

## The peralkaline nepheline syenites of the Junguni intrusion, Chilwa province, Malawi

ALAN R. WOOLLEY

Department of Mineralogy, British Museum (Natural History), Cromwell Road, London SW7 5BD, U.K.

AND

R. GARTH PLATT

Department of Geology, Lakehead University, Thunder Bay, Ontario, Canada

### Abstract

The mineralogy of the highly peralkaline Junguni nepheline syenite intrusion of the Chilwa alkaline province has been investigated. The rocks comprise alkali feldspar, very abundant nepheline, locally exceptionally abundant sodalite, sodic pyroxenes, scarce biotite, rare amphibole, and an extensive range of accessory minerals. Electron microprobe analyses indicate that the pyroxenes define an evolutionary trend from salite through aegirine-augite to aegirine, which is unusual in its broadness and ill-definition. This is explained by a series of overlapping trends produced by fluctuating  $\text{Fe}^{3+}/\text{Fe}^{2+}$  ratios caused by variations in alkali content of the magma, probably produced by periodic alkali loss by surface de-gassing. Much of the sodalite occurs as a primary liquidus phase, but the paragenesis of certain ramifying sodalite veins is more problematical. It is possible that such ramifying masses are the product of coupled migration of alkalis and volatiles by diffusion in a gravitation field under pressure gradients generated by eruptive events, or by the formation of immiscible Na- and Cl-rich liquids. Both early calcic and late mangan-fluor eckermannitic/arfvedsonitic amphiboles occur. The micas vary from biotites with Mg:Fe ratios < 0.5 to almost pure annites; they are fluor-micas and characterized by high Mn contents. Analyses of niobian rutile, mangan ilmenite, ferroan pyrophanite, manganese-rich euclite, lâvenite, mangan-titan lâvenite, rosenbuschite, wöhlerite, pyrochlore, eudialyte and what is believed to be only the second occurrence of kupletskite are given. Many of these minerals are rich in Zr, Nb, Na and Mn and thus typical of the assemblages found in extreme agpaitic complexes such as Ilimaussaq and Lovozero.

**KEYWORDS:** nepheline syenites, Chilwa province, Malawi, rutile, ilmenite, pyrophanite, euclite, lâvenite, rosenbuschite, pyrochlore, wöhlerite, eudialyte, kupletskite.

### Introduction

THE Junguni nepheline syenite is a horseshoe-shaped intrusion some 2.5 km in diameter, situated in the northern part of the Chilwa Province of alkaline rocks, Malawi (Bloomfield, 1965), and lying five km north of the east-west-trending group of nepheline syenite-syenite complexes of Chikala, Chaone, Mongolowe and Chinduzi (see

map in Woolley and Platt, 1986, Fig. 1). The mineralogy of the last four complexes has recently been described by Woolley and Platt (1986) and the geochemistry of this part of the province by Woolley and Jones (1987). Junguni has certain unusual chemical and mineralogical features which distinguish it from the nepheline syenites further south, and thus a separate study is justified.

The petrography of the Junguni rocks was first

briefly described by Dixey *et al.* (1937), which paper included an appendix by Shand (Dixey *et al.*, 1937, Appendix D) who described in some detail several foyaitic specimens furnished by Dixey. He noted the presence of ramifying masses of sodalite, which appeared to invade and corrode feldspar and nepheline. The fullest published account is that of Bloomfield (1965) who described the general geology and petrography of the hill, together with two smaller satellite hills to the northeast. He noted the presence of eudialyte on one of these hills, Kadongosi, but identified an isotropic mineral occurring in some of the rocks as analcime.

Eighteen of the rocks forming the subject of this study have been chemically analysed (Woolley and Jones, 1987). Some of these rocks display unusual chemical features, notably Na<sub>2</sub>O values up to 22.5% and Cl up to 4.5%. These high sodium and chlorine values reflect the presence of sodalite which may reach as much as 90% modally. The trend of soda-enrichment towards rocks close in composition to pure sodalite has been illustrated in chemical diagrams by Woolley and Jones (1987, Fig. 2). Although sodalite has been identified in the nepheline syenite complexes to the south, in none of them is it so abundant.

All the Junguni rocks are not only strongly silica-undersaturated, with > 60% normative *ne* in some rocks, but they are also strongly peralkaline with *ac* values up to 28.

### Petrography

The Junguni nepheline syenites are generally coarse-grained rocks consisting principally of sub-prismatic perthitic alkali feldspar and prismatic or interstitial nepheline. Sodic pyroxene is ubiquitous, biotite occurs in moderate amounts and often mantles pyroxene, and alkali amphibole, which may mantle pyroxene or form acicular prisms in some pegmatites, is relatively minor. Sodalite forms rounded masses, interstitial patches and in some rocks, rectangular areas within feldspar prisms. In two specimens, sodalite forms between 80 and 90% of the rock; from the textural evidence it is not clear whether the sodalite is primary or secondary in these rocks. Accessory minerals include magnetite, ilmenite, pyrrhotine, pyrite, chalcopyrite, sphalerite, sphene, a carbonate, zircon, apatite, pyrophanite, eudialyte, rosenbuschite, mangan-titan-lavenite, wöhlerite, kupleskite, strontian-fluorite, pyrochlore, britholite, astrophyllite, and other as yet unidentified minerals.

