Petrology and geothermometry of the Little Michiru Complex, Malawi

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Abstract

The Little Michiru complex is a composite intrusion of pyroxenite and pyroxene syenite which is located at the boundary between amphibolite and granulite facies gneisses in the Shire rift valley. Pyroxene and feldspar chemistry shows that the intrusion consolidated from two magmatic fractions, one a pyroxenite cumulate that equilibrated at 870–1000 °C, the other a partly anatectic pyroxene syenite magma which metasomatized the surrounding gneisses during granulite-facies metamorphism and equilibrated at a temperature of 730–830 °C at 7 kbar.

KEYWORDS: pyroxenite, pyroxene syenite, petrology, geothermometry, Little Michiru complex, Malawi.

Introduction

THE Little Michiru complex forms three hills in southern Malawi (Fig. 1) that extend southwards from Matope on the Shire river to the Nkmadzi stream (Fig. 2). It is transected by the Lirangwe river. The largest of the hills, Little Michiru (494 m), is formed by a coarse-grained dark-green websterite which forms a central spine running southwards for 11 km and averaging 1.5 km in width. At its southern extremity it passes into biotite pyroxenite and glimmerite, whilst the pyroxenite as a whole is surrounded by an envelope of pyroxene syenite. The complex has a canoe-shaped outcrop lying within inward dipping country rocks of gneiss and amphibolite. It is elongated in the direction of the gneissic foliation. Bloomfield (1965) considers it to be a folded synorogenic infracrustal ring complex. The eastern contacts with the granulites are gradational but the western margin of the intrusion is strongly sheared with lit-par-lit interlayering of flaser pyroxene-syenite and the enclosing amphibolite facies gneisses (Bloomfield, 1965; Morel, 1961*a*, *b*).

Exposures in the bed of the Lirangwe river display intermingled relations between the websterite and pyroxene syenite with the latter forming veins, schlieren, and segregations within it. Mafic schlieren and dykes of websterite with perthite porphyroblasts also lie in the pyroxene syenite (Morel, 1958, pl. XI).

Petrography

Websterite and related rocks. The websterite consists of schillerized augite and hypersthene forming a mosaic of bent, fractured or granulated crystals from 1 to 5 mm across. The larger pyroxenes are anhedral but smaller ones are subhedral. The two pyroxenes are present in about equal amounts with clinopyroxenes larger than hypersthenes. Both contain exsolution lamellae that are too narrow to resolve with the electron probe. Microprobe analyses were made on crystals which are relatively free from exsolution lamellae. The fabric of the pyroxenite indicates that it is a sheared cumulate.

Secondary edenitic amphibole and pale brown biotite are products of a later alteration of the pyroxenes. Opaque minerals include intergrowths of hematite, magnetite, and ilmenite, with rare pyrite and chalcopyrite. Rounded grains of apatite are common. Some specimens carry a little interstitial andesine-labradorite.

Pyroxene syenite. The websterite is flanked by a melanocratic gneissose pyroxene syenite which extends southwards for 20 km from Chipilanje hill. It is medium- to coarse-grained and varies in colour, grain size, and texture with the number of perthite porphyroblasts, many of which exceed 1 cm in diameter. Flakes of biotite give the rock a slight foliation.

Exposures in the bed of the Lirangwe river show unchilled veins of pyroxene syenite penetrating the pyroxenite. Mafic schlieren and dykes

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of biotite norite are also present within the pyroxene syenite in some places. These contain granulose schillerized hypersthene and augite and opaque oxides in a groundmass of granular oligoclase. A weak foliation concordant with that of the enclosing pyroxene syenite is defined by biotite flakes.

Contacts of the pyroxene syenite with the surrounding gneisses and mangerites are poorly exposed but near to them the gneisses have developed perthite porphyroblasts and are converted into banded perthitic pyroxene granulites. In the section to the west of the confluence of the Lirangwe and Lunzu rivers it is intrusive into mafic mangerites but chilled contacts are absent.

