine some constraints on the temperature and pressure of formation of these minerals.

**Experimental methods:** Microprobe analyses were carried out using a Link System model 290-ZX energy-dispersive spectrometer, fitted to a Cambridge Geocam. The method used is the same as described by Dunham and Wilkinson (1978) using an accelerating potential of 15kV and 100 live seconds counting time. Detection limits for the minor elements in the pyroxene and amphiboles calculated as three standard deviations of the background count under the peak position are as follows, expressed in terms of oxide percentage: Na<sub>2</sub>O, 0.20; Al<sub>2</sub>O<sub>3</sub>, 0.24; K<sub>2</sub>O, 0.13; TiO<sub>2</sub>, 0.23; Cr<sub>2</sub>O<sub>3</sub>, 0.11; MnO, 0.15. The chemical analyses were made by X-ray fluorescence spectroscopy using the fusion method of Norrish and Hutton (1969).

**Description of the camptonites.** The camptonites range from medium to fine-grained aphyric types rich in euhedral brown amphibole, interlocking laths of plagioclase and opaque oxides, to porphyritic types containing varying amounts of clinopyroxene (up to 1 cm long) and brown amphibole phenocrysts (up to 2 cm long) set in a matrix similar to the aphyric types. The relative proportions of phenocrysts range from rocks in which the amphibole is exclusively present to those in which pyroxene is overwhelmingly dominant; but, in most of the porphyritic rocks the phenocrysts are evenly distributed. Occasional phenocrysts of ilmenite, often partly oxidized, also occur and rare calcite and/or chlorite pseudomorphs may be after olivine. The matrix feldspars are always zoned, compositions between An<sub>50</sub> - An<sub>24</sub> being obtained by measurements of extinction angles. The bulk of any feldspar is usually in the range An<sub>40</sub> - An<sub>70</sub>. Apatite is a constant accessory. Xenoliths comprising aggregates of brown amphibole, clinopyroxene and opaque oxides are present in many of the sills. In some rocks small ocelli have formed during a late stage of crystallization. These contain either laths of Na-rich plagioclase, calcite or both minerals. There is a varying degree of alteration to the matrix of most rocks: the amphibole is altered to a mass of opaque oxides; the feldspar is sericitized and calcite is abundant.

**The Pyroxenes:** The pyroxene phenocrysts are euhedral to subhedral but invariably the edges are ragged and altered to a mass of opaque oxides and ill-defined brown amphibole. This alteration commonly extends along cracks and cleavages into the bulk of the phenocryst, where occasionally more

clearly defined brown amphibole crystals have grown. A few phenocrysts are unaltered and contain inclusions of the normal matrix minerals. Matrix-sized pyroxene have heavily corroded perimeters and are considered to be residual crystals rather than a directly crystallizing groundmass phase. Zoning can be most easily recognized in thin sections of the least altered phenocrysts. It is a simple concentric type with either an almost colourless core surrounded by an outer pinkish zone or the reverse in which the bulk of the crystal is faintly pinkish in colour when compared with the margin. The former can be called 'normal zoning' because the chemical changes described below are those to be predicted from experimental data, when the outer part of the crystal forms at a lower temperature and pressure than the core. The latter is given the name 'reversed zoning'. Rare examples of a concentric oscillation of colour zones limited at most to a single repeat cycle of colours have also been observed. There is always a sharp contact between zones and both normal and reversed zoning can occur in phenocrysts from the same rock. Hourglass crystals have not been observed.

The pyroxenes are pleochroic with extremes of colour being w = very pale yellow;  $\bar{y}$  = v. very pale pink. Other optical properties are as follows:  $\chi_1$  = colourless zones = 40 - 49°;  $\chi_2$  = pinkish zones = 46 - 52°, 2V<sub>x</sub>, colourless zones = 54 - 57°; 2V<sub>y</sub>, pinkish zones = 51 - 54°. In any individual crystal there is an increase in  $\chi_1$  of 2 of 4 - 6° and a decrease in 2V<sub>y</sub> of 3 - 4° from the colourless to pinkish zones.

Representative electron microprobe analyses of zoned crystals and chemical analyses of separated mineral fractions are presented in Table 1. One disadvantage of the energy dispersive method of probe analysis is the relatively high detection limit. This most probably accounts for the absence of Na, Mn and probably Cr in some of the analyses. Although, when Cr is detected in the pyroxenes it is well above the detection limit of the method and a real difference in Cr between zones must exist.

The pyroxenes span a limited range of composition from diopside to aegite and are Ti-rich with a corresponding high substitution of Al for Si in tetrahedral co-ordination. They are similar to pyroxenes from other camptonites (Vincent, 1953; Velle and Fournon, 1970; Brooks and Rucklidge, 1975; Brooks and Platt, 1975) and alkali basaltic and alkali gabbroic rocks (e.g. Aoki and Kushiro, 1968; Binns, 1969; Le Maître, 1969; Scott, 1976). In normal zoned crystals an increase in Fe, Ti and Al and a decrease in Mg and Si occurs in the outer zone (Table 1, analyses 4 and 5, 6 and 7). In the reversed zoned crystals there is an increase in Fe, Ti and Al and a decrease in Mg and Si in the centre of the crystal (analyses 11 and 12, 13 and 14). The same pattern of compositional changes occurs in oscillatory zoned crystals with the increase in Fe, Ti and Al and decrease in Mg and Si being in the pinkish coloured zones (analyses 8, 9 and 10). Cr does not show a consistent pattern between zones and, although usually the more Mg-rich zones contain more Cr, this is not exclusively the case (e.g. analyses 6 and 7). Na is a minor constituent in these pyroxenes and it is sometimes not detected. However, when detected this element always shows a small increase when Fe, Ti and Al also increase. Analyses 13 and 14 refer to an early crystallising reversed zoned pyroxene included within a zoned amphibole (Table 2, analyses 19 and 20). It seems that the variable conditions in the magma operating to cause the zoning in the pyroxene continued during crystallization of the later amphibole.

