Occurrence of zoned uvarovite–grossular garnet in a rodingite from the Vumba Schist Belt, Botswana, Africa: implications for the origin of rodingites

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Abstract

Based on petrographic, mineralogical and geochemical data, two groups of rodingites have been documented from the polymetamorphic Vumba Schist Belt of Botswana. Group I rodingites contain relict chromite grains with zoned uvarovite–grossular + clinopyroxene + epidote/zoisite $\pm$ quartz, whereas group II rodingites contain no chromite and uvarovite. Although the presence of chromite with $Cr/(Cr + Al + Fe^{3+})$ ratio > 90, similar to chromites found in komatiites, suggests a possible komatiitic origin of group I rodingites, the major and trace element chemical data of most analysed basic rocks from this belt indicate that the protoliths of both groups of rodingites are related to basalt/gabbro of komatiitic affinity. The rodingites formed during the M3 phase of metamorphism.

KEYWORDS: rodingite, chromite, uvarovite, grossular, Vumba, Botswana.

Introduction

RODINGITES were first described by Bell et al. (1911) as a coarse grained gabbro-like rock associated with dunite and containing diallage, grossular, prehnite and/or serpentine. These are calcium-rich, silica undersaturated rocks that form by metasomatism of mafic and ultramafic rocks during serpentinization (Thayer, 1966; Coleman, 1977). They are reported among others, from present day equatorial Mid-Atlantic ocean floors (Honnorez and Kirst, 1975), Archaean serpentinites (Anhaeusser, 1979), as eclogite-metarodingite-garnet lherzolite suite in Cima Lunga-Adula nappe, Central Alps (Evans et al., 1981; Trommsdorff et al., 1975), in serpentinized ultramafic rocks of the Abitibi greenstone belt, Ontario (Schandl et al., 1989) and from the Tauern Window, Austria (Dietrich et al., 1986).

Calc-silicate rocks with chromite and uvarovite are rare and occur chiefly in metamorphosed limestones and skarns as has been reported from the Hemlo area, Ontario (Yuanming and Fleet, 1989), and the Karelia deposit in Finland (von Knorring, 1951). Uvarovite is one of the rarer forms of garnet and its wide stability is suggested to be exemplified by the range of environments in which uvarovite as a phase and component (in grossular–andradite) may be found (Kalamarides and Bjerg, 1988). Uvarovite-rich garnet occurs in mafic and ultramafic rocks that have undergone metamorphism or serpentinization at low temperature and pressure (e.g. in the Bushveld Complex: Willemse and Bensch, 1964). Cr-rich garnet in association with Cr-rich clinopyroxenes, amphiboles and chlorites has been reported from metacarbonates of the Austrian Alps (Mogessie et al., 1988).
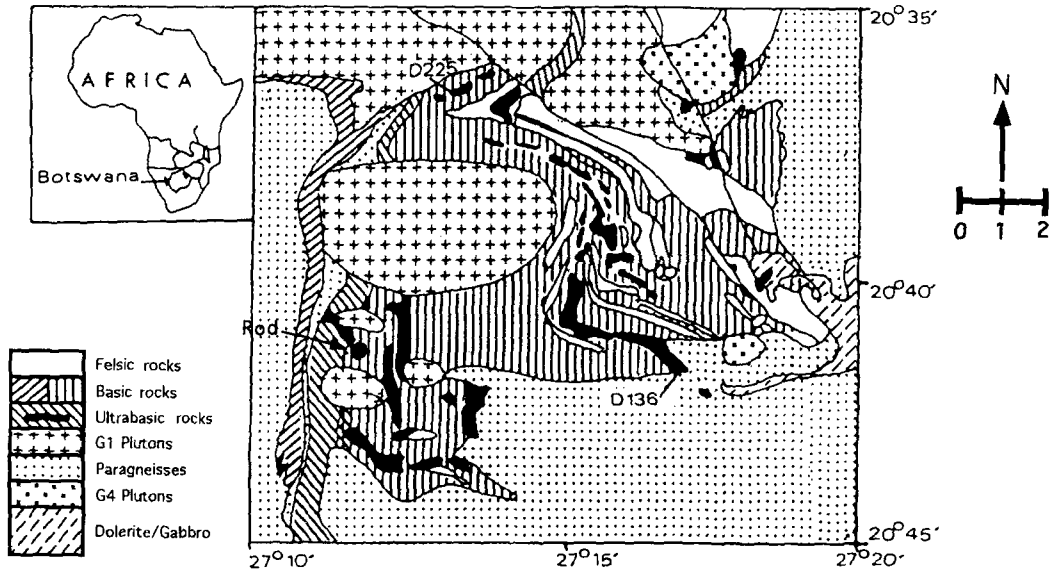
FIG. 1. A simplified geologic map of the Vumba schist belt, Botswana (Litherland, 1975), showing the locations of högbomite-bearing samples D-136 and D-225 (Rammlmair *et al.*, 1988) and the rodingites (Rod). G1 plutons are deformed tonalites and monzonites; G4 plutons are, generally, adamellitic granites.

Rodingites containing zoned uvarovite-grossular-andradite garnet, chromite, diopside, epidote/zoisite ± plagioclase and titanite have been documented in the polymetamorphic Vumba Schist Belt of Botswana. In this study we present mineralogical, textural and chemical data of the phases making up the rodingite, bulk chemistries of the rodingite and possible protoliths, and also discuss the significance of the presence of chromite and uvarovite in deciphering the nature of the protolith.