Although the relative proportions of pyroxenes and perthite are very variable in samples of the pyroxene syenite from various locations within the complex, their coarse grain size and the similar compositions of their co-existing pyroxenes suggest that they attained equilibrium during anatexis. Cryptic variation is absent. Both ortho-and clinopyroxenes have exsolution lamellae. Spongy pale green augites up to 2 mm across contain brown platelets and inclusions of ilmenite, apatite, and plagioclase within their cleavages. They are generally fractured or bent. Orthopyroxene fragments tend to surround the augites as angular grains 0.5–1 mm across and have strong pink–green pleochroism.

Angular hematite and ilmenite form intergrowths and rare veins between the pyroxenes and feldspars. Perthites are mesoperthites forming irregular crystals up to 6 mm across, generally twinned on the Carlsbad law, and contain lines of ilmenite and gas bubble inclusions.

Zoned plagioclases have andesinic centres passing out into perthitic intergrowths of orthoclase and oligoclase. In some rocks the feldspar is entirely mesoperthite, in others granular oligoclase-andesine forms the groundmass, usually having a grain size of about 0.25 mm. Where perthite is absent plagioclase forms a fine-grained granulitic mosaic enclosing pyroxene fragments. Interstitial microcline and myrmekite and rounded zircons are common. The perthite porphyro-

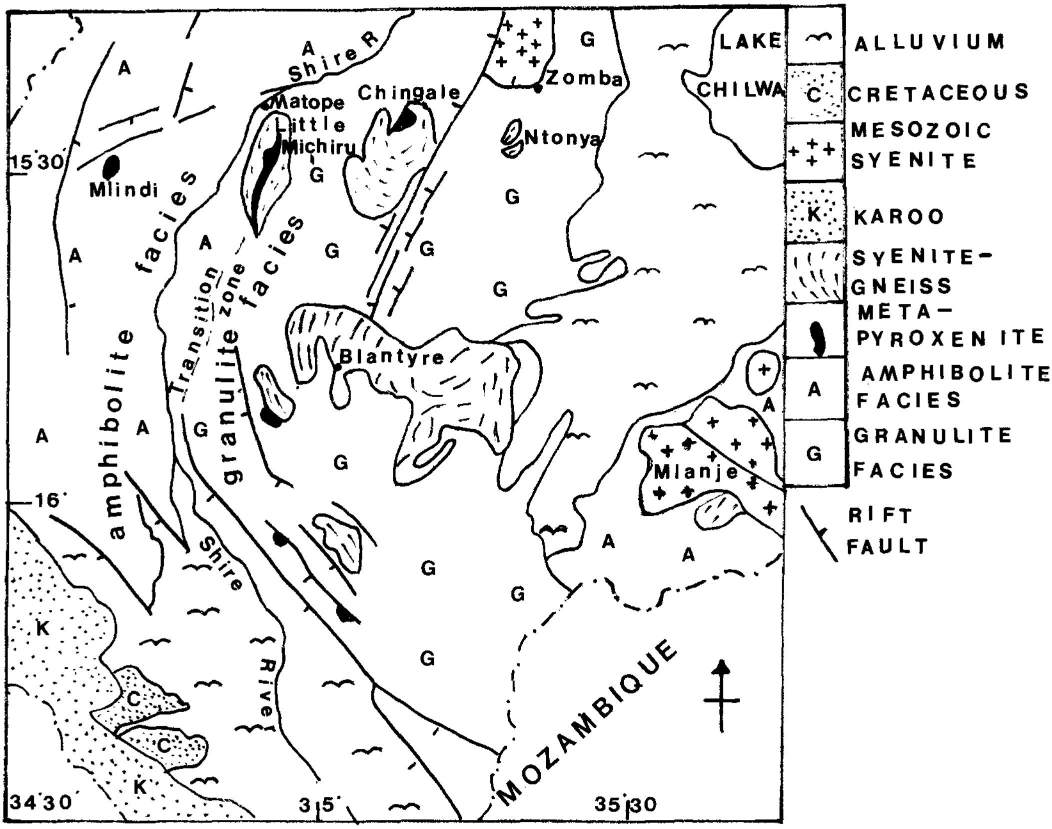

FIG. 1. Geological map of southern Malawi.

