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SAMEVATTING

Die 1,0 Ga oue Lurio gordel strek vir ca. 1 000 km vanaf Nsanje (S Malawi) deur NO Mosambiek tot by die Indiense Oseaan. Laerkorsvlakke is blootgestel langs die suidelike tektoniese front. In hierdie artikel word mineralogiese en geochemiese data vir 'n andesiniet-mafies- ultramafiese suite vanaf Nsanje gerapporteer. Ons resultate toon aan dat hierdie komplekse terrein in ewewig gekom het by $P \approx 13$ kbar en $T \approx 900^{o}C$ en daarna afgekoel het onder 'n eklogietgranaat granuliet geoterm. Tydens 'n latere gebeurtenis ($P \approx 7-10$ kbar, $T \approx 650 - 800^{o}C$) is onderskeidende metasomatiese glimmer, amfibool, skapoliet, apatiet, diopsidiese pirokseniet (sg MASAD)-draende versamelings en pegmatoïede gevorm deur Co_2, Cl, H_2O, S en F-ryke vloeistowwe met hoër REE, U, Th en Zr konsentrasies as die hoëgraad voorgangers.

MASAD en ouer hoëdruk granuliet parageneses het gevolglik ontwatering en her-ewewigvorming ondergaan onder mediumdruk-granulietfasies toestande, moontlik gedurende die Lurio orogeniese gebeurtenis.

MASAD-agtige versamelings is redelik algemeen binne die laat-Proterosoïese medium- en hoëdruk granulietterreine van Sentraal Gondwanaland, veral in die nuutgedefinieerde Lurio-Zambezi Eklogieprovinsie.

Die data wat gelewer word, toon aan dat die metasomatiserende, MASAD-vormende vloeistowwe, kripto-karbonatitiese affiniteite gehad het en toegevoeg is tot die kors vanaf die bomantel gedurende proto-slenkdalvormende episodes tussen ca. 1,1 en 0,5 Ga gelede. Die MASAD versameling mag daarom die kors-ekwivalent van die metasomatiese en MARID-suite verteenwoordig, wat in mantel xenoliete ontdek is.

ABSTRACT

The 1,0 Ga old Lurio belt extends for ca. 1 000 km from Nsanje (S Malawi) through NE Mozambique to the Indian ocean. Lower crustal levels are locally exposed along its southern tectonic front. In this article we report mineralogical and geochemical data for an andesinite-mafic-ultramafic suite from Nsanje. Our results indicate that this complex terrane equilibrated first at $P \simeq 13$ kbar and $T \simeq 900\ ^{o}C$ and subsequently cooled under an eclogite-garnet granulite geotherm.

During a later event ($P \simeq 7-10$ kbar, $T \simeq 650 - 800\ ^{o}C$) distinctive metasomatic mica, amphibole, scapolite, apatite, diopsidic pyroxene (MASAD)-bearing assemblages and pegmatoids were formed by CO_2, Cl, H_2O, S and F rich fluids with higher REE, U, Th and Zr concentrations than the high-grade precursors.

MASAD and older high-pressure granulite parageneses underwent subsequent dehydratation and reequilibration under medium-pressure granulite facies conditions perhaps during the Lurio orogenic event.

MASAD-like assemblages are relatively common within the late Proterozoic medium- and high-pressure granulite terranes of Central Gondwana, especially in the newly defined Lurio-Zambezi Eclogite Province.

The data we provide indicate that the metasomatizing, MASAD-forming fluids had crypto-carbonatitic affinities and were introduced into the crust from the upper mantle during protorifting episodes between ca. 1,1 and 0,5 Ga ago. The MASAD assemblages may therefore represent the crustal equivalent of the metasomatic and MARID suites discovered in mantle xenoliths.

1 INTRODUCTION

An important advancement in planetary evolution models made in the last decade is the recognition of widespread mantle metasomatism (Wyllie, 1980; Bailey, 1982). Petrological and geochemical studies of mantle-derived magmas and associated deep-seated inclusions indicate that metasomatism is caused by fluids bearing F, CL, C, H, O, B, S and P, and enriched with large incompatible lithophile (LIL) elements (Haggerty et al., 1983; Barker, 1983).

If we consider the subcontinental mantle in southern Africa, we find evidence for several discrete metasomatic episodes: at ca. 3,2 Ga (Richardson et al., 1984); ca. 1,4 - 1,0 Ga and ca. 0,19 - 0,15 Ga ago (Hawkesworth et al., 1983). In addition, mantle heterogeneities prior to 2 Ga ago - possibly related to metasomatism - have been described below the Kaapvaal craton by Erikson (1984).

Sillitoe (1974) and Sawkins (1976, 1984) suggested that subcontinental mantle hotspots and plumes may cause crustal enrichments in volatiles (F, Cl, CO_2) and metals (Sn, W, U, Cu, Pb, Zn) under anorogenic conditions. More recently Nicolaysen (1985) presented evidence for intracontinental hotspot activity related to deep-mantle degassing, while Plimer (1985) suggested that the Broken Hill deposits of NS Wales are the product of mantle metasomatism in a rift environment. If these models are correct, fertilized granulites should occur locally at the base of the crust in many parts of the world. However, Newton et al. (1980), Wass & Hollis (1983) and many others have attributed a mantle origin to the CO_2 present as fluid inclusions in granulites worldwide. There is now increasing speculation that deep-seated CO_2-rich fluids are strictly interlinked with the generation of late Archaean charnockite, granulite and granite in the lower crust of southern India (Weaver & Tarney, 1983; Friend, 1985). If these models are correct, fluxing of the crust by volatiles would be a petrogenetic process of major importance, especially if metals and halogens took part in this migration process.

To test the above hypotheses we have carried out an in-depth study of a high-grade terrane in the southern Mozambique belt which experienced severe metasomatism by metal- and halogen-rich carbonic fluids (Andreoli, 1981, 1984a, 1984b). An additional component of this study is represented by a search for comparable metasomatic rocks in correlatable Proterozoic terranes of central Gondwana.

2 REGIONAL SETTING OF THE NSANJE AREA, S MALAWI

The type area of our study is represented by a fault-bound inlier of Zambezi-Mozambique belt basement rocks within the Karoo and Recent cover formations of the Shire/lower-Zambezi region (Bloomfield, 1958, 1968; Fig.1).

A first-order feature of this inlier is represented by a marked contrast in the metamorphic grade and lithologies across a zone of complex folds which we believe represents the southwestern extension of the Lurio belt front (Fig. 2). This structure is one of the most spectacular features of the Mozambique belt as it extends for over 900 km in a NE direction from the Nsanje area across northern Mozambique to the Indian Ocean (Jourde & Vialette, 1980; Fig. 1).

Near Nsanje the terrane north of the "Lurio front" is characterized by monotonous and steeply dipping dark-green granulitic gneisses, and anorthosite sheets (Fig. 2) intruded by occasional pegmatite and Karoo dolerites. Granitoids and rocks of clear metasedimentary parentage are either rare or absent.

South of the "Lurio front" the metamorphic sequence comprises gneisses and amphibolites of much lower metamorphic grade, and often of clear supracrustal and sedimentary origin (Bloomfield, 1958; Andreoli, 1981).

3 FIELD RELATIONSHIPS

In the present study we investigate a suite of specimens collected across a short traverse between localities 1 and 3 of Fig. 2. In

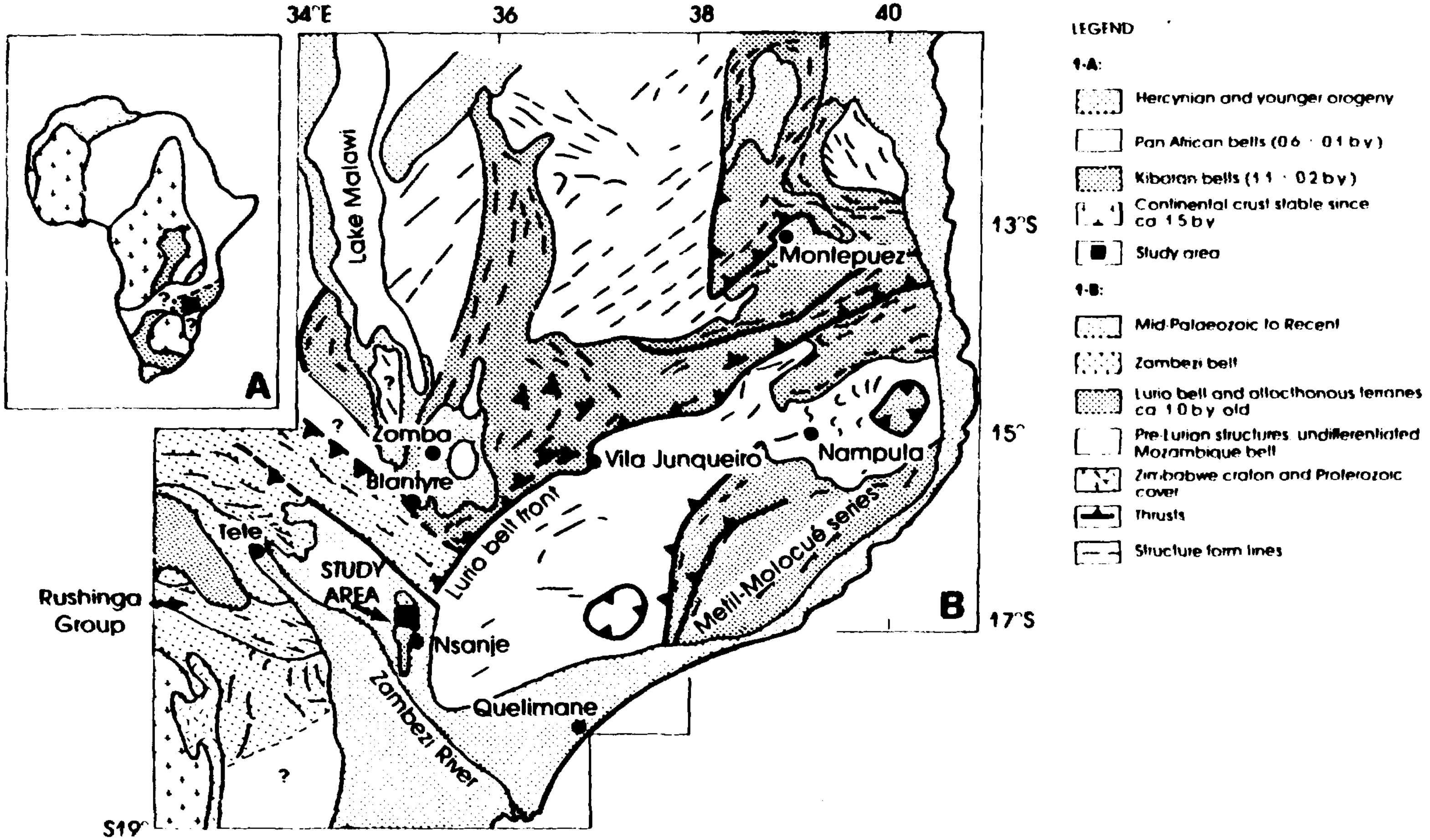

Fig. 1(A) Generalized map of major structural units of Africa, modified after Clifford (1974).

