The Southern Marginal Zone. (Fig. 1.4). Volumetrically the most important rock types in the SMZ are the pyroxene-bearing tonalitic gneisses, referred to as the Baviaanskloof Gneiss, and metapelitic granulite of the supracrustal Bandelierkop Formation, which also comprises mafic and ultramafic granulites and banded iron formation (e.g. Van Reenen and Smit, 1996). Homogeneous igneous charnoenderbite and enderbite in the SMZ (Bohlender et al., 1992) are volumetrically minor and are restricted to the Matok Complex that intruded the lithologies of the Bandelierkop Formation at about 2670Ma (e.g. Kreissig et al., 2001). Highly attenuated supracrustal fragments defining complex sheath fold structures bounded by broad gneissic shear zones characterize the SMZ (Fig. 1.4) (Smit *et al.*, 1992). These sheath folds and $D_2$ shear zones are interpreted to be the result of post-peak $D_1/M_1$ exhumation of this high-grade zone (Van Reenen et al., 1999). The resulting $D_2$ fabric is penetratively developed in high-grade lithologies from $D_2$ shear zones (Smit et al., 2001).

The minimum age of southward directed thrusting along $D_2$ shear zones in the SMZ is constrained to about 2664 Ma by a syn-tectonic granodiorite of the Matok Complex, which intrudes one of the $D_2$ shear zones (Barton and Van Reenen, 1992). This age also corresponds to the age of migmatisation and the end of high-grade metamorphism at 2663 ±4 Ma for the SMZ (Kreissig *et al.*, 2001).

The SMZ is subdivided into a northern granulite sub-zone and a southern sub-zone of rehydrated granulite by the presence of a retrograde orthoamphibole isograd (Fig. 1.4) (Van Reenen, 1986). Important to note is that metapelite from the granulite sub-zone is characterized by two distinct PT paths that are dependent on the position of the rocks with respect to the Kaapvaal craton (Perchuk *et al.*, 1996). Metapelitic rocks within 35km of the tectonic contact with the KVC show an early decompression-cooling P-T path followed by isobaric cooling, while metapelites occurring 60-70km away from the contact with the KVC show only a decompression-cooling P-T path (Perchuk *et al.*, 1996, Smit et al., 2001). The presence of two P-T paths in the same high-grade terrain is explained (Perchuk et al., 2000) by the difference in the movement of different crustal blocks during exhumation. Crustal blocks far away from the contact with the cool rocks of the Kaapvaal Craton were transported along a decompression cooling P-T path. Crustal blocks close to the contact with the under thrusted cool foot wall rocks of the Kaapvaal Craton were rapidly cooled during exhumation at mid-crustal levels, resulting in isobaric cooling.

The Hout River Shear Zone (HRSZ) (Fig. 1.4) that bounds the SMZ in the south, is a composite structure at least 5 km wide that has been mapped as individual segments over a distance of more than 200 km (Roering *et al.*, 1992a; Smit *et al.*, 1992; Smit and Van Reenen, 1997; Van Reenen, *et al.*, 1995). It consists of E-W trending, steeply northward dipping reverse fault segments and several near-vertical NE trending strike-slip faults (Fig. 1.4) (Smit and Van Reenen, 1997). The HRSZ controlled the exhumation and subsequent rehydration of the southern part of the granulite terrane (Smit and Van Reenen, 1997). The age of deformation and prograde metamorphism of the lower-grade rocks in the footwall section of the HRSZ is well constrained at about 2670±5Ma (Kreissig *et al.*, 2001). This age corresponds with the age of peak metamorphism in the SMZ (2690Ma, Kreissig et al., 2001).

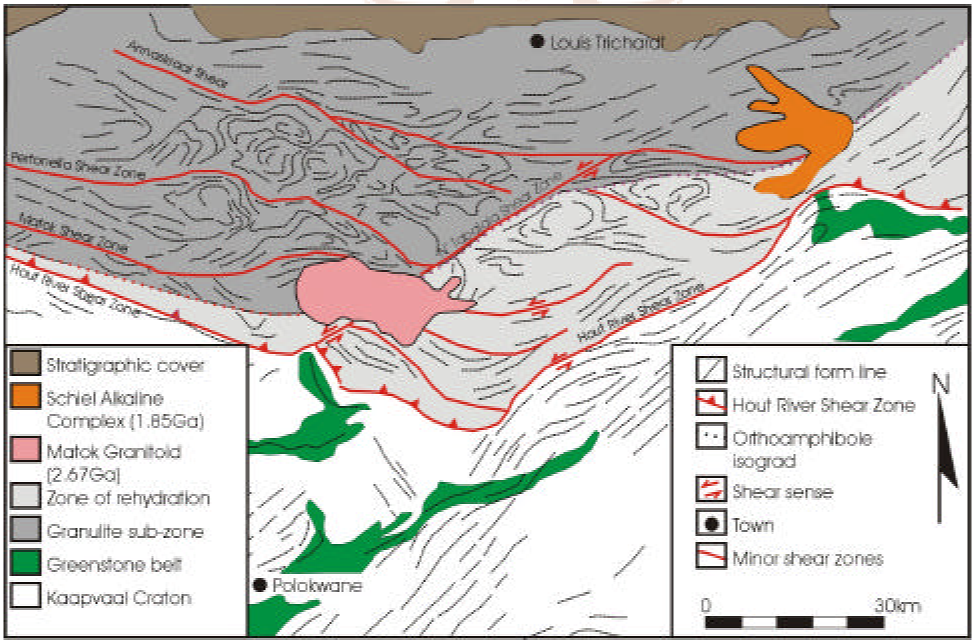

*Figure1.4: Structural sketch map of the Southern Marginal zone (After Smit and Van Reenen, 1997).*

## 1.2.Geology of the Central Zone

### 1.2.1. Rock types

The CZ mainly comprises of the supracrustal Beit Bridge Complex, the Sand River Gneisses, several suites of grey gneisses, the Messina Layered Suite, quartzofeldspathic gneisses (Singelele-type gneisses), and the Bulai Pluton (SACS, 1980).