The cluster of points along straight lines in Fig. 1a illustrates the Mg/Fe substitution between zones in the pyroxenes. The data on each graph include all analyses from a single rock. Clearly the Mg-Fe substitution differs in amounts from one rock to another as the slopes of the graphs vary and, as none of the slopes are unity, Mg-Fe substitution is not

TABLE 1. Chemical and electron microprobe analyses of clinopyroxenes.

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	No.
Sample	88/75	88/75	73/15	88/75	88/75	84/75	84/75	80/75	80/75	80/75	88/75	88/75	80/75	80/75	Sample
SiO <sub>2</sub>	48.65	47.42	51.86	51.84	45.46	52.76	47.68	44.67	47.77	44.16	48.18	49.93	46.41	48.90	SiO <sub>2</sub>
TiO <sub>2</sub>	0.91	1.32	1.17	0.59	3.23	0.71	1.98	2.87	2.32	3.76	1.45	1.11	2.76	1.63	TiO <sub>2</sub>
Al <sub>2</sub> O <sub>3</sub>	4.35	5.57	5.12	3.19	7.83	3.33	7.55	8.32	5.20	8.68	6.65	4.29	7.79	5.03	Al <sub>2</sub> O <sub>3</sub>
Cr <sub>2</sub> O <sub>3</sub>	-	-	-	0.69	n.f.	0.29	0.45	n.f.	n.f.	n.f.	n.f.	0.32	n.f.	n.f.	Cr <sub>2</sub> O <sub>3</sub>
+FeO	5.52	7.03	6.33	4.08	7.63	4.31	5.83	8.63	6.84	7.50	7.63	5.66	7.85	6.00	+FeO
MnO	0.15	0.10	0.07	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	MnO
MgO	15.80	14.73	14.76	16.52	12.09	15.96	13.32	10.45	13.60	11.28	13.26	15.29	11.29	13.74	MgO
CaO	21.60	21.22	19.12	22.93	25.26	23.13	23.14	23.68	23.81	24.06	21.62	22.43	23.86	24.00	CaO
Na <sub>2</sub> O	0.49	0.56	0.51	0.30	0.36	n.f.	0.34	0.48	n.d.	0.36	0.54	n.f.	0.43	0.33	Na <sub>2</sub> O
K <sub>2</sub> O	0.04	0.14	0.17	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	K <sub>2</sub> O
H <sub>2</sub> O, CO <sub>2</sub> etc.	1.90	1.45	1.33	-	-	-	-	-	-	-	-	-	-	-	H <sub>2</sub> O, CO <sub>2</sub> etc.
Total	99.41	99.54	100.44	100.14	99.86	100.49	100.29	99.10	99.54	99.80	99.33	99.03	100.39	99.63	Total
Formula on basis of 6 oxygens															
Si	1.843	1.801	1.931	1.898	1.712	1.919	1.765	1.707	1.794	1.671	1.805	1.860	1.739	1.826	Si
Al <sub>IV</sub>	0.157	0.199	0.069	0.102	0.288	0.081	0.235	0.293	0.206	0.329	0.195	0.140	0.261	0.174	Al <sub>IV</sub>
Al <sub>VI</sub>	0.037	0.051	0.156	0.036	0.060	0.062	0.094	0.082	0.024	0.058	0.099	0.048	0.083	0.047	Al <sub>VI</sub>
Ti	0.026	0.038	0.033	0.016	0.092	0.020	0.055	0.063	0.066	0.107	0.041	0.031	0.078	0.046	Ti
Cr	-	-	-	0.020	-	0.008	0.013	-	-	-	-	0.010	-	-	Cr
Fe	0.175	0.223	0.197	0.125	0.240	0.131	0.181	0.276	0.215	0.237	0.239	0.176	0.246	0.187	Fe
Mn	0.004	0.003	0.002	-	-	-	-	-	-	-	-	-	-	-	Mn
Mg	0.892	0.854	0.819	0.901	0.679	0.865	0.735	0.595	0.762	0.636	0.741	0.849	0.630	0.765	Mg
Ca	0.877	0.864	0.763	0.899	0.939	0.901	0.918	0.970	0.958	0.976	0.868	0.895	0.958	0.960	Ca
Na	0.036	0.041	0.037	0.021	0.026	-	0.024	0.036	-	0.026	0.039	-	0.031	0.024	Na
K	0.002	0.006	0.008	-	-	-	-	-	-	-	-	-	-	-	K
ΣXY	2.049	2.060	2.015	2.018	2.036	1.987	2.020	2.042	2.025	2.040	2.027	2.009	2.026	2.029	ΣXY
Relative atom %															
Ca	45.1	45.0	42.8	46.7	50.5	47.5	50.0	52.6	49.5	52.8	47.0	46.6	52.2	50.7	Ca
Mg	45.9	43.4	46.0	46.8	36.6	45.6	40.1	32.3	39.5	34.4	40.1	44.2	34.4	40.4	Mg
Fe	9.0	11.6	11.2	6.5	12.9	6.9	9.9	15.0	11.0	12.8	12.9	9.2	13.4	9.9	Fe

