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RECOGNITION OF THE ORIGINAL VOLCANIC SUITE IN ALTERED MAFIC VOLCANIC ROCKS AT SOFALA, NEW SOUTH WALES

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ABSTRACT. In an Ordovician basic volcanic suite at Sofala, New South Wales, the sole remaining igneous phases are phenocrystic clinopyroxene and hornblende. The remainder of the rock yields a suite of metamorphic phases characteristic of the greenschist facies. Original textural features of the volcanic material are well preserved indicating the predominance of porphyritic pyroxene-andesites. Bulk compositions of selected lithologies determined by wet chemical methods demonstrate considerable redistribution of components during the metamorphic alteration, even leading to the development of ultramafic bulk compositions from rocks that still retain porphyritic andesitic volcanic textures. Phase chemistry of the relict igneous clinopyroxene and hornblende therefore provides the only reliable source of chemical information concerning the original volcanic suite.

The combined textural and chemical evidence suggests that the rocks were originally island-arc calc-alkaline in the sense of Jakeš and White (1972).

THE SOFALA AREA

The small area of the present study lies just south of Sofala in central western New South Wales, within altered basic volcanic rocks of greenschist facies. These belong to an Ordovician unit, the Sofala Volcanics (Packham, ms, 1968, 1969), one of the oldest exposed formations of the Lachlan Geosyncline (Packham, 1960). The rocks of the Lachlan Geosyncline comprise a series of north trending volcanic rises separated by troughs filled with thick sedimentary sequences. The Sofala Volcanics constitute part of the eastermost volcanic rise known as the Capertee Rise (fig. 1.)

Sofala is situated at the western margin of the Capertee Rise, where the massive, concentrically deformed Sofala Volcanics become foliated along a narrow, somewhat discontinuous north-south trending zone associated with a major discontinuity—the Wiagdon Thrust. To the west of the Wiagdon Thrust zone, the Sofala Volcanics are unconformably overlain by an Early Silurian formation, the Tanwarra Shale, which is about 80 m thick and comprises fine pelitic material with a thick band of conglomerate bearing abundant pyroxene-andesite and limestone cobbles. Unconformably above the Tanwarra Shale the Bells Creek Volcanics are developed, with lower lithologies of rhyolites and acid tuffs (fig. 2).

A wide range of volcanically derived sediments (from conglomerates to siltstones) is characteristic of the Sofala Volcanics together with radiolarian cherts and cherts that carry abundant sponge spicules. In the western part of the area mapped, limestone lenses (mainly breccias), which yield a conodont fauna of Gisbornian (Mid-Ordovician) age (Pickett, ms), are associated with extensively carbonated volcanic sediments. Rapid lateral sedimentary facies changes are characteristic, and intertonguing of units is common.

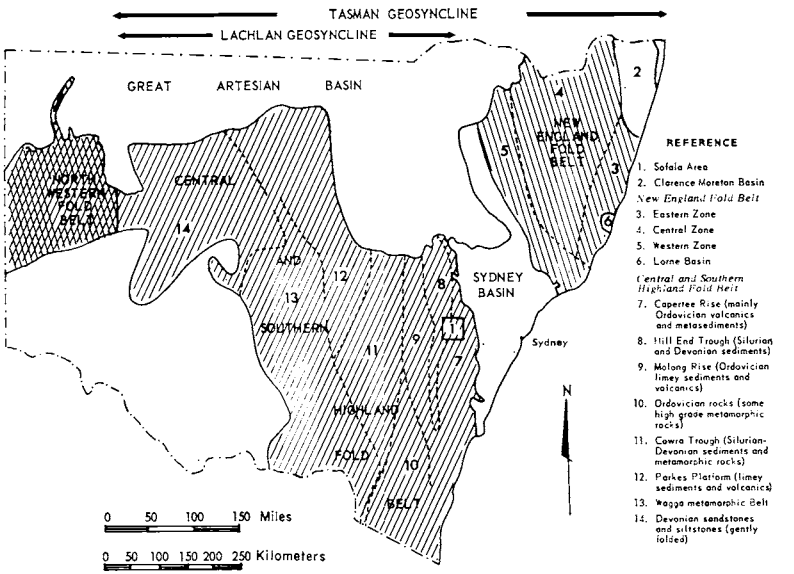


Fig. 1. Geological provinces in New South Wales (modified after Packham, 1969).

The most outstanding feature of the Sofala rocks is the large volume of broken lithic volcanic debris which is generally coarse and angular. This material is favorably compared with lahar or mud flow deposits recognized from modern active volcanic areas such as in New Zealand.

A large breccia pipe (probably a former conduit) of altered porphyritic andesite blocks and fragments, together with some coarse grained igneous varieties, intrudes the western part of the mapped section and is associated with the major faults in the area.

Most of the primary phases in the rocks have undergone post-depositional alteration to quartz, chlorite, carbonates, albite, epidote, tremolite, talc, and a variety of other secondary phases. The apparent andesitic character of these altered rocks is recognized by consideration of original volcanic textural features, together with the chemistry of phenocrystic clinopyroxene and hornblende, the only relict primary phases.

The five-figure numbers quoted below refer to samples in the collection of the University of Sydney Geology Department.

THE VOLCANIC ROCKS

The most common volcanic lithology of the Sofala Volcanics carries abundant euhedral or broken angular igneous clinopyroxene which is commonly zoned parallel to the outer margins of euhedral phenocrysts and/or more rarely forms hour-glass structures. The pyroxenes are mainly non-plechroic, colorless, pale yellow, or pale green clinopyroxene (pl. 1-A, B, C). These phenocrysts may occupy up to 40 percent of some lithologies. In addition to fresh clinopyroxene some rocks carry a completely altered

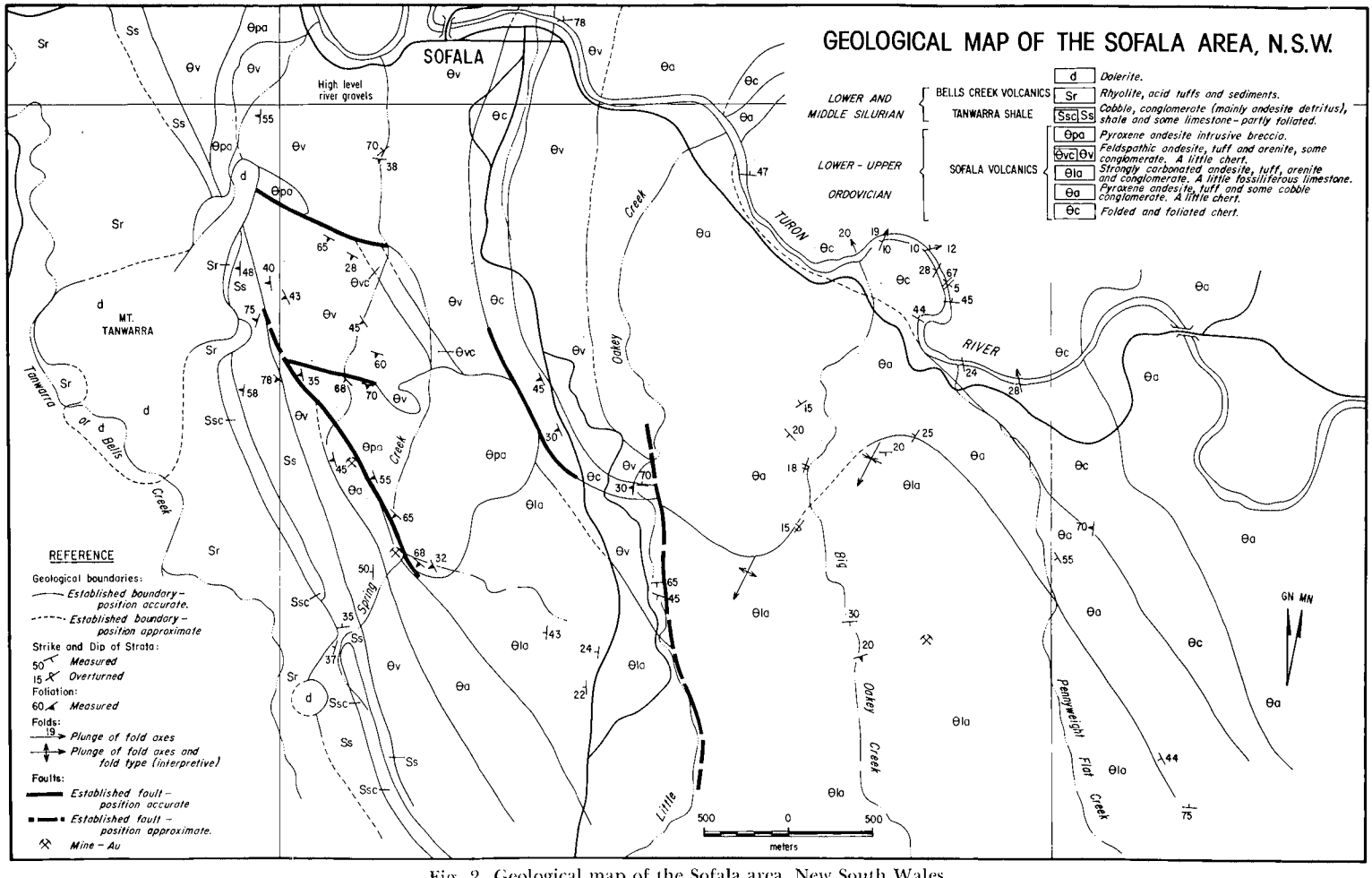


Fig. 2. Geological map of the Sofala area, New South Wales.

euhedral phenocrystic pyroxene perhaps hypersthene and/or pigeonite which is replaced by metamorphic chlorite, carbonates, et cetera. Large hornblende phenocrysts and aggregates with distinct rims of an altered opaque phase are also common in selected lithologies (pl. 1-D). These crystals have X = yellow brown, Y = pale yellow brown, Z = olive green and occur mainly with epitaxial overgrowths of pale green actinolite. Less commonly, euhedral, mafic phenocrysts, which now consist only of chlorite and carbonate, probably represent former olivine phenocrysts (see Barron and Barron, 1976).