(B) Main structural units of the southern Mozambique belt, modified after Sacchi *et al.* (1984), Jourde & Vialette (1980) and Andreoli (1984a).

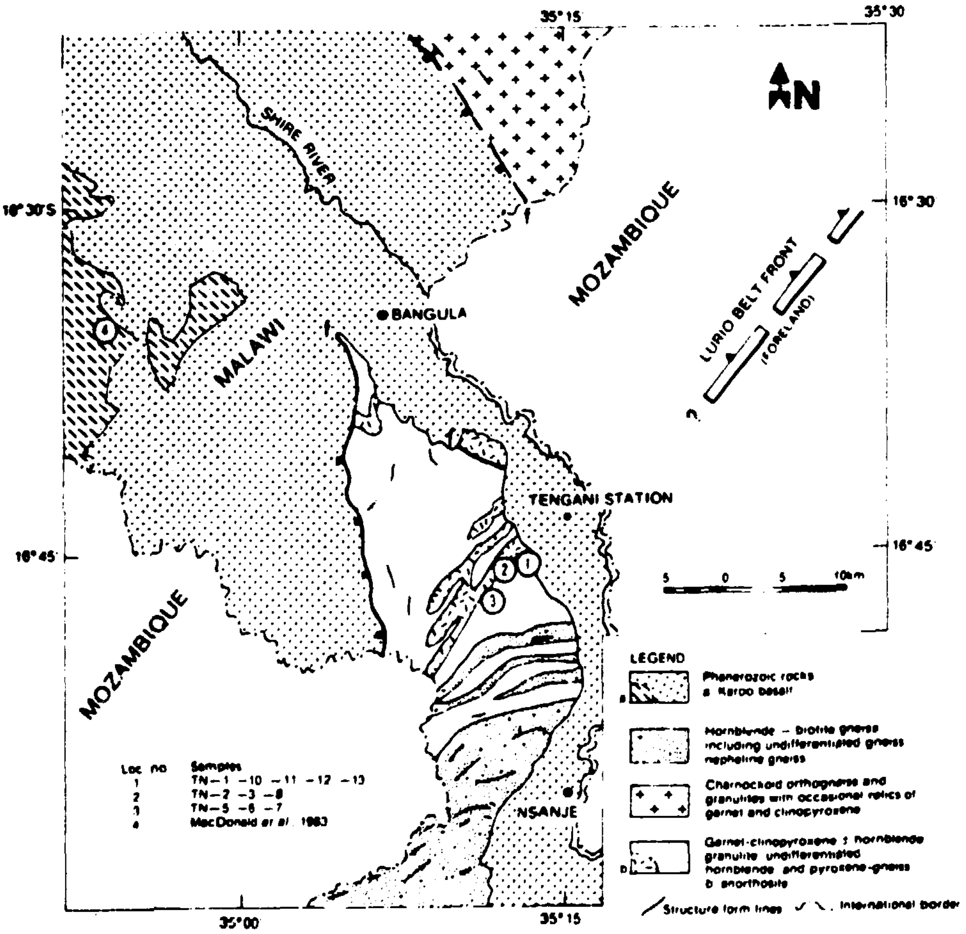

Fig. 2. General geology of the Nsanje area, S Malawi, modified after Bloomfield (1958) and Cannon (1970). Numbers are localities referred to in the text.

this area mesocratic garnet-clinopyroxene granulites grade through flaser leucogranulite into spotted anorthosite and (oligoclase/ andesine) leucoanorthosite. This rock frequently hosts thin and impersistent ilmenite-rutile-garnet seams. Mafic garnet granulites with frequent eclogitic lenses and interbands predominate near locality 1. Mesoscopic structures are generally granulitic, often blastomylonitic but in domains of reduced ductile deformation the anorthosite occasionally preserves pristine igneous-looking textures. In these cases the grain size is megacrystic (> 5 cm) and pyroxenes > 20 cm in length are common.

In the study area there is widespread evidence of metasomatic petrogenetic processes. In locality 2 and environs we observed the widespread gradation of anorthosite to sheared pale-green scapolite/prehnite felses (Andreoli, op. cit.). Coarse hornblendite has a scattered development and occurs either as veins crosscutting anorthosite or more frequently as pressure-release pockets within boudinaged anorthosite. In the later case the rock could also be interpreted as an ultramafic igneous pegmatite. In locality 3 melanocratic garnet granulites are often sheared and downgraded to biotite and hornblende-rich tectonites with scapolite augens. These rocks occasionally host lenticular boudins of megacrystic scapolite-hornblende clinopyroxenite. Finally, frequent hornblendite and peridotite cobbles in the stream gravels of localities 1 to 2 suggest that these rocks probably outcrop in the surrounding ridges.

4 PETROLOGICAL RELATIONSHIPS

Characteristic mineral assemblages and paragenetic sequences in the area investigated record a complex and polyphasic history of progressive depressurization from (garnet-clinopyroxene-plagioclase-quartz) high-pressure granulite facies to (orthopyroxene-plagioclase) medium-pressure granulite facies (Andreoli, op. cit.). Because this previous work was based on a limited set of samples, we now describe a number of more recently collected lithologies which may help to document the early high P-T metamorphic events and the subsequent metasomatic episode.

Megacrystic anorthosite. In sample TN 1 the magmatic oligoclase-andesine megacrysts are unzoned and antiperthitic, and host abundant rutile inclusions. Widespread deformation is manifested by grain-size reduction, lattice dislocations and strong mineral bending. In sample TN 3 deformation-induced polygonization of plagioclase is accompanied by corundum blastesis. In an incipient stage brownish-grey platelets of this mineral separate dislocated subgrains of the relic feldspar. In a more advanced stage of recrystallization we have found colourless and idioblastic sapphire (ca. 200 x 40 µm) within a polygonized plagioclase matrix.

Megacrystic bronzite is the typical femic mineral in the anorthosite and is characterized by ubiquitous exsolution rods of garnet (Andreoli, op. cit.), and by more scattered lamellae of clinopyroxene and rutile. The maximum size reached by the bronzite could not be estimated owing to its intense kinking, but it is of the order of several tens of centimetres.

Primary clinopyroxene was found only in sample TN 1 where it presents a pale green colour and exceeds 20 cm in length. This Ca-pyroxene hosts evenly spaced rods of garnet (ca. 20%) and ilmenite (ca. 5%) and scattered lamellae of orthopyroxene. Shear-induced polygonization of this megacryst results in a fine-grained clinopyroxene-garnet-rutile (eclogitic) paragenesis. In addition, fine-grained coronitic garnet outlines the contacts between megacrysts of clinopyroxene and plagioclase.

Ilmenite-magnetite and rutile are generally associated and their textural relationships suggest the following reaction:

ilmenite + (antiperthitic) plagioclase →
garnet + rutile + alkali feldspar

Eclogite. There is a complete gradation between eclogitic rocks and the common melanocratic garnet granulites. The samples investigated are fine- to medium-grained, and K 519 (from the approximate locality 2, Fig. 2; collection of the Malawi Geological Survey) shows a distinct segregation of orange garnet and greyish-green pyroxene granoblasts in stripes 1-3 mm wide. Rutile is the diagnostic accessory, but secondary plagioclase, reddish-brown hornblende and scapolite may be locally present.

Hornblende-biotite pegmatoid. This distinctive hypermelanic lithology (e.g. TE 3, Loc. 2) presents a pegmatoid (igneous ?) texture and consits of coarse hornblende crystals about 3 cm across. These crystals are largely unsheared and intergrown with biotite. The mica has a uniform distribution and a ribbon-like habit (ca. 2,0 x 0,8 x 0,05 mm) with orientation parallel to the c-axis of the host. Minor constituents and accessories comprise interstitial zoned plagioclase and pyrite.

Diopside-scapolite pegmatoid. In the boudins of megacrystic clinopyroxenite the constituent pyroxene is greenish and non-pleochroic, and forms poikiloblastic intergrowths with scapolite, hornblende and quartz. Grains of metamictic allanite, reddish sphene and some carbonate are also included in the sieve-like pyroxene oikocrysts, which appear largely unsheared. Ductile deformation is confined to occasional crosscutting veinlets 1-3 mm wide composed by an assemblage of quartz, diopside, red sphene and pyrite. Megacrystic hornblende hosting biotite lamellae as in TE 3 is an additional minor constituent of the clinopyroxenite boudins.

This diopside-scapolite pegmatoid bears close resemblance to the descriptions of syntectic diopside-scapolite ± davidite pegmatoids from Tete (Andreoli, 1984a; Davidson & Bennett, 1950).

Blastomylonite with scapolite augens. A characteristic of these blastomylonites is the presence of occasional scapolite augens ca. 3 to 1,5 cm across. This mineral falls in the dipyre-mizzonite compositional range and hosts abundant and ubiquitous sulphide needles and gas-filled prismatic cavities up to 50 x 20 µm in size. These augens closely resemble gem-quality scapolite from Sri-Lanka, Tanzania and related terranes (Schmetzer & Bank, 1983). Because the augen is rimmed by fine-grained scapolite and perthite, and because the plagioclase of the downgraded scapolite granulites hosts distinctive pyrite inclusions (Andreoli, 1981), we think that the following reaction takes place during shearing:

fluid, sulphate/sulphide-bearing scapolite →
pyrite-bearing feldspar + NaCl, CO_2-rich fluid

In these rocks (e.g. TN 6) apatite is relatively abundant and occurs in lenticular granular aggregates up to 2,5 - 0,5 mm across. Accessory zircon is occasionally present and may form unusual granoblastic-hypidioblastic grains 0,8 x 0,5 mm in size with biotite inclusions. Small grains of recrystallized and non-metamictic allanite are also occasionally present in the fine-grained granular matrix.