TABLE 1. REPRESENTATIVE ANALYSES OF PYROXENES

	1	2	3	4	5	6	7	8	9
SiO <sub>2</sub>	50.32	50.00	49.95	50.10	51.13	51.41	50.38	57.99	51.95
TiO <sub>2</sub>	0.99	0.61	0.80	0.56	0.36	0.61	0.46	0.31	0.54
Al <sub>2</sub> O <sub>3</sub>	2.99	1.83	2.49	1.08	1.34	1.56	1.33	1.30	1.62
Fe <sub>2</sub> O <sub>3</sub> *	6.10	6.07	6.66	16.50	12.96	24.76	13.71	27.30	30.04
FeO	5.74	10.03	8.57	7.91	7.02	1.78	8.46	2.19	0.14
MnO	0.75	1.13	0.96	1.30	1.24	0.54	1.45	0.34	0.31
MgO	10.22	7.34	7.93	2.54	5.41	2.20	3.75	0.60	0.46
CaO	21.03	19.97	19.96	11.43	14.74	5.70	14.46	2.97	3.17
Na <sub>2</sub> O	2.01	2.28	2.46	7.04	5.30	10.54	5.56	11.94	12.36
K <sub>2</sub> O	0.04	0.02	0.00	0.02	0.08	0.02	0.00	0.02	0.06
Zr <sub>2</sub> O <sub>2</sub>	0.07	0.24	0.35	1.19	0.28	0.80	0.46	0.67	0.39
Total	100.26	99.52	100.13	99.67	99.86	99.92	100.02	99.63	101.04
Structural formula based on 4 cations and 6 oxygens									
Si	1.892	1.934	1.910	1.958	1.966	1.966	1.955	1.999	1.968
Al	0.133	0.083	0.112	0.050	0.051	0.070	0.061	0.059	0.072
Ti	0.028	0.018	0.023	0.016	0.010	0.018	0.013	0.009	0.050
Fe <sup>3+</sup> *	0.173	0.177	0.192	0.485	0.375	0.713	0.400	0.790	0.857
Fe <sup>2+</sup>	0.180	0.324	0.274	0.258	0.226	0.057	0.275	0.070	0.004
Mn	0.024	0.037	0.031	0.043	0.040	0.017	0.048	0.011	0.010
Mg	0.573	0.423	0.452	0.148	0.310	0.125	0.217	0.034	0.026
Ca	0.847	0.828	0.818	0.479	0.607	0.234	0.601	0.122	0.129
Na	0.147	0.171	0.182	0.533	0.395	0.782	0.418	0.890	0.908
K	0.002	0.001	0.000	0.001	0.004	0.001	0.000	0.001	0.003
Zr	0.001	0.005	0.007	0.023	0.005	0.015	0.009	0.013	0.007
Molecular per cent of end-member molecules									
Di	63.50	45.03	49.26	15.82	32.72	13.74	23.08	3.80	2.90
Hd	22.65	38.47	33.25	32.26	28.09	8.15	34.30	8.99	1.61
Ac	13.85	16.50	17.49	51.90	39.19	78.11	42.62	87.21	95.49

\* Fe<sub>2</sub>O<sub>3</sub> calculated on the basis of 4 cations and 6 oxygens.

Molecular proportions calculated after the method of Larsen (1976).

1. Pale salitic core (BM 1980, P25, 9)
2. Pale salitic core (BM 1980, P25, 2)
3. Pale salitic core (BM 1980, P25, 2)
4. Green-brown aegirine-augite (BM 1980, P25, 3)
5. Green-brown aegirine-augite (BM 1980, P25, 4)
6. Green-brown aegirine-augite (BM 1980, P25, 10)
7. Green-brown aegirine-augite (BM 1980, P25, 12)
8. Green-brown aegirine-augite (BM 1980, P25, 15)
9. Aegirine (BM 1980, P25, 6)

### Mineralogy

Nineteen samples of Junguni rocks were selected for detailed mineralogical studies by electron microprobe. All the analyses were made at the British Museum (Natural History) using a Cambridge Instruments Geoscan and Link Systems energy dispersive analyser. Live time counts of 100 seconds and an acceleration voltage of 15 kV were the general analytical conditions. Fluorine was determined semi-quantitatively on a Cambridge Instruments Mark 9 microprobe.

*Clinopyroxenes* from syenite and alkali granite complexes have compositions which are essentially solid solutions of diopside, hedenbergite and acmite, and often, when expressed in terms of the

molecular proportions of these three components, pyroxenes from individual complexes display discrete trends of evolution from salite towards acmite (see, for example, Mitchell and Platt, 1978 and 1982; Platt and Woolley, 1986; Woolley and Platt, 1986). Such trends develop from the interplay of  $f_{O_2}$  and peralkalinity within the magma (Mitchell and Platt, 1978; Platt and Woolley, 1986; Woolley and Platt, 1986), and as a result, the actual evolutionary path from salite towards acmite varies from one intrusion to another.

