The tectono-metamorphic event at 2 Ga in the Limpopo Belt and the resetting behaviour of chronometers at high temperature

L. Holzer, B.S. Kamber, J.D. Kramers and R. Frei
Gruppe isotopengeologie, Min.- Pet.Institut, Erlachstrasse 9a, 3012 Bern, Switzerland

Structural observations with garnet and monazite dates from the Messina area, Central Zone of the Limpopo Belt, are presented, as well as Rb-Sr and zircon ages from the Transition Zone between the Triangle shear zone and the Northern Marginal Zone. It is shown that the 2.57 Ga Bulai pluton NW of Messina is deformed by a later high grade event involving minor local remelting. Within samples, monazite concordia ages broadly concur with garnet-feldspar Pb-Pb results. In some samples they document full resetting of both chronometers at 2.0 Ga, but in some they display mixed ages indicating pre-existing parageneses of at least 2.6 Ga. Unlike the 2.0 Ga metamorphism, the age of earlier events could not be well constrained. Reset ages can be related to the presence of melt, rather than deformation, at 2.0 Ga, but no strict rule can be applied. In the Transition Zone, Rb-Sr whole rock and zircon dating did not reveal the 2.0 Ga event. A suite of granites, gneisses and migmatites yielded an apparent magmatic Rb-Sr age of 2.59 ± 0.04 Ga, whereas zircon U-Pb dating gave upper intercepts between 2.22 and 2.35 Ga, of uncertain significance. An overview in histogram form of available age results from the Limpopo Belt shows peaks at 2.6 - 2.7 Ga in the Northern and Southern Marginal Zones but not in the Central Zone, and a peak at 2.0 in all three zones, indicating that the 2.0 Ga event is the first episode common to the three zones of the Limpopo Belt.

Introduction

The Limpopo Belt (Fig. 1), straddling the border between South Africa, Zimbabwe and Botswana is a province with a complex structure and a tectono-metamorphic history comprising multiple events in the time span from before 3 Ga to 2 Ga (e.g. Barton *et al.*, 1990;. Kamber *et al.*, 1995). The regional setting and large-scale structure of the Belt are reviewed in recent papers (van Reenen *et al.*, 1992; Roering *et al.*, 1992; and references therein). It is wedged between the Zimbabwe and the Kaapvaal cratons, trends as a whole ENE-WSW and is ca. 250 km wide. It consists of two marginal zones (NMZ and SMZ) resembling the adjacent cratons (but having high grade mineralogy) with the boundaries to these cratons being reverse fault zones, and a Central Zone (CZ) made up of high grade metasediments (the Beit Bridge Group) with a preceding tonalitic basement (the Sand River Gneisses) and mafic as well as felsic plutonism of various ages (the Messina Layered Intrusion and the Singelele and Bulai granitoid plutons). This CZ is separated from the marginal zones by lateral shear zones, the enormous dextral Triangle shear zone in the North, and the Palala shear zone in the South (McCourt and Vearncombe, 1987).

Until recently tectonic models for the Limpopo Belt were dominated by the view that a major collisional event in the late Archaean (2.7 - 2.6 Ga) caused the observed tectonism and the high grade metamorphism in all three zones. However, the 2.0 Ga age of the main tectonism visible in the Triangle shear zone and the transition zone to the NMZ, along with a high grade high pressure metamorphism, is described by Kamber *et al.* (1995 and in press). These authors also found evidence of high grade metamorphism at 2 Ga in the CZ. The importance of a ca. 2 Ga high grade metamorphic event in the CZ is also emphasised by Barton *et al.* (1994) who further pointed out that it is very risky to constrain the timing of metamorphic events by using intrusive ages of plutons.

One reason why the importance of the 2 Ga tectono-metamorphic event in the Limpopo Belt was not recognised earlier by most workers, is that age determinations - particularly whole rock Rb-Sr and Pb-Pb ages and zircon U-Pb ages - do not show any signs of disturbance or resetting by it. At the same time the many biotite Rb-Sr data indicating ages around 1.9 or 2.0 Ga were interpreted as either dating late uplift (Barton and van Reenen, 1992b) or a thermal event or reactivation of unspecified but minor nature (e.g. Ridley, 1992). The convincing evidence consisted of Pb-Pb, Sm-Nd and Ar-Ar dates obtained directly on assemblages and minerals which could be characterised texturally and in terms of PT conditions of crystallisation (Kamber *et al.*, 1995 and in press).

As the 2 Ga event in the Limpopo Belt comes more to the fore, the nature of earlier events becomes more obscure. Clearly the Limpopo Belt remains a key area for the study of Archaean tectonism in spite of this; but before the Archaean aspect can be properly addressed anew, the nature of the 2 Ga event has to be better understood. The purpose of this paper is, first, to review existing evidence of tectonism and high temperature conditions postdating 2.6 Ga, second, to present new geochronological data on tectonically well characterised sites in the CZ and the NMZ, and third, to give an overview of existing geochronological data on the Limpopo Belt. The main aim is to provide a further perspective on the 2.0 Ga tectono-metamorphic event. Some paradoxical behaviour of isotopic systems is also discussed, which allows the Limpopo Belt to be identified as an interesting natural laboratory for the study of geochronometers.

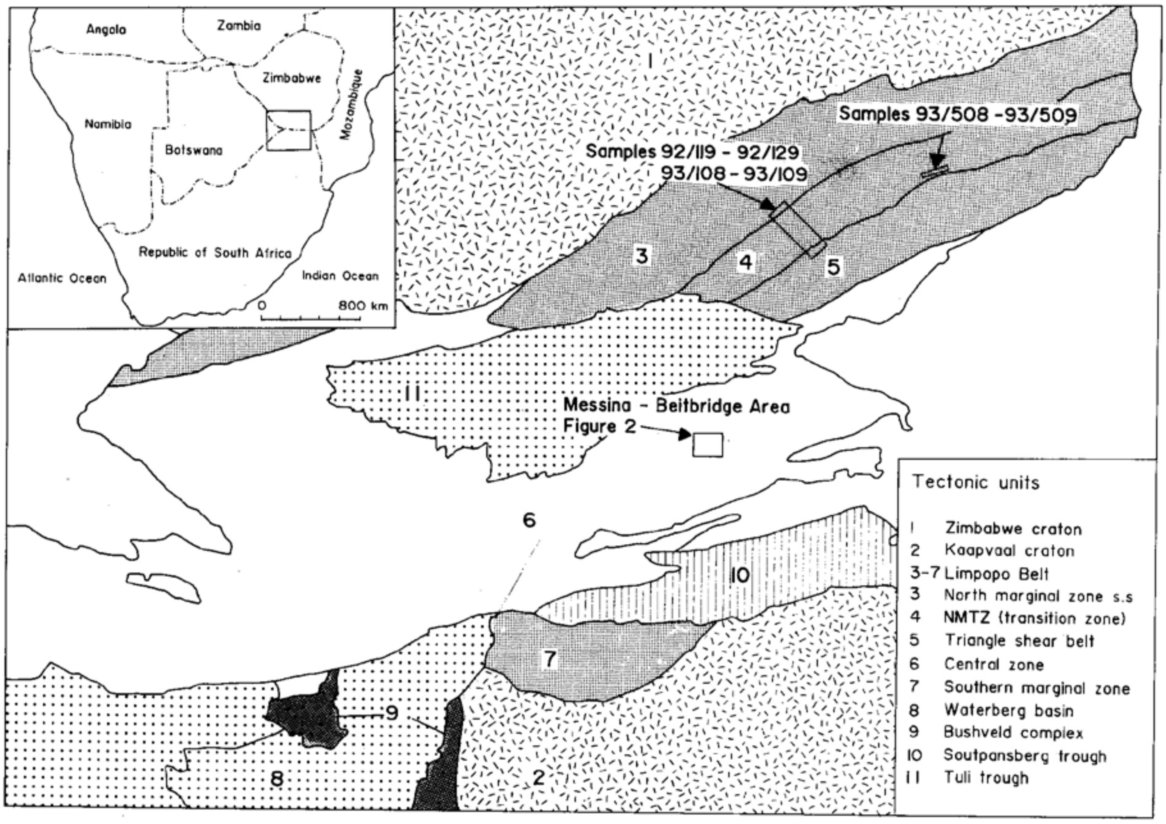

Figure 1: Geological map of the Limpopo Belt, showing features mentioned in the text.

