THE NEOARCHEAN LIMPOPO COMPLEX
1952-2024

Official workshop field guide
July 22-26, 2024

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1. Introduction

The 2024 Limpopo Field Workshop was organized as a platform for collaborators to assess the outcome of many years of highly successful collaborative research in the Limpopo Complex (LC) of South Africa (Fig. 1). Collaborative research in the LC comprised of internationally recognized earth scientists that resulted in numerous publications in accredited journals and presentations at national and international conferences and workshops. This collaborative research culminated with two recent publications published in the South African Journal of Geology (Van Reenen et al., 2023a, b) that respectively considered the linked complex evolutionary histories at 2.72-2.62 Ga of the Southern Marginal Zone (SMZ) and Central Zone (CZ) of the LC. The workshop field guide is an official record of the 2024 Limpopo Complex field workshop, and a copy is posted on Dirk van Reenen's profile in the Department of Geology webpage, University of Johannesburg.

2. Goals of the July 2024 field workshop

The main goals of the field workshop are to present for critical scrutiny structural-geological and laboratory-based data that have been integrated as the basis to unravel the complex evolutionary history of the LC at 2.72-2.02 Ga. *Regional and detailed field and structural geological mapping are considered essential geodynamic tools that, integrated with laboratory-based data, could be utilized to unravel the complex thermo-tectonic evolution of this complexly deformed high-grade gneiss terrane characterized by a polymetamorphic history*. This approach and the goals of the workshop are presented and discussed in the following sections.

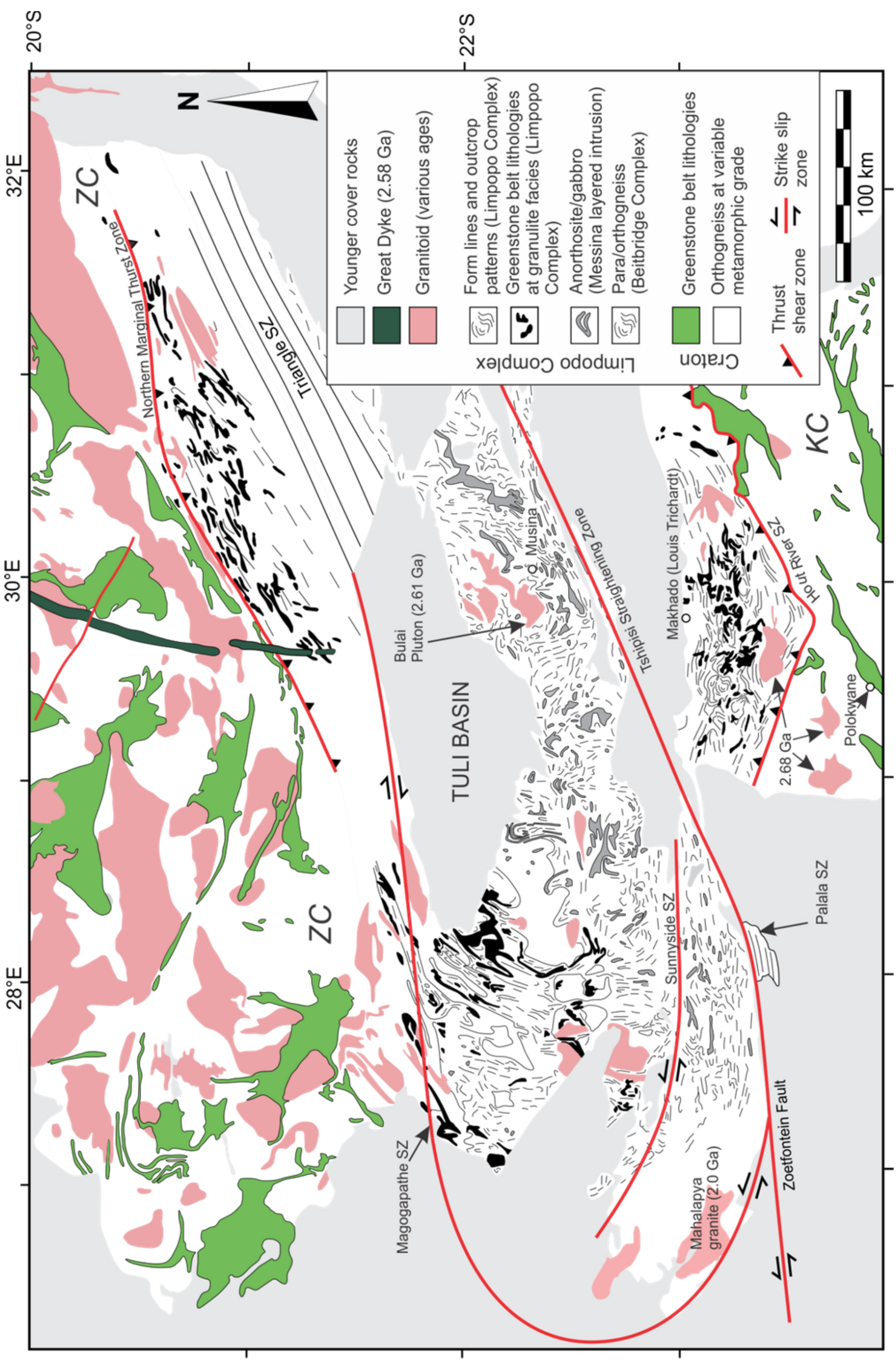


Figure 1. Geological map of the Limpopo Complex (LC) and juxtaposed granite-greenstone terranes of the Kaapvaal (KVC) and Zimbabwe (ZC) cratons (after Van Reenen et al., 2013). Note the internal subdivision into a Central Zone (CZ) that is separated from the Northern Marginal Zone (NMZ) and Southern Marginal Zone (SMZ) respectively by the Triangle Shear Zone and Tshipise Straightening Zone (TSZ). The two marginal zones are separated from the ZC and KVC by inward-dipping thrusts, respectively the Northern Marginal Thrust Zone and the Hout River Shear Zone (HRSZ).

2.1. The concept of a 2.72-2.62 Ga intra-crustal gravity-driven Limpopo orogeny

Integrated structural-geological and geophysical data were utilized to underpin the concept of an intra-crustal gravity-driven Limpopo orogeny at 2.72-2.62 Ga directed by mantle heat flow (a mantle plume) that triggered a buoyant crustal-scale granulite diapir. The melt-weakened diapir penetrated the pre-Limpopo crust at ~2.72 Ga underneath the present CZ and established the Limpopo granulite facies terrane and distinctive contact relationship with the juxtaposed Zimbabwe (ZC) and Kaapvaal (KVC) granite-greenstone cratons at 2.72-2.62 Ga (Fig. 1) (Van Reenen et al., 2019, 2023).

2.2. Distinctive relationship with juxtaposed greenstone belts

The entire granulite facies terrane comprising the NMZ, CZ, and SMZ is portrayed by a coherent but highly complex high-grade fold- and shear deformational pattern. This characteristic deformational pattern is distinct from the much less deformed low-grade granite-greenstone belts of the ZC and KVC from which it is separated by inward-dipping >2.65 Ga shear zones (thrusts): the HRSZ in the south, the NMT (North Marginal Thrust Zone) in the north, and unnamed thrusts in the west (McCourt and Vearncombe, 1992). The eastern boundary is obscured by younger formations (Fig. 1).

2.3. Absence of evidence for thermo-tectonic interaction of the KVC with the SMZ at 2.72-2.69 Ga or at 2.65 Ga apart from hot-iron-zones

Structural-geological, metamorphic, and geochronological evidence for thermo-tectonic interaction of the SMZ with the KVC at 2.72-2.69 Ga are restricted to narrow hot-iron-zones developed in the direct footwall of the north-dipping HRSZ against the Giyani greenstone belt (GGB) and the Rhenosterkoppies greenstone belt (RGB) (Fig. 2). Absence of evidence that the remainder of the KVC participated in the Limpopo orogeny (Kramers et al., 2014) argues directly against a proposed continent-continent collisional orogeny at 2.65-2.62 Ga that supposedly involved the KVC (Brandt et al., 2018).

2.4. Absence of evidence for a transpressional orogeny associated with thrust tectonics that affected the LC at ~2.02 Ga

There is no structural-metamorphic or geochronological evidence for a regional transpressional orogeny supposedly associated with thrust tectonics that involved the KVC at ~2.02 Ga (Brandt et al., 2023). (1) A regional high temperature thermal overprint at ~2.02 Ga that affected the entire Central Zone (CZ), SMZ, and juxtaposed KVC was not associated with major deformation or growth of new metamorphic mineral assemblages (van Reenen et al., 2019, 2023). (2) Evidence for thrust tectonics in the LC is restricted to 2.72-2.69 Ga bounding thrusts developed in contact with the juxtaposed cratons (HRSZ, NMT) (Fig. 1, 2). Furthermore, the entire LC including the CZ (see Fig. 3) is characterized by steeply plunging folds and steep shear zones.

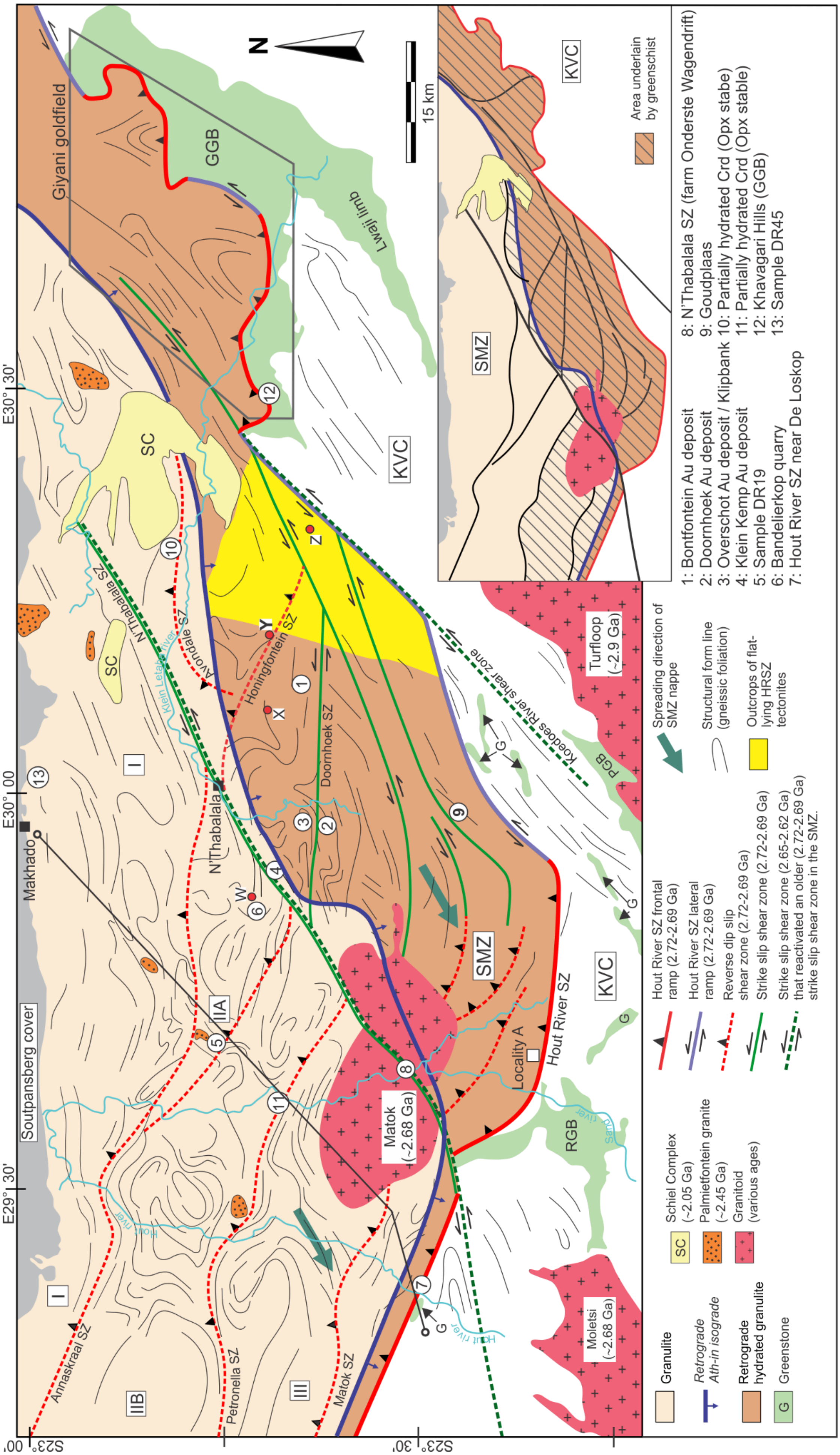

Giyani goldfield
GGB
N
15 km
Lwaji limb
KVC
SC
SMZ
Area underlain by greenschist
8: N'Thabalala SZ (farm Onderste Wagendrift)
9: Goudplaas
10: Partially hydrated Crd (Opx stabe)
11: Partially hydrated Crd (Opx stable)
12: Khavagari Hills (GGB)
13: Sample DR45
1: Bontfontein Au deposit
2: Doornhoek Au deposit
3: Overschot Au deposit / Klipbank
4: Klein Kemp Au deposit
5: Sample DR19
6: Bandelierkop quarry
7: Hout River SZ near De Loskop
E30° 30'
E30° 00
E29° 30'
S23° 00'
S23° 30'
Soutpansberg cover
Makhado
N'Thabalala
N'Thabalala SZ
Klein Letaba river
Avondale SZ
Honingfontein SZ
Doornhoek SZ
Koedoes River shear zone
Turfloop (~2.9 Ga)
PGB
Matok (~2.68 Ga)
Moletsi (~2.68 Ga)
Locality A
Hout River SZ
RGB
Sand river
Hout river
Annaskraal SZ
Petronella SZ
Matok SZ
I
IIA
IIB
III
W
X
Y
Z
G
Granulite
Retrograde Ath-in isograde
Retrograde hydrated granulite
Greenstone
Schiel Complex (~2.05 Ga)
Palmietfontein granite (~2.45 Ga)
Granitoid (various ages)
Hout River SZ frontal ramp (2.72-2.69 Ga)
Hout River SZ lateral ramp (2.72-2.69 Ga)
Reverse dip slip shear zone (2.72-2.69 Ga)
Strike slip shear zone (2.72-2.69 Ga)
Strike slip shear zone (2.65-2.62 Ga) that reactivated an older (2.72-2.69 Ga) strike slip shear zone in the SMZ.
Spreading direction of SMZ nappe
Structural form line (gneissic foliation)
Outcrops of flat-lying HRSZ tectonites