**The Beit Bridge Complex** (BBC) comprises of garnetiferous paragneisses, leucocratic quartzo-feldspathic gneisses (including the Singelele gneiss), metapelitic gneiss, marble, calc-silicate rocks, quartzite and magnetite quartzite (Van Reenen et al., 1990). These supracrustal lithologies were interpreted as a cratonic shelf sequence (Brandl, 1983; Eriksson *et al.*, 1988). Brandl (1983) subdivided the BBC into three tectonostratigraphic units: the Mount Dowe, Malala Drift, and Gumbu Groups. This subdivision is mainly based on the type outcrop area near Beit Bridge and Musina. The Mount Dowe Group consists predominantly of quartzite with subordinate magnetite quartzite, leucocratic quartzo-feldspathic gneiss, Singelele gneiss, amphibolite, metapelite, and calc-silicate layers (Brandl, 1983). The Malala Drift Group is comprised predominantly of leucocratic quartzo-feldspathic gneiss with lesser amounts of pink granitoid hornblende gneiss (similar to the Singelele Gneiss of the Mount Dowe Group), quartzite, amphibolite, marble, metapelite, and mafic granulite (Brandl, 1983). The Gumbu Group consists of calc-silicate rocks and marble with subordinate leucocratic quartzo-feldspathic gneiss, and amphibolite (Brandl, 1983). The Gumbu group forms the top and the Mount Dowe Group the bottom of the BBC (Brandl, 1983).

**The Sand River Gneisses** (SRG) are mainly comprised of interlayered tonalitic, trondhjemitic and granodioritic gneisses that are cut by mafic dykes and a variety of younger granitoids (Hofmann et al., 1998). Migmatitic and layered grey granitoid SRG are well exposed as rock pavements in the Sand River 10km to the southeast of Musina and preserve evidence of a complex history of polyphase deformation and metamorphism (Fripp, 1983; Jaeckel et al., 1997; Hofmann et al., 1998). Zircons extracted from tonalitic, trondhjemitic and leucogranitoid phases of the SRG (e.g. Retief et al., 1990; Tsunogae and Yurimoto, 1995; Jaeckel et al., 1997 and Kröner et al., 1998) have yielded ages of between 3180 and 3290 Ma interpreted to be the age of crystallisation of the precursor granitoids. Deformed mafic dykes with granulite-facies mineralogy clearly crosscut an earlier tectonic fabric within the SRG and yield ages >3000 Ma by both Pb-Pb and Sm-Nd methods (Barton et al., 1990). The age and field relationship of these dykes clearly constrains the minimum age of the SRG.

In the past the SRG has been considered as the oldest rocks in the LB (e.g. Watkeys et al., 1983; Horrocks, 1983; Brandl, 1983). Horrocks (1983) and Bahnemann (1972) suggested, on structural grounds, that the SRG represented a basement to the adjacent and infolded granulite-facies metasediments of the BBC. Kröner et al., (1998) and Hofmann et al. (1998) however showed that at the Verbaard locality granitoid gneisses considered to be part of the SRG clearly intrude supracrustal gneiss of the BBC.

Several suites of grey gneiss with similar mineralogical and chemical characteristics that occur throughout the CZ are referred to as the Alldays Gneiss, Zanzibar Gneiss, and Verbaard Gneiss. These gneisses have U-Pb zircon ages in the region of 2650Ma (e.g. Jaeckel et al., 1997 and Kröner et al., 1999).

**The Alldays gneiss,** in the Sand River southwest of Musina and further west in the CZ, is described as a multiphase suite of granitiod gneisses (Brandl, 1990). This unit consists of a variety of gneisses ranging from a compositionally layered gneiss (rare), to the less intensely deformed homogenous, and porphyroblastic (foliated megacrystic) gneisses (Brandl, 1990). These gneisses range in colour from leucocratic through grey to pink (Brandl, 1990). The Alldays Gneiss also occurs as discrete elliptical bodies or as concordant sheets, up to 1km wide with a well-defined intrusive relationship with the BBC (Brandl, 1990). Zircon ages of 2650±21Ma (upper intercept U-Pb SHRIMP age) and 2637±3Ma (concordant age) were reported from an Alldays gneiss sample containing small melt patches exposed at a hill south of Alldays (Kröner et al., 1999).

**The Verbaard Gneiss** is described as a suite of homogenous, tonalitic and granodioritic gneisses with strong foliation (Jaeckel et al., 1997). This gneiss intrudes the SRG on Verbaard Farm, south-west of Musina, and is correlated with the Alldays Gneiss (Jaeckel et al., 1997). The Verbaard gneiss consists of tonalitic and trondhjemitic gneisses with a subordinate granodiorite phase which is light to dark grey in colour (Kröner et al., 1999). The tonalitic and trondhjemitic gneisses have $^{207}$Pb/$^{206}$Pb single zircon ages of 2647±0.4Ma and 2615±0.2Ma respectively (Jaeckel et al., 1997).

**The Zanzibar Gneiss,** near Zanzibar in Botswana, consists of interlayered granodioritic and granitic gneisses similar in appearance to the SRG and Alldays Gneiss (Key, 1977, 1979; Barton and Key, 1983). Zircon ages of 2614±13 Ma and 2653±5Ma (upper intercept SHRIMP ages) and 2659±10 Ma (concordant age) were obtained from samples of the Zanzibar Gneiss (Kröner et al., 1999), which are in accordance with the finding of Brandl (1992) who considered the Zanzibar Gneiss to be an equivalent of the Alldays Gneiss. Kröner et al. (1999) consider the age of 2653±5Ma to be the time of emplacement of the Zanzibar gneiss precursor.

**The Messina Layered Suite** (anorthosites, leucogabbro and minor gabbroic gneisses) (Fig. 1.1) intruded the BBC at or before 3250 Ma (e.g. Barton, 1983). It occurs throughout the Central Zone as intensely deformed layers and lenses of plagioclase rich leucocratic gneiss with rare occurrences of chromite and magnetite (Barton, 1996). Sheets of anorthositic/leuco-gabbroic gneiss up to 200m thick have been found interlayered within the supracrustal lithologies (Watkeys, 1984).

**The Singelele Gneiss** (Söhnge, 1946; Söhnge et al., 1984; Bahnemann, 1972; Fripp et al., 1979) forms layers within the supracrustal BBC (Barton et al., 1979b) and occurs as distinct outcrops closely associated with this complex thoughout the CZ (Pienaar, 1985; Pretorius, 1986; Boshoff, 2003). It also occurs as dykes and sills intrusive into the Messina Layered Suite (Watkeys et al., 1983).

