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RELATIVELY ALUMINOUS ALKALI PYROXENE IN NEPHELINE SYENITES FROM MALAWI: MINERALOGICAL RESPONSE TO METAMORPHISM IN ALKALINE ROCKS

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ABSTRACT

The North Nyasa Alkaline Province (NNAP) of central and northern Malawi, eastern central Africa, consists of seven nepheline syenite intrusions which were, to varying degrees, affected by the Mozambique Orogenic event. We have analyzed the constituent clinopyroxene in rocks of five of these intrusions by electron microprobe. Three groups of pyroxenes can be distinguished. (a) Alkali pyroxenes range from diopside through aegirine-augite to aegirine. These have total Al < 0.15 (*apfu*) and are taken to be of primary magmatic origin. (b) Pyroxenes characterized by Al > 0.15 (*apfu*), with ^{VI}Al predominant, form a rim on group-(a) pyroxenes, cut across them and also form, in one intrusion, tiny acicular crystals within nepheline and, locally, feldspar. They comprise aluminian aegirine-augite, aluminian aegirine and omphacite. These pyroxenes are interpreted as metamorphic in origin. (c) The third group comprises Al-rich pyroxenes in which ^{IV}Al is predominant. They are diopside and aluminian diopside exhibiting no trend of alkali enrichment. They are probably of igneous origin, but could also have been affected by metamorphism. Although the production of pure jadeitic pyroxenes probably requires a minimum pressure of about 7 kbar, aluminian aegirine with higher contents of Fe^{3+} can probably be generated at much lower pressures. The preservation of primary igneous pyroxenes in the NNAP intrusions probably indicates that neither high pressures nor particularly elevated temperatures were reached. The formation of the aluminous pyroxenes was essentially the result of an isochemical event; in general, metamorphism of agpaitic rocks will give rise to aluminian aegirine and a jadeitic pyroxene, whereas miaskitic rocks will contain aluminian aegirine-augite and an omphacitic pyroxene.

Keywords: nepheline syenite, alkali pyroxene, aegirine, aluminian aegirine, aluminian aegirine-augite, omphacite, Malawi.

SOMMAIRE

La province alcaline du Nyasa méridional, dans le secteur central et nord du Malawi, partie est-centrale de l'Afrique, est faite de sept massifs intrusifs à syénite néphélinique qui ont été, à divers degrés, affectés par l'orogenèse mozambiquéenne. Nous avons analysé le clinopyroxène présent dans cinq des sept massifs par microsonde électronique. Nous distinguons trois groupes de compositions: (a) pyroxènes alcalins allant de diopside vers l'aegyrine, en passant par l'augite aegyrinique. Ces pyroxènes possèdent moins de 0.15 d'atomes d'Al par unité formulaire, et seraient d'origine primaire (magmatique). (b) Les pyroxènes contenant plus de 0.15 atomes d'Al, surtout sous forme de ^{VI}Al, forment une bordure sur les cristaux du groupe (a), les recoupent, et apparaissent aussi, dans un cas, sous forme d'aiguilles à l'intérieur de la néphéline et du feldspath. Les compositions sont représentatives d'augite aegyrinique alumineuse, d'aegyrine alumineuse et d'omphacite, et seraient d'origine métamorphique. Les pyroxènes du groupe (c) sont aussi alumineux, mais l'aluminium y occupe surtout le site tétraédrique. Il s'agit de diopside et de diopside alumineuse sans indication d'enrichissement en alcalins. Ceux-ci seraient probablement d'origine ignée, mais pourraient bien avoir été affectés par métamorphisme. Quoique la production de la jadéite pure requiert une pression minimale d'environ 7 kilobars, l'aegyrine alumineuse ayant une teneur élevée en Fe^{3+} est tout probablement stable à une pression de beaucoup inférieure à cette valeur. La préservation de pyroxènes primaires dans ces massifs témoigne probablement des conditions plutôt modérées de température et de pression atteintes lors du métamorphisme. La formation de pyroxènes alumineux résulterait essentiellement d'une recristallisation isochimique. En général, on peut s'attendre que le métamorphisme de roches agpaïtiques produise une aegyrine alumineuse et un pyroxène jadéitique, tandis que les roches miaskitiques devraient produire une augite aegyrinique alumineuse ou un pyroxène omphacitique.

(Traduit par la Rédaction)

Mots-clés: syenite néphélinique, pyroxène alcalin, aegyrine, aegyrine alumineuse, augite aegyrinique alumineuse, omphacite, Malawi.

INTRODUCTION

The alkaline igneous rocks of central and northern Malawi (Fig. 1) that Bloomfield (1970) included in his *North Nyasa Alkaline Province* (NNAP) consist of seven intrusions, namely Kasungu, Chipala, Chikangawa, Mphompha, Telelele, Ulindi and Ilomba. The dominant rock-type of these intrusions is nepheline syenite, with a little syenite and pyroxenite. The only general study of the NNAP is that of Bloomfield (1965), who described the petrology and general field relationships. The Chilwa Alkaline Province lies in southern Malawi, to the south of the NNAP (Fig. 1).

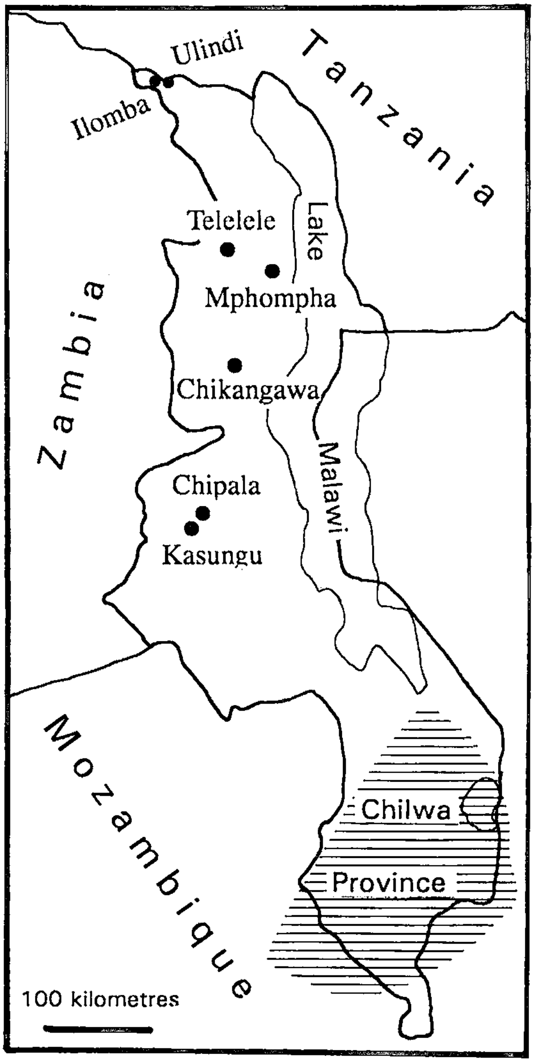

FIG. 1. Location of the major intrusions of the North Nyasa Alkaline Province (NNAP) in central and northern Malawi. The area containing the Chilwa Alkaline province in southern Malawi is also indicated.