Geologic setting

The Vumba schist belt (VSB) of Botswana can be described as an Archaean greenstone–granite association which has a complex metamorphic and tectonic history (Fig. 1). It consists of a sequence of rocks of ultrabasic, basic, felsic and sedimentary origin which are highly deformed and intruded by granitic rocks. This belt is considered to be polymetamorphic by several workers (Litherland, 1975; Rammlmair *et al.*, 1988; Mosigi and Rammlmair, 1991). The majority of the ultrabasic rocks outcropping in the Vumba Schist belt occur as prominent morphological features cutting through the entire belt. These rocks were interpreted as syntectonic sills or dikes

by Litherland (1975). Lüdtke *et al.* (1989) considered them to be the feeders of komatiitic flows.

In the VSB the characteristic spinifex textures of komatiites cannot be observed due to the intensive polymetamorphism in the region. However, the occurrence of weathering horizons, sediments or felsic volcanics document a break in the volcanic activity, suggesting that the ultrabasics were actually flows similar to the observations made in other regions (Bavinton and Taylor, 1980; Groves *et al.*, 1984)

Litherland (1975) suggested that the granitic intrusion and tectonic events of Vumba are accompanied by regional or localized metamorphism. In this belt five different metamorphic phases (M1–M5) are recorded. The M1 event probably occurred in the VSB within the stability field of kyanite, but most probably did not exceed the greenschist facies. Kyanite relics in prismatic sillimanite are considered to represent M1. The M2 event shows its most intensive evolution in the western part where the orthopyroxene isograd was reached. Characteristic mineral parageneses for metabasic rocks are clinopyroxene + orthopyroxene + plagioclase + rutile ± garnet ± quartz. For the metapelites, sillimanite + garnet + corundum + rutile is a characteristic paragen-

TABLE 1. Mineral assemblages of the rodingites and possible protoliths (see analyses Table 3)

Sample No.		Mineral assemblage
		Rodingites
653	4w260	Cpx + Gt + Ep/Zois + Tit + Carb + Hb + Pl + Qz
678	4w1965	Cpx + Gt + Ep/Zois + Tit + Pl + Qz
681	4w2290	Cpx + Gt + Ep/Zois + Tit + Pl + Qz +Hb + Pl + Prehnite
684	4w2590	Cpx + Gt + Ep + Tit + Qz
		Possible Source rocks (metamorphosed gabbros of komatiitic affinity) – Amphibolites
691	4w810	Hb + Pl + Ep/Zois + Tit + Carb + Sericite
696	5w1072	Hb + Pl + Chl + Tit
697	5w1225	Hb + Pl + Ep + Tit + Qz ± Opaque
700	5w1375	Cpx (relict) + Hb + Chl + Opaque
701	5w1475	Hb + Pl + Ep + Tit + Opaques
704	5w2025	Hb + Pl + Ep + Bi + Tit + Ap
		Ultramafic rocks
699	5w 1360	Hb + Phl + Chl + Serp + Opaque
702	5w 1575	Hb + PhI + Serp + Carb + Opaque
792	5w0	Serp + Mt + Carb + Phl

Mineral symbols used

Cpx	Clinopyroxene	Gt	Garnet	Ep	Epidote
Zois	Zoisite	Tit	Titanite	Carb	Carbonate
Hb	Hornblende	Pl	Plagioclase	Qz	Quartz
Ilm	Ilmenite	Chl	Chlorite	Phl	Phlogopite
Ap	Apatite	Serp	Serpentine	Mt	Magnetite
Bi	Biotite				

esis. The M3 event is most intensive in the central and southern part of the VSB. The P-T conditions of the M3 event were such that staurolite, garnet, plagioclase, muscovite, biotite, sillimanite (fibrolite), kyanite and andalusite were stable phases in the pelitic rocks, whereas amphibole + plagioclase + ilmenite ± titanite ± quartz were stable in the metabasic rocks. M4 is considered as a second phase of M3. The M5 event is a low grade greenschist overprint characterized by actinolite + albite + sericite + zoisite/clinozoisite + chlorite + titanite + stilpnomelane. The M5 grade increases towards the southeast and is very low in the extreme southwest region of the belt where the rodingites are found.

Rodingites have been observed southwest of the main ultrabasic hill sites. The distance from the G1 plutons (Fig.1) is about 2 km. These rocks have been sampled from isolated outcrops and no direct contacts with the basic or ultrabasic rocks have been observed. They belong to a tectonically thinned sequence of clastic sediments, chemical sediments (carbonates or carbonate facies and oxide facies banded iron formation), felsic and basic volcanics, and ultramafic rocks which chemically show affinities to komatiitic rock sequences. Coarse-grained basic (texturally gabbroic) and felsic rocks (flows and laminated tuffs) occur in the immediate vicinity. Strike and schistosities follow the regional trend. The area is highly isoclinally folded and thrusting is common. Frequent stratigraphic repetitions, which are known from several localities in the belt, have to be expected since rodingites can be traced several times along a section of 1 to 2 km perpendicular to strike.

