# 7 DISCUSSION OF PUBLISHED DATA

## 7.1 The ongoing controversy: a late -Archaean versus Paleoproterozoic orogeny in the Central Zone

### 7.1.1 INTRODUCTION

After more than 50 years of research in the Limpopo Complex (LC), the timing of the "Limpopo Orogeny" still remains an outstanding challenge. Conflicting interpretations of the age of the "Limpopo Orogeny" (e.g. Van Breemen & Dodson, 1972; Barton & Van Reenen, 1992b; Barton et al., 1994; McCourt et al., 1995; McCourt & Armstrong, 1998; Holzer et al., 1998, 1999; Schaller et al., 1999) are mainly the result of two different approaches used to provide a temporal constrain on the timing of this event. One approach is based on single metamorphic mineral ages to determine the age of syn-kinematic metamorphism, and therefore the age of orogenesis. The second approach relied on granitic plutons as primary time markers characterised as pre-, syn- or post-tectonic, and dated by conventional methods.

### 7.1.2 SINGLE MINERAL DATING AND THE RECOGNITION OF THE PALEOPROTEROZOIC OROGENY IN THE CENTRAL ZONE

The earliest geochronological study in the LC was undertaken by Holmes and Cahen (1957) who obtained an average U-Th-Pb age of 2000 Ma on sphene and radioactive concentrate from a pegmatite near Beit Bridge in the CZ. They suggested that this age representing the final phase of the orogenesis. Barton & Van Reenen (1992a) subsequently showed that Rb-Sr dates of biotite and phlogopite in rocks comprising the CZ and SMS, frequently range from ~2050 Ma to ~1950 Ma, but interpreted these ages to reflect biotite cooling ages related to regional uplift that postdates the real orogeny at ~ 2600 Ma.

Isotopic analyses of metamorphic minerals in the vicinity of the Bulai Pluton in the CZ (Barton et al., 1994) also supports a Paleoproterozoic age for the Limpopo Orogeny. These authors determined an age of 1926 + 123/ -134 Ma for garnet from the Messina Layered Intrusion in the CZ, which they interpreted to date a tectono-metamorphic event that post-dated the emplacement of the ~2600 Ma Bulai Pluton. Analyses of muscovite and alkali feldspar from an undeformed pegmatite dike intruding the Ha-Tshansi fold near Musina yield an Rb-Sr age of 1773 ± 2 Ma that was interpreted as a minimum estimate of the cooling time to brittle conditions (Barton et al., 1994).

In the SMZ, Pb-Pb analyses on garnet and plagioclase from a metapelitic gneiss that was produced during prograde metamorphism at granulite facies conditions, from the Bandelierkop Quarry, yield consistent ages of about 3150 Ma (Barton et al., 1994). According to these authors, this age indicates either the time of peak metamorphism or the time when high-temperature cooling occurred. This Pb-Pb age of 3150 Ma is significantly older than the age of emplacement (~ 2670 Ma, Barton et al., 1992) of the Matok pluton that occurred syn- to late-tectonic with respect to the exhumation of the SMZ granulites. Barton et al. (1994) therefore suggested that prograde metamorphism and exhumation in the SMZ belonged to two completely separate geologic events. According to these authors granulite facies metamorphism thus occurred at different times in the CZ and SMZ with granitic magmatism preceding peak metamorphism in the CZ, and post-dating peak metamorphism in the SMZ. In this study (Barton et al., 1994), the late-Archaean Bulai (CZ) and Matok (SMZ) plutons are not considered to be accurate time-markers for tectono-metamorphic events in the CZ and SMZ.

