Chemistry of feldspars in the Ilímaussaq augite syenite with additional data on some other minerals

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The feldspars of the augite syenite have been described by Ussing (1912, p. 188), Hamilton (1964) and Ferguson (1964, 1970, pp. 49–51). These authors used optical and X-ray methods giving only crude clues to chemistry. However, Hamilton (1964, pp. 28–29) noted the scarce occurrence of corroded oligoclase cores, and Ferguson (1970) noted that the Ab/Or ratio is higher in feldspar from the augite syenite than in feldspar from the agpaitic rocks. Below are reported the results of a microprobe reconnaissance study of feldspars from the augite syenite, together with microprobe data on some other minerals. The two samples selected are the same as used in a previous investigation of the mafic minerals (Larsen, 1976). They represent the outermost chilled facies (U-106) and the innermost facies, bordering on the agpaites (150722). Since the augite syenite has apparently congealed inwards from the sides these samples should bracket the compositional range of the minerals present. The analytical technique was as described by Reed & Ware (1975) with the addition that BaO in the feldspars was calculated from the apparent TiO_2 according to the empiric relation $BaO = 1.9 \times \text{'}TiO_2\text{'}$.

Feldspar

Optically the mineral is mostly clear, untwinned and homogeneous-looking, but wavy extinctions and incipient exsolution along cracks and grain boundaries testify to the crypto- to microperthitic nature of the feldspar found by previous workers (op. cit.). In the chilled facies several feldspar grains enclose untwinned cores with slightly different extinction, sometimes with irregular and sometimes with straight-line boundaries towards the mantling
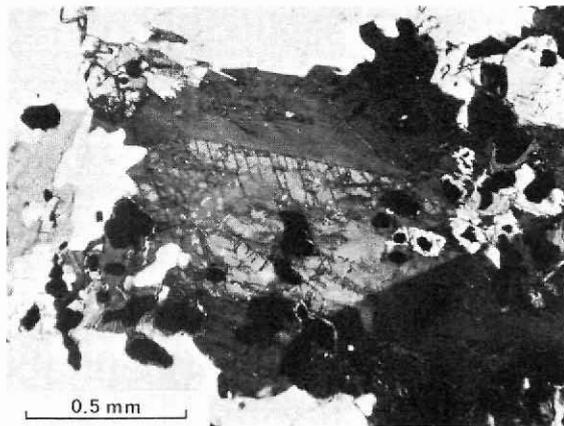

Fig. 1. Feldspar in chilled augite syenite U-106. Core of oligoclase with relatively well-defined outline, surrounded by alkali feldspar.

0.5 mm

Table 1. Representative analyses of feldspars from the Ilímaussaq augite syenite

GGU no.	U-106				150722	
SiO_2	62.35	64.55	64.46	64.03	65.66	65.79
Al_2O_3	23.44	22.22	20.78	20.06	19.87	19.92
BaO	0.68	0.34	1.25	0.48	0.21	0.00
CaO	4.19	2.55	1.29	1.10	0.75	0.53
Na_2O	8.85	9.48	5.69	5.41	6.98	6.37
K_2O	0.76	1.21	7.13	8.07	6.43	7.43
	100.27	100.35	100.60	99.15	99.90	100.04

Cations on the basis of 32 oxygens

Si	11.086	11.398	11.614	11.689	11.790	11.809
Al	4.913	4.626	4.414	4.317	4.206	4.214
Ba	0.047	0.024	0.088	0.034	0.015	0.000
Ca	0.798	0.482	0.249	0.215	0.144	0.101
Na	3.051	3.246	1.988	1.915	2.430	2.219
K	0.172	0.273	1.639	1.879	1.473	1.701
	20.067	20.049	19.992	20.049	20.058	20.044

An	19.6	12.0	6.3	5.3	3.5	2.5
Ab	75.0	80.6	50.2	47.4	59.8	55.2
Or	4.2	6.8	41.3	46.5	36.3	42.3
Cn	1.2	0.6	2.2	0.8	0.4	0.0

feldspar (fig. 1). Such cores are not found in the innermost facies. In the sample from the innermost facies a 3 mm broad zone runs across the section and shows signs of late alteration by a volatile-bearing phase, giving rise to coarse, incoherently exsolved patches of albite in the feldspar.

The feldspar analyses were performed with the electron beam defocussed to approximately 20 microns. Representative chemical analyses are listed in Table 1, and all results are plotted in fig. 2.