The area where the samples occur was the high grade M2 metamorphic centre and the M3 overprint was very intensive . A plagioclase + clinopyroxene ± orthopyroxene? + quartz (M2) assemblage was almost completely altered to a M3 rodingite assemblage (garnet + clinopyroxene

TABLE 2. Representative electron microprobe analyses of uvarovite (Gr(c)), chromite (Chr) and the associated minerals (Cpx = clinopyroxene, Tit = titanite, epidote = Ep, zois = zoisite, An = anorthite, Ab = albite) from the rodingites of the Vumba schist belt (VSB), Botswana. GA(r) and GA(c) = rim and core compositions of garnet from the metabasites of the VSB; GR(r) and GR(c) = rim and core compositions of garnet from the rodingites of VSB respectively

	GA(r)	GA(c)	GR(r)	GR(c)	Chr	Cpx	Tit	Ep	Zois	An	Ab
SiO_2	38.11	37.24	38.29	35.67	0.13	52.31	31.47	39.59	40.87	44.59	65.86
TiO_2	0.00	0.08	0.51	0.16	0.07	0.07	37.02	0.07	0.00	0.00	0.00
Al_2O_3	21.01	20.68	13.03	3.61	2.75	1.22	2.43	26.48	32.95	32.34	22.41
Cr_2O_3	0.00	0.03	0.31	23.20	61.28	0.00	0.03	0.00	0.00	0.00	00)3
Fe_2O_3c	0.00	0.30	12.10	3.71	2.91						
FeO	28.83	26.78	3.61	3.71	30.37	16.48	0.82	8.45	0.06	0.08	0.03
MnO	4.76	6.14	0.30	0.21	0.55	0.17	0.02	0.00	0.00	0.00	0.04
MgO	3.70	3.04	0.47	0.15	0.16	7.08	0.06	0.10	0.05	0.86	0.00
CaO	3.69	4.83	32.08	29.93	0.72	22.29	27.65	23.86	24.13	22.17	1.38
Na_2O	0.00	0.00	0.04	0.03	0.09	0.32	0.00	0.00	0.00	0.16	10.45
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.45	0.08
Total	100.10	99.12	100.74	100.38	99.03	99.94	99.51	98.55	98.06	100.65	100.28
Oxygens	24	24	24	24	32	6	20	13	13	8	8
Si	6.06	6.00	6.01	5.89	0.04	2.02	4.05	3.08	3.09	2.07	2.89
Ti	0.00	0.01	0.06	0.02	0.02	0.00	3.63	0.00	0.00	0.00	0.00
Al	3.94	3.93	2.41	0.70	0.96	0.06	0.37	2.43	2.94	1.77	1.15
Cr	0.00	0.00	0.04	3.01	14.34	0.00	0.00	0.00	0.00	0.00	0.00
Fe^{3+}	0.00	0.04	1.43	0.46	0.65	0.00	0.09	0.49	0.00	0.01	0.00
Fe^{2+}	3.83	3.61	0.47	0.51	7.51	0.53	0.00	0.00	0.00	0.00	0.00
Mn	0.64	0.84	0.04	0.03	0.14	0.01	0.00	0.00	0.00	0.00	0.00
Mg	0.88	0.73	0.11	0.05	0.07	0.41	0.01	0.01	0.01	0.06	0.00
Ca	0.63	0.83	5.40	5.29	0.23	0.92	3.86	1.99	1.96	1.10	0.07
Na	0.00	0.00	0.01	0.01	0.05	0.02	0.00	0.00	0.00	0.00	0.89
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01
Total	15.98	15.99	15.98	15.97	24.01	3.97	12.01	8.00	8.00	5.03	5.01
Ps-%	-	-	-	-	-	-	-	16.83	0.12	-	-
Ab	-	-	-	-	-	-	-	-	-	1.26	92.76
An	-	-	-	-	-	-	-	-	-	96.41	6.77
Or	-	-	-	-	-	-	-	-	-	2.33	0.47
Alm	63.72	59.86	7.88	11.71	-	-	-	-	-	-	-
And	1.61	1.58	35.62	6.49	-	-	-	-	-	-	-
Py	14.82	12.20	1.83	0.60	-	-	-	-	-	-	-
Sp	10.84	14.00	0.66	0.48	-	-	-	-	-	-	-
Gr	9.01	12.26	53.06	5.93	-	-	-	-	-	-	-
Uv	0.00	0.10	0.96	74.79	-	-	-	-	-	-	-

Fe_2O_3c = calculated

(relict M2) + hornblende + epidote/zoisite + albite); syn- to postkinematic, partially replaced by a zoisite-sphene-actinolite-prehnite-white mica M4 assemblage. The M5 overprint seems to be negligible in this western part of the VSB.

Petrography

The VSB rodingites can be divided into two groups based on their mineral assemblages. Group I rodingites (678 and 681) are characterized by the presence of clinopyroxene, epidote,
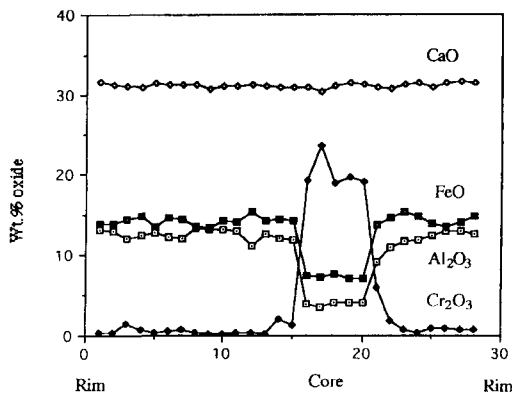
FIG. 2. Chemical profile across the zoned uvarovite–grossular garnet of sample 681 (BSE and Cr-distribution photo, see Fig. 3).

grossular-uvarovite, chromite, plagioclase, quartz; whereas the second group (653 and 684) contains mainly grossular, epidote/zoisite, diopside and quartz but no chromite or uvarovite. The chromite grains are found always enclosed in uvarovite core within a big euhedral to anhedral grossular. The presence of uvarovite is accompanied by the availability of chromite that can still be observed as relict or has completely reacted to form patches of deep green uvarovite in the grossular grains. In both groups of rodingites the spaces between the grossular garnet grains are filled by light greenish-coloured assemblages of epidote/zoisite + diopside and some quartz. Titanite is the most important accessory. Generally the petrographic observations indicate the following crystallization sequence: zoisite → prehnite → grossular → diopside. The mineral parageneses of the four rodingite samples with high Ca-content and the possible source rocks are listed in Table 1.