The NNAP intrusions in Malawi have, to varying degrees, been affected by tectonic, thermal and metasomatic events that were probably related to the genesis of the Mozambique orogenic belt. Geochronological data for the province are sparse. Rb–Sr whole-rock isochron ages of 685 ± 62 Ma and 650 ± 40 Ma have been obtained from nepheline syenites of Ilomba and Chikangawa (Ray 1974, Bloomfield *et al.* 1981), and Pb-α dating of zircon from sodalite syenite at Ilomba gave 655 Ma (Bloomfield 1968). However, K–Ar dating of these intrusions gave 508 ± 12 and 490 ± 12 Ma for Ilomba (Bloomfield *et al.* 1981) and 410 ± 16 Ma for Chikangawa (Snelling 1965). The younger K–Ar dates led Bloomfield (1970) to conclude that the intrusions had been affected by a late Mozambiquian phase of cataclasis.

Geological evidence within the NNAP intrusions for these tectonic and metamorphic events is slight. Ray (1975) considered that the most northerly intrusions, Ilomba and Ulindi, comprise part of the Songwe Syenite Complex, which forms an igneous unit over 30 km long and 2–3 km wide. The Songwe syenites locally show signs of deformation, with development of a gneissosity indicating emplacement prior to or during an episode of deformation related to the Mozambique Orogeny (Ray 1975).

During field work on all seven of the NNAP intrusions, little evidence for metamorphism or deformation was observed but, as described in the next section, there is microscopic evidence for deformation. However, detailed mineralogical work has revealed the presence of an unusual suite of pyroxenes that are interpreted as being products of the metamorphism.

GEOLOGY AND PETROGRAPHY

The pyroxenes that are the subject of this paper occur in the Kasungu, Chipala, Ilomba, Mphompha and Chikangawa intrusions (Fig. 1); they are absent from the Ulindi and Telelele intrusions, which consist essentially of biotite–nepheline syenite. The following brief geological and petrographic notes can be supplemented by the general account of Bloomfield (1965) and, for Ilomba, by that of Bloomfield *et al.* (1981).

Kasungu

The Kasungu intrusion is approximately circular, has a diameter of 2 km and forms a prominent mountain rising about 400 m above the surrounding plain (Peters 1969). The intrusive rocks, nepheline syenite, show little mineralogical or textural variation, though the mafic minerals may develop a marked banding or form irregular clots. In these coarse-grained, mesocratic rocks, turbid perthite is generally cracked and strained, and may be traversed by zones of fine-grained recrystallized feldspar. Nepheline usually forms 10–20% of most rocks, but otherwise may be minor. A sodic scapolite, which is marialite on the basis of electron-microprobe data, has been found in two samples, the first such identification in a NNAP intrusion.

The clots of mafic minerals are texturally complex and dominated by pyroxene, amphibole and biotite. The pyroxene typically occurs in the center of clots but may form at the margins where, usually intergrown with mica and amphibole, it forms symplectitic intergrowths with feldspar, as well as myriads of small, isolated grains within feldspar; this texture occurs throughout some rocks. The principal pyroxene forms green, subhedral prisms or rounded crystals that may be zoned and generally contain abundant tiny inclusions. They are usually enveloped by a green amphibole that also is turbid due to the presence of inclusions. Titanite, apatite, zircon and magnetite or ilmenite are accessory phases.

Although not apparent in hand specimen, the microscopic textures and structures of the Kasungu rocks indicate that all have been subjected to some degree of deformation and considerable recrystallization. No textures that are indubitably igneous have been recognized. Bloomfield (1965) considered that the nepheline "shows typical replacement textures" and that it is the result of nephelinization. However, we could find no unequivocal textural evidence for such a process.

Chipala and Chipala East

The Chipala intrusion forms a small hill 5 km north of Kusungu, and the smaller Chipala East intrusion occurs a kilometer to the east (Bloomfield 1965, Peters 1969). To the west of Chipala Hill, a series of essentially horizontal sheets of nepheline syenite lie within the foliation of the Precambrian gneisses. The exact relationship of these sheets to the main intrusion

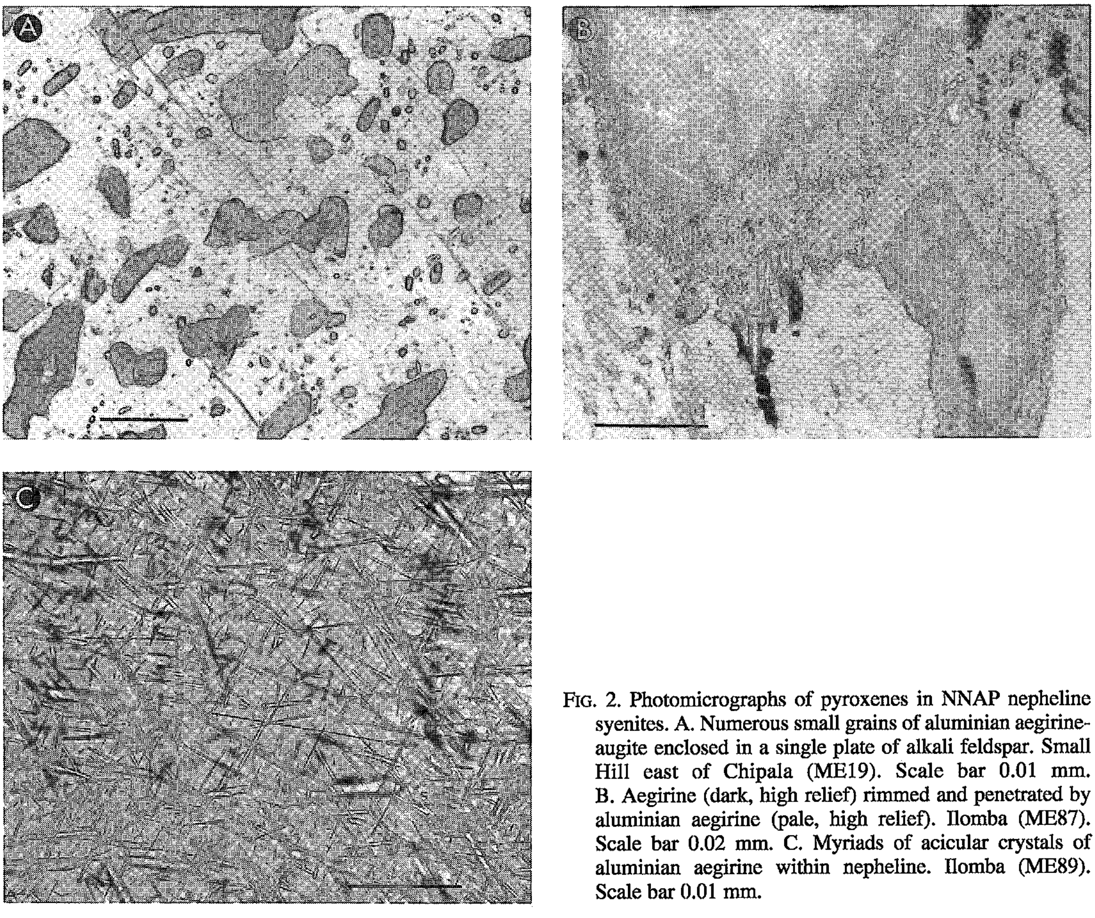

FIG. 2. Photomicrographs of pyroxenes in NNAP nepheline syenites. A. Numerous small grains of aluminian aegirine-augite enclosed in a single plate of alkali feldspar. Small Hill east of Chipala (ME19). Scale bar 0.01 mm. B. Aegirine (dark, high relief) rimmed and penetrated by aluminian aegirine (pale, high relief). Ilomba (ME87). Scale bar 0.02 mm. C. Myriads of acicular crystals of aluminian aegirine within nepheline. Ilomba (ME89). Scale bar 0.01 mm.

is not clear, as no contacts are exposed. The Chipala East intrusion also is probably a conformably emplaced sheet.