Amphibolitized ultramafics. Pebbles from stream sediments between localities 1 and 2 (Fig. 2) show the gradational passage from granulitic spinel hartzburgite (TN 9 and 10) and websterite (TN 11) to monomineralic nematoblastic hornblendite (TN 12). Petrographic relationships indicate the progressive replacement of pyroxenes, olivine and green or brown spinel by very pale green amphibole. Deformation features of the pyroxenes comprise shearing, kinking and polygonization, as seen in the least-altered granulites and anorthosites, whereas the amphiboles are generally undeformed.

Two amphiboles have been distinguished on the basis of their colour: a) a pale olive-green type which replaces the (spinel) hartzburgite, and b) a type with a colourless rim and a pale apple-green core that replaces websterite (e.g. TN 11 and 12). Common to both types of hypermelanic rocks is the evidence for late serpentinisation affecting olivine, orthopyroxene and amphibole alike.

Overall the metasomatites found north of Nsanje are characterized by the presence of a brown mica, brown to pale-green amphibole, scapolite, apatite and diopsidic Ca-pyroxene in variable proportions. In this article we will therefore refer to these metasomatic rocks and to their closely related pegmatoids by means of the mnemonic MASAD (e.g.: MASAD-type assemblage), from the initial letters of the distinctive mineral constituents.

5 ANALYTICAL DATA

5.1 Techniques

Electronmicroprobe. The analyses were obtained with an ARL SEMQ instrument at the Anglo American Research Laboratories following analytical procedures reported elsewhere (Andreoli, 1981). Standard analytical procedures involved counting for 20s on peak and for 10s on each side of the peak to calculate the background. Some samples, however, were counted for only 10s on the peak, while the background counting time remained the same. These faster analyses are distinguished from the others in Tables 1 to 3 by the single decimal digit. When the same mineral was analysed by both methods (e.g. TN 7, Table 2) the differences in the determined concentrations were found to be negligible.

Instrumental Neutron Activation Analysis (INAA). All trace element analyses, with the exception of fluorine and zinc, were performed at the Wits-CSIR Schonland Research Centre for Nuclear Science (SRCNS) using INAA, and following an analytical technique described by Erasmus et al. (1977).

Particle Induced X-ray Emission (PIXE). This technique was used to obtain multielemental qualitative data for minor and trace elements on small mineral fragments. General references to the analytical method may be found in Johansson & Johansson (1976) and in Annegarn et al. (1983). The PIXE analyses were carried out at the SRCNS by applying the following conditions: 3 MeV protons; Si-Li detector; 50 nA beam current; 4 mm beam size. In addition, a Kampton absorber of 0,5 mm with 5% hole, was used to reduce the background in the low-energy region of the spectrum (elements Na - Ca).

5.2 Mineral Chemistry

Garnet analyses were performed on two samples of eclogitic affinity and the relevant data are given in Table 1. Sample K 516 contains the garnet with the highest content of pyrope (Mg) end-member yet found in any deep-seated granulite from Malawi and also, for comparison, in lower crustal nodules from S. Australia (Fig. 3).

In contrast, garnets from all other granulitic-eclogitic parageneses of Nsanje are relatively more almandine-enriched, and straddle the compositional ranges of minerals from eclogites in high-grade terranes and in greenschists facies (Fig. 3). The Fe_2O_3 content in garnet from K 516 was investigated by Mossbaüer spectroscopy but found to be negligible (U. Karfunkel, personal communication).

Clinopyroxene compositions are listed in Table 2 and indicate profound chemical differences between eclogitic parageneses and MASAD-type intergrowths. The clinopyroxene in equilibrium with scapolite has a low Al_2O_3, TiO_2, Na_2O, and Cr_2O_3 content, but higher FeO (total iron as FeO), CaO, Na_2O/Al_2O_3, and ZnO (Table 3) than the eclogitic pyroxene.

Compositional data and end-members plots (Figs. 3 and 4) further indicate the salitic character of the scapolite-associated pyroxene, while pyroxene coexisting with garnet is always an aluminous augite of omphacitic affinity. In sample TN 1 the pre-exsolution clinopyroxene was probably a subcalcic and aluminous Na- and Cr-bearing augite megacryst (Table 3). Fig. 4 also indicates that the eclogitic pyroxenes plot in the field of omphacites of lower-crust origin.

Orthopyroxene (bronzite) megacrysts were repeatedly analysed in the course of the present investigation, but because their composition mirrored the one reported by Andreoli (1981), we refer to this work for the relative chemical data. Table 3 indicates the presence of minor amounts of chrome and titanium.

Amphibole analyses given in Table 4 indicate the strong chemical variability between different assemblages. In K 516 (an eclogite

Table 1 Electromicroprobe (EMP) analyses of eclogitic garnet

Sample	K 516	TN 1			
		a	b	c	d
Notes		coron	rods	granoblastic	
No. of Analyses	2	2	2	6	2
SiO_2	40,52	38,0	37,8	38,2	38,1
TiO_2	0,05	0,0	t	0,1	t
Al_2O_3	23,28	22,5	21,3	21,6	22,4
Cr_2O_3	0,0	t	0,2	0,0	t
FeO*	17,02	24,2	26,6	26,4	25,4
MnO	0,3	0,7	1,1	1,2	0,9
MgO	13,04	7,8	6,5	6,3	7,3
NiO	t	0,0	0,0	0,0	0,0
CaO	6,98	6,8	6,1	5,5	5,8
Na_2O	0,01	0,0	0,0	0,0	0,0
Total	101,02	100,0	99,6	99,3	99,92
Ca**	1,096	1,124	1,025	0,923	0,962
Mg	2,849	1,793	1,520	1,471	1,685
Fe	2,086	3,122	3,431	3,460	3,290

*: Total iron as FeO; **: number of cations of Ca, Mg, and Fe in structural formula on the basis of 24 oxigen atoms; t: traces; coron: coronitic.

Table 2 EMP analyses of clinopyroxene from eclogites and from a metasomatic rock

Sample	K 516	TN 1				TN 7	
		a	b	c	d	a	b
Notes	eclog	coron	megacr	polyg		interg	
No. of Analyses	2	3	2	3	2	4	1
SiO2	51,05	49,5	52,5	50,7	51,8	.3,3	52,31
TiO2	0,61	0,3	0,3	0,3	0,3	0,0	0,07
Al_2O_3	6,79	5,2	3,0	3,7	4,2	0,9	0,96
Cr_2O_3	0,0	0,1	0,1	t	t	0,0	0,0
FeO*	5,16	9,3	8,6	8,1	7,6	9,5	9,43
MnO	0,40	0,1	0,1	0,1	0,1	0,1	0,10
MgO	13,88	13,5	13,2	13,0	13,3	12,8	13,18
CaO	20,59	19,3	20,9	21,7	22,3	23,4	23,40
Na_2O	1,68	0,8	1,5	0,8	0,8	0,6	0,60
TOTAL	100,17	98,1	100,2	98,4	100,4	100,6	100,06

*: Total iron as FeO; K_2O, NiO and ZnO analysed but not detected; t: traces; eclog: eclogite; coron: coronitic; megacr: megacrystic; polygon: polygonized; intergr: clinopyroxene-scapolite intergrowth.

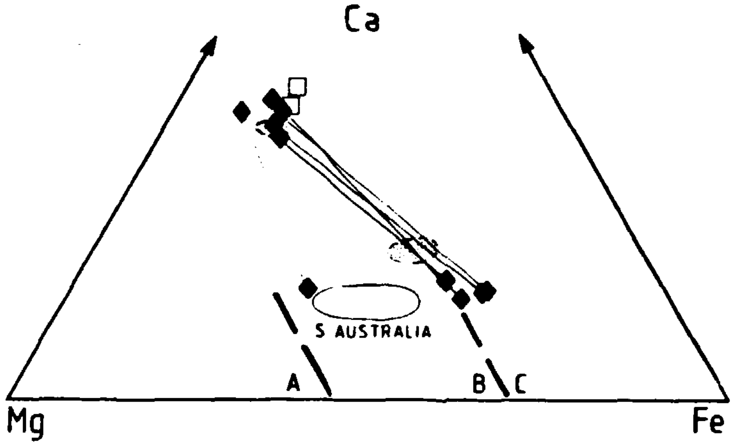

Fig. 3. Ca-Mg-Fe distribution in (◆), clinopyroxene-garnet pairs from eclogite; and (□) MASAD-type clinopyroxene -scapolite intergrowths of localities 1 and 3, Fig. 2. Contoured area is field of garnet in deep-seated xenoliths from S Australia (Wass & Hollis, 1983). Shaded field includes Nsanje minerals analysed by Andreoli (1981). A, B and C are the fields of garnets from eclogite in kimberlitic nodules, in high grade terranes, and in greenschists terranes respectively (adapted from Coleman <u>et al</u>., 1965; and Griffin <u>et al</u>., 1979).

