Geologic History of the Central Zone of the Limpopo Complex: The West Alldays Area

R. Boshoff, D. D. Van Reenen,[1] *C. A. Smit, L. L. Perchuk,*[2] *J. D. Kramers,*[3] *and R. Armstrong*[4]

Department of Geology, University of Johannesburg, P.O. Box 524, Auckland Park, 2006, Johannesburg, South Africa

ABSTRACT

New field, structural, petrologic, and age data show that tectonic styles and metamorphic histories in the West Alldays area of the Central Zone of the Limpopo Complex, southern Africa, can be linked to neo-Archean and Paleoproterozoic high-grade (granulite facies) tectonometamorphic events. The styles comprise (1) a regionally developed high-grade (S_2) gneissic fabric that evolved into a regional (D_2) system of sheath folds mapped as circular to oval-shaped structures with lineations plunging steeply to the WSW and (2) a system of mainly N-S-trending and north-verging (D_3) shear zones characterized by high-grade tectonites ("straight gneisses") with well-developed (S_3) gneissic fabrics. In the West Alldays area, the superimposition of D_3 onto the regional D_2 fold pattern produced the kilometer-scale N-S-trending Baklykraal shear zone, which, before this study, was mapped as the Baklykraal fold and interpreted as part of the regional D_2 fold pattern in the Central Zone. The Paleoproterozoic high-temperature D_3 shear event is accurately constrained to 2023 ± 11 Ma by a Pb/Pb stepwise leaching garnet date that reflects the syntectonic crystallization of a garnet-cordierite-sillimanite-biotite-quartz paragenesis formed during shearing. This tectonite records a retrograde pressure-temperature (*PT*) path from 780°C at 5.7 kbar to 600°C at 3.3 kbar. The neo-Archean age of the M_2 granulite facies metamorphism, coeval with the tight D_2 folding preserved within the Baklykraal shear zone, is evident from several garnet Pb/Pb stepwise leaching experiments that gave dates intermediate between 2000 and 2600 Ma, with large scatter in the data arrays (thus interpreted as mixed ages), and from zircon ages of protoliths of the syn-D_2 Singelele-type quartzofeldspathic gneisses. A polymetamorphic garnet-cordierite-orthopyroxene-biotite-quartz paragenesis from a D_2 outcrop within the Baklykraal shear zone records two *PT* paths: a decompression-cooling *PT* path from ~850°C at ~8.5 kbar to ~675°C at ~6 kbar at ~2600 Ma and an isobaric (6 kbar) heating event from ~675°C to ~770°C that was immediately followed by a decompression-cooling path that reflects the uplift of the high-grade rocks toward the Earth's surface (to the level of about 8–10 km). Polymetamorphic granulites that resulted from the isobaric heating event introduce new petrologic and geochronologic problems. On the basis of new data, we thus document previously unrecognized N-S-trending high-temperature shear zones and associated polymetamorphic granulites from the Central Zone of the Limpopo Complex. These shear zones developed in the Paleoproterozoic and were superimposed onto older (neo-Archean) regional fold structures. The tectonic history of the Central Zone of the Limpopo Complex is therefore characterized by two high-grade tectonometamorphic events separated by at least 550 m.yr. These data require that existing models for crust formation in the Central Zone, including those that argue for a single granulite facies event linked to an orogeny at ~2000 Ma, be reconsidered.

Online enhancements: appendix, tables.

Introduction

Precambrian high-grade metamorphic terrains occur throughout the world, and the majority of these terrains show evidence of having been affected by two high-grade events (e.g., Perchuk et al. 2006 and references therein). The problem is how these different high-grade events can be distinguished and characterized. The lack of such criteria for many

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[1] Author for correspondence; e-mail: ddvr@na.rau.ac.za.

[2] Department of Petrology, Geological Faculty, Moscow State University, Vorobievy Gory, Moscow, 119899, Russia; and Institute of Experimental Mineralogy, Russian Academy of Sciences, Chernogologvka, Moscow district, 142432, Russia.

[3] Isotope Laboratory for Geology, University of Bern, Erlachstrasse 9a, Bern, Switzerland.

[4] Research School of Earth Sciences, Australian National University, Mills Road, Canberra, 0200 Australian Capital Territory, Australia.

