Corona Textures in Proterozoic Olivine Melanorites of the Equeefa Suite, Natal Metamorphic Province, South Africa

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Summary

Olivine-plagioclase and phlogopite-plagioclase coronas have been identified from olivine melanorites of the Mid- to Late Proterozoic Equeefa Suite in southern Natal, South Africa. Olivine, in contact with plagioclase, is mantled by a shell of clear orthopyroxene, in turn rimmed by pale green (pargasitic) clinoamphibole. Locally a third rim, composed of a fine pargasite-spinel symplectite is developed adjacent to the plagioclase. The second corona reaction has produced greenish-brown pargasite at phlogopite-plagioclase interfaces. A third, less obvious reaction, between olivine and phlogopite is also noted. Analytical data of all the mineral phases present, along with the coronas, are given. Two-pyroxene thermometry yields magmatic core temperatures ($\sim 1120°C$), with rim compositions indicating equilibration at $\sim 850°C$. Consistent with this, the modelled olivine-plagioclase reaction occurs between 830–1050°C with a_{water} between 0.1 and 1.0 at 7 kbar. The three reactions took place during a prolonged history of cooling and partial hydration of the magmatic olivine melanorites from over 1000°C down to $\sim 600°C$. The P–T conditions indicated by the reactions suggest this cooling process was essentially isobaric, indicating that the area was not subjected to rapid uplift or burial throughout this entire period.

Zusammenfassung

Korona-Texturen in proterozoischen Olivin-Melanoriten der Equeefa Suite, Natal Metamorphic Province, Südafrika

Aus Olivin-Melanoriten der mittel- bis spätproterozoischen Equeefa Suite im südlichen Natal, Südafrika, wurden Olivin-Plagioklas und Phlogopit-Plagioklas-

Koronartexturen beobachtet. Olivin, der mit Plagioklas im Kontakt steht, wird von einem klaren Saum vom Orthopyroxen ummantelt, der seinerseits von blaßgrünem (pargasitischem) Klinoamphibol umsäumt wird. Stellenweise ist ein dritter Saum, bestehend aus feinkörnigem symplektitischem Pargasit-Spinell im Kontakt mit Plagioklas ausgebildet. Die zweite koronabildende Reaktion resultiert in Bildung eines grünbraunen Pargasites an Phlogopit-Plagioklas Kornkontakten. Eine dritte, weniger auffällige Reaktion zwischen Olivin und Phlogopit wurde ebenfalls beobachtet. Zwei-Pyroxen-Thermometrie ergab magmatische Temperaturen der Kernbereiche ($\sim$ 1120°C) und belegt eine Gleichgewichtseinstellung in den Randzonen bei ca. 850°C. Olivin-Plagioklas-Modellreaktionen liegen ebenfalls in einem Temperaturbereich von 830–1050°C bei Wasseraktivitäten von 0.1 bis 1.0 und einem Druck von 7 kbar. Die drei Reaktionen liefen im Zuge einer länger andauernden Abkühlung unter teilweiser Hydratisierung der magmatischen Melanorite in einem Temperaturbereich von 1000°C bis ca. 600°C ab. Die aus den Reaktionen ableitbaren P–T-Bedingungen sprechen für eine im wesentlichen isobare Abkühlungsgeschichte und zeigen, daß dieses Gebiet während dieser gesamten Periode keiner raschen Hebung bzw. keiner Versenkung unterworfen worden ist.

Introduction and Geological Setting

The Equeefa Suite is made up of a number of phases of deformed and metamorphosed mafic and ultramafic igneous rocks which are confined to the southern part of the amphibolite grade Mzumbe Terrane, Natal Metamorphic Province, South Africa (*Evans* et al., 1987; *Thomas*, 1989; *Thomas* et al., 1992a). It includes a swarm of mafic (and minor ultramafic) dykes, rare podiform noritoids and a large composite mafic/ultramafic body (the Umzinto intrusion—Fig. 1). In a recent geochemical study, *Thomas* et al. (1992a) suggested that the Equeefa Suite was derived from two discrete batches of subalkaline mafic magma. The earlier melt, which gave rise to the ultramafic and mafic rocks of the Umzinto intrusion was LIL- and LREE-enriched, whereas the second gave rise to the mafic dyke swarm.