The matrix of these porphyritic rocks commonly contains plagioclase microlites which are now albite. The groundmass textures range from trachytic to intergranular, and in some varieties amygdaloidal textures are preserved. The amygdales are well-rounded to somewhat irregular and filled with a variety of metamorphic phases.

The extent of replacement of the volcanic material by the secondary phases is gradational. However in some rocks, particularly those that contain largely chlorite, carbonate, quartz, and/or talc, alteration is complete, and no fresh igneous clinopyroxene or hornblende remains. Excellent relict textures serve to identify the former igneous nature of the rock. For example trains of opaque granules mark euhedral crystal outlines, cleavage traces, and former vesicle sites which are overprinted by the metamorphic mineralogy.

THE DEPOSITIONAL ENVIRONMENT OF THE SOFALA VOLCANICS

The wide range of volcanically derived sediments of the Sofala Volcanics is associated with radiolarian cherts in the lower part of the section and cherts, in the central and upper parts of the section, that carry abundant sponge spicules together with scarce radiolaria indicating a rather deep water marine environment for most of the section exposed.

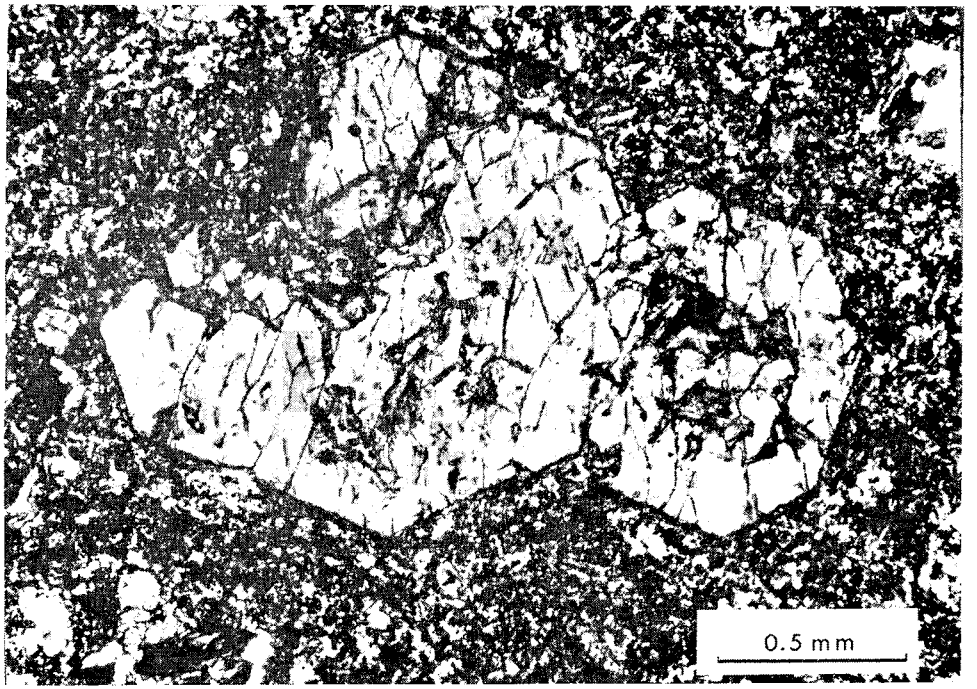
Limestone lenses toward the top of the section are associated with carbonated volcanic sediments. However, the limestones are mainly breccias in which some very large blocks are included suggesting that the limestone source was nearby. This source was probably a volcanic island reef with an apparently very steeply dipping surrounding oceanic floor.

The evidence suggests that four, more or less contemporaneous, environments of deposition can be recognized. The first is marked by a sudden influx of material, possibly analogous to turbidity current deposition, and is represented by most of the epiclastic rocks with sand-sized detritus. These rocks occur in thick bedded units, which are commonly graded and occasionally cross bedded. Sparse coarser pebble bands and conglomerates are characteristic and suggest rapid influx of the coarser material.

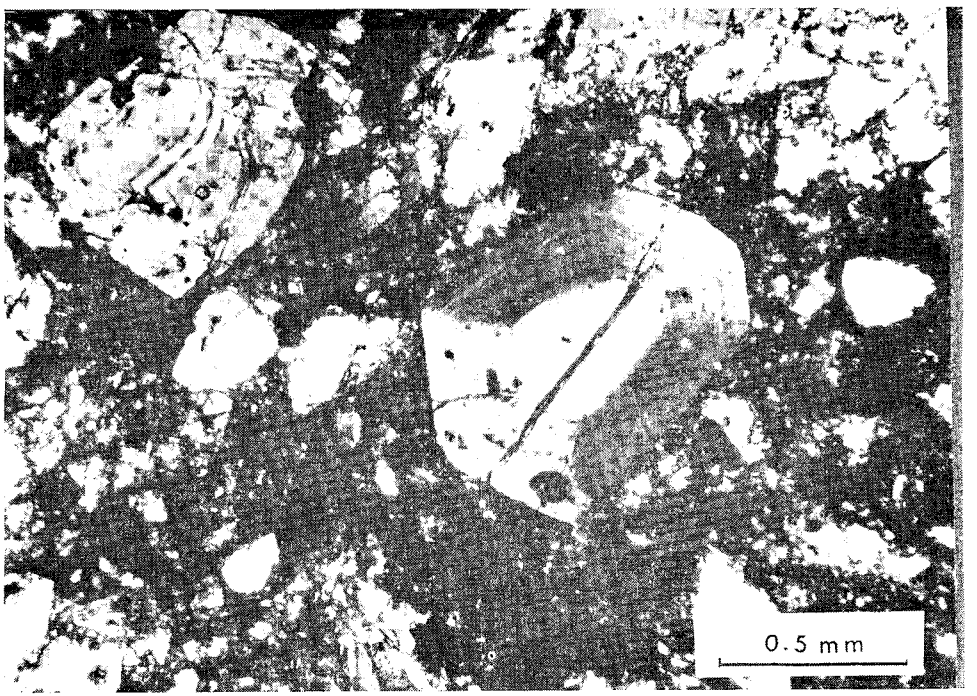
The second depositional environment allows the accumulation of banded silt sized detritus. Rocks of this type are sparsely developed in the upper Sofala Volcanics sequence and are invariably marked by small contemporaneous faults, slumps, and occasionally by brecciation suggesting

PLATE I

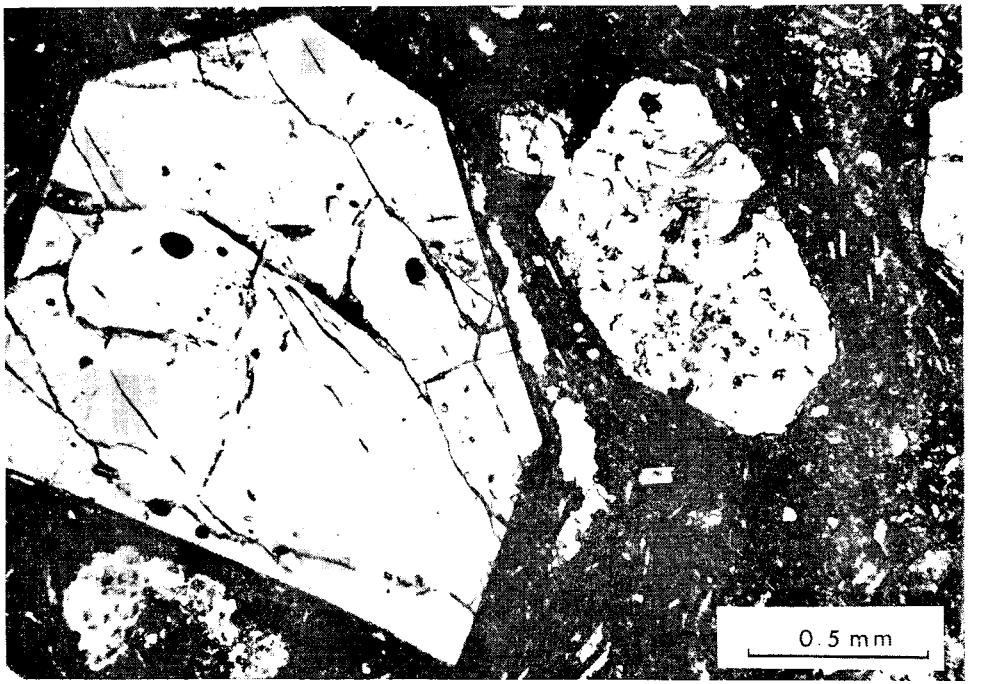
Relict igneous phenocrysts of the Sofala Volcanics.



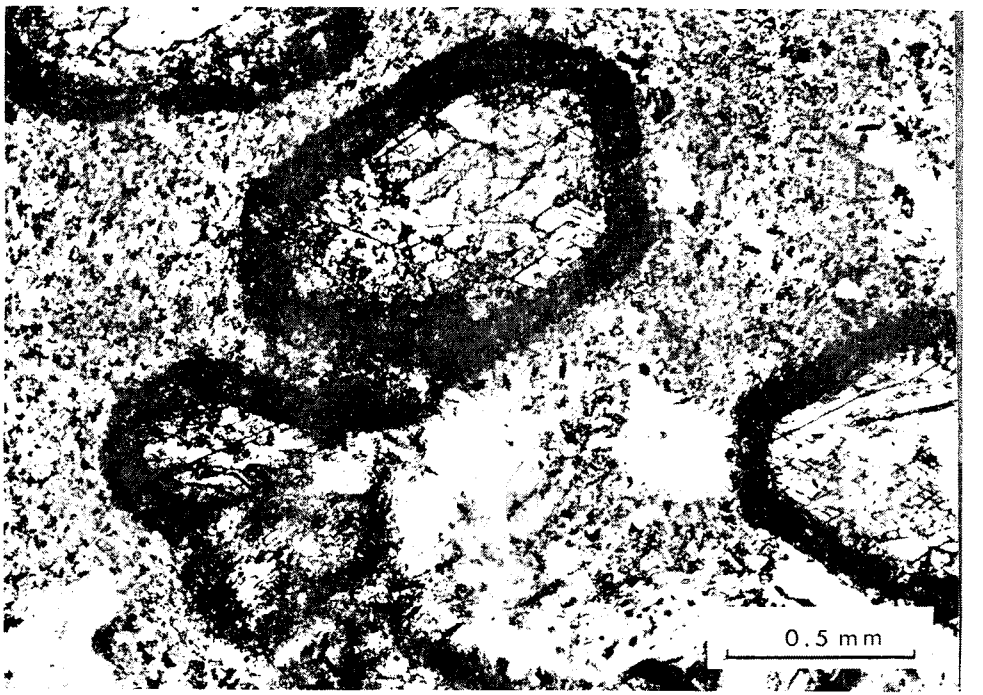
A. Subhedral clinopyroxene aggregate in 46268. Plane polarized light.