In general, the nepheline syenite of the Chipala and Chipala East centers is petrographically identical to that of Kasungu. Figure 2A illustrates a widespread texture in which numerous small grains of pyroxene are enclosed in feldspar.

Ilomba

The Ilomba complex, located 2 km south of the northern border of Malawi with Tanzania (Fig. 1), is a 2 × 1.5 km intrusion of syenite, nepheline and sodalite syenites and pyroxenite (Bloomfield *et al.* 1981). On the northwestern side of the intrusion, Bloomfield observed a gradation along strike from paragneiss to perthosite. He (Bloomfield *et al.* 1981) and Ray (1975) noted the close resemblance of the perthosite to the syenites comprising the whole of the Songwe syenite complex.

Alignment of feldspar crystals is apparent throughout the complex and, we believe, an igneous texture. A lineation, which is only apparent in some places, notably in the summit area, is, however, undoubtedly tectonic and related to structural events of the Mozambique Orogeny (Ray 1974).

The suite of nepheline syenites includes biotite- and pyroxene-bearing varieties. The rocks are generally coarse-grained but texturally variable; they contain microcline perthite, abundant nepheline, with some alteration to cancrinite, brown biotite and sparse pyroxene in the former, but abundant deep green alkali pyroxene, generally zoned, and rare biotite in the latter. The green alkali pyroxene is in some cases rimmed and partly replaced by a pale green pyroxene (Fig. 2B) that also forms small, isolated patches. Myriads of tiny needles of pyroxene, generally aligned along two directions, occur in the nepheline (Fig. 2C) and, to a lesser extent, the feldspar, of the pyroxene–nepheline syenite. Sodalite is locally abundant, and magnetite, calcite, titanite and zircon are accessory phases, with eudialyte in the pyroxene–nepheline syenite.

The main pyroxenite consists of up to 90% diopsidic pyroxene and up to 25% interstitial magnetite. There is minor colorless to pale green calcic amphibole, but an abundance of tiny green crystals of spinel. A small area of pyroxenite mapped by Bloomfield (Bloomfield *et al.* 1981) on the western limb of Ilomba, and occasionally found as xenoliths in the nepheline syenite, is variably altered, with the pyroxene crystals having a deep green color and being marginally altered to amphibole, biotite, or both.

Mphompha

The Mphompha intrusion, referred to as North Nyika by Bloomfield (1965), comprises part of the Rumphi igneous complex (Kemp 1975, Thatcher

TABLE 1. REPRESENTATIVE COMPOSITIONS OF CLINOPYROXENES FROM KASUNGU AND CHIPALA

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	50.64	51.84	51.31	50.72	50.42	50.96	52.13	51.80	51.47	51.84	50.93	50.07
TiO_2	0.80	0.37	0.41	1.03	0.11	0.80	1.15	0.50	0.45	0.14	0.84	0.62
Al_2O_3	2.06	2.06	2.17	5.93	6.98	5.52	1.68	1.81	2.18	5.31	5.58	4.32
Fe_2O_3*	4.52	6.52	8.43	7.63	10.90	12.03	2.53	6.35	7.02	5.56	8.81	12.06
FeO	7.80	8.07	8.51	7.91	4.50	5.22	8.06	10.56	11.88	10.08	7.68	7.50
MnO	0.43	0.58	0.54	0.67	0.37	0.52	0.53	0.57	0.57	0.69	0.65	0.62
MgO	9.67	8.31	6.64	5.38	5.71	5.03	11.04	7.23	5.59	6.10	5.16	4.50
CaO	20.85	18.78	16.81	15.20	14.72	13.48	21.73	18.33	16.51	16.32	15.22	14.42
Na_2O	2.03	3.22	4.16	5.16	5.71	6.40	1.59	3.23	4.01	4.25	5.31	5.57
ZrO_2	0.55	0.24	n.d.	n.d.	n.d.	n.d.	<0.20	0.17	0.38	0.26	n.d.	<0.20
Total	99.35	99.99	98.98	99.63	99.42	99.96	100.44	100.55	100.06	100.55	100.18	99.88
Structural formula based on 4 cations and 6 atoms of oxygen												
Si	1.931	1.964	1.972	1.919	1.896	1.918	1.949	1.978	1.978	1.950	1.921	1.916
^{IV}Al	0.069	0.036	0.028	0.081	0.104	0.082	0.051	0.022	0.022	0.050	0.079	0.084
^{VI}Al	0.024	0.056	0.070	0.183	0.205	0.163	0.023	0.077	0.077	0.185	0.169	0.111
Ti	0.023	0.011	0.012	0.029	0.003	0.023	0.032	0.013	0.013	0.004	0.024	0.018
Fe^{3+}*	0.130	0.186	0.244	0.217	0.308	0.341	0.071	0.203	0.203	0.157	0.250	0.347
Fe^{2+}	0.249	0.256	0.274	0.250	0.142	0.164	0.252	0.382	0.382	0.317	0.242	0.240
Mn	0.014	0.019	0.018	0.021	0.012	0.017	0.017	0.019	0.019	0.022	0.021	0.020
Mg	0.550	0.469	0.380	0.303	0.320	0.282	0.615	0.320	0.320	0.342	0.290	0.257
Ca	0.852	0.762	0.692	0.616	0.593	0.544	0.870	0.680	0.680	0.658	0.615	0.591
Na	0.150	0.237	0.310	0.379	0.416	0.467	0.115	0.299	0.299	0.310	0.388	0.413
Zr	0.010	0.004	–	–	–	–	0.004	0.007	0.007	0.005	–	0.001

Compositions reported in wt% oxides. * Fe_2O_3 calculated on the basis of 4 cations and 6 atoms of oxygen. n.d.: not determined. Samples: 1–6 Kasungu, 7–12 Chipala. 1–3 and 6–9: igneous series; 4–5 and 10–12: Al–rich pyroxenes.

1974). It is oval in outline, approximately 8 × 3 km in area, and lies within syenites, some of which are peralkaline, and granites. Pyroxene has been found in only about half the samples collected. The main rock type is a nepheline syenite composed of nepheline and perthite; there are patches and layers, which may comprise half the rock, of amphibole, biotite, pyroxene and abundant titanite. The pyroxene is generally enveloped in amphibole and is clearly partly replaced, small remnant pyroxene cores commonly being all that remains of the original crystals.