The suite was emplaced after the imposition of a penetrative fabric on the $\sim$ 1.2 Ga tonalitic gneisses of the Mzumbe Suite (*Thomas* and *Eglington*, 1990). Subsequently, intrusions of the Equeefa Suite were deformed and metamorphosed during a regional, amphibolite grade tectono-metamorphic event at $\sim$ 1050 Ma, during which extensive rapakivi-textured granitoid and charnockite plutons were emplaced (*Thomas* et al., 1992b). However, whereas the rocks at the margins of larger Equeefa bodies (such as the Umzinto intrusion) are strongly deformed and have metamorphic textures, those in the core areas have commonly retained their original igneous characteristics. The ultramafic rocks within the Umzinto intrusion thus include largely pristine coarse-grained olivine melanorites, with well-developed corona structures. Some outcrops of the ultramafic rocks, particularly near the margins of the Umzinto intrusion, and those intruded into the adjacent country rock gneisses, have been altered to clinochlore-anthophyllite/cummingtonite gneisses. The unaltered melanorites form pods and discontinuous layers (up to 100 m by 700 m in size) within enveloping massive metagabbros which make up the bulk of the Umzinto intrusion.

This paper focuses on two corona textures which have been identified in the olivine melanorites from the Umzinto intrusion. The first (olivine-plagioclase) was described by *Craig* (1965), whereas the second (phlogopite-plagioclase) is described
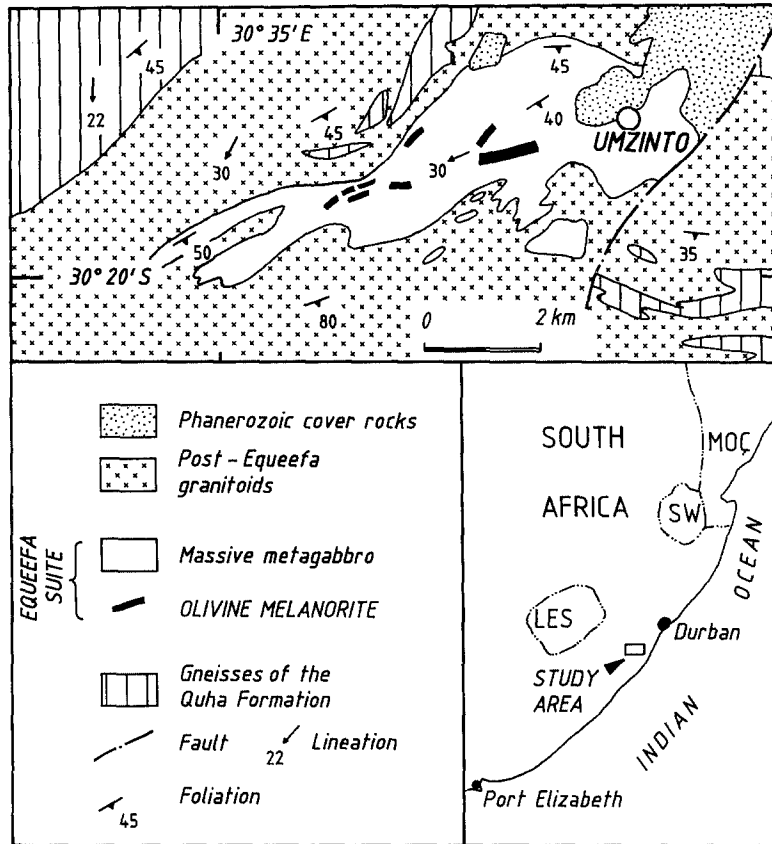
Fig. 1. Location map and simplified geological of the Umzinto intrusion, southern Natal

here for the first time. A third reaction, involving olivine and phlogopite, has also been recognised. Microprobe analyses of all mineral phases in the olivine melanorites are presented (including the coronas), and the implications for the magmatic and metamorphic history of the rocks in a regional context are discussed.