Figure 2 (previous page). Metamorphic map of the SMZ and juxtaposed Giyani (GGB) and Rhenosterkoppies (RGB) greenstone belts separated by the steeply north-dipping HRSZ. Refer to van Reenen et al. (2023a). Note the following: (1) The SMZ is subdivided into a northern granulite domain that is separated from a southern retrograde amphibolite domain by an Ath-in retrograde isograd that cuts major folds. (2) The central part of the steeply north-dipping ~2.7 Ga HRSZ has been reactivated as the strike-slip Koedoes River shear zone that extends south-westwards into the KVC. The NE-SW trending steeply dipping >2.68 Ga granulite facies N'Thabalala shear zone located within the SMZ has been reactivated as a post Matok (2.68 Ga) strike-slip shear zone that extends south-westwards into the KVC. Several NE-SW-trending steeply north dipping pre-Matok high-grade thrusts are developed within the granulite domain of the SMZ. (3) The retrograde amphibolite domain is characterized mainly by pre-Matok strike-slip shear zones with north-dipping thrusts located close to RGB. (4) A N-S trending escarpment subdivides the retrograde amphibolite domain into two distinct geographic domains, namely a brown colored western high veld region located ~1200 m above sea level and a yellow colored low veld region located ~650 meters above sea level. (5) The E-W directed crustal section (Fig. 7a) along line W-X-Y-Z is constructed across the escarpment starting at Bandelierkop quarry (locality 6) and ending at locality Z at the position of Koedoes River shear zone. (6) The inset map shows the area of the SMZ that is at depth underlain by low-grade lithologies with geophysical signatures like those of the juxtaposed greenstone belts.

2.5. Reactivation of early shear zones at ~2.02 Ga

Structural-geological, metamorphic, and geochronological evidence for thermo-dynamic interactions at ~2.02 Ga is restricted to fabric-parallel shear zones that reflect reactivation of Neoarchean shear zones: (1) N-S trending discreet shear zones dated at ~2.02 Ga in the CZ (Fig. 3), (2) reactivation at ~2.02 Ga of the NE-SW-trending and moderately SE-dipping high-grade reverse-slip TSZ (that bounds the CZ near Musina in the south) as a near vertical strike-slip mylonitic structure (the Palala Shear zone) (Fig. 3), (3) reactivation of the NE-SW-trending high-grade dip-slip HRSZ as the mylonitic strike-slip Koedoes River Shear Zone (Fig. 2), and (4) reactivation of the NE-SW-trending high-grade pre-Matok (~2.68 Ga) dip-slip N'Thabalala Shear Zone in the SMZ as a reverse-slip shear zone that cuts the Matok pluton (Fig. 2).

3. Outcrops selected for detailed studies

A small number of carefully selected outcrops that reflect essential information are presented for scrutiny in the SMZ and CZ (Figs. 2, 3, and 4). These easily accessible outcrops offer structural-metamorphic and geochronological evidence for a sequence of tectono-thermal events that affected the LC at 2.72 Ga – 2.66 Ga, 2.65-2.62 Ga, and at ~2.02 Ga. Discussions on outcrop are followed in the afternoon and evenings by interactive discussion sessions. These sessions focus on assessing the proposed integration of structural-geological field data with geophysical, metamorphic, geochronological, stable oxygen isotopic and fluid inclusion data as the basis for the construction of composite D-P-T-t paths (see Fig. 5) that document evidence for the complex 2.72-2.02 Ga evolutionary history of the LC.

The outcome of these deliberations is important to identify future topics for research and to entice a younger generation of earth scientists to become involved with research that will enhance understanding of the evolutionary history of ancient high-grade gneiss terranes located within more ancient granite-greenstone cratons. The motivation to keep doing research in the well exposed and easily accessible Limpopo Complex is because continued research has kept opening more and more questions that still need more answers, and this workshop will not be the exception to this rule.

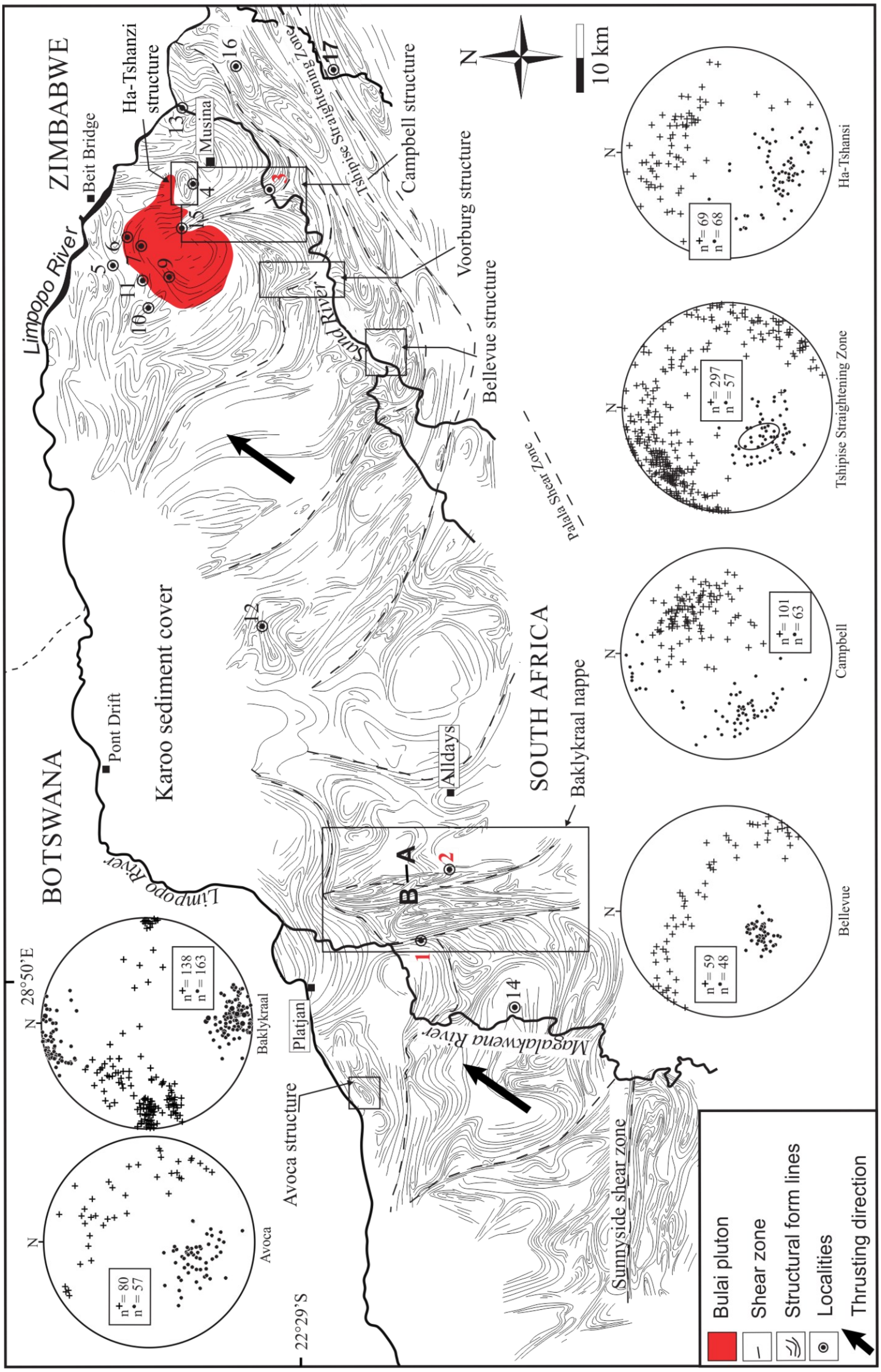

ZIMBABWE
BOTSWANA
SOUTH AFRICA
Beit Bridge
Pont Drift
Musina
Alldays
Platjan
Limpopo River
Sand River
Magalakwena River
Karoo sediment cover
Ha-Tshanzi structure
Tshipise Straightening Zone
Campbell structure
Voorburg structure
Bellevue structure
Palala Shear Zone
Baklykraal nappe
Avoca structure
Sunnyside shear zone
10 km
N
28°50'E
22°29'S
Avoca
Baklykraal
Bellevue
Campbell
Tshipise Straightening Zone
Ha-Tshansi
Bulai pluton
Shear zone
Structural form lines
Localities
Thrusting direction

Figure 3 (previous page). Regional photogeological interpretation of the complex fold- and shear deformational pattern of the CZ. This is documented (i) by ~2.7 Ga regional isoclinal folds overprinted (ii) at 2.65-2.62 Ga by major sheared structures including large, closed structures resembling sheath folds (Ha-Tshanzi, Bellevue, Avoca), major N-S trending sheared structures (Campbell, Voorburg, Baklykraal), and (iii) the 29 km wide NE-SW-trending and steeply SE-dipping TSZ. The TSZ has been reactivated at ~2.02 Ga as the upper crustal Palala shear zone (After van Reenen et al., 2023b). See text for short discussion. Shown also is the undeformed 2.618 Ga Matok granitic pluton that intruded the existing regional fold pattern of the CZ, and the localities visited during the field excursion (localities 9, 10, 11, 4, 5, 7, 9).

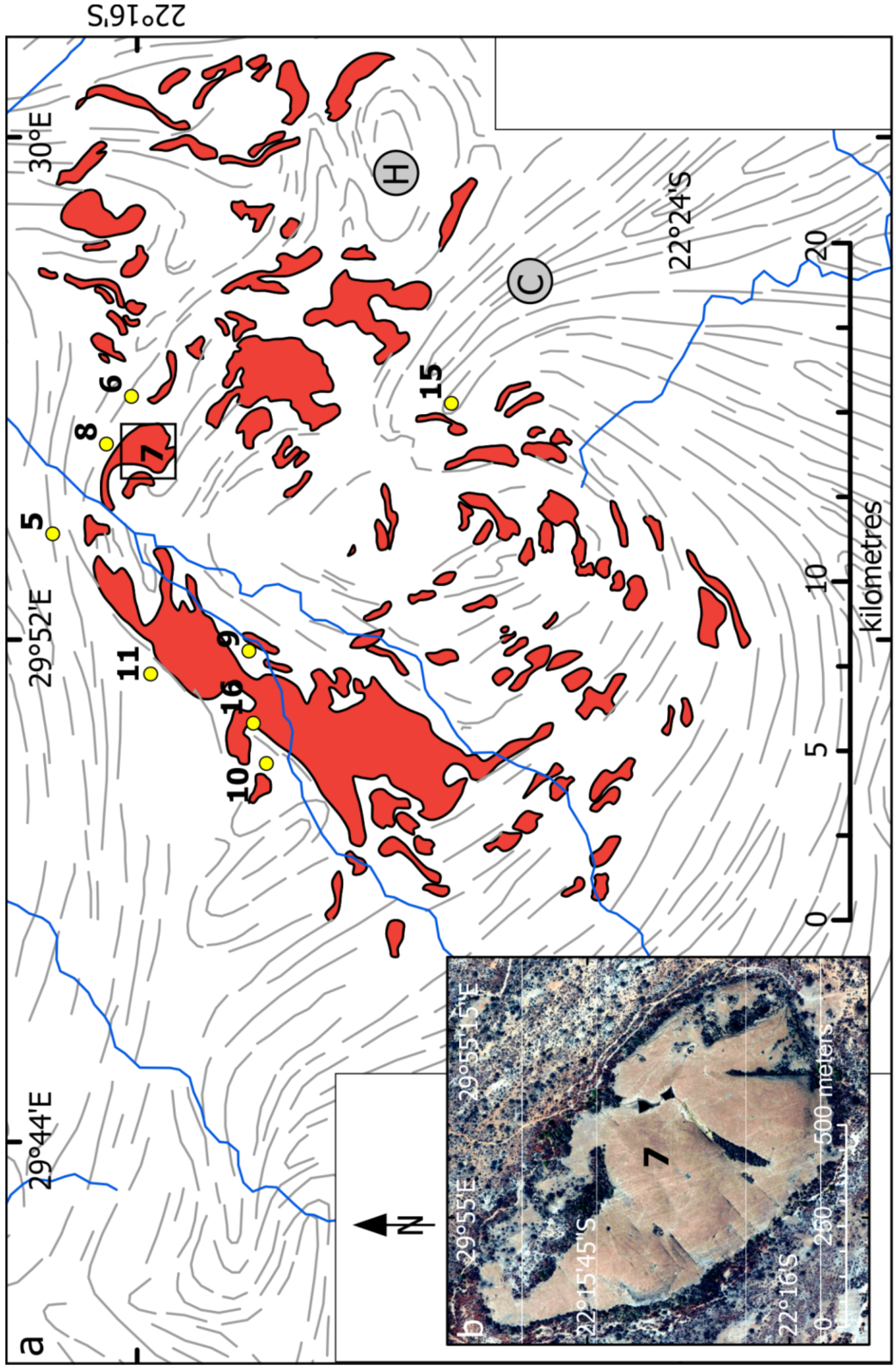


Figure 4. Structural map of Bulai and surrounding CZ (after Van Reenen et al., 2023b) showing that Bulai is not a solid plutonic body as depicted in the literature but comprises numerous small and large bodies of undeformed mainly porphyritic granite shown in red that intruded the existing regional fold pattern of the CZ without disturbing this pattern. Also shown are the localities visited during the field excursion (locality 9, 10, 11, 4, 5, 6, 7, 8). H = Ha-Tshanzi closed structure, C = N-S trending Campbell structure.

