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The evolution of high T - low P granulites in the Northern Marginal Zone sensu stricto, Limpopo Belt, Zimbabwe – the case for petrography

by *Balz S. Kamber*[1,2] and *Giuseppe G. Biino*[3]

Abstract

The Limpopo Belt of southern Africa is generally believed to represent the root of a late Archaean continental collision zone, and has been used to demonstrate the validity of the uniformitarian concept in tectonics. Large scale tectonic models have been applied in spite of the fact that large portions of the belt yet await the most basic investigations. Here we report the first detailed field and petrographic study of the northernmost part of the Limpopo Belt, the Northern Marginal Zone sensu stricto (NMZ s.s.) and conclude, on the basis of relative age relation, nature of PT evolution and deformation, that none of the current models can correctly explain the evolution of the study area. The evolution of NMZ s.s. is complex and includes four metamorphic stages, two major plutonic episodes and at least three deformation events.

The oldest rocks, mafic granulites, record all four stages of metamorphic mineral growth. The first two stages predate deposition of sediments and the intrusion of voluminous enderbite and charnockite between 2.72 and 2.62 Ga.

The bulk of our observations relate to the late Archaean (stage 3) granulite facies event. Abundant reaction textures are preserved in mafic granulite, metasediments, metamorphosed charnockite and enderbite and allow us to qualitatively reconstruct the PT evolution. Prograde heating occurred in the sillimanite stability field. During peak temperature conditions vapour-absent melting is observed in most felsic lithologies. Temperatures between 800 and 850 °C at pressures as low as 0.4–0.5 GPa are indicated by various mineral assemblages. The thermal peak was followed by an increase in pressure. Typical reactions of anti-clockwise PT evolution, like breakdown of cordierite + spinel to sapphirine and orthopyroxene + plagioclase to garnet + quartz, are frequently found. Maximum pressure is constraint to ca. 0.85 GPa by the complete absence of garnet in mafic granulites. Initial cooling was rapid, and is indicated by the back reaction of melt + orthopyroxene to biotite + quartz symplectites preserved in migmatites. This metamorphic event was accompanied by intrusion of porphyritic charnockite and granite, and by coeval compressional deformation. The observed evolution, especially the combination of an anti-clockwise PT loop and compressional tectonics, requires a strong, transient heat-source affecting the base of the crust. Neither the thermal evolution nor the relative timing is correctly predicted by existing collision models. The NMZ s.s. granulites were finally exhumed in a separate event along upper greenschist-facies thrusts, in response to a transpressive orogeny affecting the units further south at 2.0 Ga.

In spite of potential ambiguities inherent to a qualitative approach, our observations show that petrography and field work, if used in conjunction with dating of a few key age relations and structural interpretation, are a pre-requisite to the erection of realistic tectonic models. The example of the NMZ s.s. may encourage geoscientists with limited access to analytical facilities to reassess the geological evolution of terrains which lack basic description.

Keywords: granulite, reaction texture, anti-clockwise PT loop, transient heat source, Archaean, Early Proterozoic, Limpopo Belt, Zimbabwe.

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1. Introduction

The relative stability of continental plates is variable. The stable, usually interior part of a continental plate can be called a craton, and contrasts the relatively mobile orogenic belts. Modern orogenies are generally localised along plate margins and can be understood with the concept of the "Wilson cycle". A major field of geological research in the past two decades has focused on the question whether the "Wilson cycle" can also explain Precambrian, in particular Archaean geology. Yet, the response of the earth to such fundamental changes in physical parameters, like the decline of radiogenic heat production through time (i.e. its influence on the continental and oceanic geotherms), is still poorly known. A good understanding of the origin and tectonic significance of Precambrian metamorphic belts, many of which record high T/P values (GRAMBLING, 1980), plays a key role in the debate on Precambrian tectonics, but is also of importance to discussions as to the rate at which processes operate in metamorphic belts.

Few Precambrian provinces are known in such detail like Phanerozoic counterparts. The majority has only been mapped at a very coarse scale and detailed petrographic information is either restricted to small "key" areas, often related to ore deposits, or simply not available. Many Precambrian provinces are not easily accessible and/or poorly exposed and hence field work is difficult. In spite of the poor knowledge of primary geological information, it has become usual to apply large scale tectonic models to entire provinces, even though, in some cases these models involve structural units that await yet the most basic investigations. The Limpopo Belt of southern Africa is a classical example. Until recently, the evolution of this granulite belt had been explained in terms of a late Archaean continental collision and keeps being used to illustrate that plate tectonics operated back at 2.7 Ga (WINDLEY, 1993; DE WIT et al., 1992; MYERS and KROENER, 1994). Yet large areas of the belt, especially in the Zimbabwean part, had not been described and most models have been proposed from studies focusing on the areally much smaller South African portion.

The number of descriptive studies has declined in recent years, since analytical equipment has become available to almost all geoscientists and indeed analytical results are required for the majority of publications. In metamorphic geology, this has led to a change in research towards application of sophisticated technique on increasingly smaller samples and has, for example, allowed direct determination of rates of metamorphic processes (BURTON and O'NIONS, 1991). But unlike in such traditional areas of geological research like the Alps, where a rich descriptive literature is available at a very detailed scale, and where the significance and validity of a result from several outcrops or even one single sample can be estimated by the reader, the implication of similar studies in many Precambrian provinces is limited. We see many of the competing tectonic models for the same tectonic province as a consequence of a lack of basic geologic information, a lack of descriptive studies. In the case of the study area, two mutually exclusive models for the metamorphic evolution have been proposed. ROLLINSON (1989) postulated an anti-clockwise PT path whereas TSUNOGAE et al. (1992) suggested a clockwise evolution characterised by near isothermal decompression. Although the obvious discrepancy between the two studies has not been discussed by TSUNOGAE et al. (1992), their study has been used as evidence for continental collision models (e.g. ROERING et al., 1992).

In this contribution, we give a detailed field and petrographical report of the northernmost

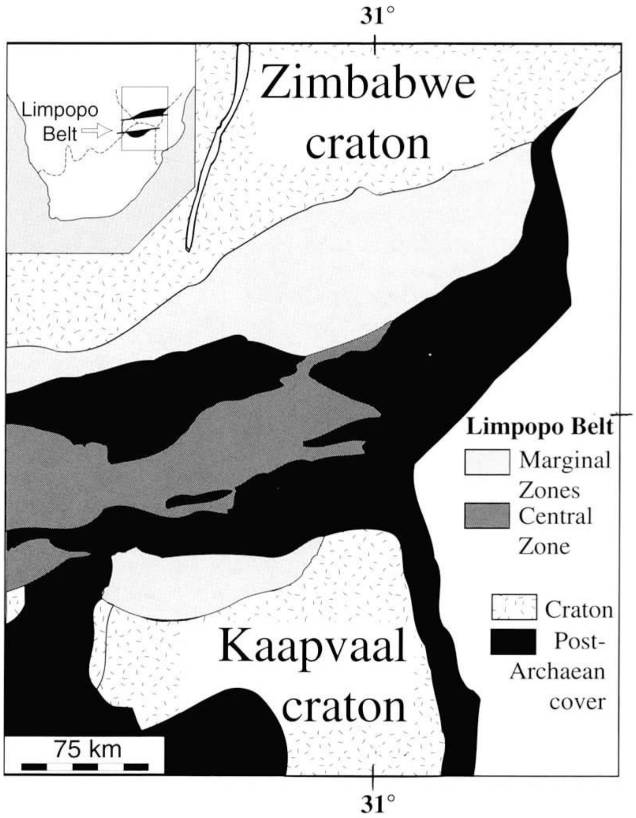

Fig. 1 Schematic tectonic map of the Limpopo belt, illustrating its position between the Zimbabwe and Kaapvaal cratons. The belt is subdivided into two marginal zones adjacent to the cratons and a central zone. The inset shows the geographic position within southern Africa.

part of the Limpopo Belt (Fig. 1). Our study is based on continuous outcrop of the Mondi-Mwenezi river profile running perpendicular to strike (Fig. 2). Additional information is given from localities known from the literature and from a similar, but poorly exposed profile crossing the belt 140 km further to the east along the Chiredzi river. Apart from providing the first detailed description of the northernmost part of the Limpopo Belt, our study aims to: (i) reassess competing petrological models in the light of our new data; (ii) define key observations which have to be explained by any tectonic model for the area and, perhaps most importantly; (iii) illustrate that field work, combined with detailed petrography and dating of key age relationships, is a necessary step before any tectonic interpretation can be made.

First we briefly describe the regional geology with emphasis on the role of the study area in the framework of the entire Limpopo Belt. Then we summarise the principle magmatic, metamorphic and structural events based on relative age relationships and published radiometric ages. The main part of the paper is a field and petrographic characterisation of all encountered lithologies. The principle source of information are well-preserved reaction textures for which mineral reactions are proposed and which are linked to the deformation sequence. These reactions are then used to qualitatively constrain the PT evolution. Finally, key observations regarding relative timing and nature of the deformation, metamorphism and plutonism are defined and it will be shown that the combination of all observations greatly limits possible tectonic models.

2. Regional geology

The Limpopo Belt, which is sandwiched between the Zimbabwean and the Kaapvaal cratons (Fig. 1), is a relatively well-known example of a Precambrian granulite belt and has been subject of numerous studies (see KAMBER et al., 1995a; BERGER et al., 1995; for a summary of previous

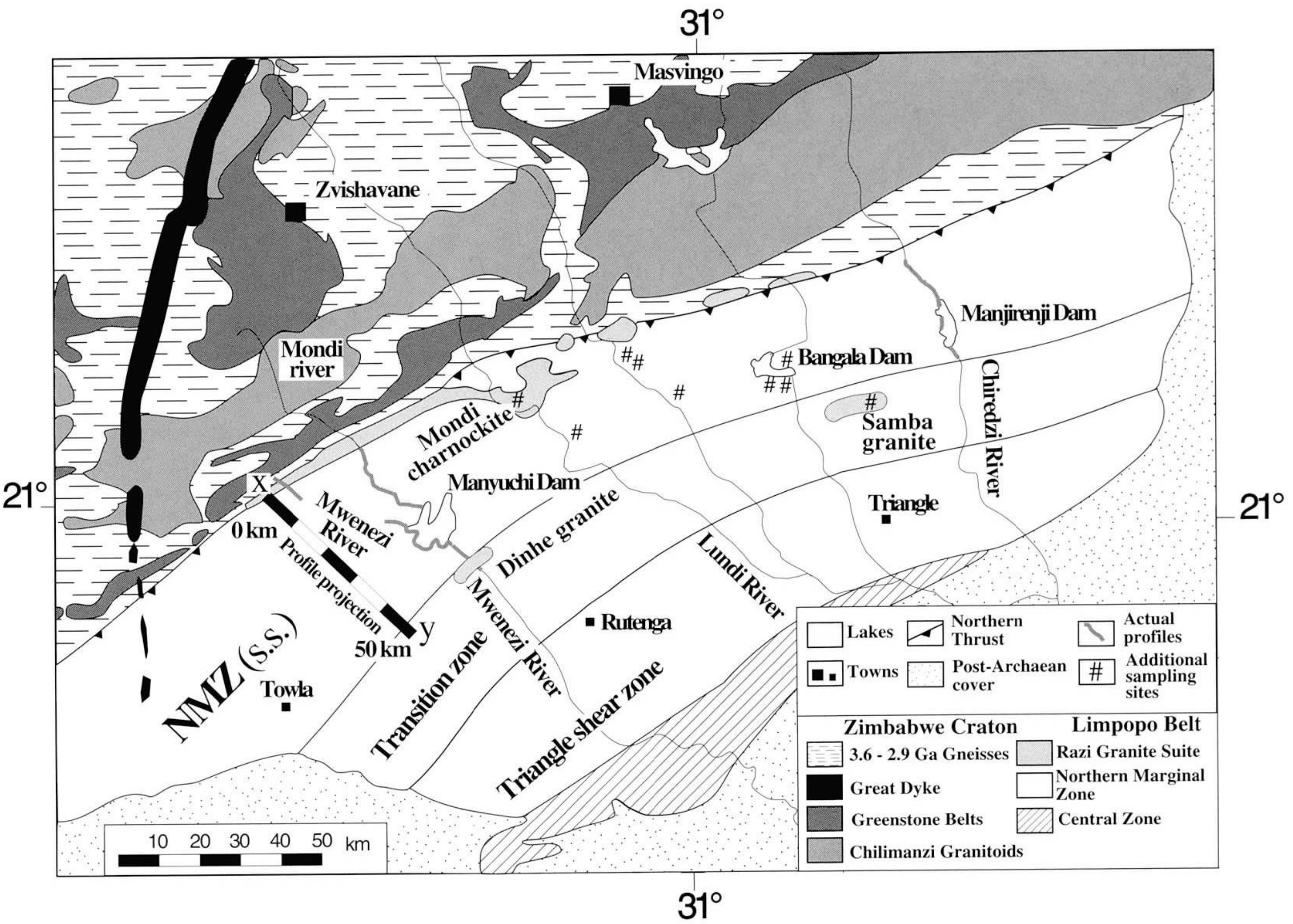

Fig. 2 Geological map of the Northern Marginal Zone of the Limpopo belt and its surroundings. Apart from the tripartite division into NMZ s.s., Transition zone and Triangle shear zone, the two river profiles are highlighted and additional localities are shown.

work). All geologists agree on a tripartite division of the Limpopo Belt into two marginal zones and a central zone. The assembly of the belt has long been believed to represent a single collisional event of the two cratons in the late Archaean (e.g. van Reenen et al., 1987; Roering et al., 1992). However new geologic and petrologic data show a poly-metamorphic evolution. Geochronology supports a more complex history characterised by a last transpressive tectono-metamorphic event at 2.0 Ga, affecting all of the Central Zone as well as the adjacent part of the Northern Marginal Zone (van Breemen and Hawkesworth, 1980; Barton et al., 1994; Kamber et al., 1995a; Kamber et al., 1995b; Holzer et al., 1995; Jaeckel et al., 1995). No current model can correctly explain the evolution of the entire belt and it has become evident that the geological evolution of all three subunits has to be assessed separately. In this study we focus on the Northern Marginal Zone (hereafter abbreviated with NMZ), which is autochthonous to the Zimbabwe craton (Berger et al., 1995) from which it is separated by a thrust zone.

Based on Rollinson and Blenkinsop (1995), Kamber et al. (1995b) proposed a tripartite division of the NMZ (Fig. 2), reflecting the intensity and nature of its 2.0 Ga overprint. The southernmost unit is the right-lateral Triangle Shear Zone which was active at granulite grade (Kamber et al., 1995a) and together with the adjacent mid-amphibolite facies Transition Zone was deformed during a major phase of 2.0 Ga transpression (Kamber et al., 1995b). In the NMZ sensu stricto (NMZ s.s.), the northernmost unit, the early Proterozoic overprint is of localised extent and is characterised by upper greenschist facies retrogression (Kamber, 1995). In this contribution we concentrate on this northernmost unit so as to avoid confusing the late Archaean with the Proterozoic record.

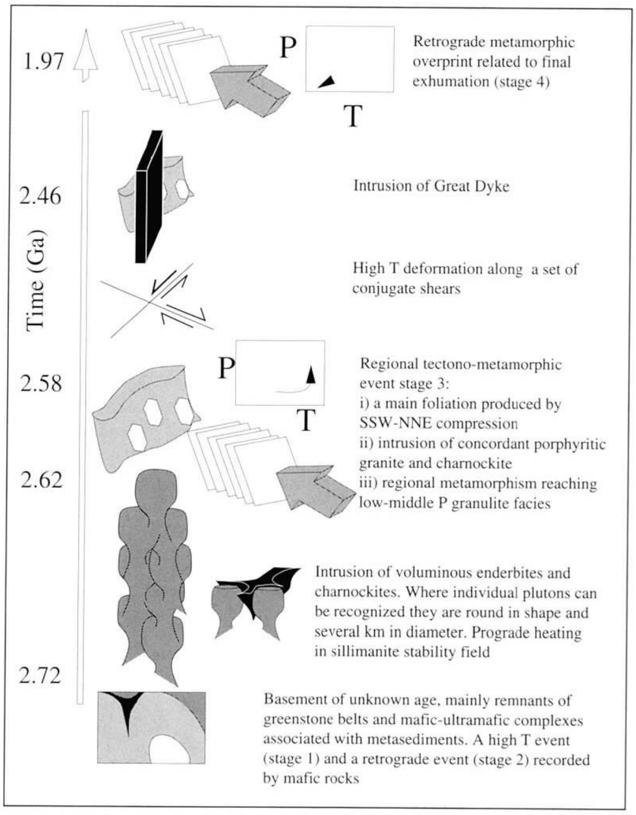

Fig. 3 Schematic geological evolution of the Northern Marginal Zone showing principal magmatic, tectonic, and metamorphic events.