Existing geological evidence for an important Proterozoic tectono-metamorphic event in the Central Zone of the Limpopo Belt

The Bulai Pluton

Traditionally, plutons have been used as primary time markers in tectonic provinces because they can be characterised as pre-, syn- or post-tectonic and can be dated by conventional methods. However, the differentiation between syn- and post-intrusive structures is difficult because "retrograde" textures (originating from tectonism that was active during cooling and crystallisation of the pluton) can look similar to "prograde" textures (which are produced during a high grade tectono-metamorphic overprint). The review of literature relevant to this subject confirms that structural arguments are often ambiguous (Paterson *et al.*, 1989; Paterson, 1989; Karlstrom, 1989; Castro, 1987; Blumenfeld and Bouchez, 1988). Within the CZ, the Bulai pluton, situated W of the town of Messina, has provided such a time marker. Earlier whole rock age determinations for the Bulai Pluton (2.63 ± 0.06 Ga, van Breemen and Dodson, 1972, recalculated for $\lambda^{87}Rb = 1.42 \times 10^{-11}$/yr, and 2.65 0.09 Ga, Barton *et al.*, 1979) overlapped in error with the zircon U-Pb age of the Matok intrusion (2.67 Ga, Barton *et al.*, 1992), which has been used to date the tectonism between the SMZ and the Kaapvaal Craton. The postulated tectono-metamorphic event was called the Limpopo Orogeny (Barton and Van Reenen, 1992a). The Limpopo Belt was considered as the product of a continent-continent collision at ca. 2.65 Ga. Within this context the Bulai Pluton was thought of as a "late syntectonic" intrusion, its age was the only one in the CZ which fitted with the postulated Limpopo Orogeny.

Barton *et al.* (1994) produced a U-Pb zircon age of

sample	grains	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	±2s(%)	$^{207}Pb/^{235}U$	±2s(%)	$^{206}Pb/^{238}U$	±2s(%)	$^{207}Pb/^{235}U$	±2s	$^{206}Pb/^{238}U$	±2s	$^{207}Pb/^{206}Pb$	+2s	-2s
93/035	11	2910	0.1778	0.03	7.1897	4.8	0.2932	4.6	2135	42	1658	68	**2633**	230.0	0.5
93/116	8	8340	0.1660	0.01	6.5175	6.8	0.2848	6.7	2048	58	1616	96	**2517**	230.0	0.2
93/070	6	601	0.1222	0.04	7.0176	3.7	0.4164	3.6	2114	32	2244	67	**1989**	0.7	50.0
93/050	10	2092	0.1305	0.05	9.3153	3.8	0.5178	3.8	2370	34	2690	82	**2104**	0.8	90.0

Table 1: U-Pb isotope data from monazites

2.57 Ga for the Bulai Pluton. This age must be regarded as the most precise and accurate age for this magmatic body. This zircon age is 100 Ma younger than the zircon age of the

Matok intrusion (mentioned above). Thus time markers can be resolved, and the Bulai Intrusion is post-tectonic with regard to the 2.67 Ga event, in which the SMZ was thrust onto the Kaapvaal Craton, as documented and dated in the Matok area. It follows that any tectonism and thermal events affecting the Bulai pluton must belong to a later episode, separate from this 2.67 Ga SMZ-Kaapvaal tectonism. Features of the structural and metamorphic geology of the Bulai and its environs are described by Barton *et al.* (1994); they comprise the following observations:

The intensity of deformation within the Bulai Pluton is very heterogeneous, but generally gneissic fabrics prevail. These planar fabrics are defined by the orientation of plastically deformed feldspar, quartz and biotite and therefore they cannot be a magmatic flow texture. The mapping of the area (see Fig. 2) has shown that the Pluton was deformed along with the dominant regional-scale structures. The gneissic foliation can be followed through the contact to and within the host rock. The intrusion thus clearly predates this first post-intrusive ductile deformation (DB_1).

At least one further deformation (DB_2) locally transects and obliterates the DB_1 fabric: the gneissic foliation, and minor crosscutting mafic and felsic dykes, have been folded and refolded, producing structural interference patterns. Big ductile shears crosscut the gneissic fabric. Locally sets of subparallel shear zones define a shear belt which may reach up to 1 km in width. These shear zones may show crosscutting relationships among each other, but can in places also appear coeval, producing an anastomosing pattern. Particularly the N-S striking ductile shear zones have a large vertical displacement component. Within all shear zones of this family, ductile folding is seen in the gneissic banding of the Bulai rocks.

The Bulai granitoid itself locally shows anatectic features. Particularly in the shear zones, undeformed leucosomes can be observed. In some areas melt became mobilised and small undeformed granitic bodies, up to

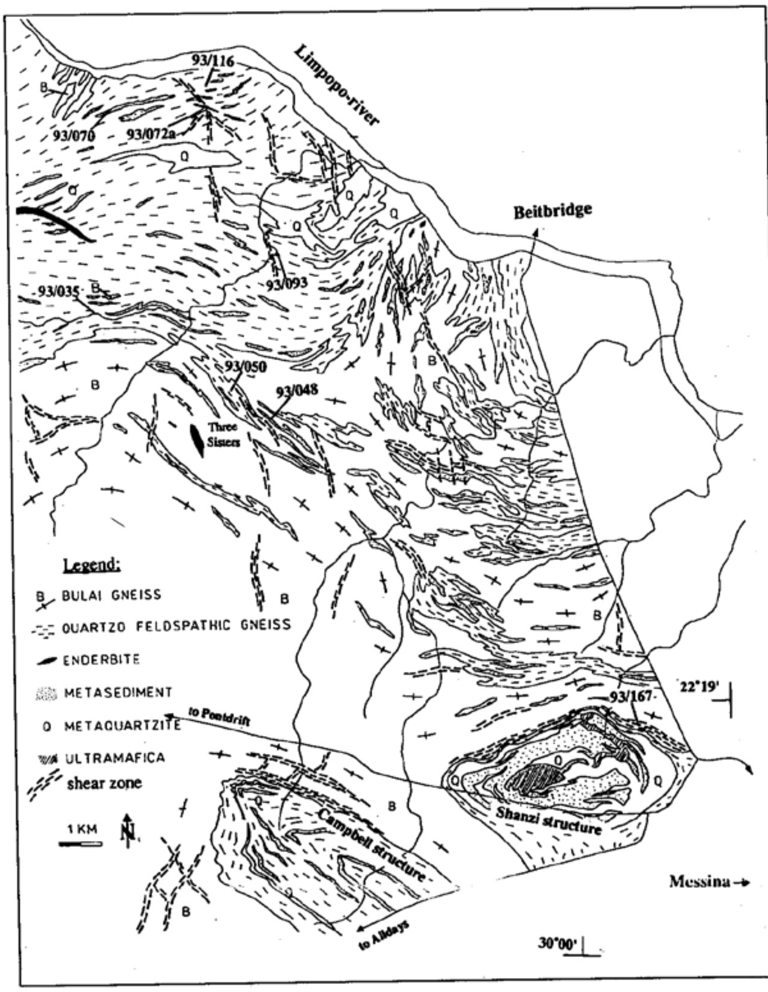

Figure 2: Geological map of the area NW of Messina, South Africa, covering parts of the Bulai Batholith. Structural features are discussed in the text. Sample localities for garnet and monazite dating are indicated by the corresponding sample numbers (see Tables 1 and 2).