Schandl *et al.* (1989) define three types of rodingites in the Abitibi belt representing a different extent, or regime, of rodingitization. (1) Epidote-rich rodingites represent the initial stage of rodingitization, in which either clinozoisite or zoisite may be the dominant modal phase; (2) Grossular-rich rodingites, which formed by the alteration of epidote-group minerals to hydro-grossular and prehnite, represent a second stage of rodingitization; (3) Diopside-rich rodingites, in which the epidote-group minerals, hydrogrossular, prehnite and relict pyroxene recrystallize to fine-grained diopside.

In the VSB one recognizes the three different stages of rodingitization in the samples under

discussion. The process of rodingitization that took place at fracture zones may have been related to the different stages of polyphase metamorphism and metasomatism in this part of the VSB.

X-ray data

In most rodingites the garnet coexisting with epidote/zoisite is considered to be hydrogrossular. In order to characterize the nature of the garnet in the VSB rodingites, separated garnet grains have been studied with X-ray diffraction. The following intense *d* spacings correspond with grossular: 2.98, 2.66, 2.54, 2.43, 2.34, 2.17, 1.93, 1.65, 1.59 and 1.49 Å. The calculated cubic cell dimension a = 11.914(1) Å. Infra-red spectroscopic studies on these garnet grains also indicate that there is no water molecule in the structure.

Mineral chemistry

Analyses of zoned uvarovite–grossular garnet, chromite and associated phases were carried out with an ARL-SEMQ electron microprobe operated at 15 kV accelerating voltage, 0.03 μA sample current and 20 seconds counting time, at the Institute of Mineralogy and Petrography, University of Innsbruck. Duplicate analyses have been made with a similar type of electron microprobe at the Institute of Mineralogy and Petrology, Mining University of Leoben, and at the Institute of Mineralogy-Crystallography and Petrology, University of Graz. In all cases, the standards used were natural minerals: spinel, chromite, tephroite, kaersutite, tremolite, jadeite, garnet and adular. The matrix effects were corrected according to Bence and Albee (1968). The structural formulae of the minerals were calculated with HYPER-FORM (Bjerg *et al.*, 1992).

Garnet. Representative electron microprobe analyses of zoned and unzoned garnets are presented in Table 2. The end member molecules were calculated according to Rickwood (1968). The unzoned garnets in all four samples are grossular-andradite with average formula: ($Alm_5And_{39}Py_1Spes_1Gross_{52}Uv_2$) and contain Cr_2O_3 ranging in value between 0.13 to 0.88 wt.%; FeO_{tot} 13.66 to 14.50 wt.% and Al_2O_3 from 12.29 to 14.11 wt.%. This is comparable to the rim of the zoned garnet in samples 678 and 681 which contain a core of Cr-garnet. The core composition (ave. $Alm_{12}And_6Py_1Spes_1Gross_5Uv_{75}$) has Cr_2O_3 ranging from 23.55 to 19.27 wt.% which drastically decreases to a value below 1wt.% Cr_2O_3 at the core-rim boundary. Fe_2O_3 increases from 3.71 (core) to 12.10 wt.% (rim); and the
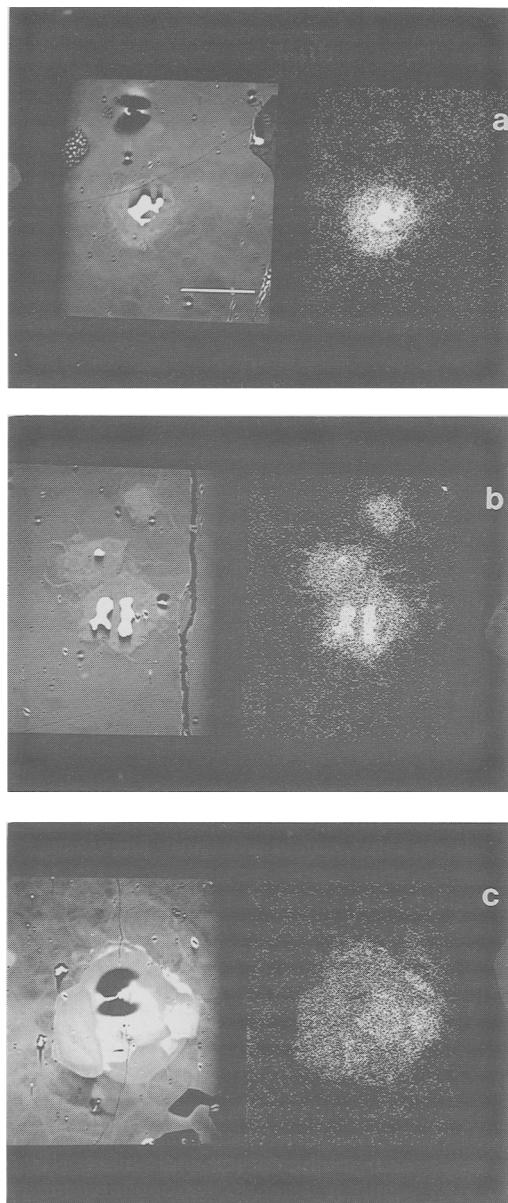
FIG. 3. Back Scattered Electron picture and Electron-beam scanning image of Cr distribution in relict chromite (core)–uvarovite–grossular (a and b). In (c) the chromite grain is completely reacted to uvarovite and the Cr-distribution photo shows only a uvarovite core and grossular rim. Scale bar = 20 µm.