Data for the Junguni complex (Table 1) broadly suggest a similar trend in pyroxene evolution but, unlike many similar complexes, there is a broad scatter of pyroxene compositions (Fig. 1). Essentially the pyroxenes vary from sodian magnesian

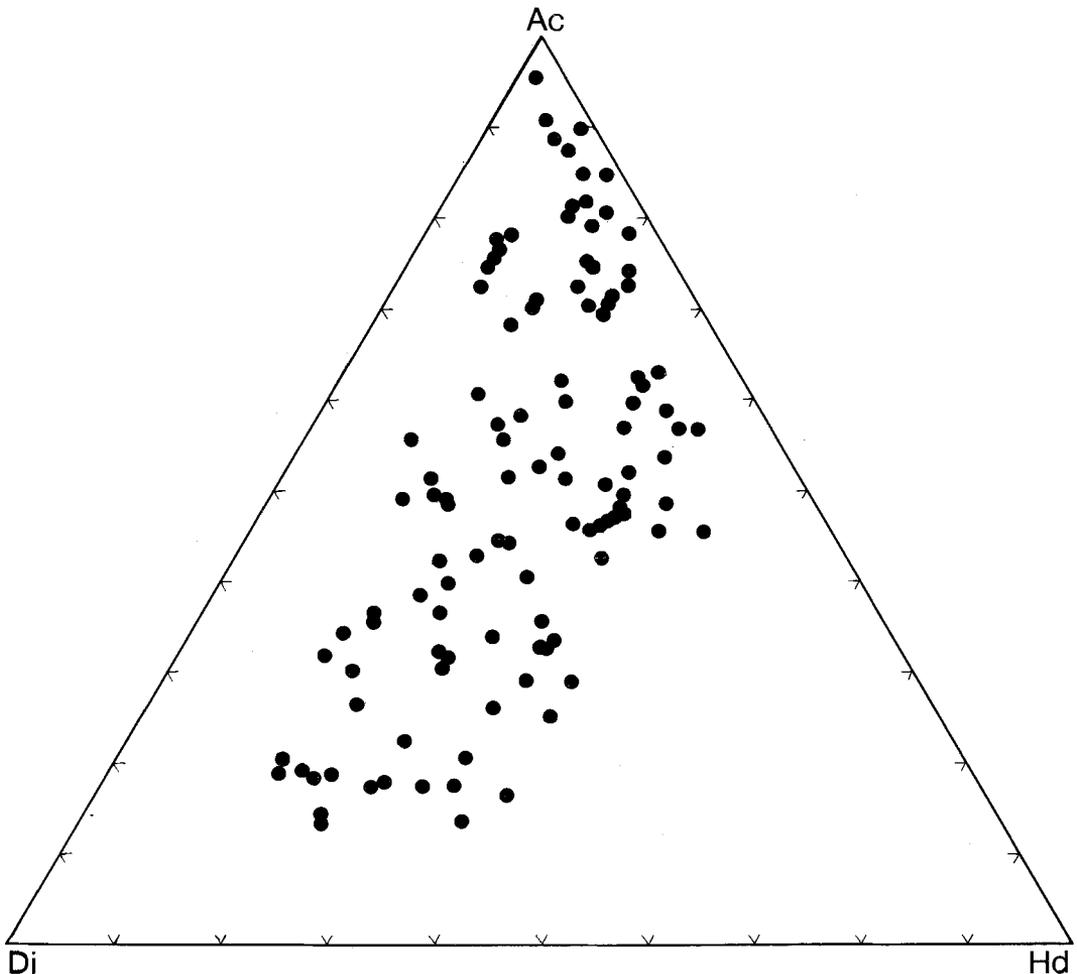


FIG. 1. Compositional variations of pyroxenes from Junguni plotted in terms of acmite–diopside–hedenbergite.

salites through aegirine-augites to aegirine. The earliest salites occur as pale brown, somewhat irregular cores in some crystals. In this respect, they resemble the occurrence of such pyroxenes in the adjacent nepheline syenite complexes of Mongolowe, Chaone, Chikala and Chinduzi (Woolley and Platt, 1986). The dominant Junguni pyroxenes are green-brown pleochroic aegirine-augites, which show general enrichment in the acmite component towards the crystal margins. Aegirine itself occurs both as a late-stage replacement of aegirine-augite and as small discrete grains. A late-stage metasomatic origin of these aegirines, as has been observed in the Mongolowe and Chaone nepheline syenites (Woolley and Platt, 1986), appears likely.

The Junguni pyroxenes are replaced primarily by biotite and with the exception of late-stage development of metasomatic eckermannite/arfvedsonite, replacement by 'early' amphibole is rarely observed.

*Amphiboles* are relatively rare, consisting mainly of fluorine-rich eckermannite, ferro-eckermannite, magnesio-arfvedsonite and arfvedsonite (Table 2). Manganese is abundant in the alkali amphiboles (ranging up to 5.25 wt. %) and in all it is present in excess of 0.5 atoms per formula unit. This justifies the prefix 'mangan' by the terminology of Leake (1978). These amphiboles replace aegirine-augite.