3. Lithostratigraphy and chronological framework

A general description of the evolution of the NMZ s.s. is given in chronological order and illustrated in figure 3. The division into mapable lithologic units and relative age relationships is essentially in agreement with results of field and petrographic reconnaissance studies by Worst (1962), Robertson (1973; 1974) and Odell (1975). It should be noted that most of the primary charno-enderbites were mapped as felsic granulites and interpreted as metamorphosed basement gneisses before Ridley (1992), Rollinson and Blenkinsop (1995) and Berger et al. (1995) showed that they are intrusive rocks with magmatic orthopyroxene (± clinopyroxene). Relative age relationships have since been substantiated by radiometric dating (Mkweli et al., 1995; Berger et al., 1995; Kamber, 1995).

Since all Archaean rocks in the NMZ s.s. underwent granulite facies metamorphism and varying degrees of retrogression, we will indicate each lithology with the name of the presumed protolith. A total of four metamorphic stages, four deformation events and two plutonic episodes was distinguished. In this study we will use the four metamorphic mineral blastesis[4] events as relative time markers in the petrographic description. This chronological concept is essentially based on our observation and its usage will be justified in section 5.1.

i) The pre-intrusive units are characterised by an association of metaironstones, metapelites, quartzites and metabasites and subordinate ultramafics. The majority of them represent remnants of greenstone belts (e.g. Rollinson and Lowry,

[4] The term mineral blastesis is synonymous with "growth of a metamorphic mineral".

1992; ROLLINSON and BLENKINSOP, 1995). Their protolith ages are unknown, however, BERGER et al. (1995) demonstrate a minimum age of 2.72 Ma, given by the oldest enderbite intrusion. Xenoliths of metabasites and metasediments in later intrusions sometimes show a pre-intrusive metamorphic fabric which is a compositional banding of pyroxene, hornblende and plagioclase (Fig. 4a). We will refer to this high grade event as metamorphic "stage 1", which was followed by a retrograde "stage 2".

ii) Charno-enderbitic[5] plutons intruded the NMZ s.s. from 2.72 to 2.62 Ga (BERGER et al., 1995). In general, these intrusives are macroscopically little deformed and their distribution appears to be random. Where deformation is least developed, the rounded shape of individual plutons can be seen, as well as magmatic fabrics.

iii) Between 2.62 to 2.58 Ga (MKWELI et al., 1995; BERGER et al., 1995; KAMBER, 1995) porphyritic granites and subordinate charnockites intruded the NMZ. These bodies intruded as concordant sheets preferentially along the contact between the craton and the NMZ (Fig. 2) during a major phase of NNW–SSE compression. The coeval low P granulite facies metamorphic event affected all lithologies except the very latest intrusions and is termed here metamorphic "stage 3".

iv) After the peak of metamorphism, intrusion of granitic melts ceased and the regional structures were transected by a conjugate set of ESE-striking dextral and NNW-striking sinistral shears, which also occur throughout the southern part of the Zimbabwe craton (TRELOAR and BLENKINSOP, 1995). These shears predate the 2.46 Ga intrusion of Great Dyke system (HAMILTON, 1977).

v) A retrograde upper greenschist facies metamorphic event, "stage 4", occurred at ≈ 1.9 Ga (VAN BREEMEN et al., 1966; VAN BREEMEN and DODSON, 1972; KAMBER, 1995). Mineralogical changes, turning high grade rocks into typical upper greenschist facies assemblages, only occurred where H_2O-rich fluids were available, mainly in dm to m wide reverse shear zones. These reverse shear zones are sub-parallel to the compressional structures developed during stage 3. This event has also affected the craton, since K–Ar and Rb–Sr biotite ages are reset (WILSON and HARRISON, 1973).

[5] The term charno-enderbite is used to maintain consistensy with previous work. It is used to describe intrusive rocks of tonalitic-granodioritic to granitic composition which carry igneous Opx. The presence of magmatic Opx in these rocks implies H_2O under-saturated, hot melts. Although this mineralogy is indicative of felsic granulites, intrusion of charno-enderbite does not require that the intruded basement was at granulite facies.

4. Field and petrographic characterisation

This section describes field relation and microstructural evolution of all rock types encountered in the NMZ s.s. The majority of the 130 rocks collected for this study have been taken along the Mondi and Mwenezi rivers. Samples taken along this main profile are referred to in cumulative km starting from NNW (Tab. 1). Figure 5 is a projection of mapped observations along the profile onto a line perpendicular to strike indicated with x–y on figure 2. The description combines information of the entire mapable lithology. Where variations were found, either systematically along the profile or from single localities, these are separately described and interpreted in the subsequent sections.

Every lithology is introduced by a description of field relations and a brief review of information from the literature. We use a relative chronological framework based on the recognition of four metamorphic blastesis stages, and describe from oldest to youngest.

Where a mineral can be assigned to one of these metamorphic events or the magmatic precursor it is denoted by a subscript (1, 2, 3, 4 = metamorphic stage 1, 2, 3, 4; m = magmatic precursor). Subscripts were omitted for minerals which could not confidently be linked to these categories. Mineral abbreviations generally follow KRETZ (1983) and are listed in the appendix.

4.1. PRE-INTRUSIVE UNITS

The pre-intrusive rocks in the entire NMZ dominantly occur as associations of mafic-ultramafic with metasedimentary units, comprising quartzite, Mag-quartzite, Px-Grt-Mag quartzite, metapelite, calcsilicate rocks and minor Di-bearing marble. Where mafic and metasedimentary rocks dominate, a greenstone belt origin has been suggested (ROLLINSON and BLENKINSOP, 1995). Where ultramafic rocks prevail, their protoliths could have been mafic-ultramafic complexes (e.g. WORST, 1962; ROBERTSON, 1974). Both associations invariably occur as synclinal structures, intruded by charno-enderbites or as xenoliths (several meters long) or septa (dm to several 100 m long) in the plutons The mafic-ultramafic complexes show a variety of rock types, mainly ser-

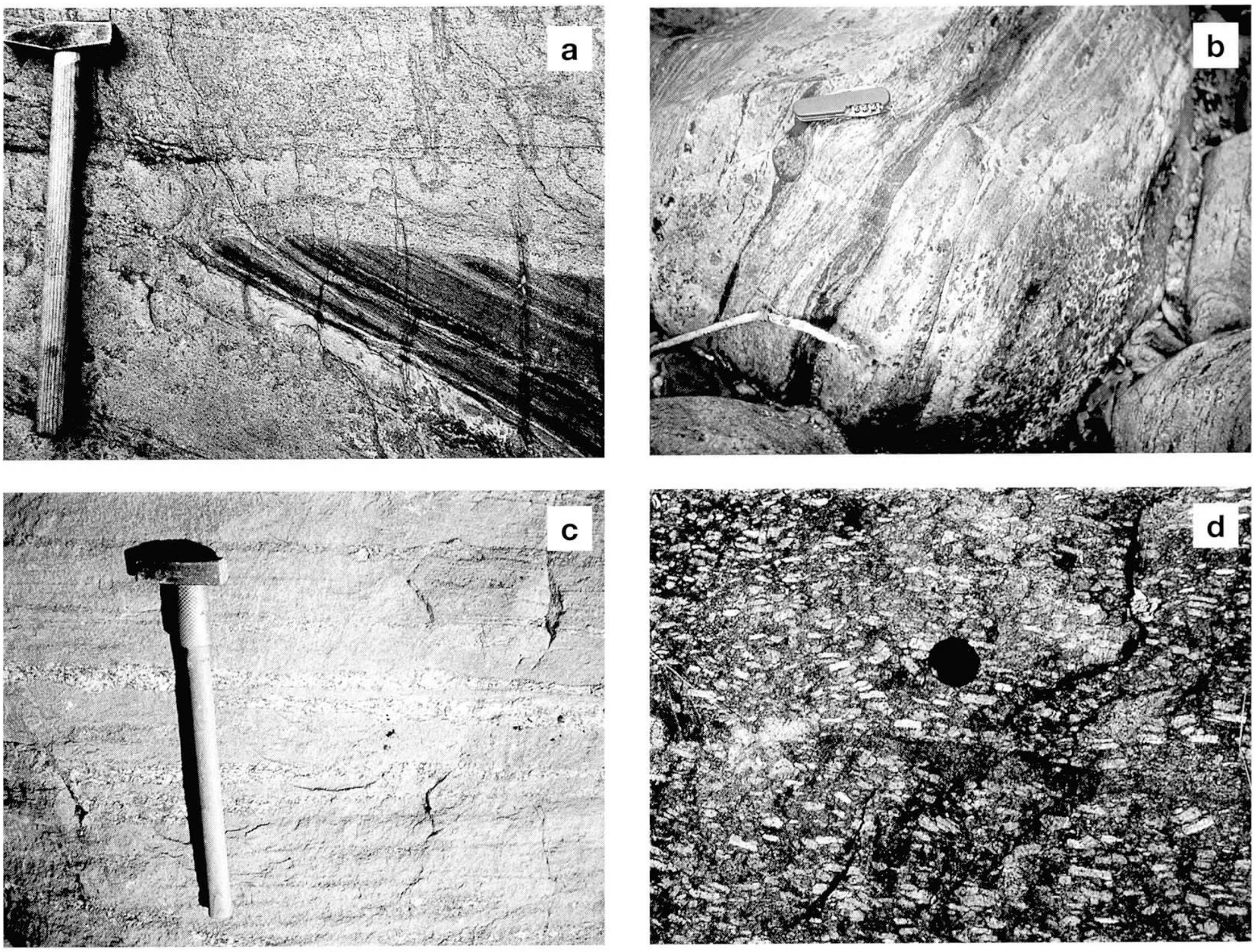

Fig. 4 Key field relationships along the Mwenezi profile: a) Mafic granulite xenolith in 2.68 Ga old intrusive showing an older metamorphic structure. b) Syn-tectonic migmatisation in metapelite. The garnet (near the knife) has columnar sillimanite inclusions (see Fig. 7b). c) Banded migmatite in charno-enderbite. The leucosome is concordant with stage 3 mylonitic foliation. d) Syn-tectonic porphyritic granite. Kfs evidences a magmatic lineation concordant with the stretching in the xenolith (below the lens lid).

pentinites, in some cases preserving primary Chr segregation layers, two-Px granulites, Am-pyroxenites, amphibolites and rare meta-anorthosites associated with minor calc-silicates and Mag-quartzite. Examples are the Towla, Neshuro, Crown and Chingwa-Ma-Karoro complexes, which have been described in some detail (Worst, 1962; Robertson, 1973; 1974; Odell, 1975).

4.1.1. Mafic rocks

Mafic granulites are the dominant component of the pre-intrusive rocks and are frequently found. With very few exceptions (i.e. sample 93/548) they are polymetamorphic and invariably consist of Opx, Cpx, Am, Pl and ore minerals, sometimes with Bt and Qtz. Ore minerals are either Mag and/or Ilm. The absence of Grt is striking when compared to mafics from the Transition and Triangle shear zones, where it is frequently found.

First high T metamorphic assemblage (stage 1)

During the first blastic event a near equilibrium micro-structure of equigranular $Pl_1 + Opx_1 + Cpx_1 + Ore \pm Hbl_1 \pm Qtz$ was formed. Grain size is in the order of 1mm. A compositional banding is made up by alternating Opx-rich and Cpx-rich layers. Hbl_1, which is not always present (like at km 25.2), frequently contains acicular Ilm exsolution along cleavage planes.

At km 33.3 and 2 km N of Bangala dam (93/549), mafic granulites with a different textural history can be found. They show rounded Pl as inclusions in Opx, indicating the igneous texture of

Tab. 1 Rock types encountered along the Mondi-Mwenezi profile. Listed from NNW–SSE.

Sample No	Cumulative distance (km)	Rock-type	Rremarks	Sample No	Cumulative distance (km)	Rock-type	Remarks
92/015	0.0	charno-enderbite	migmatised	92/100	12.7	ultramafic rock	
92/008	0.5	porph. intrusives		92/101	12.7	metasediment	
92/009	1.0	charno-enderbite	migmatised	92/105	12.7	marble	
92/010	1.5	charno-enderbite	migmatised	92/038	14.2	charno-enderbite	migmatised
92/011	2.0	charno-enderbite	migmatised	92/039	14,5	charno-enderbite	
92/016	3.5	porph. intrusives		92/064	14.5	porph. intrusives	
92/014	5.0	porph. intrusives		92/065	14.7	charno-enderbite	
92/013	5.2	porph. intrusives		92/066	14.7	charno-enderbite	
92/012	8.1	porph. intrusives		92/070	15.7	metasediment	
92/022	8.2	porph. intrusives		92/069	15.8	metasediment	
92/023	8.2	porph. intrusives		92/067	16.0	charno-enderbite	
92/024	8.2	porph. intrusives		92/068	16.0	charno-enderbite	
92/017	8.6	charno-enderbite	migmatised	92/072	19.5	porph. intrusives	
92/018	8.6	charno-enderbite		92/071	19.7	mafic granulite	
92/019	9.0	charno-enderbite		92/073	20.7	charno-enderbite	migmatised
92/020	9.0	charno-enderbite		92/074	22.7	charno-enderbite	migmatised
92/021	9.3	charno-enderbite		92/075	22.7	charno-enderbite	
92/027	11.3	charno-enderbite		92/076	22.7	charno-enderbite	
92/028	11.3	charno-enderbite		92/077	23.7	porph. intrusives	
92/025	12.0	charno-enderbite		92/102	25.2	mafic granulite	
92/026	12.0	mafic granulite		92/103	26.7	charno-enderbite	
92/029	12.2	charno-enderbite		92/104	26.8	charno-enderbite	
92/035	12.6	charno-enderbite	migmatised	92/078	27.3	charno-enderbite	migmatised
92/036	12.6	charno-enderbite	migmatised	92/081	27.8	mafic granulite	
92/037	12.6	charno-enderbite	migmatised	92/082	27.8	charno-enderbite	
92/030	12.7	charno-enderbite		92/109	28.5	charno-enderbite	migmatised
92/031	12.7	charno-enderbite	migmatised	92/110	28.5	charno-enderbite	migmatised
92/032	12.7	charno-enderbite	migmatised	92/111	28.5	charno-enderbite	
92/090	12.7	ultramafic rock		92/107	29.8	mafic granulite	
92/091	12.7	ultramafic rock		92/108	29.8	mafic granulite	
92/092	12.7	porph. intrusives		92/106	30.3	charno-enderbite	
92/093	12.7	metasediment		92/079	33.3	charno-enderbite	
92/094	12.7	metasediment		92/080	33.3	mafic granulite	
92/095	12.7	metasediment	migmatised	92/112	36.8	charno-enderbite	migmatised
92/096	12.7	metasediment		92/113	37.8	charno-enderbite	
92/097	12.7	metasediment		92/114	37.8	charno-enderbite	
92/098	12.7	metasediment		92/115	37.8	charno-enderbite	migmatised
92/099	12.7	ultramafic rock		92/116	37.8	charno-enderbite	migmatised
				92/117	37.8	charno-enderbite	

a gabbro. In sample km 33.3 a reaction rim of Opx developed where Cpx_1 and Pl_1 were in contact. At this locality Pl_1 also shows bead perthites and a calcic myrmekite (An-rich Pl and Qtz) due to the reaction:

$$\text{Ab-rich } Pl_m + Cpx_m \Rightarrow \text{An-rich } Pl_1 + Qtz_1 + Opx_1 \quad (1)$$

First retrograde event (stage 2)

An early stage of post peak cooling and hydration is suggested by Hbl_2 + Ore_2 growth at the expense of Opx_1 and Cpx_1. The second ore generation formed at Opx_1-Hbl_2 and Cpx_1-Hbl_2 grain boundaries. Hbl_2 is characterised by a deep green, pale bluish pleochroism.