Chikangawa

The Chikangawa intrusion (Gaskell 1973), originally referred to by Bloomfield (1965) as South Vipya, is oval in outline, with a longer axis of 6.5 km. It comprises nepheline–biotite syenites which are coarse, relatively homogeneous, and of low color index. Pyroxene has been identified in only one specimen, in which it forms sparse clusters of small grains enclosed in microcline. This habit is closely similar to the fine-grained granular pyroxene found in some rocks of Kasungu and Chipala.

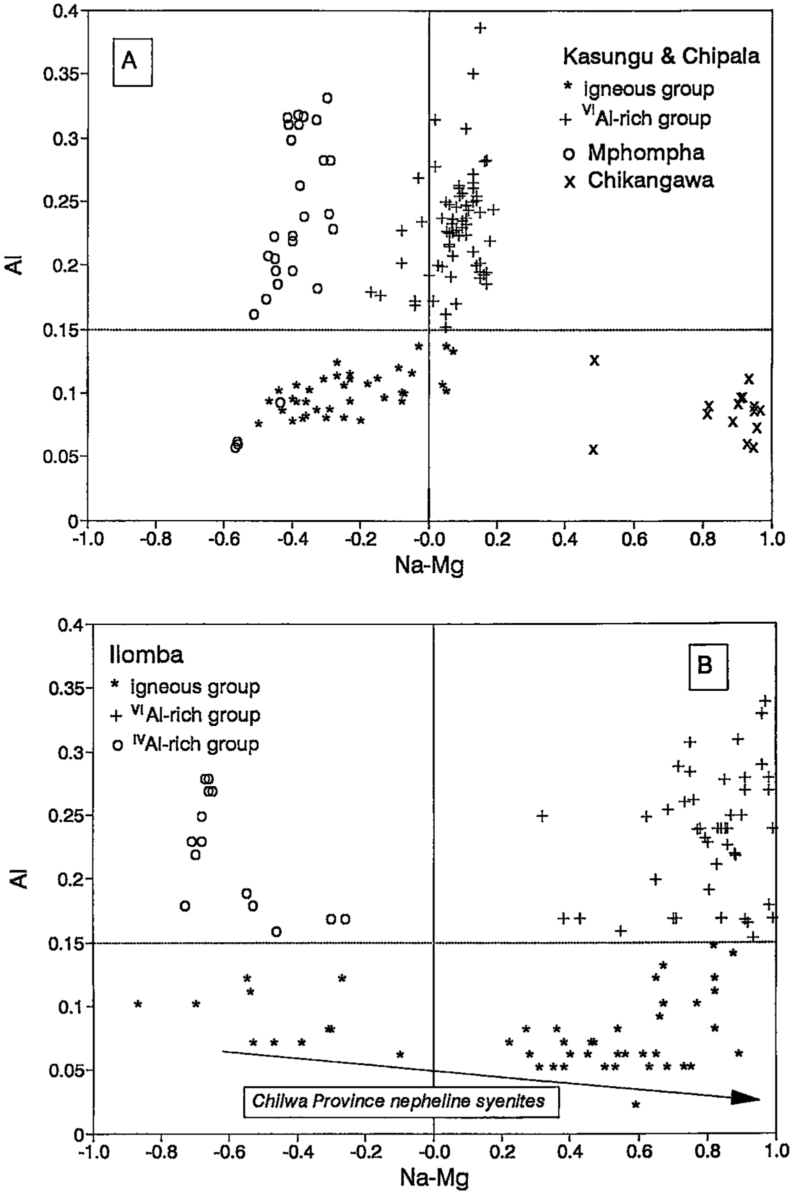

FIG. 3. Plots of Al against Na–Mg (atoms per formula unit) in pyroxenes of the North Nyasa Alkaline Province. A. Kasungu and Chipala, Mphompha and Chikangawa. The igneous and Al-rich groups of Kasungu and Chipala are divided at 0.15 Al. B. Ilomba. ^{VI}Al-rich, ^{IV}Al-rich and igneous groups are distinguished. The arrow shows the general trend of pyroxenes (based on approximately 200 analyses) in nepheline syenite of the Chilwa Province, Malawi (Woolley & Platt 1986).

PYROXENE

Pyroxenes were analyzed using both a Hitachi S2500 scanning electron microscope equipped with a Link AN10/55S energy-dispersion X-ray analysis system, operated at 15 kV and a current of 1 nA measured on vanadium metal, and a Cameca SX50 wavelength-dispersion electron microprobe operated at 20 kV and a current of 20 nA measured on a Faraday cage. Representative compositions of pyroxenes are given in Tables 1–3.

Kasungu and Chipala

The pyroxene population of Kasungu and Chipala nepheline syenites may be divided on the basis of Al content into two distinct types, Al-poor and Al-rich, the division being taken at 0.15 Al (*apfu*) (Figs. 3A, 4A). The Al-poor pyroxene occurs as cores, and the Al-rich ones as overgrowths and as small grains in the groundmass. The Al-poor pyroxene is considered to have an igneous paragenesis, as discussed below; compositions are distinguished on Figures 3A, 4A and later diagrams