The results of the early single-phase geochronologic studies in the CZ were subsequently substantiated by a large single mineral geochronologic database. Metamorphic zircons from *grt-crd-sil* gneisses exposed at the Causeway locality in the Sand River southeast of Musina, yielded an age of 2026 ± 7 Ma (Jaeckel et al., 1997), interpreted to reflect a high *P-T* event (>10 kbar, 825 ± 25$^{o}$C, Jaeckel et al., 1997). Using PbSL of metamorphic silicates in high-grade gneisses, Holzer et al. (1998) dated multiple granulite facies metamorphic episodes in the CZ, that reflect three distinct high grade events at about 3200-3100 Ma, 2650-2520 Ma and 2000 ± 5 Ma. Each of these events corresponds to a tectonic episode of distinct character, with the Paleoproterozoic event in this interpretation reflecting the peak metamorphic and fabric-forming event and thus the "Limpopo Orogeny". Based on Pb-Pb single phase age data from metamorphic minerals Holzer et al. (1998) proposed a tectonic thickening event caused by the collision of the Kaapvaal and Zimbabwe Cratons during the Paleoproterozoic (~2 005 – 1950 Ma ). According to them the time of the final exhumation of the CZ and post-orogenic transcurrent faulting are bracketed by the ages of the Entabeni granite (1950 Ma; Barton et al., 1995), which is unconformably overlain by the Soutpansberg basal conglomerates, and the Schiel Alkaline Complex (1850 Ma; Barton et al., 1996), which reflects the final stages of the Soutpansberg rifting tectonics. As a synthesis a model was postulated which describes the Paleoproterozoic event as a transpressive orogeny between >2030 and 1850 Ma. Schaller et al. (1999) combined petrographical work with geochronology in their study of the tectono-metamorphic history of the Palala Shear Zone and suggested that the Palala Shear Zone played an important role in the exhumation of the Paleoproterozoic granulites during the transpressive orogeny between 2050 and 1950 Ma.

The interpretation of the Paleoproterozoic Limpopo Orogeny (Holzer et al., 1998; Schaller et al., 1999) is therefore mainly based on metamorphic mineral ages and can be summarized:

*(i)* The Paleoproterozoic event accompanied by the peak metamorphic and fabric forming event in the CZ is responsible for the complex regional fold pattern of the CZ (e.g. Figure 18), at ~ 2000 Ma and was thus responsible for the development of both sheath- and cross folds at the same time.

*(ii)* Late-Archaean granitic magmatism (e.g. Bulai Pluton and Singelele Gneiss) is considered to be pre-tectonic with reference to the Paleoproterozoic orogenic event.

*(iii)* The CZ granulites were exhumed as the result of a transpressive orogeny between 2050 and 1950 Ma.

*(iv)* It must be noted that the interpretation of the relationships between peak metamorphism and the emplacement of the Matok pluton in the SMZ is not substantiated by subsequent data (Kreissig et al., 2001) that showed that peak metamorphism in the SMZ occurred in the late- and not the Mid-Archaean.

### 7.1.3 GRANITIC MAGMATISM AS IMPORTANT TIME-MARKERS FOR A LATE-ARCHAEAN LIMPOPO OROGENY

A Rb-Sr whole rock isotopic study of the ~ 2600 Ma syngenetic Bulai and Singelele gneissic granites by Van Breemen & Dodson (1972) formed the basis for the proposed late-Archaean Limpopo Orogeny (e.g. Barton and Van Reenen, 1992b). Van Breemen & Dodson (1972) based their argument on metamorphic, structural, and field evidence, presented by Bahnemann (1972), which indicates that the formation of the Bulai Pluton and Singelele granites were contemporaneous with high-grade metamorphism and isoclinal folding in the Musina area. Furthermore, the impressive north-south-trending Great Dyke cut the foliation of the high-grade Limpopo gneisses in the NMZ (Robertson, 1968), thus postdating movements that deformed the gneiss. Previous age determinations of the Great Dyke include those of Allsopp (1965) who established a minimum age of 2477 ± 30 Ma using Rb-Sr and K-Ar methods on biotites. Recently, Oberthür et al. (2002) precisely constrains the crystallization age of the Great Dyke to 2575.4 ± 0.7 Ma using U-Pb ages of zircon and rutile from bronzitites of the pyroxenite layer of the Great Dyke. According to Van Breemen & Dodson (1972), the age of 2477 ± 30 Ma reported by Allsopp (1965), is inconsistent with the proposed 2000 Ma mineral age for the high-grade metamorphism in the LC, and they considered the 2000 Ma event to reflect a significant thermal event related to igneous intrusions on the adjacent craton such as the Bushveld complex. Coward (1976) and Coward et al. (1976), based on structural data, first proposed that the LC was a zone of compressional interaction between the Kaapvaal and Zimbabwe Cratons. Coward et al. (1976) suggested a maximum age of 2600 Ma for this deformation if the ages of some granitic units and greenstone belts of southern Zimbabwe obtained by Hawkesworth and others (1975) are considered.