Petrography

The olivine melanorites are coarse-grained (2–5 mm average), equigranular rocks made up of orthopyroxene ($\sim$28%), olivine (24%), plagioclase ($\sim$20%), phlogopite ($\sim$17%), clinoamphibole ($\sim$5%), clinopyroxene ($\sim$3%), along with minor opaque minerals and apatite. Sub-ophitic texture, with pyroxenes partially enclosing plagioclase is commonly preserved. Olivine, occurring as fractured, sub-rounded grains ($\sim$2 mm across) is locally poikilitically enclosed by large ($\sim$5 mm) grains of orthopyroxene which is typically turbid and pink. Olivine is also commonly associated with phlogopite. Clinopyroxene is generally less turbid, but contains numerous exsolved opaque needles, presumed to be ilmenite. Plagioclase exhibits both albite and Carlsbad-Albite twinning.

Three reactions are recognised, two of which (reactions 1 and 2) produced corona textures:

1) *Olivine-plagioclase*—This texture comprises a reaction-rim around olivine grains where they are in contact with plagioclase (Fig. 2). These coronas consist of two or three distinct shells:
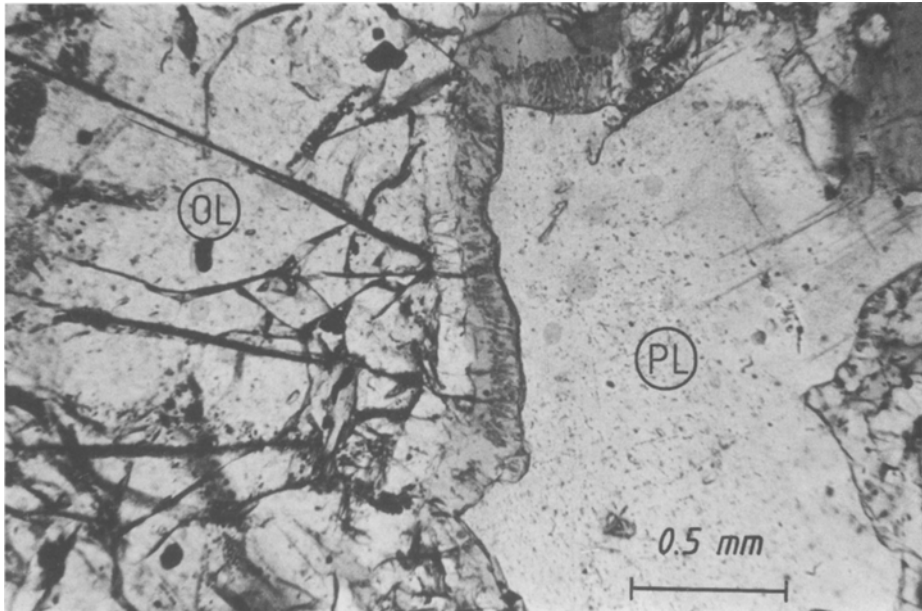

Fig. 2. Corona structure surrounding olivine (OL) grain in contact with plagioclase (PL). The inner rim (next to olivine) is composed of colourless orthopyroxene and the outer rim (next to plagioclase) is made up of a symplectic pargasite-spinel intergrowth with spinel vermicles
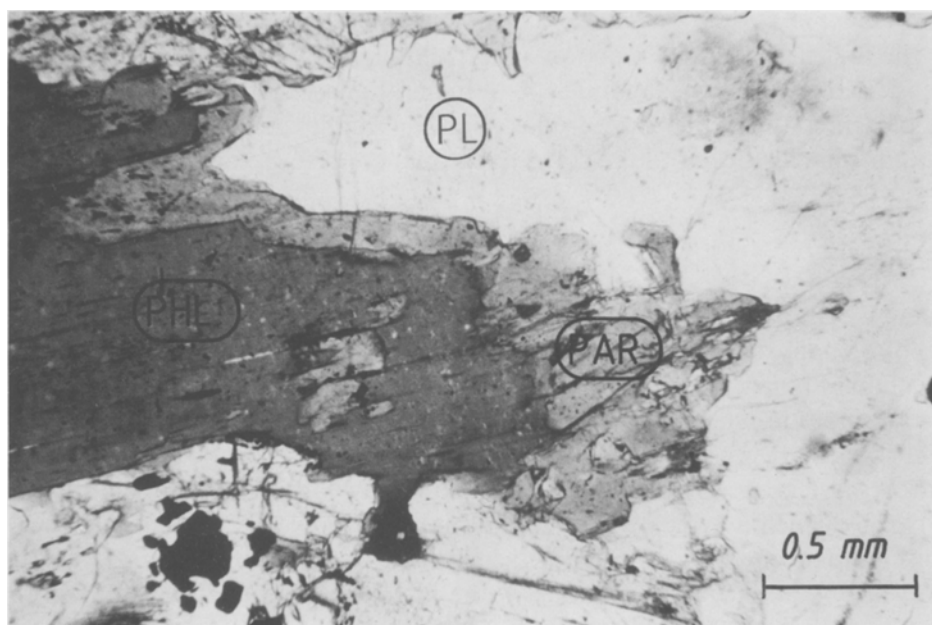