Sample Nr/Name	206/204 Fr. corr.	+/- 2s (abs)	207/204 Fr.corr.	+/- 2s (abs.)	208/204 Fr.corr.	+/- 2s (abs.)	r 7/4-6/4	r 8/4-6/4	Pb-Pb age Ma
93/035 Grt	24.041	0.066	16.784	0.046	54.815	0.152	0.993	0.993	2394±50
93/035 Fsp	14.895	0.023	15.373	0.025	34.539	0.056	0.988	0.982	
93/048 Grt	27.442	0.449	17.456	0.287	46.974	0.77	0.996	0.998	2514±160
93/048 Sil	47.91	0.877	20.845	0.382	76.282	1.398	0.998	0.999	
93/050 Grt	22.566	0.166	16.498	0.122	37.651	0.279	0.996	0.998	1938±275
93/050 Fsp	15.91	0.069	15.707	0.07	34.672	0.153	0.967	0.985	
93/070 Grt	155.692	24.502	41.085	6.468	102.843	16.186	1	1	1826±700
93/070 Fsp	57.917	0.85	30.161	0.443	70.915	1.042	0.999	0.999	
93/072a Grt	18.663	0.078	16.133	0.077	37.285	0.157	0.873	0.991	2548±260
93/072a Fsp	15.445	0.057	15.588	0.058	35.771	0.135	0.99	0.986	
93/093 Grt	20.712	0.066	16.543	0.053	57.881	0.186	0.991	0.994	2406±110
93/093 Fsp	15.798	0.023	15.779	0.023	39.798	0.06	0.981	0.977	
93/116 Grt	38.938	0.139	18.959	0.068	43.459	0.157	0.995	0.996	2264±41
93/116 Fsp	15.498	0.075	15.608	0.076	34.967	0.171	0.995	0.995	
93/167 Grt	1351.79	55.892	181.315	7.497	1146.769	47.418	1	1	2011±6
93/167 Fsp	18.925	0.028	16.392	0.025	44.604	0.069	0.982	0.98	

Table 2: Pb-Pb data from garnet, feldspar and sillimanite.

several hundred meters in diameter, intruded the Bulai Pluton. These leucogranites crosscut the DB_1 and DB_2 foliations and shear zones.

These observations are in good agreement with the detailed structural investigations from Watkeys *et al.* (1983) and from Watkeys (1984). However, these authors interpret the deformations and the partial melting in the Bulai pluton as retrograde features of a single PT loop, which therefore should have lasted over 1 Ga. In contrast we interpret these observations as strong indication for a distinct tectono-thermal event which took place in its entirety after the Bulai pluton was consolidated at ca. 2.57 Ga. The effects of this event can be seen to extend much beyond the pluton itself into its host rocks, and with reference to the pluton age, a set of important large- and medium-scale structures previously noted in the CZ can thus be regarded as Proterozoic:

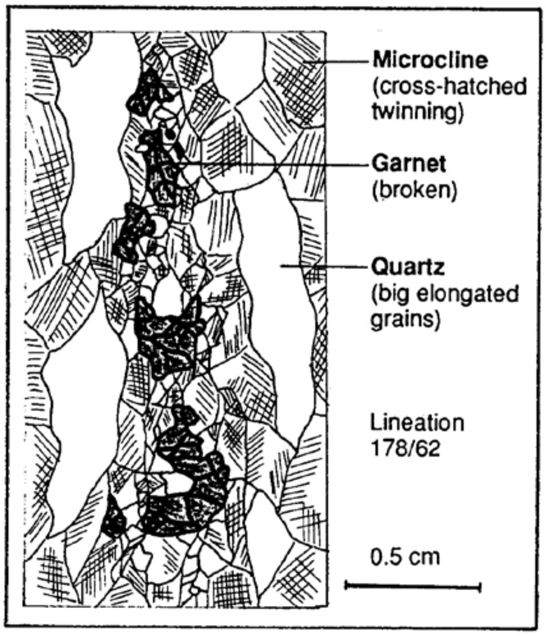

Figure 3: Cut of a thin section from Sample 93/116, garnetiferous quartzo-feldspathic gneiss from farm Tuinbou, West of Beitbridge.

Watkeys (1984) describes the large Shanzi- and Campbell fold structures (see Fig. 2) as products of deformations which postdate the Bulai intrusion (Watkeys D_3: F_4 and F_5 folding). We interpret these large-scale fold structures in good agreement with Watkeys (1984) as refolded folds, affected by DB_1 and DB_2. Within the Shanzi structures indicators of the DB_2 shear sense show thrusting to the ENE. This movement was indirectly dated: Pb-Pb ages of syntectonic, aligned garnets (Kamber *et al.*, 1995, sample 92/137) indicate their crystallisation at 2006 ± 44 Ma. The corresponding cooling path is documented by Rb-Sr biotite ages around 1.97 Ga in the whole central zone (Barton *et al.*, 1992b) and Rb-Sr dates on retrogressive muscovites which give ages be-

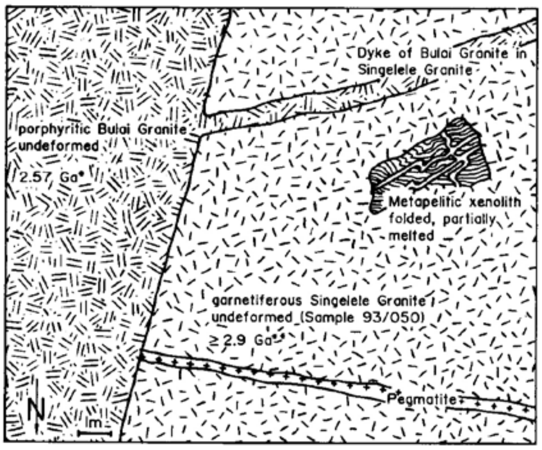

Figure 4: Contact between Bulai Granite and Singelele Granite, 1 km North of "Three Sisters" on the Farm Proefplaas Messina. Age references: * Barton *et al.* (1994), ** Barton *et al.* (1979).

tween 1.92 and 1.90 Ga (Barton *et al.*, 1994).