1 - 2 Magnetically separated phenocryst fractions corresponding to colourless pinkish zones respectively observed in this section.  
3 Chemical analysis of unaltered pyroxene phenocrysts from camptonite containing pyroxene as only phenocryst phase.  
4 - 5 Normal zoning. Centre and outer pinkish zones respectively.  
6 - 7 Normal zoning. Centre and outer pinkish zones respectively.  
8 - 10 Oscillatory zoning. Centre of phenocryst is intermediate colourless zone, and outermost pinkish zone respectively. The latter zone does not extend around the entire crystal.

11 - 12 Reversed zoning. Centre pinkish zone and outer colourless zones respectively.  
13 - 14 Reversed zoned crystal inclusion within an amphibole phenocryst. Pinkish centre and outer colourless zones respectively.  
1-2 are chemical analyses. 3-4 are microprobe analyses.  
+ Total Fe recorded as FeO.  
H<sub>2</sub>O, CO<sub>2</sub> Loss on ignition plus an amount equal to oxidation of Fe. The value arises from the small alteration of the pyroxene and carbonate impurities.

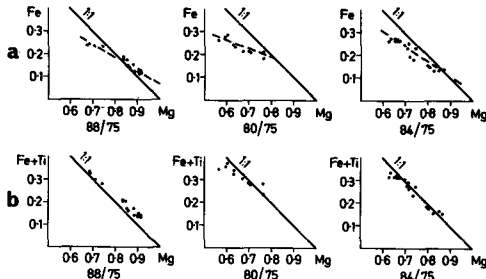


Fig. 1. Plots of atoms per formula unit of Fe and Fe + Ti against Mg for zoned pyroxene phenocrysts from three rocks.

independent of other substitutions. When Ti is added to Fe (Fig. 1b) graphs with slopes closely approaching unity are formed, suggesting that in different rocks varying amounts of Ti could substitute with Fe for Mg. In terms of end-member molecules these substitutions involve  $CaTiAl_2O_6$  (hypothetical titanopyroxene molecule) and  $CaFeSi_2O_6$  (hedenbergite) for  $CaMgSi_2O_6$  (diopside). A plot of Ti against Al and Ti against  $Al_{IV}$  is given in Fig. 2a and 2b respectively. If all of the Al can be accounted for as  $CaTiAl_2O_6$  points should cluster around the line of slope 2.0. However, an excess of Al is present in Fig. 2a and this excess becomes slightly greater at higher values of Al. From Fig. 2b it is clear that the increasing excess is at least partly within tetrahedral sites and hence, probably represents substitution of  $CaAl_2SiO_6$  (Tschermak's molecule) which increases in small amounts as  $CaTiAl_2O_6$  increases. The relatively high substitution of  $CaTiAl_2O_6$  plus  $CaAl_2SiO_6$  particularly in the darker zones is reflected in the Ca-Mg-Fe ratios of Table 1, in which Ca often approaches and sometimes exceeds 5%. It can be concluded that during crystallization of the pyroxenes conditions fluctuated such that incorporation of  $CaFeSi_2O_6$  plus  $CaTiAl_2O_6$  and  $CaAl_2SiO_6$  varied inversely with  $CaMgSi_2O_6$ .

**Amphiboles:** Unlike the pyroxenes, the amphibole phenocrysts in most rocks are completely fresh and unaltered, euhedral and range from equant to elongate crystals in which the long axis is up to 4-times the crystal diameter. A few crystals in some rocks are embayed. Rocks in which the amphibole is not fresh show evidence of alteration throughout the body of the rock, possibly caused by a late stage build up of volatiles. In thin section most phenocrysts show strong colour zoning in shades of brown; the zoning being best observed in the position of maximum absorption of polarized light. The zoning is concentric. A normal type (cf. pyroxene zoning) in which the crystal becomes darker towards the margin, but without a sharp contact between zones, occurs sometimes. The more usual zoning is an oscillatory type with most commonly a core of darker brown occupying a major part of the crystal, followed by an outer lighter zone and then a margin of the crystal.

