A metamorphosed pyroxenite at Nero Hill, Central Tanzania

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SUMMARY. The pyroxenite of Nero Hill has been metamorphosed under relatively low water pressure at the centre and higher water pressure at the margins. Thus a central pyroxenite consisting of diopside, hypersthene, oligoclase, garnet, and a little hornblende grades outward into a hornblende–cummingtonite amphibolite.

NERO HILL is a prominent, isolated conical hill in west central Masailand, Tanzania, with co-ordinates 36° 17′ 20″ E., 4° 41′ 50″ S. It is about 2000 ft in diameter at the base. The summit is composed of pyroxenite, about 150 ft in diameter, which is surrounded by amphibolites. Numerous boulders of pyroxenite obscure exposure over the lower slopes. The rocks around the hill, of which the nearest exposure is two miles to the north-north-west, are north-south trending migmatitic quartz–microcline–oligoclase–biotite gneisses of the Mozambique belt (Walker, in preparation). The soils surrounding the hill are typical of those derived from these rocks and small float fragments of similar gneisses occur in them.

Petrology. The metamorphosed pyroxenite that forms the summit of the hill contains euhedral orthopyroxene, up to 7 mm in length, with anhedral diopside, plagioclase, garnet, and hornblende. The pyroxenes, which both contain exsolution lamellae, are the most abundant. Plagioclase is interstitial to the pyroxenes; it is about An_{40}, with rather irregular zoning, forming large, extensive crystals, and, less often, aggregates of smaller grains. Most of the garnet is enclosed in the plagioclase, generally near the margins, and separated from pyroxene (either variety) or amphibole by a thin layer of plagioclase. The hornblende is a pale greenish-brown variety, and occurs chiefly in aggregates at the contacts between pyroxene and plagioclase. The accessory minerals are brown biotite, which forms aggregates usually in contact with plagioclase or amphibole, and rare opaque iron ore. Analysis 1 in table I is of a specimen from the summit of the hill. Cloudiness, exsolution, inclusions, and intergrowths made it impossible to separate samples of the pyroxenes of sufficient purity for analysis.

The pyroxenite, before metamorphism, appears to have consisted of orthopyroxene, clinopyroxene, and plagioclase, with accessory biotite and iron ore. During meta-

morphism, there was incomplete reconstitution of the main minerals. Some unmixing took place in the pyroxenes, and perhaps minor recrystallization, but the larger crystals survived and the texture remains essentially as in the igneous rock. The garnet and amphibole were formed entirely during the metamorphism, the further development of amphibole being restricted by the availability of volatiles.

TABLE I. *Chemical analyses and norms of rocks*

	Chemical analyses					Norms			
	1	2	3	4		1	2	3	4
SiO_2	53·34	52·83	53·13	52·31	Q	—	—	0·1	—
TiO_2	0·43	0·41	0·50	0·41	Or	1·1	1·7	1·1	1·1
Al_2O_3	4·26	5·17	4·28	5·38	Ab	5·8	7·8	5·9	5·9
Fe_2O_3	0·21	0·58	0·77	0·71	An	8·1	9·3	8·2	11·3
FeO	10·21	8·62	10·51	8·92	Di	38·9	37·4	29·1	37·9
MnO	0·20	0·20	0·23	0·18	en	13·4	13·4	10·2	13·5
MgO	18·88	18·59	19·33	17·90	fs	5·3	4·4	3·8	4·7
CaO	11·34	11·12	8·81	11·62	wo	20·2	19·6	15·1	19·7
Na_2O	0·68	0·91	0·67	0·71	Hy	40·8	36·3	53·5	39·4
K_2O	0·19	0·31	0·15	0·17	en	29·3	27·5	38·8	29·3
H_2O+	0·21	1·28	2·03	1·97	fs	11·5	8·8	14·7	10·1
H_2O-	0·03	0·02	0·03	0·02	Ol	4·3	5·8	—	2·6
P_2O_5	0·04	0·05	0·05	0·05	fo	3·0	4·3	—	2·0
Total	100·02	100·09	100·49	100·35	fa	1·3	1·5	—	0·6
$\dfrac{MgO}{MgO+FeO+Fe_2O_3}$	0·64	0·67	0·63	0·65	Mt	0·2	0·9	1·2	1·0
					Il	0·8	0·8	0·9	0·8
					Or+Ab+An	15·0	18·8	15·2	18·3
$\dfrac{Fe_2O_3}{FeO+Fe_2O_3}$	0·020	0·063	0·068	0·074	Di	38·9	37·4	29·1	37·9
					Hy+Ol	45·1	42·1	53·5	42·0

1. Pyroxenite from the summit of Nero Hill. BW 205.
2. Pyroxene amphibolite. BW 211.
3. Hornblende–cummingtonite rock. BW 204.
4. Hornblende rock. BW 212.
Analyst: H. W. Haslam.