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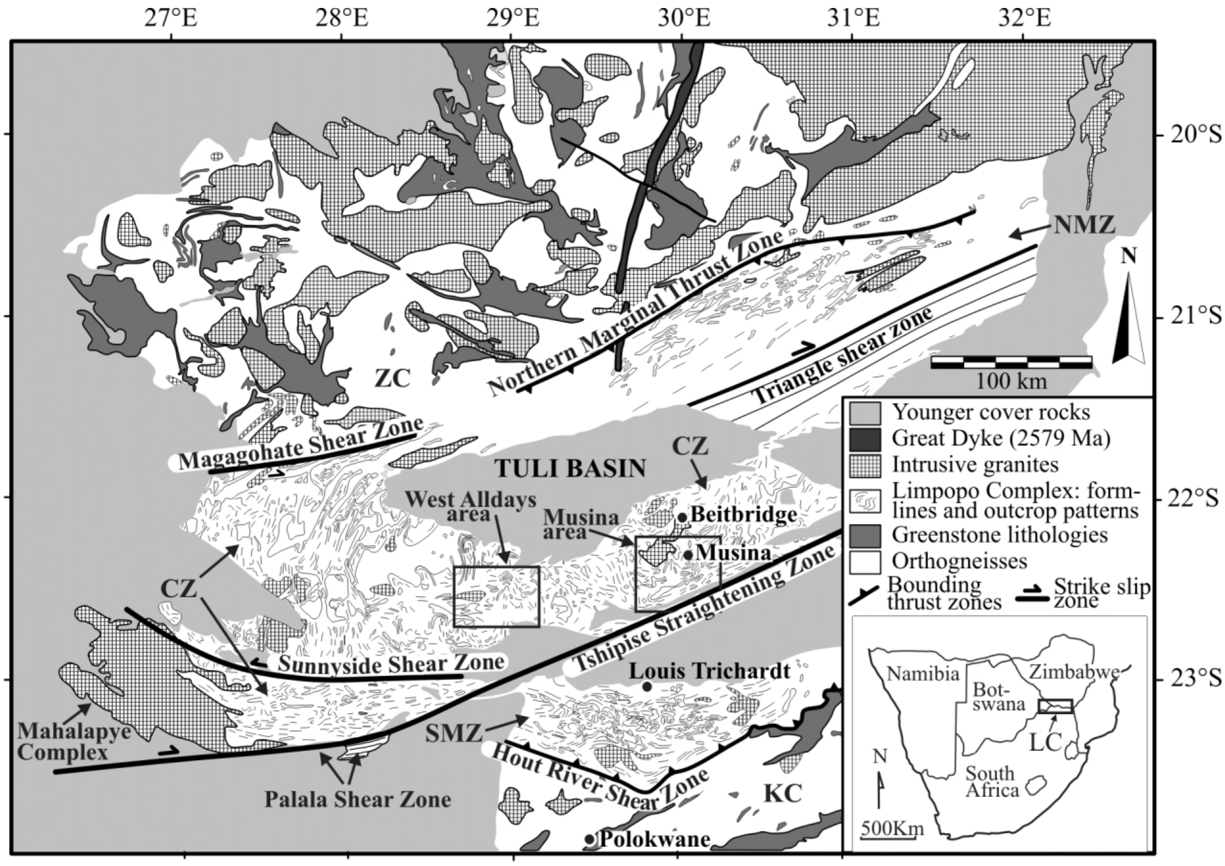


Figure 1. Sketch map of the Limpopo Complex, located between the Archean Kaapvaal (*KC*) and Zimbabwe (*ZC*) cratons. Shown is the subdivision into a Central Zone (*CZ*), which is separated from Southern (*SMZ*) and Northern (*NMZ*) Marginal Zones by strike-slip shear zones, and the major bounding shear zones. The locations of the Musina and West Alldays areas are also shown. The inset map shows the location of the Limpopo Complex (*LC*) in southern Africa. Modified after Van Reenen et al. (1990) and Boshoff (2004).

years formed the basis of numerous discussions and publications on high-grade terrains that often were incorrect, mainly because researchers relied on geochronologic and structural data without paying attention to detailed petrologic studies (e.g., Aftalion et al. 1991; Kröner et al. 1998). This article is a first attempt to demonstrate the importance of detailed petrologic studies in understanding crust formation in the high-grade terrain of the Limpopo Complex.