Singelele-type gneisses that are interlayered with rocks of the BBC (e.g. at Verbaard locality) are regarded as a product of local anatexis during a high-grade metamorphic event ($M_2$) in the Late-Archaean (Hofmann et al., 1998). Also at the Verbaard locality (see Fig. 2.1 for locality), veins of quartzo-feldspathic gneisses, interpreted to be Singelele Gneiss intruded into SRG, syntectonically with the $D_2$ folding event (Hofmann et al., 1998). The syntectonic emplacement of the precursor to this gneiss accurately constrains the timing of the Late-Archaean $D_2$ and $M_2$ events (Hofmann et al., 1998). Jaeckel et al. (1997) dated single zircons from the Singelele Gneiss to the east of

Musina, and yielded a $^{207}$Pb/$^{206}$Pb age of 2568±3 Ma by vapour digestion and an age of 2582.5±0.3 Ma by the evaporation technique. Zircons from a Singelele Gneiss sample ~5km southeast of the Verbaard locality, on the farm Ostend yielded an upper intercept SHRIMP age of 2681±8 Ma (Kröner et al. 1999). These ages are interpreted by Jaeckel et al. (1997) and Kröner et al. (1999) to reflect the crystallization age of the igneous precursor to the Singelele Gneiss units, implying more than one anatectic episode.

**The Bulai Pluton**, a syn- to late- tectonic granite (Watkeys, 1984) includes enderbitic, charnockitic, tonalitic, and granodioritic varieties intimately associated with the main porphyroblastic granitic gneiss (Watkeys, 1984). This main phase has an intrusive relationship with the supracrustal succession and contains xenoliths of metapelitic gneiss and Singelele Gneiss (Barton *et al.*, 1994). The granitic phase yielded an age of 2572.0 ±4Ma and the enderbitic phase has an age of 2605±0.2Ma (Barton et al., 1994). The Bulai Pluton is an important time marker that constrains the Main $D_2$ deformation event in the CZ to the Late-Archaean (McCourt and Armstrong, 1998).

The Phikwe and Makowe Granites, from the western margin of the CZ, have a similar syn-kinematic character, composition and ages as the Bulai Pluton (McCourt and Armstrong, 1998).

### 1.2.2. Geochronology

Three grouping of ages obtained from lithologies from the CZ reflect three distinct tectono-metamorphic events (e.g. Barton and Key, 1981; Horrocks, 1980; 1983; Fripp, 1982; Waykeys et al., 1983; Barton et al., 1990b; McCourt and Vearncombe, 1992; Barton and Van Reenen, 1992a; Rollinson, 1993; Holzer et al., 1998; Kröner et al., 1998; McCourt and Armstrong, 1998). The first event occurred during the mid-Archaean (3.2-3.1Ga) and is recorded in the crystallisation/emplacement ages of the precursor granitoids to SRG and related granitoid gneisses (e.g. Kröner et al., 1999), the second during the late Archaean (2.65-2.52Ga) and the third during the Paleoproterozoic (2.0±0.05Ga). The main area of debate concerns the significance of the last two events. One school of thought believes that the main orogenic event occurred during the Paleoproterozoic (e.g. Barton et al., 1994; Kamber et al., 1995; Holzer et al., 1998; Schaller et al., 1999), while a second school believes that it occurred during the Late Archaean (e.g. Van Reenen et al., 1987; Roering et al., 1992a; Hofmann et al., 1998; Kröner et al., 1998; McCourt and Armstrong, 1998). The contrasting interpretations are outlined below:

### The geochronology of the CZ according to Holzer et al. (1998)

Single-phase metamorphic mineral isotope data from CZ lithologies indicate a history ranging from 3800 until 2000 Ma (Holzer *et al.*, 1998) with well defined peaks at ~3200, ~2600 and ~2000 Ma (Holzer *et al.*, 1998).

Isotopic data from the SRG and the Messina Layered Suite indicate Mid-Archaean magmatic activity between 3100 and 3300 Ma (Holzer *et al.*, 1998). Due to subsequent high-grade tectono-metamorphic events the pre-3000 Ma geologic history of the CZ is still poorly understood, but is interpreted as the $D_1/M_1$ event (Holzer *et al.,* 1998).

The late Archean ($D_2/M_2$) event in the CZ is attributed to widespread magmatism spanning the period ≥2655Ma (Alldays granodiorite) to ≤2550Ma (Singelele and other granitoids of the CZ) (Holzer et al., 1998). The interpretation, is based mainly on unpublished data, and specifically that pseudomorphic sillimanite after chiastolitic andalusite occurs with garnet and cordierite in a metapelitic sample on the farm Boston NW of Musina. According to Holzer et al., (1998) this implies a prograde metamorphic event of high temperature and low pressure defined by an anticlockwise P-T path. This event was dated at 2521±4Ma using the Pb stepwise leaching method (PbSL dating) on garnet and sillimanite (Holzer et al., 1998). The Bulai intrusion with an age of 2572±4Ma postdates the $M_1/D_1$ structures and is late syntectonic with respect to the $M_2/D_2$ event (Holzer et al., 1998). The Bulai granite was subsequently affected by a $D_3$ event that is interpreted to be a product of ENE-WSW directed shortening and ENE-WSW trending dextral shears (Holzer et al., 1998).

The third event ($D_3/M_3$), considered to be the major fabric forming event in the CZ, was dated accurately using calcsilicate enclaves from a shear zone developed at the contact between the Bulai granite and the BBC exposed on the eastern side of Ga-Tshanzi near Musina (Holzer et al., 1998). PbSL ages of garnet and titanite (2010±17Ma and 2007±5Ma respectively) are interpreted to indicate synkinematic recrystallization of these minerals and the onset of near-isothermal decompression (Holzer et al., 1998). An U-Pb age of 2026±7Ma on metamorphic zircon (Jaeckel et al., 1997) derived from metapelites also recorded the time of the high-pressure granulite facies metamorphism (Holzer et al., 1998). Undeformed leucosomes (melt patches) within the SRG interpreted to be the result of decompression melting related to this event yielded a zircon age of 2008±8Ma (Jaeckel et al., 1997). The age of retrograde metamorphism during the $D_3/M_3$ event is constrained by Rb-Sr biotite-whole rock cooling ages throughout the CZ that concentrate around 1970Ma (Barton et al., 1992). The most important conclusion of the study by Holzer et al. (1998) is that both the cross folds and the sheath folds (folds with circular outcrop patterns) in the CZ reflect the Paleoproterozoic event, and that evidence for the Late-Archaean event is mainly restricted to xenoliths occurring within the Bulai pluton near Musina.