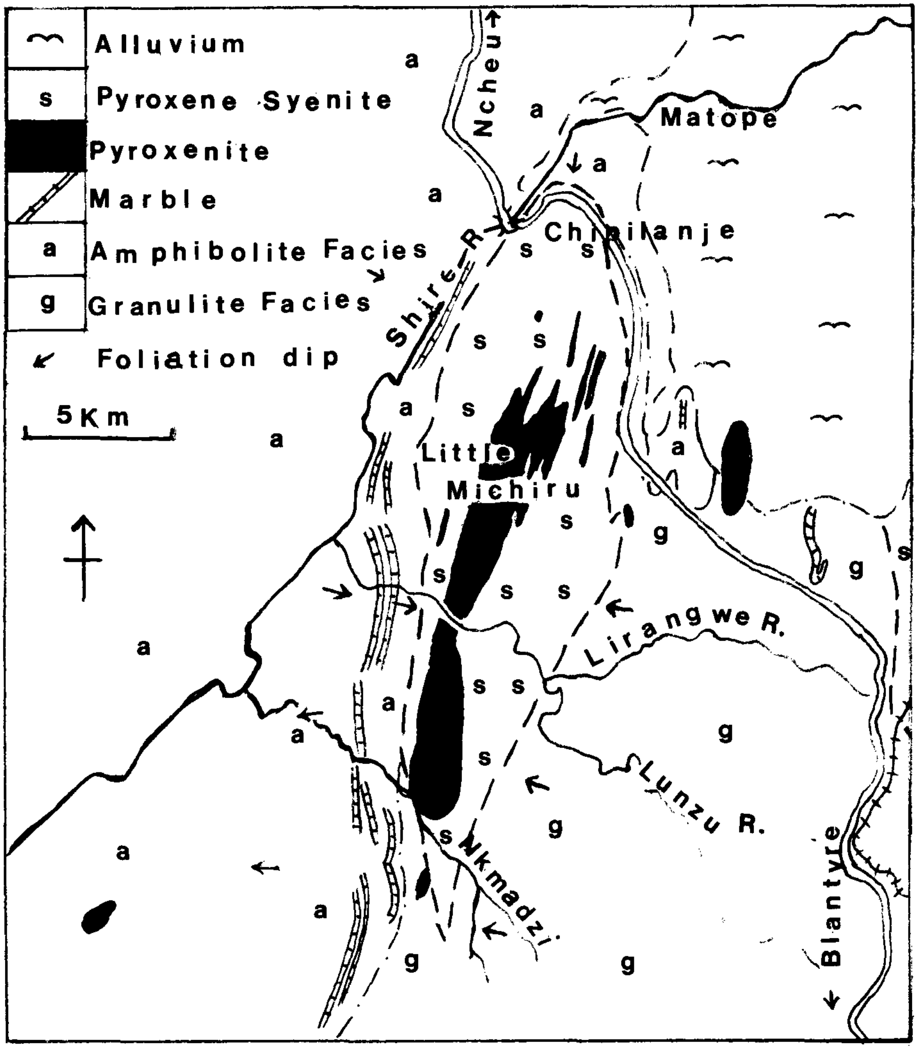

FIG. 2. The Little Michiru complex.

blasts are undeformed, indicating that exsolution post-dates movement. All the rock types in the complex are intruded by quartz-microcline pegmatites which carry hornblende, biotite or muscovite.

Mineral chemistry

Mineral analyses were made with a Cambridge Microscan 9 electron probe with an accelerating voltage of 20 kV and a specimen current of 25 mA. The main elements were measured with reference to a set of natural and synthetic standards; diopside for Si and Ca, gehlenite for Al, forsterite for Mg, fayalite for Fe, rhodonite for Mn, jadeite for Na, and orthoclase for K. Minor elements were analysed with reference to synthetic compounds; V_2O_5, Cr_2O_3, ZnO, and NiO. Precision is approximately 1–2% for the main elements above a level of 10% and 5% for the minor elements. Three to six grains of each mineral were analysed in every sample.

