4. DISCUSSION

4.1. Introduction

It is suggested in the literature that the Cross Folded Zone in the CZ was the result of a late-Archaean tectono-metamorphic event and resulted in the development of both closed and cross folds (e.g. Roering et al., 1992). Roering et al. (1992) also suggested that the fold structures with elliptical outcrop patterns were actually large-scale sheath folds that can be linked to top-to-the-NE thrusting of high-grade material during this high grade metamorphic event. These authors therefore attributed all major fold and fabric forming processes that affected the rocks of the CZ to the late Archaean event. Holzer et al. (1998) and Schaller et al. (1999), on the other hand, suggested that a Paleoproterozoic transpressive orogeny with ENE directed dextral shear movement along the Tshipise Straightening Zone and the Palala Shear Zone affected the rocks of the CZ under peak metamorphic conditions resulting in the complex deformational pattern as is observed in the CZ today. Boshoff (2003) and Van Reenen et al. (2004), based on recent data from the Alldays area in the western part of the CZ, suggest that the sheath folds developed during the peak metamorphic late Archaean event while the cross folds are the result of the Paleoproterozoic event.

The new data of this study contribute towards solving this long-standing geological problem and will be discussed within the context of the previously published data from the CZ.

4.2. The late-Archaean tectono-metamorphic event

4.2.1. Significance of the Singelele Gneiss

Hofmann et al. (1998) and Kröner et al. (1998; 1999) described three tectono-metamorphic events for the CZ based on field relationships preserved in rock pavements within the Campbell structure in the Sand River southeast of Musina, supported by geochronological data: A D_1/M_1 event (~3.25Ga), a D_2/M_2 event (~2.6Ga), and a D_3/M_3 event (~2.0Ga). Little is known about the Mid-Archaean event but these authors considered the Late-Archaean event to reflect the main fold deformational event that affected the CZ. This event was accompanied by widespread magmatism of Alldays Gneisses with single-zircon $^{207}Pb/^{206}Pb$ mean ages of 2647 $\pm$ 0.4 Ma intruding into SRG and metapelite from the BBC as was observed at the

Verbaard locality near Musina. The late-Archaean event was also accompanied by anatexis where large volumes of the precursors to quartzofeldspathic gneisses (e.g. Singelele Gneiss) intruded with single-zircon $^{207}Pb/^{206}Pb$ ages of 2568 $\pm$ 3 Ma into the older sequences. The third (D_3/M_3) event is characterised by less intense deformation but high-grade metamorphism (Kröner et al., 1998). Later D_4 shear zones accompanied by coarse-grained granitic melt patches (Hofmann et al., 1998) have a mean single-zircon Pb-Pb and U-Pb age of 2006±4Ma (Jaeckel et al., 1997).

4.2.2. Significance of sheath fold formation in the CZ

The Avoca fold located in CZ, west of Alldays (Fig. 1.3), is a circular shaped structure in outcrop pattern and interpreted to be a D_2 sheath fold with a central fold axis that plunges steeply to the southwest (Roering et al., 1992), parallel to that of the Ga-Tshanzi fold in the eastern part of the CZ (Fig. 2.10). The outer rim of the structure is defined by a coarse-grained, foliated and lineated quartzo-feldspathic gneiss, named the Avoca gneiss, while an unfoliated, but penetratively lineated to massive variety, called the Avoca "granite" outcrops near the centre of the structure (Boshoff, 2003). U-Pb zircon SHRIMP ages constrain the formation of the Avoca Gneiss, interpreted to be a syn-tectonic to D_2, at 2651±8Ma, while the Avoca "granite", interpreted to be late to post tectonic with reference to D_2, gave a significantly younger age of 2626.8±4.5Ma. This data thus constrains the age of sheath fold formation to ~2630Ma (Boshoff, 2003). If the logical assumption is made that all similar sheath folds in the CZ, including Ga-Tshanzi, are related to the early D_2 event, it follows that this event must be linked to the Late-Archaean peak metamorphic and deformational event.