B. Zoned and sector twinned clinopyroxene crystal in 46164. The central core does not appear to be zoned. Crossed nicols.



C. Porphyritic fragment in conglomerate pebble. The large phenocryst is clear, zoned euhedral clinopyroxene. The euhedral phenocryst (right center) is completely altered to carbonate and chlorite. 46105. Plane polarized light.



D. A hornblende porphyritic clast in 46274 showing distinct alteration rims of sphene granules. Plane polarized light.

interruption of sedimentation possibly by movement on a sloping ocean floor.

The third type suggests that "normal" deposition ceased, and quiet periods permitted accumulation of pelagic siliceous material including the voluminous spiculites and radiolarites of the upper Sofala Volcanics. Small pockets of cherty spiculites in the upper section probably represent quiet shallow water basin deposits.

A fourth depositional environment (possibly an extension of the first) includes rocks deposited by catastrophic events. These rocks are breccias with angular blocks of all sizes up to about 6 m across. They are probably the result of submarine slides perhaps initiated by volcanic shocks. They include mainly volcanic debris but also a large amount of limestone.

The depositional environment of the Sofala Volcanics was therefore somewhat analagous to that of present day island arcs such as Tonga-Kermadec (Karig, 1970) and Fiji (Gill, 1970; Dickinson, 1967, 1968): The main eruptive centers of the Sofala Volcanics were situated in a deep-water marine environment where limy sediments accumulated around rather sparsely distributed volcanic islands. According to the subdivision of Mitchell and Reading (1971) for modern active island arcs the rocks of the Sofala Volcanics comprise group (1) volcanic arc deposits, mainly epiclastic, pyroclastic, and autoclastic volcanic rocks and clastic reef derived limestones and group (2) submarine trench deposits consisting mainly of turbidites rich in quartz-deficient calc-alkaline volcanic detritus and siliceous pelagic sediments. Missing from the Sofala area are group (3) rocks containing ocean floor oceanic crustal rocks such as tholeiitic lavas, gabbros, and ultramafic rocks.

BULK CHEMISTRY

On a scale involving the present area of investigation, the alteration of the Sofala Volcanics appears to be quite heterogeneous: some rocks undergoing almost complete alteration to hydrated and carbonated phases, and some rocks retaining certain primary igneous phases.

Since there is generally widespread redistribution of components, including concentration and depletion of the mobile alkali elements, even in the superficially altered lithologies, specific magmatic character cannot be recognized by the statistical bulk chemical methods used successfully to distinguish more recent basic volcanic rocks. The recognition of specific magmatic character is best approached either by reconstruction of bulk composition by deriving an average composition from many analyses of a patchy single lava flow (Smith, 1968; Vallance, 1969) or by consideration of relic primary phase chemistry, in particular that of pyroxenes (Vallance, 1969; 1974). The former approach (Smith, 1968) is essentially precluded in the present study, since alteration has not taken place on the scale of single outcrop but on a more regional scale.

The bulk compositions of three "least altered" Sofala rocks are presented in table 1. Sample 46252 represents a pebble from a conglomerate

horizon, and 46263 is a breccia fragment; both these specimens are from the upper Sofala Volcanics. The third analysis (46120) is from a breccia pipe also in the upper Sofala Volcanics. The first and second examples (46252 and 46263) are rather sparsely pyroxene-porphyritic and contain abundant sub-trachytic albite phenocrysts. Alteration products include minor sericite, patchy chlorite, small epidote granules, and a little quartz and carbonate. Sphene granules are rather abundant. Pseudomorphs after olivine cannot be distinguished with certainty, but olivine may have occupied some of the small, abundant chlorite patches. The third example (46120) is a breccia carrying extremely pyroxene-porphyritic fragments together with some that are pyroxene- and olivine-porphyritic. There are no plagioclase phenocrysts, and the fragments were apparently glassy with some distinctly vesicular (now amygdaloidal). Secondary phases in the larger euhedral olivine sites are chlorite and carbonate. Actinolite, chlorite, and a little carbonate with epidote have replaced the matrix material.

TABLE 1

Compositions and norms of three relatively "unaltered" Sofala rocks

	Compositions				Norms		
	46252	46263	46120		46252	46263	46120
SiO_2	50.89	50.75	44.98	or	10.58	15.54	2.13
Al_2O_3	16.25	17.40	9.17	ab	43.64	37.04	10.74
Cr_2O_3	<0.005	<0.01	0.17	an	15.54	20.06	18.26
TiO_2	0.88	1.00	0.71	c	0.13	0.00	0.00
ZrO_2	<0.01	—	<0.01	di	0.00	2.16	15.08
Fe_2O_3	4.49	4.66	1.61	hy	6.33	2.10	27.66
FeO	6.34	6.17	9.31	ol	10.16	11.21	12.51
MnO	0.21	0.22	0.26	cs	0.00	0.00	0.00
MgO	5.41	4.97	14.96	mt	6.51	6.76	2.33
CaO	4.02	4.81	9.84	cm	0.01	0.01	0.25
SrO	0.01	0.08	<0.005	il	1.67	1.90	1.35
BaO	0.02	0.11	0.01	ap	0.65	0.60	0.44
Na_2O	5.16	4.38	1.27	cc	0.98	0.14	3.82
K_2O	1.79	2.63	0.36	H_2O	3.54	2.91	5.18
P_2O_5	0.28	0.26	0.19				
H_2O^+	3.25	2.81	4.58	Total	99.74	100.43	99.75
H_2O^-	0.29	0.10	0.60				
CO_2	0.43	0.06	1.68	plag(An)	26.26	35.12	62.96
S	0.045	—	0.040	oliv(Fo)	72.02	72.26	76.52
NiO	0.006	<0.01	0.049				
CuO	0.02	—	0.02	A(oxides)	29.97	30.73	5.93
ZnO	0.02	—	0.02	F(total)	46.70	47.48	36.69
As_2O_3	<0.003	—	<0.003	M(MgO)	23.33	21.79	54.38
WO_3	0.07	—	<0.01				
Total	99.88	100.41	99.83				
Less O = S	0.02	—	0.02				

Analyst: D. Rice (New South Wales Geol. Survey)
Sample:
46252 Pyroxene "andesite". Cobble from conglomerate.
46263 Pyroxene "andesite". Cobble from conglomerate.
46120 Pyroxene ?olivine "basalt". Breccia pipe.
(These are catalogue numbers of New South Wales Geological Survey.)

The first two rocks are apparently very different lithologically from the third, a fact reflected in their normative chemistry. The first and second are hypersthene–olivine-normative with rather high orthoclase and albite, and the third is diopside–hypersthene–olivine-normative. Comparative data are presented in table 2. In this table, analysis 1, although slightly ne normative, can be compared mineralogically and chemically with 46252 and 46263. Analysis 2 is similar to 46120. The basic nature of the latter is probably a reflection of high modal phenocrystic clinopyroxene.

It is clear from the comparative data that either redistribution of the alkali elements has occurred since there is 43 percent normative albite and 10 percent normative orthoclase in 46252 reflecting the very high Na_2O and K_2O, or this lithology was originally alkali rich. The former observation is preferred when the state of alteration of the rock is taken into account. Also, there has been depletion of Ca compared with analyses of fresh volcanic rocks. This is reflected in the norm calculation where the most Ca has been allocated to anorthite leaving little Ca for normative diopside, and consequently a large proportion of Mg is left for allocation to normative hypersthene and olivine.

Although these rocks are hypersthene normative, a comparison with the normative pyroxene chemistry (see p. 627) conflicts with this trend. Most of the analyzed pyroxenes are nepheline-normative including 46132 and 46133 from the same breccia pipe as 46120—a rock that is highly hypersthene-normative.

Chemically then, the Sofala rocks can hardly be called andesites in the sense of Chayes (1969) who rejects, as andesite, those rocks that are nepheline-normative (compare analysis 1, table 2, Gill, 1970) and suggests that since silica saturation is so characteristic of Cainozoic andesites this should be made a part of the definition (of 1775 andesite analyses only 26 contain normative olivine—see also Chayes, 1971).

On the other hand, olivine-bearing "andesites" are rather common in the volcanic rocks of the ocean basins, for example the Hawaiian "andesites" which consist essentially of andesine or oligoclase, monoclinic pyroxene, magnetite, ilmenite, and a little olivine. Hornblende is very rare, and hypersthene is absent. Such rocks are named hawaiites (MacDonald, 1960).

The Sofala Volcanics are distinctly rich in clinopyroxene, hornblende is rather rare, pseudomorphs after olivine are rather common, and there is a notable absence of dacitic to rhyolitic associates. Instead, small volumes of trachytic-textured associates occur with the ubiquitous pyroxene-porphyritic rocks. It is thus tempting to label these rocks as belonging to an oceanic suite, but titanium levels are certainly not as high as those that are characteristic of oceanic island hawaiites. Silica levels of the Sofala rocks are slightly higher, and alumina is significantly higher (compare analysis 1, MacDonald, 1960).

The Sofala rocks thus belong in a suite that has chemical and petrographic features somewhere between the undersaturated, commonly

nepheline- and olivine-normative hawaiites of MacDonald (1960) and those silica-saturated andesites selected by Chayes (1969). These chemical and petrological features are consistent with those listed in Jakeš and White (1972) to distinguish *island-arc* calc-alkaline rocks from those of *continental* margins. In their scheme, island-arc rocks have (1) lower SiO_2; (2) lower $FeO + Fe_2O_3/MgO$ ratios; (3) K_2O/Na_2O ratios that overlap but are generally lower; (4) phenocrysts of clinopyroxene, hornblende, some orthopyroxene, rare biotite, no quartz, garnet, or cordierite; and (5) for hornblende-bearing andesites, a phenocryst crystallization sequence: clinopyroxene–hornblende–clinopyroxene instead of hornblende–clinopyroxene–orthopyroxene.