Geological Framework. The Limpopo Complex of southern Africa is wedged between two Archean granite-greenstone cratons (fig. 1) from which it is separated by neo-Archean inward-dipping shear zones with outward-directed sense of thrust movements (Roering et al. 1992; Kreissig et al. 2001). The high-grade gneiss terrain is further subdivided (Mason 1973; fig. 1) into three tectonic zones, namely, a Central Zone and southern and northern marginal zones that are separated from it by strike-slip shear zones that were active in the Paleoproterozoic (e.g., Schaller et al. 1999).

The complex deformational pattern of the Central Zone (Söhnge 1946) includes kilometer-scale N-S-trending foldlike structures that are oriented across the ENE trend of the Limpopo Complex (figs. 1, 2). These structures are spatially associated sheath folds (e.g., fig. 2) that are mapped as large, nearly circular structures (Roering et al. 1992). All sheath folds in the Central Zone are characterized by strongly developed gneissic foliations and penetrative mineral-stretching lineations that plunge consistently 55° to the SW. The Central Zone is bounded on the south by a major ENE-trending high-grade shear zone termed the Tshipise Straightening Zone (fig. 1; Bahnemann 1972; Watkeys 1984).

Conceptual Significance. Cratons and associated Precambrian high-grade gneiss terrains have for many years been the focus of basic geologic re-