The feldspar in the chilled facies (U-106) spans a relatively large compositional range, from oligoclase $An_{20}Ab_{76}Or_4$ to sodic K-feldspar $An_{3.5}Ab_{43.5}Or_{53}$. All analyses with An $\geqq 10\%$ are from the cores mentioned above, and the gap at $Or_{20}-Or_{30}$ is real and represents the break between the cores and the broad margins. The cores are volumetrically subordinate and are overrepresented in the number of dots in fig. 2. The main feldspar is of composition $An_{4-9}Ab_{47-61}Or_{32-48}$ and thus straddles the boundary at Or_{37} between anorthoclase and K-feldspar. The analysis of a bulk feldspar separate from chilled Ilímaussaq augite syenite given by Upton (1964, p. 68) as $An_{8.5}Ab_{58.5}Or_{32}Cn_1$ is in excellent agreement with the microprobe results (fig. 2).
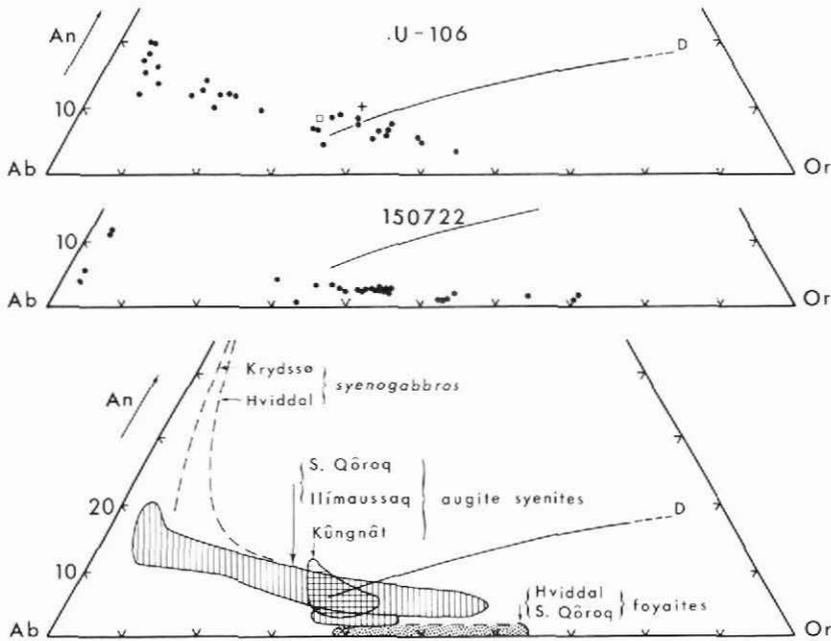
Fig. 2. Feldspar analyses from the Ilímaussaq augite syenite. U-106: chilled facies. Open square = bulk feldspar analysis from the chilled facies (sample 40527, Upton, 1964). Cross = normative feldspar composition of U-106. 150722: innermost facies of augite syenite, bordering on the agpaites.

Comparative Gardar feldspar trends from Upton (1960, 1964) and Stephenson (1976). The feldspar cotectic curve, D, is taken from Tuttle & Bowen (1958).

In the innermost facies (150722), the common feldspar has a much more restricted range in composition, namely $An_{2-4}Ab_{52-63}Or_{34-45}$. The coarsely exsolved K-feldspar in the volatile-influenced patch enlarges the compositional range to $An_{0.5-4}Ab_{28-67}Or_{29-70}$. The exsolved plagioclase feldspar, $An_{4-12}Ab_{85-94}Or_{2-3}$, is Ca-enriched compared to the remaining feldspar.

Barium is a significant minor element. The feldspars from the chilled facies (U-106) have from 0.3 to 1.3 wt% BaO, corresponding to 0.5 to 2.3 mole% celsian. There is no obvious relation between barium and calcium content (fig. 3). The feldspars from the innermost facies (150722) have much lower barium contents, from below the lower limit of detection (approx. 0.15%) to 0.3% BaO. The Fe_2O_3 content is in nearly all cases below the detection limit (approx. 0.15%).