The style of these regional-scale structures differs from other structures because of different lithologies and thus different rheological behaviour. The well layered sequences contain incompetent quartzite and competent ultramafic rocks. In addition, small portions of melt were present during the deformations. The high competence contrasts in the lithological sequences of the Campell and Shanzi structures enabled plastic deformation and therefore much higher strain rates and larger finite deformation occurred. This affected the deformation within the Bulai rocks found adjacent to these big fold structures. There we find highly ductile penetrative planar fabrics and shear zones, refolded folds, crenulations and circular structures (see Fig. 2).

These observations lead to the conclusion that the whole region around Messina was affected by a Proterozoic tectono-thermal event. Other classical localities in this region must be reviewed in the light of the new data, e.g. the youngest ductile shear zones in the Sandriver Gneisses with their spectacular sheath folds may be considered as coeval with the tectonism described above.

Metamorphic studies on CZ rocks (Horrocks, 1983; Chinner and Sweatman, 1968; Harris and Holland; 1984; Droop, 1989; Windley *et al.*, 1984) have shown that the last major event in the CZ was characterised by high pressure (up to 11 kb) and rapid decompression. Together with the field observations summarised above, this leads to the conclusion that the post-Bulai tectono-metamorphic event was this same major high pressure episode. This is in agreement with the results of Kamber *et al.* (1995) on the Triangle shear zone, which showed that the high pressure (up to 10 kb) paragenesis there was formed at 2 Ga.

Proterozoic activity of the Palala shear zone

The sinistral strike-slip Palala shear zone is regarded as the boundary between the CZ and the SMZ. McCourt and Vearncombe (1987) describe the following relationship: 50 km NE of Ellisras, Northern Transvaal, a portion of this shear zone cuts through rocks belonging to the Bushveld Igneous Complex dated at 2.05 Ga, showing that at least some movement along the Palala shear zone postdates this age. The mylonites at this locality show greenschist facies metamorphic conditions, which may not apply to the whole of the Palala shear zone. The question about the southwards extension of high grade conditions in the CZ at 2 Ga therefore remains open.

New geochronological evidence for a 2 Ga event in the CZ

Age determinations on garnet-bearing parageneses and monazites from the CZ

Following the reporting by Kamber *et al.* (1995) and

sample	rock-name	Rb (ppm)	2SE%	Sr (ppm)	2SE%	87Rb/86Sr	2SE%	87Sr/86Sr corr.	2SE%
92/119	Biotite-Gneiss	79.62	0.041	279.11	0.072	0.828	0.113	0.736405	0.0046
92/120	Biotite-Gneiss	106.59	0.235	204.15	0.018	1.518	0.253	0.762238	0.002
92/121	Biotite-Gneiss	105.23	0.099	168.88	0.093	1.814	0.192	0.774059	0.0136
92/123	Biotite-Gneiss	126.99	0.162	189.25	0.042	1.954	0.204	0.774528	0.0044
92/125	Grt-Leucosome	162.41	0.056	96.54	0.017	4.956	0.073	0.895437	0.0024
92/127	Biotite-Gneiss	139.28	0.058	108.81	0.02	3.753	0.078	0.845049	0.004
92/128	Grt-Leucosome	99.71	0.088	127.88	0.012	2.274	0.1	0.790958	0.0018
92/129	Grt-Leucosome	188.17	0.117	34.07	0.021	16.961	0.138	1.335294	0.0038
93/108	Granite	122.38	0.049	194.8	0.047	1.829	0.096	0.770159	0.0048
93/109	Migmatite	41.92	0.107	372.58	0.079	0.326	0.186	0.716496	0.0052
93/508	Granitic gneiss	75.57	0.28	396.68	0.161	0.552	0.441	0.722846	0.0108
93/509	Enderbitic gneiss	86.57	0.097	719.53	0.08	0.348	0.177	0.714868	0.0038

Table 3: Rb-Sr analtical results of various lithologies from the Transition Zone of the NMZ, Zimbabawe.

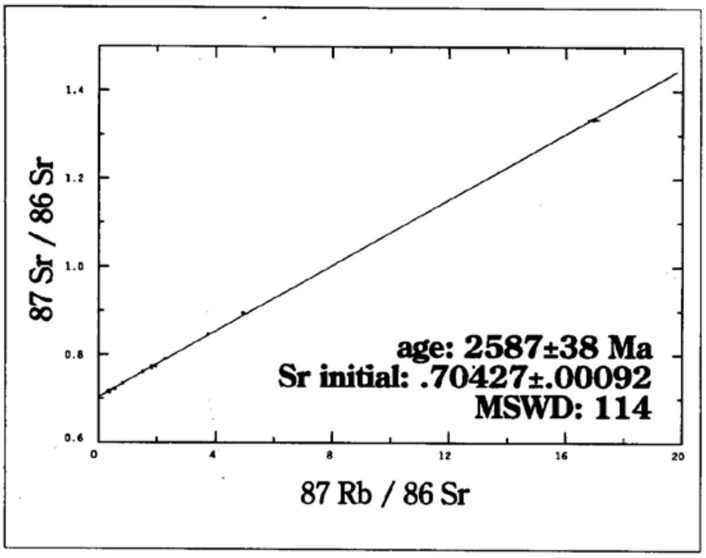

Figure 5: Rb-Sr isochron diagram of the analytical results (presented in Table 3) from various lithologies in the Transition Zone of the NMZ, Zimbabwe.

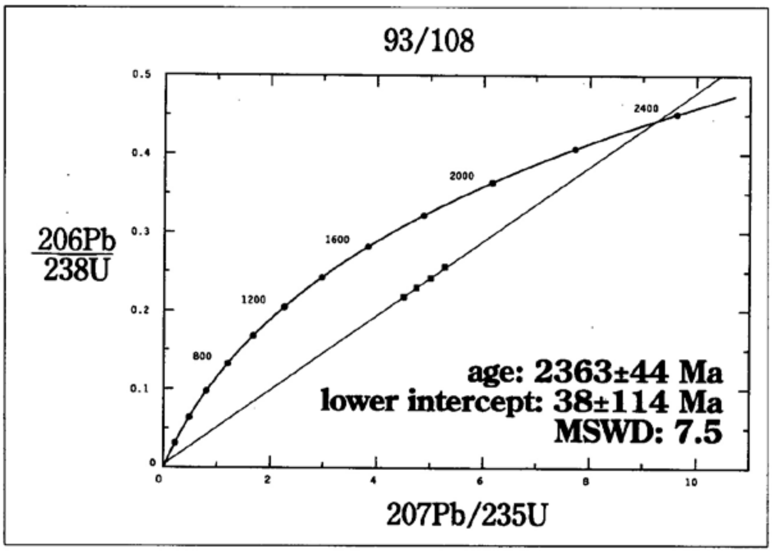

Figure 6: Concordia plot of the analytical results (presented in Table 4) of four zircon fractions from Sample No 93/108, a granite from the Transition Zone of the NMZ, Zimbabwe.