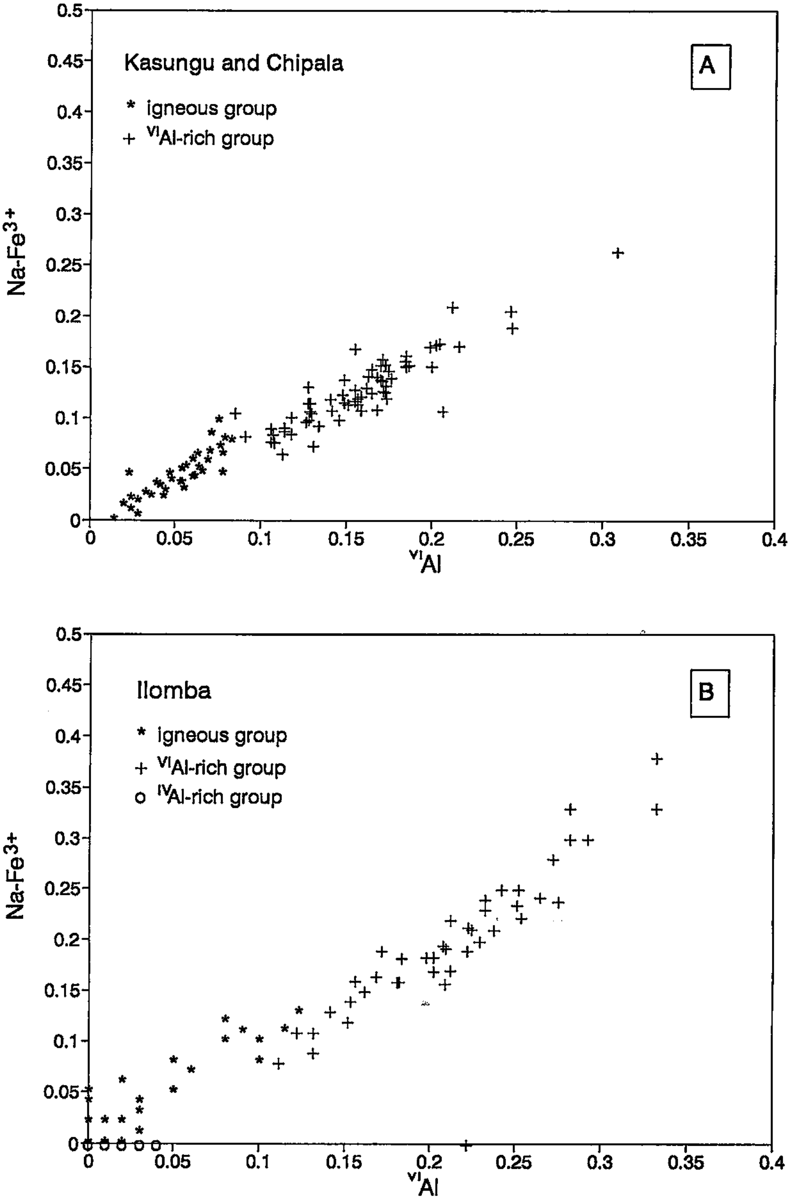

FIG. 4. Plots of (Na–Fe^{3+}) against ^{VI}Al in pyroxenes of the North Nyasa Alkaline Province intrusions. A. Kasungu and Chipala; igneous and ^{VI}Al-rich groups are distinguished. B. Ilomba; ^{VI}Al-rich, ^{IV}Al-rich and igneous groups are distinguished.

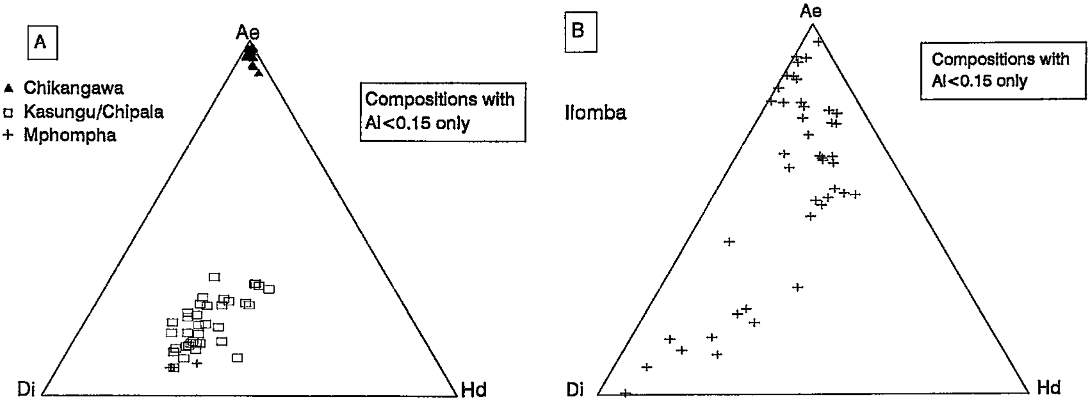

FIG. 5. Plots of NNAP pyroxenes, excluding Al-rich groups (*i.e.*, Al > 0.15), in terms of diopside – hedenbergite – aegirine. A. Kasungu and Chipala, Mphompha and Chikangawa. B. Ilomba.

as the "igneous group". Both types are represented in the Kasungu and the Chipala intrusions (Table 1).

The Al-poor suite consists essentially of diopsidic pyroxene with a Mg/(Mg + Fe^{2+}) value varying from 0.46 to 0.74, with most grains having a value greater than 0.5. Concomitant increases in Na (1.59–4.80 wt% Na_2O) and Fe (2.66–10.78 wt% Fe_2O_3) reflect a moderate increase in the aegirine component (Fig. 5A), which is represented in Figure 3A by the variable (Na–Mg). Compared with observed increases in other nepheline syenite complexes, for example the Chilwa alkaline province of southern Malawi (Woolley & Platt 1986), this enrichment is not pronounced, as indicated by the arrow on Figure 3B. Al contents (1.68–3.06 wt% Al_2O_3) are slightly higher than in pyroxenes from typical nepheline syenite complexes.

The suite of Al-rich pyroxene is distinctly richer in Na (3.90–6.71 wt% Na_2O), Al (3.59–8.71 wt% Al_2O_3), and hence the jadeite component, and ^{VI}Al (Figs. 3A, 4A). The amount of Fe (5.73–12.03 wt% Fe_2O_3) partially overlaps the range of the Al-poor pyroxenes, *i.e.*, the extent of solid solution toward aegirine is essentially similar in both suites. Mg/(Mg + Fe^{2+}) values are also similar to those of the Al-poor suite.

The nomenclature of the Al-rich pyroxenes can partly depend on the method used to reduce the analytical data. Moreover, differences exist in the published nomenclatures of the fields defined in terms of the aegirine – jadeite – diopside or hedenbergite molar proportions (*cf.* Clark & Papike, 1968, Deer *et al.* 1978). In this paper, we use the nomenclature of Morimoto *et al.* (1988). The nomenclature suggested by Curtis & Gittins (1979) for pyroxene of a similar paragenesis to those described here, has not been adopted, but their classification diagram has been adapted (Fig. 6A) to the IMA-sanctioned system of Morimoto *et al.* (1988).

The bulk of the Kasungu and Chipala Al-rich pyroxenes correspond to aluminian aegirine-augite, with some classifying as omphacite (Fig. 6A). The Al-poor pyroxenes are diopside and aegirine-augite, with rare aluminian diopside. Tie lines on Figure 6A join compositions of cores and rims (for clarity only a selection is shown), the latter always proving to be the more aluminous and sodic.

Ilomba

Pyroxene compositions in 17 samples of Ilomba nepheline syenite and pyroxenite fall into three distinct groups, two of which have elevated Al contents (Fig. 3B, Table 2), but differ in the proportions of ^{IV}Al and ^{VI}Al (Fig. 7). The third group is comparatively poor in total Al.

The "low"-Al pyroxene compositions vary from diopside to aegirine (Figs. 5B, 6B) and thus, unlike the Kasungu and Chipala pyroxenes, show an extensive evolution typical of clinopyroxene in many types of alkaline igneous series, for example, the nepheline syenite suites of the Chilwa Province, as depicted by the arrow on Figure 3B. Small excesses of Na over that required for the formation of aegirine component, combined with ^{VI}Al, suggest limited solid-solution toward jadeite. This pyroxene is generally the most abundant in the Ilomba nepheline syenite, but is also the principal pyroxene in the alkali-pyroxene-rich pyroxenite occurring near the summit of Ilomba. In the nepheline syenite, this pyroxene commonly has a rim of ^{VI}Al-rich pyroxene, and in the pyroxenite, a core rich in ^{IV}Al. This series will be referred to hereafter as the "igneous group".