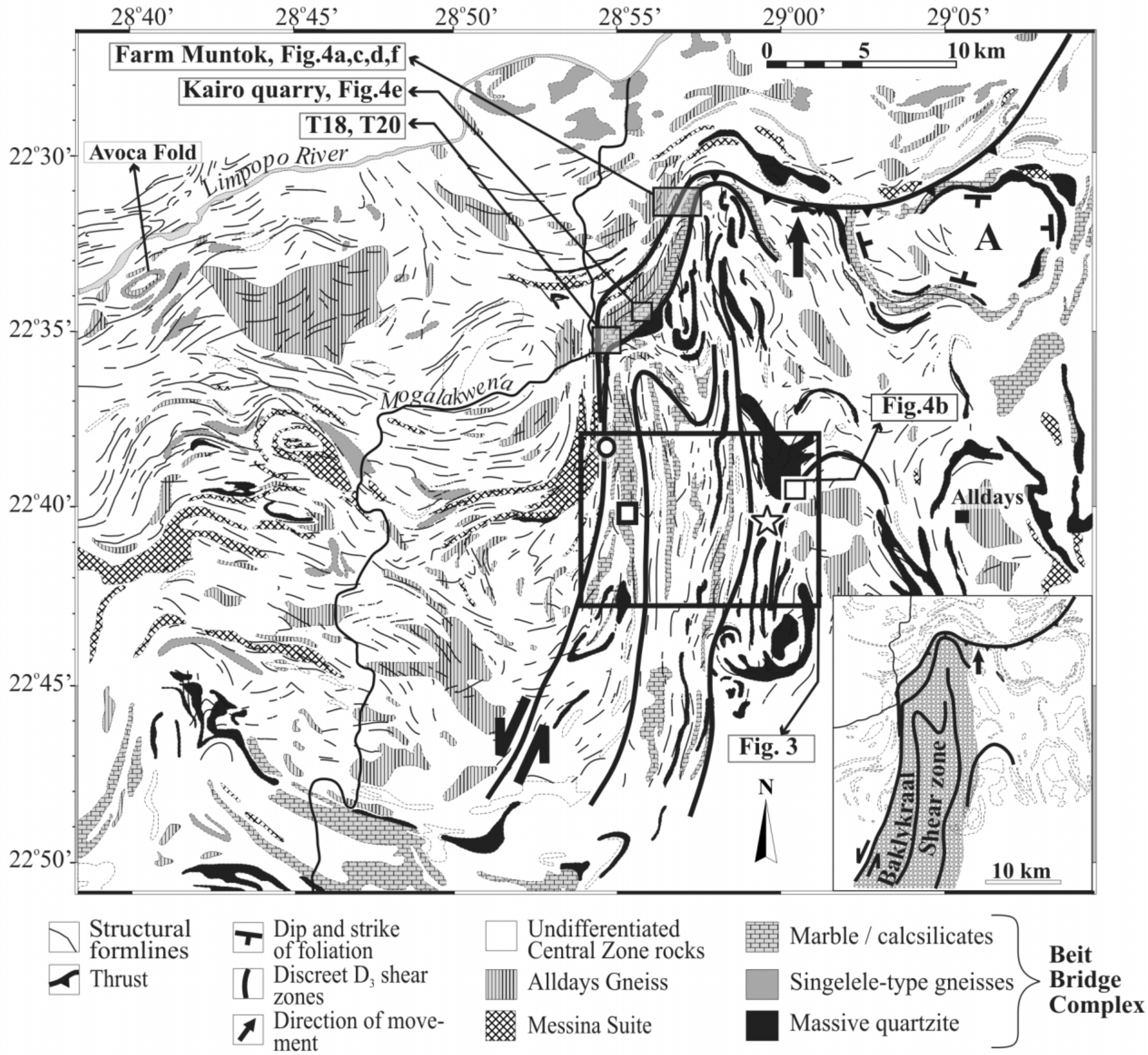


Figure 2. Geological map of the West Alldays area after the published Council for Geoscience 1 : 250,000 map (Brandl and Pretorius 2000). Bold black lines (discrete N-S- and E-W-trending shear zones) highlight the Baklykraal shear zone (see also the inset map) developed within metasedimentary rocks of the Beit Bridge Complex. The location of a large sheath fold just east of the Baklykraal shear zone is shown (*A*), as well as the locations of the photographs in figure 4 and sample localities T18 and T20. *Circle* = sample T73; *bold square* = Baklykraal quarry; *star* = sample JC1. The Avoca sheath fold is located in the northwest corner of the map.

search with the goal of understanding crust formation during the early stages of the Earth's geologic history (e.g., Vielzeuf and Vidal 1990; De Wit and Ashwal 1997). The Limpopo Complex of southern Africa is a classic example of a high-grade terrain that has drawn the continued attention of researchers (e.g., Van Reenen et al. 1992; Kramers et al. 2006) with a specific interest in this highly complex topic. This high-grade gneiss terrain comprises (fig. 1) monometamorphic marginal zones and a polymetamorphic Central Zone that displays evidence of a highly complex deformational history that extended from the neo-Archean to the Paleoproterozoic (e.g., Kramers et al. 2006). Mineral assemblages preserved in gneisses from this high-grade terrain further suggest that these rocks developed under conditions that ranged from ~950° to 550°C (Tsunogae et al. 2004; Perchuk et al. 2006).

All efforts over many years to study crust formation in the Limpopo Complex and in similar high-grade gneiss terrains from other parts of the world (Perchuk et al. 2006) have been severely hampered by a lack of consensus among different researchers concerning the nature and timing of high-grade events (e.g., Kramers et al. 2006).

Review of Previous Knowledge. The granulite facies metamorphism exposed within the Limpopo Complex (fig. 1) has for a long time been interpreted as the result of a neo-Archean continent-continent collision at ~2600 Ma between the Kaapvaal and Zimbabwe cratons (e.g., Van Reenen et al. 1987, 1990; Roering et al. 1992; Treloar et al. 1992). De Wit et al. (1992) suggested that this "Limpopo Orogeny" marked the final stages of the formation of a southern African Archean continent.