### The geochronology of the CZ according to Hofmann et al. (1998) and Kröner et al. (1999)

Hofmann et al. (1998) and Kröner et al. (1999) described five deformational and three metamorphic events during the evolution of the CZ.

The oldest group of ages concentrate around 3240 Ma and were obtained from the Dorothy gneiss and the SRG exposed in the Sand River on Verbaard farm, SSE of Musina (Kröner et al., 1999). These ages are interpreted to represent the emplacement age of the precursor to the SRG that intruded into rocks of the BBC during the $D_1/M_1$ event (Kröner et al., 1999). The $D_1$ event was associated with strong coaxial deformation and the formation of the first foliation with lithological layering (Kröner et al., 1999). The effects of high-grade metamorphism is preserved as partial melt veins that occur within metapelitic gneiss and the SRG that became flattened during continued $D_1$ deformation (Kröner et al., 1999).

The second tectonometamorphic event ($D_2/M_2$) occurred between 2580 and 2510 Ma (Kröner et al., 1999). This age was recorded by a metapelite (Pb-Pb sillimanite-garnet isochron age of 2573±15Ma) from the BBC (Kröner et al., 1998 and Holzer et al., 1998), and is also reflected by the intrusion of the anatectic Singelele Gneiss precursor and other granitoid gneisses interlayered with the BBC (Kröner et al., 1998, 1999; Jaeckel et al., 1997; Holzer et al., 1998). $D_2$ deformation, interpreted to represent the major fabric-forming event in the CZ, involved non-coaxial deformation of $D_1$ foliations and layering producing a second axial planar foliation (Kröner et al., 1999). $M_2$ metamorphism is reflected as partial melt veins that were flattened during continued $D_2$ deformation (Kröner et al., 1999). The $M_2/D_2$ event is interpreted to be the first granulite facies metamorphism to have occurred within the CZ (Kröner et al., 1999).

Kröner et al. (1999) discussed a third deformational event to have occurred between the $M_2$ and $M_3$ events. This $D_3$ event took place between 2500 and 2000 Ma and is preserved as small-scale asymmetrical folds and partial melt veins parallel to the axial plains of $D_3$ folds (Kröner at al., 1999).

The $D_4/M_3$ event occurred at about 2000 Ma (Jaeckel et al., 1997) and is preserved as various sets of shear zones interpreted to have been associated with the second granulite facies event (Kröner et al., 1999). The important conclusion from this study is that the major fabric-forming event ($D_2$) occurred in the late-Archaean, and that subsequent deformation ($D_3$, $D_4$) was much less intense, supporting the suggestion (McCourt and Armstrong, 1998) that this was mainly a static, thermal event.

### 1.2.3. The Regional Structural Framework of the Central Zone

The CZ is mainly comprised of the following regional structural elements arranged in belt-like zones extending in a general ENE-WSW direction: the high-grade "Tshipise Straightening Zone," located to the north of the Soutpansberg Trough and bounding the CZ in the south, and the complexly folded area north of the Straightening Zone commonly referred to as the "Cross Folded Zone” (Fig. 1.3) (Söhnge, 1946; Bahnemann, 1972; Watkeys, 1983).

**The Tshipise Straightening Zone.** The southern boundary of the CZ is characterized by an approximately 10km wide planar structure referred to as the Tshipise Straightening Zone (Fig. 1.3) (Horrocks, 1980; Holzer et al., 1998). This crustal scale shear or straightening zone is characterized by intensely deformed supracrustal rocks of the BBC and a monotonous ENE- WSW trending foliation pattern that dips steeply towards the SSE. Fold axes and lineations within the straightening zone plunge moderately towards the WSW (Horrocks, 1983).

**The Cross Folded Zone** is represented by two fold types that differ both in shape and orientation: (a) large circular to oval-shaped structures (e.g. the Ga-Tshanzi, Avoca, and Bellevue sheath folds, Fig. 1.3, 1.5, 1.6) (Roering et al., 1992 and Van Reenen *et al.*, 2004), and (b) large NNW -SSE trending cross folds with near horizontal fold axes plunging at variable but low angles to the SSE (e.g. Söhnge, 1946; Bahnemann, 1972; Watkeys, 1983; Pienaar, 1985; Pretorius, 1986; Feldtmann *et al.*, 1995; Feldtmann, 1996). Due to their orientation relative to the general ENE trend of the CZ, these structures were referred to as cross folds by early researchers (e.g. Söhnge, 1946; Bahnemann, 1972; Watkeys, 1983).

Several large circular structures are developed in different rock types of the CZ. The large oval-shaped structure on the Farm Avoca (Fig. 1.5) west of Alldays is developed in quartzofeldspathic and tonalitic gneisses (Roering *et al.*, 1992b), whereas the large circular structure (Fig. 1.6) on the Farm Bellevue (Roering *et al.*, 1992b) southwest of Musina deforms a variety of BBC lithologies, including quartzofeldspathic gneisses, mafic gneisses, quartzites, marble, calc-silicate and metapelitic gneisses. The foliation in all cases defines a large-scale sheath fold with mineral stretching lineations developed parallel to the core axis of the folds and consistently plunging steeply (~ 60º) towards the SSW (Roering *et al.*, 1992b). Roering *et al.* (1992), Smit *et al.* (1992), and Smit & Van Reenen (1997) showed that circular folds in both the Central and Southern Marginal Zones represent mega-sheath folds characterized by a single population of linear elements with no evidence for superimposed folding as was previously suggested (e.g. Fripp, 1983; Watkeys, 1983). Similar oriented stretching lineations are also developed in a variety of orthopyroxene-bearing gneisses and granitoids, suggesting that intense simple shear deformation in the CZ occurred under high-grade metamorphic condition (Roering et al., 1992). The Ga-Tshanzi fold in the present study area also deforms BBC lithotypes and is another example of this fold type.

The cross folds in the CZ are major structures that strike perpendicular to the regional trend of the Limpopo Complex and occur throughout the Cross Folded Zone (Van Reenen *et al.*, 2004.). The best exposed cross folds include the Campbell fold WSW of Musina, and the Baklykraal fold located about 25 km west of Alldays (Fig. 1.3) (Van Reenen *et al.*, 2004). The 40km long and 8 km wide Baklykraal fold (Fig. 1.3), developed in lithologies of the BBC, is the largest of the NNW-SSE trending cross folds (Van Reenen *et al.*, 2004) and is characterised by a fold axis that plunges at about ~4° to the SSE. The Campbell fold deforms both BBC and SRG lithologies.