Barton & Van Reenen (1992b) used available geochronological data from muscovite-kyanite prograde metamorphic assemblages, zircon in igneous charnoenderbites and enderbite, muscovite in syntectonic pegmatite bodies formed in shear zones, partial melts and syn- and post-tectonic plutons of granodioritic and granitic composition to indicate that the Limpopo Orogeny occurred during the time interval from ~2700 Ma ago to ~2650 Ma ago. The U-Pb isotopic data obtained by Barton et al. (1994) for zircon from granitic and enderbitic orthogneisses from the Bulai Pluton, yield concordia intercept ages of 2570 and 2600 Ma, respectively, which are much younger than previously published ages. The zircon age of 2.57 is approximately 100 Ma younger than the zircon age of the Matok Pluton (2670 Ma, Barton et al., 1992b).

McCourt & Armstrong (1998) provided additional evidence in support of a late-Archaean “Limpopo Orogeny” based on U-Pb (SHRIMP) data for zircons from syn- and post-tectonic granites in the western part of the CZ in Botswana. They stated that the published mineral ages of 2000 Ma from the eastern part of the CZ date metamorphism during reworking of Archaean aged shear zones. An important aspect of this point of view is that some of these granites intruded into the thrust sense shear zones forming the external boundaries to the LC (Smit & van Reenen, 1997). These shear zones accommodated uplift of the granulites across the LC (Van Reenen et al., 1987), therefore the crystallization age of the associated granites provide a minimum age for crustal thickening during the collisional stage of the Limpopo orogeny.

Hofmann et al. (1998) and Kröner et al. (1998) showed that the Singelele-type gneisses in the area around Musina, formed as the result of *in situ* partial melting from pre-existing granitic gneisses as well as from supracrustal gneisses. These authors thus regarded that the Singelele Gneiss as the product of local anatexis. Single zircon ages of 2569 ± 0.3 and 2582 ± 0.3 Ma reported by Jaeckel et al. (1997), for two compositionally different samples of Singelele Gneiss from the Musina area, was interpreted (Hofmann et al., 1998) to provide the timing for both the main metamorphic event ($M_2$) and the main fabric-forming event ($D_2$) in the CZ.

Published models for the late-Archaean Limpopo Orogeny are mainly based on the interpretation of granitic plutons as accurate time-markers in the LC:

*(i)* The main fabric-forming event ($D_2$) in the CZ is dated by the syn-tectonic emplacement of precursors to the Singelele Gneiss to the late-Archaean.

*(ii)* The Bulai (CZ) and the Matok (SMZ) plutons are considered to be late- to post-tectonic with respect to this event.

*(iii)* The fold pattern of the CZ (e.g. Figure 18), including both sheath- and cross folds are interpreted to reflect the late-Archaean event, while later deformation events are considered to be sub-ordinate.

*(iv)* In this interpretation, the Paleoproterozoic event is considered to be mainly a thermal event, not associated with regional deformation. Shear deformation was restricted to the bounding shear zones (Palala Shear Zone in the south, and Triangle Shear Zone in the north) that developed under relative shallow crustal levels producing major mylonitic linear structures.

## 7.2 Three distinct high-grade events in the Central Zone

All workers (e.g. Barton & Key, 1981; Horrocks, 1980; 1983; Fripp, 1982, Watkeys et al., 1983; Barton et al., 1990b; McCourt & Vearncombe, 1992; Barton & Van Reenen, 1992a; Rollinson 1993; McCourt & Armstrong, 1998; Holzer et al., 1998; Kröner et al., 1998; Hofmann et al., 1998; Schaller et al., 1999) agree that the CZ was affected by three distinct events. During the mid-Archaean (3200 – 3100 Ma), in the late-Archaean (2650 – 2520 Ma), and during the Paleoproterozoic (2000 ± 0.05 Ma).