Second high T metamorphic event (stage 3)

The most common mineral transformation during this event is the symplectite intergrowth of Opx_3 + Pl_3 + Cpx_3 replacing $Hbl_{1,2}$. Grain boundary migration can be proved by relict Ore_2 layers, included in Opx_3 or in the symplectite, still defining the old Hbl crystal shape (Fig. 6). All mafic samples were inspected by electron microprobe and no significant chemical difference between Px_1 and Px_3 and Pl_1 and Pl_3 was found, be-

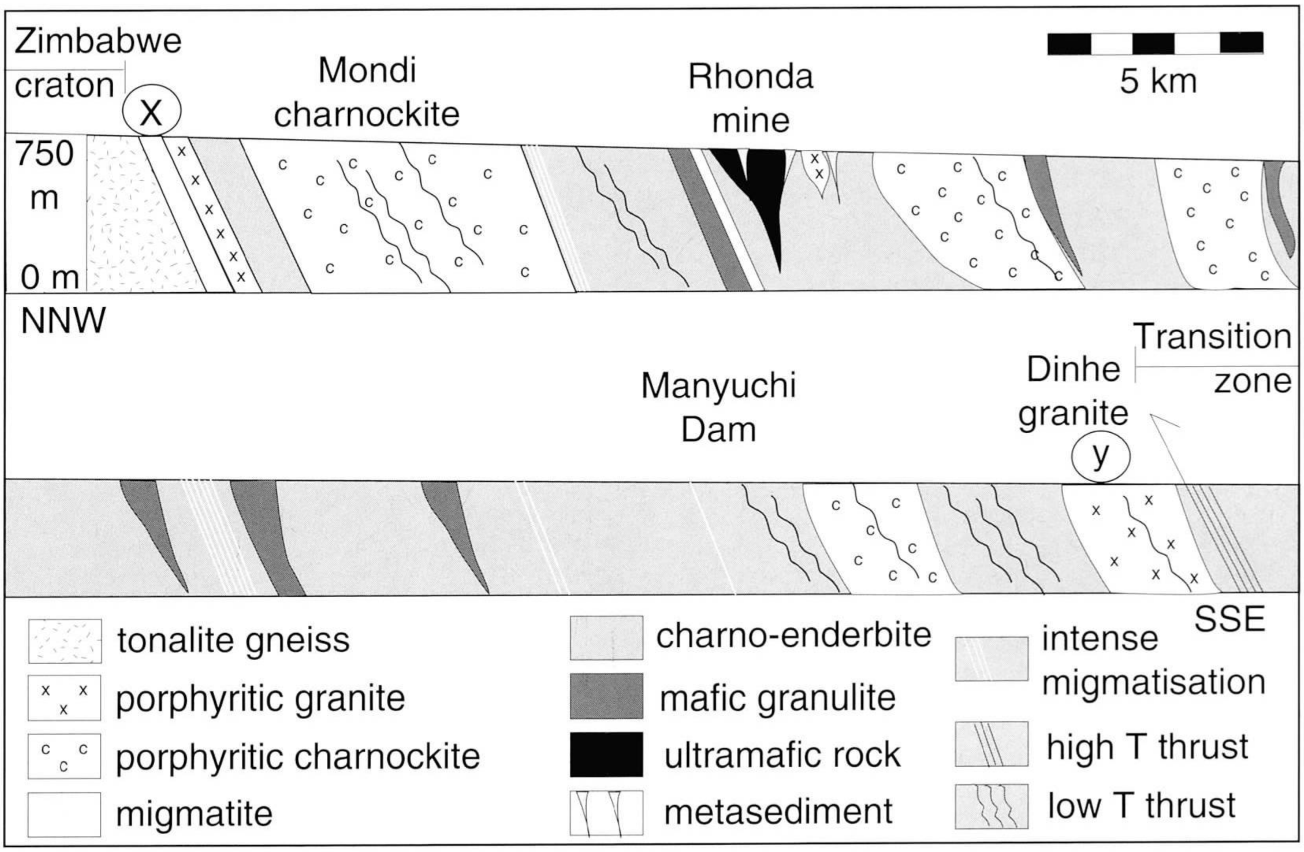

Fig. 5 Projection of the mapped Mondi-Mwenezi traverses onto a line x–y, indicated on figure 2.

cause in Grt-free assemblages Px and Pl chemistries are not very sensitive to changes in PT conditions. The observed frozen reaction can be written as:

$$Hbl_{1,2} \Rightarrow Pl_3 + Opx_3 + Cpx_3 + H_2O \quad (2)$$

A second reaction (e.g. at km 25.2) has been observed:

$$Cpx_1 + Pl_1 \Rightarrow Pl_3 + Opx_3 \quad (3)$$

Rare mm-wide shear zones are made up of granoblastic aggregates (0.2–0.4 mm) of Opx_3 + Cpx_3 + Pl_3 but always lack $Hbl_{1,2}$.

Second retrograde event (stage 4)

Stage 4 is defined as the hydration event of the granulite assemblages. A new generation of Am (Hbl_4) developed. Hbl_4, replacing Opx_3 and Cpx_3, can be recognised by the absence of inclusions. Tiny flakes of red biotite are restricted to zones of intense hydration and have not been found in the other stages, implying K-metasomatism during stage 4 hydration:

$$Opx + Hbl + Pl + fluid \Rightarrow Bt_4 \quad (4)$$

Microstructural evolution

Plagioclase: Pl is the most deformable phase in these rocks since Qtz and Bt are either absent or accessory. In all samples studied it shows albite and pericline twins of tectonic origin. These twins are closely spaced, curved, discontinuous and tend to be taper at the crystal edge. A microstructural change, superimposed on the stage 1 equigranular texture, can be observed along the N–S profile (Fig. 6). In the N, Pl crystals show internal strain, commonly deformation lamellae and wavy extinction. After 12 km, crystallisation of Pl_3 at Pl_1 grain boundaries produced low-strain polygonal aggregates of new small (0.2 mm) blasts. In samples where this recrystallisation is well developed, deformation twins in the big grains tends to disappear or be confined to the central part of the crystal. At 19.7 km the recrystallisation to subgrains along grain-boundaries is replaced by, first, bulging, and further SSE, complex cuspate grain boundary migration. At km 27.8, the mafic granulites are equigranular and Pl triple junctions are common. Nevertheless, the grain boundaries are not planar, but show small cuspate and lobate irregularities (bulging is not present). S of km 29.8

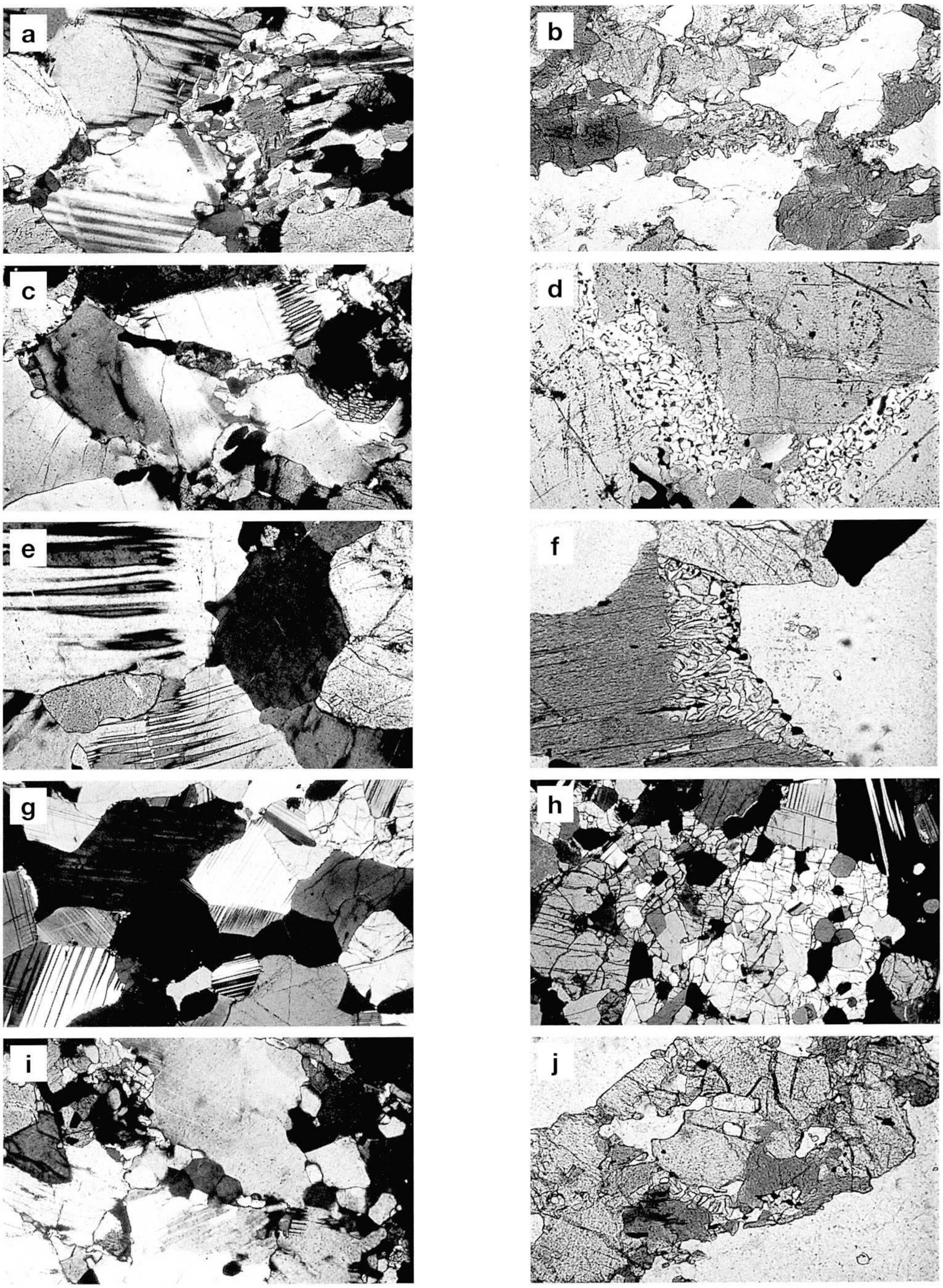

Fig. 6 Microstructural observations in mafic granulite along the Mwenezi profile showing a systematic textural evolution (the width of each photo is 4.5 mm). Systematic change of plagioclase grain boundaries and internal deformation is shown on the left hand side (a: 92/026, c: 92/071, e: 92/081, g: 92/061, i: 92/107). The right hand side illustrates increase in stage 3 symplectite width toward south (b: 92/026, d: 92/071, f: 92/081, h: 93/548, j: 92/107). Note that in the southernmost sample (92/107) recrystallisation related to stage 3 is less evolved. We suggest a minor tectonic repetition of the series. Sample 93/548 from Bangala Dam (locality indicated in Fig. 2) shows a magmatic texture which was only partially re-equilibrated during stage 3.

micro-structures identical to the northernmost samples re-appear.

Pyroxene: Opx and Cpx show wavy extinction, but dynamic recrystallisation is confined to small stage 3 shear zones.

Symplectite: In accordance with the systematic change in Pl deformation mechanisms along the profile, the thickness and grainsize of the stage 3 symplectite increases from N to km 27.8, where it becomes part of the equigranular texture (Fig. 6). S of km 29.8, a sudden decrease in the symplectite development is observed, but increases again towards SSE.

Hornblende: Distinction of different generations of Hbl is difficult. Clearly Hbl_2 carries Ilm exsolution, whereas Hbl_4 does not. Polygonal Hbl_4 mimetically replaces Px in the mm-size stage 3 shear zones. Where Hbl_2 has replaced Hbl_1 blasts, ore exsolutions of Hbl_1 are recrystallised. Where stage 4 recrystallisation was penetrative, stage 3 symplectites survived in pressure shadows of Hbl_4 blasts.

Quartz: Qtz is seldom present and does not play an important role in the microstructural evolution.

Biotite: Red Bt flakes are a late feature. (001) planes of the undeformed flakes define a foliation, which overgrows pre-existing fabrics.

Apart from microstructural and mineralogical features reflecting regional tectono-metamorphism the mafic rocks found as small (dm to several m scale) xenoliths in charno-enderbites also show "contact-metamorphic" features. Since these have been widely described in the literature (see ROLLINSON and BLENKINSOP, 1995, for a discussion), it seems appropriate to briefly explain differences between "contact" and regional metamorphic reaction textures. Mafic xenoliths found in enderbite and charnockite show a distinctive (dark weathering) alteration rim, which had been interpreted as a zone of Am dehydration during entrainment into the hot, H_2O undersaturated melt. Two such rims have been studied under the microscope and indeed they are Am-free and consist of Opx + Cpx + Pl + Bt + Qtz. In contrast to stage 3 dehydration symplectites, the alteration rims contain appreciable amounts of Bt (5–10%) and Qtz (5–10%). The presence of Bt, although usually concentrated along the xenolith-host contact, suggests that these rims are the result of a reaction which is more complex than Am dehydration. We prefer to describe them more generally as a partial host-xenolith equilibration in which a fluid was involved. This may have taken place syn-, late- or post-magmatic. The important observation is that such rims can easily be identified (and distinguished from stage 3 dehydration) and that they indicate a T-X disequilibrium between the charno-enderbite (melt) and the country rock.

4.1.2. Ultramafic rocks

Along the Mondi-Mwenezi profile three occurrences of ultramafic and mafic rocks are known, the biggest of which is an antiformal structure at km 12.7, which has been described by MWATAHWA (1992). This occurrence is predominantly composed of mafic and ultramafic rocks associated with Mag-quartzite, quartzite and rare marble, and hosts the Inyala and Rhonda chromium mines. In general, the core of these bodies preserves primary magmatic or high-grade structures, whereas the rims are strongly serpentinised, brittely deformed or pervasively altered (Carb and Qtz veining). Other smaller occurrences along the profile are described by WORST (1972).

Mineralogy

The ultramafic rocks in the core of the bodies are composed of Opx + Spl ± Cpx ± Am. This high T assemblage could either represent metamorphic stage 1 or 3. No hint for two high grade events was found. The high T mineralogy gradually gives way to carbonate-bearing serpentinites towards the rim of the bodies. Serpentinisation can tentatively be linked with stage 4.

Fabric

The rim is mostly brittely deformed at low T. Cal and Dol typically fill fractures. However, the core shows primary cumulitic structures defined by alternating layers of medium grained Opx ± Spl and fine grained Spl ± Opx. Three generations of black-brown Spl have been characterised. Coarse grained interstitial Spl shows maple-leaf texture. Small sub-mm Spl idioblasts are included in Opx and vermicular black Spl is observed in the Opx rim (usually when in contact with Cpx). Both Cpx and Hbl are very rare, interstitial and mostly replace Opx.

4.1.3. Metasedimentary rocks

Metasediments are also rare along the profile (Fig. 4) and other selected localities had to be examined in addition (Fig. 2). Apart from the typical association with mafic and/or ultramafic rocks, little can be said about the relation with other lithologies. Metasediments tend to be found along the rims of mafic and ultramafic complexes (e.g. Bangala Dam area; ODELL, 1975 or Mount Towla; WORST, 1962), or as concordant lenses within charno-enderbite gneiss (Manjirenji Dam area; ROLLINSON, 1989). Their mineral assemblages are typical of low to medium P granulite facies and preserve abundant reaction textures. All metasediments have been strongly deformed during NNW–SSE compression. On one hand this allows us to relate specific portions of the PT path of metamorphic stage 3 with the main deformation, but on the other hand it inhibits correlation of the pre-stage 3 evolution. In other words, some predeformational phases could either represent stage 1 or 2 relics or prograde stage 3 products. The syn- and post-deformational minerals can, however, be correlated with stage 3 and 4, respectively.