Al_2O_3 content ranges from 3.61 in core to 13.03 wt.% at the rim. The CaO value is in the range of 30–32 wt.%. The compositional variation from core to rim is thus a substitution of Cr by Al and Fe^{3+} (Fig. 2). The Cr-rich garnet (Uv_{75}) occurs in garnet where there is relict chromite enclosed in the core. In sample 681 the relict chromite is still present. In sample 678, there are randomly-scattered small grains of chromite and irregularly distributed greenish Cr-rich garnet within a mass of light brown grossular garnet.

The back scattered electron (BSE) and the Cr-distribution photos show an interesting reaction texture and also indicate the mobility of Cr along trails within the garnet grains (Fig. 3). The chemistry of the unzoned garnet in the rodingites ($Alm_5And_{39}Py_1Spes_1Gross_{52}Uv_2$) is quite different compared to the garnets found in the garnet-bearing metabasites of the region (see Table 2). The formation of uvarovite is thus related not only to the metamorphic-metasomatic process but also to the chemistry and mineralogy of the original rock.

The decrease in the amount of Cr from core to rim is not a continuous process but discontinuous, as seen in the electron microprobe profile (Fig 2). The formation of the Cr-rich core is thus ascribed to a reaction between the relict chromite grain and the grossular garnet. The following possible reaction is postulated:

grossular–andradite + chromite = uvarovite-rich garnet
+ grossular–andradite
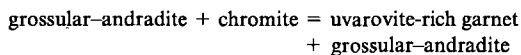
This reaction may have taken place during the rodingitization process and the final zoning of the garnet may be a result of the M3 metamorphism. It is important to note that the Cr was mobile, as can be seen in the backscattered electron and the Cr-distribution pictures. The mobility of Cr may have been caused by the fluid involved in the rodingitization process.

Clinopyroxene. Representative electron microprobe analyses of calcic pyroxenes are presented in Table 2. Based on the nomenclature of Morimoto (1988), the pyroxenes are diopsidic. Compared to the analysed clinopyroxenes of the metabasite country rocks of the VSB they do not show any characteristic difference in chemistry. Since the clinopyroxene is associated with the uvarovite-chromite, grossular–andradite, epidote–zoisite mineral assemblages one expects enrichment of the pyroxene in Cr. However, analysis of several clinopyroxene grains shows that the Cr-content is almost zero.

Epidote/zoisite. Epidote and zoisite are abundant in the rodingites investigated. They are products of anorthite-rich plagioclase. Representative electron microprobe analyses are presented in Table 2. The chemistry varies from an

TABLE 3. Bulk-rock and trace element chemistry of rodingites and possible protoliths from the Vumba schist belt, Botswana