The orthopyroxenes of the metapyroxenite (Table 1) have $Fe^{2+}/(Fe^{2+} + Mg)$ ratios of about 0.25. Those of the pyroxene syenite rise from 0.33 adjacent to the pyroxenite to 0.38 at the outer margin of the intrusion. The websterite clinopyroxenes (Table 2) have ratios of 0.17–0.22 and

TABLE 1. Analyses of orthopyroxenes

	Metapyroxenite		Pyroxene syenite				
Specimen No.	A50	M89	M82	M85	M88A	M104	M174
SiO_2	53.26	53.58	53.33	53.66	52.00	53.19	52.72
Al_2O_3	2.49	2.48	0.93	1.14	0.62	0.62	0.79
TiO_2	0.10	0.11	0.07	0.08	0.04	0.06	0.07
Cr_2O_3	0.07	0.05	0.01	0.16	0.02	0.01	0.01
Fe_2O_3	1.01	–	0.30	–	2.65	0.78	0.09
FeO	15.08	16.17	22.13	20.82	21.44	23.09	23.73
MnO	0.37	0.33	0.64	0.57	0.80	0.76	0.77
MgO	26.42	26.37	22.64	23.68	21.20	21.84	21.19
NiO	0.12	–	–	–	0.08	–	–
CaO	0.87	0.02	0.51	0.47	0.55	0.57	0.57
Na_2O	–	0.02	0.01	0.02	0.30	0.03	0.02
	99.79	99.13	100.57	100.60	99.70	100.95	99.96
No. of ions on basis of 6 oxygens							
Si	1.929	1.949	1.974	1.971	1.958	1.975	1.980
Al^{iv}	0.071	0.051	0.026	0.027	0.028	0.025	0.020
Al^{vi}	0.036	0.055	0.015	0.022	–	0.002	0.015
Ti	0.003	0.003	0.002	0.002	0.001	0.002	0.002
Cr	0.002	0.001	–	0.005	0.001	–	–
Fe^{+3}	0.018	–	0.006	–	0.050	0.022	0.001
Fe^{+2}	0.467	0.492	0.688	0.640	0.705	0.717	0.746
Mn	0.011	0.010	0.020	0.018	0.026	0.024	0.024
Mg	1.427	1.430	1.249	1.296	1.190	1.209	1.186
Ca	0.034	0.001	0.020	0.018	0.022	0.023	0.023
Na	–	0.001	0.001	0.001	0.022	0.002	0.001
Ca%	1.73	0.05	1.00	0.9	1.1	1.1	1.1
Mg%	72.80	73.97	62.98	65.7	59.7	60.6	59.8
$(Fe^{+2}Fe^{+3}Mn)$%	24.74	25.96	36.00	33.3	39.1	38.2	38.9
$Fe^{+2}/(Fe^{+2}+Mg)$	0.24	0.25	0.35	0.33	0.37	0.37	0.38

Fe^{+3} calculated on the assumption of stoichiometry

		Lat. South	Long. East
A50	Metapyroxenite, Lirangwe river	15°30'30"	34°52'30"
M89	Metapyroxenite	15°32'07"	34°52'27"
M82	Pyroxene syenite	15°33'35"	34°52'25"
M85	Pyroxene syenite	15°33'40"	34°52'50"
M88A	Pyroxene syenite	15°33'08"	34°52'15"
M104	Pyroxene syenite	15°30'50"	34°53'00"
M174	Pyroxene syenite	15°35'37"	34°52'12"