Different researchers agree that the two marginal zones were formed in the neo-Archean (Kreissig et al. 2001; Blenkinsop et al. 2004) but disagree on the nature and timing of high-grade events that affected the Central Zone. Kröner et al. (1998, 1999) were among the first who tried to distinguish different major tectonometamorphic events that might have affected the Central Zone on the basis of detailed structural studies and single-grain zircon geochronology. They concluded that the first event, termed "D_1/M_1," occurred at ~3300 Ma. These rocks were subsequently deformed at ~2600 Ma during a major deformation event (D_2) that was accompanied not by high-grade metamorphism but by limited partial melting. According to these authors, the peak of metamorphism in the Central Zone occurred in the Paleoproterozoic at ~2000 Ga during a high-grade event that was not accompanied by regional deformation. Other researchers (e.g., Barton et al. 1994; Kamber et al. 1995; Holzer et al. 1998, 1999; Schaller et al. 1999), mainly on the basis of a large single-phase Pb-Pb stepwise-leaching age database involving metamorphic minerals such as garnet, titanite, and sillimanite from various paragneisses, strongly believe that the Central Zone was affected by a single high-grade tectonometamorphic event in the Paleoproterozoic at ~2000 Ma. Holzer et al. (1998) have not discussed the neo-Archaean granulite facies event in the Central Zone and its possible causes in detail, but they see it as mainly thermal in nature and have argued that field relationships associated with this mainly thermal event were largely disrupted by the intense Paleoproterozoic overprint (Schaller et al. 1999). The proposal for a single Paleoproterozoic high-grade event is strongly supported by recent publications (e.g., Buick et al. 2003; Zeh et al. 2005) in which it is stated that there is no unequivocal evidence for a high-grade metamorphic event in the Central Zone before ~2000 Ma.

In contrast, other authors (e.g., Van Reenen et al. 1990; Barton and Van Reenen 1992; Roering et al. 1992; McCourt and Armstrong 1998) view the neo-Archean event as the true Limpopo Orogeny. McCourt and Armstrong (1998) regarded the ~2000-Ma mineral ages (and thus the Paleoproterozoic event) as dating metamorphism during reworking of neo-Archean shear zones that bound the Central Zone.

This Study. We integrate new field, structural, and isotopic data with petrologic data and show that distinct fabric-forming events and pressure-temperature (*PT*)-time paths can be accurately linked to distinct major structural features in the Central Zone of the Limpopo Complex. This approach demonstrates for the first time that crust formation in the Central Zone of this high-grade terrain is linked to two distinct high-grade (granulite facies) tectonometamorphic events: (1) a regional neo-Archean fold-dominated event, here termed "D_2/M_2," that characteristically includes sheath folds (Roering et al. 1992) and (2) a Paleoproterozoic shear-dominated event that is reflected by the presence of major N-S-trending foldlike structures that include the D_3/M_3 Baklykraal structure in the West Alldays area (figs. 1, 2). This structure was previously mapped as the N-S-trending Baklykraal fold and interpreted as part of the regional fold pattern of the Central Zone. The D_1/M_1 event is not further discussed because evidence for this event is restricted to pavement outcrops of the ~3340-Ma Sand River gneisses exposed in the Sand River near Musina (e.g., Kröner et al. 1998, 1999).

Geology

Introduction. The Central Zone in the West Alldays area (fig. 2) comprises rocks of the Beit Bridge Complex, the Messina Suite, and the Alldays Gneiss Suite (Brandl and Pretorius 2000; Van Reenen et al. 2004). The Beit Bridge Complex mainly consists of massive metaquartzite and magnetite quartzite, marble and calc-silicates, mafic gneisses, pinkish garnet-bearing quartzofeldspathic gneisses, garnet-bearing paragneisses, and relatively rare layers of metapelitic gneisses. The pinkish garnet-bearing quartzofeldspathic gneisses closely associated with rocks of the Beit Bridge Complex are correlated with the Singelele-type gneiss in the Musina area (fig. 1; Söhnge 1946; Bahnemann 1972; Fripp et al. 1979; Watkeys 1984). The term "Singelele-type gneiss" has also been widely applied to garnet-free quartzofeldspathic gneisses throughout the Central Zone that are not spatially associated with the Beit Bridge Complex (e.g., fig. 2). Zircon U-Pb dating of different structural varieties of the Singelele-type gneiss, within which the Avoca sheath fold is developed (fig. 2), yield precise U-Pb zircon ages that vary between ~2620 and ~2650 Ma (Boshoff 2004; Boshoff et al. 2006), compatible with ages obtained from Singelele-type gneisses in the Musina area (e.g., Kröner et al. 1999). These ages are interpreted as dating the crystallization of igneous protoliths to the respective quartzofeldspathic gneiss units, implying an anatectic origin for them and thereby a long-lasting period of high-grade metamorphism in the neo-Archean (Kramers et al. 2006).