4.1.3.1. Quartzite and magnetite quartzite

Quartzitic rocks are the most abundant metasediments. They range in composition from pure quartzite, Mag quartzite, Mag-Px quartzite to Mag-Px-Grt quartzite. The Mag bearing varieties display a primary banding, typical of banded ironstones. They behaved completely ductile during deformation and can often be found as tightly folded bands either within charno-enderbite gneiss or around mafic inliers.

Mineralogy and structure

Mag free quartzites consist of Qtz and rare Kfs, which form a granoblastic, equigranular texture. Qtz usually shows complete recovery. No accessory minerals have been detected – in agreement with a chemical origin of these sediments.

Most common are Mag quartzites. They consist of Mag and Qtz and subordinate Kfs, and also lack accessory minerals. The compositional banding is often strongly folded. Mag occurs either as massive layers or as epigranular, fine-grained Qtz-Mag bands alternating with almost pure Qtz bands. Where Kfs can be found in the Qtz bands, it shows internal deformation, like Qtz which did not recover from the last deformation.

Another type of impure quartzite is made up of Mag + Qtz + Opx ± Cpx ± Kfs. These rocks are usually coarse grained (Px can reach up to 1 cm in diameter). Opx grew around Mag aggregates and was thus possibly produced by:

$$\text{Qtz} + \text{Mag} \Rightarrow \text{Opx} + \text{oxygen} \quad (5)$$

In all studied samples Opx is a pre-deformational phase, but as mentioned above, it could either be a prograde stage 3 product or a stage 1, 2 relic. Where Opx is scattered in the Qtz matrix, it appears euhedral but is rotated. Within several mm thick Px bands, big Opx crystals are not only rotated but also bent and recrystallised. Accessory Zrn can be found in the Opx-rich domains.

A similarly structured variety of impure quartzite contains Pl, which is always strongly deformed, either showing internal deformation or more often grain-boundary migration. The occurrence of Grt is restricted to these Pl bearing quartzites. Two generations of Grt can be distinguished. A first garnet generation is intergrown with Mag forming myrmekite textures which are syn-deformational. The second generation of garnet is post-deformational and formed either in Cpx or Pl rich varieties. It replaces Pl and Opx (Fig. 7a), sometimes together with Cpx and Qtz, according to the reactions:

$$\text{Opx} + \text{Pl} \Rightarrow \text{Grt}_3 + \text{Qtz}_3 \quad (6)$$
$$\text{Opx} + \text{Pl} \Rightarrow \text{Grt}_3 + \text{Cpx}_3 + \text{Qtz}_3 \quad (7)$$

The only retrograde transformation is the growth of rare green Am around Px correlative with stage 4. Hem and Fe-hydroxides grew upon weathering and give these rocks their rusty appearance.

4.1.3.2. Metapelite

No metapelite was encountered along the main profile. The rocks described here are from the mouth of Manjirenji Dam and two localities of the Chiredzi river profile (20 km S of the Zimbabwe craton, Fig. 2). All five samples were migmatised during the main NNW–SSE compressional stage 3 deformation. Various degrees of melt segregation are encountered. Figure 5b shows a concordant-stromatic example where leucosome and melanosome are well distinguishable. Other samples are poorly segregated and melanosomes are found as rafts and irregular streaks in leucosome pockets. In these samples it is often difficult to assign a phase to the reactant or product side of a postulated reaction. Nevertheless, based on mineralogy and texture, the high T evolution of the metapelites can be divided into a pre-migmatisation, a syn-migmatisation/deformation and a post-migmatisation portion (similar to the evolution of impure quartzite):

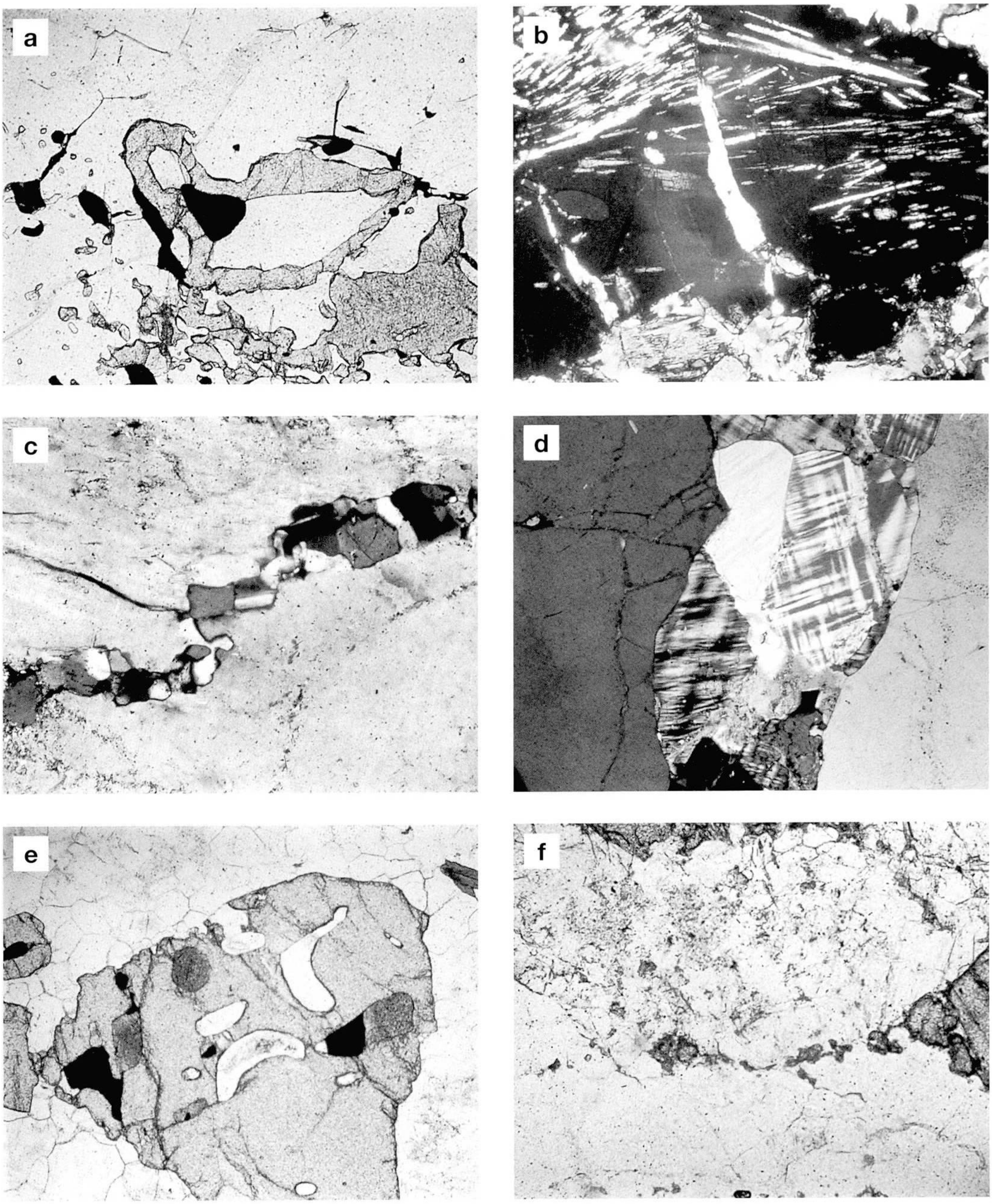

Fig. 7 Microstructural relationship. a) Garnet rimming plagioclase in a magnetite-bearing impure quartzite (the width of the photo is 1.1 cm). b) Pre-deformational (stage 3) sillimanite inclusions in garnet (the width of the photo is 4.5 mm). c) Cuspate and lobate grain boundary at a plagioclase-plagioclase contact in a charnockite. Pl_3 granoblasts grew during stage 3 (the width of the photo is 4.5 mm). d) Grain boundary at a K feldspar-K feldspar contact in porphyritic granite. K feldspar recrystallised in a granoblastic aggregate of microcline, plagioclase and quartz (the width of the photo is 4.5 mm). e) Green spinel, magnetite and lobate quartz inclusions in magmatic garnet formed during stage 3 migmatisation in charnockite (the width of the photo is 1.1 cm). f) Magmatic orthopyroxene in a charnockite. The granoblastic metamorphic tail is made up of metamorphic clinopyroxene-orthopyroxene-plagioclase (the width of the photo is 1.1 cm).

Pre-migmatisation
(hence stages 1, 2 or prograde stage 3)

The pre-migmatisation assemblage contains Qtz + Bt + Opx + Grt + Sil. The earliest reaction texture is marked by randomly oriented fibrolitic or columnar Sil inclusions in big Grt porphyroblasts (Fig. 5b and 7b). The first garnet thus grew in the Sil stability field, possibly due to St breakdown:

$$St + Qtz \Rightarrow Grt + Sil + H_2O \quad (8)$$

Migmatisation

All encountered leucosomes either carry Grt or Crd which implies H_2O undersaturated breakdown of Bt ± Sil ± Qtz ± Kfs. Since the leucosome contains Kfs blasts with up to 50% Pl exsolution in addition to Qtz, Pl and Grt (typically only containing kidney shaped Qtz inclusions) or Crd, we believe that Kfs was a product in our rocks (cf. CARRINGTON and WATT, 1995). Typical reactions are:

$$Bt + Sil + Qtz \Rightarrow Kfs_3 + Grt_3 + melt_3 \quad (9)$$
$$Bt + Sil + Qtz \Rightarrow Kfs_3 + Crd_3 + melt_3 \quad (10)$$

or the sub-reaction:

$$Bt + An\text{-}rich\ Pl \Rightarrow Spn_3 + Kfs_3 + melt_3 \quad (11)$$

During melting all Sil was consumed because it only survived as inclusion in the big Grt porphyroblasts in the melanosome. The old Grt, where it was in contact with the melt, was overgrown by a texturally recognisable, fine rim of Grt_3. Spn was found in a poorly segregated migmatite, generally concentrated in the Bt-poor parts. The main deformation produced granoblastic Mc + Pl + Qtz aggregates in the leucosome.

Post-migmatisation

After migmatisation fine-grained Grt-Qtz symplectites were formed around older Grt by reaction (6) where it was near Opx and Pl.

The high T migmatite structure was partly destroyed in low T shear-zones (stage 4). Where this last deformation was accompanied by aqueous fluid infiltration, Crd_3 porphyroblasts were replaced by white mica. In dry micro-shear zones Opx and Grt porphyroblasts were rotated and Qtz completely recrystallised.

4.1.3.3. Marble and calcsilicate

Cal-Di marbles are extremely rare. One sample (92/105) was found in the Inyala area by MWATAHWA (1992). It is a coarse grained rock with a high T assemblage of Cal and Cpx ($Di_{54-47}Hd_{35-42}Fs_{7-12}$). Cal shows strong deformation and defines a mortar structure. Di is rimmed by Kfs and Qtz. Late stage 4 Fac partially replaced Di.

Calcsilicate granulites (Di, Pl, Qtz, Am, Spn, ± Scp, ± Grt) have been described by ROBERTSON (1973; 1974) and ODELL (1975) but were not found along the Mwenezi-Mondi profile.

4.1.3.4. Highly aluminous granulite

ROBERTSON (1973) described two localities of aluminous magnesium-rich granulites (Opx, Ath, Spl, Spr, Crd and Bt). No similar rocks were found in this study. We have examined the thin sections of Robertson's collection and confirm his detailed petrographic description (pp. 43, ROBERTSON, 1973). Important reaction textures are preserved. On page 44, Fig. 4C, a symplectite of Spr, separating Spl and Crd, is shown. Growth of Spr in this rock can thus be explained by:

$$Spl_3 + Crd_3 \Rightarrow Spr_3 \quad (12)$$

Fig. 4B shows Spr and Opx overgrowing Spl, due to:

$$Crd_3 + Spl_3 \Rightarrow Spr_3 + Opx_3 \quad (13)$$

Crd is a syn-deformational blast, but the proposed reaction products are post-deformational. This allows to correlate both assemblages with stage 3.

4.2. CHARNO-ENDERBITES, THE "PLUTONIC ASSEMBLAGE"

The dominant rock types in the NMZ s.s. are charnockites and enderbites. The presence of magmatic Opx and minor Cpx has been described by RIDLEY (1992). ROLLINSON and BLENKINSOP (1995) introduced the term "Plutonic Assemblage" for this magmatic differentiation series, which has been characterised by BERGER et al. (1995). The chemistry of these magmatic Opx-bearing rocks ranges from gabbro, quartz-diorite, tonalite, granodiorite to granite, the last three dominating. Different lines of evidence have been followed to demonstrate the magmatic origin of Opx, hence water undersaturated silicic melts, and are summarised in BERGER et al. (1995), who also showed that intrusion occurred over a period of 100 Ma. Corresponding higher-level plutons, mainly tonalites and granodiorites of the same age, can be found throughout the Zimbabwe craton (e.g. TAYLOR et al., 1991; JELSMA, 1993). The majority of the plutons are little deformed on an outcrop scale, carrying only a weak foliation. On a map scale, however, it can be seen that they have been deformed into huge (several km amplitude) open to isoclinal folds. The eastern part of the NMZ s.s. has been more pervasively folded than the west, where folds are more open. Along the main profile, parasitic folding on m and dm scale can only be found in hinge zones of km scale folds. Intrusive contacts are well preserved in the western part of the NMZ s.s. and individual plutons can be seen on satellite images (ROLLINSON and BLENKINSOP, 1995). The syn-formal shape of mafic-ultramafic complexes has been explained as a result of doming by MWATAHWA (1992). All geologists agree that the charno-enderbites intruded during a period of little regional stress.

After intrusion, the charno-enderbites experienced variable degrees of stage 3 and 4 deformation/recrystallisation. The SSE–NNW compression led to a penetrative weak to medium-strength foliation. This deformation was coeval with incipient to total migmatisation. Two migmatite types have been recognised in the field. The first type has a hololeucocratic leucosome with typical charnockite appearance, is coarse-grained (Kfs up to 1 cm) and was produced from charnockite (Fig. 4c). The second type is always white, granitic in composition and Grt-Mag bearing, described as white granites by ROLLINSON and BLENKINSOP (1995). Where migmatisation was pervasive, restites with unusual chemistries and mineralogy (Opx, Sil, Grt, Spl, Crd, Qtz) occur as m-sized lenses or in narrow bands. The migmatites normally concentrated more strain than the surrounding lithologies. Retrograde greenschist to lower amphibolite facies assemblages (Chl, Ep, Spn, Bt, dark green Hbl) are found in dm to m wide shear zones, most frequently within a few km of the craton. Corresponding fluid-absent retrograde recrystallisation is widespread (RIDLEY, 1992).

The observed fabric is thus dependent on the original magmatic mineralogy, the degree of stage 3 high-grade recrystallisation (including migmatisation) and the intensity of retrograde stage 4 overprint. We describe the features associated with this evolution in a chronological order. Because the intrusion of charno-enderbites post-dates the metamorphic stages 1 and 2, the high grade tectono-metamorphism can be correlated with stage 3, of which the migmatites record various portions.

Magmatic precursor

RIDLEY (1992) has given a detailed description of charnockite textures in the NMZ. Our observations concerning the igneous stage are largely in agreement. The degree of preservation of both magmatic mineralogy and texture decreases from NNW to SSE along the profile. Even in the SSE, most rocks preserved at least parts of their magmatic mineralogy, which ranges from Opx + Cpx + Qtz + Pl ± Bt, Opx + Pl + Qtz ± Bt, Pl + Qtz + Kfs + Opx ± Bt to Kfs + Pl + Qtz. The following order of crystallisation is inferred: Pl –> Qtz –> ± Cpx –> Opx –> ± Kfs ± Bt. An even-grained (average grain size of Fsp is between 5 to 10 mm, Px normally 50% smaller) massive magmatic structure, sometimes with cumuli of Pl or Px, is occasionally preserved. RIDLEY (1992) and BERGER et al. (1995) describe Bt-Qtz intergrowths spatially associated with Opx as indicating a magmatic reaction relationship. Although we observed a similar texture in a few of our samples, we find it hard to demonstrate that this feature should be characteristic of the entire NMZ s.s. The following observations are used to justify this statement: (i) we have found a number of Opx-bearing samples entirely lacking a hydrous phase; (ii) Bt interfingered with Qtz is frequently found overgrowing Opx in those rocks which suffered strong retrograde overprint (iii) the degree of migmatisation (which produced similar textures) has been drastically under-estimated by all previous studies in the NMZ s.s., and (iv) the most common late magmatic myrmekites in our samples are bulbous Qtz-Pl intergrowths replacing Kfs.