TABLE 2. Analyses of clinopyroxenes

	Metapyroxenite		Pyroxene syenite				
Specimen No.	A50	M89	M82	M85	M88A	M104	M174
SiO_2	50.81	51.36	52.76	52.24	51.69	52.85	52.65
Al_2O_3	3.89	4.46	1.90	2.91	1.35	1.86	1.64
TiO_2	0.61	0.70	0.21	0.37	0.21	0.22	0.16
Cr_2O_3	0.11	0.14	0.04	0.02	0.02	0.02	0.02
Fe_2O_3	1.96	–	–	–	2.65	1.92	1.51
FeO	4.72	7.27	8.68	8.57	7.85	7.86	8.06
MnO	0.14	0.16	0.25	0.26	0.35	0.33	0.31
MgO	14.66	14.71	13.63	13.39	13.35	13.38	13.28
NiO	0.06	–	–	–	0.06	–	–
CaO	20.93	20.04	21.63	21.46	20.39	21.42	21.59
Na_2O	0.74	0.74	0.68	0.82	0.82	0.84	0.73
Total	98.63	99.58	99.78	100.04	98.74	100.70	99.95
No. of ions on basis of 6 oxygens							
Si	1.895	1.900	1.968	1.943	1.956	1.957	1.964
Al^{iv}	0.105	0.100	0.032	0.057	0.044	0.043	0.036
Al^{vi}	0.066	0.094	0.052	0.071	0.016	0.038	0.036
Ti	0.017	0.019	0.006	0.010	0.006	0.006	0.004
Cr	0.003	0.004	0.001	0.001	0.001	0.001	0.001
Fe^{+3}	0.037	–	–	–	0.075	0.053	0.042
Fe^{+2}	0.166	0.225	0.271	0.267	0.249	0.244	0.252
Mn	0.004	0.005	0.008	0.008	0.011	0.010	0.010
Mg	0.815	0.811	0.758	0.742	0.753	0.738	0.739
Ni	0.002	–	–	–	–	–	–
Ca	0.836	0.794	0.864	0.855	0.827	0.850	0.863
Na	0.054	0.053	0.049	0.059	0.060	0.060	0.053
Ca%	44.9	44.1	45.4	45.6	43.1	44.8	45.2
Mg%	43.8	43.2	39.8	39.6	39.3	38.9	38.7
$(Fe^{+2}Fe^{+3}Mn)$%	11.1	12.5	14.6	14.6	17.5	16.2	15.9
$Fe^{+2}/(Fe^{+2}+Mg)$	0.17	0.22	0.26	0.26	0.25	0.25	0.25

Fe^{+3} calculated on the assumption of stoichiometry

$K_DFe\text{-}Mg$	1.36	1.24	1.55	1.37	1.48	1.52	1.58

those of the pyroxene syenite 0.25–0.26 with higher Al and lower Mn indicating that the websterite pyroxenes originally crystallized at a higher temperature than those of the pyroxene syenite. The rather uniform $Fe^{2+}/(Fe^{2+}+Mg)$ ratios of the pyroxenes of the pyroxene syenites suggest that they crystallized with only slight differentiation along an outwardly declining temperature gradient from the central websterite. In Table 3 analyses of the central pyroxenite (KB849), intervening perthitic pyroxenite (M86) and the marginal pyroxene syenite (M83) show an outward enhancement of SiO_2, K_2O, Al_2O_3, Fe_2O_3, TiO_2, P_2O_5, and water and sharply reduced CaO and MgO towards the surrounding granulites.

Table 3 Pyroxenites and pyroxene syenites

Specimen No.	KB849	M86	M83
SiO_2	49.65	55.37	58.22
TiO_2	0.74	0.60	1.30
Al_2O_3	3.60	13.26	15.04
Cr_2O_3	0.19	–	–
Fe_2O_3	2.88	6.22	4.38
FeO	5.79	5.89	5.49
NiO	0.19	–	–
MnO	0.19	0.09	0.09
MgO	16.12	5.98	5.49
CaO	19.01	9.20	6.01
Na_2O	0.57	0.98	0.45
K_2O	–	0.05	1.05
P_2O_5	0.08	0.27	1.25
H_2O+	0.46	1.46	0.82
H_2O-	0.19	0.07	–
CO_2	0.59	–	–
	100.25	99.44	99.59
Specific gravity	3.28	3.16	–

KB849 Hypersthene metadiallagite, Little Michiru (Bloomfield, 1965)

M86 Perthitic pyroxenite, 1.6 km E. of Mkmadzi stream (Yusufi, 1969)

M83 Pyroxene syenite, Mkmadzi stream (Yusufi, 1969)

Geothermometry

Tuttle and Bowen (1958) showed that a continuous solid solution is present between the Na and K feldspars above 660 °C. The original homogeneous alkali feldspar of the pyroxene syenite crystallized above this temperature and has unmixed to form mesoperthite following the peak of the amphibolite-granulite metamorphism. The exsolved plagioclase lamellae in the mesoperthites carry 29–35% An, indicating that the original feldspar crystallized above 770–800 °C (Yoder *et al.*, 1957) if no subsequent Ca diffusion took place.