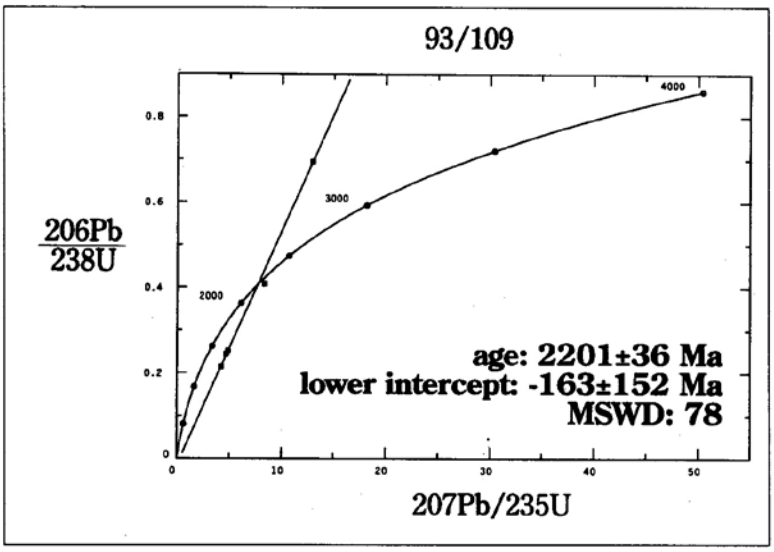

Figure 7: Concordia plot of the analytical results (presented in Table 4) of five zircon fractions from Sample No 93/109, a migmatite from the Transition Zone of the NMZ, Zimbabwe.

Barton *et al.* (1994) of ca. 2 Ga garnet and 1.92 Ga muscovite ages from Mt. Shanzi, we have selected eight samples from lithologies in and around the Bulai Pluton for garnet Pb-Pb dating. Four of these also contained suitable quantities of monazite. Garnet and monazite are both documented as retentive for the U-Pb system even under high grade metamorphic conditions (Burton *et al.*, 1993; Parrish, 1988); a complete "resetting" of either chronometer is seen as implying recrystallisation and thus a significant metamorphic event.

Sample localities are shown in Fig. 2, and sample descriptions are given in the appendix. They include three pelites, one calcsilicate, three quartzo-feldspathic gneisses (including a Singelele "granite" sample) and a leucosome. Grt-fsp and grt-sil parageneses were chosen for determination of Pb-isotopic compositions. With regard to strain the samples vary widely, from macroscopically undeformed granites (e.g. 93/050) to strongly deformed gneisses (93/116). In the undeformed rocks no textural evidence for disequilibrium between garnet and feldspar can be observed. In the deformed rocks both minerals define the same structures (e.g. lineations), indicating dynamic recrystallisation of garnet and feldspar at the same time. These observations justify the assumption that feldspar and garnet (or sillimanite and garnet respectively) are in equilibrium with respect to their isotopic Pb compositions. Analytical methods and calculation of errors on two point Pb-Pb ages are as described by Kamber *et al.* (1995).

The results are presented in Tables 1 (monazites) and 2 (garnet parageneses). For the monazites, the common Pb correction was largely uncritical but the feldspar data from the same samples were used. The garnets are highly variable both in their Pb content (as judged from the Pb signal size) and their isotopic compositions. Most are quite unradiogenic, resulting in fairly imprecise ages, but sample 93/167 has the most radiogenic Pb ever measured in a garnet, giving a small error of 6 Ma. The monazites show both positive (up to 30% and negative (up to 25%) discordance and the $^{207}Pb/^{206}Pb$ age errors are correspondingly asymmetrically enlarged. The apparent $^{207}Pb/^{206}Pb$ ages are considered maxima where the discordance is negative, and minima where it is positive. The uncertainty is based on the experience with zircon populations that real or virtual lower concordia intercepts for Archaean and lower Proterozoic regions without later orogenies have apparent lower concordia intercepts between 0 and 600 Ma.

The apparent ages vary, and rather than defining discrete clusters, they are spread out over a range with a minimum of 2.0 Ga, clearly populated by some precise dates, and a less clearly defined maximum around 2.6 Ga. Samples 93/050 and 93/070 show complete resetting of the chronometers at 2.0 Ga (although the error is very large). This indicates new growth or full recrystallisation of both garnet and monazite. The abundance of monazite in these samples explains the unradiogenic nature of the garnet. Likewise, the garnet of 93/167 grew or recrystallised at 2 Ga and, as its Pb is so radiogenic, this result is not affected by arguments concerning original isotopic equilibration with the feldspar. The age results on these three samples thus clearly confirm the importance of the 2.0 Ga metamorphic event in the Messina area of the CZ.

The apparent ages obtained on the other samples are higher than 2 Ga. This qualitatively confirms the high retentivity of the U-Pb system in both garnet and monazite during high grade metamorphism if no recrystallisation takes place. The results are interpreted as "mixed ages" resulting from partial recrystallisation or overgrowth of parageneses inherited from one or more earlier metamorphic events. The oldest apparent age is the 2633 Ma result on the monazite of 93/035. This clearly predates the Bulai intrusion. Further, the result is 30% positively discordant, therefore indicating a minimum actual age with a large upper error range of 230 Ma (see Table 1). The group of apparent ages larger than 2 Ga, particularly the 93/035 monazite, merely helps to establish a lower age limit of ca. 2.64 Ga for the earlier metamorphism in the CZ.

Apparent ages, structures and textures: Concurrences and a paradox

If the notion that mixed ages in the garnet and monazite U-Pb systems indicate partial regrowth or recrystallisation is correct, then agreement with textural observations could be expected since PT conditions should not have varied much over the sampling area of ca. 10 km radius. In sample 93/167 a Pb-Pb age of 2011 ± 6 Ma is given by garnet which builds atolls around plagioclase. These undeformed aggregates of garnet postdate the strong gneissic foliation. Sample 93/116, which has a very strong down-dip lineation, gave mixed apparent ages for both garnet and monazite. Fig. 3 shows the texture of this sample. While quartz and feldspar appear fully recrystallised in the lineation, garnet exists as strings of broken grains, showing its pretectonic character, with which its mixed apparent age of 2264 ± 41 Ma is in agreement. Samples 93/035 and 93/093, although from outcrops with localised shearing associated with DB_2, are themselves not sheared; the relatively high apparent ages for monazite (035) and garnet (both samples) are in accord with this observation. For monazite no textural checks could be made, but for the garnets of 93/035, 93/093, 93/167 and 93/116 the textural data concur with the apparent age data, and from the comparison between 93/167 (melt present, undeformed, 2 Ga ages) and 93/116 (no melt, strongly deformed, mixed age) it appears that the presence of some melt may be an important factor aiding recrystallisation or regrowth of monazite and garnet and thus age resetting. Pelite samples 93/048 (from a xenolith within the Bulai intrusion) and 93/072a, have metamorphic textures which are certainly (93/048) and probably (93/072a) pre-Bulai, and their mixed garnet-feldspar ages are not

sample	fraction (um)	color	shape	weight (mg)	$^{206}Pb/^{204}Pb$ measured	U (ppm)	Pb rad (ppm)	Pb tot (ppm)	$^{207}Pb/^{206}Pb$	±1s(%)	$^{207}Pb/^{235}U$	±1s(%)	$^{206}Pb/^{238}U$
93/108	250-200	violet	rounded	1.62	1719.69	2412	615.4	633.24	0.150 154	0.038	4.760194	0.113	0.229926
93/108	200-165	violet	rounded	3.17	1797.59	529.6	149.1	153.21	0.150092	0.074	5.293774	0.147	0.255804
93/108	165-110	violet	rounded	0.443	1836.88	2630.5	692	710.86	0.150441	0.028	5.026233	0.131	0.242313
93/108	110-90	violet	rounded	3.68	2186.75	1625.3	388.4	397.42	0.150012	0.038	4.513117	0.724	0.218197
93/109	120-100	violet	tabular	2.25	234.07	2296.3	515	641.43	0.14204	0.098	4.213812	0.358	0.215161
93/109	120-100	cream	elongate	1.12	493.02	880.1	628.8	700.26	0.135415	0.073	12.93893	1.522	0.692995
93/109	200-160	violet	elongate	0.515	323.99	1627.4	693	813.36	0.147289	0.25	8.304809	1.145	0.408938
93/109	90-80	violet	elongate	2.19	324.97	2321.8	603.4	708.54	0.139945	0.046	4.830414	0.207	0.250338
93/109	140-100	dark red	tabular	0.63	1738.22	2940.7	768.8	792.47	0.141832	0.041	4.90531	0.193	0.250836