The ^{IV}Al-rich group (Fig. 3B) has compositions ranging from diopside to aluminian diopside (Fig. 6B); compared with the ^{VI}Al-rich group, the group of

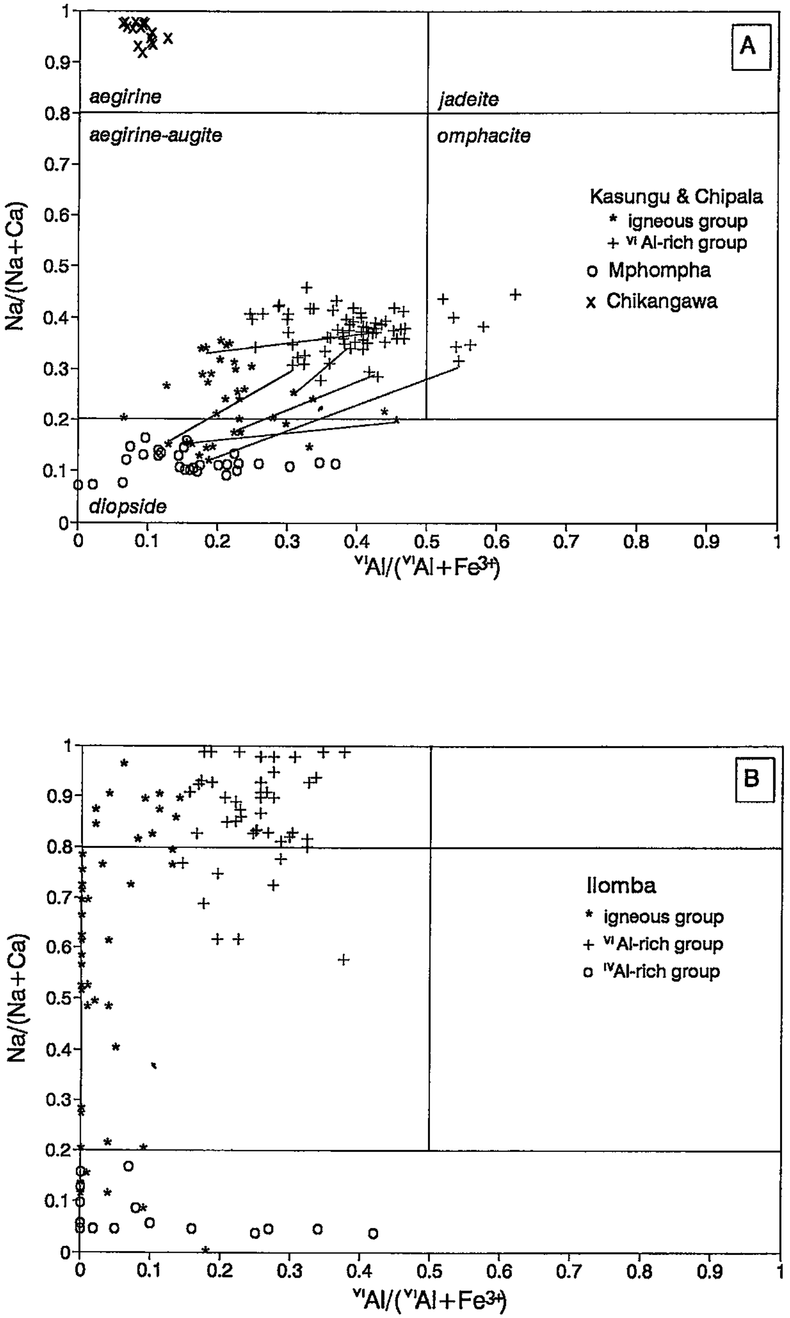

FIG. 6. Plots of Na/(Na+Ca) against ^{VI}Al/(^{VI}Al+Fe^{3+}) (atoms per formula unit) for NNAP pyroxenes. The pyroxene names, given in A only, follow the nomenclature of Morimoto *et al.* (1988). A. Kasungu and Chipala (^{VI}Al-rich and igneous groups are distinguished), Mphompha and Chikangawa. A selection of Kasungu and Chipala pyroxenes representing individual crystal cores and rims are joined by tie-lines. In all cases, rims are more sodic and aluminous than cores. B. Ilomba. ^{VI}Al-rich, ^{IV}Al-rich and igneous groups are distinguished.

TABLE 2. REPRESENTATIVE COMPOSITIONS OF PYROXENES FROM ILOMBA

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	49.48	51.12	51.59	50.72	53.30	54.36	51.90	53.32	52.81	52.82	47.94
TiO_2	0.15	0.80	0.23	0.34	0.19	0.27	0.19	0.06	0.17	0.16	3.07
Al_2O_3	1.23	1.35	2.84	1.13	5.81	7.68	3.93	5.65	4.95	5.16	6.03
Fe_2O_3*	10.75	23.38	22.94	18.02	13.43	23.13	17.42	18.68	25.30	24.90	2.86
FeO	8.22	3.46	5.21	6.94	4.92	1.51	4.08	2.98	1.17	1.02	3.28
MnO	1.02	0.77	0.89	1.48	0.39	0.00	0.52	0.70	0.37	0.37	0.00
MgO	6.30	2.71	1.25	3.49	4.75	0.15	3.65	2.27	0.47	0.68	14.06
CaO	17.38	7.47	5.68	11.73	10.42	0.26	9.32	6.98	2.75	3.12	22.06
Na_2O	3.60	9.38	10.00	6.82	7.93	13.64	8.47	10.18	12.38	12.23	0.75
ZrO_2	0.24	0.50	0.16	0.61	0.00	0.20	0.17	0.00	0.01	0.01	0.00
Total	98.37	100.94	100.79	101.28	101.14	101.20	99.65	100.82	100.38	100.47	100.06
Structural formula based on 4 cations and 6 atoms of oxygen											
Si	1.941	1.949	1.967	1.947	1.966	1.989	1.966	1.980	1.979	1.975	1.771
^{IV}Al	0.057	0.051	0.033	0.051	0.034	0.011	0.034	0.020	0.021	0.025	0.229
Fe^{3+}*	0.002	–	–	0.002	–	–	–	–	–	–	–
^{VI}Al	0.000	0.010	0.095	0.000	0.219	0.320	0.141	0.227	0.198	0.202	0.033
Ti	0.004	0.023	0.007	0.010	0.005	0.007	0.005	0.002	0.005	0.004	0.085
Fe^{3+}*	0.315	0.671	0.658	0.518	0.373	0.637	0.497	0.522	0.713	0.700	0.080
Fe^{2+}	0.270	0.110	0.166	0.223	0.152	0.046	0.129	0.093	0.037	0.032	0.101
Mn	0.034	0.025	0.029	0.048	0.012	0.000	0.017	0.022	0.012	0.012	0.000
Mg	0.368	0.154	0.071	0.200	0.261	0.008	0.206	0.126	0.026	0.038	0.774
Ca	0.730	0.305	0.232	0.482	0.412	0.010	0.378	0.275	0.110	0.125	0.873
Na	0.274	0.693	0.739	0.508	0.567	0.968	0.622	0.733	0.899	0.886	0.054
Zr	0.005	0.009	0.003	0.011	0.000	0.004	0.003	0.000	0.000	0.000	0.000

Compositions reported in wt% oxides. * Fe_2O_3 calculated on the basis of 4 cations and 6 atoms of oxygen. Samples: 1–4 igneous group, 5–10 ^{VI}Al-rich group, 11 ^{IV}Al-rich group. 8–10 fine needles in nepheline.