The equilibration temperatures of the coexisting pyroxenes in the websterite and pyroxene-syenite (Table 4) lie about 100 °C above this range, where they are based on the data of Wood and Banno (1973), Wells (1977), and Kretz (1982). Lindsley (1983) regards these geothermometers as being 100 °C or more too high. For charnockites and pyroxene granulites from Sri Lanka, Jayawardena and Carswell (1976) obtained temperatures of 858 ± 11 °C from the Wood and Banno geothermometer and 700 ± 50 °C from a garnet clinopyroxene equilibrium. The latter data agree with those of Fonarev and Graphchikov (1982) who considered that Adirondack pyroxene-bearing metamorphic rocks had undergone temperatures no higher than 650–700 °C. On their data the pyroxenes of the Little Michiru websterite could have equilibrated at 800 °C. Magma temperatures in the Little Michiru intrusion therefore probably lay between 730 and 1100 °C, whilst geobarometric data suggest that pressures were at or near 7 kbar (Morel, 1988*a*).

Table 4. Orthopyroxene–clinopyroxene equilibrium temperatures °C.

	Websterite grading into pyroxene syenite						
Specimen No.	A50	M89	M88A	M82	M85	M104	M174
Wood & Banno (1973)	950	978	878	855	858	844	833
Wells (1977)	941	987	908	867	861	860	849
Kretz (1982) >1080	945	1025	965	927	917	915	904
<1080	807	975	847	773	754	750	730
Mg/Fe	881	1295	869	932	1102	823	793
Lindsley (1983)							
Clinopyroxene 5 kbar	930	900	910	580	640	600	710
10 kbar	950	910	950	620	690	640	740
Orthopyroxene 5 kbar	1000	550	700	800	650	800	780
10 kbar	1000	650	700	850	900	870	850

The K_D Fe–Mg values in Table 2 average 1.45, which is consistent with equilibration of the pyroxene above 1080 °C. Equilibrium temperatures for the co-existing ortho- and clinopyroxenes in the websterite (Table 4) are rather higher than those of the pyroxene syenite, as indicated by the higher Fe^{2+} of the latter and reinforcing the possibility that the websterite pyroxenes represent an early cumulate.

Origin of the complex

The pyroxene syenite attained a magmatic condition as is shown by its intrusive veining of the websterite but its gradational boundaries with the mangeritic granulites suggest a metasomatic origin. Indicated temperatures are above the dry melting temperature for biotite tonalite (Wyllie, 1977), whilst the reaction of biotite and K-feldspar, quartz, and CO_2–H_2O vapour to form orthopyroxene plus liquid lies within the temperature–pressure range of 700–800 °C and 4–8 kbar so that it is possible that the pyroxene syenite magma is partly derived from anatexis of the biotite gneiss lying on the western side of the complex and the mangerites to the east.

Bloomfield (1965, p. 96) suggested that the ultramafics of the Mlindi, Little Michiru and Chingale complexes (Fig. 1) were intruded into gently folded metasediments in the early stages of and during an orogeny. He considered that a wave of alkali metasomatism found egress upwards, around and over their pipe-like bodies, firstly to form perthosite gneiss and syenogabbro hybrids and then, with local mobilization, anatectic syenites. At Mlindi the alkali (potassic) metasomatism was considered to have converted much of the central pyroxenite to a biotite rich rock.

The Little Michiru pyroxene syenite is similar to rocks included by Michot and Michot (1969) as the mangeritic facies in South Rogaland, Norway. They explained mesoperthite as a product of differential anatexis and migmatization that led to the formation of alkali-rich leucogranitic melts. Tuttle (1952) showed that mesoperthite was formed by the unmixing of homogeneous alkali feldspar in which 50–60% K-feldspar is present.