The petrographic features of the Sofala Volcanics and certain chemical features of the less altered rocks compare favorably with the above criteria of Jakeš and White (1972) for calc-alkaline rocks that belong to the island-arc suite.

Although relict volcanic textures are all but ubiquitous in the Sofala Volcanics, the present bulk compositions of many Sofala lithologies cannot be compared with those of any modern volcanic lithologies; for example the analyses of table 3, with generally enriched or depleted SiO_2. High CO_2 in some of the analyses reflects high modal carbonate, and high H_2O+ reflects high modal chlorite and/or talc. Two alteration trends are defined by either increased silica and alkalis or strongly depleted silica and alkalis, the latter leading to ultramafic compositions and enrichment

TABLE 2

Comparative bulk chemical data

	Compositions			Norms	
	1	2		1	2
SiO_2	49.43	47.90	or	16.02	2.8
Al_2O_3	15.82	11.84	ab	23.57	14.1
Fe_2O_3	5.92	2.32	an	22.19	23.4
FeO	4.50	9.80	ne	0.48	—
MgO	5.77	14.01	di	20.20	17.0
CaO	10.08	9.29	hy	—	20.5
Na_2O	2.89	1.66	ol	4.93	14.7
K_2O	2.71	0.54	cs	—	—
H_2O^+		0.59	mt	8.53	3.3
H_2O^-	1.41	—	cm	—	—
TiO_2	1.00	1.65	il	1.90	3.2
P_2O_5	0.38	0.19	ap	0.83	0.4
MnO	0.20	0.15	cc	—	—
CO_2	—	—	H_2O	—	—
Cl	—	—			
F	—	—	Total	98.70	99.4
Total	100.11	99.94			

Sample:

1. Clast from volcanic conglomerate. Koroimavua Andesitic Group Fiji. Phenocrysts: zoned labradorite (20 percent, zoned pale green augite (30 percent), olivine pseudomorphs (2 percent). Matrix (48 percent): plagioclase, pyroxene, opaque (Gill, 1970).
2. Average tholeiitic olvine basalt (Nockolds, 1954, p. 1021).

TABLE 3

Bulk compositions of some typical altered

	46258*	46187	46191	46259	46260	46261
SiO_2	23.21	64.72	46.93	32.42	48.34	33.82
Al_2O_3	12.15	8.76	7.76	8.56	10.83	9.43
Cr_2O_3	0.32	0.05	0.29	0.27	0.22	0.22
TiO_2	0.56	1.21	0.34	0.43	0.39	0.56
ZrO_2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Fe_2O_3	—	0.60	1.10	0.06	0.80	0.30
FeO	14.15	6.24	9.14	9.36	9.76	10.79
MnO	0.16	0.05	0.10	0.22	0.10	0.25
MgO	19.45	11.35	22.55	16.49	15.33	18.31
CaO	3.91	0.36	1.93	9.45	2.80	9.40
SrO	0.005	0.005	0.005	0.01	0.005	0.01
BaO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Na_2O	0.23	<0.01	<0.01	0.04	<0.01	<0.01
K_2O	1.22	0.017	0.015	0.035	0.021	0.020
P_2O_5	0.22	0.35	0.22	0.17	0.15	0.18
H_2O^+	5.92	5.82	7.69	5.86	7.64	7.62
H_2O^-	0.39	0.04	0.51	0.60	0.28	0.31
CO_2	17.95	0.26	1.75	15.75	3.50	8.42
S	1.77	0.009	0.009	0.067	0.013	0.043
NiO	0.078	0.024	0.103	0.103	0.046	0.058
CuO	0.005	0.01	0.005	<0.005	0.05	0.02
ZnO	0.03	0.01	0.01	0.01	0.02	0.02
As_2O_3	0.03	<0.003	<0.003	0.03	0.003	0.007
WO_3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	101.76	99.90	100.45	99.93	100.31	99.78
Less O = S	0.89	<0.01	<0.01	0.03	0.01	0.02
Total	100.87	99.89	100.44	99.90	100.30	99.76

* The FeO figure for 46258 is higher than the actual amount due to the presence of sulphide sulphur. The total iron in this sample as FeO is 13.29 percent.
Analyst: D. Rice (New South Wales Geol. Survey)
Sample
46258 Quartz-chlorite-fuchsite rock. Sofala, N.S.W.
46187 Chlorite–quartz–rutile rock. Sofala, N.S.W.

in Mg and/or Fe. Figure 3 presents bulk chemical variation in terms of $A = K_2O + Na_2O$, $F = FeO + Fe_2O_3$, and $M = MgO$, and figure 4 illustrates chemical variation in terms of $A = Al_2O_3 + Fe_2O_3 - (Na_2O + K_2O)$, $C = CaO$, and $F = (Fe, Mg, Mn)O$.

PRIMARY PHASE CHEMISTRY

Clinopyroxene and hornblende are the only relict primary phases that are apparently "unaltered".

All phase analyses (unless otherwise stated) were carried out at the Australian National University using a T.P.D. microprobe (Delft) with 0.1 percent limit of detection and relative error limits of ± 2 percent major elements (N. Ware, personal commun.).

Pyroxene compositions.—The compositions of some zoned and unzoned pyroxene phenocrysts of the Sofala Volcanics are presented in table 4. These range in composition from diopside to salite, and a small

porphyritic rocks from the Sofala Volcanics

	19538**	46211	19599**	46264	46265
SiO_2	44.78	37.54	26.49	66.24	27.15
Al_2O_3	13.12	5.27	20.34	10.42	18.45
Cr_2O_3	<0.01	0.30	<0.01	<0.01	0.02
TiO_2	0.95	0.26	0.17	0.07	0.76
ZrO_2	0.02	0.01	0.02	0.01	0.02
Fe_2O_3	0.82	0.59	3.11	0.24	8.06
FeO	7.65	9.48	22.63	1.11	16.91
MnO	0.15	0.27	0.58	0.06	1.45
MgO	4.02	14.68	15.21	16.05	15.23
CaO	7.62	7.96	0.22	0.04	0.78
SrO	0.07	0.09	0.005	0.01	<0.005
BaO	0.05	0.03	0.01	<0.01	<0.01
Na_2O	2.71	0.01	0.02	0.006	0.06
K_2O	2.86	0.30	0.06	0.016	0.04
P_2O_5	0.70	0.22	0.06	0.04	0.22
H_2O^+	1.38	3.05	11.01	5.87	9.75
H_2O^-	0.01	0.16	0.18	0.13	0.64
CO_2	12.49	19.57	0.09	0.09	0.10
SO_3	0.38	0.04	0.03	<0.02	<0.02
NiO	0.008	0.08	0.003	<0.003	0.011
CuO	0.05	<0.01	0.04	<0.01	0.57
ZnO	0.01	0.01	0.05	0.03	0.06
Total	100.34	99.92	100.34	100.43	100.28

46191 Quartz–chlorite–talc rock. Sofala, N.S.W.
46259 Quartz–chlorite–ankerite rock. Sofala, N.S.W.
46260 Quartz–chlorite–calcite–ankerite rock. Sofola, N.S.W.
46261 Chlorite–talc–calcite–ankerite rock. Sofala, N.S.W.
19538** Quartz–ankerite–chlorite–albite–muscovite rock. Sofala, N.S.W.
46211 Quartz–chlorite–ankerite–magnesite rock. Sofala, N.S.W.
19599** Quartz–chlorite–ankerite–magnesite rock. Sofalo, N.S.W.
46264 Quartz–chlorite–talc albite rock. Cow Flat, N.S.W.
46265 Chlorite–garnet–talc rock. Walang, N.S.W.
** These are catalogue numbers of the New South Wales Geological Survey.

number extend into the endiopside and augite compositional fields (fig. 5). Most of these pyroxenes contain appreciable amounts of Cr_2O_3. The maximum amount is 1.04 percent in 46132 (1). TiO_2 is generally quite low, and the maximum analyzed value is 0.54 percent in 46105 (8). MnO is extremely low but increases slightly with increasing FeO.

The pyroxene phenocrysts, where possible, have been analyzed progressively from core to rim to determine the nature of zoning where this is developed. These progressive compositions probably relate to differentiation trends of the primary magma, and the marginal compositions of the phenocrysts were possibly in equilibrium with the magma at depth before quenching.

The following chemical observations of the pyroxene crystallization history are important to determine the progressive relative variation of Ca, Mg, and Fe during fractionation processes of the original melt that produced the Sofala Volcanics. From the analytical data the most strongly zoned phenocryst is represented by the following progressive analyses

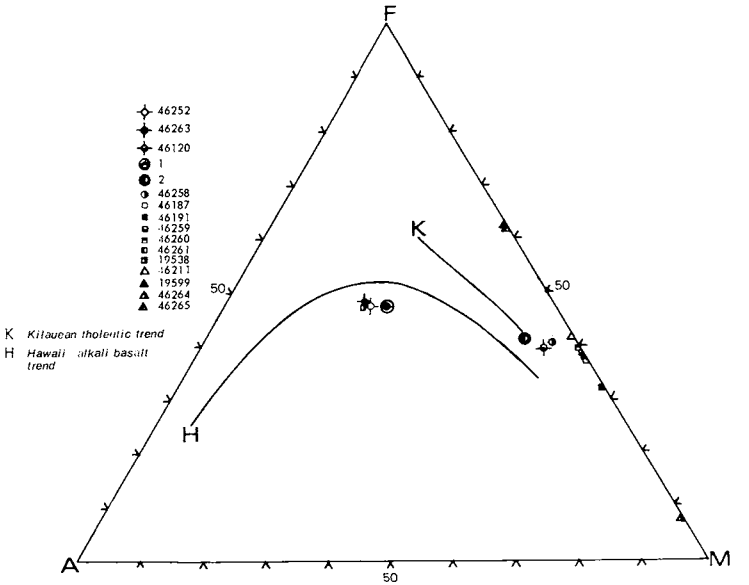


Fig. 3. FMA diagram for Sofala bulk analyses (least altered rocks are marked by an open circle with protruding lines).