Gray orthogneisses of broadly tonalitic, trondhjemitic, and granodioritic (TTG) compositions (fig. 2) have been termed the "Alldays Gneiss" (Brandl and Pretorius 2000). The Alldays Gneiss intruded rocks of the Beit Bridge Complex, consists of variable amounts of plagioclase, quartz, biotite, hornblende, and minor K-feldspar, and has yielded zircon ages between 2600 and 2660 Ma (e.g., Kröner et al. 1999), broadly similar to those of the Singelele-type gneisses. Orthogneisses of the Messina Suite, principally consisting of anorthositic and leucogabbroic gneisses (fig. 2) were emplaced at 3153 ± 47 Ma (Rb-Sr whole-rock isochron of 20 samples; Barton et al. 1979).

Regional Structure. The Central Zone in the West Alldays area (figs. 1, 2) displays the complex regional D_2 deformation pattern that characterizes much of the Central Zone in South Africa (Pienaar 1985; Brandl and Pretorius 2000). This map pattern includes the major N-S-trending foldlike structure termed the "Baklykraal structure" (Pienaar 1985; Van Reenen et al. 2004) as well as large, nearly circular structures, such as the Avoca sheath fold located in the northwest corner of figure 2 and a similar structure located just northeast of the Baklykraal shear zone (labeled "*A*" in fig. 2).

Pienaar (1985) interpreted the Avoca fold (fig. 2) as a structural dome and the Baklykraal structure, developed in metasedimentary rocks of the Beit Bridge Complex, as a N-S-trending isoclinal fold with steeply dipping limbs and a subhorizontal axis. Roering et al. (1992) subsequently showed that the oval map-shaped Avoca structure was not a structural dome but a sheath fold characterized by a well-developed gneissic foliation and a long axis plunging 55° to the SW. The SW-plunging long axis is also defined by ubiquitous mineral-stretching lineations. The same authors also showed that similarly shaped folds in the Musina area, located more than 120 km to the east (fig. 1), have identical fold geometries.

Feldtmann (1996) remapped a small area in the western part of the Baklykraal structure that includes the Baklykraal quarry (fig. 2) in which marble and calc-silicate rocks are exposed. That study confirmed both the nearly vertical regional fabric of the Baklykraal structure and the nearly horizontally oriented nature of all linear structural elements (e.g., mineral lineations and the long axis of cigar-shaped boudins).

Van Reenen et al. (2004) recently discussed the metamorphic evolution of highly sheared garnet-cordierite-sillimanite–bearing metapelitic gneisses from the western part of the Baklykraal structure (fig. 2) and showed that these gneisses record a high-temperature decompression-cooling *PT* path from 780°C at 5.7 kbar to 600°C at 3.3 kbar. Boshoff (2004) dated garnet from a highly sheared sample at ~2000 Ma based on the Pb-Pb stepwise leaching method. Our study was undertaken to further document the nature and significance of this ~2000-Ma high-temperature shear deformation event in the Central Zone of the Limpopo Complex.

The Baklykraal Structure

Introduction. The published geological map of the West Alldays area (Brandl and Pretorius 2000) shows the Baklykraal structure (fig. 2) as a prominent, N-S-trending, linear outcrop pattern defined by bands of metaquartzite, marble, calc-silicate gneiss, mafic gneiss, and garnet-biotite gneiss of the Beit Bridge Complex. This outcrop pattern is in sharp contrast to the mainly E-W structural trend and associated sheath folds of the Messina Suite and the Singelele and Alldays gneisses to the west, north, and east, respectively (fig. 2). In addition to the difference in outcrop pattern, the N-S-trending Baklykraal structure is characterized by intense fabric development comprising a subvertical foliation and a subhorizontal mineral elongation lineation. Our interpretation of the outcrop pattern and deformation fabrics is that the Baklykraal structure is a high-grade ductile shear zone, and hence it is hereafter referred to as the "Baklykraal shear zone."