Stage 3 high T tectono-metamorphism without migmatisation

Charno-enderbites which escaped migmatisation, and thus an obvious high T metamorphic overprint, record corresponding, but sometimes subtle, deformation phenomena. During the main NNW–SSE compression a weak to medium foliation was developed. In proto-mylonite Qtz is found in almost monomineralic ribbons, in which Fsp and Px grains are rotated. In the majority of rocks Qtz has undergone later recrystallisation either into polygonal aggregates or into lobate, coarse-grained single crystals (exaggerated grain growth). Both Pl and Kfs are recrystallised. Although sub-grain formation along Fsp grain boundaries is dominant, the rotated igneous Fsp crystals are cut by sub-mm shear domains, characterised by cuspate intra-grain boundaries (Fig. 7c). Bulbous Qtz + Pl myrmekites only survive in big, relatively undisturbed Fsp clasts from the northern third of the section and again S of Manyuchi dam (km 33.3). Usually they recrystallised to Pl_3 + Qtz_3 + Mc_3 during the HT deformation. Magmatic Kfs, sometimes preserving Karlsbad twins, invariably recrystallised to Mc_3 (Fig. 7d). Opx grains show internal deformation (wavy extinction), but are recrystallised only marginally. However, in micro-shear domains, a new granoblastic assemblage of Opx_3 + Pl_3 + Qtz ± Cpx_3 can frequently be observed. It is interesting to note that samples carrying Cpx_3 lack Cpx_m.

Stage 3 high T tectono-metamorphism with migmatisation

Migmatite structures in charno-enderbites are commonly concordant with the main (stage 3) foliation and are found where deformation was strongest. Migmatites are stromatic (leucosome bands are several cm wide), but in places melt segregation was poor and m sized leucosome pockets exist.

The two types of migmatites have different leucosome mineralogy. The first type, greasy brown to greenish in appearance, consists of perthitic Kfs (up to 50% Pl exsolution), Qtz and minor Pl and Mag. The second type, white in colour, carries Grt, green Spl and very fine-crystalline Sil in addition. Both types show a similar microstructural evolution. Pl exsolutions are coarser at grain boundaries, where Pl locally even mantled Kfs. In the most deformed, mylonitic samples, intense Fsp recrystallisation led to a grain-size reduction by a factor of 10 to 20. In less deformed samples the plastic behaviour of Kfs (sometimes magmatic lasts up to 1 cm can be recognised) also points to deformation at still high T. Relatively high T outlasted the time of deformation as the deformed and grain-size reduced Fsp had time to statically recrystallise to a mortar texture producing Mc + Pl + Qtz aggregates.

The presence of Grt, Sil and green Spl in the second type of leucosomes indicates an Al excess during migmatisation. Columnar Sil is a prograde phase which only survived when rimmed by Pl and Kfs. Green Spl occurs as inclusions in Mag and Grt, but also in the fine grained matrix, at equilibrium with Pl, Mc and Qtz. Grt only has few inclusions, namely Spl, Mag and kidney-shaped Qtz (Fig. 7e), typical of magmatic garnet (e.g. SEVIGNY, 1993).

The mineralogy of restites is primarily a function of how much melt has been extracted. Where little melt was produced, the restites contain an assemblage similar to the protolith, with a modal decrease of Kfs and a clear increase of Opx. Restites are invariably strongly recrystallised and form a granoblastic texture of Opx + Pl + Qtz ± Kfs. In rocks where melting was more extensive, exotic restites developed. Sample 92/073 consists of 40% Qtz, 40% Crd, 15% Opx and 5% Bt and appreciable amounts of Zrn. Opx and Crd form porphyroblasts of 2 and 0.5 cm respectively. Crd is strongly deformed and contains Mnz and Xen, but no Bt. Opx appears undeformed and crystallised together with Qtz and Bt, which form myrmekite enclosed by Opx. Along Opx-Crd grain boundaries, a bimineralic granoblastic seam is typical. Sample 92/078 underwent a very high degree of melting, but not all the melt was extracted from the restite. This led to a complex reaction history. The sequence of crystallisation is Qtz + Opx + Mag –> green Spl_3 –> Grt_3 –> Kfs_3 + Grt_3 + Qtz_3 –> Bt. Green Spl and the first Grt formed during the first stages of melting. Later Grt formed as a result of a reaction between the crystallising remaining melt (Qtz and Kfs with 40% Pl exsolution) as a rim around existing Grt. This rock is also very enriched in Zrn, but lacks Ap.

Stage 4 retrogression

Retrogression of those charno-enderbites which escaped migmatisation is similar to and described with, the porphyritic granites and charnockites. In migmatites, retrogression is commonly developed along restite-leucosome interfaces. Bt overgrew Opx, Chl partly formed pseudomorphs after leucosome Grt and replaced Bt. Marg can be found in Crd and Sil. These replacements are more pervasive in dm-sized shear zones, such as those found N of Manjirenji dam.

4.3. PORPHYRITIC GRANITES AND CHARNOCKITES

The intrusion of porphyritic granites and charnockites followed the charno-enderbites with no evident time gap. Radiometric dating confirmed the relative age relations. A Rb–Sr whole-rock errorchron on the Razi suite holds 2583 ± 52 Ma (MKWELI et al., 1995) which compares well with a similar errorchron of 2587 ± 38 Ma on the Dinhe body (HOLZER et al., 1995). U–Pb Zrn ages range between 2591 ± 4 for the Samba granite (KAMBER, 1995) and 2627 ± 7 Ma for the Mondi body, which forms part of the Razi suite (MKWELI et al., 1995). All porphyritic intrusions are thus the same age or younger than the youngest enderbite intrusion.

The porphyritic granites and charnockites can generally be distinguished from the older intrusions on the basis of three criteria: (i) their pluton shape; they form elongate (few km wide, tens of km long), sheet-like bodies, concordant in the foliation; (ii) their state of deformation, which includes either syn-intrusive deformation fabrics typically involving flow lineation of euhedral, 3–5 cm long Kfs phenocrysts and elongate (l/w = 10–20) basic xenoliths (Fig. 4d), or mylonite fabrics and (iii) the lack of evidence for migmatisation.

They are most common along the Northern Thrust Zone (Figs 2 and 3), where they are called the Razi Suite (e.g. MKWELI et al., 1995), but similar bodies can be found further south (e.g. the Renco body, RIDLEY, 1992; the Samba granite, ODELL, 1975 and the Dinhe granite, KAMBER et al., 1995b).

The porphyritic intrusions are the most important structural marker in the NMZ s.s. The majority intruded coeval with the main NNW–SSE compression and the metamorphic peak and hence allow for indirect dating of stage 3 tectono-metamorphism. However, the very latest intrusions, very K-rich granites, usually pink and pegmatitic in texture, escaped high T tectono-metamorphism. They are spatially associated with irregular, cm to m wide zones of pink alteration in the surrounding charno-enderbites. These retrogressive zones have been termed "retrogressive granodiorites" by BERGER et al. (1995) and can be seen as the opposite of classical arrested charnockites (e.g. RAITH and SRIKANTAPPA, 1993). In other words, instead of a CO_2-rich fluid transforming granite into charnockite, charno-enderbite was transformed into granodiorite by infiltration of a hydrous fluid, associated with the latest, K-rich granites in the NMZ s.s. MKWELI et al. (1995) described the relation between granite intrusion and thrusting along the NMZ-craton boundary and reached the conclusion that granite emplacement preferentially took place along the thrust zone. In spite of porphyritic granite intrusions locally obliterating the thrust zone, a continuous tectonic break between the craton and the NMZ is now widely accepted (e.g. BLENKINSOP et al., 1995). MKWELI et al. (1995), in agreement with previous descriptions of the Northern Thrust Zone, note a wide range in mineralogy preserved in the mylonites developed in porphyritic granite and charnockite. The first type of mylonite is characterised by a high T (stage 3) mineralogy, the second, however, reflects stage 4 mylonitisation under upper greenschist facies conditions (Qtz, Pl, Kfs, Ep, Chl, Ilm, ± Bt, ± green Am). Based on this observation, the thrust was seen as having been active during peak and retrograde conditions. Based on our mapping along the Chiredzi river, we postulate an evolution reflecting intrusion coeval with stage 3 tectono-metamorphism, followed by two distinct tectonic episodes.

Igneous features

All investigated porphyritic intrusives partially preserved their igneous mineralogy. It consists, in order of crystallisation, of Pl + Qtz + Kfs ± Opx ± Bt. Pl generally shows beads and myrmekitic exsolution, bulbous Pl + Qtz myrmekites are, however, only preserved in the northernmost five km of the main profile. Perthitic Kfs is usually found as hypidiomorphic grains (up to 7 cm long) and gives these rocks a porphyritic appearance. Opx formed interstitial grains of only several mm length. Large, zoned Zrn, Ap and ores are found as accessory phases.

In the very latest granites Qtz crystals partly show crystal faces. These rocks are true 2-Fsp granites and crystallised along the two feldspar + liquid curve (PAL). Kfs is found as Mc or subordinate as Or. In the related "retrogressive granodiorites", Pl crystals were partially replaced by Mc and Or.

Stage 3 tectono-metamorphism

MKWELI et al. (1995) described the porphyritic intrusions as preserving varying degrees of NNW–SSE compressional deformation. Our observations confirm this finding because the degree of high T recrystallisation is highly variable, sometimes subtle, but almost always present.

During high T deformation the rocks developed a gneissic texture, Fsp behaved plastically. Recrystallisation is most obvious in mm wide shear domains where a fine grained but granoblastic texture (blasts up to 0.2 mm) was formed. The new assemblage is made up of Qtz_3 + Pl_3 + Mc_3 + Opx_3 ± Cpx_3: it should be noted that Cpx in these rocks only occurs as a metamorphic mineral, a conclusion also reached by MKWELI et al. (1995). In less deformed rocks, high T recrystallisation is less obvious, especially N of km 19.5. Nevertheless, high T deformation is indicated by: (i) a mortar structure at Fsp and Opx grain boundaries (Fig. 7f), where the Opx_m recrystallised to metamorphic Opx_3; (ii) Fsp recrystallisation, especially granoblastic Pl aggregates along cracks in Kfs and Kfs-Kfs grain boundaries (usually associated with Mc) and erasure of exsolution phenomena and myrmekitic intergrowth; and (iii) Fsp deformation, dominated by wavy extinction in the N and deformation lamellae in the S part of the profile. These deformation phenomena may indicate a decrease in T, namely from granulite facies (growth of metamorphic Opx_3 and Cpx_3) to Fsp recrystallisation in the 2 Kfs stability field. This observation will be discussed in the following sections, together with the fact that the very latest 2-Fsp granites post-date this tectono-metamorphism.

ESE-striking dextral and NNW-striking sinistral shearing

ROLLINSON and BLENKINSOP (1995), MKWELI et al. (1995) and TRELOAR and BLENKINSOP (1995) describe a conjugate set of shear zones that post-date the main NNW–SSE compression fabrics. These shears are well developed in the S part of the craton. In the NMZ s.s. they are mainly recognised in the porphyritic intrusions, where they are usually a few cm wide. ROLLINSON and BLENKINSOP (1995) argue, on the basis of biotite deformation, that movement along these shears occurred at T as low as greenschist facies in the NMZ, yet TRELOAR and BLENKINSOP (1995) see them as conduits for 2.59 Ga Chillimanzi granites. It is at present unclear whether these shears are a retrograde part of stage 3 or entirely belong to stage 4.

Stage 4 retrogression

Although low T mineral assemblages and deformation phenomena had been found associated with NNW thrust mylonites in previous studies of the NMZ (see MKWELI et al., 1995, for a discussion), they were seen to be part of the same event as the high T mylonites. By analogy with the greenschist retrogression observed in all other lithologies, we describe the latest deformation of the porphyritic intrusions as a distinct event. This view and resulting implications will be justified and explained in the following section.

Greenschist assemblages are best developed in shear zones which normally are parallel or subparallel to the stage 3 foliation. The assemblage contains Ep_4, green Am_4, Spn_4, Ab_4, Qtz_4 and Bt_4. In a few samples retrogression was pervasive and a strong tectonic fabric is observed. Bt_4 and Spn_4 occur either as undeformed grains defining a growth lineation or within dm wide shear bands, in which Qtz recrystallised, but Fsp behaved brittely. Usually retrogression is only partially developed, such that Opx and Cpx are marginally replaced by $Bt_4 + Am_4$, or $Bt_4 + Qtz_4$ appear to replace Kfs and Opx via the reaction:

$$\text{Kfs} + \text{Opx} + \text{fluid} \Rightarrow Bt_4 + Qtz_4 \qquad (14)$$

Where recrystallisation was not accompanied by hydrous fluid infiltration, a low T deformation can still be seen from the behaviour of Qtz (RIDLEY, 1992). In many samples Qtz forms polygonal aggregates (high angle grain boundaries), whereas bigger grains are characterised by internal deformation and low angle sub-grain boundaries.

A last stage of mainly brittle deformation is associated with very low grade metamorphic recrystallisation (Prh + Pmp + Chl + Ep ± Tlc ± Spn). Tlc and Chl grew along Opx fractures, hydrothermal Ms grew in the hololeucocratic granite 92/008, and Pl was overgrown by Ab upon hydrothermal alteration in sample 92/008.

5. Summary and interpretation

The principle aim of this section is to summarise and present all our observations within the framework of a simple, coherent model for the evolution of the NMZ s.s. Obviously, an attempt to qualitatively understand this evolution benefits from the preservation of relic structural, magmatic and metamorphic features and the various frozen reaction textures. The former allows us to subdivide the evolution on a relative time scale, and the latter enables us to propose a qualitative PT evolution for the late Archaean (stage 3) granulite event. We will first summarise the different stages of the evolution based on the descriptive evidence and other available data, followed by an interpretation of reaction textures, focusing on the stage 3 granulite event only. This evolution will finally be linked to the magmatic and structural evolution in order to define key observations which have to be incorporated in tectonic models for the late Archaean NMZ s.s.

5.1. EVIDENCE FOR DISTINCTIVE EVENTS

A relative time frame has been used throughout the descriptive section. Here we justify its usage and discuss, where our concept differs from previous ideas, its significance.

5.1.1. Pre 2.72 Ga evolution (stages 1 and 2)

The best evidence for a tectono-metamorphic history that pre-dates the oldest known enderbite intrusion (2.72 Ga; BERGER et al., 1995) is recorded in the mafic granulites. In accordance with ROLLINSON and BLENKINSOP (1995) it can be postulated that the relict Pl_1 + Opx_1 + Cpx_1 + Ore ± Hbl_1 ± Qtz assemblage reflects a granulite facies metamorphic event (stage 1). The key observation is that Hbl_1 always shows a dehydration symplectite of Pl_3 + Opx_3 + Cpx_3, which is identical to the paragenesis in microscopic shear zones correlative with the main stage 3 deformation. BERGER et al. (1995) noted that mafic xenoliths in felsic intrusions carry a strong tectonic fabric cut by the melt (Fig. 4a). In this study, this fabric was recognised as a compositional banding made up by alternating Opx-rich and Cpx-rich layers. Taken together this requires a pre-2.72 Ga granulite facies tectono-metamorphic event. Although it is impossible to reconstruct its tectonic significance, the following two observations are noteworthy: (i) in none of the stage 1 granulite facies assemblage was Grt detected, which excludes the possibility of a high P granulite event, and (ii) this granulite facies metamorphism is recorded in mafic rocks from the entire NMZ s.s. The second observation is important for the interpretation of relic and/or prograde textures in the other pre-2.72 lithologies (i.e. metasediments).