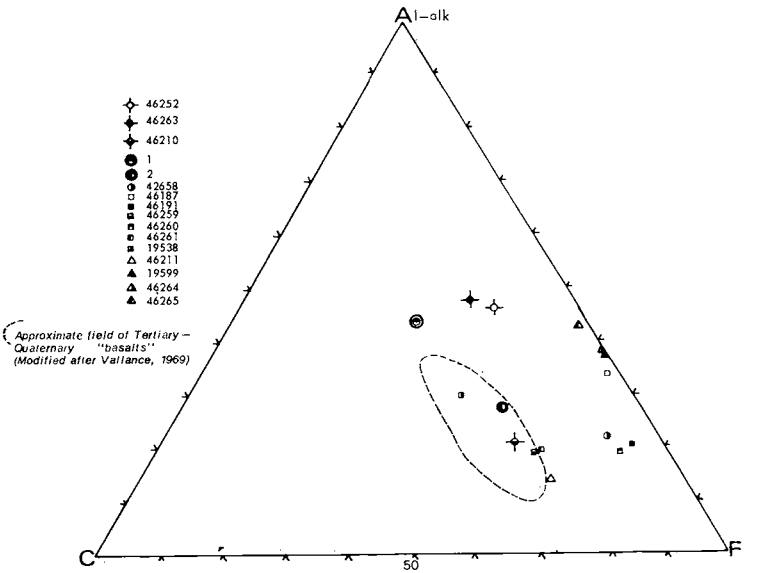


Fig. 4. ACF diagram for Sofala bulk analyses (least altered rocks are marked by an open circle with protruding lines).

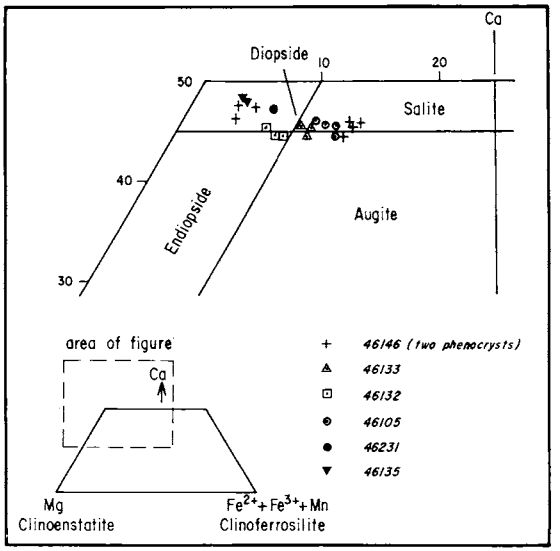


Fig. 5. Compositions of some relict clinopyroxene phenocrysts in the Sofala Volcanics with respect to Ca, Mg, and (Fe^{+2} + Fe^{+3} + Mn) atoms.

from core to rim: 46105 (5), 46105 (6), 46105 (7), and 46105 (8). In this example, there is a marked decrease in Ca from core to rim, accompanied by a particularly marked increase in Fe and corresponding decrease in Mg. The other elements also vary systematically. There is an increase in Al_2O_3 toward the margin, an increase in TiO_2, and a decrease in Cr_2O_3. The latter observation may indicate concentration of Cr in the early Mg-rich pyroxene phenocrysts due to strong partitioning of Cr, favoring pyroxene rather than the liquid (Seward, 1971), followed by Cr depletion in the magma.

Another strongly zoned phenocryst is represented by analyses 46132 (1), 46132 (2), and 46132 (3). In this phenocryst, SiO_2 decreases toward the margin as do CaO, MgO, and Cr_2O_3. There is a marked increase in Al_2O_3 and FeO. Figure 6 illustrates the variation in a number of elements from core to rim in the zoned pyroxenes.

Petrogenetic implications of the pyroxene chemistry.—Some relict pyroxenes of the Sofala Volcanics appear petrographically to be clear of the secondary low grade metamorphic phases so characteristic of the unit as a whole. It is these analyzed pyroxenes that probably afford the best indicator of original volcanic character, since other chemical parameters involving whole rock analyses such as the alkali-lime index of Peacock (1931) and total alkali versus silica plots of Tilley (1950) cannot be applied to altered rocks with any confidence (Vallance, 1969; 1974).

The recognition of magma type using pyroxene chemistry is attempted by Kushiro (1960), LeBas (1962), and Coombs (1963). A statistical study carried out by Kushiro (1960) suggests separation of three different

TABLE 4

Compositions, structural formulae and norms of some "fresh"

	46164 (1)	46164 (2)	46164 (3)	46164 (4)	46164 (5)	46164 (6)	46164 (7)
SiO_2	53.89	54.40	54.11	49.55	50.22	50.11	49.85
TiO_2	—	—	—	0.37	0.28	0.42	0.39
Al_2O_3	1.34	1.16	1.28	5.00	4.51	4.68	4.71
Cr_2O_3	0.57	0.58	0.61	—	—	0.13	0.13
FeO	3.42	2.98	2.99	9.06	9.29	9.17	9.42
MgO	17.27	17.97	17.84	13.73	14.38	14.05	13.76
MnO	—	—	—	—	—	0.12	—
CaO	24.18	23.87	24.14	22.20	22.14	22.23	22.21
Na_2O	0.27	0.23	0.27	0.33	0.39	0.34	0.30
K_2O	—	—	—	0.09	—	0.11	—
Total	100.94	101.19	101.25	100.33	101.22	101.36	100.78

Structural formulae based on 6 oxygens

Si	1.952	1.959	1.950	1.850	1.858	1.853	1.855
Al^{IV}	0.048	0.041	0.050	0.150	0.142	0.147	0.145
Al^{VI}	0.009	0.008	0.005	0.070	0.055	0.057	0.062
Ti	—	—	—	0.010	0.008	0.012	0.011
Fe	0.104	0.090	0.090	0.283	0.288	0.284	0.293
Mn	—	—	—	—	—	0.004	—
Mg	0.932	0.965	0.959	0.764	0.793	0.775	0.763
Ca	0.939	0.921	0.932	0.888	0.878	0.881	0.886
Na	0.018	0.015	0.019	0.023	0.027	0.023	0.021
K	—	—	—	0.004	—	0.005	—
Cr	0.017	0.017	0.018	—	—	0.004	0.004
Sum (X+Y)	2.019	2.016	2.033	2.042	2.049	2.045	2.040

46164 (1), (2), and (3) are analyses progressively toward the margin of a pyroxene phenocryst.

46164 (4), (5), (6), and (7) are analyses progressively toward the margin of a second pyroxene phenocryst.

(Average Fe^{2+}/Fe^{3+} ratio of 15 clinopyroxene analyses from Deer, Howie, Zussman, (1963, v. 2) is 6.20)

relict clinopyroxene phenocrysts of the Sofala Volcanics

CIPW norms of relict pyroxenes (wt percent)

		46164 (1)	46164 (2)	46164 (3)	46164 (4)	46164 (5)	46164 (6)	46164 (7)
OR		0.00	0.00	0.00	0.00	0.00	0.00	0.00
LC		0.00	0.00	0.00	0.42	0.00	0.51	0.00
AB		0.91	1.95	0.98	0.00	0.00	0.00	0.00
NE		0.74	0.00	0.71	1.51	1.79	1.56	1.37
AN		2.44	2.13	2.28	11.90	10.56	10.92	11.51
DI	Di	85.87	85.95	88.82	54.75	57.88	57.07	57.62
	Hd	6.52	5.32	3.39	14.77	15.57	15.29	16.02
HY	En	—	0.88	—	—	—	—	—
	FS	—	0.05	—	—	—	—	—
OL	Fo	2.59	3.13	3.25	7.33	7.49	7.14	6.44
	Fa	0.20	0.20	0.20	2.98	2.02	1.91	1.79
CS		0.00	0.00	0.00	3.58	2.39	2.83	2.15
MT		0.81	0.72	0.72	2.13	2.15	2.15	2.19
CM		0.84	0.85	0.90	0.00	0.00	0.19	0.19
IL		0.00	0.00	0.00	0.70	0.53	0.80	0.74
Total		100.94	101.19	101.24	99.08	100.38	100.37	100.02
PLAG (AN)		72.80	52.30	70.03	100.00	100.00	100.00	100.00
OLIV (FO)		92.94	94.17	94.15	78.76	78.80	78.87	78.24
OPX (EN)		0.00	94.17	0.00	0.00	0.00	0.00	0.00
A OXIDES		1.29	1.09	1.28	1.81	1.62	1.90	1.28
F (total)		16.32	14.07	14.17	39.03	38.61	38.74	40.12
M MgO		82.40	84.84	84.55	59.16	59.77	59.36	58.60
Niggli Mg		0.90	0.92	0.92	0.73	0.74	0.73	0.73

Molecular proportions

$NaAlSiO_4$								
$+KAlSi_2O_6$		0.7	—	0.4	1.3	1.5	1.5	1.3
$Ca(Mg,Fe)Si_2O_6$		95.0	92.6	93.9	82.2	82.71	83.2	85.5
$MgFeSiO_3$		—	2.2	—	—	—	—	—
$(MgFe)_2SiO_4$		4.3	5.2	5.4	16.5	15.79	15.3	13.2

TABLE 4 (continued)

Pyroxene analyses (relict phenocrysts)

	46133 (1)	46133 (2)	46133 (3)	46132 (1)	46132 (2)	41632 (3)
SiO_2	52.39	51.68	50.35	52.44	51.94	50.56
TiO_2	0.39	0.35	0.42	0.22	0.19	0.34
Al_2O_3	4.79	3.48	4.32	2.65	2.71	3.54
Cr_2O_3	0.65	0.38	0.61	1.04	0.65	0.73
FeO	6.52	6.42	6.85	4.81	5.23	6.03
MgO	14.46	15.16	14.70	16.62	16.30	15.44
MnO	0.11	—	—	—	0.16	—
CaO	20.43	21.77	21.42	22.04	21.91	21.25
Na_2O	0.86	0.47	0.64	0.56	0.68	0.54
K_2O	0.29	—	0.08	0.10	0.06	—
Total	100.89	99.71	99.38	100.47	99.82	98.44

Structural formulae based on 6 oxygens

Si	1.909	1.911	1.876	1.916	1.915	1.894
Al^{IV}	0.091	0.089	0.124	0.084	0.085	0.106
Al^{VI}	0.187	0.063	0.066	0.030	0.033	0.051
Ti	0.011	0.010	0.012	0.006	0.005	0.010
Fe	0.199	0.199	0.213	0.147	0.161	0.189
Mn	0.003	—	—	—	0.005	—
Mg	0.786	0.836	0.817	0.906	0.896	0.862
Ca	0.797	0.862	0.855	0.863	0.866	0.853
Na	0.059	0.032	0.045	0.039	0.047	0.038
K	0.013	—	0.003	0.004	0.003	—
Cr	0.187	0.011	0.018	0.030	0.019	0.022
Sum(X+Y)	2.242	2.013	2.029	2.025	2.035	2.025

46133 (1), (2), and (3) are analyses progressively toward the margin of a pyroxene phenocryst.