TABLE 2. REPRESENTATIVE ANALYSES OF AMPHIBOLES

	1	2	3	4	5
SiO <sub>2</sub>	42.65	50.43	51.56	52.06	51.16
TiO <sub>2</sub>	1.64	0.89	0.66	0.81	0.55
Al <sub>2</sub> O <sub>3</sub>	8.98	1.39	1.37	1.50	1.04
Fe <sub>2</sub> O <sub>3</sub> *	2.74	2.12	1.69	0.70	0.31
FeO	13.28	19.79	12.57	12.97	16.96
MnO	1.39	4.08	5.25	4.78	4.01
MgO	10.91	5.76	10.28	10.41	8.27
CaO	9.21	1.99	2.57	2.39	2.75
Na <sub>2</sub> O	4.68	7.75	8.16	8.23	7.64
K <sub>2</sub> O	1.24	2.32	2.16	2.02	2.19
ZrO <sub>2</sub>	0.38	0.12	0.16	0.28	0.31
Total	97.10	96.64	96.43	96.15	95.19
Structural formula based on 13 cations and 23 oxygens					
Si	6.503	7.900	7.858	7.914	7.968
Al <sup>iv</sup>	1.497	0.100	0.142	0.086	0.032
	8.000	8.000	8.000	8.000	8.000
Al <sup>vi</sup>	0.117	0.157	0.104	0.183	0.059
Ti	0.188	0.105	0.076	0.093	0.064
Fe <sup>3+vi</sup>	0.315	0.251	0.194	0.080	0.036
Fe <sup>2+</sup>	1.693	2.592	1.602	1.649	2.209
Mn	0.180	0.541	0.678	0.615	0.587
Mg	2.480	1.345	2.355	2.359	1.920
Zr	0.028	0.009	0.012	0.021	0.024
	5.000	5.000	5.000	5.000	5.000
Ca <sub>B</sub>	1.504	0.334	0.420	0.389	0.459
Na <sub>B</sub>	0.496	1.666	1.580	1.611	1.541
	2.000	2.000	2.000	2.000	2.000
Na <sub>A</sub>	0.887	0.685	0.831	0.815	0.766
K <sub>A</sub>	0.241	0.464	0.420	0.392	0.435
	1.128	1.149	1.251	1.207	1.201

\* Fe<sub>2</sub>O<sub>3</sub> determined after the method of Leake (1978)

1. Edenitic hornblende (BM 1980, P25, 9)

2. Arfvedsonite (BM 1980, P25, 21)

3. Magnesio-arfvedsonite (BM 1980, P25, 17)

4. Eckermannite (BM 1980, P25, 17)

5. Ferro-eckermannite (BM 1980, P25, 22)

Semi-quantitative analyses of the alkali amphiboles indicate >3 wt % F.

The more abundant amphiboles occurring in the nepheline syenites to the south define both an igneous series and a late-stage sub-solidus or metasomatic series (Woolley and Platt, 1986). The Junguni alkali amphiboles are chemically and texturally comparable to those of the sub-solidus series and are considered to have a similar petrogenesis.

In the one rock in which amphibole is seen to replace pale salitic pyroxene, the amphibole is calcic (Table 2, no. 1), and in composition corresponds closely to amphiboles of the igneous series described from the adjacent nepheline syenites (Woolley and Platt, 1986). This very minor development of 'igneous' amphibole occurs prior to the formation of aegirine-augite, and is perhaps a product of conditions prevailing in a deeper feeder magma chamber, as discussed later.

TABLE 3. REPRESENTATIVE ANALYSES OF MICAS

	1	2	3	4
SiO <sub>2</sub>	37.23	36.58	35.34	35.02
TiO <sub>2</sub>	2.36	2.34	3.25	2.95
Al <sub>2</sub> O <sub>3</sub>	12.60	10.92	11.52	11.63
FeO*	18.55	25.53	28.45	31.58
MnO	2.13	2.00	1.81	2.93
MgO	11.99	7.73	5.09	0.45
CaO	0.08	0.28	0.03	0.02
Na <sub>2</sub> O	0.65	0.32	0.22	0.24
K <sub>2</sub> O	9.59	9.65	9.51	9.35
ZrO <sub>2</sub>	0.12	0.16	0.07	0.00
Total	95.30	95.51	95.29	94.17
Structural formula based on 22 oxygens				
Si	5.749	5.854	5.749	5.889
Ti	0.274	0.282	0.398	0.373
Al	2.293	2.060	2.209	2.305
Fe*	2.396	3.417	3.871	4.441
Mn	0.279	0.271	0.249	0.417
Mg	2.760	1.844	1.234	0.113
Ca	0.015	0.048	0.005	0.004
Na	0.195	0.099	0.069	0.078
K	1.889	1.970	1.974	2.006
Zr	0.009	0.012	0.006	0.000
Fe+Mn/Fe+Mn+Mg	0.49	0.67	0.77	0.98

\* Total iron calculated as FeO

1. BM 1980, P25, 6

2. BM 1980, P25, 12

3. BM 1980, P25, 18

4. BM 1980, P25, 14

Micas are found in almost all the rocks studied and a selection of analyses is given in Table 3. Semi-quantitative analyses indicate > 3 wt. % fluorine. All the micas are biotites but there is a wide variation in the ratio (Fe<sup>T</sup> + Mn)/(Fe<sup>T</sup> + Mn + Mg) from 0.49 to 0.98, those with high ratios being essentially annites. The variation is illustrated in Fig. 2 which also indicates that there is little variation in total Al. A similar variation was found in the micas of the nepheline syenites to the south (Woolley and Platt, 1986, Fig. 7) but none of those complexes has the range of compositions encompassed by the Junguni micas.