Comparisons

The feldspar trend in the Ilímaussaq chilled facies is identical with the trend established by Stephenson (1976) for a mafic band in the augite syenite unit SS4b in the South Qôroq Centre of the Igaliko complex. Also the compositional gap at Or_{20}-Or_{30} is common to the two. Further, the normal facies of the same rock unit (SS4b) has feldspar compositions very similar to those of the inner facies of the Ilímaussaq augite syenite. Comparable feldspar
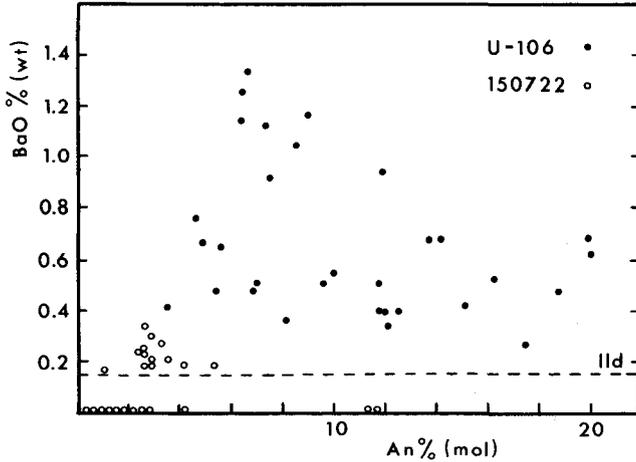
Fig. 3. Barium content versus anorthite component for feldspars from the Ilímaussaq augite syenite.
lld = lower limit of detection.

trends are also found in the Oslo larvikites (Oftedahl, 1948; Muir & Smith, 1956). These authors described corroded cores of acid plagioclase in alkali feldspar, and the feldspar diagram for the Oslo province plutonic rocks given by Oftedahl (1948, p. 53) also has a compositional gap at Or_{20-30}. Upton (1960) gave bulk feldspar analyses for augite syenites from the Kûngnât complex in the range $An_{3-11}Ab_{53-62}Or_{30-42}$. He inferred (p. 54) that more Ca-rich compositions would be present, and it is extremely likely that microprobe investigation of these rocks would yield feldspar trends similar to those for Ilímaussaq and the South Qôroq Centre.

Discussion of feldspar crystallisation

As pointed out by Upton (1964), and illustrated here in fig. 2, augite syenite feldspars occupy a compositional range between the plagioclases of syenogabbros and the alkali feldspars of foyaites. The liquids would have been lying above the solvus, and on the plagioclase side of, but fairly near to, the feldspar cotectic curve (in fig. 2 this is the case for both the bulk feldspar and the normative feldspar of the chilled facies, U-106), thus precipitating plagioclase as the first feldspar phase. The liquid quite rapidly reached the feldspar cotectic curve, and large amounts of alkali feldspar started crystallising. By equilibrium crystallisation the plagioclase would have changed composition continuously through the anorthoclase compositional area until it merged into the alkali feldspar composition at the critical solution point. Fractionation arrested this process, leaving cores of more or less equilibrated plagioclase and anorthoclase enclosed in alkali feldspar. This crystallisation scheme is as described by Tuttle & Bowen (1958, pp. 133–134, liquid X). (Also cited in Deer et al., 1963).

Resorbed cores of presumed plagioclase have been observed occasionally in augite syenite samples away from the chilled facies. The innermost facies (150722), however, does not have them. Its single primary alkali feldspar has a restricted compositional range, and the liquid may have been on the cotectic or may even have left it again.

Feldspars in the Ilímaussaq foyaite

Microprobe integration of the very coarsely exsolved feldspars from the later formed foyaite of the Ilímaussaq intrusion was attempted but gave erratic results with regard to the Na/K ratio. However, it confirmed that the foyaite feldspars are essentially Ca-free, in agreement with the foyaite feldspars from the South Qôroq Centre (Stephenson, 1976) which probably serve well as indicators of the original composition of feldspar from the Ilímaussaq foyaites.

Other minerals in the augite syenite

Nepheline occurs interstitially in the innermost facies; an analysis is presented in Table 2. The temperature range indicated by the three rather uniform nepheline analyses is 800–850°C (Hamilton, 1961). Stephenson (1976) found similar nephelines in the augite syenite SS4b of the South Qôroq Centre. These temperatures seem to be magmatic and indicate that the nephelines have not, or nearly not, re-equilibrated during cooling.

Magnetite. All the primary titanomagnetite grains are oxidised and contain ilmenite lamellae. Broad beam analyses show 24–26.5% TiO_2 (Table 2). Primary ilmenite is not present.