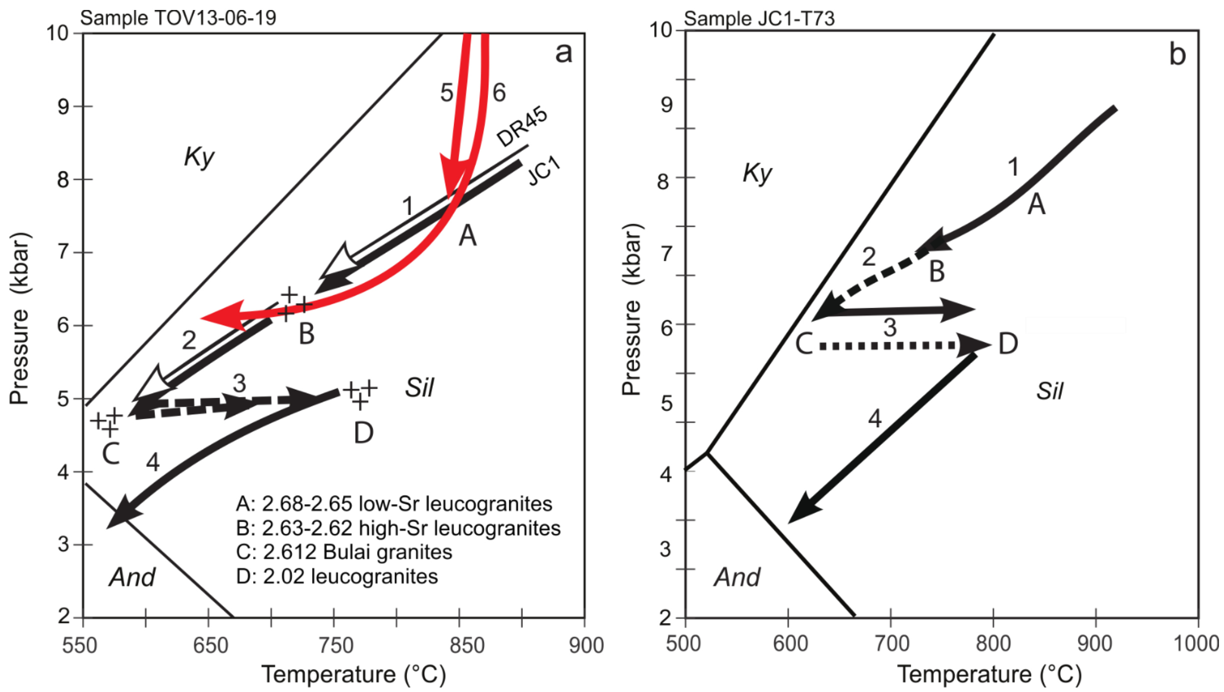


Figure 5. *D-P-T-t* paths constructed for close-pair metapelitic granulites >100 km apart in the CZ (Fig. 3) that record three distinct P-T trajectories: (a) TOV13 = 1+2 from the ~2.62 Ga Ha-Tshanzi closed structure and 06-19 = 3+4 from a ~2.02 Ga shear zone superimposed on the Campbell structure. *P-T* paths shown in red are alternative P-T paths for the CZ (path 5, after Safonov et al., 2021) and for the SMZ (path 6, after Nicoli et al., 2015). (b) JC1 (paths 1 and 2) from a boudin preserved in the Bakleikraal structure and T73 (paths 3 and 4) from a ~2.02 Ga shear zone superimposed onto the Baklykraal structure (see van Reenen et al., 2023b). Also shown in (a) is the two-stage evolution of metapelitic granulite (DR45) from the northern granulite domain of the SMZ (Van Reenen et al., 2023a).

4. Field workshop details

4.1. Lodging

Accommodation for delegates prior to (July 20 and 21) and after the field workshop (July 26, 28) is in a guest house near UJ. Food and lodging during the field workshop for 22-26 July 2024 is at Klein Bolayi Lodge located 22 km west of Musina at the contact of Bulai Pluton with CZ lithologies. Klein Bolayi Lodge offers comfortable accommodation, and our host (Elmar Uys of farm Evelyn) can organize access to important outcrops on farms located within and next to Bulai pluton.

4.2. Funding

Research funds generated by Dirk van Reenen, Andre Smit, Toshiaki Tsunogae, Oleg Safonov, and Jan Marten Huizenga will cover all costs of the workshop for all participants.

4.3. Participants

Participants are restricted to collaborators that have been actively involved for many years with UJ-based research in the LC.

- *Marlina Elburg* (Head of department, Department of Geology, University of Johannesburg).
- *Dirk van Reenen* (Department of Geology, University of Johannesburg).
- *Andre Smit* (Department of Geology, University of Johannesburg*).*
- *George Belyanin* (Department of Geology, University of Johannesburg*).*
- *Martin Clark* (Department of Geology, University of the Free State).
- *Taras Gerya* (Centrum for Geophysics, ETH, Zurich).
- *Toshiaki Tsunogae* (Department of Geology, University of Tsukuba, Ibaraki, Japan*).*
- *Oleg Safonov* (Institute of Experimental Mineralogy, Chernokolovka, and Moscow State University, Russia).
- *Jan Marten Huizenga* (Norwegian University of Life Sciences, Ås, Norway).
- *Alex Parker* (James Cook University, Australia).

4.4. Workshop itinerary

July 20-21
Participants arrive at OR Tambo International Airport on July 20/21 and sleep over at a guest house near UJ before and after the workshop. The guest house will organize transport from and to OR Tambo before and after the workshop.

July 22
07:30: Drive to Musina with three stops in the SMZ, arriving at Klein Bolayi Lodge in the late afternoon.
Evening: General introduction to the agenda of the workshop for July 23-26 (Dirk and Andre).

July 23-25
Field workshop.

July 26, 08:00
Drive to Johannesburg arriving at University of Johannesburg not later than 14:30.

5. Research methodology

Research methodology utilized to generate integrated structural-metamorphic and geochronological data that underpins the proposed 2.72-2.02 Ga evolutionary history of the LC comprises the following (Van Reenen et al., 2023a, b).

5.1. Regional photogeological study of major fold- and shear deformational features that characterize the SMZ and CZ

Regional and detailed structural-geological studies on the map- and outcrop-scales established the complex structural-geological framework of the LC characterized by successive deformational events, as outlined below.

First, the most significant geological feature of the entire LC (SMZ, CZ, and NMZ) is the published geological map (Fig. 1) that highlights the complex fold- and shear deformational pattern of this high-grade gneiss terrane depicted mainly by granulite facies gneisses. This complex deformational pattern is in complete contrast with the structural pattern of the low-grade KVC characterized by continuous greenstone belts (Fig. 1).

Second, The HRSZ is recognized as a crustal scale south verging thrust that bounds the SMZ in the south, whereas several deep crustal high-grade shear zones (Annaskraal, Petronella, Matok, N'Thabalala) associated with steeply plunging isoclinal folds occur within the SMZ (Fig. 2).

Third, A complex deformational pattern characterizes the CZ (Fig. 3). This complex pattern comprises steeply plunging isoclinal folds, moderately plunging sheared mega closed structures (Ha-Tshanzi, Bellevue, Avoca), sheared mega N-S trending structures (e.g., Campbell, Baklykraal), the NE-SW-trending and moderately SE-dipping Tshipise straightening zone (TSZ) that bounds the CZ in the south. Discreet cm-meter-sized fabric-parallel shear zones overprint early N-S trending sheared structures in the CZ as well as the NE-SW trending TSZ that towards the SW developed into the Palala shear zone (Fig. 3).

Fourth, a photo-geological study of the Bulai pluton and surrounding CZ (Fig. 4) shows that Bulai is not a solid plutonic body as always depicted in the literature (e.g. Brandt et al., 2018). Instead, it comprises numerous small and large granitic bodies that intrude the regional fold deformational pattern of the CZ without disturbing this pattern (Van Reenen et al., 2019, 2023). This is evidence that numerous large outcrops of CZ lithologies within the "pluton" cannot be depicted as enclaves/xenoliths (Brandt et al., 2018; Kröner et al., 2018) but form part of the regional fold pattern.

Fifth, regional photo-geological data highlights the essential role of heterogeneous deformation as a critically important geodynamic tool that ordered the formation and subsequent preservation of three distinct high-grade metamorphic events at 2.72-2.66 Ga, 2.65-2.62 Ga, and at ~2.02 Ga in the CZ. Evidence for three distinct metamorphic events linked with three distinct superimposed fold- and shear deformational features is preserved on scales that vary from the regional, map scale, outcrop scale (Fig. 3), and finally at thin section scale (see Van Reenen et al., 2023).

Sixth, high resolution drone imagery underpinned detailed structural-geological mapping of important poorly exposed localities within and next to the Bulai "pluton" in the CZ (Van Reenen et al., 2023b). This exercise proved to be of special significance because it highlights the role of the mostly undeformed ~2.62 Ga Bulai granitic "pluton" as a decisive geodynamic tool that constrains *all* regional thermo-tectonic activity in the CZ to the Neoarchean.

Three fold- and shear deformational events in the CZ can be highlighted (Fig. 3). (1) Steeply plunging isoclinal folds are regionally associated with granoblastic granulites that are devoid of discreet kinematic elements (mineral lineations, sigmoidal grains, S-C relationships). This is an indication of annealing/ recrystallization of hot granulites that were initially emplaced and cooled at the mid-crustal level at ~2.72 Ga (Van Reenen et al., 2019, 2023; Zhao et al., 2022). (2) Major sheared structural features associated with sheared granulites that overprint isoclinal folded granoblastic granulites. Major sheared structural features comprise the N-S trending Campbell and Baklykraal structures, major closed structures resembling sheath folds (Ha-Tshanzi, Bellevue, Avoca), and the NE-SW trending and steeply SE dipping Tshipise Straightening Zone (TSZ) (Fig. 3). This sequence of fold- and shear deformational events collectively defines the complex fold- and shear deformational pattern of the CZ that was established prior to intrusion of the ~2.62 Ga undeformed Bulai granitic pluton (Figs. 3 and 4). (3) Early sheared structural features, the Bulai "pluton" as well as the NE-SW trending TSZ are in turn overprinted by discreet (cm-meter size) fabric-parallel shear zones (Fig. 3).

5.2. Vibro-seismic and deep electrical sounding studies

Geophysical studies (Fig. 6) done across the KVC-HRSZ boundary along the Hout River (locality 7 in Fig. 2) provide uncontroversial evidence (De Beer and Stettler, 1992) (1) that the entire SMZ was thrust SW-wards against and over the granite-greenstone terrane of the KVC at the exact position of the steep north-dipping section of the bounding HRSZ, and (2) that more than 60% of the SMZ in the south is at depth underlain by greenschist material with geophysical signatures same as that of granite-greenstones of the juxtaposed KVC (see inset map Fig. 2).

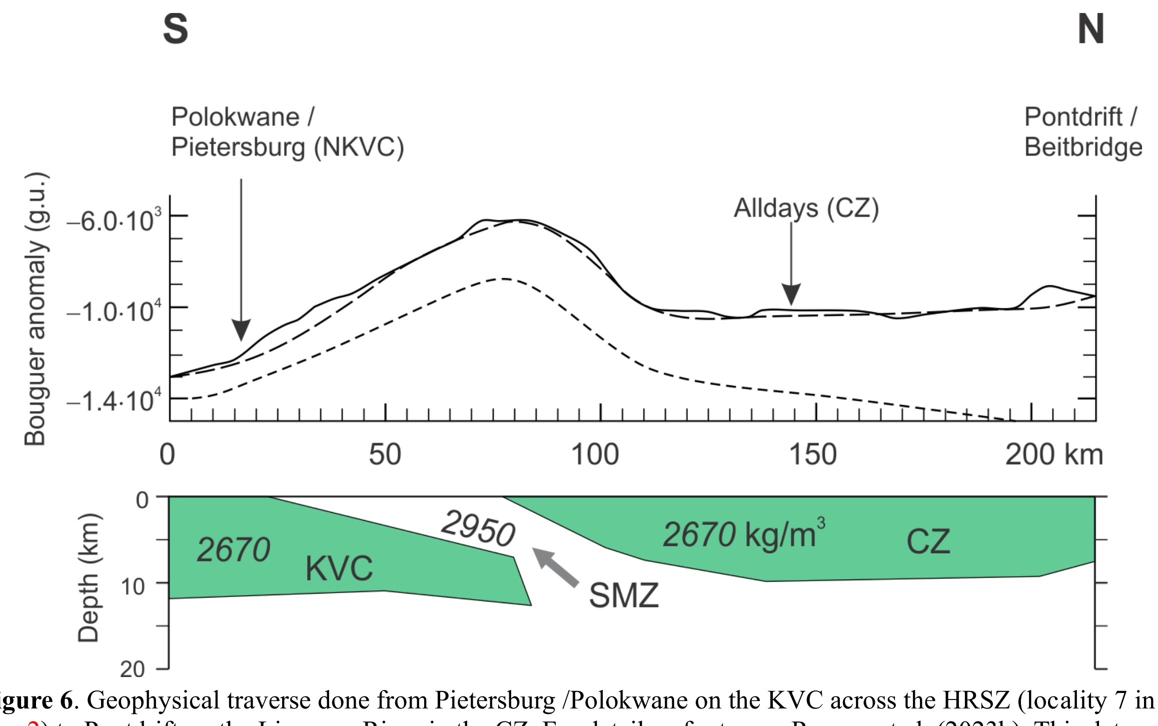


Figure 6. Geophysical traverse done from Pietersburg /Polokwane on the KVC across the HRSZ (locality 7 in Fig. 2) to Pontdrift on the Limpopo River in the CZ. For details refer to van Reenen et al. (2023b). This data shows that the entire SMZ was thrust south-westwards onto the adjacent KVC along the entire length of the steeply north-dipping HRSZ. The data also shows that much of the SMZ is underlain by low grade greenschist facies rocks (also inset map in Fig. 2).