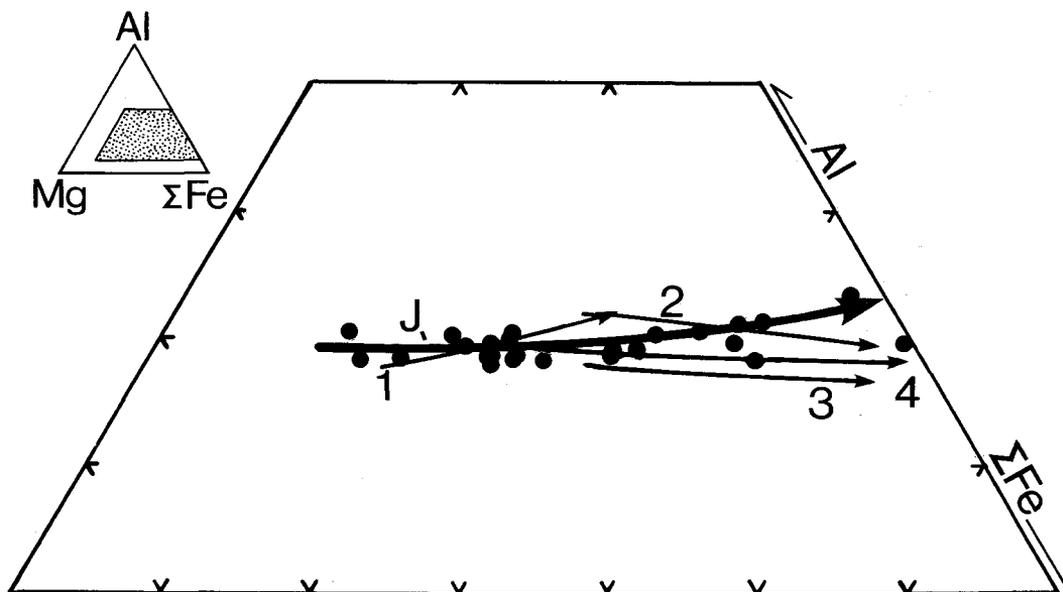


FIG. 2. Junguni micas plotted in terms of Al, Mg and Fe (as total  $\text{Fe}^{2+}$ ). The trend for Junguni (J) is more extensive, but closely parallels the trends for the adjacent nepheline syenite complexes of Chaone (1), Chikala (2), Chinduzi (3) and Mongolowe (4).

The micas of Junguni are noteworthy for their high Mn contents. In most igneous biotites Mn is less than 0.2 atoms per formula unit (Deer *et al.*, 1962, p. 61), but those from Junguni vary from 0.191 to 0.826 atoms, with only one below 0.21. Although there is a gradual increase in Mn through the series, in sympathy with the increasing ratio of Fe:Mg, four rocks with intermediate Fe:Mg ratios have exceptionally high Mn contents of  $> 0.56$  atoms, the reason for which is not clear. Similar enrichment in Mn was noted by Nash and Wilkinson (1970) in late, annitic micas in the Shonkin Sag laccolith.

**Feldspathoids.** The principal feldspathoids of the Junguni intrusion are nepheline and sodalite. The former generally forms euhedral to subhedral grains with relatively restricted compositions. The compositional range overlaps those recorded from the four other Chilwa Province nepheline syenite complexes previously described by Woolley and Platt (1986) (Fig. 3). All have an excess of Si over that required by stoichiometry and the Morozewicz-Buerger convergence field of plutonic nephelines (Tilley, 1954).

Crystallization temperatures of the Junguni nephelines fall in the general range of 900–700° (Hamilton, 1961) (Fig. 3). This would indicate crystallization of the nephelines within relatively high-level chambers in which cooling was suf-

ficiently rapid to prevent compositional readjustment to the Morozewicz-Buerger convergence field. Support for this is obtained from the nepheline phenocrysts of a dyke of microfoyaite associated with the Junguni intrusion (BM 1980, P25,16). These phenocrysts have compositions overlapping those of the main intrusion nepheline syenites.