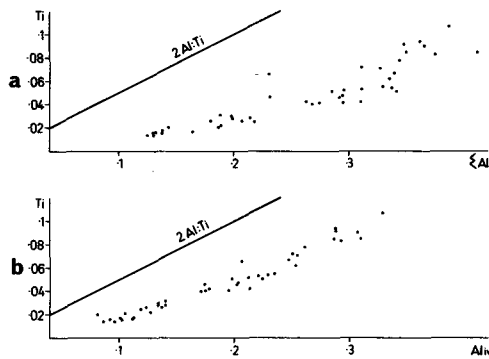


Fig. 2. Plots of atoms per formula unit of Ti against Al and  $Al_{IV}$  for all pyroxene analyses.

darker colour again (Fig. 3). Within each of the inner two zones further concentric minor variations in colour may be present. In the core zone there is sometimes a peppering of minute unidentifiable opaque minerals. The contact between zones is generally sharp, although on occasions, and especially when small scale variations are observed, a gradual darkening of colour extending outwards is present within a single zone. The line of contact between inner zones does not necessarily follow the external outline of the crystal. This line is often rounded and occasionally irregular. Presumably, if one assumes that zones represent individual growth stages of the phenocryst, resorption has taken place after crystallization of the zone and before further growth. Resorption has clearly been taken in the embayed crystals as the pattern of zoning is cut off by the embayment.

Brown matrix amphiboles are euhedral and vary from tabular or lath shaped to reticulating needles. Larger matrix crystals are zoned in a similar way to the phenocrysts. Inclusions of small opaque and apatite euhedra are common in the phenocrysts, and the presence of occasional pyroxene inclusions (with their own pattern of zoning) suggests the later crystallization of the amphibole. This relationship is confirmed in the xenoliths where euhedral pyroxenes are always surrounded (sometimes completely) by large brown amphiboles.

A second pale green amphibole forms thin optically continuous patchy overgrowths to some phenocrysts or matrix brown amphiboles in some rocks. There is a sharp contact between the green overgrowth and brown crystal. Optical properties of the amphiboles are as follows: Brown amphibole: Pleochroism,  $\alpha$ : pale brownish yellow.  $\beta$ : medium brown.  $\gamma$ : medium

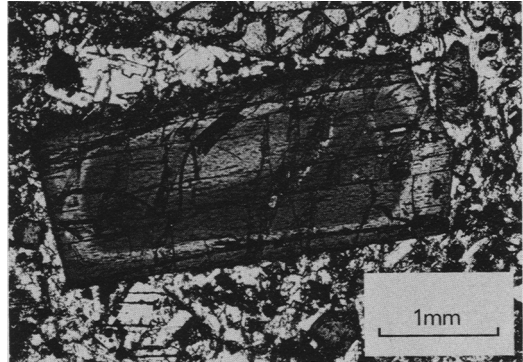


Fig. 3. Photomicrograph of zoned kaersutite phenocryst. Plane polarized light.

orange brown.  $\gamma$ :  $\alpha = 16 - 26^\circ$ .  $2V_{\gamma} = 73 - 80^\circ$ . In zoned phenocrysts  $\chi$ :  $\alpha$  is 2 - 3° higher and  $2V_{\chi}$  is 1 - 2° lower in the lighter coloured zones. Green amphibole: maximum of pleochroism is  $\alpha$ : colourless,  $\gamma$ : pale watery green.  $\chi$ :  $\alpha = 17^\circ$ .

A bulk chemical analysis of phenocrysts separated from one rock and representative electron microprobe analyses of individual zones, matrix crystals and the green amphibole are presented in Table 2. The brown amphibole has a relatively small range of composition. Most analyses fulfil the definition of kaersutite (Wilkinson, 1961) in having Mg > 2 atoms and Ti > 0.5 atoms per formula unit and the majority plot in the field of kaersutite (Leake, 1978). Those with Ti < 0.5 atoms range from titanian pargasite and titanian ferroan pargasite to titanian ferro-pargasite (Leake, 1978); but, as they fall out of the range of kaersutite only marginally in most cases, all are referred to as kaersutite in the present discussion (cf. Aoki, 1970; Brooks and Platt, 1975). The bulk composition of phenocrysts (Table 2, analysis 1) falls near the boundary between titanian ferroan pargasite and kaersutite. The amphibole analyses are similar to kaersutites crystallizing from other comagmatic (Vincent, 1953; Campbell and Schenk, 1950; Velde and Tournon, 1970) and as inclusions, or as megacrysts and phenocrysts in alkali basalts and derivative rocks (Le Maître, 1969; Borley et al., 1971; Frisch and Schmincke, 1969). The composition of the green amphibole sharply contrasts with the kaersutites (Table 2, analysis 24). It is actinolite (Leake, 1978) with low Al, Ti and alkalis. The Mg/Fe ratio is low when compared with the most evolved kaersutite compositions (Table 2, analysis 18). It is most likely a product of the metasomatic activity and associated with the feldspar alteration and calcite formation rather than a consequence of magmatic crystallization.

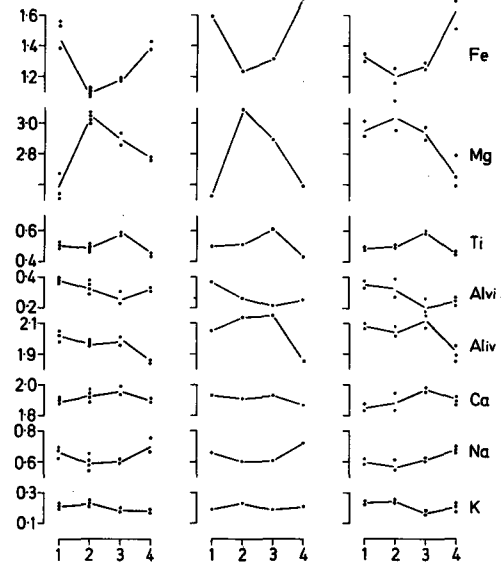


Fig. 4. Diagrammatic representation of changes in chemistry (expressed in atoms per formula unit) between major zones in three oscillatory zoned kaersutite phenocrysts.