46132 (1), (2), and (3) are analyses from one phenocryst.

CIPW norms of relict pyroxenes (wt percent)

	46133 (1)	46133 (2)	46133 (3)	46132 (1)	46132 (2)	41632 (3)
OR	1.71	0.00	0.41	0.59	0.35	0.00
LC	0.00	0.00	0.00	0.00	0.00	0.00
AB	7.12	3.98	1.84	3.20	2.32	3.12
NE	0.08	0.00	1.94	0.83	1.86	0.79
AN	8.35	7.39	8.71	4.42	4.17	7.24
DI Di	63.04	68.80	67.01	75.19	73.36	67.97
DI Hy	10.89	11.07	10.40	7.55	9.33	9.85
HY En	—	0.21	—	—	—	—
HY Fs	—	0.03	—	—	—	—
OL Fo	5.52	4.67	4.55	5.09	5.24	5.55
OL Fa	0.95	0.75	0.71	0.51	0.67	0.81
CS	0.00	0.00	0.00	0.00	0.00	0.00
MT	1.52	1.58	2.12	1.15	1.22	1.39
CM	0.96	0.56	0.90	1.53	0.96	1.08
IL	0.74	0.66	0.80	0.42	0.36	0.65
TOTAL	100.89	99.71	99.38	100.48	99.83	98.43
PLAG(AN)	53.99	65.01	82.56	58.02	64.27	69.88
OLIV(FO)	85.27	86.14	86.56	90.87	88.72	87.34
OPX(EN)	0.00	86.14	0.00	0.00	0.00	0.00
A OXIDES	5.20	2.13	3.19	2.99	3.32	2.45
F (total)	29.46	29.12	30.77	21.77	23.48	27.40
M MgO	65.34	68.75	66.04	75.24	73.19	70.15
Niggli Mg	0.80	0.81	0.80	0.86	0.85	0.82

Molecular proportions

$NaAlSiO_4$						
$+KAlSi_2O_6$	0.1	—	1.8	0.7	1.7	0.8
$Ca(Mg,Fe)Si_2O_6$	88.3	90.7	89.3	90.0	88.9	88.5
$(Mg,Fe)SiO_3$	—	0.1	—	—	—	—
$(Mg,Fe)_2SiO_4$	11.6	9.2	8.9	9.3	9.4	10.7

TABLE 4 (continued)

Pyroxene analyses (relict phenocrysts)

	46105 (1)	46105 (2)	46105 (3)	46105 (4)	46231	46135 (1)	46135 (2)
SiO_2	50.69	51.13	50.27	50.95	52.31	51.51	51.70
TiO_2	0.33	0.27	0.32	0.37	—	0.17	0.14
Al_2O_3	3.76	3.63	4.15	3.82	2.75	3.16	2.95
Cr_2O_3	—	0.16	0.14	—	0.70	0.19	0.22
FeO	7.84	7.18	8.22	8.23	4.62	6.00	5.69
MgO	14.71	15.19	14.74	14.76	16.32	15.07	15.18
MnO	—	—	0.20	0.19	—	—	—
CaO	22.62	22.73	22.06	22.49	23.47	23.59	23.61
Na_2O	0.39	0.46	0.44	0.48	0.26	0.32	0.36
K_2O	—	0.11	—	0.08	0.07	0.17	0.15
Total	100.33	100.85	100.54	101.38	100.51	100.17	100.01

Structural formulae based on 6 oxygens

Si	1.882	1.884	1.866	1.876	1.914	1.905	1.912
Al^{IV}	0.118	0.116	0.134	0.124	0.086	0.095	0.088
Al^{VI}	0.047	0.042	0.048	0.042	0.033	0.043	0.040
Ti	0.009	0.007	0.009	0.010	—	0.005	0.004
Fe	0.243	0.221	0.255	0.253	0.142	0.186	0.176
Mn	—	—	0.006	0.006	—	—	—
Mg	0.814	0.834	0.815	0.810	0.890	0.830	0.837
Ca	0.900	0.898	0.877	0.887	0.920	0.934	0.936
Na	0.027	0.032	0.031	0.034	0.018	0.022	0.025
K	—	0.005	—	0.004	0.003	0.008	0.007
Cr	—	0.005	0.004	—	0.020	0.006	0.007
Sum(X+Y)	2.04	2.044	2.045	2.046	2.026	2.034	2.032

46105 (1), (2), (3), and (4) are analyses progressively toward the margin of a pyroxene phenocryst.

46135 (1) and (2) are analyses toward the edge of a phenocryst that has been marginally altered to actinolite.

CIPW norms of relict pyroxenes (wt percent)

	46105 (1)	46105 (2)	56105 (3)	46105 (4)	46231	46135 (1)	46135 (2)
OR	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LC	0.00	0.51	0.00	0.37	0.32	0.79	0.69
AB	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NE	1.79	2.11	2.02	2.20	1.19	1.47	1.65
AN	8.51	7.52	9.35	8.03	6.13	6.68	5.99
DI di	63.92	65.18	61.37	62.60	76.92	67.78	70.13
DI hd	13.95	12.44	14.38	14.66	8.47	10.98	10.74
OL fo	5.85	6.22	6.85	6.47	4.01	5.01	4.38
OL fa	1.28	1.19	1.61	1.51	0.44	0.81	0.67
CS	1.91	2.41	1.66	2.15	0.66	3.45	2.84
MT	1.83	1.70	1.91	1.93	1.09	1.41	1.32
CM	0.00	0.24	0.21	0.00	1.03	0.28	0.32
IL	0.63	0.51	0.61	0.70	0.00	0.32	0.27
Total	99.67	100.02	99.96	100.62	100.27	98.98	99.01
PLAG (AN)	100.00	100.00	100.00	100.00	100.00	100.00	100.00
OLIV (FO)	82.09	83.97	81.02	81.02	90.08	86.06	86.72
A OXIDES	1.70	2.48	1.88	2.38	1.55	2.27	2.39
F(total)	34.18	31.30	35.13	34.95	21.72	27.83	26.61
M MgO	64.12	66.22	62.99	62.68	76.73	69.90	71.00
Niggli Mg	0.77	0.79	0.76	0.76	0.86	0.82	0.83

Molecular proportions

$NaAlSiO_4$ + $KAlSi_2O_6$	1.5	2.0	1.7	2.0	1.1	1.7	2.0
$Ca(Mg,Fe)Si_2O_6$	86.7	85.8	84.2	85.9	91.8	88.4	89.7
$(Mg,Fe)_2SiO_4$	11.9	12.2	14.1	14.1	7.1	9.9	8.3

TABLE 4 (continued)

Pyroxene analyses (relict phenocrysts)

	46105 (5)	46105 (6)	46105 (7)	46105 (8)	46232 (1)	46232 (2)
SiO_2	54.64	51.11	50.57	49.89	51.01	50.47
TiO_2	—	0.29	0.36	0.54	0.37	0.28
Al_2O_3	0.94	3.51	4.41	4.31	2.61	3.17
Cr_2O_3	0.66	0.13	0.31	—	0.16	—
FeO	3.02	7.53	7.99	9.24	9.76	9.06
MgO	17.81	14.91	14.65	14.06	14.14	14.29
MnO	—	0.13	0.20	0.17	0.31	0.27
CaO	24.05	22.69	22.73	21.76	20.69	20.51
Na_2O	0.31	0.38	0.58	0.29	0.56	0.43
K_2O	0.07	—	0.09	—	0.15	—
Total	101.50	100.69	101.90	100.25	99.78	98.49

Structural formulae based on 6 oxygens

Si	1.964	1.900	1.855	1.863	1.916	1.911
Al^{IV}	0.036	0.100	0.145	0.137	0.084	0.089
Al^{VI}	0.004	0.053	0.046	0.053	0.032	0.052
Ti	—	0.008	0.010	0.015	0.010	0.008
Fe	0.091	0.233	0.245	0.289	0.307	0.287
Mn	—	0.004	0.006	0.005	0.010	0.009
Mg	0.954	0.821	0.801	0.783	0.792	0.806
Ca	0.926	0.899	0.893	0.871	0.833	0.832
Na	0.021	0.026	0.040	0.020	0.039	0.031
K	0.003	—	0.004	—	0.007	—
Cr	0.019	0.004	0.009	—	0.005	—
Sum(X+Y)	2.018	2.048	2.054	2.036	2.035	2.025

46105 (5), (6), (7) and (8) are analyses progressively toward the margin of a second pyroxene phenocryst.

46232 (1) and (2) are analyses progressively toward the margin of a phenocryst.