In the rocks surrounding the central pyroxenite, the texture is similar, but hornblende becomes more abundant and coarser grained, farther from the centre, growing at the expense of the other silicates, until the garnet has disappeared. At this stage hornblende makes up over 50% of the rock. Many large prisms of orthopyroxene survive, but they are much corroded by hornblende. There are also smaller crystals of both pyroxenes, some accessory iron ore, and sometimes a little plagioclase. Analyses of a specimen from this zone and its constituent hornblende and pyroxenes are given in tables I (2) and II (1, 2, and 3). This is the only zone in which samples of the pyroxenes of sufficient purity for chemical analysis could be separated.

The next stage is a coarse-grained and friable hornblende–hypersthene rock. The hornblende (table II, 4) is euhedral and lacks visible exsolution lamellae. The hypersthene is much altered, to a fine aggregate of bastite and iron ores; there is no cummingtonite visible among the alteration products.

The final zone, around the circumference of the boss, consists of a coarse-grained, friable pyroxene-free amphibolite, rich in hornblende. Cummingtonite is often present, and is sometimes quite abundant. The accessory minerals are magnetite, ilmenite, and occasionally biotite. Both amphiboles contain exsolution lamellae, even in the hornblende when, on the hand-specimen scale, no co-existing cummingtonite can be observed. When the two amphiboles coexist, they normally form discrete crystals, but there are a few composite crystals with sharp, irregular boundaries separating the lime-bearing from the lime-free phase. Two specimens were selected from this zone for analysis, representing the two extremes in composition; BW 204 contains an unusually large amount of cummingtonite, while BW 212 is pure hornblende, apart from a little accessory iron ore.

Chemistry and discussion. Three analyses of hornblendes and one of cummingtonite are given in table II. Analysis 4 in table I is of a rock that is almost pure hornblende, containing in addition a very small quantity of iron ore. If allowance is made for rather high ferric and ferrous iron values, this analysis represents very nearly the composition of hornblende from a part of the outermost zone where it is not apparently associated with cummingtonite, and it resembles closely the composition of the hornblende (table II, 5) from a part of the same zone where it is associated with cummingtonite. Following the nomenclature proposed by Leake (1968), they are actinolitic hornblendes. Hornblende 4, which coexists with orthopyroxene, is also very similar, while hornblende 3, from a rock containing substantial amounts of clinopyroxene and orthopyroxene, is a magnesian hornblende, significantly richer in Al_2O_3, TiO_2, Na_2O, and K_2O. These elements are not readily accommodated in the pyroxene lattice. In the igneous rock before metamorphism the Al_2O_3, Na_2O, and K_2O were contained in the plagioclase; in the hornblende-bearing rocks they are contained in the hornblende, in greater concentration when the hornblende is less abundant.

Analyses 5 and 6 represent a coexisting hornblende–cummingtonite pair. They conform to the general pattern outlined by Klein (1968) in his account of the chemistry of coexisting cummingtonite and lime amphibole. The Al_2O_3, CaO, and Na_2O contents of the cummingtonite are well within the observed limits. The MnO content of the cummingtonite is nearly three times that of the hornblende. The $Mg/(Mg+Fe+Mn)$ ratio of the hornblende is markedly higher than that of the cummingtonite. One result of the higher iron content of the cummingtonite is that it has higher density and magnetic susceptibility than the hornblende, and so the difficulties in separating the two amphiboles that were met by other writers (e.g. Eskola, 1950; Watters, 1959) were not encountered, and pure samples of the minerals could be obtained, except for a very little iron staining in both samples. Both minerals also have exsolution lamellae; if unmixing took place during post-metamorphic cooling, the analyses represent the composition at the time of metamorphism.