- 1: Dark core zone. 2: Intermediate light coloured zone.
- 3: Outer dark zone. 4: Extreme edge of outer dark zone.

Table 2

Chemical and electron microprobe analyses of amphiboles																	
No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	No.
Sample	84/75	84/75	84/75	84/75	84/75	84/75	84/75	88/75	88/75	88/75	88/75	88/75	88/75	88/75	88/75	88/75	Sample
SiO <sub>2</sub>	39.35	40.02	40.76	40.95	41.05	41.19	41.51	40.28	40.00	39.92	40.50	39.83	39.90	39.69	41.00	SiO <sub>2</sub>	
TiO <sub>2</sub>	4.42	4.52	4.60	4.61	4.52	5.15	4.10	4.31	4.37	4.54	5.29	4.03	4.47	4.66	5.52	TiO <sub>2</sub>	
Al <sub>2</sub> O <sub>3</sub>	13.25	13.81	13.45	12.87	13.27	13.07	12.53	14.02	14.09	13.49	12.78	12.59	13.78	13.87	13.67	Al <sub>2</sub> O <sub>3</sub>	
*FeO	12.37	12.57	11.19	9.18	8.91	9.72	11.07	10.59	10.91	9.38	10.01	12.05	12.79	10.04	10.66	*FeO	
MnO	0.13	0.23	0.23	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	0.29	n.f.	n.f.	n.f.	MnO	
MgO	12.87	11.34	12.14	13.92	13.81	13.07	12.58	13.74	13.30	14.26	13.44	12.55	11.36	14.13	13.15	MgO	
CaO	12.00	11.89	11.94	12.08	12.38	12.32	12.02	11.94	11.62	12.25	12.43	11.98	12.08	12.12	12.24	CaO	
Na <sub>2</sub> O	2.28	2.39	2.41	2.10	2.27	2.15	2.60	2.04	2.16	1.89	2.15	2.40	2.29	2.11	2.15	Na <sub>2</sub> O	
K <sub>2</sub> O	1.15	1.04	1.19	1.27	1.17	0.94	0.93	1.30	1.18	1.33	0.89	0.93	0.99	1.23	0.99	K <sub>2</sub> O	
H <sub>2</sub> O	2.42	-	-	-	-	-	-	-	-	-	-	-	-	-	-	H <sub>2</sub> O	
Total	100.24	97.81	97.91	96.98	97.38	97.61	97.34	98.11	97.91	97.14	96.91	97.32	97.59	98.06	98.07	Total	
*Formula on basis of 23 O, OH.																	
Si	5.820	5.954	6.019	6.044	6.028	6.045	6.146	5.901	5.927	5.913	5.933	6.044	5.942	5.860	5.844	6.152	Si
Al <sub>IV</sub>	2.180	2.046	1.981	1.956	1.972	1.955	1.854	2.099	2.073	2.087	2.067	1.956	2.058	2.140	2.156	1.848	Al <sub>IV</sub>
Al <sub>VI</sub>	0.130	0.396	0.360	0.283	0.325	0.306	0.332	0.371	0.360	0.263	0.171	0.259	0.365	0.261	0.164	0.253	Al <sub>VI</sub>
Ti	0.492	0.505	0.511	0.512	0.500	0.569	0.457	0.477	0.483	0.505	0.591	0.452	0.501	0.515	0.611	0.434	Ti
Fe	1.530	1.564	1.381	1.133	1.094	1.192	1.370	1.300	1.343	1.159	1.244	1.504	1.595	1.234	1.312	1.708	Fe
Mn	0.013	0.029	0.029	-	-	-	-	-	-	-	-	0.037	-	-	-	0.042	Mn
Mg	2.837	2.515	2.673	3.063	3.023	2.858	2.776	3.010	2.918	3.142	2.978	2.792	2.526	3.093	2.887	2.854	Mg
Ca	1.902	1.895	1.889	1.911	1.948	1.937	1.907	1.879	1.832	1.941	1.979	1.916	1.908	1.908	1.932	1.875	Ca
Na	0.654	0.689	0.689	0.602	0.647	0.612	0.747	0.582	0.616	0.542	0.620	0.636	0.665	0.600	0.614	0.722	Na
K	0.217	0.198	0.223	0.240	0.220	0.176	0.176	0.244	0.223	0.251	0.168	0.177	0.190	0.231	0.187	0.214	K
OH	2.386	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	OH
{ Y	5.002	5.009	4.954	4.991	4.942	4.925	4.935	5.116	5.115	5.069	4.984	5.044	4.987	5.103	5.026	5.021	{ Y
{ X	2.773	2.782	2.801	2.753	2.815	2.725	2.830	2.705	2.671	2.734	2.767	2.789	2.783	2.739	2.733	2.811	{ X
No.	17	18	19	20	21	22	23	24	1	Kaersutite phenocrysts. Chemical analysis of separated mineral grains. The value for H <sub>2</sub> O is the loss on ignition plus an amount for the oxidation of Fe.							
Sample	80/75	80/75	80/75	80/75	84/75	84/75	88/75	88/75		2 - 7 Oscillatory zoned kaersutite phenocryst. 2 - 3: dark brown core, 4 - 5: light coloured intermediate zone, 6 - 7: centre and extreme outer edge respectively of the dark outermost zone.							
SiO <sub>2</sub>	38.92	36.42	39.46	35.94	40.38	40.86	39.52	52.85		8 - 12 Oscillatory zoned kaersutite phenocryst. 8: dark brown centre of crystal, 9: outer part of dark brown centre zone, 10: light coloured intermediate zone, 11: centre of dark outer zone, 12: Extreme edge of dark outer zone.							
TiO <sub>2</sub>	5.10	2.84	5.03	5.69	5.53	4.17	4.59	0.34		13 - 16 Oscillatory zoned kaersutite phenocryst. 13: dark brown centre of crystal, 14: light brown intermediate zone, 15: dark outer zone, 16: extreme edge of dark outer zone.							
Al <sub>2</sub> O <sub>3</sub>	13.84	13.72	13.76	16.15	12.75	13.01	12.87	0.90		17 - 18 Centre and extreme outer edge respectively of "normal" zoned kaersutite phenocryst.							
*FeO	9.97	23.84	8.98	15.58	10.44	11.03	11.29	19.10		19 - 20 "Normal" zoned kaersutite phenocryst. 19: medium brown coloured zone at centre of crystal, 20: extreme outer edge of crystal.							
MnO	n.f.	0.58	n.f.	0.25	0.25	n.f.	n.f.	0.77		21 - 23 Centre of unzoned matrix kaersutite crystals.							
MgO	13.50	4.54	13.31	7.67	12.82	12.44	12.58	11.96		24 Green amphibole overgrowth.							
CaO	12.59	10.94	12.74	12.09	12.03	12.02	12.17	10.72		2-24 are microprobe analyses.							
Na <sub>2</sub> O	1.86	2.45	1.91	2.22	1.96	2.40	2.31	0.33		* Analysis 1, formula is on basis of 24 O, OH.							
K <sub>2</sub> O	1.38	1.74	1.40	1.36	0.96	0.96	0.97	n.f.		+ Total Fe recorded as FeO.							
H <sub>2</sub> O	-	-	-	-	-	-	-	-									
Total	97.16	97.07	96.59	96.95	97.12	96.89	96.30	96.97									
*Formula on basis of 23 O, OH.																	
Si	5.789	5.827	5.872	5.524	5.989	6.079	5.948	7.946									
Al <sub>IV</sub>	2.211	2.173	2.128	2.476	2.011	1.921	2.052	0.054									
Al <sub>VI</sub>	0.216	0.414	0.286	0.449	0.218	0.360	0.231	0.052									
Ti	0.570	0.341	0.563	0.658	0.617	0.467	0.520	0.038									
Fe	1.241	3.190	1.117	2.002	1.295	1.372	1.422	2.401									
Mn	-	0.063	-	0.032	0.031	-	-	0.080									
Mg	2.993	1.082	2.952	1.758	2.836	2.760	2.823	2.680									
Ca	2.007	1.876	2.031	1.991	1.912	1.916	1.962	1.662									
Na	0.537	0.759	0.551	0.661	0.562	0.693	0.675	0.096									
K	0.262	0.354	0.266	0.266	0.181	0.183	0.187	-									
OH	-	-	-	-	-	-	-	-									
{ Y	5.020	5.090	4.918	4.899	4.997	4.959	4.996	5.251									
{ X	2.806	2.969	2.848	2.918	2.655	2.732	2.824	1.758									