Sodalite has variable abundance ranging from the status of an accessory mineral in some rocks to that of a major rock-forming mineral with modal percentages as high as 80–90%. Paragenetically, sodalite occurs either as a primary liquidus phase, associated with nepheline and alkali feldspar, or as late-stage ramifying masses. Primary sodalite occurs partly as euhedral dodecahedral crystals. Occasionally, however, elongate rectangular forms, which are poikilitically enclosed in feldspar, and similar in appearance to hexagonal prismatic sections of nepheline, are observed. This latter habit could be used as evidence for the replacement of nepheline by sodalite although nepheline is commonly replaced by cancrinite or Na-rich zeolite in rocks of the Junguni intrusion. It is more likely however, that the prismatic habit of sodalite is in fact of primary origin. The Junguni rocks containing rectangular sodalites within feldspar are texturally very similar to some of the naujaite cumulates of the Ilmaussaq complex, which also contain rectangular sodalite poikilitically enclosed

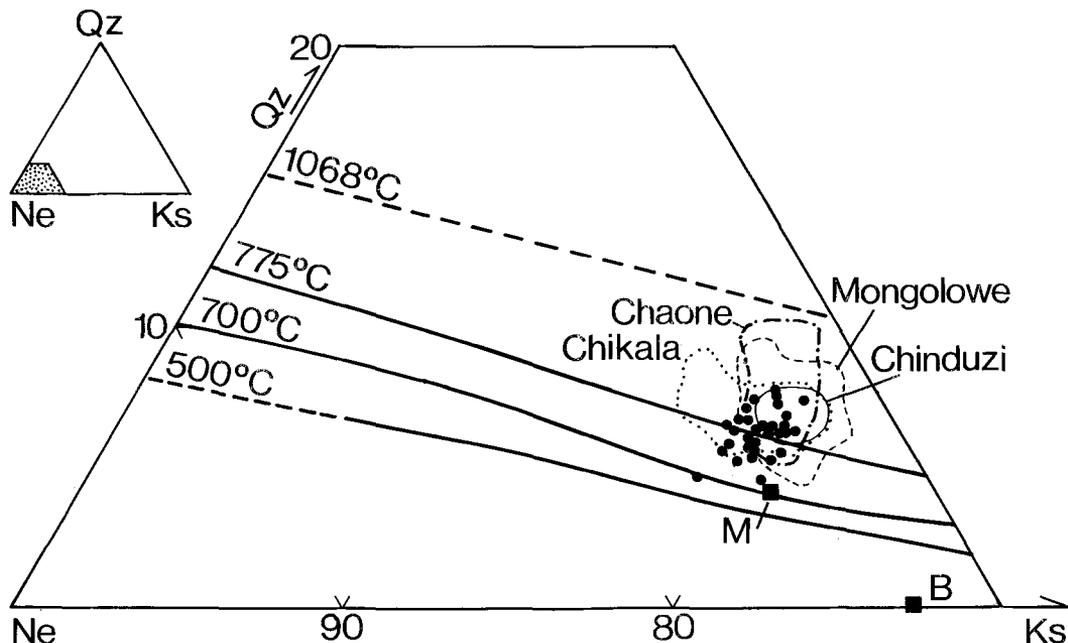


FIG. 3. Nepheline compositions plotted in a portion of the system nepheline-kalsilite-silica (wt. %). The isotherms show the limits of nepheline solid solution at the indicated temperatures (after Hamilton, 1961). M and B are the Morozewicz and Buerger ideal nepheline compositions. The diagram also shows the areas occupied by analyses from the adjacent nepheline syenite complexes (from Woolley and Platt, 1986, Fig. 2).

in alkali feldspar (Ferguson, 1964, p. 54), while Barker (1976) observed primary sodalite of rectangular habit in his experimental quench products.

In rocks containing primary liquidus sodalite, accumulation effects, probably flotation, would explain the sodalite-rich syenites observed in the field. The intrusive habit of late-stage ramifying masses of almost pure sodalite (Shand in Dixey *et al.*, 1937) can not be accounted for by accumulation or replacement mechanisms. A late-stage sodalite-rich mobile fluid appears necessary to explain this. The nature of this sodium- and chlorine-rich fluid is not apparent from field evidence. It is possible that it separated as one of a pair of immiscible fluids. This topic will be returned to in the discussion.

**Feldspars.** Detailed studies have not been undertaken of the feldspars of the Junguni intrusion, although certain general observations can be made. The primary feldspar of the nepheline syenites is perthitic alkali feldspar, which is subsequently replaced by albite. In the initial stages, this generally appears as a marginal replacement and in more advanced stages as almost total replacement with the original perthite remaining as corroded islands, this being particularly prevalent in fractured syenites, suggesting again the introduction of

a 'late-stage' sodium-rich fluid phase. Albite also occurs as fracture fillings and as the principal feldspar in late-stage pegmatitic phases.

**Accessory minerals.** The Junguni intrusion contains a wide variety of late-crystallizing minerals which are often difficult to analyse quantitatively, owing to their small size or their sometime volatile nature under the electron beam. No claim can be made that all such minerals have been studied in detail, or even that all have been observed. There is no doubt, however, that the Junguni intrusion will provide a rich sampling ground for those interested in exotic minerals.