5.3. Close-pair composite D-P-T-t paths

The concept of heterogenous deformation guided the construction of *composite D-P-T-t* paths that reflect evidence for the entire polymetamorphic evolutionary history of the LC at 2.72-2.02 Ga (Fig. 5a, b) (Van Reenen et al., 2023B). Close-pair samples are obtained from *granoblastic* granulites associated with steeply plunging isoclinal fold in close association with *sheared* metapelitic granulites from major shear deformational structures. Such close-pair samples have similar mineralogy (Grt-Crd-Sil/Opx-Sp-Bt-Qz-Pl) and similar bulk chemistry but are characterized by distinct non-overlapping chemical compositions of Fe-Mg phases (Perchuk et al., 2008; Van Reenen et al., 2019, 2023b). This is a direct manifestation of the metamorphic facies concept requiring that individual members of such close-pair samples equilibrated at distinctly different *P-T-X* conditions.

5.4. Conventional geothermobarometry and the principal of local chemical equilibria

Conventional geothermobarometry and the principal of local chemical equilibria was successfully utilized to obtain *P-T* data (Fig. 5a, b) from close-pair polymetamorphic CZ granulites characterized by complex reaction textures (see Perchuk, 2008). Pseudo-section modelling provided important complimentary data in some cases (Safonov et al., 2021).

5.5. Time

Time is mainly constrained by dating the intrusive products of long-lived anatectic granitic events that accompanied high-grade metamorphism in the CZ at three time intervals, 2.72-2.66 Ga, 2.65-2.62 Ga, and ~2.02Ga. Interpretation of U-Pb zircon/monazite SHRIMP dating of high-grade polymetamorphic metapelitic granulites with complex reaction textures proved to be a highly intimidating exercise that often leads to interpretation of geochronological data that directly conflicts with structural-geological field data. For conflicting data refer to the intrusive relationships of undeformed ~2.62 Ga granitoids (Singelele-types and Bulai porphyritic granite) with deformed and metamorphosed granulites dated at *~2.02 Ga* (see Fig. 9) (Van Reenen et al., 2008, 2023b).

6. Field itinerary

6.1. Field day 1, July 22

Three localities studied in the SMZ are shown as locality A,9 and Y (Fig. 2). Locality A is the SMZ in contact with Rhenosterkoppies greenstone belt (RGB) at the position of the steep north-dipping HRSZ. Locality **9** shows steeply dipping highly deformed unsheared Baviaanskloof migmatitic gneisses located in a dry riverbed in the retrograde amphibolite domain of the SMZ next to the HRSZ. Locality Y shows nearly flat-lying highly sheared retrograde altered equivalents of the steeply dipping unsheared Baviaanskloof migmatitic gneisses located at the base of an escarpment.

6.1.1. Locality A, 11:40-12:00. SMZ in contact with the RGB

View to the SW. The stop is next to a dirt road (Bylsteel road) that turns towards the west from the N2 a couple of km after passing through the RGB. It offers an instructive view to the SW of the RGB in the footwall of the steeply north-dipping section of HRSZ that bounds the SMZ in the south. This structural setting is the same as that of the Giyani greenstone belt

(GGB) located further to the east and of De Loskop greenstone belt remnant located further to the west (Figs. 1 and 2) (Van Reenen et al., 2023a).

The view towards the south and west shows steeply dipping low grade greenstone lithologies in the south that flattens towards the north in the central part of the RGB before dipping steeply northwards underneath the SMZ at the contact with the steeply dipping HRSZ. This observation provides structural-geological field evidence in support of metamorphic and geophysical (see Fig. 6) data showing that the SMZ was thrust against and over the KVC at the exact position of the HRSZ.

Structural and metamorphic evidence for interaction of underthrusted low-grade RGB greenschists with overriding SMZ granulites are restricted to the central and northern portions of the RGB in the immediate footwall of the steeply north-dipping HRSZ (Figs. 1 and 2). Low-grade steeply dipping greenschists in the southern limb of the RGB show no evidence for interaction with the SMZ of the LC, and thus no evidence that the southern part of the RGB was affected by the 2.72-2.62 Ga Limpopo orogeny (Koizumi et al., 2023). This situation is like that of the GGB in the east where Kramers et al. (2014) discussed a thermo-tectonic event at ~2.86 Ga (termed the Lwaji-Pietersburg greenstone belt orogeny) for which evidence is restricted to north verging structures developed in the southern Lwaji limb of the GGB (Fig. 2) that are not affected by the 2.72-2.62 Ga Limpopo orogeny.

Telescopic increase in *P-T* conditions from ~450°C (derived from BIF) in the south to peak conditions at 7-8 kbar and 640-680°C in the footwall of the HRSZ in the north (Koizumi et al., 2023) are documented by Grt-bearing and Grt-free amphibolite, and by Ky-bearing quartz schists (Koizumi et al., 2023). This situation describes a narrow hot-iron-zone restricted to the footwall of the HRSZ and is like the hot-iron-zone described in the case of the GGB (e.g., Smit et al., 2019; Van Reenen et al., 2023).

Pb-Pb and Rb-Sr mineral ages of 2.63-2.72 Ga obtained from amphibolite and granitoids, respectively in the immediate footwall of the HRSZ (Koizumi et al., 2023) are like the ages of 2.72-2.62 Ga derived from the northern limb (the hot-iron-zone) of the GGB in the footwall of the HRSZ. These ages accurately constrain the timing of events associated with HRSZ-linked thermo-tectonic activity that intermittently continued up to 2.62 Ga (Kramers et al., 2014; Smit et al., 2019; Van Reenen et al., 2023).

That part of the GGB located next to the narrow hot-iron-zone in the footwall of the HRSZ participated in the ~2.86 Ga Lwaji-Pietersburg (PGB) greenstone belt orogeny described by Kramers et al. (2014). Vearncombe et al. (2022) provided additional evidence that the Murchison greenstone belt was also involved with this pre-Limpopo orogeny at ~2.86 Ga.

6.1.2. Locality 9, 12:30-13:30. Goudplaas (S 23°31'1.81", E 30°2'50.89") (Fig. 2)

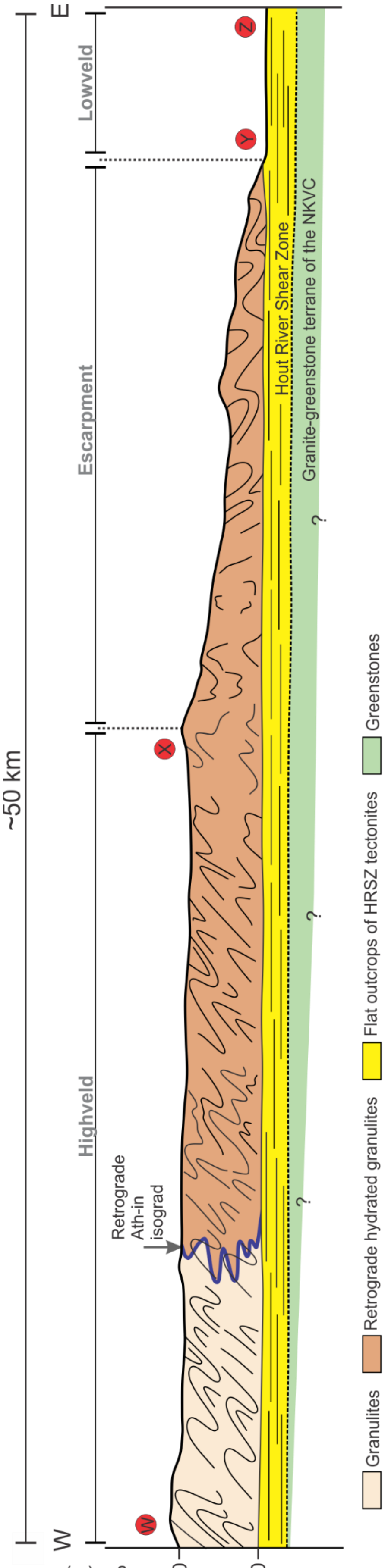
This instructive locality is in a dry riverbed in the SSW-NNE trending escarpment that separates the *highveld region* of the SMZ in the WNW characterized by steeply plunging isoclinal folds and steep shear zones from the *lowveld region* in the ESE characterized by flat-lying shear zones associated with the HRSZ sole thrust that underlies the SMZ. The escarpment displays a ~550 meter near vertical crustal section through the SMZ (see Fig. 7a) in which unsheared steeply dipping granulites are underlain by intensely sheared and retrograde altered flat-lying equivalents at the base of the escarpment. Locality 9 highlights the following (e.g., Van Reenen et al., 2023).

First, steeply plunging isoclinal folded and retrograde altered Baviaanskloof migmatitic gneisses in a dry riverbed in the retrograde amphibolite domain (locality 9 in Fig. 2) are shown to be cut by narrow flat lying high-grade shear zones (thrusts).

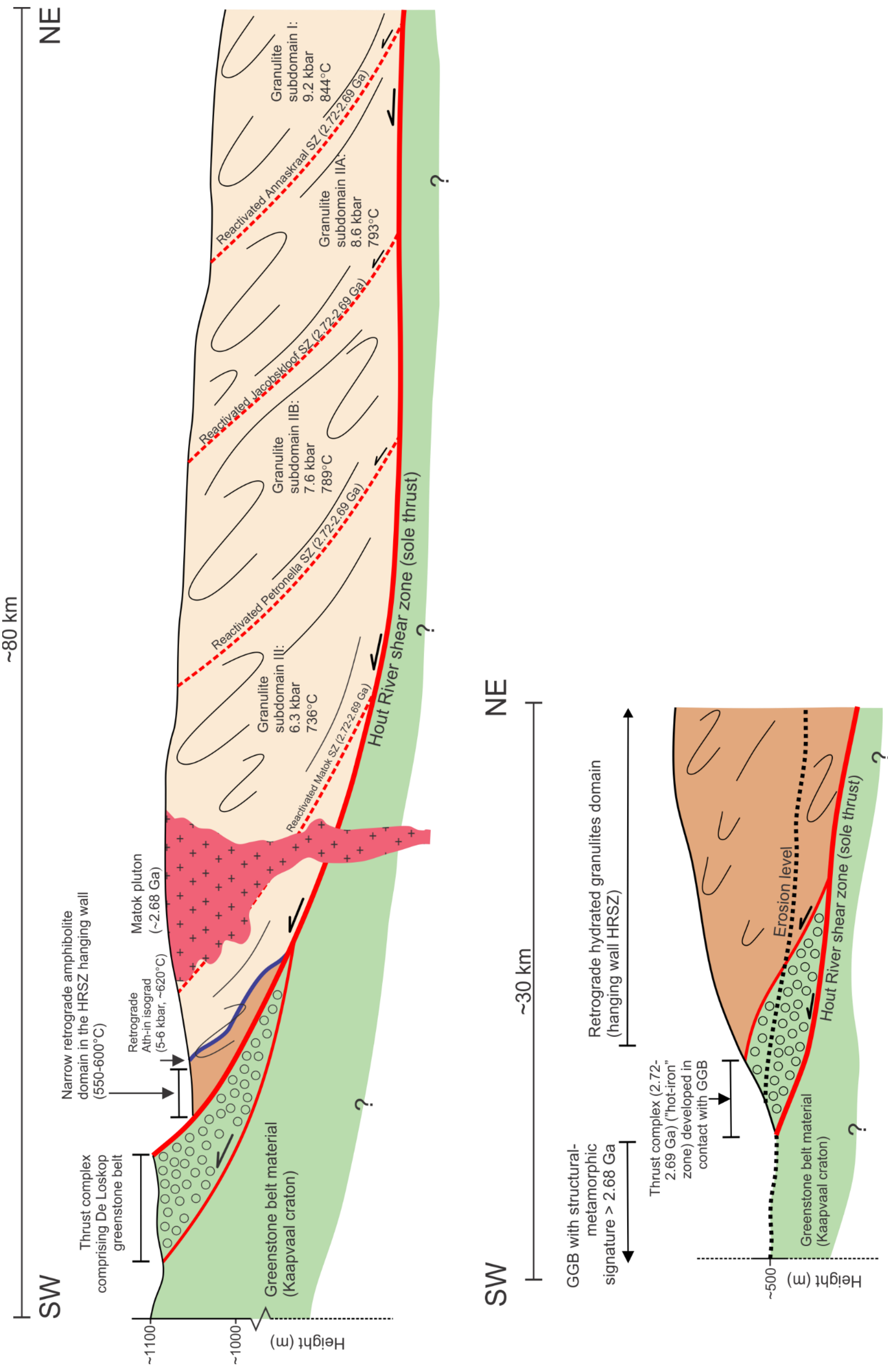
Second, near vertical dipping sub-volcanic (Palmietfontein-type) granitic dikes dated at ~2.46 Ga intrudes the flat-lying high-grade thrusts and steeply dipping retrograde altered migmatitic gneisses. Completely undeformed small Palmietfontein granitic plutons also intrude the granulite facies domain of the SMZ in the north at various localities (Fig. 1, 2). This is conclusive evidence that all regional thermo-tectonic activity in the SMZ was restricted to the at least before ~2.64 Ga. Additional evidence for a Neoarchean Limpopo orogeny is provided by the mainly undeformed Matok granitic pluton (Fig. 2) that intrudes the deformed and metamorphosed SMZ already at ~2.68 Ga.