The chemical changes between zones in the kaersutites do not always follow a systematic pattern corresponding to colour changes observed in thin section. Comparison of analyses of spots from different zones is further complicated by continuous changes within some zones. Ideally each zone should be represented by a range of compositions. In the 'normal' zoned crystals there is an increase in Fe and a decrease in Mg in outer zones (Table 2, analyses 17 - 20). The Fe enrichment in some cases is extreme (Table 2, analysis 18) and this zone is also relatively enriched in alkalis and Al<sub>VI</sub>. It is depleted in Ca and Ti. This kaersutite phenocryst is zoned outwards to a titaniferous-pargasite composition.

Within the outer dark zone of oscillatory zoned crystals a less strong, but obvious enrichment of Fe occurs along with a small increase in Al<sub>VI</sub> and Na, a decrease in Mg and Ti and a small decrease in Ca and Al<sub>IV</sub> towards the extreme edge of the crystal (Table 2, analyses 2 - 5, 8 - 10, 13 - 12 and 15 - 16). The chemical changes between zones in some oscillatory zoned crystals are illustrated diagrammatically in Fig. 4. The range of compositions within the dark outer zone is as great as that between the inner zones, even though the more obvious colour changes occur between the inner zones (Fig. 5). The only consistent difference obtained between the

innermost dark brown core and surrounding light coloured zone in the oscillatory zoned crystals is the decrease in Fe and corresponding increase in Mg from the dark to lighter zones (Table 2, analyses 2 - 5, 8 - 10, 13 - 14) (Fig. 4). Significant detectable differences in other elements do exist between spots in these two zones as the analyses show, but results are not consistent in the direction of change with this zoning. The nature of element substitution in the kaersutites is more complex than in the pyroxenes. The matrix kaersutites (Table 2, analyses 21 - 23) are similar to the phenocrysts although crystals appear to have compositions most like the dark outermost zone of the oscillatory zoned phenocrysts.