The interpretation of the tectonic evolution of the CZ is still an ongoing controversy. Watkeys (1983) initially interpreted different structures within the Beit Bridge-Musina area of the Cross Folded Zone as the result of three deformation events that occurred at ca. 2700 Ma, with the last two fold events being superimposed onto older folds to produce either Type 1 or Type 3 interference folds (Ramsay and Huber, 1983). Kröner et al. (1998, 1999) reinterpreted the structural evolution of the Verbaard locality in the Sand River 8km southwest of Musina and suggested that the widespread granitoid gneisses were emplaced into already deformed gneisses of the BBC, and that several of the precursor granitoids (e.g. the Singelele Gneiss) were derived by partial melting of the BBC rocks during a high grade metamorphic event. Zircons from the syntectonic Singelele Gneiss gave U-Pb SHRIMP ages of ~2560-2575Ma, that were interpreted to date the age of crystallization of precursors to this gneiss and thus the maximum age of the deformation event responsible for the gneisses (Kröner et al., 1998; 1999).

The important conclusion (e.g. Kröner et al., 1998) is that this anatectic event constrains the maximum age of the ($D_2$) fabric-forming event in the CZ to the Late Archaean. However, the same authors also suggest that peak metamorphism in the CZ occurred at 2027± 4 Ma, based on zircon SHRIMP ages from undeformed melt patches that occur in a variety of rock types in the Musina area. The Paleoproterozoic event, according to these authors, was not accompanied by significant deformation.

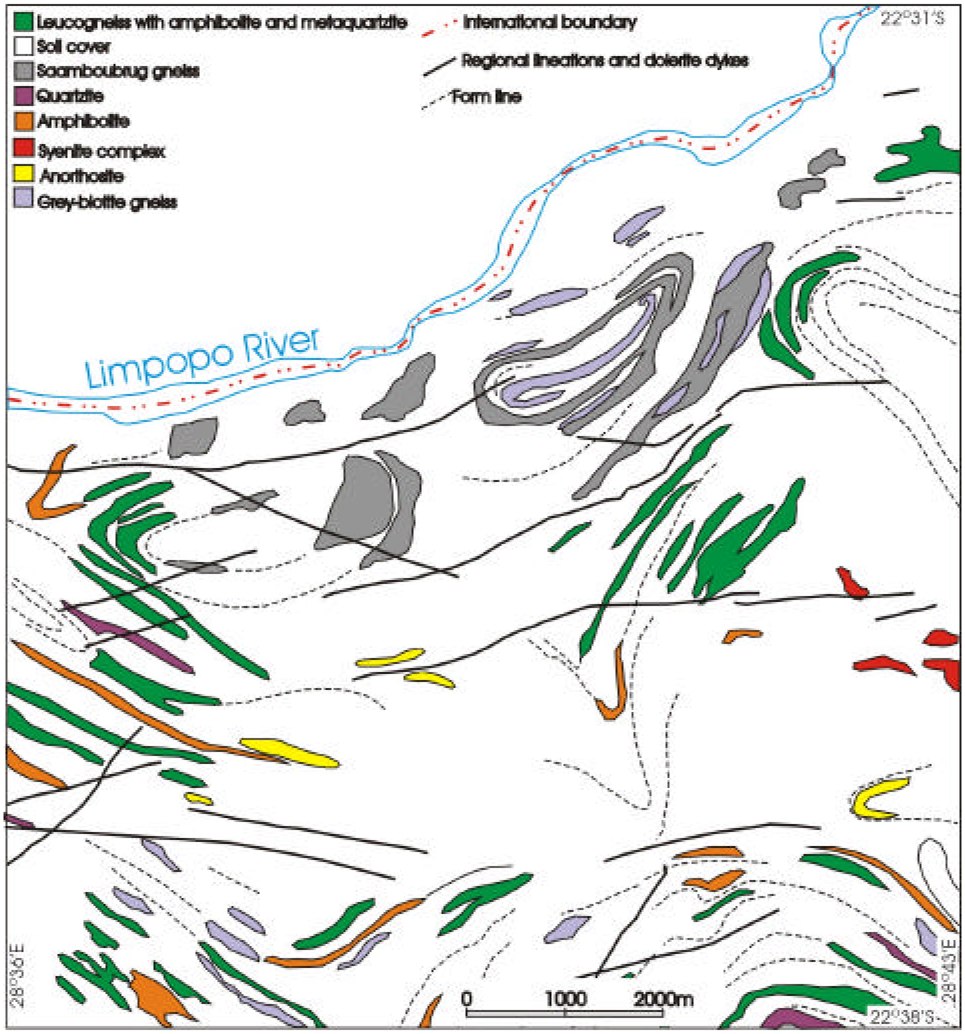

*Figure 1.5: The oval structure on the farm Avoca in the Central Zone (modified after Roering et al., 1992) are defined by Saamboubrug gneiss, grey biotite gneiss, and Leucogneiss with amphibolite and quartzite.*

Holzer *et al.* (1998), on the other hand, argued that the entire Cross Folded Zone and the Tshipise Straightening Zone are the products of dextral transpression at about 2030-2010 Ma. This model suggests that ENE-WSW directed movement and associated strike slip motion were concentrated along shear zones bordering the CZ (the Palala and Triangle Shear Zones and the Tshipise Straightening Zone) that lead to the regional scale isoclinal cross folds at granulite facies conditions including both the Campbell and Ga-Tshanzi folds (Holzer *et al.*, 1998).