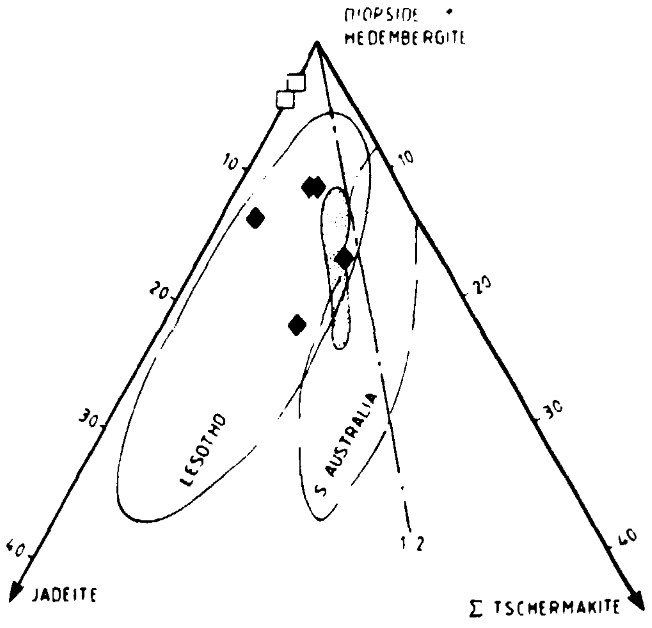

Fig. 4. Distribution of jadeite -(Ti, Al) tschermakite - Ca pyroxene (diopside - hedembergite) end- members in clinopyroxenes from (◆) eclogite and (□) MASAD-type scapolite intergrowths. The Jd:Ts = 1:2 line separates eclogitic from granulitic pyroxenes (White, 1964), while the fields of deep seated pyroxenes from Lesotho and S Australia are after Griffin <u>et al</u>. (1979) and Wass & Hollis (1983) respectively. Shaded field includes Nsanje pyroxenes analysed by Andreoli (1981).

sample) the amphibole is a hornblende s.l. enriched in Ti and Al, but K-free; whereas in the hartzburgite-hornblendite-pyroxenite suite it is rich in Cr, Mg, Ca and Cl but poor in Ti, Fe and K (Tables 3 and 4). In contrast, Ti, Fe and K are enhanced in a pegmatoid amphibole (Table 4, TN 8) relative to most hornblendes s.l. from high-grade terranes of S Malawi (Andreoli, 1981). The relative distribution of $Al^{vi*}=(Al^{vi} + Ti + Cr)$ and Al^{iv} in the amphiboles is shown in Fig. 5 and indicates the broad granulitic affinities of the minerals of Nsanje. In fact, they plot adjacent to the field of medium- and high-pressure granulite facies amphiboles from elsewhere in S Malawi. Fig. 5 also shows that most metasomatic amphiboles of Nsanje are common hornblende-pargasite solid solutions with appreciable content of the tschermakite component.

Biotite has been probed only in sample TN 8 (Table 4) but its composition indicates that the ribbon mica intergrown with hornblende has a TiO_2 content appreciably lower than that of minerals from granulite assemblages elsewhere in Malawi (TiO_2= 5,4%. Andreoli, op. cit.). Since this ribbon-type biotite is probably in chemical equilibrium with the host amphibole, Table 4 indicates a prefential partition of Ti and Fe in the hornblende.

Scapolite analyses given in Table 4 correspond to a sulphate-bearing mizzonite (An_{eq} 62-67). Experimental data by Vanko & Bishop (1982) suggest that appreciable Na could be lost during electronmicroprobe analyses. However, the good correspondence between two analytical procedures, one of which is very rapid, suggests a reasonable approximation of our data. At the present time it is unclear whether or not the abundant sulphide inclusions observed in the scapolite represent exsolutions from an iron- and sulphate-enriched precursor. Published scapolite analyses (Evans et al., 1969) have very low iron values ($Fe_2O_3 \leq 0,18\%$), a fact suggesting that the opaque Fe-sulphide rods are primary intergrowths rather than exsolutions.

Table 3 PIXE qualitative analyses of minor and trace elements in selected minerals

	Ti	Cr	K	Cl	Sr	S	Zn	Ni	Notes
NA 135b*	x	x							Megacr opx
TN 1		x							Megacr cpx
TN 2	x		x	x	x				Megacr plg
TN 7	x		x	x		x	x		Cpx-scap interg
TN 12	x	x	x	x				x	Hornblendite

*: EMP analysis given by Andreoli (1981); scap: scapolite; opx: orthopyroxene; cpx: clinopyroxene; plg: plagioclase.

For other abbreviations see Table 2.

Table 4 EMP analyses of metasomatic minerals

Sample	K 516	TN 9	TN 12		TN 8		TN 5	TN 7
Mineral	horn	horn	horn	trem	horn	biot	scap	scap
Note	eclog	hartz	hornbl, te		interg		augen	interg
No. of Analyses	2	1	3	1	2	1	6	1
SiO_2	41,38	42,0	42,00	52,7	39,22	36,	53,04	51,6
TiO_2	2,13	0,5	0,64	t	1,87	5,	0,0	0,0
Al_2O_3	14,99	13,7	12,13	2,7	13,52	14,	23,37	24,3
Cr_2O_3	-	0,8	1,37	0,2	-	-	0,0	0,0
FeO*	9,02	4,6	6,82	3,6	17,88	17,1	0,12	0,01
MnO	0,03	t	0,13	0,1	0,14	t	t	0,0
MgO	14,33	17,3	16,33	21,7	8,83	12,7	t	0,0
NiO	0,0	0,1	0,09	t	t	t	t	0,0
CaO	11,46	13,4	13,72	14,2	11,18	t	11,34	12,9
Na_2O	2,7	2,4	2,19	0,5	1,81	0,1	6,82	6,7
K_2O	0,0	0,6	0,9	t	2,1	9,4	0,94	0,6
Total	96,04	95,4	96,52	95,7	96,55	94,3	97,00**	96,2

*: All iron as FeO; **: total includes SO_3 = 1,37% as average of 8 determinations recalculated from a pyrite standard; t: traces; -: not measured; biot: biotite; horn: honblende; trem: tremolite; hartz: hartzburgite; hornbl,te: honblendite.

For other abbreviations see Tables 2 and 3.

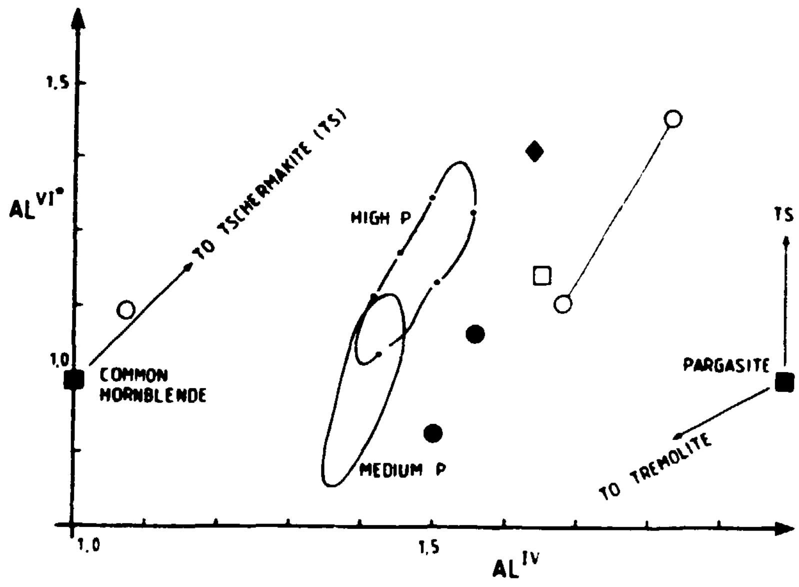

Fig. 5. Distribution of Al^{iv} and Al^{vi*} = $(Al^{vi} + Ti + Cr)$ in amphiboles from Table 4: (●) MASAD hornblendite; (□) MASAD biotite-hornblende intergrowth; (◆) eclogite; (○) Nsanje garnet granulite (Andreoli, 1981). Amphibole end-members are after Deer _et_ _al_. (1963, Vol 2, p. 273). Fields of amphiboles from Malawi high/low pressure granulite terranes are after Andreoli (1981).

Pyrite was qualitatively analysed in the sample of scapolite-clinopyroxenite (TN 7) and we detected minor amounts of Cu (Andreoli, unpublished data).

Spinel analyses (Andreoli, unpublished data) indicate that the brown type of TN 9 contains Al_2O_3 (46,6%), Cr_2O_3 (16,6%), FeO + MnO 17,9%), NiO (0,3%) and MgO (16,2%). This composition compares with that of ferroan chromian spinels (pleonaste) found in lherzolite- wherlite xenoliths of deep-seated origin (Griffin _et_ _al_., 1984).

5.3 Geochemistry

The rare earths elements (REE), Ba, Na, Cr, Zr, Hf, Th and U were all analysed by INAA in selected rocks from the eclogite, from the ultramafic granulite and from the metasomatized suites. The results are presented in Table 5. The chondrite normalized REE data are shown in Fig. 6 and indicate -

(a) slopes of regularly decreasing abundances with increasing atomic weight;

(b) absence of a marked positive/negative Europium anomaly for the more REE enriched samples; and

(c) strong overall enrichment of the light REE.

In general our data are consistent with field and petrographic observations and with the concept of metasomatic addition. The metasomatized ultramafic and mafic granulites are enriched in REE relative to their granulitic precursors. In addition, there is a great spread in light/heavy REE ratios and both non-metasomatized and metasomatized groups overlap, showing no apparent change.

In addition to the REE data, available evidence suggests that the metasomatized suite is also enriched in Rb, Ba, Hf, Th, U, Ta and possibly Zn and halogenes, as indicated by the F enrichment. This is also supported by the presence of abundant Cl-bearing scapolite in the metasomatized rocks.

Fig. 7 compares the trend of two MASAD rocks with that of possible analogues from elsewhere in Africa. It is interesting that there is a strong correlation between TN 7 and a Lesotho granulite which was interpreted as a metasomatized lower-crust rock (Griffin et al., 1984).