To obtain the general picture of element substitutions in the range of kaersutite compositions found in individual zones and crystals, a series of plots of atomic proportions against one another has been made in the same way as for the pyroxenes in this and other studies (e.g. Brooks and Platt, 1975; Scott, 1976). Apart from the inverse relationship of Mg and Fe which is obvious from Fig. 4 and the discussion so far, the only other elements which seem to give broadly compatible or incompatible trends in their substitutions are Ti and Al<sub>IV</sub> (or Si). With the exception of one point (the titaniferous-pargasite) there is a general increase in Ti with

increase in  $Al_{IV}$  (or decrease in Si) (Fig. 5). It is interesting that this same trend is present in the pyroxene and, by analogy with CaTlAl<sub>2</sub>O<sub>6</sub> substitution in pyroxenes, one can visualize a hypothetical CaTlAl amphibole end-member (Ti-tschermakite) present in kaersutites. Substitution of this CaTlAl amphibole occurs in pargasite - ferro-pargasite and hastingsite - magnesio-hastingsite (i.e. theoretical end-members of Ti-free kaersutite compositions). A similar correlation between  $Al_{IV}$  and Ti has been observed by Helt (1973) in experimentally produced kaersutitic hornblende; substitution of  $Al_{IV}$  and Ti increased with increasing temperature at 5 kb pressure and reducing conditions.

**Discussion.** Camptonites are normally placed with other porphyritic minor intrusives into the lamprophyre group of igneous rocks. However they contrast with other lamprophyres (excluding monchiquite) in containing a brown amphibole with or without clinopyroxene, rather than a green amphibole and/or biotite. The structural and genetic relationship between minor lamprophyre intrusions and an associated major igneous suite is often speculative (cf. Rock, 1977) yet a possible connection between camptonites and alkali basaltic magmatism is now becoming evident. For example, Woodland (1962), Upton (1965) and Horne and Thompson (1967) have considered camptonite intrusions to have a common source with alkali basaltic magmatism (the latter having an exposed expression as lavas, associated dolerite intrusions, or alkali gabbroic stocks and bosses) centred in the same area, or in some cases, far removed from the camptonite intrusions (e.g. Ramsay, 1955; Gallagher, 1965). Rock (1977) states that camptonites represent alkali basaltic gneiss which became unusually hydrous through influence of an alkaline pluton and then evolved at relatively low

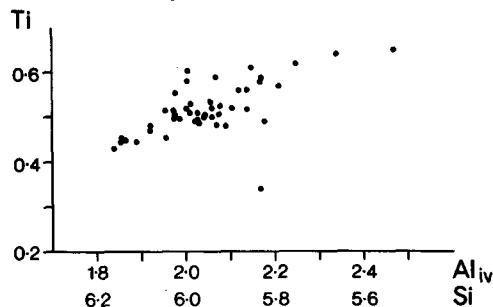


Fig. 5. Plot of atoms per formula unit of Ti against  $Al_{IV}$  for all kaersutite analyses.

pressures. The line of five Oslo-essetite plugs a few kilometres to the west of Gran seems to be the obvious exposed magmatism of the correct type which could be a source for the camptonites as suggested by Brügger (1894), although alkali basalts (ne-normative basanites) have now been found elsewhere in the Oslo rift valley (Ramberg and Larsen, 1978). Ultimately the source of basic magma out of which the pyroxenes and kaersutites could have crystallized is not a problem as Ramberg (1976) interprets gravity data to show that basic intrusives and accumulates, probably along with steeped blocks of less dense material occur at depth in the Oslo region.

The high concentration of pyroxene phenocrysts in some camptonites, the existence of xenolithic aggregates and general petrographic relationships indicate that the pyroxene is an early cumulate phase crystallizing from the parent alkali basalt magma. The composition of the first pyroxene most likely corresponds to the cores of the normal zoned phenocrysts (i.e. diopside with approximately Ca<sub>0.7</sub>Mg<sub>0.3</sub>Fe<sub>0.2</sub>, up to 0.75 Cr<sub>2</sub>O<sub>3</sub> and restricted amounts of Ti and Al when compared with other zones). The reduced amounts of Ti and Al may be a result of the higher pressure of crystallization compared with other zones as Yagi and Onuma (1967) have shown that the solubility of CaTlAl<sub>2</sub>O<sub>6</sub> in diopside decreases with increased pressure. Chromian diopside phenocrysts of closely similar composition have been described by Brooks and Platt (1975) and were interpreted as crystallizing at depths of around 20 km. If a similar depth is argued for the present earliest pyroxene zones it corresponds with crystallization in Ramberg's (1976, p. 142) position (20 kms below the present surface) for a dense crustal body of gabbroic composition, i.e. the magma chamber for the basic rocks in the Oslo region.