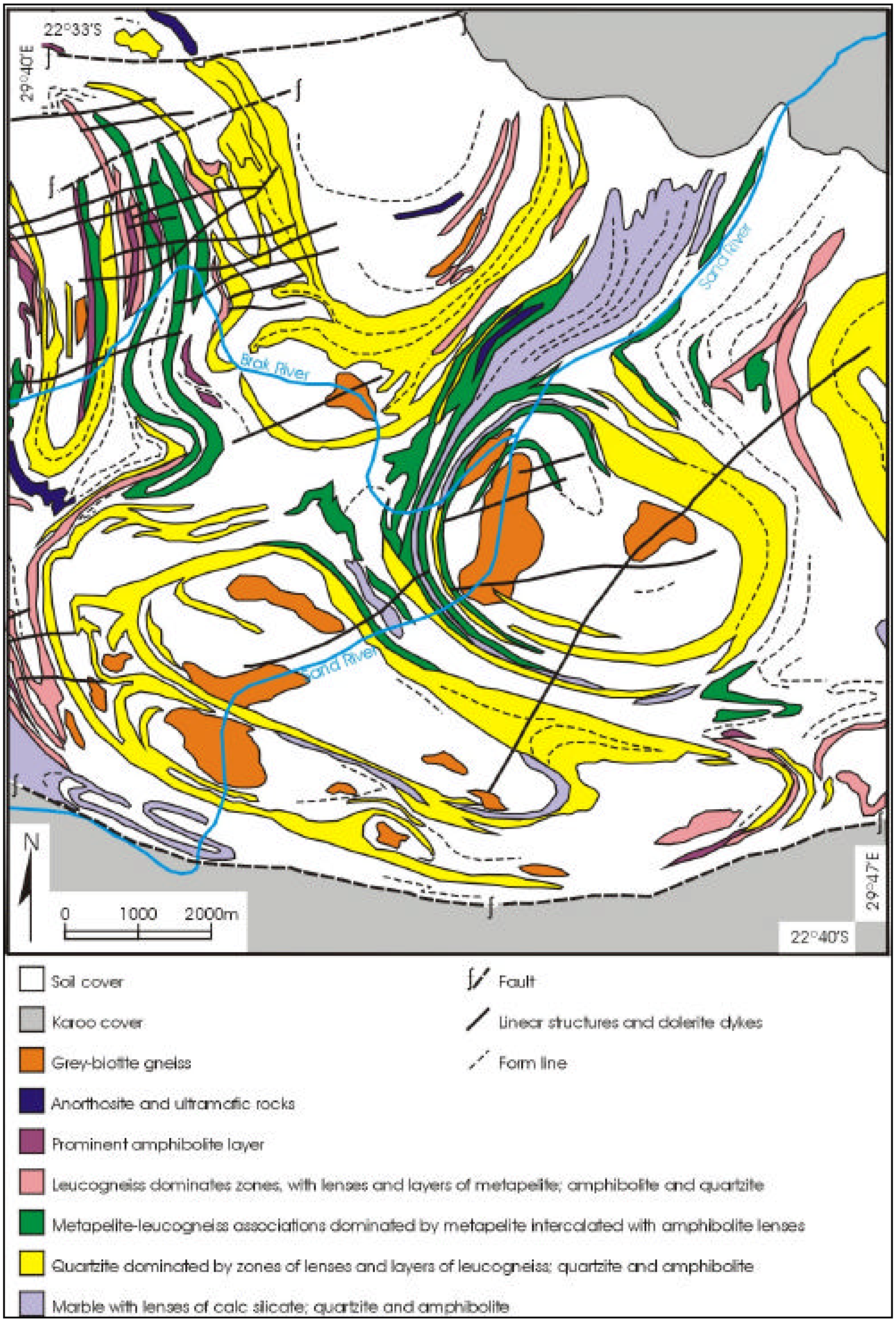

*Figure 1.6: The circular structure on the Farm Bellevue in the Central Zone (modified after Roering et al., 1992).*

### 1.2.4. Published P-T paths for the metamorphic evolution of the CZ

There is little agreement among researchers regarding the timing, type or number of major metamorphic events that have affected the CZ of the Limpopo complex of southern Africa.

Four types of P-T paths have been described for the CZ (Fig. 1.7), isothermal decompression followed by isobaric cooling (Watkeys, 1984; Van Reenen et al., 1990), isothermal decompression (Tsunogae *et al.*, 1992), decompression cooling (Perchuk *et al.*, 1996; Boshoff, 2003; Van Reenen et al., 2004), and a counter clockwise P-T loop (Holzer et al., 1998). In a recent study (Zeh et al., 2004), discussed evidence for a clockwise prograde P-T loop from an area southeast of Musina.