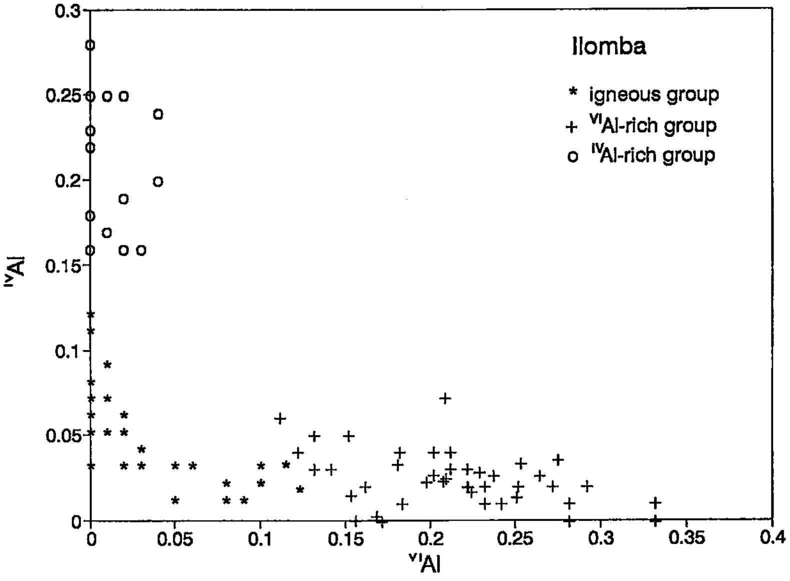

FIG. 7. Plot of Ilomba pyroxenes in terms of ^{IV}Al and ^{VI}Al. The ^{VI}Al-rich, ^{IV}Al-rich and igneous groups are distinguished.

^{IV}Al-rich pyroxenes have lower Fe^{3+}:Fe^{total} and Fe^{2+}:Mg values and higher Ti contents (Table 2). Any excess of Na over Fe^{3+} is small, and the content of ^{VI}Al is low. Such pyroxene is the major rock-forming phase of the pyroxenites.

The ^{VI}Al-rich group lies in the compositional fields of aegirine-augite and aegirine, with many warranting the modifier aluminian (Fig. 6B). High Fe^{3+}:Fe^{total} ratios, lower Ti contents and higher Na values also distinguish this group from the ^{IV}Al-rich pyroxenes. The excess of Na over Fe^{3+} (Fig. 4B), combined with ^{VI}Al, indicate a significant trend of increasing solid-solution toward jadeite in this group. This is the pyroxene that occurs as a rim around, and small patches adjacent to, the Al-poor pyroxene in the nepheline syenite, and as a rim on ^{IV}Al-rich pyroxene in some samples of pyroxenite.

The fine needles of pyroxene that occur within nepheline (Fig. 2C) and, to a lesser extent, feldspar, in some rocks, were found to be generally too narrow (commonly 1 μm or less wide) to be analyzed with the electron microprobe, although some slightly larger grains were analyzed. They all proved to belong to the ^{VI}Al-rich group (Table 2, anal. 8–10) and are aluminian aegirine.

The pyroxene of the alkaline pyroxenite from near the summit of Ilomba is generally Al-poor, *i.e.*, it belongs to the igneous series, but it may contain a core of ^{IV}Al-rich pyroxene, suggesting that these rocks represent blocks of pyroxenite caught up in and modified by the nepheline syenite. The correlation of pyroxene type with rock type at Ilomba can be summarized as follows: (1) ^{IV}Al-rich: principal pyroxene of pyroxenite; core in alkali pyroxene of pyroxenite. (2) ^{VI}Al-rich: forms a rim on Al-poor pyroxene and discrete grains in nepheline syenite; forms tiny acicular prisms within nepheline in nepheline syenite; forms a rim to ^{IV}Al-rich pyroxene in pyroxenite. (3) Al-poor: common as a core to ^{VI}Al-rich pyroxene in all samples of pyroxene-bearing nepheline syenite.

TABLE 3. REPRESENTATIVE COMPOSITIONS OF PYROXENES FROM MPHOMPHA AND CHIKANGAWA

	1	2	3	4	5	6	7	8
SiO_2	51.58	49.37	47.79	47.94	46.11	46.33	52.07	51.90
TiO_2	0.43	1.58	1.49	1.55	1.80	2.09	0.24	0.28
Al_2O_3	1.43	3.66	4.94	5.06	6.32	7.18	2.83	2.18
Fe_2O_3*	3.94	3.74	7.76	7.43	8.36	5.81	28.74	30.14
FeO	7.60	6.06	4.97	5.24	6.41	6.42	0.37	0.06
MnO	1.03	0.50	0.62	0.54	0.55	0.51	0.14	0.27
MgO	11.38	10.81	9.53	9.49	7.67	8.78	0.26	0.46
CaO	22.28	22.35	21.37	21.55	20.93	21.62	1.27	1.64
Na_2O	0.99	1.31	1.86	1.82	2.02	1.52	12.92	12.74
ZrO_2	0.00	0.16	0.17	0.06	0.12	0.10	0.05	0.02
Total	100.66	99.54	100.50	100.68	100.29	100.36	98.89	99.69
Structural formula based on 4 cations and 6 atoms of oxygen								
Si	1.937	1.865	1.803	1.804	1.759	1.752	1.994	1.981
^{IV}Al	0.063	0.135	0.197	0.196	0.241	0.248	0.006	0.019
^{VI}Al	0.000	0.028	0.023	0.028	0.043	0.072	0.122	0.079
Ti	0.012	0.045	0.042	0.044	0.052	0.059	0.007	0.008
Fe^{3+}*	0.111	0.106	0.220	0.210	0.240	0.165	0.828	0.866
Fe^{2+}	0.239	0.192	0.157	0.165	0.205	0.203	0.012	0.002
Mn	0.033	0.016	0.020	0.017	0.018	0.016	0.005	0.009
Mg	0.637	0.609	0.536	0.532	0.436	0.495	0.015	0.026
Ca	0.896	0.905	0.864	0.869	0.855	0.876	0.052	0.067
Na	0.072	0.096	0.136	0.133	0.149	0.111	0.959	0.943
Zr	0.000	0.003	0.003	0.001	0.002	0.002	0.001	0.000

Compositions expressed in wt% oxides. * Fe_2O_3 calculated on the basis of 4 cations and 6 atoms of oxygen. Samples: 1–6 Mphompha, 7–8 Chikangawa.

Mphompha

Pyroxene grains were analyzed in four samples of nepheline syenite (Table 3). They all proved to be diopside (Fig. 6A) which, apart from those in one rock, are characterized by high Al (>0.15 Al *apfu*) (Fig. 3A). Thus they trend to aluminian diopside. However, the Al is essentially tetrahedrally coordinated, and so the pyroxene is similar to the ^{IV}Al-rich group of Ilomba. At Mphompha, the pyroxene has only a small amount of Na (generally 1–2 wt% Na_2O) with no indication of a trend toward more sodic compositions (Fig. 6A).

Chikangawa

The pyroxene grains in the one pyroxene-bearing nepheline syenite found all proved to be aegirine (Figs. 5A, 6A), with only moderate amounts of Al (maximum 2.8 wt% Al_2O_3) (Table 3).