The minerals identified so far include wöhlerite, eudialyte, rosenbuschite, dawsonite, britholite, pyochlore, 'pyrophanite', kupletskite, lävenite and mangan-titan lävenite. Where reasonable analyses of these have been obtained, they are given in Tables 4 and 5. Of particular note are the Mn-rich minerals which again reflect this element's importance in minerals crystallizing from the more evolved Junguni magmas and late fluids; a fact previously noted in the composition of the Junguni micas and alkali amphiboles. This is further exemplified by the occurrence of the mangan analogue of astrophyllite, kupletskite. To our knowledge, this

TABLE 4. REPRESENTATIVE ANALYSES OF ACCESSORY MINERALS

	1	2	3	4	5	6
SiO <sub>2</sub>	0.48	0.34	0.43	28.19	29.76	33.63
TiO <sub>2</sub>	91.16	49.94	50.74	1.38	9.19	9.08
Al <sub>2</sub> O <sub>3</sub>	0.13	0.24	0.07	0.02	0.04	0.78
FeO*	1.56	31.24	9.41	1.58	2.53	7.72
MnO	0.11	14.99	35.80	7.39	13.85	27.18
MgO	0.14	0.18	0.03	0.09	0.00	0.71
CaO	0.33	0.00	0.07	15.34	9.28	1.25
Na <sub>2</sub> O	0.15	0.74	0.59	11.47	10.07	2.63
K <sub>2</sub> O	0.00	0.00	0.00	0.04	0.00	5.83
ZrO <sub>2</sub>	0.13	0.00	0.24	29.74	16.90	2.00
Nb <sub>2</sub> O <sub>5</sub>	4.88	0.59	1.15	0.46	2.83	1.61
Others				2.75		
Total	99.07	98.26	98.53	98.45	94.45	92.42

\* Total iron calculated as FeO

1. Niobian rutile (BM 1980, P25, 10)
2. Mangan ilmenite (BM 1980, P25, 1)
3. Ferroan pyrophanite (BM 1980, P25, 14)
4. Låvenite. Others - 2.75% F (BM 1980, P25, 13)
5. Mangan-titan låvenite (BM 1980, P25, 19)
6. Kupletskite (BM 1980, P25, 13)

TABLE 5 REPRESENTATIVE ANALYSES OF ACCESSORY MINERALS

	7	8	9	10	11
SiO <sub>2</sub>	31.23	31.13	1.26	48.42	47.09
TiO <sub>2</sub>	9.14	7.63	7.80	0.61	0.05
Al <sub>2</sub> O <sub>3</sub>	0.00	0.02	0.10	0.57	0.02
FeO*	0.19	0.70	1.56	4.30	2.11
MnO	1.99	2.90	0.44	4.55	7.78
MgO	0.09	0.13	0.03	0.16	0.02
CaO	26.59	25.53	7.88	10.67	11.47
Na <sub>2</sub> O	9.95	10.39	8.79	11.75	9.23
K <sub>2</sub> O	0.00	0.01	0.28	0.50	0.19
ZrO <sub>2</sub>	14.86	15.45	1.74	11.24	11.40
Nb <sub>2</sub> O <sub>5</sub>	1.08	1.45	59.06	1.62	3.88
Others		3.75	6.56	0.11	4.85
Total	95.12	99.09	95.50	94.50	98.09

\* Total iron calculated as FeO

7. Rosenbuschite (BM 1980, P25, 22)
8. Wöhlerite. Others - 3.75% F (BM 1980, P25, 12)
9. Pyrochlore. Others includes 5.65 %ThO<sub>2</sub> and 0.91% UO<sub>2</sub> (BM 1980, P25, 5)
10. Eudialyte. Others = 0.96% Cl (BM 1980, P25, 17)
11. Manganese-rich eucolite. Others includes 1.49% Cl, 1.21% La<sub>2</sub>O<sub>3</sub> and 1.15% Ce<sub>2</sub>O<sub>3</sub> (BM 1980, P25, 17)

is only the second occurrence of this mineral, the first having been described from the Lovozero Massif of the Kola Peninsula (Semenov, 1956).

### Discussion

The similarity of Junguni pyroxenes with those observed in the spatially and temporally related nepheline syenite complexes of Chikala, Chaone, Mongolowe, and Chinduzi (Woolley and Platt, 1986) strongly suggests a close genetic relationship in the development of all these complexes. Woolley and Platt suggest a two-stage process of magma evolution, namely a fundamental stage in which a parent source magma is pooled at depth, and subsequently a complex-forming stage, in which this source magma is periodically injected into shallow-level chambers to form the individual nepheline syenite complexes. By analogy with the four complexes, the remnant salitic cores of the

Junguni pyroxenes, which are similar in composition to the salitic-trend described by Woolley and Platt (1986), reflect the fundamental stage of magma development, whereas the main group of aegirine-augites formed subsequent to injection into the shallow-level chamber.

Within the shallow-level chamber, the evolution of pyroxenes towards more aegirine-rich compositions is governed by the Fe<sup>3+</sup>/Fe<sup>2+</sup> ratio. This in turn is controlled by high alkali activity (Fudali, 1965; Paul and Douglas, 1965) and/or high oxygen fugacity (Stephenson and Upton, 1982; Platt and Woolley, 1986). The highly peralkaline nature of the Junguni intrusion suggests that the high activity of Na may well be the controlling factor during pyroxene evolution.