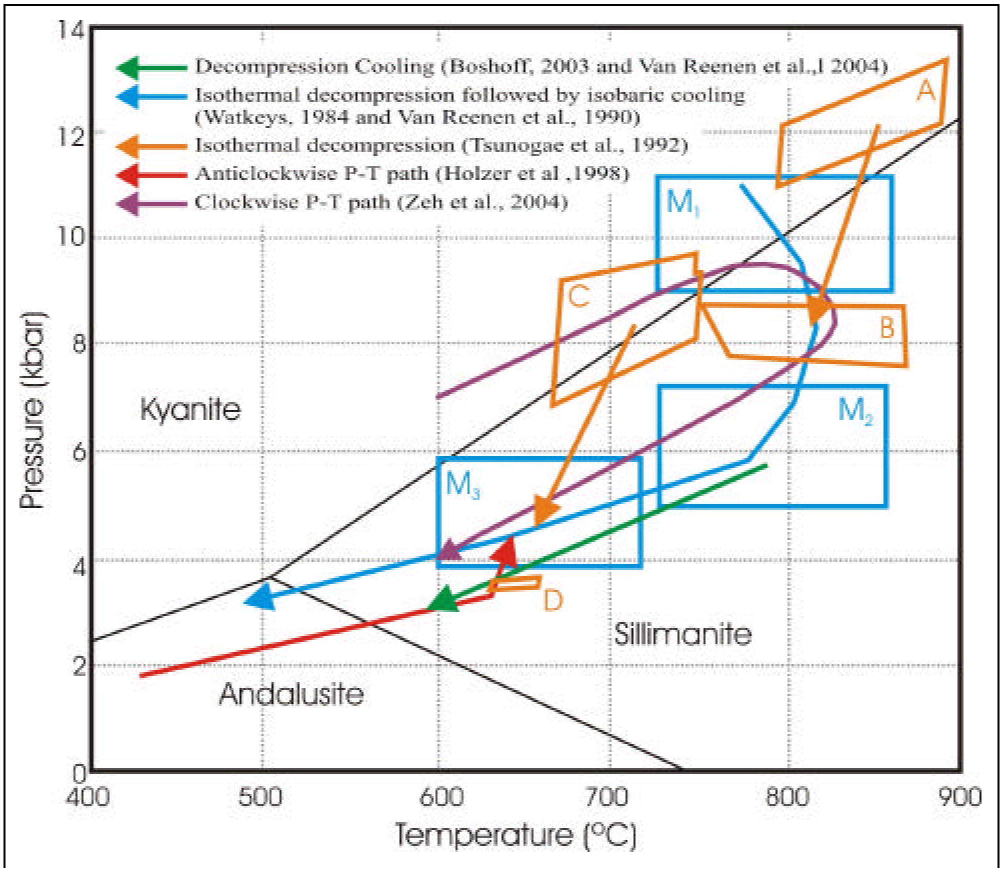

*Figure 1.7: The published P-T paths calculated for the Central Zone. Five different P-T paths have been suggested for the CZ. Watkeys (1984) and Van Reenen et al., (1990) attributed isothermal decompression followed by isobaric cooling to the exhumation of the CZ while Tsunogae et al. (1992) proposed an isothermal decompression PT- path, and Boshoff (2003) and Van Reenen et al (2004) calculated a decompression cooling P-T path. Holzer et al (1998) proposed an anticlockwise P-T path (~2.6Ga event) and attributed isothermal decompression P-T paths to the ~2.0 Ga event, while Zeh et al., (2004) calculated a P-T loop.*

### A. Isothermal decompression followed by isobaric cooling

A retrograde P-T path for the CZ, in which isobaric cooling followed isothermal decompression was proposed by Watkeys (1984) and Van Reenen et al. (1990). This P-T path (blue curve in Fig. 1.7) consists of 3 distinct metamorphic stages, $M_1$, $M_2$ and $M_3$. In this model the lithologies of the CZ were subjected to peak granulite-facies conditions ($M_1$) during burial to a depth of about 35km followed by a decompression event ($M_2$) also at granulite facies during exhumation as indicated by numerous decompression reaction textures, including various symplectites. The introduction of an $H_2O$-bearing fluid phase during cooling ($M_3$) resulted in widespread retrogression of the high-grade mineral assemblages (Horrocks, 1983a; Watkeys *et al.,* 1983; Watkeys, 1984, Van Reneen et al., 1990). Evidence for "peak" metamorphic conditions ($M_1$) during the prograde stage has been almost completely obliterated by the subsequent events ($M_2$ and $M_3$, Van Reenen et al., 1990), but close to peak conditions ($M_1$) were calculated to be in the region of 800±80ºC and 10±1kbar (Fig. 1.7) (Watkeys, 1984; Van Reenen *et al.,* 1990). Further support for relatively high pressures during $M_1$ is given by the rare presence of kyanite inclusions within garnet from metapelitic granulites northeast of Musina (Light, 1980), and by the equally rare presence of relict kyanite that is partially replaced by fibrolite sillimanite from metapelitic granulites southeast of Musina (Miyano *et al.,* 1988).

Isothermal decompression ($M_2$) in the CZ occurred under essentially static conditions (Van Reenen et al., 1990) as is illustrated in metapelite by the replacement of garnet and quartz by a symplectitic intergrowth of cordierite and unorientated, second-generation worm-like hypersthene, according to the reaction: garnet + quartz = cordierite + hypersthene. Metapelites throughout the CZ are also characterized by various other decompression textures, including the replacement of garnet by hypersthene and plagioclase, garnet-sillimanite-quartz by cordierite and biotite-sillimanite-quartz by cordierite and K-feldspar (Horrocks, 1980; 1983b; Watkeys *et al.,* 1983; Watkeys, 1984; Pienaar, 1985; Pretorius, 1986). $M_2$ conditions were estimated to be in the region of 800ºC and 6kbar (Fig. 1.7) (Watkeys, 1984).

Decompression was followed by cooling and retrogression ($M_3$) (Fig. 1.7) during the introduction of a fluid phase into lithologies still at high-grade (Horrocks, 1983a; Light and Watkeys, 1977; Watkeys *et al.*, 1983; Watkeys, 1984). This event resulted in wide spread retrogression throughout the CZ, and also established an area located between Musina and Alldays (Fig. 1.3) in which all lithologies are almost completely retrogressed (Van Reenen *et al.*, 1990). Evidence for retrogression is indicated by a number of hydration reactions, involving mainly the partial to complete replacement of orthopyroxene by hornblende in mafic granulites and the replacement of hypersthene by anthophyllite or biotite in metapelitic granulites (Van Reenen *et al.*, 1990). Final cooling and retrogression occurred until about 475ºC and 2.5kbar pressure (Watkeys, 1984).

**B. Isothermal decompression**

Tsunogae *et al.*, (1992) calculated P-T conditions experienced by mafic, quartzofeldspathic and pelitic gneisses. Peak P-T conditions are recorded by garnet-bearing mafic gneisses consisting of garnet, clinopyroxene, hornblende, plagioclase, and quartz. Using the garnet-clinopyroxene geothermometer (Ellis and Green, 1979), and the garnet-pyroxene-plagioclase-quartz geobarometer (Perkins and Newton, 1981) Tsunogae et al. (1992) calculated peak P-T conditions of 11.0-13.3 kbar and 790-890ºC (orange block A in Fig. 1.7). Lower P-T conditions of 7.6-8.8kbar and 750-870ºC (orange block B in Fig. 1.7) were calculated from the same sample using the garnet-hornblende geothermometer (from Graham and Powell, 1984) and the garnet-quartz-hornblende-plagioclase geobarometer (from Kohn and Spear, 1984) based on the garnet-hornblende-plagioclase-quartz assemblage (Tsunogae et al., 1992).

Quartzofeldspathic gneisses consist of quartz, plagioclase, K-feldspar and lesser amounts of biotite, garnet, hornblende and clinopyroxene. Using the garnet-clinopyroxene-plagioclase-quartz assemblage Tsunogae et al. (1992) calculated P-T conditions of 6.9-9.7 kbar at 660-750ºC (orange block C in Fig. 1.7) from quartzofeldspathic gneiss samples 7-13C and sample 9-2B respectively.

The lowest P-T conditions calculated by Tsunogae et al. (1992) were from pelitic gneiss comprising of garnet, cordierite, sillimanite and quartz. Using the garnet-cordierite thermometer of Thompson (1976) and the garnet-cordierite-sillimanite-quartz barometer of Harris and Holland (1984) Tsunogae et al. (1992) calculated P-T conditions of 3.4-3.7kbar at 630º-660º (orange block D in Fig. 1.7), which they interpret as being retrograde conditions.