Fig. 3. Corona structure composed of greenish-brown pargasite (PAR) developed at a phlogopite (PHL)-plagioclase(PL) interface

Shell a) adjacent to olivine, a ~100 μm thick rim of colourless orthopyroxene,

Shell b) a ~50 μm thick shell of pale-green, fibrous clinoamphibole and;

Shell c) in contact with plagioclase, a ~100 μm thick rim of a clinoamphibole-spinel symplectite (not always present).

2) *Phlogopite-plagioclase*—This reaction is illustrated by the growth of a rim (~100 μm thick) of greenish-brown clinoamphibole separating juxtaposed phlogopite and plagioclase (Fig. 3).

3) *Olivine-phlogopite*—This reaction is manifested in thin section by the intimate association of phlogopite adjacent to olivine grains. From the petrographic relationships, it is not possible to establish the sequence in which these reactions occurred, suggesting that they may have occurred at approximately the same time.

Mineral Chemistry

Analyses of the various mineral phases, excepting spinel, in the olivine melanorites rocks were made at the Geological Survey using a Jeol 733 microprobe, using wavelength dispersive techniques. Spinel analyses were made at the University of Pretoria, also using a Jeol 733 microprobe using wavelength dispersive techniques, but with an energy dispersive Kevex attachment fitted, to ensure that the microprobe beam was restricted to the thin spinel lamellae. The full dataset of mineral analyses can be obtained from the senior author, and only the mean and ranges (where significant) of analyses are given in the Tables 1 and 2.

Whereas amphiboles, olivine, enstatite and phlogopite are fairly uniform in composition, plagioclase and clinopyroxenes are variable (Tables 1 and 2). Amphibole ionic structures were calculated using the program "RECAMP" (*Spear* and *Kimball*, 1984). However, the mole fractions Mg/(Mg + Fe) in the amphiboles vary between .75 and .95 depending on the assumption of all the Fe as Fe^{2+} (.75) or whether the SUM_{FM} = 13.00, an option recommended by *Leake* (1978). The amphiboles fall into the pargasitic field according to *Leake*'s (op. cit.) classification. Fe_2O_3 contents in spinel were estimated using the algorithm proposed by *Droop* (1987). Mica compositions are expressed in terms of phlogopite and eastonite. Fe^{3+} contents in the clinopyroxene and orthopyroxene are calculated on a charge balance basis after *Droop* (1987).

Two-Pyroxene Thermometry

A number of analyses of rim compositions of juxtaposed orthopyroxene-clinopyroxene pairs is given in Table 1. The compositions have been plotted on the isothermal grid of the pyroxene triangle (Fig. 4), following *Lindsley* (1983). The higher temperatures of ~1100°C indicated from clinopyroxene compositions are clearly magmatic, whereas the more calcic clinopyroxene compositions probably represent partial high-temperature metamorphic re-equilibration down to ~850°C.

Modelling of the Reactions

The two corona reactions and an olivine-phlogopite reaction have been modelled using the program "THERMOCALC" (*Powell* and *Holland*, 1988). Activities (a) used for the various phases were calculated on the following basis: anorthite (An)

Table 1. *Mean mineral compositions and ranges (wt%) and cation formulas used for the pyroxene thermometry (OPX = orthopyroxene, CPX = clinopyroxene) and for the plagioclase biotite corona thermobarometry (PLAG = plagioclase, PHL = phlogopite, PARG = pargasite)*