Our observations regarding a pre-2.72 Ga evolution go beyond the recognition of a relic granulite event by ROLLINSON and BLENKINSOP (1995). The stage 1 assemblage was, in some rocks, found to be partially hydrated. Hbl_2 + Ore_2 grew at the expense of Opx_1 and Cpx_1. We termed this retrogression stage 2. It pre-dates 2.72 Ga because Opx and Cpx in the charno-enderbites are never retrogressed prior to stage 3 granulite-facies metamorphism. The textural evolution of mafic granulite is distinctive for two high T events (stages 1 and 3), because Hbl_2 + Ore_2 are partially replaced by a stage 3 symplectite (Fig. 6).

5.1.2. 2.72 to 2.62 Ga charno-enderbite intrusions

The petrography, petrology, geochemistry and geochronology of these rocks has been described by RIDLEY (1992) and BERGER et al. (1995) and our observations are largely in agreement with these previous studies. As far as the igneous history is concerned, our observations differ only in one respect: the presence of igneous Bt; RIDLEY (1992) postulated that the reaction of residual melt with Opx to form Bt + Qtz was a major feature of the NMZ charnockites. We find this statement hard to confirm since we found enderbites and charnockites lacking Bt and, more importantly, Bt in our samples has almost always taken part in later metamorphic reactions and therefore cannot be used to infer a magmatic origin.

5.1.3. 2.62 to 2.58 Ga porphyritic intrusions, coeval low P high T granulite facies metamorphism and NNW-SSE compression

The bulk of our observations relates to imprints of this most important stage (3) of the NMZ s.s. evolution. Indeed, the excellent preservation of reaction textures enables us to qualitatively model the metamorphic evolution (see section 5.2. below) and link it with the magmatic and structural history (see section 5.3. below). Careful microscopic examination has revealed that this very high T metamorphism is recorded in more than 90% of our samples. The qualitative PT evolution derived below can thus be regarded as significant for the entire NMZ s.s. The very latest K-rich granites escaped granulite facies overprint and the fact that only these are true 2 Fsp granites may indicate that the NMZ s.s. was already cooling at 2.58 Ga.

5.1.4. Retrogression and low T thrusting

This study proposes to regard the upper greenschist-lower amphibolite facies retrogression as a distinct stage (4) of the NMZ evolution, in other words a tectono-metamorphic event on its own. This is based on three sources of information:

(i) field and petrographic observations: Retrogression and NNW thrusting at low T had been widely recognised in previous studies and were considered to reflect recrystallisation and deformation during cooling from peak stage 3 conditions (see MKWELI et al., 1995, for a summary). Our observation is that growth of retrograde minerals, with the exception of static very low grade (Prh-Pmp facies) alteration, is always syndeformational and always characteristic of upper greenschist-lower amphibolite facies. In other words, no upper amphibolite facies retrogression has been found, a feature which would be expected in the "continuum concept" of MKWELI et al. (1995). Along the Chiredzi river section, numerous dm wide low grade thrusts can be found developed in rocks which lack a strong high T fabric. Their orientation is sub-parallel to the typically much wider (100 m to several km) high T thrusts. Therefore, two distinct sub-parallel types of thrusts exist.

(ii) The Great Dyke extension: The 2.46 Ga Great Dyke (HAMILTON, 1977) extends into the

NMZ s.s. ROBERTSON (1973) and WILSON and PRENDERGAST (1989) observed that in the NMZ s.s., this intrusion is exposed at a significantly deeper level than on the craton. WILSON and PRENDERGAST (1992) interpreted the NMZ s.s. portion of the Great Dyke as a feeder structure to overlying (eroded) magma bodies. This implies that the NMZ s.s. experienced significant exhumation since 2.46 Ga. We postulate that the low grade thrusts accommodated this exhumation. Our view is confirmed by a recent palaeomagnetic study of the Great Dyke extension into the NMZ s.s. by MUSHAYANDEBVU et al. (1994), who found a magnetic component, which significantly deviates from the primary component and is seen as an overprint. Its direction plots onto the apparent polar wander path of the Limpopo Belt at 1.98 Ga (MORGAN, 1985; HATTINGH and PAULS, 1994). Remagnetisation on one hand documents a post 2.46 Ga thermal event, the survival of a primary component on the other hand places constraints on the duration and maximum T of the overprint.

(iii) Early Proterozoic mineral ages: 1.8 to 1.9 Ga Rb–Sr Bt ages have been known from the NMZ s.s. for a long time (VAN BREEMEN et al., 1966; VAN BREEMEN and DODSON, 1972). Similarly, K–Ar mica ages from the southern Zimbabwe craton were reset at ≈ 1.9 Ga (WILSON and HARRISON, 1973). Given that the Transition Zone (Fig. 2) and the Triangle Shear Zone further S were deformed during a major phase of transpressive tectonism at 2.0 Ga, it is straightforward to see the rejuvenation of low closure temperature geochronometers in the NMZ s.s. and the craton occurred in response to the early Proterozoic orogeny. The data require a separate early Proterozoic, low grade tectono-metamorphic event, which is a response to an orogeny, that reached granulite facies at 2.00 Ga, some 60 km further S (HOLZER et al., 1995).

5.2. QUALITATIVE PT MODEL FOR LATE ARCHAEAN STAGE 3 METAMORPHISM

Frozen reaction textures have been shown to be a very powerful tool to delineate the PT evolution in granulites (e.g. DROOP and BUCHER-NURMINEN, 1984; HARLEY, 1985), although most textures are produced through complex continuous reactions which are at least divariant in nature. However, as pointed out by HARLEY (1989), certain types of reactions are diagnostic of either near-isobaric cooling or near-isothermal decompression. Mineral parageneses can furthermore be compared to experimentally determined PT grids for a given rock composition (X) and important information regarding PT conditions of equilibration can be obtained. We will first describe a PT model for the NMZ s.s. stage 3 metamorphic evolution, based on the above mentioned tools.

5.2.1. Anti-clockwise PT evolution

PT evolution paths are most easily interpreted when the reaction products form coronitic symplectites around the reactants. The comparatively simple structural history in the NMZ s.s. is recorded as only one deformational fabric (the main foliation) during the high T portion of stage 3 evolution. We have thus described the stage 3 metamorphic evolution in terms of pre-, syn- and post-deformational assemblages. Table 2 summarises our observations and a compilation of the observed reactions in PT space can be found in figure 8.

Pre-deformational evolution

Pre-deformational relic assemblages useful to constrain the prograde stage 3 PT evolution are rare and their time relation is generally equivocal. However, relic Sil is found in restites of migmatised charno-enderbite, and shows prograde heating in the Sil field. Pre-deformational assemblages from metapelite and impure quartzite are also useful but they may contain relic stage 1 or 2 phases, as discussed in the description. However, two observations render such a possibility unlikely. First, no relic fabrics have been found in pre-deformational porphyroblasts, which contrasts with the mafic granulites where stage 1 metamorphism was accompanied by deformation. Second, all pre-intrusive mafic rocks are characterised by a stage 1 granulite assemblage. If metapelite were involved in stage 1 tectono-metamorphism at PT conditions comparable to mafic granulites, they would have undergone considerable melting, and no such pre-deformational relic melting reactions are preserved. We therefore suggest that the metasediments studied were deposited after stage 1 and 2 but prior to stage 3. In this case, the key reaction (reaction 8) postulated on the basis of abundant, randomly oriented Sil inclusions in pre-deformational Grt porphyroblasts of metapelite (depicted on Fig. 8) can be seen as prograde stage 3. Independent of the true reaction, this assemblage indicates Grt growth within the Sil stability field.

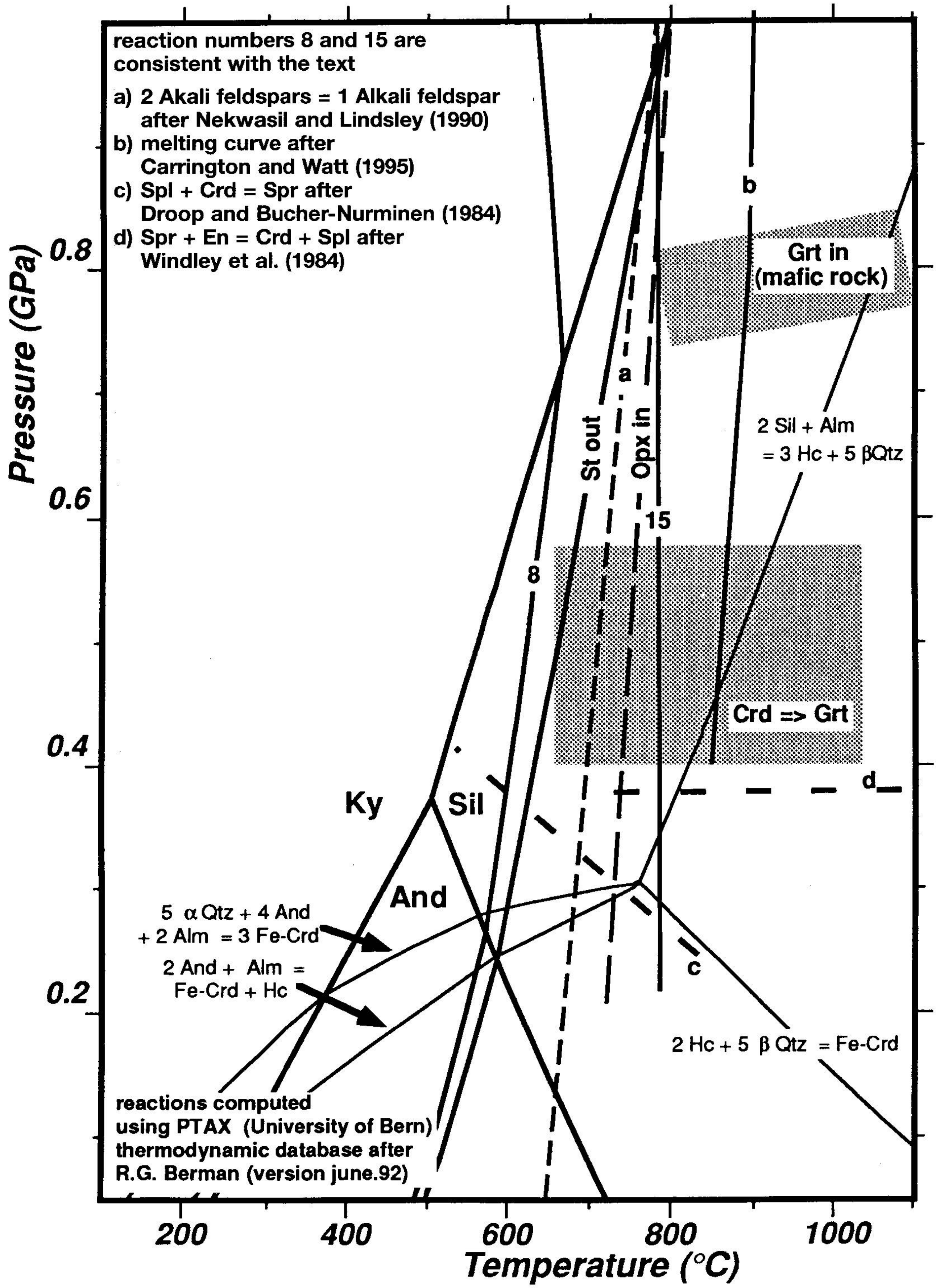

Fig. 8 Compilation of relevant metamorphic reactions in a PT diagram. For reference see text.

Syn-deformational evolution

Mineral assemblages which grew or were stable during NNW–SSE compression are all indicative of very high T. Several of the postulated reactions can be compared to experimental PT grids based on comparable rock composition. Locations of dry melting reactions 9 and 10 as depicted on figure 8 have been taken from CARRINGTON and WATT (1995) and require T ≥ 800 °C. High T during stage 3 deformation is also indicated by the fact that perthitic Kfs was stable and by the described Fsp deformation mechanisms (e.g. bulging). The 2-Kfs stability field is after NEKVASIL and SPEAR (1990). Further evidence of high T during deformation is given by the stability of Spl in Al-rich migmatites.

Pressure: Syn-deformational high T conditions were experienced by the NMZ s.s. at shallow depth. This is evident from the fact that Crd is sometimes observed as the stable FeMg phase in the leucosome. The strongest indication for low P and high T conditions are the stable assemblages in rocks which escaped migmatisation. Impure quartzites are characterised by the co-existence of Opx and Pl in highly aluminous granulite by Spl and Crd. Both stability fields depend on X but the latter assemblage may indicate P as low as 0.4 GPa (WINDLEY et al., 1984).

Post-deformational evolution

Post-deformational reaction textures are well preserved, but the majority may indicate a P increase and/or a T decrease. We first evaluate P and then T. Reactions 12 and 13, the growth of Spr (± Opx) after Spl + Crd, require an increase of P after stage 3 deformation. Locii of reactions are after DROOP and BUCHER-NURMINEN (1984) and WINDLEY et al. (1984) respectively. The stability of Spr precludes the above mentioned alternative of a significant drop in T. Reactions 6 and 7 (observed in the metasediments) are classical indicators of an anti-clockwise PT evolution. They have a moderate slope in PT space, the absolute position of which depends on X and therefore they are not shown on figure 8. The maximum P attained by the NMZ s.s. can be estimated from the absence of Grt in mafic granulites. In other words, reactions 6 and 7 did not take place in mafic granulites, in contrast to the felsic lithologies. Similar mafic granulites are found in the entire NMZ. However, S of the NMZ s.s., they all carry Grt, which grew during the 2.0 Ga tectonometamorphism. P estimated for equilibration of Grt + Cpx + Pl + Qtz at comparable T (800 °C) in these rocks are 0.77 to 0.79 GPa (KAMBER et al., 1995a,b). We therefore regard 0.8 GPa as the maximum P experienced by the NMZ s.s. True indicators for a post-deformational drop in T can also be found. The best indicator is the Bt + Qtz myrmekite enclosed in migmatitic Opx in sample 92/073. This reaction can be explained by:

$$\text{Opx} + \text{melt} \Rightarrow \text{Bt} + \text{Qtz} + \text{vapour} \qquad (15)$$

Its location (following RIDLEY, 1992) is shown on figure 8. A drop in metamorphic T may also be inferred from the observation that the very latest porphyritic granites crystallised in the 2-Kfs stability field. However, whether a granitic magma crystallises one ternary or two feldspars depends on its composition relative to An-Ab-Or, its SiO_2 and H_2O content and T (cf. NEKVASIL, 1992). Nevertheless, Fsp in the latest granites has crystallised at T lower than 800 °C, possibly as low as 760 °C (NEKVASIL and LINDSLEY, 1990). This implies that the entire NMZ s.s. had already cooled 50 to 100 °C since the metamorphic T peak.

We interpret the PT evolution to reflect prograde heating in the Sil stability field to peak T ≥ 800 °C attained during NNW–SSE compression, followed by an initially near-isothermal increase of P to maximum 0.8 GPa and near-isobaric cooling (this evolution is shown on Fig. 8 by an arrow). This qualitative PT model for stage 3 is in agreement with the quantitative PT loop of ROLLINSON (1989). Therefore, the clockwise PT loop proposed by TSUNOGAE et al. (1992) does not characterise the late Archaean metamorphic evolution of the NMZ s.s. As discussed by KAMBER et al. (1995b) it reflects a mixture of samples equilibrated during both the Archaean (northern samples) and the early Proterozoic event (southern samples).