4.2.3. The high-temperature shear deformational event

The Campbell cross fold is a very important area for studying the tectono-metamorphic history of the CZ as, in contrast to the Ga-Tshanzi fold, it actually displays evidence for two superimposed deformational and metamorphic events. The Campbell fold probably developed during the same Late-Archaean event that was responsible for Ga-Tshanzi and other sheath-like folds in the CZ. This is based on its early structural and metamorphic history as is preserved in an early S_1 fabric present in all the rocks of the fold. The spatial distribution of this fabric defines the geometry of the fold while metamorphic studies from metapelite displaying an S_1 fabric

(Chapter 3) suggest the fold developed under similar high-grade conditions. Structral data (Fig. 2.18, 2.24) indicate that the Campbell fold is an isoclinal structure with the ß-fold axis plunging at a moderate angle to the WSW, parallel to the development of the major population of linear elements (both L_1 and L_2). The Campbell fold also displays a well developed system of shear planes accompanied by a mineral stretching lineation that is clearly superimposed onto the early S_1 fabric and that has a strong shear character. This prominent geometry of the fold cannot be reconciled with this intensive shear fabric. It is therefore suggested that the Campbell fold was later strongly affected by the Palaeoproterozoic Tshipise Straightening Zone under mid- to upper-crustal conditions. Two different events therefore affected the rocks of the Campbell fold: a Late-Archaean event that took place at deep to mid-crustal levels that can be linked to the partial exhumation of granulites of the CZ, and a Palaeoproterozoic shear event that took place at mid- to upper-crustal levels that can be linked to the development of the neighbouring Tshipise Straightening Zone. The calculated decompression-cooling P-T path for sheared metapelitic gneisses from the Campbell cross fold (Fig.3.35 and 3.40) support this interpretation, showing that the superimposed shear deformational event occurred at mid-crustal levels indicated by peak P-T conditions at 4.98kbar/681ºC, followed by decompression and cooling down to 585ºC/3.61kbar.

Similar sheared metapelitic gneisses sampled from N-S oriented shear zones developed in the Baklykraal cross fold located west of Alldays show a similar PT-evolution (Fig. 3.40) (Van Reenen et al., 2004), suggesting that the studied metapelites sampled from shear zones in both the Campbell and Baklykraal cross folds developed as the result of the same shear deformational event. Pb/Pb lead leaching of garnet from a sheared metapelitic gneiss (sample T-73) used to calculate the PT-path for the Baklykraal structure defined an isochron age of 2023±11Ma (Boshoff, 2003), which is interpreted to be a precise age for the high-temperature shear-deformational event that affected the Baklykraal cross fold in the Paleoprotorozoic.

4.3 Significance of the Paleoproterozoic event

4.3.1. A transpressive shear system in the CZ

Shear movement within the Palala Shear Zone (PSZ) is timed by the crystallization of titanite at 2020±8Ma (Schaller et al., 1999). This age of shear deformation is supported by the 2117±17Ma intrusive age for a retrogressed charnockite that occurs within the PSZ (Schaller et al., 1999). Evidence for the Late-Archaean event (2602±40Ma) is also rarely preserved within the PSZ (Schaller et al., 1999), and was obtained by stepwise leaching of M_1 garnet from metapelitic gneiss occuring within the PSZ (Schaller et al., 1999). Schaller et al. (1999), similar to Holzer et al. (1998), attributed the 2.0Ga shearing event to a transpressive orogeny. This transpressive orogeny caused ENE-directed dextral shear movement in the TSZ and the PSZ and displacement of the CZ towards the WSW (Holzer et al., 1998; Schaller et al., 1999).

In contrast to the interpretation of the Paleoproterozoic transpressive event as the peak tectono-metamorphic event that affected the CZ (e.g. Schaller et al., 1999), the results of this study, supported by that of Boshoff (2003) and Van Reenen et al. (2004), suggest that the Paleoproterozoic event in the CZ was a major high-temperature shear deformational event restricted to well-defined shear zones that occur as relatively narrow zones of intense deformation, apparently throughout the CZ.

4.3.2. Significance of cross fold formation on the timing of events of the CZ

The Paleoproterozoic age that Boshoff (2003) presented on the formation of the Baklykraal structure is in agreement with that of Holzer et al. (1998). According to these authors the Campbell structure is interpreted to be the result of dextral transpression associated with movement along the Triangle Shear Zone (TSZ), Palala Shear Zone (PSZ) and the Tshipise Straightening Zone. Holzer et al. (1998) however, also recognise areas within the CZ where evidence for this Paleoproterozoic event is absent (e.g. the Bulai pluton).