Fig. 8 compares the U and Th concentrations with those in ultramafic rocks of deep seated origin from elsewhere in the world, including

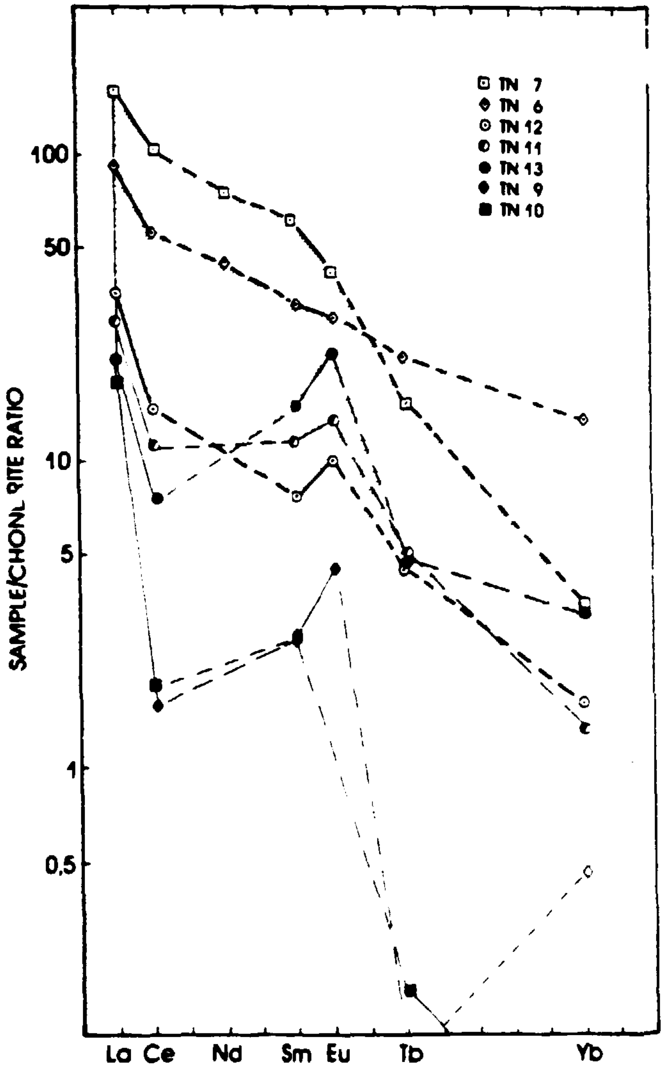

Fig. 6. Chondrite-normalized REE concentrations in Nsanje rocks (after Table 5). Shaded area is the MASAD field.

Central Malawi. In all cases the MASAD-related rocks from Nsanje and Central Malawi (Lilongwe) appear significantly enriched in U relative to typical deep-seated ultramafics.

In conclusion, although our data are sparse, the evidence supports the claim that the Nsanje MASAD suite represents addition of REE and the incompatible elements to more depleted precursors.

Table 5 INAA trace element data (ppm) for granulitic
and metasomatic rocks

	TN 13	TN 10	TN 9	TN 11	TN 12	TN 6	TN 7*
La	7,4	6,2	6,2	9,6	11,8	30,6	53,7
Ce	6,4	1,6	1,4	9,8	12,9	48,3	90,
Nd						28,1	47,4
Sm	3,2	0,6	0,6	2,4	1,6	6,6	12,6
Eu	1,8		0,35	1,0	0,8	2,3	3,2
Tb	0,2			0,3	0,2	1,1	0,8
Yb	0,7		0,1	0,3	0,7	3,0	0,7
Rb				4,4	1,2	56,1	29,7
Ba	68	56	52	101	91	947	656
Cr**	123	756	855	3034	2070	57	75
Zr						215	
Hf	2,1				0,5	5,6	3,5
Th					0,13	0,75	10,9
U	0,26	0,2	0,26	0,3	0,47	0,66	0,91
Ta	0,3	0,1	0,4	0,21	0,39	1,1	0,16
F***	90					570	280
La/Yb	10,6	62	32	32	16,8	10,2	76,7

TN 13: Sheared plg-pyroxenite with bronzite and augite megacrysts
TN 10: Spin-hartzburgite cut by Cr-parg vein
TN 9 : Serpentinized spin-hartzburgite with 20% Cr-parg
TN 11: Spin-Websterite with 30 - 40% green Cr-parg
TN 12: Hornblendite: 60% Cr-parg, 30% trem, 10% op min
TN 6 : Sheared, scapolitized garnet-granulite
TN 7 : Cpx-horn megacrysts with scapolite intergrowths

Blank: below detection; -: not calculated; *: sample includes 175 ppm Zn (X-ray fluorescence analysis, Bergström and Bakker lab.). **: average of two determinations; ***: whole-rock F measurements (iron-electrode method, Bergström and Bakker Laboratory, Johannesburg); op min: opaque minerals; spin: spinel; Cr-parg: chrome-pargasite.
For other abbreviations see Tables 2 to 5.

Table 6 Temperature calculations from garnet-clinopyroxene pairs in eclogite

Sample		K 516	TN 1			
			a	b	c	d
K_D'		3,508	4,5037	6,281	6,785	6,089
$T^{o}C$ (Wells, 1979)	5 Kb	912	833	743	727	751
	10 Kb	928	848	757	740	765
$T^{o}C$ (Ellis & Green, 1979)	5 Kb	886	786	677	650	681
	10 Kb	904	802	691	664	696

K_D' calculated by recasting all Fe as FeO in clinopyroxene and garnet.

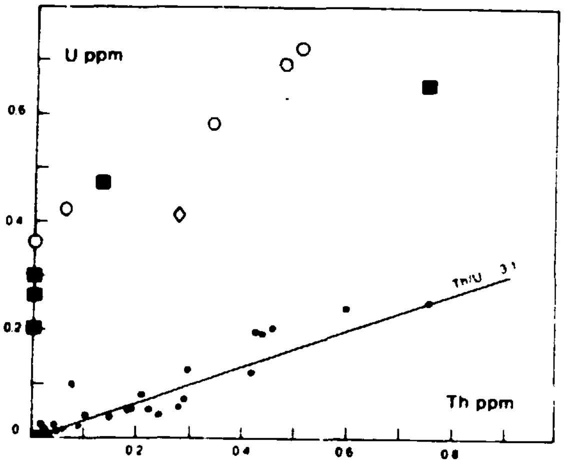

Fig. 7 Distribution of U and Th in (■) ultramafic granulites and some MASAD rocks from Nsanje (after Table 5) in relation to: (●) deep seated ultramafic rocks worldwide, (◇) hornblendite xenolith in kimberlite (Morgan & Lowering, 1971); and (○) garnet-olivine ultramafics from Lilongwe (Andreoli, 1984a; Andreoli & Hart, unpublished data).

6 P-T ESTIMATES

Eclogitic parageneses. Using the data from Tables 1 and 2 we have calculated T from formulas by Ellis & Green (1979) and Wells (1979). The results are shown in Table 6 and Fig. 9. The broad pressure constraints imposed in Fig. 9 are provided by the coexistence in localities 1 and 2 of eclogitic and garnet-clinopyroxene-plagioclase-quartz parageneses in rocks with the composition of quartz tholeiite (Andreoli, 1981). This observation is in accordance with experimental data on the gradual transition from garnet-granulite to eclogite (Green & Ringwood, 1967). It is also significant that the eclogitic clinopyroxenes, though markedly aluminiferous and coexisting with Na-rich plagioclase, have a relatively low jadeite content ($Na_2O \leq 1{,}7\%$; and $Al_2O_3 \leq 7{,}0\%$) corresponding to omphacitic augite transitional to omphacite (Fig. 4).

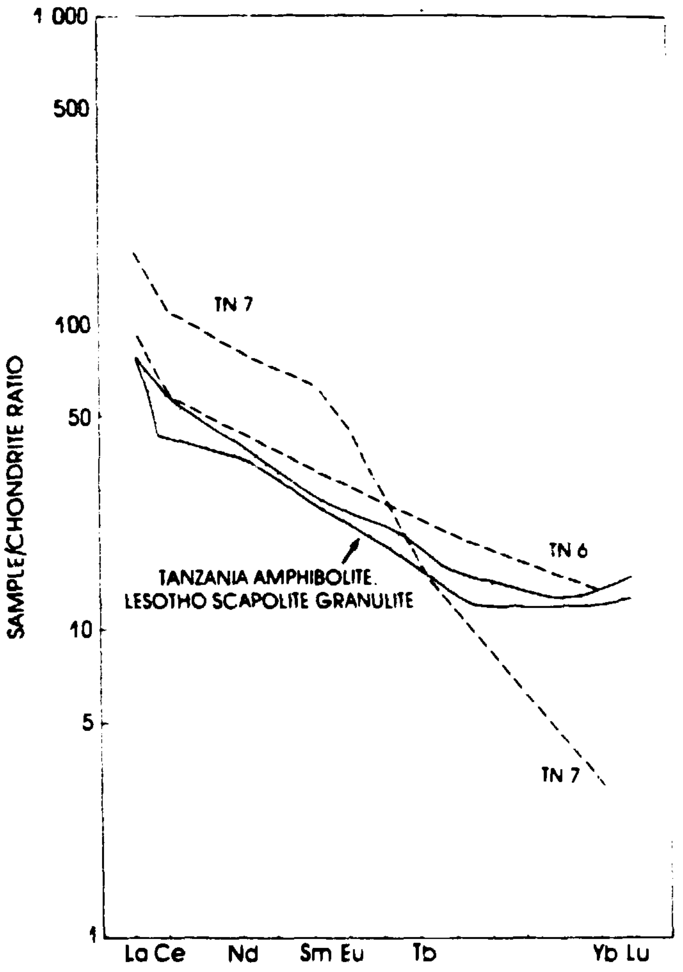

Fig. 8. Chondrite-normalized REE distribution of scapolite-bearing MASAD rocks from Nsanje in relation to possible MASAD equivalent from Tanzania and Lesotho (dotted field, Rogers, 1977; Prochaska & Pohl, 1983).