5.2.2. Spatial variation in PT evolution

The rather large sampling area requires to consider variations in the observed PT array. These could principally reflect an original variation in the geotherm or differential exhumation during stage 3 and 4 thrusting. ROLLINSON (1989) has noted a decrease in maximum P from E to W. Our study has not confirmed this finding, but rather shows systematic variations across strike. Mafic granulites, for example, show a systematic increase in stage 3 symplectite thickness and Pl deformation from NNW to SSE. However, this variation indicates minor changes in recorded PT conditions, as our observations, like the absence of Grt in mafic granulite, hold true for all samples, with no exception. Given that the Proterozoic event (stage 4) exhumed increasingly deeper portions of the orogen from NNW to SSE (2.0 Ga maximum P is ≈ 0.6 GPa in the Transition Zone, 0.85 GPa in the Triangle Shear Zone and 1.2 GPa in the Central Zone; see KAMBER et al., 1995a,b; HOLZER et al., 1995), it appears most probable that the systematic variations in the NMZ s.s. also reflect differential exhumation. This conclusion is supported by the distribution of stage 4 assemblages. From North to South, Bt_4 changes color (from green-brown to reddish) and Am_4 change composition from a hastingsitic hornblende to a hornblende. Therefore low amphibolite facies conditions occur in the southernmost NMZ s.s., whereas true greenschist facies assemblages prevail close to the craton.

5.3. STAGE 3 – RELATION BETWEEN METAMORPHISM, DEFORMATION AND PLUTONISM

Low P granulites, reflect a strong transient perturbation of the continental geotherm. A number of theoretical models for the PTt history experienced by a granulite terrane are available (e.g. HARLEY, 1989). Comparison of the evolution recorded by a specific terrane with model predictions is a widely used tool to determine the tectonic setting in which these granulites had formed. This is of particular interest in the ongoing debate about granulite genesis and exhumation. A full understanding of these processes will greatly improve our concepts of the style of Precambrian tectonics. Indeed, the PTt paths recorded in the three units of the Limpopo Belt have been used to infer late Archaean crustal thickening caused by continental collision (e.g. ROERING et al., 1992). By deriving a tectonic model from a specific PTt loop only, implications are made on the tectonic and usually also the magmatic history of the terrane. In the NMZ s.s., all three sources of information are now available, which provide severe constraints on potential tectonic models. Below, we define the temporal relation between metamorphism, tectonism and magmatism and evaluate the style of tectonism and the source of magmas. A schematic illustration is given in figure 9.

5.3.1. Relation between deformation and metamorphism

Most felsic lithologies underwent partial melting during stage 3. This allows to examine relative timing of the metamorphic peak with the structural evolution already in the field. Migmatites are syn-deformational throughout the NMZ s.s. and hence the metamorphic peak was synchronous with the main NNW–SSE compression. They preferentially formed in zones of high deformation. This can either mean that they represented particularly weakened portions of the belt or that aqueous fluid infiltrated along shear zones thereby lowering the minimum melting T. Two observations favour the first explanation as the dominant process. First, many of the observed leucosomes are characteristic of vapour absent melting and thus show that aqueous fluids were not significantly involved. Second, also mineral growth-deformation relation in rocks which escaped melting indicate, that the thermal peak was attained syn-deformational (e.g. recrystallisation to peak metamorphic assemblages of micro-shear domains in mafic granulite, charno-enderbite, porphyritic charnockite and granite). Table 2 gives a summary of observed mineral growth-deformation relations and reveals that many rocks contain mineral assemblages which are compatible with vapour-absent melting, and in some cases reflect equilibration at PT conditions well above hydrous melting.

5.3.2. Structural history

This study found evidence of four separate deformational episodes. The oldest deformation is only recorded by pre-intrusive mafic xenoliths and is hence irrelevant for the stage 3 granulite event. The remaining three episodes are the syn-stage 3 peak NNW–SSE compression, the post-metamorphic peak horizontal displacement in a conjugate set of shears, and SSE over NNW thrusting during metamorphic stage 4 in a set of low T reverse shear zones, sub-parallel to the old compressional fabric. The only cm-wide horizontal shears may have disrupted the original stage 3 structure to some degree. However, the other two deformations are the major features influencing granulite evolution, because they are responsible for the relative vertical movements, and are discussed below:

Stage 3 deformation was responsible for the prevalent SSW–NNE trending, moderately steep SSE to SE or rarer, steep NNW–NW dipping foliation. Lineations are down-dip and the rare shear sense indicators show a reverse character. On a map scale, large (several km amplitude) isoclinal folds, with limbs parallel to the main foliation, can be recognised. All these structures are compatible with a bulk strain consisting of

Tab. 2 Relative timing between mineral growth and deformation (stages 3 and 4).

	pre-stage 3	stage 3			stage 4	
rock type		pre-deform.	syn-deform.	post-deform.	syn-deform.	very late
mafics	Hbl, Opx ← Pl, Cpx		Opx, Cpx / Pl, Qtz		red Bt / green Am	
impure quartzite	Mag, Qtz ←	Opx / Cpx		Grt		Hem / Fe-Hydrox
meta-pelite	? ←	St (?); Grt / Sil; Opx, Crd	Grt, Crd / Pert, melt	Grt / Qtz; Bt	Bt, Chl / white	mica
aluminous granulite	? ←	Crd, Spl / ±Bt		Spr / Opx		
marble	← Cal		Di, Kfs		Fac	
charno-enderbite	Pl, Opx ←		Opx, Cpx / Pl, Kfs	Hbl / Bt	Bt, Ep, Fac / Spn	Prh, Pmp / Chl
migmatised	Kfs, (Cpx) (Hbl)	Sil	Spl, Grt / melt, Pert	Grt, Qtz / Pl, Kfs; Bt		
porphyritic granitoids		← Pl, Pert,	Opx, (Hbl); Opx, Cpx / Pl, Kfs	Hbl / Bt	Bt, Ep, Fac / Spn	Prh, Pmp / Chl
age	2.62 Ga >	< 2.62 Ga	2.58 Ga	>2.46 Ga	< 2.0 Ga	

NNW–SSE horizontal shortening and vertical extension (ROLLINSON and BLENKINSOP, 1995). Strain was concentrated along the NMZ-craton boundary, the Northern Thrust Zone, which also indicates a NNW–SSE shortening direction (MKWELI et al., 1995). Thrusting of the entire NMZ over the craton can therefore, at least partially, be seen as a result of stage 3 deformation.

Stage 4 deformation was responsible for final exhumation of the NMZ s.s. at ≈ 2.0 Ga, along a set of SSW–NNE trending, moderately SE dipping, several m wide, low T thrusts. The observation that the NMZ s.s. granulites were only finally exhumed in a separate tectono-metamorphic event is pertinent to the understanding of the granulite evolution. Previously, the maximum crustal thickness during stage 3 granulite formation had been estimated at ≈ 55 km (e.g. RIDLEY, 1992) by means of comparing maximum P recorded on either side of the Northern Thrust Zone. It is proposed here that 55 km is an overestimate since it encompasses both stage 3 and stage 4 vertical movement. Preliminary estimates of stage 4 vertical displacement are based on strain analysis of low T mylonites and are in the order of 10 km (BLENKINSOP et al., 1995). This figure is in agreement with the fact that the Great Dyke is exposed at a substantially deeper level in the NMZ s.s. than on the craton, and implies that maximum crustal thickness during stage 3 was ≈ 45 km. BOHLEN (1987) has, on a theoretical basis, predicted that isobarically cooled granulites are not expected to reach the erosional surface during the same event in which they were formed, and another, not necessarily related, tectonic event is required to exhume such rocks. It is concluded that the NMZ s.s. granulites have resided in shallow crustal levels (≈ 10 km) after stage 3 until they were exhumed during stage 4 tectonometamorphism.

5.3.3. Temporal relation between magmatism and metamorphism

Ascent of large melt volumes through the crustal column and crystallisation of magmatic under-, intra- or overplates greatly influenced the thermal evolution of many high-grade metamorphic belts (e.g. WELLS, 1980). Two major magmatic episodes are recorded in the NMZ s.s. A charno-enderbite suite intruded between 2.72 and 2.62 Ga and was followed with no apparent time break by sheet-like porphyritic granites and charnockites.

The charno-enderbitic melts pre-date the stage 3 metamorphic peak, as they have been metamorphosed by it, and are deformed by the coeval NNW–SSE compression. Nevertheless, intrusion of such voluminous melts must have influenced the continental geotherm. We argue that intrusion of the charno-enderbite suite caused prograde heating but that the country rocks were not at granulite facies T on a regional scale prior to stage 3. This is indicated by the difference between pervasive stage 3 dehydration of pre-intrusive amphibole-pyroxenites and "contact-metamorphic" dehydration of rims of similar rocks entrained in charno-enderbite melts (section 4.1.1.). The very fact that amphibole-pyroxenites were dehydrated when entrained in these melts implies that the country rocks were at a different T-X(H_2O) during intrusion, hence allowing for either a lower country rock T, a higher country rock X(H_2O), or both. The observed dehydration is confined to the outermost few cm of such xenoliths. Pervasive dehydration of amphibole-pyroxenite bodies as wide as several 100 m can clearly be attributed to stage 3 metamorphism. The thermal perturbation caused by the charno-enderbite intrusions has led to an overall prograde heating of the NMZ s.s., but in terms of granulite facies metamorphism it was of local extent.

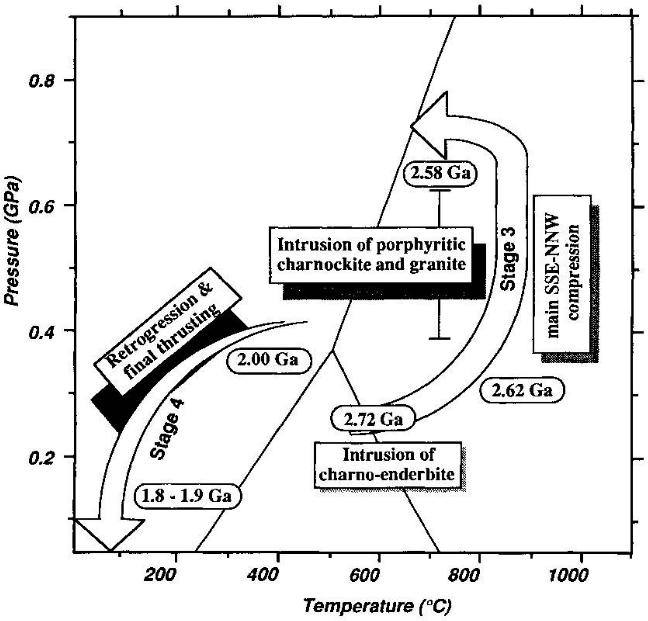

Fig. 9 Schematic PTt path for stage 3 and 4 illustrates the timing between metamorphism, magmatism and deformation.

The thermal peak of granulite evolution coincides with the main deformation (Tab. 2, Fig. 9). The observed T/P values (≥ 800 °C at 0.5 GPa) can only be a transient feature (e.g. STÜWE et al., 1993). On one hand this lends further support to the postulation that the NMZ s.s. cannot have been at granulite T during the 2.72–2.62 Ga charno-enderbite plutonism. On the other hand it requires rapid (initial) cooling after stage 3 granulite metamorphism. Indeed several observations indicate such an evolution: (i) The excellent preservation of high T reaction textures indicates that post-peak cooling to a thermal regime where fluid-absent reaction rates become negligible was rapid. (ii) This is in agreement with preservation of prograde mineral-chemistry zonation described by ROLLINSON (1989). (iii) We have described that the very latest granites lack perthitic Kfs and that spatially related retrogression of charno-enderbite is also characterised by recrystallisation in the 2 Kfs stability field. These observations may be explained by intrusion of the last melts into an already cooling crust.

It is interesting to note that charno-enderbite intrusion was a long-lived (100 Ma) process compared to the intrusion of the porphyritic granites and charnockites. However, even though the latter intruded on a shorter time-scale, we note that they make up no more than 10% of the entire NMZ s.s. and their thermal perturbation could not explain the regional granulite facies metamorphism. An extra heat source is thus required to explain the observed metamorphic reactions.

5.3.4. Magma and heat sources

BERGER et al. (1995) argue on the basis of major- and trace-element geochemistry and Sr and Nd isotope signatures that both the charno-enderbites and the porphyritic intrusions were derived from underlying, older continental crust efficiently mixed with new mantle-derived melts. Furthermore, their study demonstrates that equivalent intrusions can be found throughout the Zimbabwe craton and they reach the conclusion that the NMZ is autochthonous to the Zimbabwe craton. Whilst the 2.72 to 2.62 Ga intrusions volumetrically dominate in the NMZ, late K-rich porphyritic granitoids dominate on the craton. These are known as the Chillimanzi-type granites and make up ≈ 50% of the presently exposed craton. The genetic link with the porphyritic granites and charnockites of the NMZ s.s. proposed by BERGER et al. (1995) is supported by the similarity in age of the Chillimanzi plutons (2.570 ± 25 Ma to 2601 ± 10 Ma: HICKMAN, 1978; JELSMA, 1993).

A discussion of the nature of possible heat sources is beyond the scope of this paper. However, because of the coincidence of lower-crustal melting with compression and anti-clockwise metamorphic PT evolution in the middle crust and ponding of vast granite plutons in the upper crust a strong, transient heat source must have affected the base of the crust. One process able to explain the 2.62 to 2.58 Ga evolution of the NMZ s.s. is lithospheric mantle thinning (LOOSVELD and ETHERIDGE, 1990).

6. Discussion and conclusions

6.1. DISCUSSION OF TECTONIC MODELS FOR THE LATE ARCHAEAN STAGE 3 EVOLUTION

The geological evolution of the entire NMZ is linked to both the Zimbabwe craton and the entire Limpopo Belt. Based on present knowledge, it is impossible to erect a model which can confidently explain this evolution. The bulk of proposed tectonic models for the Limpopo Belt evolve around the concept of a late Archaean continental collision (e.g. TRELOAR et al., 1992) and hence aim to explain stage 3 evolution. The validity of these models has recently been questioned, based on the discovery of a 2.0 Ga tectono-metamorphic event which affected large parts of the Limpopo Belt (e.g. BARTON et al., 1994; KAMBER et al., 1995a,b; HOLZER et al., 1995). The tectonic implication of this (stage 4) event has been discussed by KAMBER et al. (1995b). Furthermore, BERGER et al. (1995) concluded that, based on the intrusion ages and petrogenesis of charno-enderbites, the Archaean record of the NMZ s.s. also fails to be explained by the collision models. Our observation regarding stage 3 tectono-metamorphism are entirely in agreement with their conclusion.

Two aspects contradict 2.68 Ga continental collision models (e.g. ROERING et al., 1992):

(i) The thermal history of the NMZ s.s. during stage 3 contradicts a 2.68 Ga continental thickening. The metamorphic peak represents a transient thermal perturbation, which occurred between ≥ 2.58 and ≤ 2.62 Ga. This is at least 60 Ma later than the proposed collision and metamorphic peak in the Southern Marginal Zone. Our finding agrees with MKWELI et al. (1995) and BERGER et al. (1995) who pointed out that thrusting of the NMZ over the Zimbabwe craton also occurred between 2.58 and 2.62 Ga, hence at least 60 Ma too late to fit a single collision model.

(ii) The continental collision models were largely based on the structural and metamorphic symmetry of the Limpopo Belt. The proposed clockwise PT loops with steep isothermal decompression episodes supported a crustal-thickening model (e.g. ROERING et al., 1992). However, we find that the late Archaean metamorphic PT loop can only be anti-clockwise. As discussed by KAMBER et al. (1995a,b), the competing loop by TSUNOGAE et al. (1992) reflects an artefact of probing Archaean as well as Proterozoic mineral assemblages.

The most recent studies in the NMZ and Central Zone show that, at present, no model correctly describes the evolution of the Limpopo Belt. TRELOAR and BLENKINSOP (1995) already proposed modifications to the TRELOAR et al. (1992) model based on an re-interpretation of structural patterns. Instead of a single collision at 2.68 Ga, these authors propose a double collision of first the Kapvaal craton into the Central Zone and a later collision of this amalgamated unit into the Zimbabwe craton. However, our study shows that all the structural, metamorphic and plutonic evidence needs to be explained. The key to the understanding of the stage 3 event obviously lies in the identification of the heat source responsible for the observed T/P values and melting of the lower crust in a compressional regime. LOOSVELD and ETHERIDGE (1990) have provided a simple numerical model which shows that only delamination (or thinning) of the lithospheric mantle can account for the amount of heat required to generate such high T-low P granulites in a compressional setting. In any case it seems inevitable, especially in the light of coeval plutonism (notably reflecting variable amounts of mantle derived melts) in the entire Zimbabwe craton, to consider the role of the mantle for the thermal evolution.