	Pyroxene pairs			Plagioclase biotite corona				
ELT	OPX (N=5) WT%	CPX (N=8) WT%	RANGE	PLAG (N=5) WT%	RANGE	PHL (N=5)	PARG (N=5)	RANGE
SiO_2	53.02	50.92	(49.38–51.84)	60.41	(56.99–62.24)	37.86	42.78	(42.11–43.72)
Al_2O_3	1.46	3.25	(2.96–4.20)	25.88	(24.60–28.48)	16.17	15.40	(14.26–16.78)
FeO	16.89	5.87	(5.07–7.09)	0.50	(0.10–1.11)	10.06	9.92	(9.73–10.21)
MnO	0.34	0.11	(0.03–0.17)	0.27	(0.00–0.84)	0.03	0.08	(0.05–0.12)
MgO	25.67	15.45	(14.84–15.92)	0.00		17.96	13.80	(13.43–14.05)
CaO	1.81	20.78	(18.88–21.80)	6.54	(5.41–9.47)	0.01	11.17	(11.01–11.29)
Na_2O	0.05	0.86	(0.77–1.09)	7.23	(5.90–7.74)	0.79	2.98	(2.87–3.10)
K_2O	0.00	0.00		0.10	(0.06–0.11)	8.45	0.54	(0.52–0.59)
TiO_2	0.48	0.83	(0.62–1.01)	0.00		4.31	1.82	(0.99–2.57)
Cr_2O_3	0.01	0.40	(0.23–0.69)	0.00		0.23	0.08	(0.01–0.19)
Total	99.73	98.47		100.93		95.87	98.57	
Cation proportions						All Fe^{2+}	SUM FM = 13	AV Fe^{3+}
SiO_2	1.940	1.906		2.665		6.159	6.096	6.127
Al_2O_3	0.063	0.143		1.346		2.614	2.587	2.600
Fe_2O_3	0.000	0.000		0.000		0.000	0.472	0.237
FeO	0.517	0.184		0.018		1.194	0.710	0.951
MnO	0.011	0.003		0.010		0.010	0.010	0.010
MgO	1.400	0.862		0.000		2.961	2.931	2.946
CaO	0.071	0.834		0.309		1.723	1.705	1.714
Na_2O	0.004	0.062		0.619		0.832	0.823	0.828
K_2O	0.000	0.000		0.006		0.099	0.098	0.099
TiO_2	0.013	0.023		0.000		0.197	0.195	0.196
Cr_2O_3	0.000	0.008		0.000		0.009	0.009	0.009
Total	4.017	4.026		4.974		13.135	13.000	13.067
X_{Fs} =	0.260	0.094						
X_{En} =	0.704	0.442						
X_{Wo} =	0.036	0.407						

X_{An} = 0.331
X_{Ab} = 0.663
X_{Or} = 0.006
X_{Ann} = 0.239
X_{Phl} = 0.761

	PHL	PARG	AV Fe^{3+}
$Fe^{2+}/Fe^{2+} + Mg$ =	0.287	0.195	0.244
$Fe^{3+}/Fe^{3+} + Fe^{2+}$ =	0.000	0.399	0.200

Table 2. Mean mineral compositions and ranges (wt%) and cation formulas used for the plagioclase-olivine corona thermobarometry. (OL = olivine, OPX = orthopyroxene, PARG = pargasite, PLAG = plagioclase, SPL = spinel)

Olivine plagioclase coronas

ELT	OL (N=5)	OPX (N=7)	PLAG (N=8)	RANGE	SPL (N=7)	RANGE	PARG (N=8)	RANGE
SiO_2	37.48	54.17	53.21	(50.7–54.76)	0.00	(59.6–62.45)	42.30	(41.70–42.95)
Al_2O_3	0.00	1.80	30.87	(30.24–31.5)	61.11	(0.58–3.12)	16.85	(15.79–17.68)
Fe_2O_3	0.00	0.00	0.00		1.58	(21.99–27.39)	0.00	
FeO	28.61	17.38	0.22	(0.09–0.64)	23.87		9.05	(8.40–9.42)
MnO	0.34	0.37	0.00		0.00		0.12	(0.07–0.15)
MgO	34.09	26.80	0.07	(0.00–0.32)	11.04	(8.99–11.82)	14.86	(14.47–15.35)
CaO	0.00	0.22	12.41	(11.33–14.28)	0.20	(0.11–0.47)	11.05	(10.86–11.21)
Na_2O	0.00	0.01	4.18	(3.82–4.66)	0.00		2.99	(2.89–3.11)
K_2O	0.00	0.00	0.05	(0.02–0.11)	0.00		0.48	(0.44–0.51)
TiO_2	0.00	0.01	0.00		0.00		0.18	(0.14–0.29)
Cr_2O_3	0.03	0.04	0.00		0.16	(0.01–0.46)	0.03	(0.01–0.08)
ZnO	0.00	0.00	0.00		1.61		0.00	
Total	100.55	100.80	101.01		99.57		97.91	