The rather broad compositional range of the aegirine-augites, particularly with respect to diopside content (Fig. 1), probably reflects a series of overlapping pyroxene trends towards aegirine. This is somewhat unusual, as in many felsic alkaline complexes pyroxene compositions tend to define trends which are much more sharply defined (e.g. Larsen, 1976; Mitchell and Platt, 1978 and 1982; Platt and Woolley, 1986). One explanation is that crystallization within the high-level chamber did not occur in a closed system, and that fluctuations in the Fe<sup>3+</sup>/Fe<sup>2+</sup> ratio were produced by variations in the alkali content of the magmas during crystallization. Variations in the alkali content could conceivably be produced either by loss to the wall rocks or, more likely, by loss during episodes of degassing at the surface. It is very probable that the intrusion, as presently exposed, was only one or two kilometres below the surface at the time of emplacement. The presence of masses of metamorphosed nephelinitic lavas in the Chaone and Mongolowe complexes to the south (Woolley and Jones, 1987) gives support to this hypothesis. We are observing, therefore, a very shallow-level magma chamber, forming part of an igneous system which was probably very highly charged with volatiles that discharged periodically to the surface.

The high Mn content of many of the Junguni rock-forming and accessory minerals must also reflect the high Fe<sup>3+</sup>/Fe<sup>2+</sup> ratio of the Junguni magma crystallizing in the shallow-level magma chamber. Mn appears to be largely excluded from entering the structure of the principal mafic mineral forming at this time, i.e. Fe<sup>3+</sup>-rich aegirine-augite. Mn, therefore, becomes concentrated in the liquid phase awaiting suitable receptor minerals. As noted previously, some is taken up by Mn-enriched varieties of mica and amphibole. The formation of only small amounts of these minerals, however, allows Mn to concentrate in the late residual

liquids, and it is from these that minerals such as kupletskite, mangan lävenite and pyrophanite crystallize.

Perhaps the most striking mineralogical difference between Junguni and the adjoining nepheline syenite complexes is the widespread and often extreme development of sodalite in the former. The formation of primary liquidus sodalite, crystallizing in association with alkali feldspar and/or nepheline, occurs extensively in experimental studies of the silica-undersaturated portion of the system Ab-Ne-NaCl-H<sub>2</sub>O (Barker, 1976; Binsted, 1981), and Ab-Ne-NaCl (Koster van Groos, 1966; Wellman, 1968; Kogarko *et al.*, 1974) at pressures of 1 kbar. Consequently, the origin of sodalite as a primary liquidus phase in the Junguni magmas presents little difficulty, particularly in view of the fact that the Junguni intrusion is the most peralkaline (persodic) of the northern Chilwa Province nepheline syenites (Woolley and Jones, 1987).

It has been suggested that the late-stage ramifying masses of sodalite could be the product of crystallization from a Na- and Cl-enriched fluid or liquid phase. Binsted (1981) in his studies of the system Ab-Ne-NaCl-H<sub>2</sub>O recognized the presence of a NaCl-enriched hydrous fluid phase in equilibrium with silicate melt. With the additional components of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> in this phase, the potential for subsequent sodalite crystallization appears possible. Certainly such a fluid phase may be responsible in the more complex system of Junguni for the late-stage metasomatic replacement of pyroxene by magnesio-arfvedsonite/eckermannite. The potential for such a fluid as the source of the ramifying sodalite masses cannot be discounted.

However, such a hypothesis presupposes that H<sub>2</sub>O was an important volatile component of the Junguni magmas. There is little evidence to support this. Indeed, the general lack of hydrous minerals and the presence of fluor amphibole and/or fluor mica would suggest otherwise, at least as far as the major rock-forming process is concerned. In this respect the agpaite Junguni magmas appear similar to other agpaite nepheline syenite magmas (Kogarko *et al.*, 1977; Kogarko, 1987). In relatively dry agpaite magmas, volatile components such as Cl have low fugacities and are retained within the liquid phase (Kogarko, 1987). With the concomitant build up of both alkalis and volatiles in such agpaite magmas, Kogarko suggests (*op. cit.* p. 540) that 'coupled migration of alkalis and volatiles in such processes as thermodiffusion and diffusion in gravitation fields under pressure gradients' may occur. The latter mechanism may generate the ramifying masses of sodalite, particularly if pressure gradients are generated by

periodic eruptive events affecting the shallow magma chamber.

Alternatively the retention of Cl in the soda-rich silicate melt might also lead to the formation of immiscible liquids. Such liquids have been identified in the system Ab-Ne-NaCl by Koster van Groos (1966), Wellman (1968) and Kogarko *et al.* (1974) in which silicate-rich and NaCl-rich liquids co-exist. The ramifying masses of sodalite may crystallize from the NaCl-rich liquid or by reactions of pre-existing crystallization products with such a liquid. It must be stressed again, however, that replacement reaction relationships have not been observed in the sodalite-rich masses. We can not at present distinguish between this mechanism and that presented above.

In conclusion, the Junguni intrusion appears to be the product of open-system crystallization at low pressures (1-2 kbar) of a chlorine-enriched persodic (agpaite) magma. We believe that the parental magma is itself a late-stage derivative magma of a more fundamental melt that existed at depth, from which were derived the major nepheline syenite complexes of the northern part of the Chilwa Alkaline Igneous Province, i.e. Chikala, Chaone, Mongolowe, Chinduzi and Junguni.

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