sample	±1s(%)	$^{207}Pb/^{235}U$ age	±1s(%)	$^{207}Pb/^{238}U$ age	±1s(%)	$^{207}Pb/^{206}U$ age	+1s	-1s age	r
93/108	0.1048	1777.91	0.94	1334.11	1.26	2347.68	0.65	0.65	0.923
93/108	0.1233	1867.86	1.26	1468.34	1.61	2346.97	1.27	1.26	0.835
93/108	0.1273	1823.75	1.11	1398.71	1.6	2350.94	0.48	0.48	0.969
93/108	0.7221	1733.39	6	1272.34	8.33	2346.07	0.64	0.65	0.998
93/109	0.2862	1676.71	2.93	1256.26	3.26	2252.22	1.69	1.69	0.769
93/109	1.5167	2675.22	14.24	3394.03	39.9	2169.36	1.28	1.27	0.997
93/109	0.9757	2264.84	10.33	2210.07	18.23	2314.69	4.28	4.3	0.82
93/109	0.1853	1790.21	1.74	1440.22	2.39	2226.52	0.8	0.79	0.876
93/109	0.1845	1803.17	1.63	1442.79	2.38	2249.7	0.71	0.71	0.951

Table 4: U-Pb analytical results of zircon fractions from a granite (93/108), and a migmatite (93/109) from the Transition Zone of the NMZ, Zimbabawe.

in conflict with this.

The apparent ages on sample 93/050, however, present a puzzle. This sample was taken from pre-Bulai Singelele granite (older than 2.9 Ga, Barton *et al.*, 1979), at a locality with the least apparent disturbance by post-Bulai tectonism, specifically to try and "capture" the age of a pre-Bulai event. The lithological relationships in outcrop are shown in Fig. 4, from which it is apparent that the intrusive contact of Bulai into Singelele is quite undeformed. Further, no evidence of post-Bulai melting is present in this outcrop. Yet both the monazite (2104 + 0.8/-90 Ma) and the garnet paragenesis age (1938 ± 275 Ma) of this sample are fully or almost fully reset by the 2 Ga event. In the pelitic sample 93/070 there is likewise no evidence of late melting, yet its monazite U -Pb age is 1989 +0.7/-50 Ma and the garnet - feldspar age is also young, albeit with a very large error. Thus neither textural criteria, nor lack of evidence of melt during a high grade event can provide a fully realistic assessment of whether recrystallisation of garnet and monazite occurred.

Perspective on the 2 Ga event in the Northern Marginal Zone

Whole rock Rb-Sr and zircon U-Pb dates from the "North Marginal Transition Zone"

Up to 20 km to the north of the Triangle shear zone, WSW-ENE striking uplift structures occur in the southern part of the NMZ. Amphiboles grown in associated lineations were dated at 2 Ga (Kamber *et al.*, 1995). This zone was named the Transition Zone by Rollinson and Blenkinsop (in press, see Fig. 1). It is largely situated in partly migmatitic biotite gneisses with amphibolite rather than granulite facies parageneses. Sheet-like bodies occur along its northern side. In outcrop pattern these are similar to the Razi granites which intruded along the NMZ-Zimbabwe Craton thrust 2.6 Ga ago (Mkweli *et al.*, in press); however, unlike the Razi Granites they do not contain hornblende, and are locally deformed and migmatised. The Transition Zone and the NMZ-Zimbabwe Craton thrust zone thus differ not only in age, but also in the character of the granites. In an attempt to constrain the extent and effect of the 2 Ga event in the NMZ, biotite gneisses from the Transition Zone, leucosomes within them, granites belonging to a sheet-like intrusion forming the southernmost range of dwala-type hills in Zimbabwe, and a migmatite on the boundary of the granites and the biotite gneisses, were sampled along the Mwenezi River, 2-4 km NW of Dine Mission, for whole rock Rb-Sr dating; a granite and a migmatite sample were further selected for zircon U-Pb dating.

Sr isotope analyses were done as described in Mkweli *et al.* (in press); Rb and Sr concentrations were determined by isotope dilution. The results of the Rb-Sr analyses are presented in Table 3 and plotted in Fig. 5.

Although the data do not define an isochron (which is common for Archaean crustal rocks if Sr isotope ratios are measured precisely) there are no obvious individual outliers and the 12 samples yield a well defined age of 2587 ± 38 Ma with a rather high initial ratio of 0.704± 0.00 1. Both results are indistinguishable from those obtained on a mixed suite of granites and enderbites from near the NMZ-Zimbabwe Craton thrust (Mkweli *et al.*, in press).

The linear array comprises data from very diverse samples. The small-scale (ca. 10 cm wide) garnet-bearing leucosomes (exsudations) within biotite gneisses are on the whole the most radiogenic, and we can be confident that the ca. 2.6 Ga apparent age is that of their formation. While it is possible that the enderbitic gneiss, collected from the N side of the granite, is somewhat older than the apparent errorchron age (it is very unradiogenic), the Rb-Sr whole rock method can in this situation not resolve age differences between the event producing the biotite gneisses, the intrusion of the granite, and the exsolution of the leucosome veins and patches from the biotite gneiss, which must therefore all have occurred within an 80 My time span. The data do not show any indication that the 2.0 Ga event has affected these rocks.

Granite sample 93/108 and migmatite sample 93/109, the Rb-Sr data for both of which plot on an errorchron array, yielded 4 and 5 zircon fractions respectively as listed in Table 4. The zircons from the granite are all violet and rounded; size was the only discriminating criterion. In contrast, the migmatite yielded a population mixed with respect to colour, degree of metamicti-