Cation proportions

	OL	OPX	PLAG	SPL	PARG All Fe^{2+}	SUM FM = 13	AV Fe^{3+}
SiO_2	0.999	1.951	2.382	0.000	6.097	5.970	6.033
Al_2O_3	0.000	0.076	1.630	15.726	2.863	2.803	2.833
Fe_2O_3	0.000	0.000	0.000	0.260	0.000	0.963	0.486
FeO	0.638	0.523	0.008	4.357	1.091	0.105	0.593
MnO	0.008	0.011	0.000	0.000	0.015	0.014	0.014
MgO	1.355	1.438	0.005	3.591	3.192	3.125	3.158
CaO	0.000	0.008	0.595	0.047	1.707	1.671	1.689
Na_2O	0.000	0.001	0.363	0.000	0.836	0.818	0.827
K_2O	0.000	0.000	0.003	0.000	0.088	0.086	0.087
TiO_2	0.000	0.000	0.000	0.000	0.020	0.019	0.019
Cr_2O_3	0.000	0.001	0.000	0.018	0.003	0.003	0.003
Total	3.000	4.011	4.986	23.99	13.278	13.000	13.137

SUMFM	13.278	13.000	13.137
$Fe^{2+}/Fe^{2+} + Mg$	0.255	0.033	0.158
$Fe^{3+}/Fe^{3+} + Fe^{2+}$	0.000	0.901	0.451

X_{Fs} = 0.266
X_{En} = 0.730
X_{Wo} = 0.004
X_{Fo} = 0.68
X_{Fa} = 0.32
X_{Ab} = 0.619
X_{An} = 0.378
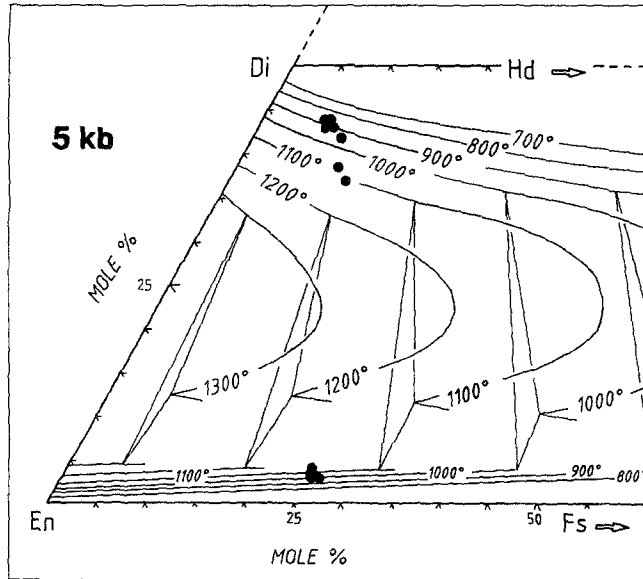X_{Or} = 0.003
X_{Spl} = 0.45
X_{Hc} = 0.55

Fig. 4. Ortho-/clinopyroxene pair compositions plotted on the pyroxene compositional triangle. Isotherms after *Lindsley* (1983)

and albite (Ab) were calculated using the recommendations of *Newton* et al. (1980), whereas orthopyroxene (En) activities were calculated after *Aranovich* and *Kosyakova* (1987). *Nell* and *Wood* (1989) have shown that spinel (spl) solid solutions are highly disordered and that the activity of spinel with X_{Mg} between ~ 0.7 and ~ 0.3 at 1000°C is ~ 0.5. The average spinel composition determined has $X_{Mg} = 0.45$. Ideal mixing models were assumed for olivine (Fo) and pargasite (Parg). Although olivine shows non-ideal mixing (*Davidson* and *Mukhopadhyay*, 1984) the deviation from ideal mixing is of a similar magnitude to analytical error and sample variation. The activities of phlogopite (Phl), and eastonite (East), were calculated after *Essene* (1989), assuming that the OH site is completely taken up by OH. For the ferromagnesian phases other than amphibole and spinel, it was assumed that all Fe is Fe^{2+}.
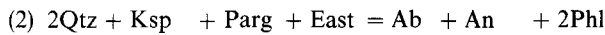
a) Olivine-plagioclase