6.2. CONCLUSIONS

In spite of potential ambiguities inherent to field and petrographic observations and resulting interpretations, this study allows to greatly limit potential tectonic models for the study area and to reject a number of conclusions based on quantitative results:

(i) The NMZ s.s. records at least 4 stages of metamorphic mineral growth. Three of them (stage 1, 3 and 4) were coeval with separate tectonic events. This relative time frame is the first coherent evolutionary model for the NMZ s.s.

(ii The preservation and recognition of abundant reaction textures enabled us to qualitatively model the PT evolution during the late Archaean stage 3 granulite facies metamorphism. The sum of all observed reaction textures is only compatible with an anti-clockwise PT evolution, characterised by high T/P values, possibly as high as ≥ 800 °C / 0.4 GPa, followed by a moderate increase in P. Such an evolution is in agreement with the PT loop proposed by ROLLINSON (1989) and incompatible with the results of TSUNOGAE et al. (1992). Because this study covered wide parts of the NMZ s.s., an anti-clockwise PT evolution can now be regarded as significant for the entire NMZ s.s.

(iii) Field and micro-structural observations allowed us to link the magmatic and deformational record to the metamorphic evolution (Fig. 9). The stage 3 thermal peak in the NMZ s.s. postdated the intrusion of voluminous charno-enderbites but was coeval with syn-deformational intrusion of porphyritic granite and charnockite. The combination of an anti-clockwise high T-low P granulite metamorphism, compressional deformation and intrusion of granite into the overlying craton greatly reduces possible tectonic settings.

(iv) The classical late Archaean continent-continent collision model has recently been questioned on the basis of the re-discovery of a major 2.0 Ga tectono-metamorphic event which affected large parts of the Limpopo Belt. Moreover, BERGER et al. (1995) concluded that the late Archaean magmatic history of the NMZ s.s. cannot be explained by the collisional models. This study provides evidence that also the late Archaean metamorphic record contradicts crustal thickening in a continental collision.

(v) With respect to future models, our observations regarding stage 3 tectono-metamorphism reject continental extension and require a pronounced, transient heat source.

(vi) A systematic variation of recorded deformation features along the NNW–SSE traverses was observed in this study. This variation either reflects exposure of slightly different crustal levels during stage 4 exhumation or a small variation in the original geothermal gradient.

Finally, we believe our study shows that petrography and field work are a cost-effective tool to delineate the basic geological evolution of a poorly known terrane, when used in conjunction with structural interpretation and dating of a few key age relationships. Indeed, such studies are a pre-requisite for the erection of realistic tectonic models. The example of the NMZ s.s. may encourage geoscientists with limited access to analytical facilities to reassess the geological evolution of terranes which lack basic description.

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References

BARTON, J.M., HOLZER, L., KAMBER, B., DOIG, R., KRAMERS, J.D. and NYFELER, D. (1994): Discrete metamorphic events in the Limpopo Belt: Implications for the interpretation of P-T-t paths in metamorphic terrains. Geology 22, 1035–1038.

BERGER, M., KRAMERS, J.D. and NÄGLER, T.F. (1995): An Archean high grade province adjacent to a granite greenstone terrain: geochemistry and geochronology of charnoenderbites in the Northern Marginal Zone of the Limpopo Belt, Southern Africa, and genetic models. Schweiz. Mineral. Petrogr. Mitt. 75, 17–42.

BLENKINSOP, T.G., MKWELI, S., FEDO, C., PAYA, B.K., KAMBER, B., KRAMERS, J. and BERGER, M. (1995): The North Limpopo Thrust Zone (NLTZ): The northern boundary of the Limpopo Belt in Zimbabwe and Botswana. Centennial GEOCONGRESS, April 1995, Johannesburg, R.S.A., Extended abstract volume, Spec. Publ. Geol. Soc. S.A., 174–177.

BOHLEN, S.R. (1987): Pressure-temperature-time paths and a tectonic model for the evolution of granulites. J. Geol. 95, 617–632.

BURTON, K.W. and O'NIONS, R.K. (1991): High-resolution garnet chronometry and the rates of metamorphic processes. Earth and Planet. Sci. Lett. 107, 649–671.

CARRINGTON, D.P. and WATT, G.R. (1995): A geochemical and experimental study of the role of K-feldspar during water-undersaturated melting of metapelites. Chem. Geol. 122, 59–76.

DE WIT, M., ROERING, C., HART, J.R., ARMSTRONG, R.A., DE RONDE, C.E.J., GREEN, R.W.E., TREDOUX, M., PEBERDY, E.P. and HART, R.A. (1992): Formation of an Archaean continent. Nature 357, 553–562.

DROOP, G.T.R. and BUCHER-NURMINEN, K. (1984): Reaction textures and metamorphic evolution of sapphirine-bearing granulites from the Gruf complex, Italian Central Alps. J. Petrol. 25, 766–803.

GRAMBLING, J.A. (1981): Pressures and temperatures in

Precambrian metamorphic rocks. Earth and Planet. Sci. Lett. 53, 63–68.

HAMILTON, J. (1977): Sr isotope and trace element studies of the Great Dyke and Bushveld Mafic Phase and their relation to early Proterozoic magma genesis in Southern Africa. J. Petrol. 18, 24–52.

HARLEY, S.L. (1985): Garnet-orthopyroxene bearing granulites from Enderby Land, Antarctica: Metamorphic Pressure-Temperature-Time Evolution of the Archean Napier Complex. J. Petrol. 26, 819–856.

HARLEY, S.L. (1989): The origins of granulites: a metamorphic perspective. Geol. Mag. 126, 215–247.

HATTINGH, P.J. and PAULS, N.D. (1994): New palaeomagnetic results from the northern Bushveld Complex of South Africa. Precamb. Res. 69, 229–240.

HICKMAN, M.H. (1978): Isotopic evidence for crustal reworking in the Rhodesian Archean craton, southern Africa. Geology 6, 214–216.

HOLZER, L., KAMBER, B.S., KRAMERS, J.D. and FREI, R. (1995): The tectono-metamorphic event at 2 Ga in the Limpopo Belt and the resetting behaviour of chronometers at high temperature. In: MCMANUS, M.N.C. (Ed.): Proterozoic Crustal and Metallogenic Evolution . Special Publication of the Geological Survey of Namibia, 127–138.

JAECKEL, P., KRÖNER, A., WENDT, I.J., BRANDEL, G. and TODT, W. (1995): The Limpopo Belt, South Africa: New evidence from zircon ages for extended late Archean to early Proterozoic evolution. EUG 8 Strasbourg 9–13 April 1995, Terra Abstracts 7, 102.

JELSMA, H.A. (1993): Granites and greenstones in Northern Zimbabwe: tectono-thermal evolution and source regions. Unpubl. Ph.D. Thesis, Vrije Universiteit Amsterdam.

KAMBER, B.S. (1995): Contrasting Proterozoic and Archean tectonic styles in the Limpopo Belt, Southern Africa. Unpubl. Ph.D. Thesis, Universität Bern.

KAMBER, B.S., KRAMERS, J.D., NAPIER, R., CLIFF, R.A. and ROLLINSON, H.R. (1995a): The Triangle Shearzone, Zimbabwe, revisited: new data document an important event at 2.0 Ga in the Limpopo Belt. Precamb. Res. 70, 191–213.

KAMBER, B.S., BLENKINSOP, T.G., VILLA, I.M. and DAHL, P.S. (1995b): Proterozoic transpressive deformation in the Northern Marginal Zone, Limpopo Belt, Zimbabwe. J. Geol. 103, 493–508.

KRETZ, R. (1983): Symbols for rock-forming minerals. Amer. Mineral. 68, 277–279.

LOOSVELD R.J.H. and ETHERIDGE, M.A. (1990): A model for low-pressure facies metamorphism during crustal thickening. J. metamorphic Geol. 8, 257–267.

MKWELI, S., KAMBER, B.S. and BERGER, M. (1995): A westward continuation of the Zimbabwe Craton-Northern Marginal Zone tectonic break and new age constraints on the timing of thrusting. J. Geol. Soc. London 152, 77–83.

MORGAN, G.E. (1985): The paleomagnetism and cooling history of metamorphic and igneous rocks from the Limpopo Mobile Belt, southern Africa. Geol. Soc. Amer. Bull. 96, 663–675.

MUSHAYANDEBVU, M.F., JONES, D.L. and BRIDEN, J.C. (1994): A palaeomagnetic study of the Umvimeela Dyke, Zimbabwe: evidence for a Mesoproterozoic overprint. Precamb. Res. 69, 269–280.

MWATAHWA, C. (1992): The Geology of the area around Rhonda and United Mines (Mberengwa). Unpubl. B.Sc. Thesis, University of Zimbabwe.

MYERS, S. and KRÖNER, A. (1994): Archaean tectonics. In: HANCOCK, P.L. (Ed.): Continental Deformation. Pergamon Press Oxford, 355–369.

NEKVASIL, H. (1992): Feldspar crystallisation in felsic magmas: a review. Trans. Royal Soc. Edin. 83, 399–407.

NEKVASIL, H. and LINDSLEY, D.H. (1990): Termination of the 2 feldspar + liquid curve in the system Ab-Or-An-H_2O at low H_2O contents. Amer. Mineral. 75, 1071–1079.

ODELL, J. (1975): Explanation of the Geological Map of the Country around Bangala Dam. Rhod. geol. Surv. Bull., 42.

RAITH, M. and SRIKANTAPPA, C. (1993): Arrested charnockite formation at Kottavattam, southern India. J. metam. Geol., 11, 815–832.

RIDLEY, J. (1992): On the origins and tectonic significance of the charnockite suite of the Archaean Limpopo Belt, Northern Marginal Zone, Zimbabwe. Precamb. Res., 55, 407–427.

ROBERTSON, I.D.M. (1973): The geology of the country around Mount Towla, Gwanda District. Rhod. geol. Surv. Bull., 68.

ROBERTSON, I.D.M. (1974): Explanation of the Geological Map of the Country South of Chibi. Unpubl. Rhod. geol. Surv. Bull., 41.

ROERING, C., VAN REENEN, D.D., SMIT, C.A., BARTON, J.M., DE BEER, J.H., DE WIT, M.J., STETTLER, E.H., VAN SCHALKWYK, J.F., STEVENS, G. and PRETORIOUS, S. (1992): Tectonic model for the evolution of the Limpopo Belt. Precamb. Res. 55, 539–552.

ROLLINSON, H.R. (1989): Garnet-orthopyroxene thermobarometry of granulites from the north marginal zone of the Limpopo belt, Zimbabwe. In: DALY, J.S., CLIFF, R.A. and YARDLEY, B.W. (Eds): Evolution of metamorphic belts. Blackwell Sci. Publ. Oxford 43, 331–335.

ROLLINSON, H.R. and BLENKINSOP, T. (1995): The magmatic, metamorphic and tectonic evolution of the Northern Marginal Zone of the Limpopo Belt in Zimbabwe. J. Geol. Soc. London 152, 66–75.

ROLLINSON, H.R. and LOWRY, D. (1992): Early basic magmatism in the evolution of the Northern Marginal Zone of the Archaean Limpopo Belt. Precamb. Res. 55, 33–45.

SEVIGNY, J.H. (1993): Monazite controlled Sm/Nd fractionation in leucogranites: An ion microprobe study of garnet phenocrysts. Geochim. Cosmochim. Acta 57, 4095–4102.

STÜWE, K., SANDFORD, M. and POWELL, R. (1993): Episodic metamorphism and deformation in low-pressure, high-temperature terranes. Geology 21, 829–832.

TAYLOR, P.N., KRAMERS, J.D., MOORBATH, S., WILSON, J.F., ORPEN, J.L. and MARTIN, A. (1991): Pb/Pb, Sm–Nd and Rb–Sr geochronology in the Archean Craton of Zimbabwe. Chem. Geol. 87, 175–196.

TRELOAR, P.J. and BLENKINSOP, T.G. (1995): Archaean deformation patterns in Zimbabwe – true indicators of Tibetan style crustal extrusion or not? J. Geol. Soc. London, in press.

TRELOAR, P.J., COWARD, M.P. and HARRIS, N.B. (1992): Himalayan-Tibetan analogies from the evolution of the Zimbabwe Craton and Limpopo Belt. Precamb. Res. 55, 571–587.

TSUNOGAE, T., MIYANO, T. and RIDLEY, J. (1992): Metamorphic P-T profiles from the Zimbabwe Craton to the Limpopo Belt, Zimbabwe. Precamb. Res. 55, 259-277.

VAN BREEMEN, O. and DODSON, M.H. (1972): Metamorphic chronology of the Limpopo Belt, Southern Africa. Geol. Soc. Amer. Bull. 83, 2005–2018.

VAN BREEMEN, O., DODSON, M.H. and VAIL, J.R. (1966): Isotopic age measurements on the Limpopo orogenic belt, southern Africa. Earth and Planet. Sci. Lett. 1, 401–406.

VAN BREEMEN, O. and HAWKESWORTH, C.J. (1980): Sm–Nd isotopic study of garnets and their metamorphic host rocks. Trans. Royal Soc. Edin. 71, 97–102.

VAN REENEN, D.D., BARTON, J.M., ROERING, C., SMITH, C.A. and VAN SCHALKWYK, J.F. (1987): Deep crustal response to continental collision: The Limpopo belt of southern Africa. Geology 15, 11–14.

WELLS, P.R.A. (1980): Thermal models for the magmatic accretion and subsequent metamorphism of continental crust. Earth and Planet. Sci. Lett. 46, 253–265.

WILSON, A.H. and PRENDERGAST, M.D. (1989): The Great Dyke of Zimbabwe, I. Tectonic setting, stratigraphy, petrology, structure, emplacement and crystallization. In: PRENDERGAST, M.D. and JONES, M.J. (Eds): Magmatic Sulfides – The Zimbabwe Volume. Inst. Min. Metall. London, 1–20.

WILSON, J.F. and HARRISON, N.M. (1973): Recent K–Ar age determinations on some Rhodesian granites. In: LISTER, L.A. (Ed.): Symposium on granites, gneisses and related rocks. Geol. Soc. South Africa Spec. Pub., 69–78.

WINDLEY, B.F. (1993): Uniformitarianism today: plate tectonics is the key to the past. J. Geol. Soc. London 150, 7–19.

WINDLEY, B.F., ACKERMAND, D. and HERD, R.K. (1984): Sapphirine/kornerupine-bearing rocks and crustal uplift history of the Limpopo belt, Southern Africa. Contrib. Mineral. Petrol. 86, 342–358.

WORST, B.G. (1962): The geology of the Buhwa Iron Ore deposits and the adjoining country: Belingwe District. Rhod. geol. Surv. Bull., 53.

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Appendix: Mineral abbreviations

Ab	=	albite	Fs	=	ferrosilite	Pmp	=	pumpellyite
Am	=	amphibole	Fsp	=	feldspar	Prh	=	prehnite
Ap	=	apatite	Grt	=	garnet	Px	=	pyroxene
Bt	=	biotite	Hbl	=	hornblende	Qtz	=	quartz
Cal	=	calcite	Hd	=	hedenbergite	Scp	=	scapolite
Carb	=	carbonate	Ilm	=	ilmenite	Sil	=	sillimanite
Chl	=	chlorite	Kfs	=	K-feldspar	Spl	=	spinel
Chr	=	chromite	Mag	=	magnetite	Spn	=	sphene
Cpx	=	clinopyroxene	Mc	=	microcline	Spr	=	sapphirine
Crd	=	cordierite	Mnz	=	monazite	Srp	=	serpentine
Di	=	diopside	Ms	=	muscovite	St	=	staurolite
Dol	=	dolomite	Opx	=	orthopyroxene	Tlc	=	talc
Ep	=	epidote	Or	=	orthoclase	Xen	=	xenotime
Fac	=	ferroactinolite	Pl	=	plagioclase	Zrn	=	zircon