	Rodingites					Amphibolites (gabbro of komatiitic affinity)					Ultramafic rocks		
Sample	653	678	681	684	691	696	697	700	701	704	699	702	792
SiO_2	39.87	50.14	43.34	47.64	54.13	48.16	55.22	47.63	50.63	50.20	43.96	37.19	39.58
TiO_2	0.20	0.57	0.98	0.35	0.54	0.34	0.61	0.65	0.80	0.64	0.21	0.14	0.13
Al_2O_3	20.51	12.09	11.92	13.79	14.82	7.56	8.92	5.ft3	9.17	8.90	3.83	2.76	2.74
Fe_2O_3	6.03	9.19	13.14	6.44	8.56	9.89	10.61	8.93	8.85	11.52	10.19	9.58	8.91
MnO	0.12	0.13	0.19	0.24	0.14	0.24	0.19	0.15	0.19	0.23	0.16	0.14	0.12
MgO	0.05	2.16	2.40	2.18	6.20	19.25	10.21	21.47	12.26	12.87	27.54	34.33	35.70
CaO	26.65	23.13	25.55	27.64	9.15	9.82	10.34	11.13	14.72	11.59	4.86	1.54	0.03
Na_2O	0.66	0.56	0.68	0.20	3.52	0.69	1.72	0.45	0.83	1.68	0.43	0.14	0.20
K_2O	0.02	0.07	0.13	0.01	0.64	0.08	0.40	0.15	0.30	0.40	0.07	0.01	0.01
P_2O_5	0.10	0.24	0.32	0.16	0.14	0.01	0.08	0.34	0.35	0.06	0.03	0.01	0.01
LOI	4.66	0.76	0.74	0.85	1.50	3.03	1.04	2.99	1.14	0.99	7.28	12.50	11.28
Total	98.87	99.04	99.39	99.50	99.34	99.07	99.34	98.92	99.24	99.08	98.56	98.34	98.71
						Trace elements in ppm							
As	14.00	22.00	1.00	13.00	25.00	23.00	8.00	7.00	1.00	11.00	1.00	1.00	1.00
Ba	7.00	44.00	42.00	1.00	113.00	2.00	21.00	44.00	46.00	165.00	1.00	1.00	446.00
Ce	1.00	81.00	11.00	1.00	24.00	3.00	115.00	46.00	12.00	1.00	72.00	61.00	64.00
Cr	37.00	295.00	442.00	95.00	275.00	1758.00	245.00	2122.00	1014.00	771.00	4127.00	4011.00	3977.00
Ni	9.00	52.00	115.00	116.00	455.00	1176.00	270.00	426.00	179.00	176.00	1087.00	2380.00	1772.00
Sc	18.00	21.00	39.00	1.00	23.00	22.00	47.00	30.00	61.00	55.00	23.00	20.00	21.00
Sr	204.00	185.00	171.00	67.00	268.00	6.00	141.00	187.00	411.00	78.00	9.00	4.00	24.00
V	292.00	199.00	105.00	189.00	42.00	75.00	155.00	38.00	63.00	136.00	63.00	78.00	63.00
Y	9.00	22.00	28.00	14.00	12.00	8.00	20.00	19.00	28.00	17.00	13.00	4.00	1.00
Zr	38.00	51.00	65.00	33.00	89.00	20.00	74.00	110.00	133.00	43.00	13.00	11.00	14.00
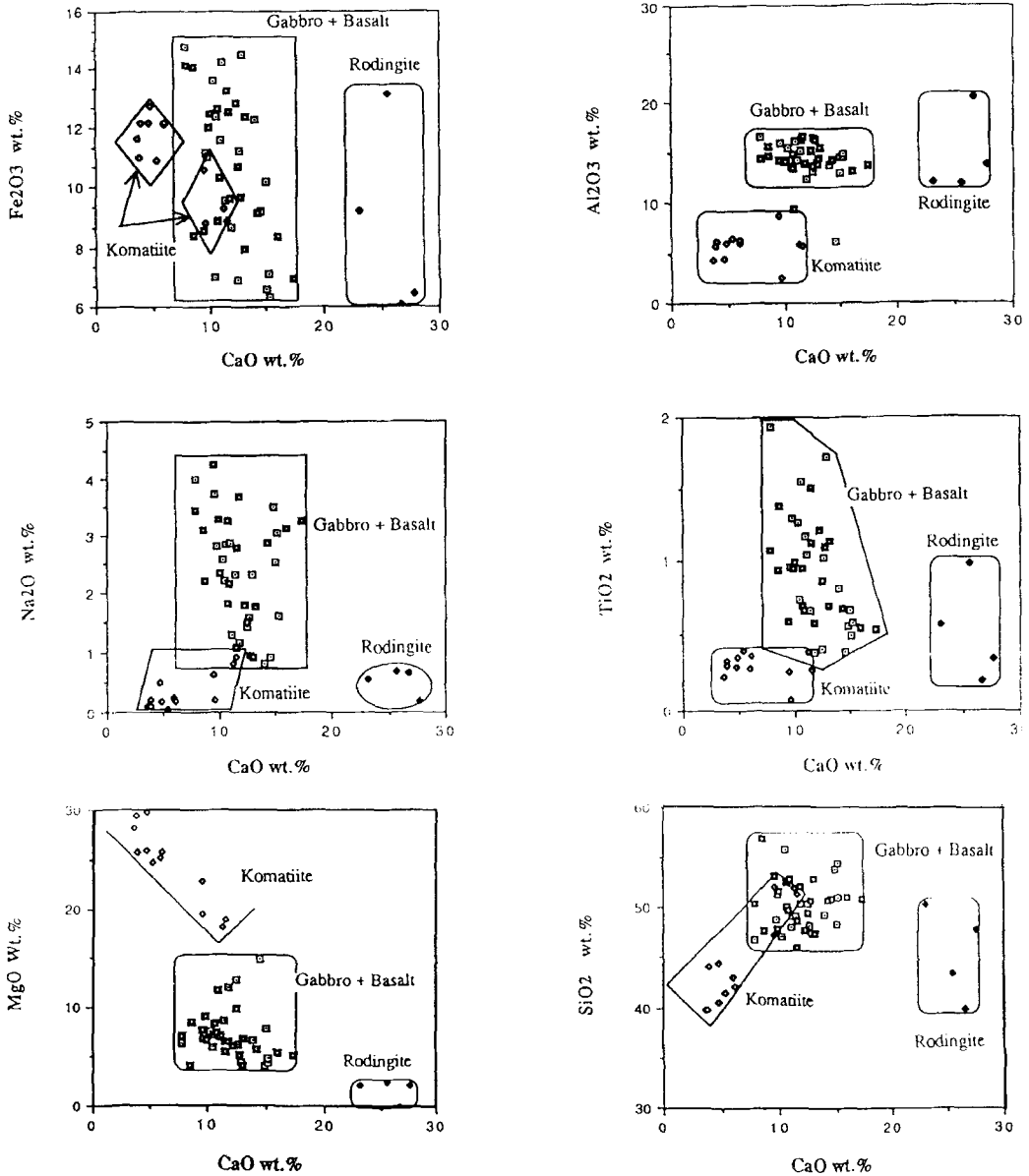
FIG. 4. Correlations of major elements (wt.%) and CaO (wt.%) in the rodingites, komatiites and basalt/gabbro of the Vumba schist belt, Botswana.

iron-free (FeO = 0.06 wt.%) zoisite to an iron-rich epidote (FeO = 8.45 wt.%) with a corresponding range of pistacite values (Ps-% = 0.12 to 16.83). Although epidote/zoisite enclose grossular garnet with a Cr-rich core, these phases have no or very negligible Cr_2O_3 content of less than 0.08 wt.%.

Chromite. A representative electron microprobe analysis of the relict chromite within uvarovite is given in Table 2. Several analyses of

chromite grains have been made to find out if there is a variation in oxide chemistry from core to rim. They are found to be homogeneous with a Cr_2O_3 content of about 61.28 wt.%; FeO 30.37 wt.%, Fe_2O_3 2.91 wt.% and a low amount of Al_2O_3 with a value of 2.75 wt.%. All other oxides have a value below 1 wt.%. The $Cr/(Cr+Al)$ or the $Cr/(Cr+Al+Fe^{3+})$ values are >0.90, comparable to chromites from komatiitic rocks.

Plagioclase. Representative electron microprobe analyses of plagioclase and a newly-formed albite are presented in Table 2. The formation of the albite is related to the formation of actinolitic hornblende + epidote ± zoisite/clinozoisite ± titanite. The plagioclase composition is comparable to those reported from calc-silicate rocks with $An_{98}Ab_2$.