The Oslo-essetite plugs are considered by Ramberg (1976) to be storage magma chambers at shallow depth (approx. 3 km below the Permian surface) fed by basaltic magma through narrow vents or feeders from considerably greater depth. These or similar storage chambers at greater depth may be the position of crystallization of the remaining pyroxene zones and the zoned kaersutite phenocrysts. Accumulation of pyroxene and kaersutite crystals took place to varying degrees within the storage chamber prior to emplacement of the camptonites. The high concentration of phenocrysts in some camptonites may be a direct result of the amount of accumulation. Alternatively some filter press action may further concentrate the phenocrysts during intrusion. The increased incorporation of CaTlAl<sub>2</sub>O<sub>6</sub> in the outer zones of normal zoned pyroxene crystals and in the reversed and oscillatory zoned pyroxenes is indicative of a low pressure of crystallization. Also, the overall  $Al_{IV}$  and K contents of the kaersutites are suggestive of relatively low pressure crystallization (Beet, 1970) when compared with some kaersutite megacrysts (e.g. Mason, 1968; Binn, 1969; Aoki, 1970; Brooks and Rucklidge, 1973) which are thought to crystallize at high pressure in the lower part of the crust.

The minimum depth for the storage chamber in which the kaersutite phenocrysts can form is governed by the lower limit of stability of amphiboles in basaltic compositions at 1.4 kbars (Yoder and Tilley, 1962). This is equivalent to approximately 5 km depth, and would rule out the Oslo-essetite plugs as the chambers in which accumulation of pyroxene took place, unless  $P_{20} > P_{10}$  (possible during the build up of water pressure prior to an eruption) or the estimates for post-Permian erosion are in error. The experimental work of Yoder and Tilley (1962) and Holloway and Burnham (1972) which has recently been discussed by Baxter (1978) shows that plagioclase would be expected to crystallize before kaersutite at pressures up to about 3 kbars (11 - 12 km depth) in basalts with tholeiitic or calc-alkali affinities; but, the petrographical relationships within the camptonites clearly indicate that kaersutite crystals formed and accumulated prior to the onset of plagioclase crystallization. However, in Yoder and Tilley's (1962) alkali basalt, the crossover point where plagioclase begins to crystallize before amphibole is at a lower pressure than with other basalts. Thus, the minimum pressure for the crystallization of the phenocrysts could be less than 3 kbars. No firm conclusions can be drawn, but, if the exposed Oslo-essetite is the direct source of material for the camptonites, they were in a position near or at the lower limit for kaersutite to form as a cumulate phase. It is more likely that

the source magma chamber in which the bulk of the pyroxene and kaersutite crystals accumulated was at a greater depth (say 7 - 15 km in Permian time than the Oslo-essetite plugs. The gabbroic rocks in the plugs represent upward migration and crystallization of the basaltic liquid at low  $P_{20}$ . The sills and dykes of camptonite are the result of tapping a high temperature cumulate suspension of ferromagnesian minerals in their host basaltic liquid. A temperature of > 950°C at the pressures envisaged prevented the crystallization of plagioclase in the magma chamber (using the data of Yoder and Tilley, 1962). A high  $P_{20}$  enabled crystallization of matrix kaersutite before feldspar after intrusion.

The presence of varying relative amounts of phenocryst pyroxene and kaersutite indicates that the cumulate phases tapped in the magma storage chamber were either clinopyroxene or kaersutite, or more usually, both minerals. In the latter case there is a random mixture of the phases showing no signs of segregation, and thus the minerals will have had closely connected and possibly interdependent crystallization histories. The magma rising from depth to the storage chamber contained some early formed pyroxene crystals as already discussed. It may also have contained olivine and an opaque phase. Continued cooling in the storage chamber produced crystallization of the outer zones of normal zoned pyroxene crystals and possibly nucleation of other pyroxenes of similar composition to the outer zones. Following an increase in  $P_{20}$ , either as a natural consequence of cooling and crystallization of the pyroxene or from external influence (such as water contained in an alkaline pluton, or possibly Pre-Cambrian gneiss or Cambrosilurian sediments), kaersutite crystallized possibly accompanied by partial resorption of the pyroxenes. The minor variation within major zones in the kaersutite may reflect gradual changes in  $P_{20}$ , composition of liquid and/or temperature; but, the overall contact between the major zones is more likely to be a response to a sudden change such as would occur on eruption of material from the storage chamber. On continued crystallization after eruption and consequent loss of water, pyroxene would form in preference to kaersutite giving rise to a reversal in zoning, especially if there had been a supply of more basaltic liquid at higher temperature from depth. The kaersutites would become unstable and be resorbed, accounting for the rounded shape of inner zones. The amphibole resorption might cause an increased oxygen fugacity and consequent reversal in zoning of the pyroxene as suggested by Friesch and Schmincke (1969) and Brooks and Rucklidge (1973). A further build up in  $P_{20}$  would once again result in kaersutite crystallizing in place of pyroxene. The composition of the new amphibole will correspond to the intermediate light coloured zone, richer in Mg just as is the outer zone of the reversed zoned pyroxenes. Theoretically this postulated alternation of phases and zones could continue indefinitely while crystals accumulated and until they were intruded to their present position. However evidence for continued alternation is not common as the oscillatory zoning is generally restricted to one major cycle only; unless the minor oscillations in the kaersutite are a response to similar, but perhaps smaller changes which affected only the kaersutite or are not detectable in the pyroxene.

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