This corona may result from the following reaction:

$$2\ Ab + 12\ Fo + 4\ An + 2H_2O = 7\ En + 2\ Parg + 2\ Spl \quad \text{(Reaction 1)}$$
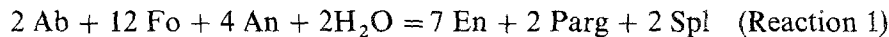
Modelled curves at given temperatures and pressures for this reaction are shown in Fig. 5. Four curves are shown (1a, b, c, and d), based on differing activities of plagioclase, water and pargasite (tabled on Fig. 5). In curves 1a and 1b, $a_{water} = 1.0$, whereas in curves 1c and 1d, $a_{water} = 0.1$. It is clear that reducing a_{water} from 1.0 to 0.1 has the effect of reducing the reaction temperature from $\sim 1030°C$ to 830°C at 7kbar ($\sim 200°C$), whereas varying $a_{pargasite}$ and $a_{plagioclase}$ has a much lesser influence. Pressure estimates from other geobarometric studies in southern Natal (e.g. *Grantham*, 1983; *Evans* et al., 1987; *Thomas* et al., 1992c) indicate pressures of 5–8 kbar. At 7 kbar, varying a_{water} between 1.0 and 0.1 yields temperatures consistent with the temperature range given by two-pyroxene thermometry. However, it is known that a_{water} cannot have been one, because the mineral assemblages are largely anhydrous and therefore $a_{water} < 1.0$.
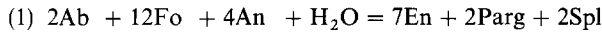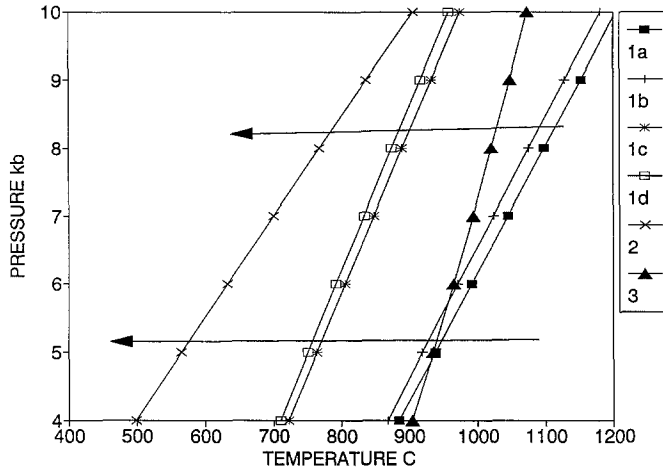
(1) 2Ab   + 12Fo   + 4An   + H$_2$O = 7En + 2Parg + 2Spl
(a) 0.4   0.68   0.6   1.00   0.54   0.75   0.5
(b) 0.34   0.68   0.66   1.00   0.54   0.95   0.5
(c) 0.4   0.68   0.6   0.1   0.54   0.75   0.5
(d) 0.34   0.68   0.66   0.1   0.54   0.95   0.5

(2) 2Qtz + Ksp   + Parg + East = Ab   + An   + 2Phl
     0.35   0.05   0.8   0.38   0.61   0.27   0.38
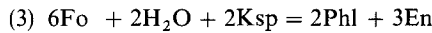
(3) 6Fo   + 2H$_2$O + 2Ksp = 2Phl + 3En
     0.68   0.1   1.0   0.38   0.54