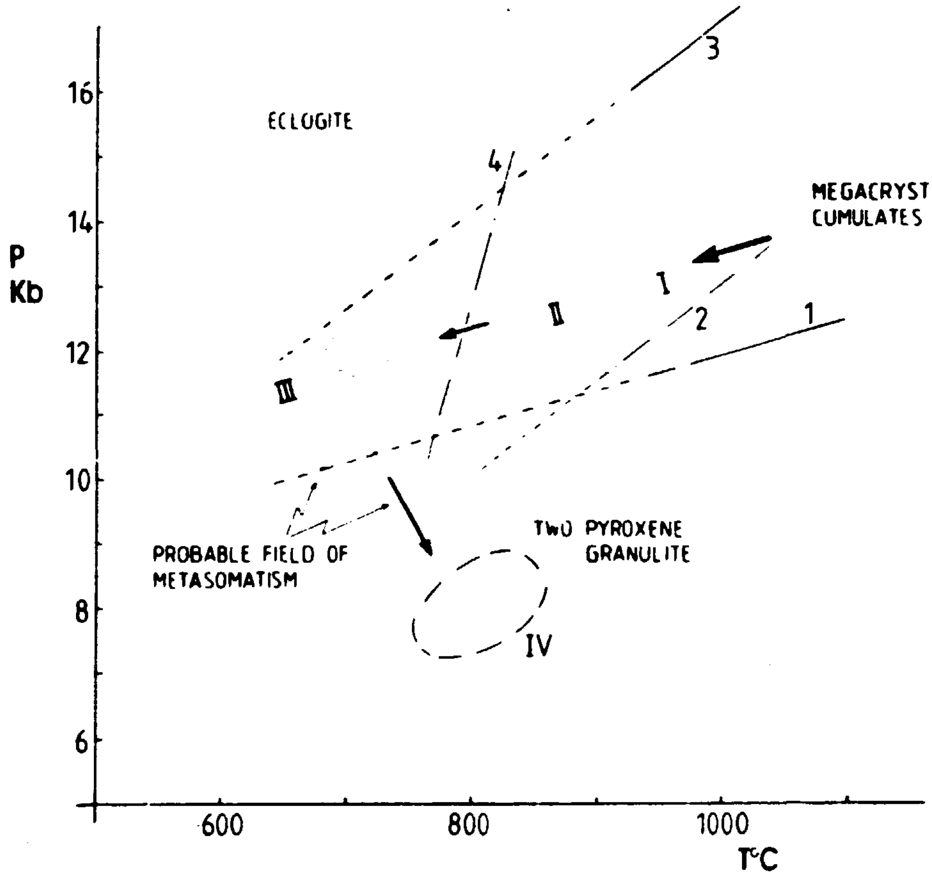

Fig. 9 Some experimental data relevant to the determination of the P-T pathway (arrows) of the Nsanje eclogite-MASAD suite: 1, upper limit to olivine + plagioclase in basalt with $Mg/(Mg+Fe^{2+}) \approx 0,6$ (Green & Ringwood, 1967); 2 and 3, lower and upper limit to plagio-clase stability in quartz-tholeiite compositions (ibid.); 4, equilibration conditions for garnet-bearing orthopyroxene megacryst (Andreoli, 1981; Wood, 1974); I, II and III, P-T fields of anorthosite-granulite reequilibration from temperature data of Table 6; IV, approximate field of MASAD dehydration (Andreoli, 1981).

Pressures in excess of 10 kbar are consistent with the presence in sample TN 1 of garnet-ilmenite(-orthopyroxene) exsolutions from a subcalcic augite precursor. As far as the authors are aware, similar textures have in fact only been reported in xenoliths of deep-seated origin and reequilibrated at $P \geq 11-16$ kbar and $T \geq 700 - 1\,100\ ^{\circ}C$ (Shervais et al., 1973; Irving, 1974; Schultze et al., 1978; Griffin et al., 1984). Moreover, garnet exsolutions in orthopyroxene comparable with those of Nsanje have been reported in a mantle-derived eclogite ($P \gg 10$ kbar, $T > 1\,000\ ^{\circ}C$) from the Saxony granulite complex (Reiche & Bautsch, 1985).

MASAD parageneses. The P-T conditions for the MASAD-forming event are inferred from data in Fig. 5. The chemistry of the amphiboles indicates the presence of Cr and of the end-member tschermakite in varying proportions. These observations are relevant since a) the presence of tschermakite component seems to distinguish the amphiboles of the high-pressure terranes in S Malawi (Andreoli, 1981); and b) the Cr-amphibole compositions compare with those of lherzolite amphiboles equilibrated at $P \approx 11$ kbar near the crust-to-mantle transition in Victoria, Australia (Griffin et al., 1984). A very broad upper limit to T may be provided by the equilibrium coexistence in TN 12 of Cr-pargasite cores and tremolitic rims. Experimental data on tremolite stability (Valley et al., 1983) indicated that this is stable relative to enstatite + diopside + quartz + vapour up to 800 °C if $P \approx 6 - 10$ kbar and $X_{H2O} \approx 0,5$.

Conditions of crystallization for scapolite were not calculated from the scapolite-plagioclase geothermometer because this becomes less accurate for $An_{eq} < 70\%$ (Goldsmith & Newton, 1977).

Qualitative indications on pressure may be deduced from the appreciable content of SO_3 ($\approx 1,5\%$) in the scapolite augen of sample TN 5. Lovering & White (1964) and Goldsmith & Newton (1977) suggested that high pressure favours high SO_4 values in scapolite and Kwak (1977) concluded that no sulphur is contained in scapolite up to upper amphibolite facies grade. An additional evidence for a high pressure origin of the MASAD is provided by the SO_3 content (1,5 - 2,6%) of scapolite from garnet granulites (P ≈ 8,4 kbar) of the Dubtfoul Sound Area, New Zealand (Blattner & Black, 1980; Oliver, 1977).

Finally, indication that the MASAD-forming event took place under deep-seated conditions is provided by evidence for subsequent partial replacement of biotite by orthopyroxene under medium-pressure granulite facies conditions. Since these conditions were compared by Andreoli (1981) with those of the Blantyre-Zomba area (Fig. 1), the MASAD-forming event can be bracketed between P ≈ 10-7 kbar and T ≈ 650 - 800 °C (Fig. 5).

7 POSSIBLE CORRELATIVES OF NSANJE IN RELATED TERRANES OF CENTRAL GONDWANA

The first question that arises from the assessment of the MASAD-forming event in Nsanje relates to its regional distribution. To this end we conducted an extensive search through the available geological records for descriptions of MASAD-type rocks in the Zambezi, Mozambique and related mobile (orogenic) belts.

We have deliberately excluded from this search (CO_2-rich) meionitic scapolite-diopside granulites and (NaCl-rich) marialitic scapolite-anhydrite schists. These represent the high-grade metamorphic derivations of calcareous sedimentary rock and evaporite respectively (Winkler, 1979; Oliver & Wall, 1985; Mc Clay & Carlyle, 1978). We have also excluded LIL-enriched shear zones since the retrograde fluids may originate from an undepleted continental crust source (Sandiford, 1985).

The results of this survey are summarized in Table 7 and Fig. 10, and indicate how a wealth of accessories and minor components such as zircon, apatite, allanite, monazite, davidite, red Ce-sphene, etc. fingerprint the MASAD-type assemblages.

The MASAD from Hoits, Springbok (Ref. 23, Table 8) is characterized by small miarolitic cavities (a few millimetres across) and pegmatoid diopside (ca. 1 x 2 x 4 cm) grown along strikingly narrow (ca. 1 - 1,5 cm) foliation planes scattered within a fine-grained amphibolite. The diopside is also characterized by common ilmenite inclusions.

Our data therefore indicate that the type of processes first studied in Nsanje and Tete have a widespread, regionally extensive distribution within the late Proterozoic to early Palaeozoic mobile belts of Central Gondwana.

Table 7 and Fig. 10 highlight additional features which are interesting both in terms of both petrology and regional geology:

i) Road cuts from the Hoits area (Springbok-Pofadder road, ref. 22) provide compelling evidence that MASAD-type assemblages and LIL-enriched charnockitic veins are most likely the complementary end-products of CO_2, H_2O, LIL-element fluxing through interlayered amphibolite and acidic gneisses.

ii) The Zambezi belt and the frontal zone of the Lurio structure host several occurrences of eclogite, garnet-granulite, and garnet-olivine ultramafics in a region stretching from NW Zambia (G. Martinotti, pers. comm.) to NE Mozambique. We propose to call this E-W orientated region the Zambezi-Lurio Eclogite Province, and because its length is in excess of 1 500 km it may rank among the largest pre-Caledonian eclogite and garnet-granulite domains anywhere in the world.

iii) Major structural discontinuities such as thrust ramps and shear zones became zones of crustal weakness during the break-up of Gondwana. The site of separation of Madagascar from Sri-Lanka coincides with the easterly extension of the Lurio belt front and that of Antarctica from SE Africa with the extensions of the Natal and the Namaqua belt thrusts.

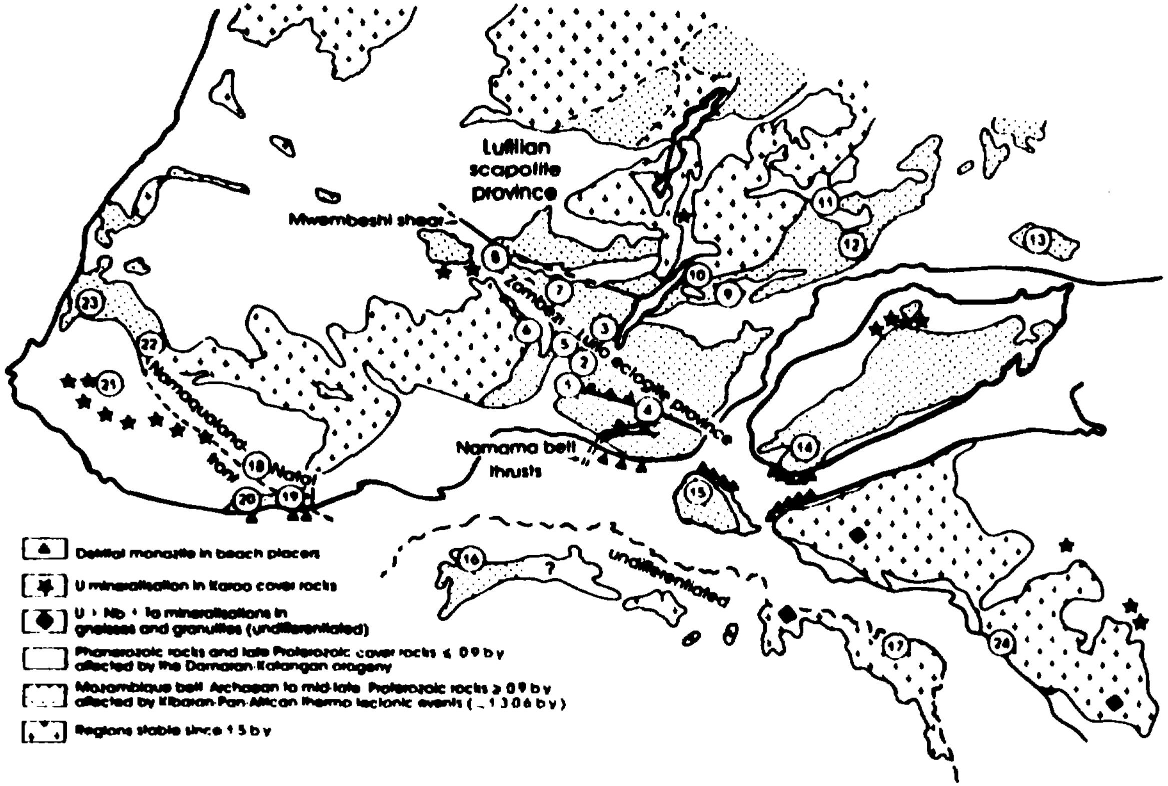

Fig.10 Distribution of inferred MASAD assemblages in central Gondwana. Numbers refer to localities mentioned in Table 7 and in the text (geology modified after Clifford, 1974; Choubert *et al.*; 1976; de Wit *et al.*, 1985; Premoli, 1979).