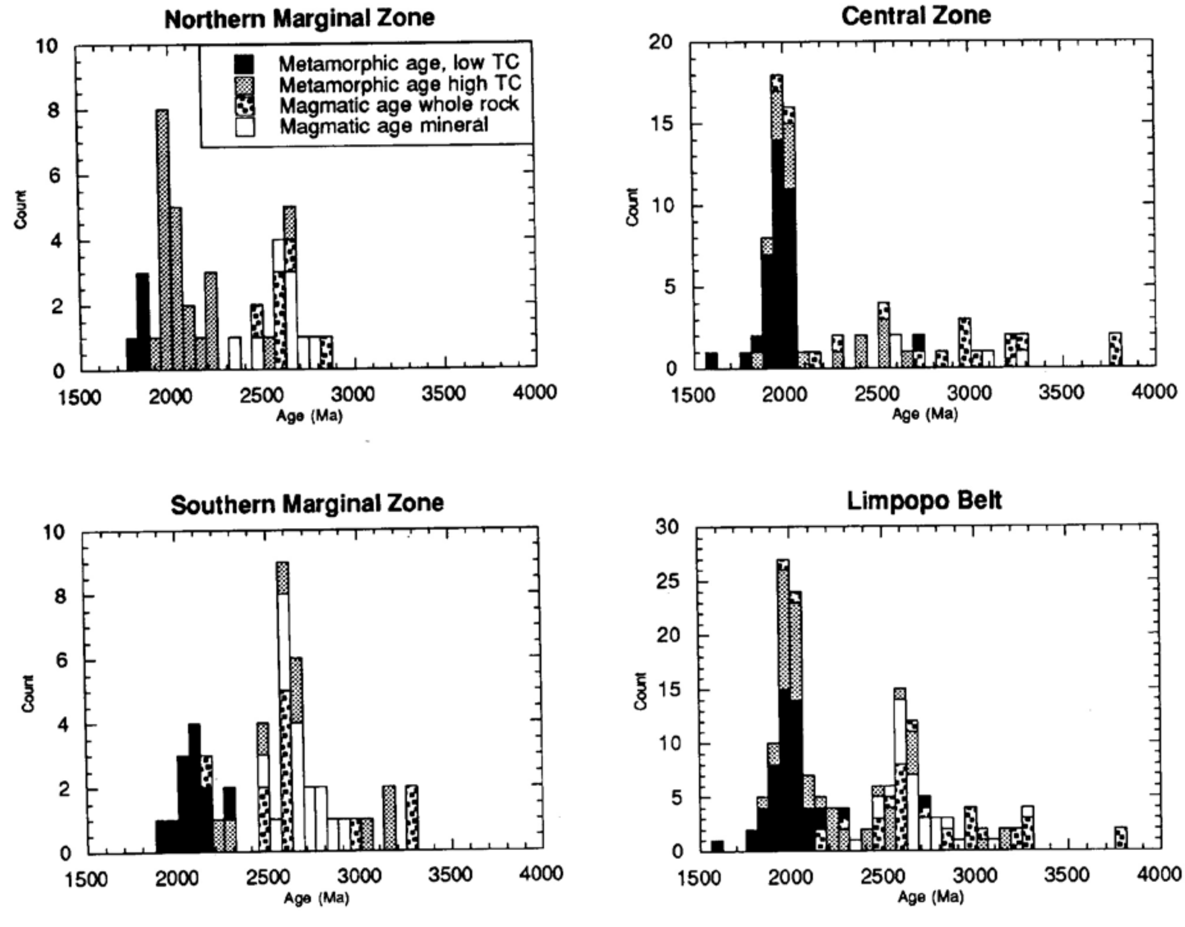

Figure 8: Histogram of available radiometric age data.

The database: available radiometric age data have been compiled from the literature. Ages without clear geological meaning are neglected for clarity (eg. whole rock ages of mafic dykes, mica ages of young pegmatites); a reference list may be ordered from the authors. The age data have been grouped for their occurrence: NMZ, CZ, SMZ and one histogram for the whole Limpopo Belt. They are classified into four types:

Type 1: Metamorphic ages with low TC, that is to say: Rb-Sr mica and feldspar ages, K-Ar mica and amphibole ages and Rb-Sr thin slice ages.

Type 2: Morphic ages with high TC, under which Sm-Nd and Pb-Pb mineral ages, Ar-Ar amphibole and U-Pb sphene and monazite ages are classified.

Type 3: Magmatic (Pb-Pb and Rb-Sr) whole rock ages.

Type 4: Magmatic ages based on U-Pb zircon and monazite constraints. For monazite the interpretation of the original contribution is followed.

sation, and crystal habit.

The results, presented in Table 4 and Figs. 6 and 7, show a puzzling picture. The 4 size fractions of granite 93/108 plot ca. 50% discordantly with little spread but good colinearity, defining a lower intercept consistent with subrecent lead loss and an upper intercept of 2363 ± 44 Ma. The good colinearity of the array makes it unlikely that it could be interpreted as resulting from a partial 2.0 Ga lead loss from older zircons, followed by subrecent lead loss. Further, the grains show no sign of any overgrowths.

The five fractions from the mixed population in migmatite 93/109 mostly have low U concentrations. They yielded relatively unradiogenic ^{206}/Pb/^{204}Pb ratios an corrections were made with feldspar lead from the same rock. The violet, elongate, large grain size fraction plots near-concordantly at ca. 2315 Ga, the others are strongly discordant. The cream coloured elongate fraction is strongly metamict and shows extreme inverse discordance (U loss, probably subrecent). The close clustering of the two violet coloured elongate fractions with the high-U, red tabular one is remarkable; regression with all data yields an upper intercept of 2201 ± 36 Ma but a negative lower intercept, showing that this approach is unrealistic. Also, the near concordant fraction does not lie on the line. If the metamict and reverse discordant fraction is ignored, an upper intercept of 2266 + 94/-71 Ma and a lower intercept of 72 ± 250 Ma result. With this approach the zircon apparent ages of samples 93/108 and 93/109 are within error of each other and indicate an event around 2.3 Ga which is totally unrecorded in the whole rock Rb-Sr systematics. A similar problem has been encountered within enderbites of the NMZ at Bangala Dam by Berger *et al.* (submitted), who found a zircon age of ca. 2.4 Ga in rocks dated at 2.89 Ga by whole rock Rb-Sr . (Hickman, 1978).

No tectonic episode is recorded around 2.3 - 2.4 Ga in the NMZ and the intact Rb-Sr systematics render a magmatic event highly unlikely. While the significance of these zircon ages is not understood, it is important to note that in the Dine Mission area neither Rb-Sr whole rock ages, nor zircon ages show any hint of a relation to the 2.0 Ga event. Nevertheless, texturally selected hornblendes from the same region, which were dated at 2.0 Ga by Ar-Ar, crystallised under high amphibolite facies conditions (Kamber *et al.*, in press). The lack of resetting of the other systems at 2.0 Ga may mean that no melting took place at this time and the circulation of fluids was minimal.

An overview and discussion of available age information from the Limpopo Belt

In Fig. 8 all available age data with a clearly defined geological meaning (e.g. dating magmatism or dating cooling after a thermal event) for the three zones of the Limpopo Belt and the Belt as a whole are shown in histogram form. The graph for the NMZ includes data from the Triangle shear zone and the Transition Zone. It shows clear peaks at 2.6 Ga, corresponding to the NMZ-Zimbabwe Craton thrusting and the ages of many NMZ chamoenderbites, and at 2.0 Ga, which is the time of high grade metamorphism and tectonism in the Triangle shear zone. There is a considerable number of garnet parageneses and zircon dates between 2.6 and 2.0 Ga, the former being possibly mixed ages and the latter of uncertain significance. Qualitatively, the picture for the SMZ is not dissimilar, but here the 2.0 Ga event is as yet documented almost exclusively by biotite Rb-Sr cooling ages. Also, a longer pre-2.6 magmatic and even metamorphic history than in the NMZ is in evidence.

The CZ appears quite distinct from the Marginal Zones in that there is no abundance peak around 2.6 Ga. Magmatic ages go back to the early Archaean, whereby some are problematic: the 3.8 Ga Rb-Sr age for the Sand River Gneisses (Barton *et al.*, 1983) is not confirmed by Nd model ages and zircon dates of 3.2 Ga (Retief *et al.*, 1990; Harris *et al.*, 1987). Metamorphic paragenesis ages range from 2.6 to 2 Ga, with all dates older than 2.0 Ga probably being mixed ages as discussed. The 2 Ga event is chiefly documented by biotite data (Barton and Van Reenen, 1992b), along with garnet paragenesis and monazite ages presented in this paper.