DISCUSSION

Pyroxene compositions in five alkaline intrusive centers of the North Nyasa Alkaline Province fall into three distinct groups, one of which, the Al-poor group, ranges from diopside through aegirine-augite to aegirine and thus is typical of pyroxenes in igneous nepheline syenite, some ijolite-series rocks and even peralkaline granite. The completeness of this series in Ilomba reflects the general peralkalinity of the intrusion and contrasts with the restricted series of alkali pyroxene compositions in Kasungu, Chipala and Mphompha. The Al-poor nature of the aegirine in the single pyroxene-bearing rock sampled from Chikangawa is consistent with a primary origin.

In contrast to these igneous pyroxenes, a second series has been identified that is rich in ^{VI}Al; we are unaware of such alkali-rich pyroxenes having been described from pristine magmatic rocks. These pyroxenes form a rim on the igneous ones, cut across them and also form fine needles within nepheline at Ilomba and small grains in Kasungu and Chipala. Such aluminous pyroxenes, some of which are omphacite, are likely to be metamorphic in origin.

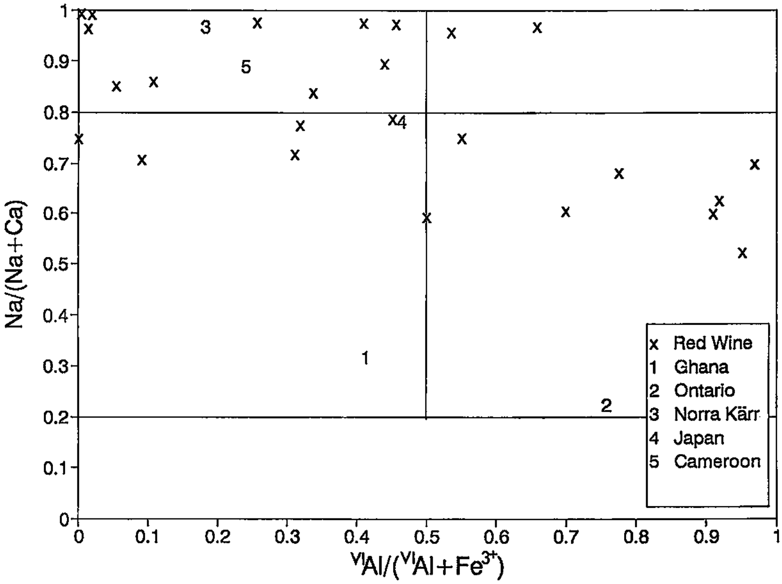

FIG. 8. Plot of Na/(Na+Ca) against ^{VI}Al/(^{VI}Al + Fe^{3+}) (atoms per formula unit) for pyroxenes from metamorphosed alkaline rocks including Red Wine, Labrador (Curtis & Gittins 1979); Ghana (Holm 1971); Nkonglong, Cameroon (Kornprobst *et al.* 1976); Norra Kärr, Sweden (Adamson 1944); Japan (Iwasaki 1960) and Ontario (Lumbers 1976). Key to symbols given on figure. Pyroxene fields as on Figure 6A.

The Al-rich pyroxene needles within nepheline are generally oriented in two directions, which are clearly determined by the nepheline structure, and this orientation would seem to preclude an origin as a liquidus phase. Nepheline generally contains an excess of silica and a small amount of iron, so that an origin either by exsolution, subsolidus growth or through metamorphic heating seems feasible. The last is favored as being more consistent with the rimming and cross-cutting aluminous pyroxene, which is interpreted as being metamorphic.

Aluminous pyroxene has been reported from metamorphosed alkaline rocks at a number of localities (Fig. 8) including the Nkonglong nepheline syenite gneiss, Cameroon (Kornprobst *et al.* 1976), schistose nepheline syenite at Norra Kärr, Sweden (Adamson 1944), undersaturated syenite in Japan (Iwasaki 1960), nepheline gneiss in Ghana (Holm 1971) and regionally metamorphosed nepheline syenite in the Grenville Province of Ontario (Lumbers 1976). However, the only detailed account of pyroxenes from a metamorphosed alkaline complex is that of Curtis & Gittins (1979). Their pyroxene data for the regionally metamorphosed agpaitic rocks of the Red Wine alkaline complex, in Labrador (Fig. 8) cover much of the upper part of the diagram. Also shown on Figure 8 are data for the other localities mentioned above, from which it is clear that pyroxenes of wide degrees of alkalinity and Al-enrichment may be formed as a result of metamorphism of alkaline rocks. The ^{VI}Al-rich pyroxenes from Ilomba have similarities to some of those from Red Wine, but those from Kasungu and Chipala have compositions, in terms of Figure 8, rather different from any so far described for this paragenesis.

The ^{IV}Al-rich pyroxenes from Ilomba, from textural and chemical evidence, are interpreted to be essentially of primary, igneous origin and are considered to be igneous cumulus minerals. These pyroxenes, and those of Mphompha, trend toward aluminian diopside compositions, but it is not clear whether this trend is a primary igneous feature or reflects a metamorphic overprint.

Jadeitic pyroxenes are generally considered to be indicative of high pressures. However, this is not necessarily the case. The aluminous pyroxenes in the agpaitic Red Wine rocks were formed under amphibolite-facies conditions; Curtis & Gittins (1979) suggested that the presence of jadeitic and omphacitic pyroxenes in nepheline-bearing rocks do not indicate the high pressures normally attributed to silica-saturated or oversaturated rocks that contain these minerals. Although experimental work indicates that formation of pure jadeite probably does require a minimum pressure of about 7 kbar, replacement of Al by Fe^{3+} will probably lead to the generation of pyroxene at much lower pressures (Deer *et al.* 1978). The preservation of early igneous pyroxenes in the NNAP intrusions suggests that the metamorphism was neither of high-pressure type nor reached particularly elevated temperatures. This metamorphism may have been the "Pan-African thermal event", which is widespread over much of the northern half of the African continent, or part of the Mozambique Orogeny.

It is not clear whether the production of metamorphic pyroxenes in the NNAP intrusions was an isochemical process. Although the aluminian aegirine at Ilomba and aluminian aegirine-augite and omphacite at Kasungu and Chipala are slightly more sodic than the coexisting igneous pyroxenes, and the presence of sodic scapolite in nepheline syenite at Kasungu and Chipala is probably indicative of Cl, and possibly Na, metasomatism, clearly the enhanced Na in the metamorphic pyroxenes may simply reflect re-equilibration under metamorphic conditions but within a closed chemical environment. The fact that the more alkaline igneous pyroxenes in the Ilomba rocks coexist with highly alkaline aluminous pyroxenes, whereas the less alkaline igneous pyroxenes in the Kasungu and Chipala suites occur with less alkaline aluminous pyroxenes, may be evidence that the systems were essentially closed. Thus in this paragenesis, metamorphism of agpaitic rocks will give rise to aluminian aegirine and a jadeitic pyroxene, whereas miaskitic alkaline rocks lead to aluminian aegirine-augite and an omphacitic pyroxene.

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