Third, Rb-Sr biotite ages of ~2.0 Ga derived from the retrograde altered Baviaanskloof gneisses at this locality are complimented by similar Rb-Sr biotite/phlogopite ages derived from a variety of paragneisses (including metapelitic granulite) and deformed and undeformed igneous granitoids that outcrop throughout the SMZ, CZ, and juxtaposed Kaapvaal craton up to the Murchison greenstone belt (Barton et al., 1992; Van Reenen et al., 2023a). Absence of evidence for associated deformation and new metamorphic mineral growth at ~2.02 Ga at this locality and at all the other studied localities outside reactivated shear zones is clear indication for a regional high-grade thermal event that overprinted much of the LC in the Paleoproterozoic (Van Reenen et al., 2023a).

Fourth, evidence for thermo-tectonic action that was associated with the ~2.02 Ga regional thermal event in the SMZ is restricted to the reactivation of two major NE-SW-trending and steeply dipping high-grade shear zones as upper crustal mylonitic structures, i.e. the NE-SW-trending HRSZ-Koedoes River Shear Zone and the N'Thabalala Shear Zone, that both cut south-westwards into the KVC (Fig. 2).



Height (m)
~1200
~400
W
E
~50 km
Highveld
Escarpment
Lowveld
W
X
Y
Z
Retrograde
Ath-in
isograd
Hout River Shear Zone
Granite-greenstone terrane of the NKVC
?
Granulites
Retrograde hydrated granulites
Flat outcrops of HRSZ tectonites
Greenstones



SW
NE
~80 km
Height (m)
~1100
~1000
Thrust complex comprising De Loskop greenstone belt
Greenstone belt material (Kaapvaal craton)
Narrow retrograde amphibolite domain in the HRSZ hanging wall (550-600°C)
Retrograde Ath-in isograd (5-6 kbar, ~620°C)
Matok pluton (~2.68 Ga)
Reactivated Matok SZ (2.72-2.69 Ga)
Granulite subdomain III: 6.3 kbar 736°C
Reactivated Petronella SZ (2.72-2.69 Ga)
Granulite subdomain IIB: 7.6 kbar 789°C
Reactivated Jacobskloof SZ (2.72-2.69 Ga)
Granulite subdomain IIA: 8.6 kbar 793°C
Reactivated Annaskraal SZ (2.72-2.69 Ga)
Granulite subdomain I: 9.2 kbar 844°C
Hout River shear zone (sole thrust)
?
SW
NE
~30 km
GGB with structural-metamorphic signature > 2.68 Ga
Thrust complex (2.72-2.69 Ga) ("hot-iron" zone) developed in contact with GGB
Retrograde hydrated granulites domain (hanging wall HRSZ)
Erosion level
Hout River shear zone (sole thrust)
Greenstone belt material (Kaapvaal craton)
Height (m)
~500

Figure 7 (previous two pages). Three crustal sections that document evidence that the granulite facies SMZ is at depth underlain by a near horizontal sole thrust (the HRSZ) along which this granulite facies terrane was thrust SW-wards against and onto the KVC (van Reenen, 2023a). **(a)** A 50 km long E-W directed crustal section through the SMZ constructed along traverse **W-X-Y-Z** (Fig. 2). The crustal section starts at Bandelierkop quarry (**W**) in the light brown granulite domain where complexly folded steeply dipping granulites are exposed. It crosses N'Thabalala shear zone, the Ath-in retrograde isograd and the dark brown retrograde amphibolite domain at **X** that is also characterized by complexly folded steeply dipping retrograde altered granulites. The crustal section then continuous across the SSW-NNE-directed escarpment and into the yellow Lowveld domain at **Y** that exposes intensely sheared nearly flat-lying retrograde altered granulites. The crustal section ends at **Z** against the steeply dipping Koedoes River strike-slip shear zone in the SE. The escarpment exposes a ~ 500 meter near vertical crustal section through the SMZ that provides field evidence that complexly folded Bandelierkop granulites and their retrograde altered equivalents are at depth underlain by highly sheared nearly horizontal retrograde altered Bandelierkop Formation lithologies that are linked with the near horizontal section of the sole thrust (HRSZ). **(b)** Two SW-directed crustal sections that demonstrate the thrust-controlled relationship of the SMZ with the granite-greenstone terrane of the KVC and are constructed across widely apart steeply north-dipping sections of the HRSZ. **A.** This 60 km long travers starts near Makado in the light brown granulite domain in the north, crosses the narrow dark brown retrograde domain at the type locality (locality 7 in Fig. 2) of the HRSZ west of Matok pluton and continuous SW-wards into the granite greenstone terrane. **B.** This SW-directed short traverse starts in the retrograde amphibolite domain NW of Giyani GGB and crosses the steeply north-dipping HRSZ and Giyani greenstone belt at locality 12 (Fig. 2). The top section crosses major SW-NE trending and steeply NE-dipping thrusts (Annaskraal, Petronella, Matok) showing that these structures are allochtonous (and thus older than) the ~2.7 Ga HRSZ sole thrust onto which an allochthonous granulite nappe was thrust SW-wards onto the KVC. The bottom section best demonstrates the development of a thrust complex associated with a "hot-iron-zone" developed in the footwall of the steeply north-dipping section of the HRSZ. See van Reenen et al., (2023a) for further details.

6.1.3. Locality Y, 14:00-14:30. Base of the escarpment (*S23°23'50.96", 30°5'14.81"*)

Flat lying sheared and retrograde altered Baviaanskloof gneiss outcrops in a dry riverbed at the base of the escarpment and at different localities throughout the lowveld region of the SMZ (yellow area, Fig. 2). These flat-lying sheared outcrops comprising Baviaanskloof gneiss and <u>all</u> retrograde altered equivalents of former Bandelierkop Formation granulites (mafic-ultramafic gneisses, metapelitic gneisses, and BIF) (Van Reenen et al., 2023a) are linked to the flat-lying section of the HRSZ sole thrust that underlies much of the SMZ (Fig. 7a). Flat-lying shear zones that cut northwards underneath the steeply dipping retrograde altered Bandelierkop Formation lithologies are exposed in the escarpment and are provide structural-geological field evidence that a SW-directed crustal-scale allochtenous SMZ granulite nappe is riding on a flat-lying sole thrust (HRSZ) (Fig. 7b) (Van Reenen et al., 2023A). This scenario is supported by geophysical and metamorphic evidence (Fig. 6). The flat-lying shear zones ramp eastwards against the steeply dipping NE-SW-trending Koedoes River Shear Zone in contact with the KVC (locality Z in Fig. 2).

Narrow hot-iron-zones developed at 2.72-2.69 Ga in the footwall section of the steeply north-dipping HRSZ against the GGB and the RGB (Fig. 2) provide a direct link to a deep-seated metamorphic source for low water activity gold mineralized metamorphic fluids released as the result of thrusting hot granulites-over-cool greenschists at 2.72-2.69 Ga. Fluids thus released infiltrated the overlying crust to establish at 2.65-2.62 Ga the Giyani Goldfield in the hanging wall (SMZ) and footwall (GGB) of the HRSZ and the Ath-in retrograde isograd. This isograd subdivides the SMZ into a northern granulite domain and a southern retrograde amphibolite domain (Fig. 2). Thrusting hot granulites over cool ~2.86 Ga gold-bearing greenstones provided a deep-seated metamorphic source for gold mineralizing fluids associated with HRSZ tectonism as is supported by different data: (1) north-verging structures dated at ~2.86 Ga in the southern Lwaji limb of the GGB that did not participate in the 2.72-2.69 Ga Limpopo Orogeny (Fig. 2) (Kramers et al., 2014); (2) ~2.86 Ga ages derived from the Eersteling gold deposit of the Pietersburg greenstone belt (PGB) (Kramers et al., 2014); (3) ~2.86 Ga ages of gold mineralization derived from the gold-antimony line of the Murchison greenstone belt (MGB) (Vearncombe et al., 2022).

6.1.4. Late afternoon

Arrive at Klein Bolayi Lodge at about 17:30.

6.1.5. Evening

Short introduction to the workshop agenda by Dirk van Reenen.

6.2. Field day 2, July 23

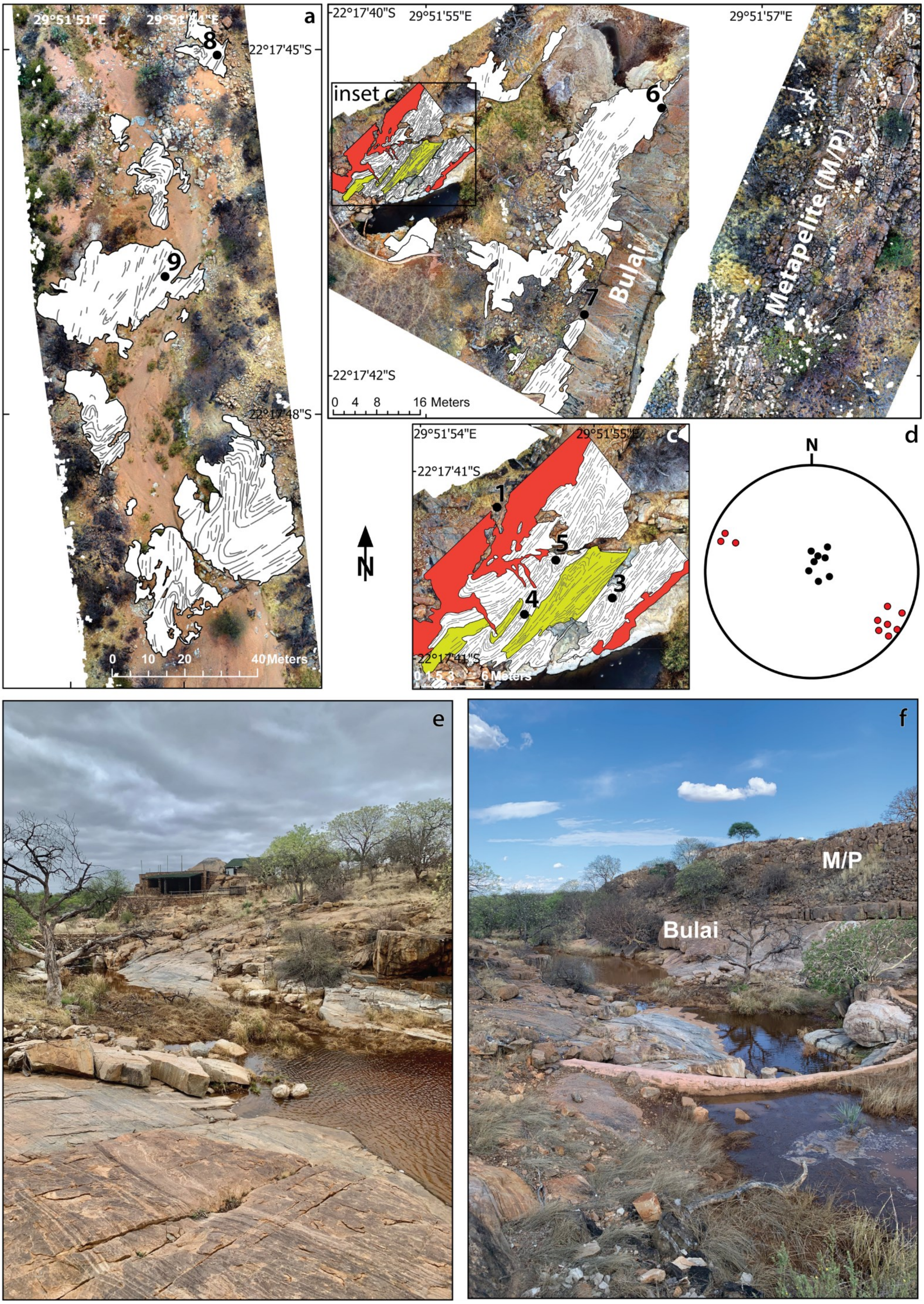
6.2.1. Locality 9, 8:00 – 10:30. Evelyn locality located in the Bulai pluton (S22°17.39', E29°51.53').

The highly instructive Evelyn locality 9 (highlighted as such in Figs. 3 and 4) comprises three separate, but *structurally continuous* sections that outcrop over a combined distance of 250 meters in Klein Bolayi River in the Bulai "pluton" (Fig. 8) (Van Reenen et al., 2023b). Isoclinal deformed and *steeply dipping* CZ granulites at this important locality were first studied by Kröner et al. (2018) and Brandt et al. (2018) who coined the term "enclave" based on the assumption that this major outcrop was trapped as a very large enclave/xenolith by the intruding 2.62 Ga Bulai granite. Subsequent detailed outcrop mapping supported by high resolution drone imagery and regional aerial photography (Figs. 4 and 8) provided structural-geological data that directly conflicts with the concept of an enclave/xenolith (see Van Reenen et al., 2023b).

Limpopo Complex lithologies at the Evelyn locality comprise members of the Musina Suite, Grt-Crd-Sil-Bt-bearing metapelites, calc-silicate gneisses, and a few outcrops of Singelele-type granitoids (Van Reenen et al., 2023b). This outcrop provides vital information.

First, intrusive relationships are expressed by completely undeformed Bulai porphyritic granite dated at 2.62 Ga and Bulai granodiorite that neatly cut the steep gneissic fabric of isoclinal folded CZ granulites (Fig. 8) with metamorphic ages ~2.62 Ga (Kröner et al., 2018). The age data is consistent with the observed intrusive relationships.