The two main schools of thought concerning the evolution of the CZ can thus be summarized:

(i) Barton et al. (1994), Kamber et al. (1995a), Holzer et al. (1998), and Schaller et al. (1999), based on single phase dating of metamorphic minerals, interpreted the evolution of this zone as follows: a *mid-Archaean* (~ 3200 Ma) event mainly reflected by magmatic activity with relic traces of an early deformational and metamorphic event (referred to as $D_1/M_1$); a *late-Archaean* (~ 2570 – 2650 Ma) low pressure "anticlockwise" granulite facies event (termed $D_2/M_2$) associated with granitic/charnockitic magmatism that resulted from vertical crustal growth of the ZC; and a *Paleoproterozoic* (~ 2050 – 1950 Ma) high pressure, high temperature clockwise granulite facies event (termed $D_3/M_3$) caused by the collision of the Zimbabwe and Kaapvaal Cratons. In this interpretation, the complex deformational pattern, and the *P-T* paths of figure 21, mainly reflects the Paleoprotorerozoic event ($D_3/M_3$) that obliterated most of the field evidence for the two Archaean events.

(ii) Hofmann et al. (1998) and Kröner et al. (1998, 1999), on the basis of single-zircon dating of syntectonic granitic magmatism also documented evidence for three distinct events, but with a significantly different emphasis on the relative significance of the last two events. These authors concluded that the late-Archaean $D_2/M_2$ event represents the major fabric-forming episode in the CZ, while later deformation events are subordinate. Apparently, they concluded that the peak metamorphic event ($M_3$) was not associated with the peak deformation, but occurred in the Paleoproterozoic. These authors thus consider the Paleoproterozoic event to be mainly a high-grade static metamorphic event (also McCourt & Armstrong, 1998). Syn- and post-tectonic granitic melt patches as well as various sets of shear zones are related to the Paleoproterozoic event. The logical conclusion that follows from their study is that the complex deformational pattern of the "cross folded zone" of the CZ mainly reflects the late-Archaean $D_2/M_2$ event.

The main elements of the three events and their interpretation are summarized in Table 1.

**Table 1**: The three events that affected the CZ (Holzer et al., 1998; Hofmann et al., 1998).

| *Age in Ga* | *Igneous Events* | *Deformational Events* | *Metamorhpic Events* |
|---|---|---|---|
| **(i) Barton et al. (1994), Kamber et al. (1995), Holzer et al. (1998), and Schaller et al. (1999)** | | | |
| ± 2.0 | Granitic plutons of the Mahalapye Complex and charnockites in the Koedoesrand Window | "Crossfolds" with NNW-SSE trending fold axis, ENE-WSW "Limpopo trend" shearing, Tshipise-Mahalapye Straightening Zone, Palala and Triangle Shear Zones (D3) | Peak granulite facies event (M3) |
| 2.85 - 2.51 | Intrusion of syntectonic Singelele granitoids and the Bulai Pluton | Polyphase ductile folding (D2) | Low P/ high T anti-clockwise event (M2b) |
| 2.65 - 2.62 | Intrusion of Alldays Gneiss precursors | Ductile recumbent folding (D2a) | Migmatization (M2a) |
| > ± 3.0 | Intrusion of SRG precursors and Messina suite | First fabric forming event in the Central Zone (D1) | Early high grade metamorphism (M1) |
| **(ii) Hofmann et al. (1998) and Kröner et al. (1998, 1999)** | | | |
| < 2.0 | Intrusion of mafic dykes | Brittle deformation & cataclasites (D5) | |
| ± 2.0 | Syn- and post-tectonic granitic melt patches | Various sets of shear zones (D4) | Peak granulite facies event (M3) |
| 2.85 - 2.51 | Intrusion of anatectic Singelele Gneiss precursor, Bulai interlayered with BBC | Major folding event & axial plane foliation (D2) | Parial melt veins that become deformed (M2) |
| 2.65 - 2.62 | Intrusion of Alldays Gneiss precursors | | |
| > ± 3.0 | Intrusion of SRG precursors and Messina suite | Early defromational fabric in SRG xenoliths (D1) | Partial melt veins in metapelitic gneiss and SRG (M1) |