An isothermal decompression P-T path (orange curve in Fig. 1.7) is implied from the difference in the P-T conditions experienced by the mafic gneisses and from the difference in P-T conditions experienced by the quartzofeldspathic gneisses and the pelitic gneiss (Tsunogae et al., 1992).

### C. Decompression cooling

A decompression cooling P-T path (green curve in Fig. 1.7) for the CZ has been calculated from metapelitic gneisses consisting of garnet, cordierite, orthopyroxene, or sillimanite, biotite, quartz and K-feldspar (Perchuk *et al.*, 1996; Van Reenen et al., 2004). The retrograde reaction in which garnet and quartz reacted to produce cordierite and orthopyroxene, or where garnet, sillimanite and quartz reacted to produce cordierite, allowed the calculation of the changes in temperatures and pressures from the simultaneously operating Mg-Fe exchange reaction between garnet and cordierite and the net transfer reaction: garnet + quartz = cordierite + orthopyroxene, or garnet + sillimanite + quartz = cordierite (Perchuk *et al.*, 1996). Decreases in $N_{Mg}$ (Mg formula units within garnet) and increases in $N_{Mg}$ (formula units of Mg within cordierite) from core to rim of the two phases indicate cooling and the progression of the net transfer reaction to the right indicates decompression (Perchuk *et al.*, 1996; van Reenen et al., 2004). The P-T path calculated for the metapelitic gneisses in the Baklykraal cross fold, in the western part of the CZ in the region of Alldays, decreases from 786º at 5.68 kbar to 591ºC at 2.95 kbar along a decompression-cooling P-T path with no evidence for isothermal decompression (Boshoff, 2003).

### D. Counter clockwise P-T path (Holzer et al., 1998)

Holzer et al., (1998) proposed two contrasting P-T paths for the evolution of the CZ: a counter clockwise P-T path reflecting a late-Archaean low-pressure granulite facies metamorphism associated with voluminous granitic and charnockitic plutonism, and a Palaeoproterozoic high-pressure isothermal decompression path. Evidence for the counter clockwise P-T path (Fig. 1.7) is based mainly on the results of unpublished data (Holzer, 1995) from metapelitic gneiss from an area northwest of Musina in which rectangular sillimanite was interpreted to reflect pseudomorphs after andalusite.

**E. Clockwise P-T loop (prograde P-T paths) (Zeh et al., 2004)**

In a recent study of metapelitic gneisses Zeh et al. (2004) presented the first evidence for a clockwise P-T loop from an area southeast of Musina (purple curve in Fig. 1.7). The P-T loop displays a prograde P-T increase from 600ºC, 7.0 kbar to 780ºC, 9-10 kbar (peak pressure), and 820ºC, 8kbar (thermal peak), followed by decompression cooling to 600º, 4 kbar. Zeh et al (2004) constrained the prograde P-T path from inclusions within garnet from metapelitic gneiss sampled SW of Musina. The inclusions within the garnet (Gt) include staurolite (St), plagioclase (pl), rutile (Rt), kyanite (Ky) and sillimanite (Sl). The prograde P-T path was then constrained from the inferred assemblage sequence: Gt + St + Pl + Rt ? Gt + Ky + Pl + Rt ? Gt + Sl/Ky + Rt ±liquid ? Gt + Sl + Pl + Rt ± Liquid.

It is important to note that the retrograde portion of this P-T loop shows no evidence for isothermal decompression, in agreement with the decompression cooling P-T paths of Perchuk et al. (1996) and Van Reenen et al. (2004).

## 1.3. Scope and research methods

The area under investigation is situated west and south-west of Musina in the Central Zone of the Limpopo Belt in South Africa, (Figure 1.3) and includes the closely associated Ga-Tshanzi sheath fold and the Campbell cross fold. The lithologies of the study area include the SRG, lithologies of the Bulai Pluton, Singelele Gneiss, and BBC. The study area forms part of the 1:50 000 scale topographic sheets 2230AA &AC Messina, and 2229BD Kamkusi.

The Ga-Tshanzi fold is an oval-shaped structure located 5km WNW of Musina and "outcrops" on the farms Tovey 154MS, Vogelenzang 3MT, and Munnichshausen 151MS. The Campbell fold is located WSW of Musina and was first described as a cross fold by Söhnge (1946) and Bahnemann (1972). Outcrops of the Campbell fold were investigated on the farms Dovedale 156MS, Tralee 204MS, Plaatjies 200MS, Papenbril 205 MS, T'Velde 157MS, Brookham 50MT, Pangebourne 52MT, and Verbaard 53MT. The study area can be accessed via the national roads between Musina and Pontdrift, and Musina and Venetia.

The aim of this dissertation is to document the results of the M.Sc study. The aim of the study was to contribute to our understanding of the geologic evolution of the CZ of the Limpopo Belt through a detailed structural and metamorphic study of two closely associated major fold types with distinctly different fold morphologies. The Ga-Tshanzi fold (see Fig. 2.1, 2.2) is an example of a structure with an ovate outcrop pattern similar to the Bellevue - and Avoca folds (Fig. 1.5 and 1.6) previously mapped as large-scale sheath folds by Roering et al. (1992). These two sheath folds, located more than 100km apart, display identical fold geometries with moderate to steeply SSW-plunging central fold axis (see Fig. 2.10) suggesting NNE-SSW direction of movement (Roering et al., 1992). The Campbell cross fold, on the other hand is a large NNW-SSE trending fold with a fold axis plunging moderately to the WSW (Holzer, 1998). Both folds are developed in similar lithologies of the BBC, and offer an excellent opportunity to establish whether they developed as the result of the same tectono-metamorphic event, or because of different tectono-metamorphic events.

This study focuses on the following:

(1) Structural studies: Structural mapping and the interpretation and comparison of structural data from the two different fold types.

(2) Petrographic study: Chemically similar metapelite samples from the two folds were selected for a detailed petrographic study to establish the metamorphic evolution, and to determine whether rocks from the two fold types display similar of different strain characteristics.

(3) Microprobe study: Chemically similar metapelite samples from the two different fold types were selected for detailed microprobe profiling to establish the chemical evolution of rock forming minerals involved in different types of reactions.

(4) P-T parameters for local equilibria: calculated using the 'core-core rim-rim' method (e.g. Smit et al., 2001).

(5) P-T trajectories for the studied metapelitic samples are derived and forms the basis to establish whether the two fold types developed under similar, or different P-T conditions.

(6) A geodynamic interpretation of the P-T paths.