Titanite. Titanite is one of the characteristic accessories found in the rodingite mineral parageneses. A representative electron microprobe analysis is given in Table 2.

Bulk chemistry

The major- and trace element chemistries of the rodingites and representative analyses of the possible protoliths (gabbros/basalts and ultrabasics of komatiitic affinity) occurring in the same area are set out in Table 3 and plotted in Figs. 4 and 5.

The major element correlation diagrams (Fig. 4) indicate enrichment of CaO and depletion of SiO_2 and alkalis in the rodingites compared to a mafic or ultramafic protolith. The variation in the trace element concentrations (Sr, Y, Zr, Ce and Ba) between the basalt/gabbro protolith and rodingites is not, on average, so different as to be considered significant when plotted against the wt.% CaO (Fig. 5). Compared to the komatiites, the VSB rodingites are enriched in CaO, Al_2O_3, TiO_2 and depleted in MgO and, to a certain extent, in SiO_2, whereas Sr, Y, Zr, Ce, V increase and Cr decreases in the rodingites.

Discussion

Mittwede and Schandl (1992) suggested two possible models for the formation of rodingites. The first considers that calcium metasomatism, or the process of rodingitization, is genetically and temporally related to serpentinization (Bilgrami and Howie, 1960; Honnorez and Kirst, 1975; Coleman, 1967, 1977; Anhaeusser, 1979); the second model suggests introduction of calcium-rich hydrothermal solutions and/or leaching of gabbro (Bloxam, 1954; De, 1972; Hall and Ahmed, 1984).

For the formation of the rodingites in the VSB one can consider rodingitization due to shearing parallel to the contact of basic and felsic rocks; or metasomatic reactions of basic rocks with chemical sediments such as epidote quartzites (epidote + quartz + titanite) to form rodingites. The epidote quartzites have been observed to occur in the same stratigraphic position, but no direct contacts are known. Common to both possible origins is that the age of the rodingitization is M3 and occurred most probably along layers parallel syn M3 shears.

During the rodingitization process in the VSB the Ca-plagioclase has been replaced by albite and additional minerals such as zoisite, prehnite, epidote, grossular garnet and diopside are formed. The formation of epidote + grossular assemblages of the VSB seems to have taken place by the reaction:

$$5 \text{ prehnite} = 2 \text{ epidote} + 2 \text{ grossular} + 3SiO_2 + 4H_2O \tag{1}$$

as suggested by Honnorez and Kirst (1975). In general the rodingites of the VSB have mineral assemblages that can be expressed by the several reactions proposed by Coleman (1967, 1977) to describe the onset of rodingitization:

$$3CaAl_2Si_2O_8 + Ca^{2+} + 2H_2O = 2Ca_2Al_3Si_3O_{12}(OH) + 2H^+$$
(anorthite)   (zoisite)   (2)

$$2Ca_2Al_3Si_3O_{12}(OH) + 5Ca^{2+} + 1.5SiO_2 + 7H_2O = 3Ca_3Al_2Si_{2.5}O_{10}(OH)_2 + 10H^+$$
(zoisite)   (hydrogrossular)   (3)