TABLE 3 Possible occurrences of fertilized deep seated rocks in late Proterozoic/early Palaeozoic belts of Central Gondwana

State/Area	Ref.*	Fertilized rocks	Description of process	Age of event (Ga)	References
MALAWI					
Mlanje	1	Garnet granulite, anorthosite, eclogite, peridotite from the Lurio belt front	Shearing and development of sapphire-bearing MASAD assemblages, at P = 7-10 kbar and T = 750 °C, by a fluid enriched in CO_2, Cl, F, H_2O, K, REE, P, Zr, Cu, Zn, Th, U	1,0 (?)	This paper
Middle Shire	2	Migmatitized orthogneisses grading to two-pyroxene granulites	Swarm of glimmerite bodies scattered over a 500 km^2 belt.	0,84 - 1,15	Bloomfield, 1968; Andreoli, 1981
Lilongwe	3	Lenticular bodies of garnet - olivine ultramafics in amphibolite facies gneisses	REE, Ba, Th, U, Ta, W, Zr enrichment in amphibolitized ultramafic bodies and adjacent mylonitic/cataclastic gneisses	0,7 (?)	Andreoli, 1984a; Andreoli & Hart, unpublished data
MOZAMBIQUE					
Vila Junqueiro	4	Rocks of eclogitic affinity from the Lurio belt front	Scapolite amphibole eclogite, and garnet-pyroxene-Ca scapolite-quartz rocks. Scapolite of this area contains rounded zircon inclusions. Sphene-rutile-apatite replacement veins in augite metagranite	1,0 (?)	Holmes, 1917
Tete	5	Mafic igneous complex of anorthositic affinity (~ 1.6 Ga) metamorphosed to pyroxene-granulite facies	Shearing and syntexis of MASAD-suite assemblages including albitite and carbonate rocks by a CO_2, Cl, P, B and F bearing fluid strongly enriched in Fe, Ti, Cu, Mo, U, REE, Nb and Ta over an area $\geq$ 800 km^2 at P = 6 kbar and T = 630-700 °C	0,59 (?)	Andreoli, 1981, 1984 a; M. Daly, pers. comm.; Cahen *et al*., 1984

* Reference numbers refer to localities shown in Fig. 10.

(cont.)

TABLE 7 Possible occurrences of fertilised deep seated rocks in late Proterozoic/early Palaeozoic belts of Central Gondwana (continued)

State/Area	Ref.*	Fertilised rocks	Description of process	Age of event (Ga)	References
ZIMBABWE					
Buchinga	6	Eclogite and garnet-clinopyroxene granulite in gneissic terrane	Metagabbro and garnet-clinopyroxene granulite sheared and replaced by MASAD assemblages; Retrogression of eclogite U and REE rich carbonate rocks	?	M. de Wit, pers. comm.
ZAMBIA Minga	7	Chindeni belt paragneiss and calc-silicate rocks (hornblende-granulite facies)	Regional soda metasomatism and scapolitization caused by K, Na, Ca, CO_2, P, Cl, S, Fe, Ti and Mg bearing fluids	0,5 (?)	Phillips, 1961
Lusaka	8	Eclogite-metagabbro meta-lherzolite south of the Zambezi belt front	Retrogressive MASAD-type assemblages in eclogite. Porphyroblasts of sodic mizzonite scapolite (An_{eq} 55.3) with 3,2-4,2% SO_3 in marbles	0,5 (?)	Vrana *et al*., 1975; Drysdall & Stillman, 1966
TANZANIA					
Furua 1981; Complex 1982	9	Two-pyroxene granulite facies terrane (P = 7-11 kbar)	Primary S bearing scapolite in granulites. Mantle signature in S isotopes. Lower crust signature in C isotopes	0,6 (?)	Hoefs *et al*., Coolen *et al*.,
Ligenge Complex	10	Noritic gabbro and gabbroic anorthosite bodies within charnockite, granulite and gneiss	Shearing, formation of MASAD suite assemblages and albitization by Fe, Th, REE enriched fluids	?	Wright, 1963

* Reference numbers refer to localities shown in Fig. 10.

(cont.)

TABLE 7 Possible occurrences of fertilised deep seated rocks in late Proterozoic/early Palaeozoic belts of Central Gondwana (continued)

State/Area	Ref.*	Fertilised rocks	Description of process	Age of event (Ga)	References
Lashaine Volcano	11	Xenoliths of garnet granulite and garnet anorthosite	S-rich scapolite relaces plagioclase with kyanite inclusions. Reequilibration under granulite facies conditions	0,6	Jones *et al.*, 1982
Pare Mt.	12	Lower-crust metamorphic complex: anorthosite, granulite and charnockite	Scapolite, kyanite bearing anorthosite associated with light REE-enriched amphibolite	?	Prochaska & Pohl, 1983
SOMALILAND					
Alio Ghelle	13	High-grade paragneisses and granitoids of the Mozambique belt	Albitization by S- and B bearing fluids enriched in Th, U, Fe, Ti, Zr, REE, Cu, Pb and Zn is scattered over an area of ~ 5 000 km^2.	?	Cameron, 1970
MADAGASCAR					
Betroka	14	Granulites of the (≥ 2,2 Ga) Tranomaro Group; Anosyan charnockites (0,74 Ga)	Monazite-apatite lenses and veins (max 50 m x 5 m) within Anosyan granites. Regional scale formation of sapphire-bearing MASAD type rocks and glimmerite by Fe, REE, U, Th, Zr, Cu, Zn, W, Sn, Mo, Ba, etc.-bearing fluids within Tranomaro metasediments. Fluids are F-B-S-CO_2 rich ($aCO_2 >> aH_2O$) at P = 5 kbar, T = 700-750 °C.	0,55	Besairie, 1966; Cahen *et al.*, 1983; Rakotondratsima & Cuney, 1984

* Reference numbers refer to localities shown in Fig. 10.

(cont.)

TABLE 7 Possible occurrences of fertilized deep seated rocks in late Proterozoic/early Palaeozoic belts of Central Gondwana (continued)

State/Area	Ref.*	Fertilized rocks	Description of process	Age of event (Ga)	References
SRI-LANKA					
Ratnapura	15	"Highland Group" pyroxene granulites and charnockite (> 2,0 Ga).	Desilicification, and formation of S-scapolite, apatite, sapphire, taffeite, etc. gemstones is related to Be, Zr, U, Th, light REE, B, P, etc. enriched pegmatitic fluids of charnockitic parentage. Local development of MASAD-like scapolite-diopside intergrowths and wollastonite-scapolite-clinopyroxene parageneses	1,2 (?)	Rupasinghe et al., 1984; Zwaan, 1982
ANTARCTICA					
Queen Maude	16	Gneiss, migmatite, charnockite	Apatite, zircon-rich hornblende-biotite "granulitic" metagabbro	1,1 (?)	M. Andreoli, unpubl. data; J. Evans person. commun.; Wolmarans & Kent, 1982
Enderby Land	17	High grade gneiss, granulite	Monazite rich charnockite comparable to that in the Anosyan granite-charnockite terrane of SE Madagascar	?	Premoli, 1979
LESOTHO					
Matsoku	18	Xenoliths of garnet-clinopyroxene granulite in kimberlite	Possible K, Nb, Zr, Hf, Ta, light REE metasomatism in garnet granulite and anorthosite	1,4	Rogers & Hawkesworth, 1982; Griffin et al., 1979

* Reference numbers refer to localities shown in Fig. 10.

(cont.)

TABLE 7 Possible occurrences of fertilized deep seated rocks in late Proterozoic/early Palaeozoic belts of Central Gondwana (continued)

<u>State/Area</u>	Ref.*	Fertilized rocks	Description of processes	Age of event (Ga)	References
<u>SOUTH AFRICA</u>					
Empangeni (N Natal)	19	Thrusted units of para- and orthogneisses near the Namaqualand-Natal belt front	Scapolite- and nepheline(quartz)-bearing "syenitic" gneisses enriched in U, REE, Nb, Zr (Bull's Run Estate). Fe, Zr, REE, U, Th and Nb anomaly in sheared gneiss south of tectonic contact with Ngoye metagranite (Ngoye Forest Reserve)	1,12 1,07	Charlesworth 1981; A. Versfelt, person. commun.; Andreoli *et al.*, unpublished data; Gain, 1983
S Natal	20	Upper amphibolite to pyroxene granulite facies transitional terrane	Introduction of U, Th, Pb in gneisses from a source with "bulk earth" abundances; hypermelanic biotite- hornblende rocks enriched in U, Th and Zr (Umzinto). Pervasive charnockitization of garnet-biotite gneisses hosting biotite, diopside, hornblende(MASAD?)-rich interbands (Port Shepstone, Umzimkulu and South Coast quarries)	1,07	Hart & Barton, 1985; Andreoli & Hart, unpublished data; P. Bekker, pers. comm.
Fraserburg	21	Megacrystic rapakivi meta-granite in biotite-garnet gneiss (SOEKOR borehole)	Diffuse charnockitization of (meta-) granite presenting occasional enrichment in radioactive minerals (e.g. metamictic allanite)	?	Andreoli, unpublished data

* Reference numbers refer to localities shown in Fig. 10.

(cont.)