Fig. 5. Modelled reaction curves in P–T space for Reactions 1, 2 and 3. The various activities for are tabulated

b) Phlogopite-plagioclase

This reaction, to produce amphibole, cannot be modelled so simply, owing to extensive solid solution in all the phases. However, using the observed phases and assuming activity values of ~0.35 for silica (Qtz) (consistent with equilibrium with the compositions of olivine and orthopyroxene in the rocks at 850°C and 7 kbar) and 0.05 for K-feldspar (Ksp) respectively, the following reaction may result:

$$Ab + An + 2\,Phl = 2\,Qtz + Ksp + Parg + East \quad \text{(Reaction 2)}$$

The results of the modelling of this reaction using THERMOCALC are shown on Fig. 5 (Reaction 2), along with the activities used for the various phases. A problem with this model is that it involves phases which cannot be clearly defined as end members and is hence difficult to balance. The reaction requires the production of silica, K-feldspar and a more aluminous mica (eastonite). The temperature conditions applicable to Reaction 2 above are significantly lower than those attached to Reactions 1a–1d. In Reaction 2 the K-feldspar component can be accommodated in the plagioclase. The activity of SiO$_2$ of <1 implies that free quartz is not necessarily required for the reaction, and any silica produced would react with olivine to produce orthopyroxene.

c) Olivine-phlogopite

Using the observed phases and assuming the pre-reaction presence of K-feldspar, the following reaction may explain the extensive development of phlogopite/eastonite adjacent to olivine grains:

$$6 \text{ Fo} + 2 \text{ H}_2\text{O} + 2 \text{ Ksp} = 2 \text{ Phl} + 3 \text{ En} \quad \text{(Reaction 3)}$$
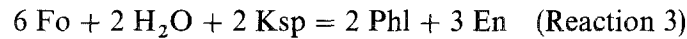
Although no K-feldspar is present in the rocks, whole-rock analyses of the olivine melanorites show K_2O contents of up to 1.38% (*Evans* et al., 1987). This translates into approximately 8% normative orthoclase, an amount which is unlikely to be accommodated in the plagioclase present. It is therefore suggested that K-feldspar may have existed as an early phase. The curve shown in Fig. 5 (Reaction 3), was calculated assuming a_{water} = 0.1. With increased a_{water} the reaction takes place at significantly higher temperatures. From Fig. 5 it can be seen that the P–T conditions applicable to Reaction 3 are comparable with those for reactions 1 (with a_{water} = 1.0) although it has a steeper slope.

Discussion and Conclusions

Using previously published pressure estimates of 5–8 kbar (e.g. *Grantham*, 1983; *Evans* et al., 1987; *Thomas* et al., 1992c), it has been seen that the modelled olivine-plagioclase corona reaction would occur at between 1030°C and 830°C at ~7 kbar, with a_{water} varying between 1.0 and 0.1. This is consistent with two-pyroxene thermometry which indicates a similar temperature range from magmatic (~1100°) to ~850°C. This corona reaction therefore appears to reflect a partial hydration of mafic rocks at high temperatures and pressures, probably shortly after consolidation or crystallisation. The second corona reaction producing pargasite from plagioclase + phlogopite appears to have occurred at significantly lower temperatures, but with a similar slope to reactions 1a–1d. Similarly, the production of orthopyroxene + phlogopite from olivine may have occurred under comparable P, T and conditions at low a_{water}, and hence possibly at the same time as, Reaction 1. The sequence of reactions seen in the olivine melanorites can be summarised as follows:

1) Emplacement of the mafic magma at ~1100°C.
2) Consolidation and cooling to between 1000 and 850°C. Commencement of hydration with reactions 1 and 3 occurring within a short time period, with varying a_{water}, at elevated temperatures of 900–1000°C. With the onset of hydration Reaction 3 was probably initiated at low a_{water}, followed by reaction 1 with increasing a_{water}.
3) Reaction 2 probably occurred slightly later, under cooler conditions. It is unaffected by variations in a_{water}, but is facilitated by the production of phlogopite by reaction 3.

The modelled reaction slopes suggest that the cooling process from magmatic temperatures, through consolidation, to partial re-equilibration and partial hydration, over temperatures ranging from ~1000 down to ~600°C, was essentially isobaric. This implies that no rapid uplift due to tectonic activity occurred during the history represented by the olivine melanorites. Possibly, therefore, the regional

amphibolite grade metamorphism seen in this part of the Mzumbe Terrane can be ascribed to a prolonged elevated thermal gradient caused by the emplacement of the voluminous, high temperature granitoid and mafic intrusions that characterise this part of the Natal belt.

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