Reaction (2) occurs in both types of rodingites. However, X-ray diffraction and infra-red studies on separated garnet grains of the VSB rodingites indicate that the garnet is grossular and not hydrogrossular. This implies that reaction (3) did not take place in the VSB rodingites. The formation of the grossular can therefore be attributed to reaction (1). These reactions show the enrichment in calcium and water contents, and depletion of silica content. However, reactions 1 and 3, which describe the formation of grossular, should be due to a retrograde process in the VSB and not prograde as suggested by Honnorez and Kirst (1975) and Coleman (1967, 1977) respectively. This argument is supported by the formation of grossular instead of hydrogrossular. It is assumed that the source rock was too hot at the M3 phase of metamorphism, such that high-T M3 rodingitization did not support low-T assemblages to form in a first M3 stage, but in a
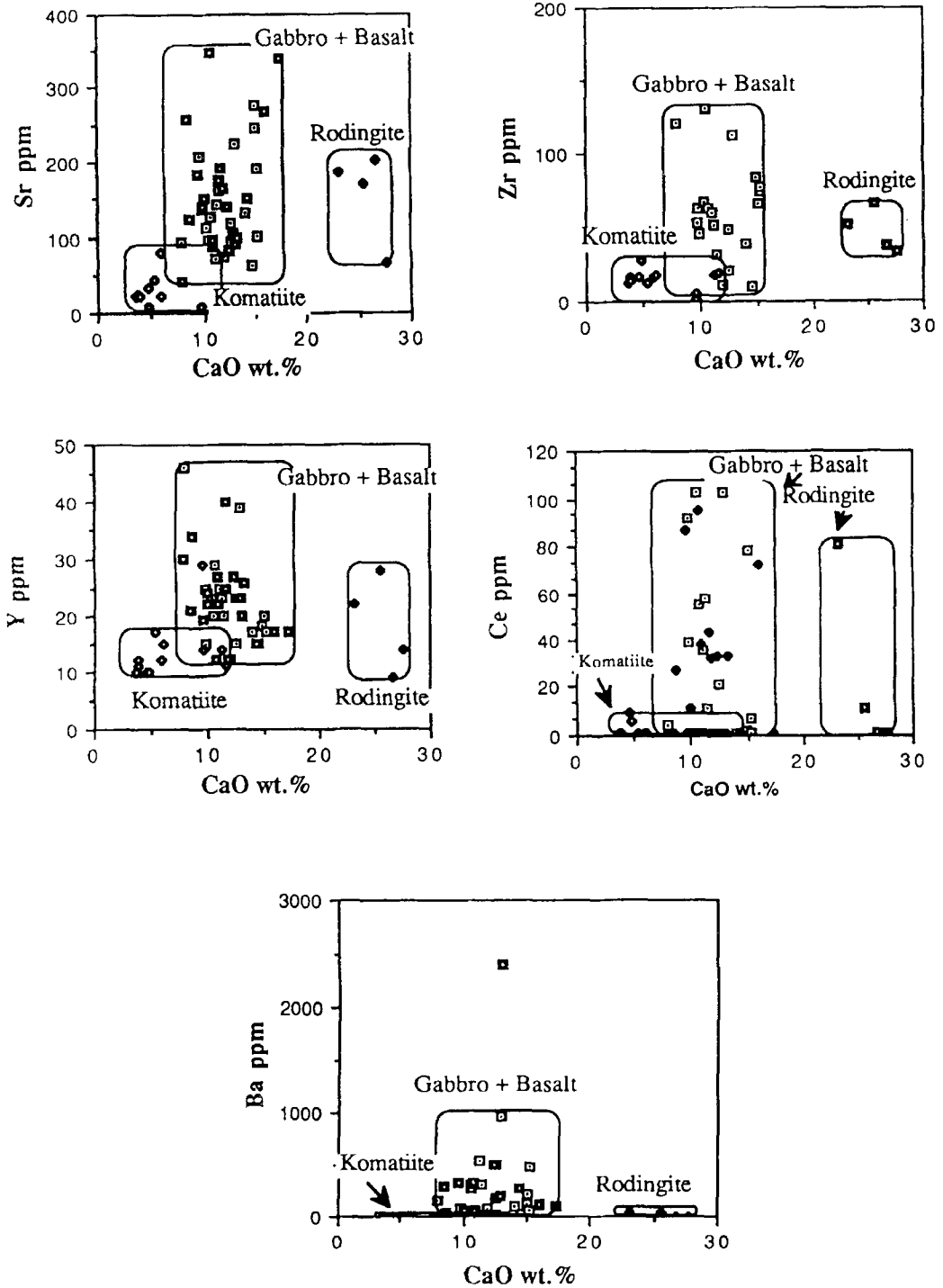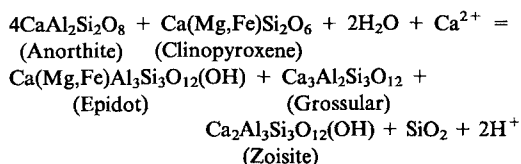
FIG. 5. Correlations among contents of trace elements (Sr, Zr, Y, Ce and Ba) versus wt.% CaO in the rodingites, komatiites and basalt/gabbro of the Vumba schist belt, Botswana.

second retrograde M4-stage. Therefore, the following possible reaction is suggested:

$4CaAl_2Si_2O_8$ + $Ca(Mg,Fe)Si_2O_6$ + $2H_2O$ + Ca^{2+} =
(Anorthite)   (Clinopyroxene)
$Ca(Mg,Fe)Al_3Si_3O_{12}(OH)$ + $Ca_3Al_2Si_3O_{12}$ +
    (Epidot)   (Grossular)
            $Ca_2Al_3Si_3O_{12}(OH)$ + SiO_2 + $2H^+$
                (Zoisite)

The change in mineralogy is accompanied by a change in bulk chemistry, suggesting that, during the process of rodingitization, which involved not only metamorphism but also metasomatism, elements such as Ca have been introduced and others Si, Na and K removed. These geochemical gains and losses in the rodingites can be explained through the interaction of the possible mafic/ultramafic protoliths with high alkaline, Ca(Mg)-rich solutions as suggested by Barriga and Fyfe (1983).

Coleman (1967) suggested that the bulk chemistry of the protolith (on an ACF plot) would have little effect on the chemistry of the rodingite. However, Schandl et al. (1989) suggest that the protolith chemistry should be emphasized because the type of chemical changes necessary to produce a rodingite will vary with the protolith, as basalts must lose alkalis and Mg, increase in ferric iron or gain Ca, whereas lamprophyres only lose alkalis and a little Mg and gain Ca to plot in the rodingite field.

As can be seen in the different major element (CaO vs. Al_2O_3, TiO_2, SiO_2, Fe_2O_3, Na_2O and MgO) and trace element (CaO vs. Sr, Zr, Y, Ce and Ba) plots (Figs. 4 and 5 respectively) and based on the petrographic, mineralogical and chemical data, it is appropriate to suggest two possible protoliths for the VSB rodingites (basalt/gabbro or komatiitic).

Group I rodingite samples contain relict chromite grains within a zoned uvarovite-grossular/andradite garnet. The group II rodingites contain no relict chromite and have no uvarovite. Considering the bulk rock and trace element chemistry data and the different chemical plots (Figs. 4 and 5) one can suggest a basalt/gabbro as a possible protolith for both groups of rodingites. However, this is true for the group II rodingites where there is no relict chromite. The presence of chromite with $Cr/(Cr+Al+Fe^{3+})$ ratio > 90, similar to chromites found in komatiites, suggests a possible komatiitic origin of the chromite-uvarovite-bearing group I rodingites. This is in agreement with Yuanming and Fleet (1989), who suggested that the Cr-rich calc-silicates from the Hemlo area, Ontario, were formed by meta-somatic replacement of komatiite and komatiitic basalt with secondary enrichment of Cr. It is important to note that in the VSB, there are normal Mg-rich tholeiites and rare Fe-rich tholeiites. However, most analysed basic rocks from this belt have komatiitic affinity, implying that the chromite chemistry of most komatiitic metabasalts/gabbros could be komatiitic.

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