## 7.3 Relative significance of the late -Archaean and Paleoproterozoic events

The main area of disagreement among the different schools of thought therefore concerns the relative importance of the two post-3000 Ma events that affected the CZ. The one school of thought (e.g. Holzer et al., 1998; Schaller et al., 1999) is of the opinion that the Paleoproterozoic event reflects the major orogenic cycle (“the Limpopo Orogeny”), and interpreted the inferred crustal thickening, which led to the high-grade metamorphism shortly before 2000 Ma, is emplaced as a product of transpressive movement between the Kaapvaal and Zimbabwe cratons (Kamber et al., 1995b). The transpressive orogenic model at 2000 Ma considers the Palala Shear Zone to have played an important role in the exhumation of the Paleoproterozoic granulites of the CZ. The main fold deformation event in the CZ, reflected by both cross- and sheath folds, thus occurred in the Paleoproterozoic, accompanied by high-pressure granulite metamorphism with a clockwise *P-T* path (e.g. Barton, et al., 1994; Jaeckel et al., 1997). All major shear zones and lineaments (e.g. Tshipise-Mahalapye Straightening Zone, Palala Shear Zone, Palala -Zoetfontein lineament, Triangle Shear Zone) are incorporated in the transpressive model. It is stated (e.g. Holzer et al., 1998; Schaller et al., 1999) that because of the intense Paleoproterozoic overprint, fold relationships of the late-Archaean event are largely disrupted, and only reflected in relict mineral paragenesis mainly preserved in xenoliths within the Bulai Pluton.

The other school of thought (e.g. Van Reenen et al., 1987; Roering et al., 1992a; McCourt & Armstrong, 1998) is of the opinion that continent-continent collision occurred in the late-Archaean and that the Paleoproterozoic high-grade event reflects an anorogenic event probably related to the emplacement of the Bushveld Igneous Complex at 2060 Ma (McCourt et al., 1995), or to a mantle plume (Treloar et al., 1997). In this continent-continent collision model, all major fold types in the CZ (cross- and sheath folds) accompanied by high-pressure-high-temperature granulite facies metamorphism, reflected by clockwise *P-T* paths (Figure 21), occurred in the late-Archaean. This model also suggests that the major ~ 2000 Ma shear zones bounding the CZ are mainly strike-slip mylonite zones reflecting re-activation of older structures in the Paleoproterozoic. The Paleoproterozoic re-activation had little influence on the creation of the "Limpopo Belt" (Van Reenen et al., 1988). The "Archaean only" Limpopo history appears to be supported by the work of Hofmann et al (1998) and Kröner et al. (1998, 1999) who concluded that the main fabric-forming ($D_2$) event in the CZ was at ~ 2600 Ma, and that the later fold deformation events were minor.

The question whether the "Limpopo Orogeny" occurred in the late-Archaean or the Paleoproterozoic, or both and the nature of these two events thus still remains an unresolved issue. Neither schools of thought have been able to unequivocally link specific *P-T* paths and age dating to specific major structures in the CZ but assume that all fold structures developed either in the late-Archaean or in the Paleoproterozoic.

## 7.4 Remaining issues

Using as a basis new age, metamorphic and structural data generated during this study, the following issues will now be addressed:

(i) Is the development of major cross- and sheath folds related to the same tectono-metamorphic event (either in the late-Archaean or in the Paleoproterozoic), or to different events?

(ii) Did peak granulite facies metamorphism and the main fabric-forming event occur in the late-Archaean (e.g. Droop, 1989; Van Reenen et al., 1990; Perchuk et al., 2000), or in the Paleoproterozoic (e.g. Barton et al., 1994; Holzer et al., 1998; Schaller et al., 1999)?

(iii) The significance of late-Archaean granite magmatism in the evolution of the CZ (Grey Gneiss Unit, Singelele-type quartzo-feldspathic gneisses, and the Bulai Pluton).

(iv) Finally, remaining issues that will be addressed as part of a planned PhD study in the CZ, will be highlighted.