From this summary view, the common history of the different zones of the Limpopo Belt appears to be limited to the 2.0 Ga event. This episode, which may have been of a collisional nature with transpression (Kamber *et al.*, 1995 and in press), produced high grade, high pressure metamorphism in the CZ and the adjacent part of the NMZ (Transition Zone), representing a 100 km-wide zone across strike. The zone of reheating to at least low grade (as documented by the biotite ages) is over 300 km across strike, from craton to craton. The effects of the 2.0 Ga tectono-metamorphism in the Limpopo Belt are thus not only intense, but are found over an area of enormous geographical extent. Yet, virtually no magmatism occurred localised small-scale melts such as observed in the Bulai granitoid and its host rocks (see above) represent the only crustal anatexis associated with the 2.0 Ga event. This remarkable apparent paradox has to be taken into account in constructing models for this important episode.

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Appendix: Sample descriptions.

Sample No 93/035 Quartzo-feldspathic Gneiss

Locality: On farm "Proefplaas Messina", 2.5 km north of the farmhouse. This leucocratic orthogneiss contains pelitic xenoliths and is partially remolten and in parts intensely sheared.

Mineralogy: biotite-, hypersthene- and garnet-bearing plagioclase-quartz-K-feldspar-gneiss.

Texture: The sample itself is unsheared. The mafic clusters consisting of poikiloblastic garnet, hypersthene and biotite are set in a matrix of medium-grained feldspar and quartz. Garnet has inclusions of feldspar and quartz. Hypersthene is strongly altered. Biotite overgrows all phases and might thus be the latest mineral phase.

Sample No 93/048 Pelitic xenolith within the Bulai Pluton, containing rectangular sillimanite-rich aggregates

Locality: On farm "Proefplaas Messina", 1.5 km NE of the koppies "Three Sisters".

Mineralogy: "Sillimanite-rich aggregates": rutile-, spinel-, magnetite-, biotite-bearing garnet-cordierite-sillimanite clusters.

Texture: The rectangular sillimanite-rich aggregates are up to 1 cm in diameter. They consist to 90% of perfectly oriented sillimanite needles with minor cordierite, garnet and biotite. The perfect rectangular shape indicates a pseudomorphism after an older mineral. A possible mineral of similar shape which is aluminium rich and which contains Fe and Mg is staurolite. The garnet-cordierite-sillimanite parageneses could thus document the prograde breakdown of staurolite. These rectangular aggregates are embedded in a fine-grained metapelitic matrix of cordierite, biotite, garnet and sillimanite. The gneissic texture of this matrix flows around the pseudomorphic sillimanite nests.

Sample No 93/050 Singelele Granite

Locality (see also Fig. 4): On farm "Proefplaas Messina", 1 km N of the koppies "Three sisters", undeformed contact between the Bulai Pluton and the older Singelele Granite.

Mineralogy: magnetite- and biotite-bearing garnet-plagioclase-quartz-K-feldspar-gneiss.

Texture: The grains of this coarse K-feldspar-rich rock are randomly oriented. Mafic clusters consist of round garnet in various grain sizes. Rare and fine biotite flakes overgrow all other phases.

Sample No 93/070 petite

Locality: On farm Tuinbou, 0.5 km east of the dam, 50-m-thick aluminium-rich pelitic layer.

Mineralogy: rutile-, tourmaline- and magnetite-bearing plagioclase-garnet -sillimanite-cordierite- biotite-quartz-gneiss.

Texture: The fine-grained layers have a strong gneissic texture due to the orientation of biotite and sillimanite, which are set in a matrix of cordierite and quartz. The coarser grained layers are less foliated and consist of more quartz and cordierite and less sillimanite and biotite. Cordierite shows strong pinitisation and myrmecitic intergrowth with quartz. Round garnet grains occur in this coarser matrix. They have many inclusions of biotite, sillimanite, quartz and feldspar and are often rimmed by cordierite.

Sample No 93/072 a petite

Locality: On farm Tuinbou, 1.5 km east of the dam and 1 km south of the Limpopo River, 30-m-thick aluminium-rich pelitic layer.

Mineralogy: magnetite-bearing sillimanite-biotite-plagioclase-garnet -quartz-cordierite-gneiss.

Texture: This rock shows metamorphic banding: In bright, greenish layers medium-grained cordierite is predominant, whereas in darker layers fine-grained biotite and garnet are frequent. Garnet has many inclusions of anhedral quartz, biotite and small needle-like sillimanite and is usually rimmed by cordierite. Thin prisms of sillimanite are intergrown with biotite, both laying in a matrix of cordierite. This poikiloblastic cordierite shows strong pinitisation.

Sample No 93/093 Garnetiferous Leucosome

Locality: On farm "Proefplaas Messina", in the Soutsloot, 3.5 km NNE of the koppies "Three Sisters". This leucosome occurs in a quartzo-feldspathic gneiss and it is oriented subparallel to the gneissic foliation. A steep shear zone crosscuts the leucosome.

Mineralogy: magnetite-, hornblende-, hypersthene - and biotite-bearing plagioclase-garnet-K-feldspar-quartz gneiss.

Texture: In this pegmatoid rock the minerals are randomly oriented. The coarse-grained leucocratic domains consist of quartz, polygonal shaped K-feldspar and minor plagioclase. The mafic domains are very heterogranular: round garnet grains of different sizes and with different amounts of biotite, quartz and feldspar inclusions prevail. Less abundant and finer grained are orthopyroxene, green hornblende, magnetite and biotite. Around and within these mafic domains, quartz and feldspar are very fine grained.

Sample No 93/116 Quartzo-feldspathic Gneiss

Locality: On farm Tuinbou, 1.5 km east of the dam and 0.6 km south of the Limpopo River.

Mineralogy: garnetiferous quartz-K-feldspar-gneiss. Texture (See also Fig. 3): This rock shows a strong down-dip lineation with azimuth and dip of 178/62. The elongated quartz grains are more than 1 cm long. Also the coarse K-feldspar is recrystallised and well oriented. Garnet exists as strings of broken grains surrounded by finer grained feldspar and quartz.

Sample No 93/167 Calcsilicate-rock

Identical rocks from this **locality** were sampled and analysed by Watkeys (1984, Sample MWCS 13a, p. 292).

Locality: 4 km NW of Messina, NE-side of Mount Shanzi, calcsilicate "enclave" in a felsic shear zone, close to the contact between the Bulai Gneiss and the overlaying quartzo-feldspathic gneisses.

Mineralogy: magnetite/ilmenite-, apatite and K-feldspar-bearing titanite-quartz- ferroaugite-garnet -plagioclase gneiss.

Texture: The gneissic aspect is given by compositional banding. The mafic bands consist mainly of titanite, clinopyroxene, garnet and plagioclase. Garnet occurs as atolls around plagioclase or as thin rims around clinopyroxene. Where garnet forms coarse grains it has inclusions of clinopyroxene and titanite. The felsic matrix of this rock consists mainly of polygonally shaped plagioclase. In some domains the plagioclase rims show myrmecitic textures. Titanite and clinopyroxene are observed as inclusions within the feldspar. Plagioclase also occurs as rims around the ore minerals.