Table 2. Other minerals from the Ilímaussaq augite syenite

	Nepheline	Magnetite		Amphibole			Biotite	
GGU no.	150722	U-106		U-106	150722	150722	U-106	150722
SiO_2	45.97	TiO_2 26.25	SiO_2	40.05	38.74	40.28	35.01	33.14
Al_2O_3	32.84	Al_2O_3 1.87	TiO_2	3.73	2.03	0.15	6.04	0.00
CaO	0.52	Fe_2O_3 16.38	Al_2O_3	10.24	10.89	8.49	12.66	14.51
Na_2O	16.09	FeO 53.48	Fe_2O_3	0.00	1.13	4.18	–	–
K_2O	4.79	MnO 1.00	FeO	20.41	26.23	25.59	21.97	32.39
	100.21	MgO 0.66	MnO	0.23	0.40	0.47	0.00	0.29
		CaO 0.18	MgO	7.36	3.22	3.55	9.13	4.39
Cations		99.82	CaO	10.92	10.47	10.16	0.12	0.18
Si	8.693	FeOT 68.22	Na_2O	2.72	2.99	3.12	0.36	0.70
Al	7.320		K_2O	1.61	1.73	1.80	9.00	8.33
Ca	0.106	Cations		97.27	97.83	97.79	94.29	93.93
Na	5.901	Ti 5.848	FeOT	20.41	27.25	29.35	–	–
K	1.154	Al 0.653	Cations					
	23.174	Fe^{+3} 3.652	Z { Si	6.261	6.215	6.494	5.514	5.524
		Fe^{+2} 13.248	Al IV	1.739	1.785	1.506		
Ne	75.8	Mn 0.251	Al VI	0.148	0.275	0.108	2.350	2.850
Ks	16.5	Mg 0.291	Y { Ti	0.439	0.245	0.018	0.716	0.000
Qz	7.7	Ca 0.057	Fe^{+3}	0.000	0.137	0.507	–	–
			Fe^{+2}	2.668	3.519	3.451	2.893	4.515
		usp% 75.2	Mn	0.030	0.054	0.064	0.000	0.040
			Mg	1.715	0.770	0.853	2.144	1.092
			X { Ca	1.829	1.800	1.755	0.020	0.033
			Na	0.824	0.930	0.975	0.110	0.226
			K	0.321	0.354	0.370	1.808	1.770
				15.974	16.084	16.101	15.555	16.050

Bases for calculations: Nepheline: 32 oxygens. Magnetite: 24 cations and 32 oxygens. Amphibole: 13 Y+Z cations and 23 oxygens. Biotite: 22 oxygens.

Olivine, pyroxene and amphibole. The analyses of these phases are in very good agreement with the results obtained with a crystal spectrometer microprobe. Specifically, the compositional ranges found in olivine and pyroxene are the same as those previously reported (Larsen, 1976). The homogeneity of the red-brown interstitial amphibole in the chilled facies (U-106) was confirmed. Its name is titanian ferroan pargasitic hornblende (approaching kaersutite) according to Leake (1978). In the innermost facies (150722) the common amphibole is brownish to greenish (titanian) ferro-pargasite occurring in individual interstitial grains and as patchy replacements of the pyroxene. In the previously described, volatile-influenced zone a green to bluish green Ti-free hastingsitic to ferro-edenitic hornblende is found rimming a fayalite grain. Analyses of the various amphibole types are given in Table 2. They have all been recalculated on a cationic basis, with $Z+Y = 13$. This calculation procedure illustrates the low oxidation state of the amphiboles previously inferred (Larsen, 1976) and also indicates a certain rise in oxidation state with crystallisation. It is due to the low oxidation state that the early amphiboles are pargasitic ($Al^{VI} > Fe^{3+}$) and not hastingsitic ($Fe^{3+} > Al^{VI}$).

Biotite. Red-brown titan-biotite occurs commonly as radiating fringes around titanomagnetite grains. Grass-green Ti-free biotite is found intergrown with the above mentioned, bluish green amphibole rim on fayalite in the volatile-influenced zone. Analyses of both types are shown in Table 2. While the oxidation state of the brown biotite is uncertain, the green biotite has a cation sum larger than 16, indicating that some Fe^{3+} is definitely present.

The green Ti-free amphibole and biotite are thought to be subsolidus recrystallisation products formed during volatile percolation through the rock. They illustrate the difference between the results of this type of crystallisation and the high-temperature magmatic intercumulus crystallisation.

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