Second, a subsequent geochronological study at this locality by Zhao et al., (2022) constraint the timing of the isoclinal fold event earlier at ~2.72 Ga based on data derived from paragneisses. This age was already previously constrained by dating intrusive anatectic granitoids (Van Reenen et al., 2008; Kramers and Mouri, 2011; Kröner et al., 2018).



a
29°51'51"E
8
22°17'45"S
9
22°17'48"S
0 10 20 40 Meters
b
22°17'40"S
29°51'55"E
29°51'57"E
inset c
6
7
Bulai
Metapelite (M/P)
22°17'42"S
0 4 8 16 Meters
c
29°51'54"E
22°17'41"S
1
5
4
3
N
d
N
e
f
M/P
Bulai

Figure 8 (previous page). Structural geological map (a-c) of the Evelyn outcrop comprising ortho- and paragneisses exposed in Klein Bolayi River on Farm Evelyn within Bulai pluton (locality 9 in Figs. 3 and 4). Note that: (1) The complexly deformed but coherent structural pattern (d) can be continuously followed over a combined distance of ~200 meters. (2) Intrusive relationships of 2.618 Ga undeformed Bulai porphyritic granite (red or labeled) with orthogneisses of the Musina Suite. Such relationships are recorded either by direct intrusive contacts (c) or by lit-par-lit relationships in which narrow bands of undeformed 2.618 Ga porphyritic granite occur interlayered with narrow bands of orthogneisses from which metamorphic ages of ~2.62 Ga have been obtained (Kröner et al., 2018). Details in Van Reenen et al. (2023a). (3) Granoblastic granulites are characterized by absence of discrete kinematic structural elements (mineral lineations, S-C relationships, sigmoidal grains) apart from mineral rodding and minor fold axis. This is indicative of recrystallization-annealing that followed emplacement of these hot rocks at the mid-crustal level at ~2.72 Ga (Table 1) (Van Reenen et al., 2023b).

Table 1.
Two-stage exhumation of the CZ at 2.72-2.66 Ga, 2.65-2.62 Ga followed at ~2.02 Ga by final emplacement at the upper crustal level accompanied by a regional thermal overprint that affected the CZ, SMZ, and juxtaposed KVC (Van Reenen et al., 2023b).

Stage and structural features	**Timing of events**	**Contact with Bulai porphyritic granite**	**Petrography**	***D-P-T-t* paths** Constructed from close pair samples of metapelitic granulites.
STAGE 1 Steeply dipping isoclinal folds	~2.72 Ga Constraint by anatectic granitoids and U-Pb zircon ages (Zhou et al., 2022).	Sharp intrusive contacts of unsheared granoblastic granulites with undeformed porphyritic granite.	Unsheared granoblastic poly-metamorphic granulites characterized by lack of discrete kinematic elements.	Near-isothermal decompression (Fig. 5a) accompanied by steeply dipping isoclinal folded granulites emplaced at mid crustal level at ~2.72 Ga (Fig. 5a).
STAGE 2 Moderately SW- plunging sheared structural features (Fig. 6).	2.65–2.62 Ga U-Pb zircon-monazite ages from anatectic granitoids and M/P granulites	Sheared granulites with abundant kinematic indicators in contact with sheared porphyritic granite	Sheared poly-metamorphic granulites termed “straight gneisses”	Moderate decompression cooling *P-T* path (Fig. 5) and granitic diapirism linked to moderately SW plunging and NE-verging shear deformation.
BULAI PLUTON Emplacement of mainly undeformed Bulai Pluton	~2.62 Ga U-Pb zircon age	Undeformed in contact with isoclinal folded granulites; sheared in contact with sheared granulites.	Undeformed porphyritic granite with igneous flow foliation restricted to margins of large bodies.	Lack of compositional changes of major and trace elements during ~2.02 Ga overprint (Laurent et al., 2011 in Van Reenen et al., 2023).
STAGE 3 Steep N-S trending shear zones in the CZ. Reactivation of TSZ/ HRSZ.	~2.02 Ga U-Pb zircon ages for syntectonic anatectic granitoids.	Discrete shear zones locally overprint undeformed porphyritic granite.	Highly sheared granulites with abundant kinematic indicators.	Isobaric heating (~6 kbar) from 600 to 750°C followed by decompression-cooling (Fig. 5a, b)

Fourth, intrusive relationships of Bulai granite with CZ gneisses are also documented by lit-par-lit interactions in which cm-wide bands of undeformed steeply dipping porphyritic granite and coarse granodiorite are interlayered with narrow bands of steeply dipping CZ granoblastic granulites (Van Reenen et al., 2023).

Fifth, detailed structural-geological mapping utilizing high resolution drone imagery supported by a regional aerial photographic study show that already deformed and metamorphosed CZ lithologies that outcrop at numerous localities within Bulai pluton are passively intruded by Bulai granite without disturbing the regional fold pattern that these outcrops adhere to (Fig. 4). This regional deformational pattern that characterizes the entire

CZ can continuously be followed throughout the entire pluton (Fig. 4), and conflicts with large outcrops of CZ lithologies within Bulai (e.g. Evelyn "enclave") being described as "enclaves/xenoliths". True xenoliths within Bulai are exposed at the Three Sisters locality within Bulai pluton (locality 7, Fig. 4).

Sixth and last, the validity of constructing a *counterclockwise P-T* path from a granoblastic Grt-Crd-Sil-Bt-Qz bearing granulite characterized by complex reaction textures and linking this P-T path to a collisional orogeny involving the KVC at 2.65-2.62 Ga by Brandt et al. (2018) is questioned, as will be further discussed.

6.2.2. Locality 10, 11:00-12:00. Farm Evelyn next to Bulai pluton (S22°17.27", E29°50.19")

Steeply dipping CZ granulites closely associated with undeformed Bulai porphyritic granite occur as poorly exposed outcrops on Farm Evelyn immediately next to Bulai pluton (locality 10 in Fig. 4). Kröner et al. (2018) provided a metamorphic age of ~2.02 Ga from a granoblastic metapelitic granulite at this locality and Brand et al. (2018) linked this age to a clockwise P-T path derived from a steeply dipping granoblastic metapelitic granulite. These authors linked this P-T path to a transpressional orogeny at ~2.02 Ga associated with thrust tectonics. However, there is no evidence for thrust tectonics at this locality next to Bulai pluton (e.g. Fig. 9) or at any other locality throughout the entire CZ (Fig. 3) (Van Reenen et al., 2023b). The following is important.

First, outcrops on Evelyn Farm (locality 10 in Fig. 4) comprise the same diversity of steeply dipping granoblastic granulites (including metapelitic granulite) as have been observed at Evelyn "enclave" in Bulai pluton (locality 9 in Fig. 4). Metapelitic granulites at both localities have similar mineralogical, structural, and textural features including granoblastic textures and are characterized by absence of discrete kinematic elements.

Second, this poor outcrop area does not allow direct intrusive relationships to be studied. In contrast, evidence for intrusive relationships is documented by lit-par-lit interactions in which meters-wide bands of steeply dipping undeformed 2.62 Ga porphyritic granite alternate with meters-wide bands of steeply dipping CZ gneisses that include meta-anorthosite, metapelitic granulite, and Singelele-type granitoid (Van Reenen et al., 2023b). Van Reenen et al. (2023b) provide GPS coordinates for several localities where lit-par-lit relationships can be observed in the field.

Third, the act of linking a ~2.02 Ga metamorphic age derived from steeply dipping granoblastic granulites with a transpressional orogeny associated with *thrust tectonics* (Brandt et al., 2023) is questioned. This true because this locality is characterized by undeformed ~2.62 Ga porphyritic granite that intrudes para- and ortho-gneisses from which metamorphic ages of ~2.02 Ga have been derived. This suggests that the interpretation of the ~2.02 Ga age as representing evidence for a transpressional orogeny linked to thrust tectonics must be reconsidered.

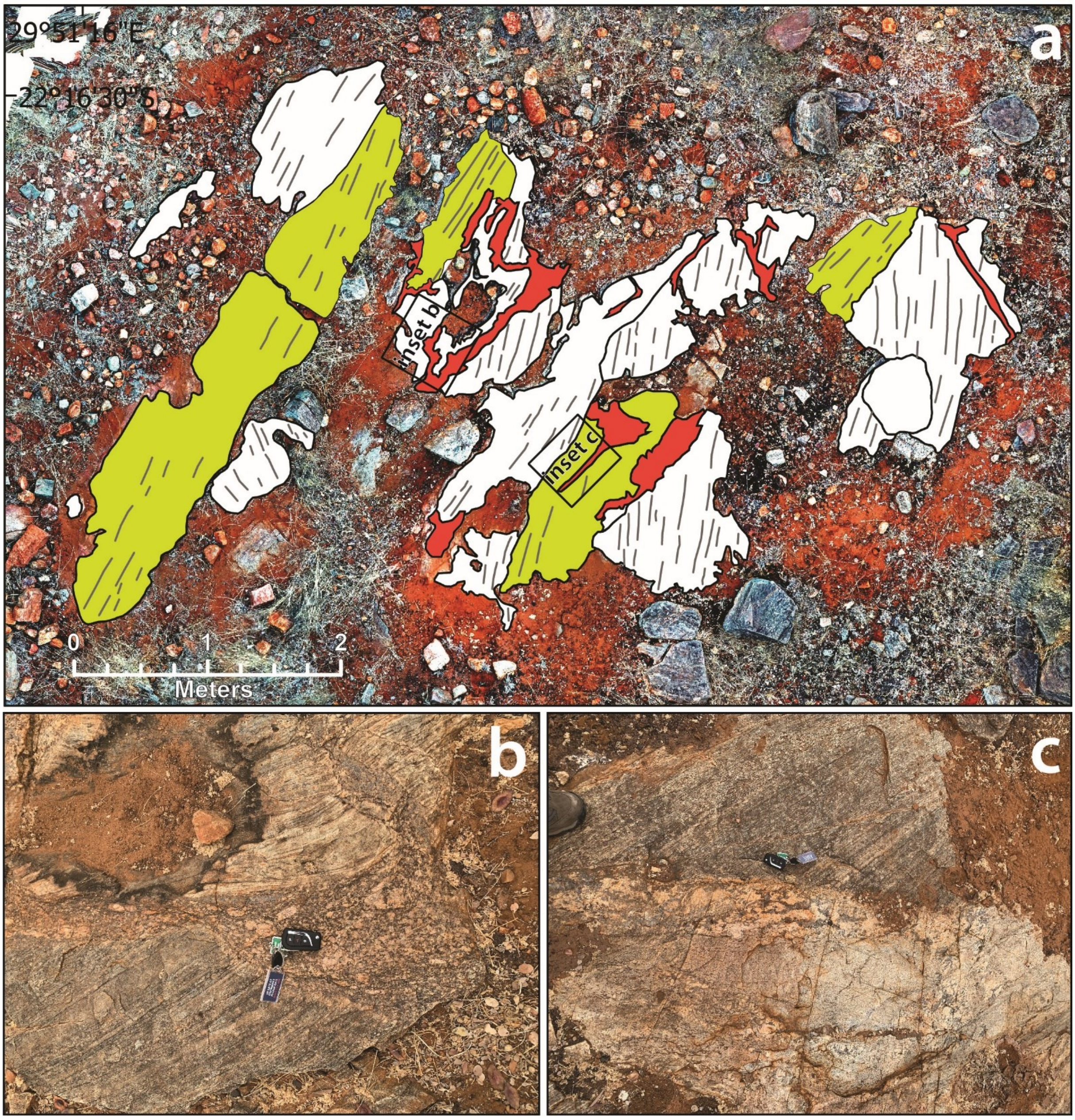


Figure 9. Outcrops like the Evelyn outcrops within the pluton (Figure 8) but on a much smaller scale are exposed on Farm Bolton next to the pluton (locality 11 in Figs. 3 and 4). Note similar intrusive relationships of ~2.618 Ga undeformed porphyritic granite (red) and Singelele gneiss (~2.62 Ga) (see Fig. 10) that in this case intrude ortho- and paragneisses from which metamorphic ages of ~2.02 Ga have obtained (Kröner et al., 2018) (Van Reenen et al., 2023b).

6.2.3. Locality 11, 12:30-13:00. Farm Bolton next to Bulai pluton (S22°16'30.0", E29°50'41")

A highly instructive small outcrop at locality 11 on Farm Bolton (Fig. 9) is located next to Bulai pluton and along the strike, to the north, from locality 10 (Fig. 4). This highly instructive locality next to and east of the dirt road exposes undeformed veins and small undeformed bodies of Bulai porphyritic granite that cleanly cut the gneissic fabric of *steeply* dipping deformed and metamorphosed Musina Suite granoblastic granulites and Singelele gneissic granite. The outcrop pattern is the same as that of the much larger outcrop pattern of Evelyn "enclave" (cf. Figs. 8 and 9). The following is important.

First, localities 10 and 11 (Fig. 9) provide conclusive evidence that a regional high-grade thermal event that overprinted granulite facies rocks of the CZ at ~2.02 Ga is not associated with deformation or with growth of new metamorphic mineral assemblages. Evidence for thermo-tectonic activity at ~2.02 Ga in the CZ is restricted to discreet N-S trending shear zones (Kramers and Mouri, 2011; Van Reenen et al., 2023) as will be observed at locality 5 (Fig. 4) next to Bulai pluton.

Second, data presented questions constructing contradicting ~2.62 Ga *counterclockwise* P-T paths (Evelyn "enclave" within Bulai) versus ~2.02 Ga *clockwise* P-T paths (Evelyn farm next to Bulai) for granoblastic metapelitic granulites with similar mineralogical and textural characteristics (see Brandt et al., 2023), given the fact that para- and orthogneisses at both localities are intruded by undeformed 2.62 Ga porphyritic granite (Figs. 8 and 9).