4.4. The significance in the development of the Ga-Tshanzi and Campbell folds in the evolution of the CZ

The results of this study show that two closely associated major fold types, namely the Ga-Tshanzi closed fold and the Campbell isoclinal fold (Fig. 2.1) that probably resulted from the same early tectono-metamorphic event are, however, differently affected by subsequent shear deformation due to their different positions with respect to the Tshipise Straightening Zone (Fig. 1.3 and 2.1). The main differences between the two fold types are summarized in table 4.1. From a metamorphic point of view it is important to note that the different decompression-cooling P-T paths (Fig. 3.40) produced for rocks of the Musina area suggest the following: (i) the P-T path (Fig. 3.40) produced from rocks of the Ga-Tshanzi fold reflects P-T conditions at deep crustal levels and low water activities (ii) the P-T path produced from rocks of the Campbell fold that were subsequently sheared under ductile conditions produced a decompression-cooling P-T path (Fig. 3.40) that reflects mid-crustal conditions and higher water activities for the shear event (iii) The younger shear event is not well established in the rocks of the Ga-Tshanzi fold (iv) the Campbell P-T path also reflects a re-heating event that occurred at the same crustal level (~5kbar) at which the Ga-Tshanzi closed structure was finally emplaced.

Two deformational events are therefore recorded by two geometrically different but closely associated fold structures. The Ga-Tshanzi structure with its sheath fold geometry, lack of later shear deformation and its decompression-cooling P-T path crustal reflects a deep crustal origin for all the sheath folds and probably also other large-scale folds (e.g. Campbell) observed in the CZ. Dating of foliated and unfoliated gneisses from the Avoca sheath fold (Roering et al., 1992a) at (~2651Ma) (Boshoff, 2003) suggest that this early sheath fold forming event was late Archaean in age. The Campbell structure, on the other hand, dominated by a superimposed shear event reflects a mid-crustal origin for the younger shear event based on a different decompression P-T path. The age of shearing is probably constrained to the Paleoproterozoic (~2023Ma) as mentioned in table 4.1. It can therefore be concluded that the early deformational event that took place at deep crustal levels, expressed by the development of large-scale sheath folds, was responsible for the late-Archaean emplacment of the granulites of the CZ to mid-crustal levels. The younger shear event that took place at mid-crustal levels, on the other hand, represents the major transpressive shear system that affected the CZ in the Paleoproterozoic as was suggested in the literature (e.g. Holzer et al., 1998; Schaller et al., 1999).

Table 4.1: The major differences between the Shanzi and Campbell structures.

Element	Ga-Tshanzi	Campbell
Fold geometry	1) Sheath fold geometry 2) Foliations define a circular structure with central axis dipping towards the SW at ~45º. 3). One type of fold axis dipping ~45ºSW, parallel to the central fold axis similar to the Avoca and Bellevue sheath folds (Fig. 2.10). 4). One population of lineations dipping SSW near parallel to the central fold axis.	1) Isoclinal fold geometry 2). Foliation indicates parallel fold limbs dipping to the WSW and axial plane trending NNW. 3). The ß-fold axes plunges at relatively shallow angles towards the WSW, parallel to the dip of the fold limbs 4). The dominant population of lineations plunges WSW parallel to the ß-fold axes (Fig. 2.17).
P-T conditions	Developed at deep crustal levels from 7.5kbar to 5.23kbar.	Developed at more shallow crustal levels from 4.98kbar to 3.7kbar.
AH_2O (Water Activity)	Very low activity with values ranging from 0.122 at peak conditions to 0.037 at the lowest recorded conditions.	Comparatively high water activity values ranging from 0.217 at peak conditions to 0.117 at the lowest recorded conditions
Age	As yet undated. However, similar fold geometries suggest that the Ga Tshanzi closed structure developed at the same time (~2651Ma) as the Avoca sheath fold dated by Boshoff (2003).	Developed during the same fold forming event as Ga-Tshanzi. The overprinted shear event is Paleoproterozoic in age dated by zircon SHRIMP dating of melt patches closely associated with the shear zones (Kröner et al., 1999). The similarity in the P-T paths of the Baklykraal and Campbell structures (Fig. 3.40) further support their formation at ~2023Ma based on single phase Pb-Pb dating of garnet of the Baklykraal P-T path (Boshoff, 2003).