The Little Michiru intrusion may be a folded funnel-shaped structure, a conclusion supported by the inward dips of the gneisses surrounding it and also around the other pyroxenite-perthosite infracrustal ring complexes in southern Malawi (Fig. 1). In the lower levels of the funnel the early fractionated pyroxenes accumulated gravitationally forming pyroxenite, permitting the separation of a volatile potassic magma fraction above them. Volatiles from this metasomatized the surrounding biotite gneisses and mangerites causing the growth of potassic feldspar porphyroblasts within them and obscuring the original contacts of the intrusion. Marginal facies of the websterite were also converted to biotite-pyroxenite and glimmerite by the potassic metasomatism. At higher crustal levels similar magmas may have produced the perthosite complexes of the Shire and Dedza Highlands, and if erupted at surface would have produced their trachytic and phonolitic equivalents. At depth the funnel probably passes into a peridotite/glimmerite complex similar to those of Kapirikamodzi and Maggi to the west of the Shire river (Morel, 1958, 1988*b*) which have affinities with potassic mantle-derived magmas.

The amphiboles of the websterite are edenites and contain up to 0.6% K_2O and 2.6% Na_2O (Table 5). They fringe the margins of the pyroxenes and are present within their cleavages. Biotite fringes orthopyroxene, ilmenite, and magnetite–hematite intergrowths. They are secondary and probably related to the later Pan-African period of folding that deformed the complexes in the Lower Palaeozoic and reset their radiometric clocks.

TABLE 5. Analyses of amphiboles and biotite

	Metapyroxenite Amphiboles		Pyroxene syenite Biotite
Specimen No.	A50	M89	M82
SiO_2	43.95	42.15	37.17
Al_2O_3	11.04	12.31	13.49
TiO_2	1.93	3.08	5.00
Cr_2O_3	0.08	0.26	-
Fe_2O_3	6.38	2.15	-
FeO	3.90	8.24	13.75
MnO	0.10	0.11	0.02
MgO	15.77	13.55	14.98
CaO	11.75	11.28	-
Na_2O	2.08	2.63	0.08
K_2O	0.60	0.52	9.63
Cl	-	0.08	1.20
	-	-	-O=Cl 0.54
	97.58	96.36	95.98
No. of ions on basis of 23(O,OH,Cl,F)			22
Si	6.339	6.228	5.591
Aliv	1.661	1.772	2.391
Alvi	0.216	0.372	
Ti	0.209	0.342	0.565
Cr	0.009	0.030	
Fe+3	0.691	0.239	
Fe+2	0.472	1.018	1.730
Mn	0.012	0.014	0.002
Mg	3.390	2.984	3.358
Ca	1.816	1.786	-
Ba	-	-	0.071
Na	0.583	0.756	0.022
K	0.011	0.098	1.848

Andreoli (1984) suggested that an ancient westward-dipping subduction zone underlies the Shire valley. Morel (1988*b*) has regarded the mangerite massifs of southern Malawi as parts of a disrupted tholeiitic island arc modified by granulite-facies metamorphism. The websterite at the heart of the Little Michiru complex is aligned with a major rift fault system trending NNE along the western margin of the Shire Highlands and is also aligned with the Mlindi, Chingali, and Ntonya ring complexes on the line of the Zambesi rift (Bloomfield, 1965). These faults are almost certainly of Precambrian age, and later provided exit routes for Mesozoic alkaline magmas in the Chilwa Volcanic episode.

Conclusion

The websterite at the centre of the Little Michiru intrusion is of cumulate origin. The surrounding pyroxene syenite is thought to represent an anatectic magma produced by potassic solutions which metasomatized the surrounding gneissic envelope. The pyroxenes of the websterite crystallized above 870 °C whilst those of the pyroxene syenite crystallized at 730 to 830 °C. The temperature gradient from the pyroxenite into the granulites to the east was slight, the latter having equilibrated at 680 to 1000 °C. The gradient was steeper to the west with temperatures in the transition zone of 550 to 680 °C at 4 to 7 kbar and in the amphibolite facies from 450 to 600 °C at 4 to 5 kbar (Morel, 1988*a*).

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