Analyses are also given in table II of a diopside and a hypersthene from an assemblage coexisting with hornblende. They are near to the ideal compositions $Ca(Mg,Fe)Si_2O_6$ and $(Mg,Fe)_2Si_2O_6$ respectively. The ratio $(Fe^{2+}/Mg)_{opx}$: $(Fe^{2+}/Mg)_{cpx}$ is 2·3, which is rather high for pyroxenes in equilibrium, though on the model of Grover and Orville

TABLE II. *Chemical analyses of pyroxenes and amphiboles*

	1	2	3	4	5	6
SiO_2	54·00	53·84	50·94	52·39	52·65	55·57
TiO_2	0·15	0·09	0·55	0·42	0·42	0·18
Al_2O_3	1·04	2·00	6·98	5·11	5·04	0·89
Fe_2O_3	0·00	0·12	0·50	0·68	0·56	0·06
FeO	18·30	4·90	7·23	8·15	8·13	17·48
MnO	0·47	0·17	0·12	0·17	0·17	0·45
MgO	25·55	15·51	18·00	18·37	18·70	21·85
CaO	0·47	23·07	12·01	11·92	11·46	1·29
Na_2O	0·02	0·70	1·12	0·78	0·80	0·13
K_2O	0·01	0·01	0·45	0·25	0·16	0·01
H_2O+	—	—	1·96	2·16	2·08	2·01
H_2O-	0·00	0·00	0·08	0·00	0·02	0·06
Total	100·01	100·41	99·94	100·40	100·19	99·98

Ions on the basis of 6 oxygens (pyroxenes) or 23 oxygens (amphiboles)

	1	2	3	4	5	6
Si	1·971	1·966	7·180	7·383	7·407	7·884
Al^{iv}	0·029	0·034	0·820	0·617	0·593	0·116
Al^{vi}	0·016	0·052	0·340	0·231	0·242	0·032
Ti	0·004	0·002	0·058	0·045	0·045	0·020
Fe^{3+}	0·000	0·004	0·053	0·073	0·059	0·007
Fe^{2+}	0·559	0·150	0·900	0·960	0·957	2·074
Mn	0·014	0·005	0·014	0·020	0·020	0·054
Mg	1·390	0·846	3·781	3·858	3·921	4·620
Ca	0·018	0·903	1·814	1·800	1·728	0·196
Na	0·001	0·050	0·307	0·213	0·218	0·036
K	0·000	0·000	0·081	0·046	0·029	0·002
Z	2·000	2·000	8·000	8·000	8·000	8·000
Y	2·002	1·059	5·146	5·187	5·244	7·041
X	—	0·953	2·202	2·059	1·975	—
$\dfrac{Mg}{Mg+Fe+Mn}$	0·71	0·84	0·80	0·79	0·79	0·68

1. Hypersthene from pyroxene amphibolite. BW 211.
2. Diopside from pyroxene amphibolite. BW 211.
3. Hornblende from pyroxene amphibolite. BW 211.
4. Hornblende from hornblende–hypersthene rock. BW 216.
5. Hornblende from hornblende–cummingtonite rock. BW 204.
6. Cummingtonite from hornblende–cummingtonite rock. BW 204.
Analyst: H. W. Haslam.

(1969) the Fe–Mg partition is on the fringe of the observed scatter for metamorphic rocks. It is possible that the explanation may lie in the existence of two generations of hypersthene, the smaller crystals, which recrystallized during metamorphism, and the larger crystals, which did not. In a cummingtonite and an orthopyroxene coexisting with hornblendes of similar composition, the cummingtonite has the lower $Mg/(Mg+Fe+Mn)$ ratio.

Analyses and norms of four rocks from different zones are given in table I. Over 90% of each norm is made up of orthopyroxene, clinopyroxene, and feldspar, which are common constituents of a pyroxenite. The normative olivine may have been