Third and last, the fact that there is no evidence in the CZ for high-grade flat-lying structures that might be linked to thrust tectonics at ~2.02 Ga (e.g. Fig. 3).

6.2.4. 13:30-14:30

Lunch at Klein Baloyi

6.3. Wednesday, July 24

6.3.1. Locality 5 (Fig. 4), 8:00-9:30. Jacht Camp next to Bulai pluton (locality of sample RB24, S22°14'45.25", E29°53'14.24" or S22°14'45.0", E29°53'12.6")

Two instructive features can be studied at locality 5 on Farm Boston NNE of Three Sisters in the CZ (Fig. 4).

First, little deformed Singelele granite dated at ~2.62 Ga trapped randomly oriented rafts/xenoliths of metapelitic gneiss (Fig. 10) that also occur as lit-par-lit interactions with meter sized bands of Singelele granite at this locality (Van Reenen et al., 2023). Similar field relationships in which little deformed Singelele gneiss intrudes already deformed and metamorphosed CZ granulites have been described at the two previous localities next to Bulai pluton as will also be observed at the next two localities within Bulai pluton (Van Reenen et al., 2023b).

Second, a discreet cm-wide N-S trending and steeply dipping high-grade shear zone cuts Singelele granite and metapelitic granulite at this locality. Similar discreet N-S trending shear zones cut undeformed Bulai porphyritic granite at different localities in Bulai pluton (Watkeys, 1984) and are well exposed in the Sand River on farm Verbaard (locality 3 in Fig. 3). Here they have been dated at ~2.02 Ga (Van Reenen et al., 2023B). Such discreet structures are the only direct evidence for thermo-tectonic activity that accompanied the ~2.02 Ga thermal event.

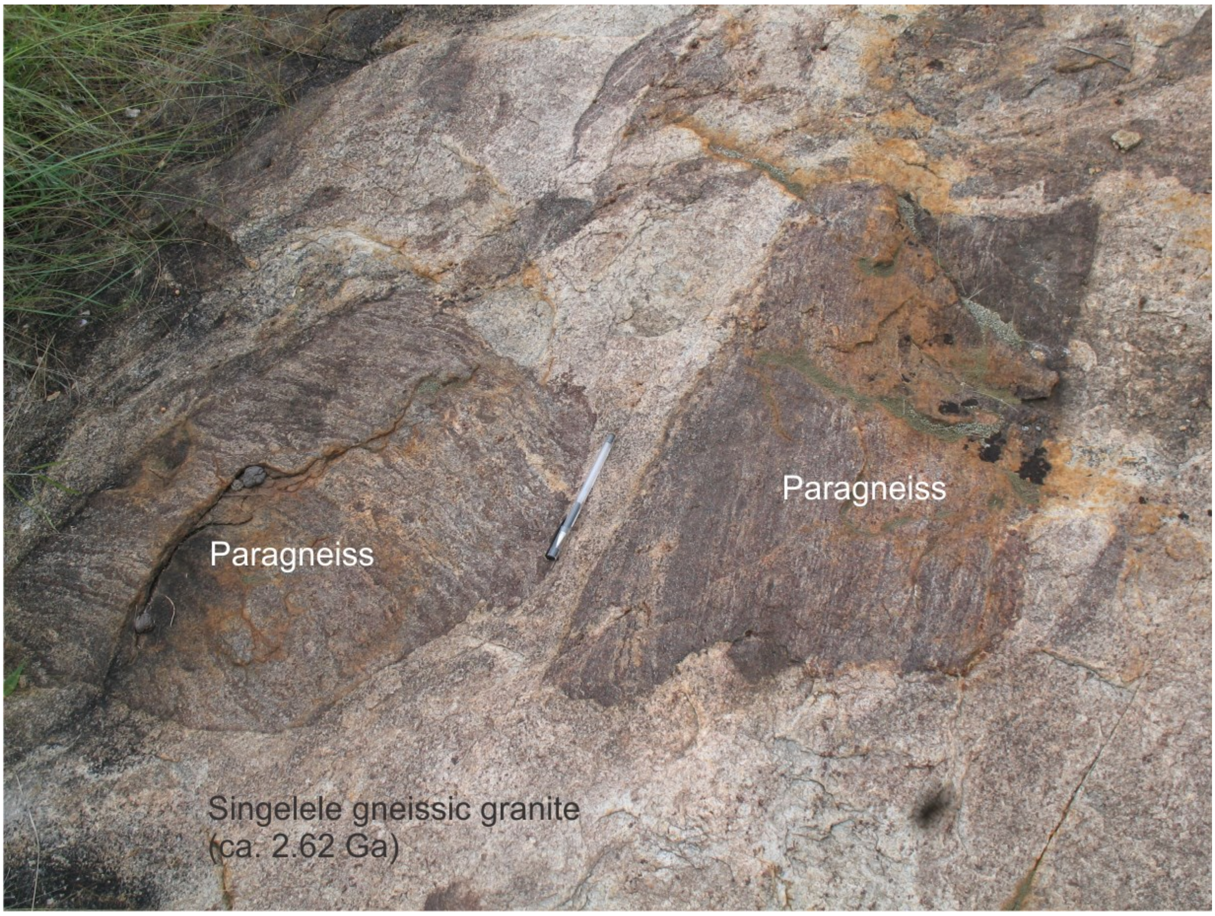


Figure 10. Deformed and metamorphosed paragneiss that outcrops next to Bulai pluton (locality 5 in Fig. 3, 4) occurs as xenoliths in slightly deformed Singelele gneiss dated at ~2.62 Ga (Van Reenen et al., 2023b).

6.3.2. Locality 8, 10:30-11:15. Next to Three Sisters on farm Boston in Bulai pluton (*RB41-S22º15'50.6", E29º55'08.9"*) *(Fig. 4)*.

This locality within Bulai pluton exposes steeply dipping meters-wide undeformed layers of porphyritic granite that occur as lit-par-lit interactions with steeply dipping lineated metapelitic granulite and Singelele granite (Van Reenen et al., 2023b). These outcrops are continuous with major outcrops that can be followed into Bulai pluton forming part of the regional fold deformational pattern of the CZ (Figs. 3 and 4) (Van Reenen et al., 2023). Direct intrusive contacts of ~ 2.62 Ga Singelele granite (Kröner et al., 1999) with metapelitic granulite are exposed at a locality a few hundred meters NNE along the strike from locality 8 (locality 6 in Fig. 4).

6.3.3. Locality 7, 11:30 - 13:30. Three Sisters locality (*S22°15'50.3", E 29°55'09.8"*) *(Fig. 4) (lunch included)*

Classic outcrops of undeformed Bulai porphyritic granite occur as three large hills in the main outcrop area of Bulai pluton (locality 7 in Fig. 4). A characteristic feature of these outcrops is the presence of true meter-sized xenoliths of steeply dipping metapelitic granulite interlayered with narrow bands of steeply dipping Singelele gneiss that are completely enclosed by undeformed ~2.618 Ga porphyritic granite. Numerous near-parallel quartz-feldspathic granitic dikes (Singelele-type) are also trapped by the undeformed porphyritic granite. Evidence for "deformation" in the form of igneous flow orientation of feldspar megacrysts is restricted to the edges of the large granitic body. The following issues need to be considered.

First, Millonig et al. (2008) derived a metamorphic age of ~2.64 Ga from granoblastic metapelitic granulite sampled from two small xenoliths trapped by undeformed 2.62 Ga Bulai porphyritic granite at Three Sisters locality. This age is like the age derived by Kröner et al. (2018) for metapelitic granulite with similar mineralogy and textural features at Evelyn "enclave".

Second, Millonig et al. (2008) and Huizenga et al. (2011) respectively utilized phase equilibrium modelling and conventional thermo-barometry and local equilibria to construct ~2.64 Ga *clockwise P-T* paths for metapelitic granulites with granoblastic textures comprising Grt-Sil-Crd-Bt-Pl-Qz.

Third, this data questions the validity of constructing contrasting *counterclockwise* (Evelyn "enclave") and *clockwise P-T* paths (xenoliths at Three Sisters) for granoblastic metapelitic granulites with similar metamorphic ages that are in both cases intruded by undeformed ~2.62 Ga Bulai porphyritic granite.

The data presented so far suggest the following:

First, that undeformed 2.62 Ga Bulai porphyritic granite and slightly deformed ~2.62 Ga Singelele granite intrude much older (~2.72 Ga) isoclinal folded and metamorphosed CZ lithologies that outcrop within and next to Bulai pluton at different localities. This is proof that the Neoarchean Limpopo orogeny affected the entire CZ and preceded emplacement of Bulai pluton at ~2.62 Ga.

Second, the data presented demonstrates that a regional high-grade thermal event at ~2.02 Ga in the CZ was not accompanied by deformation or growth of a new high-grade metamorphic mineral assemblages. Evidence for thermo-tectonic activity in the CZ at ~2.02 Ga is restricted to discrete N-S trending fabric parallel shear zones that overprint all early deformational features and Bulai porphyritic granite.

6.4. Thursday, July 25

6.4.1. Locality 10, 9:00-10:00. Sheared contact of Bulai porphyritic granite with sheared Ha-Tshanzi closed structure (S22°18'47.47", 29°57'18.11") (Fig. 11)

Highly sheared Bulai porphyritic granite is in contact with the eastern limb of the sheared and steeply SW-plunging Ha-Tshanzi closed structure (H, Fig. 4) as exposed on farm Uitenpas near Matombe Lodge next to and west of the Musina-Beitbridge main road. The onset of shear deformation that overprints undeformed porphyritic granite is well exposed at this locality (Fig. 11) where the two sheared rock bodies are shown to share the same SW-plunging kinematic indicators (Fig. 3) (Watkeys, 1984).

Sheared polymetamorphic metapelitic granulites exposed on farm Tovey in the WSW rim of the Ha-Tshanzi closed structure (H, Fig. 4) are the most instructive example of the principle of heterogenous deformation that operated on the outcrop and thin section scales. This is demonstrated by the preservation of three distinct generations of Grt-Crd-Sil-Bt-Sp each with distinct chemical compositions in sample TOV13 (Perchuk et al., 2008). These three generations respectively occur (1) in granoblastic portions of the rock; (2) associated with the main shear fabric of the closed structure that wraps preserved granoblastic portions, and (3) associated with micro-shear zones that cut the older textural features at steep angles (Van Reenen et al., 2019; 2023b; Safonov et al., 2021).

D-P-T-t history of Ha-Tshanzi.

A composite *D-P-T-t* trajectory (Fig. 5a) obtained from close-pair samples TOV 13 (S22°19'33.4", E29°58'51.5") and 06-19 (S22°26'11.4", E30°00'33.7") demonstrates the entire exhumation history from ~2.72 Ga to final emplacement of metapelitic granulites at the upper crustal level at ~2.02 Ga. Sample TOV13 is from the sheared Ha-Tshanzi closed structure (Fig. 4) and sample 06-19 is from a discreet fabric parallel shear zone that overprints the eastern limb of the closely associated N-S trending sheared Campbell structure near locality 3 (Fig. 3) (Perchuk et al., 2008; Safonov et al., 2022; Van Reenen et al., 2023b). The exhumation history comprises three stages.

Stage 1 (Fig. 5a) reflects evidence for near-isothermal decompression that commenced before 2.72 Ga and ended with emplacement at ~2.72 Ga of the CZ at the mid crustal level (Safonov et al., 2022). The evidence is preserved in granoblastic portions of sample TOV13 (Safonov et al., 2022) that are linked to granoblastic granulites that regionally are associated with steeply plunging isoclinal folds.

Stage 2 involves subsequent decompression-cooling at mid-crustal level at 2.65-2.62 Ga (Fig. 5a) that accompanied the main shear fabric that wraps early granoblastic portions in sample TOV 13. This second stage of exhumation is directed by a regional NE-verging and moderately SW-plunging shear deformational event (Fig. 3) accompanied by extensive granitic diapirism. This resulted in final emplacement of the CZ at the mid-crustal level prior to intrusion at ~2.62 Ga of Bulai pluton.

Stage 3 reflects near-isobaric heating at ~2.02 Ga (Fig. 5a) and is exemplified by numerous mm-wide micro shear zones that cut all early textures in sample TOV13 (Perchuk et al., 2008). Isobaric heating displayed by close-pair samples TOV13 and 06-19 is direct evidence for a ~2.02 Ga high temperature thermal overprint that affected much of the CZ, SMZ, and juxtaposed KVC (Barton et al., 1992a; Van Reenen et al., 2023). This is supported by close-pair metapelitic samples (JC1-T73) (Fig. 5b) studied from the N-S trending Baklykraal sheared structure located more than 100 km to the west (locality 1 and 2 in Fig. 3).

Contrasting intrusive relationships of Bulai porphyritic granite respectively with isoclinal folded granoblastic gneisses and with highly sheared CZ gneisses provide additional evidence that supports a two-stage Neoarchean exhumation history at 2.72-2.66 Ga and 2.65-2.62 Ga as is reflected by the composite *D-P-T-t* path (Fig. 5a).