CIPW norms of relict pyroxenes (wt percent)

		46105 (5)	46105 (6)	46105 (7)	46105 (8)	46232 (1)	46232 (2)
OR		0.41	0.00	0.00	0.00	0.89	0.00
LC		0.00	0.00	0.42	0.00	0.00	0.00
AB		2.05	0.00	0.00	0.00	4.49	3.64
NE		0.31	1.74	2.66	1.33	0.13	0.00
AN		0.97	7.87	9.16	10.46	4.17	6.72
DI	Di	87.41	66.93	57.74	61.32	61.27	59.86
	Hd	5.48	13.99	12.91	16.52	17.89	16.41
HY	En	—	—	—	—	—	2.06
	Fs	—	—	—	—	—	0.57
OL	Fo	2.98	5.18	7.89	5.70	5.94	5.17
	Fa	0.19	1.08	1.76	1.54	1.74	1.42
CS		0.00	1.01	4.70	0.15	0.00	0.00
MT		0.72	1.78	1.88	2.17	2.31	2.10
CM		0.97	0.19	0.46	0.00	0.24	0.00
IL		0.00	0.55	0.68	1.03	0.70	0.53
TOTAL		101.50	100.33	100.25	100.21	99.76	98.48
PLAG (AN)		32.08	100.00	100.00	100.00	48.13	64.88
OLIV (FO)		94.12	82.71	81.73	78.78	77.40	78.49
OPX (EN)		0.00	0.00	0.00	0.00	0.00	78.49
A OXIDES		1.79	1.67	2.87	1.23	2.89	1.81
F(total)		14.24	33.00	34.28	39.17	39.66	38.10
M MgO		83.97	65.34	62.85	59.60	57.46	60.09

Molecular proportions

$NaAlSiO_4$ + $KAlSi_2O_6$	0.2	1.5	2.5	1.2	0.1	—
$Ca(Mg,Fe)Si_2O_6$	94.9	88.4	81.0	86.6	87.3	83.2
$(Mg,Fe)SiO_3$	—	—	—	—	—	6.0
$(Mg,Fe)_2SiO_4$	4.9	10.2	16.5	12.1	12.5	10.7

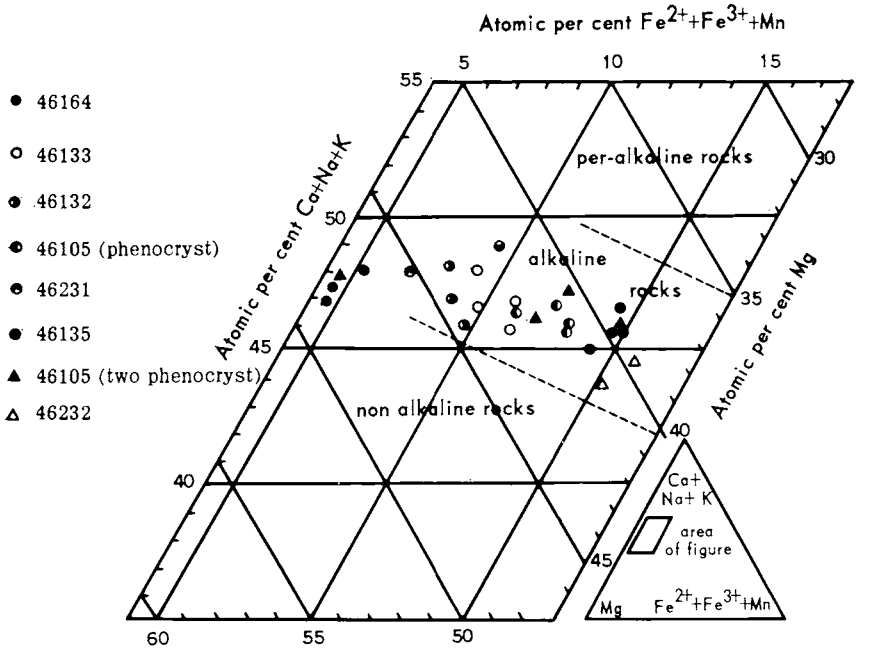


Fig. 7. Plot of pyroxenes in table 4 on part of a triangular diagram in terms of Ca + Na + K:Mg:Fe + Mn atomic percent. (Modified after LeBas, 1962.)

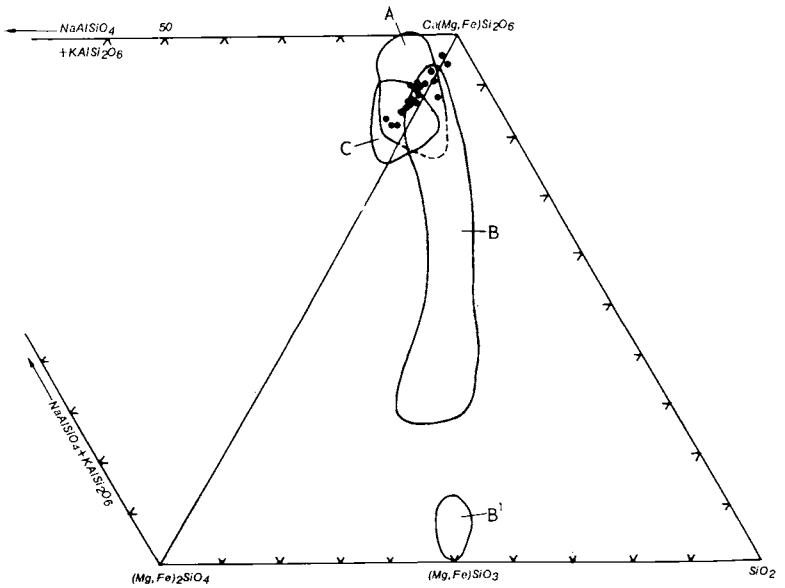


Fig. 8. Pyroxenes from the Sofala Volcanics (closed circle) plotted on a diagram after Coombs (1963). Pyroxenes from alkaline basaltic rocks plot in field A, theoleiites in field B, and peridotitic inclusions in field C.

Alternatively, the use of Al and Ti, especially in phenocryst pyroxenes, as an indicator of the degree of alkalinity of the parent magma (LeBas, 1962; Coombs, 1963) is probably not justified, since an SiO_2 versus Al_2O_3 plot of the Shiant Isles sill pyroxenes, which crystallized from one magma, plot in all three fields of LeBas (1962) (Gibb, 1973).

Superficially then, the chemistry of the Sofala clinopyroxenes resembles that of alkalic clinopyroxenes rather than tholeiitic clinopyroxenes. However, there are important differences which can be summarized as follows:

A. Titanium is low as reflected in normative ilmenite which reaches a maximum of 1.03 in 46105 (8).
B. CaO is high; normative diopside is commonly greater than 85 percent, whereas normal alkaline rocks rarely reach 70 percent normative diopside.
C. Cr_2O_3 is high; normative chromite appears in 20 of the 26 analyses listed in table 4 and reaches 1.53 percent in 46132 (1).

The comparative chemical data for igneous clinopyroxenes presented in table 5 indicate that the Sofala clinopyroxenes closely approximate compositions of clinopyroxenes from the calc-alkaline saturated and under-saturated suite of rocks of the Lesser Antilles (Arculus and Curran, 1972) especially with respect to low TiO_2 and high Cr_2O_3. Arculus and Curran (1972) however, have compared the rock and pyroxene chemistry of the Lesser Antilles with that of alkaline rocks with significantly higher TiO_2 and lower Cr_2O_3 than in their analyzed samples. The Sofala clinopyroxenes also compare favorably with those of calc-alkali rocks from Taga Volcano, Japan (Kuno, 1950) and superficially with clinopyroxenes from the Mount Dromedary complex, New South Wales, described by Boesen (1964) (see table 5, analyses 1 and 5). The latter are diopside to salite compositions with relatively low Ti compared with those of alkalic rocks (table 5, analysis 4) but with much lower Cr_2O_3 than the pyroxenes of Sofala and Grenada (Arculus and Curran, 1972).

On the basis of the above chemical criteria, the principal original volcanic eruptives of the Sofala Volcanics were calc-alkaline in character and undersaturated to mildly saturated with respect to silica. The pyroxene phenocryst chemistry suggests an alkaline source for these rocks as postulated by Arculus and Curran (1972) for the calc-alkaline rocks of the Lesser Antilles, where nepheline-normative pyroxenes occur in the under-saturated lavas of Grenada.

Hornblende compositions.—The compositions and norms of some relict amphibole phenocrysts of the Sofala Volcanics are presented in table 6, and the compositional range is shown in figures 9 and 10. It can be seen from the latter that the relict hornblendes 46123 (1), 46123 (2), and 46166 (1) are close to pargasite compositions; that is, hornblendes fairly rich in Na, Ca, Mg, and Fe^{2+}, which are relatively common compositions of hornblendes in basaltic rocks (Brown, 1967). These two pargasites are magnesian with normative olivine compositions of 75 per-

cent Fo and with 100 Mg/Mg + Fe^{2+} + Fe^{3+} + Mn = 70 and 62 respectively.

Pargasites commonly show some substitution of K for Na (Wilkinson, 1961), and, in addition, the two analyzed pargasitic amphiboles have Na + K > 1 indicating that Na shares the site occupied by Ca as well as that occupied by K. The two green amphiboles 46166 (2) and 46123 (3) (table 6) have Na + K > 1. These amphiboles, probably partially adjusted toward the compositions of metamorphic amphiboles of the area, occur marginally along two of the analyzed brown pargasite crystals. They carry considerably less Al^{IV} than the latter and plot close to metamorphic amphiboles of the area on a diagram similar to that of Leake (1965; 1971). Al^{IV} is reduced from 1.99 to about 1.43, and there is wide disparity in Al^{IV}; that is, 0.040 for 46166 (2) and 0.443 for 46123 (3) (fig. 11).