represented in the igneous rock by modal olivine, or by low silica contents in the pyroxenes; probably the latter, since no olivine or pseudomorphs of olivine have been seen in the least metamorphosed specimens of the pyroxenite. Analyses 2 and 4 are very alike. Analysis 1 contains less normative plagioclase and rather more normative ferro-magnesian silicates, which could have resulted from differences in the proportions of
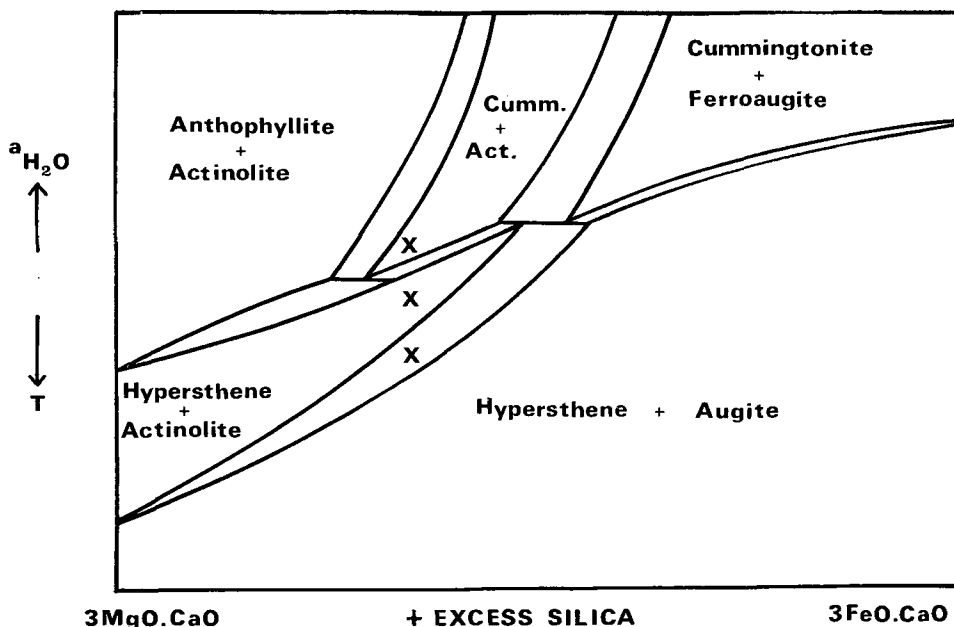

FIG. 1. Hypothetical phase diagram, reproduced from Kranck (1961), showing how the stability relationships in the system $3MgO.CaO-3FeO.CaO$ plus excess silica may change with the activity of water. The fields represented at Nero Hill are marked with crosses.

the constituent minerals in the pyroxenite. Analysis 3, of a rock especially rich in cummingtonite, also contains less normative plagioclase, but it contains much less normative diopside and much more normative hypersthene; it is also rather rich in manganese, an element that is concentrated in the lime-poor phase in two-pyroxene assemblages and in two-amphibole assemblages. These differences could be due to a difference in the mineralogy of the unmetamorphosed pyroxenite or to metamorphic differentiation.

There is an increase in water content from the almost amphibole-free pyroxenite, analysis 1, to the pure amphibole rocks of analyses 3 and 4, reflecting the abundance of amphibole. This is accompanied by an increase in the proportion of ferric iron. These gradations represent the different conditions under which the pyroxenite was metamorphosed. The centre of the boss was heated under almost dry conditions, and the partial pressure of water increased outwards, as did the partial pressure of oxygen, until at the margin the pyroxene was entirely replaced by amphibole. Under dry conditions some garnet was formed at the expense of plagioclase. Further from the centre

the plagioclase and garnet disappear, as the alumina and alkalies are absorbed in the amphibole. The higher volatile pressure at the margins also favoured recrystallization and the attainment of equilibrium. The amphiboles are fresh and coarse grained, and the hornblende composition and the presence in it of exsolution lamellae appear to be uniform throughout the zone, independent of the presence of cummingtonite nearby. This contrasts with the rocks at the centre of the boss, where recrystallization was incomplete at the time of metamorphism, and where the texture of the rock and the cloudy appearance of the pyroxenes are indicative of imperfect adjustment to prevailing conditions.

It may be noted that the lime-bearing pyroxene is replaced by amphibole at an earlier stage than the lime-free pyroxene. The stability relationships are illustrated in fig. 1. Although the rocks do not contain free quartz, there is enough silica and alumina to permit the formation of pyroxenes or amphiboles. Only a few of the assemblages in the diagram are represented at Nero Hill. No specimen has been seen completely free of amphibole. Much of the central part of the boss consists of hypersthene and augite with small amounts of lime amphibole, which increases gradually outward. The hypersthene+actinolite assemblage is represented by a narrow band, and the cummingtonite+actinolite assemblage is found in the outermost zone exposed.

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