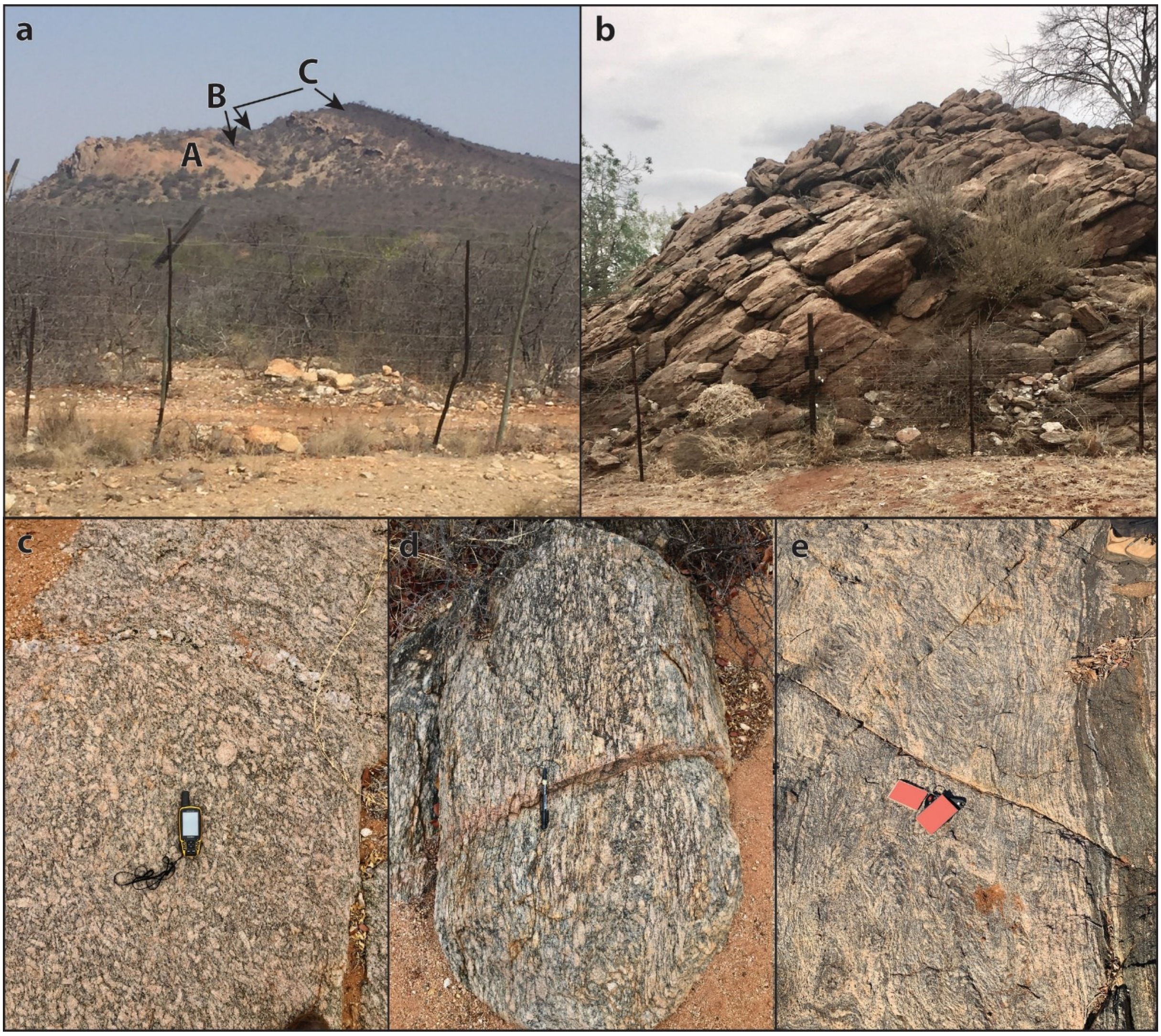


Figure 11. (a and b). Intensely sheared ~2.618 Ga Bulai porphyritic granite that is in direct contact with sheared granulites of the ~2.62 Ga SW-dipping Ha-Tshanzi closed structure (locality 8 in Fig. 4). (c, d, e) Similar sheared relationships of Bulai porphyritic granite and CZ lithologies exposed at the nose of the N-S trending and steeply dipping sheared Campbell structure (locality 15 in Fig. 4). See Van Reenen et al. (2023b).

Stage 1. Undeformed 2.62 Ga porphyritic granite directly intrudes unsheared granoblastic granulites associated with ~2.72 Ga steeply plunging isoclinal folds. This is directly observed at Evelyn "enclave" within Bulai "pluton" (Fig. 8) and at the locality on farm Bolton next to Bulai pluton (Fig. 9). The significance of this observation is that the 2.62 Ga undeformed porphyritic granite intruded much older (~2.72 Ga) granoblastic granulites long after the stress field associated with formation of the associated isoclinal folded rocks had weakened.

Stage 2. Highly sheared 2.62 Ga porphyritic granite is in direct contact (Fig. 11) with sheared granulites associated with sheared structures such as the 2.65-2.63 Ga Ha-Tshanzi closed structure, and the N-S trending Campbell structure (Figs. 3 and 4) (Van Reenen et al., 2023). The significance of this observation is that 2.62 Ga sheared porphyritic granite intruded and inherited an existing stress field associated with a major NE-directed shear deformational event dated at 2.65-2.62 Ga. This shear deformational event controlled the exhumation and emplacement of the CZ at the mid-crustal level prior to emplacement of Bulai pluton.

D-P-T-t trajectory for the ~2.02 Ga event

D-P-T-t trajectories (Fig. 5a, b) for the final thermo-tectonic event associated with centimeter and meters wide N-S trending fabric parallel shear zones, dated at ~2.02 Ga, shows that near isobaric heating associated with a regional high-grade thermal event affected the CZ at ~2.02 Ga and was followed by decompression-cooling during final emplacement of the CZ at the upper crustal level (Van Reenen et al., 2023b).

7. Conclusions

Important aspects of the 2.72-2.02 Ga evolutionary history of the Limpopo Complex addressed during the 2024 Limpopo field workshop.

7.1. Collisional orogeny (2.65-2.62 Ga) involving the KVC (Brandt et al., 2018) versus a 2.72-2.62 Ga gravity-driven orogeny not involving the KVC and directed by the action of a rising granulite diapir emplaced underneath the CZ (Van Reenen et al., 2019).

A collisional orogeny involving the KVC versus a gravity-driven orogeny that did not involve the KVC is addressed by considering different published data.

First, the regional geological map of the LC and juxtaposed ZC and KVC (Fig. 1) shows the following: (1) the entire granulite facies terrane of the LC is enclosed within > 2.68 Ga inward-dipping high-grade crustal-scale shear zones (thrusts), the HRSZ in the south, the North Marginal Thrust in the north, and unnamed shear zones in the west (see McCourt and Vearncombe, 1992); (2) the highly complex but coherent fold- and shear deformational structural pattern of this high-grade gneiss terrane is juxtaposed against much less deformed continuous low-grade greenstone belts of the adjacent cratons; (3) juxtaposition of intensely deformed granulites with low-grade and often virtually undeformed greenschist facies rocks is best demonstrated by the GGB (Fig. 1). Here, quartz-sericite schist and undeformed pillow lava and conglomerate outcrop a few hundred meters south of the HRSZ (e.g., McCourt and Van Reenen, 1992; Kramers et al., 2014).

Second, structural-geological, metamorphic, and geochronological evidence that greenstone belts of the KVC participated in the 2.72-2.69 Ga Limpopo orogeny is restricted to narrow hot-iron-zones developed in direct contact with the northern portions of the GGB and RGB. There is no evidence that the rest of the KVC participated in a continent-continent collision orogeny at 2.65-2.62 Ga, or in transpressional orogeny at ~2 Ga (Brandt et al., 2018).

7.2. Transpressional orogeny (~2.02 Ga) associated with thrust tectonics (Brandt et al., 2018) versus a regional thermal overprint not associated with deformation or with new metamorphic mineral growth.

This issue is addressed by considering the following:

- Mostly undeformed Matok porphyritic granite intruded the SMZ at ~2.68 Ga, while the mainly undeformed Bulai granitic pluton intruded the CZ at ~2.62 Ga.

- Mostly undeformed Singelele-type anatectic grantoid intrude deformed and metamorphosed CZ paragneisses at ~2.72- 2.62 Ga.
- Post-tectonic sub-volcanic Palmietfontein-type granitic dikes and small granitic plutons intruded the SMZ at ~2.46 Ga.
- Rb-Sr biotite/phlogopite ages of ~2.0 Ga derived from paragneisses (including metapelitic granulite) and from deformed and undeformed granites and orthogneisses in the CZ, SMZ, are also recorded in the KVC up to the MGB (Barton and Van Reenen, 1992a).
- Absence of evidence for thrust tectonics in the CZ apart from the >2.65 Ga dip-slip bounding shear zones (thrusts) in contact with the KVC and ZC. The remainder of the LC is characterized by steep to moderate (>40º) dipping gneissic fabrics of high-grade gneisses associated with steeply plunging isoclinal folds and steep shear zones (Fig. 3).
- Evidence for thermo-tectonic activity at ~2.02 Ga is restricted to narrow fabric parallel shear zones that overprint Early Neoarchean shear zones (Fig. 3), including: (1) discreet cm-meters sized N-S trending shear zones in the CZ dated at ~2.02 Ga, (2) NE-SW-trending mylonitic shear zones (including the Palala shear zone) that overprint the TSZ that bounds the CZ in the south, and (3) fabric-parallel mylonitic shear zones that overprint the NE-SW trending HRSZ and N'Thabalala shear zones in the SMZ.

7.3. Conflicting interpretation of age data derived from polymetamorphic paragneisses versus intrusive granitoids.

Data that highlights the conflicting interpretation of U-Pb zircon ages of ~2.02 Ga derived from polymetamorphic paragneisses (e.g. Kröner et al., 2018) versus U-Pb zircon/monazite ages of ~2.62 Ga derived from intrusive granitoids.

- Undeformed ~2.62 Ga Bulai porphyritic granite that intrudes intensely deformed and steeply dipping polymetamorphic CZ granulites (e.g., Fig. 9) with metamorphic ages of ~2.02 Ga. This data strongly questions the proposal that the 2.02 Ga age is linked to a transpressional orogeny supposedly associated with thrust tectonics (Brandt et al., 2018) for which there are no evidence for in the CZ.
- Age data obtained from polymetamorphic metapelitic granulites (samples TOV13 and LP1911) with complex reaction textures from the same locality in the western limb of Ha-Tshanzi closed structure. Sample LP1911: U-Pb zircon age of ~2.02 Ga (Safonov et al., 2022); sample TOV13: PbSL Grt age of 1956±190 Ma (MSWD = 1450) (Van Reenen et al., 2008). The highly inaccurate garnet age has been interpreted to reflect evidence for different generations of garnet in the same thin section of a polymetamorphic granulite (Fig. 5a). The true formation age at 2.65-2.62 Ga of all mega closed sheared structures including Ha-Tshanzi is determined by the fact that (1) they share the same kinematic elements associated with SW-plunging shear deformation (Fig. 3), and (2) that this shear deformational event has been accurately constrained at 2.65-2.62 Ga by dating intrusive granitoids associated with the Avoca closed structure (e.g. Van Reenen et al., 2008, 2019, 2023b).

8. Interactive discussion sessions.

8.1. Monday 22 July

Evening
Introduction to the field workshop (Dirk van Reenen)

8.2. Tuesday 23 July

15:00-16:30
Overview of many years of collaborative research in the SMZ and CZ of the Limpop Complex focused on controversial issues that impacted on the interpretation of data derived from this highly complex granulite facies terrane (Dirk van Reenen/Andre Smit). These issues include the
following:

- The concept of a Limpopo mobile belt (e.g., Brandt et al., 2018) versus a Limpopo metamorphic complex (e.g., Van Reenen et al., 2019, 2023a, b).
- The significance of the 2.72-2.69 Ga (Kramers et al., 2014) thermo-tectonic contact relationship of the SMZ with the granite-greenstone terrane of the KVC for which evidence is restricted to narrow hot-iron-zones developed in contact with GGB and RGB.
- The significance of conflicting interpretation of age data respectively derived from polymetamorphic paragneisses (~2.02 Ga) versus ages of > 2.62 Ga derived from anatectic granitoids that intrudes such gneisses.
- Significance of the fact that undeformed ~2.62 Ga Bulai porphyritic granite intrudes para-and orthogneisses from which metamorphic ages of ~2.02 Ga that are linked to a 2.02 Ga geotectonic event have been derived (Kröner et al., 2018).
- The significance of integrated structural-geological and regional photogeological data as first order geodynamic tools that are utilized to unravel the complex evolutionary histories of high-grade gneiss terranes versus an approach that relyies on petrological and age data derived from two small outcrop areas in the vicinity of Bulai pluton.

16:45-17:15
The essential role of high-resolution drone imaginary in resolving complex structural geological problems in poor outcrop areas of the CZ of the LC [*Martin Clark*].

19:00-20:30
Conflicting interpretation of the ~2.02 Ga U-Pb zircon/monazite SHRIMP data derived from polymetamorphic metapelitic granulites versus 2.72-2.02 Ga ages obtained from dating the products of intrusive anatectic granitoids *[Marlina Elburg and George Belyanin]*.

8.3. Wednesday 24 July

15:00-15:30

Case study of the interaction of the Rhenosterkoppies Greenstone Belt with the SMZ of the LC in contact with the north dipping HRSZ *[Toshiaki Tsunogae].*

15:45-16:15
Geotectonic implications of a U-Pb SHRIMP study of zircon from meta-quartzite of the Beit Bridge Complex of the CZ of the LC [*Toshiaki Tsunogae*].

16:30-17:15
Significance of fluid inclusion studies of high-grade metamorphic gneiss terranes and implications for P-T paths [*Jan Marten Huizenga and Alex Parker*].

16:30-17:15
Thermo-barometry, fluid regime/melting, garnet zoning/ diffusion modeling as it pertains to the high-grade gneiss terrane of the LC [*Oleg Safonov*].

Thursday 25 July

11:00-13:00
Precambrian geodynamics: quest for the missing paradigm [*Taras Gerya*].

14:30-16:00
Open discussions on achievements and outstanding issues following on many years of collaborative research in the Limpopo Complex, and the way forward.

Friday 26 July 26

Departure from Klein Bolayi Lodge at 08:30 to arrive at UJ around 15.00.

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