TABLE 5

Comparative data for igneous clinopyroxenes

	1	2	3	4	5
SiO_2	49.86	49.83	53.06	46.93	50.47
TiO_2	0.41	0.73	0.11	3.04	0.73
Al_2O_3	5.48	5.07	4.07	6.61	4.36
Cr_2O_3	—	0.79	0.86	—	0.01
Fe_2O_3	2.42	4.82	3.03	1.53	2.87
FeO	4.23			6.64	5.40
MgO	15.02	14.99	16.54	12.34	13.26
MnO	0.15	0.14	0.08	0.10	0.15
CaO	22.34	22.83	19.99	22.35	22.24
Na_2O	0.00	0.34	1.26	0.65	0.67
H_2O^-	0.20	—	—	0.11	0.14
H_2O^+	0.11	—	—	tr	—
Total	100.22	99.60	99.00	100.32	100.36
	Structural formulae based on 6 oxygens				
Si	1.837	1.845	1.936	1.755	1.870
Al^{IV}	0.163	0.155	0.064	0.245	0.130
Al^{VI}	0.076	0.066	0.111	0.047	0.062
Ti	0.011	0.020	0.003	0.086	0.020
Fe^{3+}	0.066	0.149	0.092	0.043	0.080
Fe^{2+}	0.130			0.208	0.167
Mn	0.004	0.004	0.002	0.003	0.004
Mg	0.831	0.827	0.899	0.686	0.733
Ca	0.882	0.906	0.782	0.895	0.884
Na	0.000	0.024	0.089	0.047	0.049
K	0.000	—	—	0.002	—
Cr	—	0.023	0.025	—	—

1. Salite in olivine–salite basalt tuff of Taga Volcano, north Izu, Japan (Kuno, 1950).
2. Basinitoid microphenocryst, Grenada, Lesser Antilles (Arculus and Curran, 1972).
3. Rim of a pyroxene from olivine basalt, St. Vincent, Lesser Antilles (Arculus and Curran, 1972).
4. Salite, magnesium-rich fraction teschenite 6.6 m above lower contact, Black Jack Sill, Gunnedah, N.S.W. (Wilkinson, 1957).
5. Pyroxene from pyroxenite enclosed by nepheline monzonite 0.8 km southeast of Central Tilba, N.S.W. (Boesen, 1964).

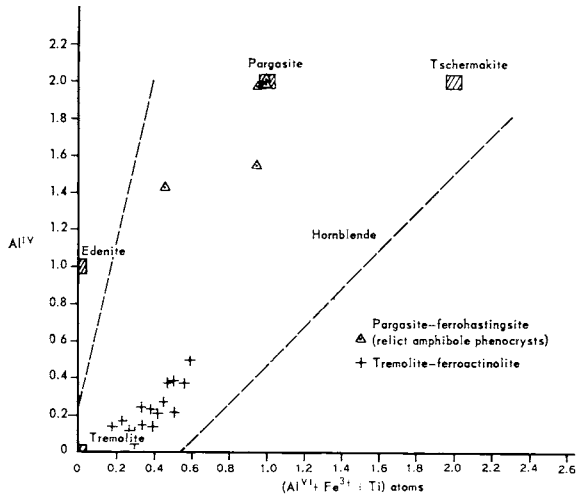


Fig. 9. The chemical variation of calcium-rich amphiboles in the Sofala area expressed as the numbers of $(Al^{VI} + Fe^{3+} + Ti)$ and Al^{IV} atoms per formula unit (method after Deer, Howie, and Zussman, v. 2, 1963).

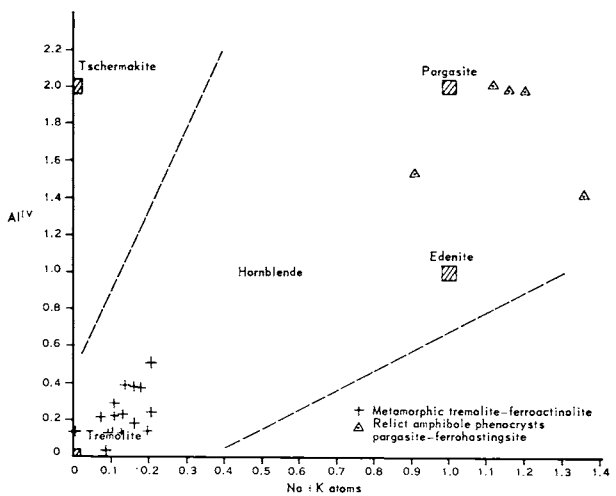


Fig. 10. The chemical variations of calcium-rich amphiboles in the Sofala area expressed as the numbers of (Na, K) and Al^{IV} atoms per formula unit (method after Deer, Howie, and Zussman, v. 2, 1963).

TABLE 6

Compositions structural formulae and norms of some relict amphibole phenocrysts of the Sofala Volcanics

		Brown amphibole		Red-brown amphibole	Green amphibole	
		46123(1)	46123(2)	46166(1)	46166(2)	46123(3)
	SiO_2	41.00	40.90	41.08	44.66	44.08
	TiO_2	1.83	1.77	2.15	1.29	1.18
	Al_2O_3	14.16	14.09	13.78	8.47	11.40
	FeO	10.73	10.57	13.44	10.00	12.20
	MgO	14.45	14.41	12.47	16.36	13.40
	CaO	11.96	11.86	12.11	11.39	12.19
	Na_2O	3.45	3.55	3.41	3.96	2.72
	K_2O	0.94	0.93	1.45	1.37	0.79
	Total	98.54	98.08	100.05	97.67	97.95
	Structural formulae based on 23 oxygens (anhydrous)					
Z	Si	5.994	6.003	6.012	6.571	6.471
	Al^{IV}	2.006	1.997	1.988	1.429	1.529
Y	Al^{VI}	0.434	0.441	0.388	0.040	0.443
	Ti	0.202	0.195	0.237	0.143	0.131
	Fe	1.312	1.298	1.645	1.230	1.498
	Mg	3.149	3.154	2.719	3.587	2.933
X	Ca	1.870	1.865	1.899	1.796	1.917
	Na	0.953	0.983	0.941	1.101	0.753
	K	0.175	0.173	0.271	0.256	0.148
	Sum X	2.999	3.021	3.111	3.153	2.818
	Sum Y	5.097	5.088	4.989	5.000	5.005
	100 Mg/(Mg+Fe+Mn)	70.60	70.84	62.31	74.47	66.19

(Fe^{2+}/Fe^{3+} average of 27 pargasite series analyses in Deer, Howie, and Zussman, (1963, v. 3) =3.99)

CIPW norms of relict amphiboles (wt percent)

	Brown amphibole		Red-brown amphibole	Green amphibole	
	46123(1)	46123(2)	46166(1)	46166(2)	46123(3)
OR	0.00	0.00	0.00	1.79	4.67
LC	4.35	4.31	6.72	4.94	0.00
AB	0.00	0.00	0.00	0.00	2.75
NE	15.81	16.27	15.63	18.15	10.98
AN	20.38	19.77	18.02	1.30	16.57
DI	10.75	10.94	11.76	44.03	35.37
OL	29.99	29.76	28.01	21.95	21.86
CS	7.89	7.85	8.50	0.00	0.00
MT	3.12	3.07	4.89	2.90	3.54
IL	3.48	3.36	4.08	2.45	2.24
Total	95.77	95.34	97.61	97.50	97.96
PLAG (AN)	100.00	100.00	100.00	100.00	85.79
OLIV (FO)	81.18	81.30	75.27	83.07	75.85
A OXIDES	14.85	15.21	15.45	16.82	12.06
F(total)	36.29	35.88	44.90	31.56	41.91
M MgO	48.87	48.91	39.65	51.63	46.03
Niggli Mg	0.71	0.71	0.62	0.75	0.67

The relict amphibole chemistry and petrology can be compared favorably with that of amphibole phenocrysts from calc-alkaline island arc associations described by Jakeš and White (1972). The Sofala amphiboles are commonly rimmed by a corona of fine opaque granules and alteration phases (opacite rims) suggesting original disequilibrium between amphiboles and host rocks. These hornblendes also have total alkali, total Al content, and Mg/Fe ratios similar to hornblendes of island arc andesites (Jakeš and White, 1972).

Such relict amphibole phenocrysts are probably important in determining the petrogenesis of the Sofala Volcanics, since there is increasing evidence to suggest that pargasitic amphiboles form an important accessory phase in the upper mantle which has been postulated as a source region for some alkaline (Oxburgh, 1964; Kesson, ms) and calc-alkaline rocks (Arculus and Curran, 1972; Sigurdsson and Tomblin, 1973).

It may be petrogenetically significant that the Sofala amphiboles are considerably more nepheline-normative than those from the alkali basalts and basanitoids of the undersaturated Grenada suite in table 4 of Cawthorn, Curran, and Arculus (1973), who infer that amphibole fractionation could generate an island arc calc-alkaline trend from the initial undersaturated melt.

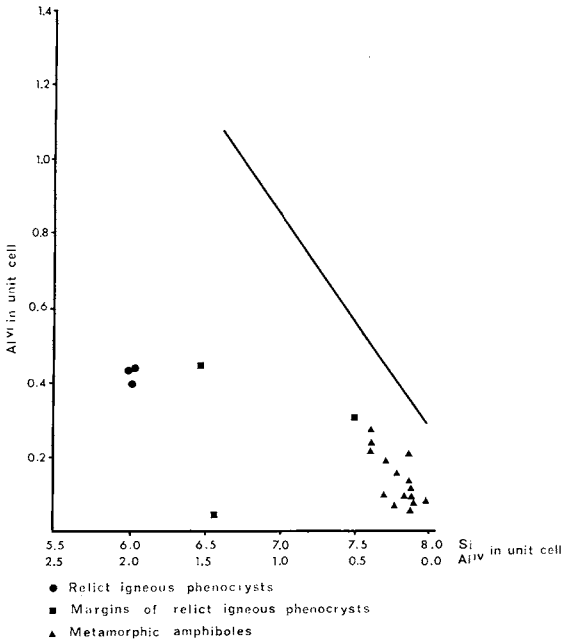


Fig. 11. Plot of octahedral Al in the half unit cell against tetrahedral Al (or Si) for analyzed amphiboles from the Sofala Volcanics (method after Leake, 1965; 1971).

CONCLUSIONS

The Ordovician rocks of the Sofala Volcanics are contained in two of the groups defined by Mitchell and Reading (1971) for rocks of modern active island arcs namely (1) volcanic arc deposits, containing epiclastic and pyroclastic volcanic rocks and clastic self-derived limestones and (2) submarine trench deposits, consisting of trench-fill sediments (mainly turbidites rich in quartz-deficient calc-alkaline volcanic detritus) and siliceous pelagic sediments.

Despite almost complete alteration to a greenschist-facies mineralogy, the original magma type of the Sofala Volcanics is recognized as possibly island-arc calc-alkaline in the sense of Jakeš and White (1972). This is determined by consideration of geological and tectonic setting, bulk chemical features of the "least altered" lithologies, chemistry of relict volcanic phases (clinopyroxene and hornblende), and a study of relict volcanic textures.

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