TABLE 7 Possible occurrences of fertilized deep seated rocks in late Proterozoic/early Palaeozoic belts of Central Gondwana (continued)

State/Area	Ref.*	Fertilized rocks	Description of processes	Age of event (Ga)	References
Upington Prieska	22	Upper amphibolite to granulite facies terranes of the Namaqualand belt front	Shearing, retrogression, and local scapolitization of hypersthene adamellite (Kalmoes); NASAD dykes in Rb enriched anorthositic rocks (Copperton area); vein-type allanite mineralizations in quartzo-feldspathic rocks (Vrede).	?	Geringer et al., 1985; Hugo, 1961., Von Backström, 1964; J.G. Geringer, person. commun.; J.V. Bever-Donker, pers. comm.
Namaqualand	23	Upper amphibolite to granulite facies terrane (1,2 - 1,3 Ga)	Transgressive, locally diffuse charnockitization of leucocratic gneisses by CO_2 (H_2O), S, P, Fe, Cu, Zr, REE, Th, U and Ta bearing fluids (e.g. Noits area, Springbok-Pofadder road; Knersvlakte area, Vanrhynsdorp district). K, Cu, Fe, P, light REE, Th, U, Ta and H_2O enriched megabreccia/shear zones (Steinkopf area), and charnockitic diorite bodies (e.g.: Bulletrap and Noits areas, Springbok). Cu, Fe, Ti, REE, Ta, etc. enriched NASAD pegmatoids with abundant miarolitic cavities (Carolusberg area, Springbok Pofadder road). U-enriched character of regional granites and gneisses of the whole Namaqualand province tentatively related to a mantle anomaly.	1,05	Andreoli, 1984b; Andreoli & Hart in prep.; Mc Iver et al., 1984; Pike, 1958; 1959; Robb and Schoch, 1985; J.A. Conradie, pers. comm.

* Reference numbers refer to localities shown in Fig. 10.

Research is now in progress to identify MASAD-type and correlative assemblages elsewhere in the Gondwana supercontinent and in other Precambrian shield terranes of the northern hemisphere. In eastern Gondwana MASAD features are seen in the F, P, Th, U and REE enriched carbonate-clinopyroxene-phlogopite assemblages from the high-grade Strangways Range of the Arunta Block, Central Australia (Wilson, 1985).

In the Visakhapatnam area of India, descriptions of F, Th, REE, Zr and Ti bearing apatite and magnetite-rich veins from the Eastern Ghats charnockites (Rao, 1976; Rao et al., 1980; loc. 23, Fig. 10) also suggest MASAD affiliation. In western Gondwana MASAD affinities have been suggested for apatite-rich granulitic rocks from the Gujana shield of Surinam (F. Sawkins, pers. comm.).

8 DISCUSSION

Origin of the fluids. Three main hypotheses were formulated by Andreoli (1984a) to explain the origin of the scapolitizing fluids in Nsanje and Tete, i.e. evaporitic, magmatic and mantle-related metasomatic. The arguments that were presented in that study against a sedimentary source for chlorine remain valid and even more so now because of the exceptionally broad distribution of the deep-seated MASAD assemblages. Furthermore, the scapolites of the metasomatic Gondwana terranes have a substantial CO_2 (SO_3) component, which is more difficult to account for with a simple evaporiti source model (Oliver & Wall, 1985; J.R. Goldsmith, pers. comm.).

The problem of the Lufilian scapolite province (Fig. 10) is at present unsolved since in different parts of the same belt both evaporitic (Drysdall & Stillman, 1966; M. Hugues, pers. comm.) and hydrothermal models (Andreoli, 1984a; Darnley, 1960; Cahen, 1954) may apply.

The data presented disprove an earlier suggestion (Andreoli, 1984a) that metasomatism in the Nsanje-Tete terrane had been caused by magmatic fluids of anorthosite-suite parentage. The isotopic and field data listed in Table 7 indicate that MASAD-forming processes took place in many cases long after the emplacement of the associated anorthosite, charnockite, and K-rich granitoids.

Evidence in Namaqualand is ambiguous however. In this region MASAD-formation, Th-U-REE-Cu mineralizations and emplacement of anorthosite-diorite (Koperberg suite) rocks with a kimberlitic REE signature occurred contemporaneously: this problem is now receiving careful scrutiny (Andreoli & Hart, in prep.).

Despite these alternate possibilities the overwhelming evidence suggests that polyepisodic migrations of metal-enriched mantle fluids most likely caused the widespread geochemical and mineralogical anomalies in the deep-seated terranes of Gondwana.

Structural Setting. If our model is correct in predicting that the Gondwana metasomatic belt was caused by mantle metasomatic fluids, it becomes important to establish the geodynamic conditions that allowed these fluids to penetrate the crust. The evidence available is limited, yet it points to a tensional environment, precursor to rifting.

Near Nsanje the supracrustal sequence south of the Lurio belt comprises numerous long bands of nepheline gneisses with the geochemical signature of nephelinitic syenites (Bloomfield, 1968; Carter & Haslam, 1973). These igneous rocks are typical of rift environments (Le Bas, 1977). The age of such a tensional and anorogenic event (Fig. 11) in Nsanje is not known. If, however, the Nsanje supracrustal suite is coeval with the monometamorphic Molocuè-Metil supracrustal series further to the east (Fig. 1; Sacchi _et al._, 1984; Jourde & Vialette, 1980), the proposed rifting occurred between 1,1 and 1,0 Ga ago.

We find evidence of a similar anorogenic tectonic setting for the

MASAD suite in Namaqualand. These rocks, especially the LIL-enriched charnockites and Koperberg-suite diorites constitute in most cases subvertical veins and bodies cross-cutting at high angle the older subhorizontal country gneisses. From structural relationships Halbïch (1978) concluded that the Koperberg suite had been intruded deep into the crust under anorogenic conditions in a tensional stress field (pure shear). Compatible views are shared by McIver et al. (1984) who noted the explosive character and alkaline affinities of the ca. 1,05 Ga old Koperberg suite.

The metasomatized rocks of Tete, especially the U- and REE-mineralized calcite ± scapolite mylonites, the albitites and the diopsidite ± phlogopite-apatite-davidite assemblages (Davidson & Bennett, 1950; Andreoli, 1984a) also suggest crypto-carbonatitic affinities under rifting conditions.

Relationships to mantle metasomatism. Our model is supported by recent data on fluids and coexisting mineral parageneses near the top of the mantle.

The MASAD assemblages present strong mineralogical, petrographic and geochemical affinities to the xenoliths of metasomatized mantle from SW Victoria, Australia (O'Reilly & Griffin, 1985). The inferred composition of the metasomatizing fluids in these nodules appears to approach a CO_2-H_2O mixture with significant Cl and S. Such carbonic fluids would yield sulphide-bearing MASAD assemblages and possibly charnockitic granulites by infiltrating melanocratic and leucocratic crustal rocks respectively.

The MASAD assemblages and their closely related (igneous ?) pegmatoids are also mineralogically and geochemically comparable to the metasomatic and to the MARID (mica, amphibole, rutile, ilmenite, diopside ± zircon) suites of mantle nodules described by Haggerty et al. (1984) from Southern Africa kimberlites. Our findings appear to mirror the conclusions of Kramers et al. (1983) that a single type of fluids or liquids of kimberlite affinity could cause both metasomatism (compare the scapolitized granulites) and the reputedly igneous MARID material (compare the hornblende-biotite-diopside pegmatoids). In addition, the incipient breakdown of hydrous MASAD phases in Nsanje (Andreoli, 1981) corresponds to the contention by Kramers *et al.* (1983) that cryptic mantle metasomatism may remain even after hydrous minerals generated by patent metasomatism have been destroyed in crystallization/dehydration events.

Finally, we also note that geochemical evidence for pre-Karoo mantle metasomatism was detected in basalts erupted ca. 30 km NW of the area investigated (loc. 4, Fig. 2) by McDonald *et al.* (1983).

We tentatively conclude that the MASAD and related lithologies of the metasomatized Gondwana terranes have their origin in deep-seated fluids released from the upper mantle (Fig. 11) mainly between about 1,0 and 0,6 Ga ago under fault/shear-assisted protorifting and crustal thinning.

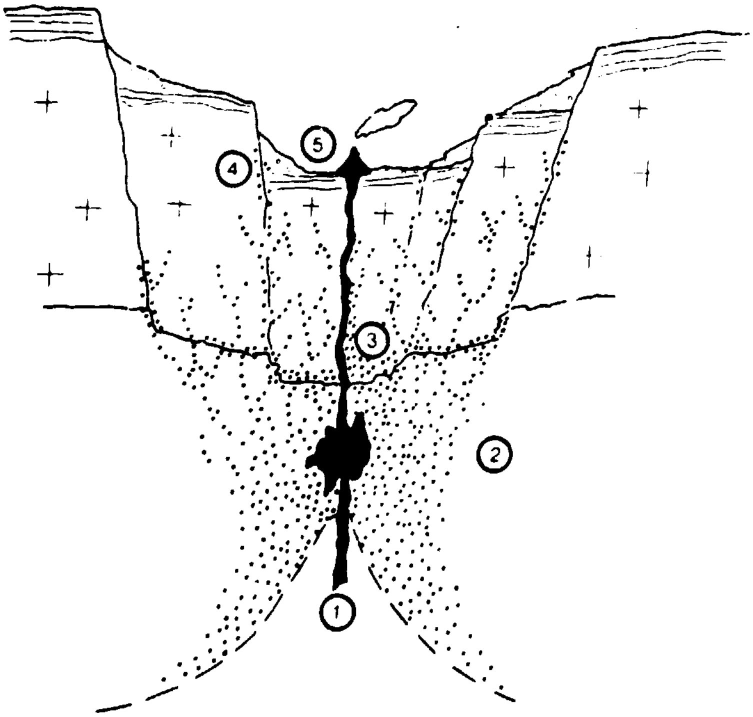

Fig. 11. Hypothetic model for the Nsanje MASAD assemblages based on a Proterozoic rifting environment: 1, asthenosphere; 2, metasomatized upper mantle ± MARID assemblages; 3, LIL-fertilized, MASAD-bearing crust; 4, rift sedimentary infill where mantle and surficial fluids may mix (Plimer, 1985); 5, nephelinitic volcano.

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