Highly sheared marble and calc-silicate gneisses with fabric-parallel megalenses of mafic gneiss characterize the central and western parts of the shear zone (fig. 3). The discordant relationship of the early D_2 gneissic fabric preserved within these lenses with the younger D_3 shear fabric is demonstrated in figure 4*a*. The northern part of the Baklykraal shear zone is dominated by kilometer-scale N-S-trending lenses of metaquartzite (fig. 2) wrapped by highly sheared marble and calc-silicate

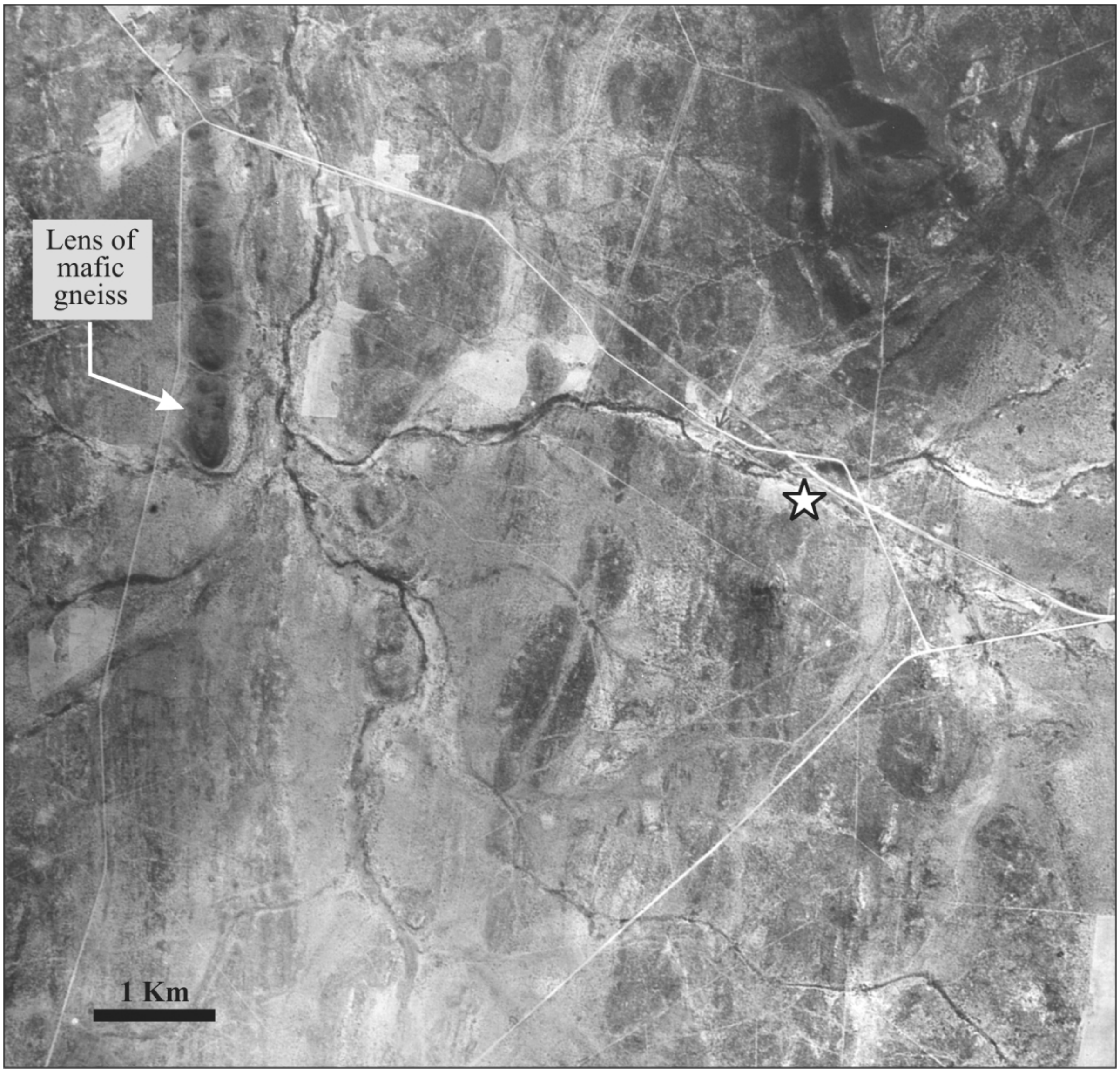


Figure 3. Aerial photograph (1 : 12,500) of the southern part of the Baklykraal shear zone (fig. 2). This photograph highlights the presence of N-S-trending shear zones expressed within marble and calc-silicate gneisses. Note the presence of megascale fabric-parallel lenses of mafic gneiss within the sheared fabric and the presence of a large folded D_2 outcrop of massive metaquartzite in the NE corner that is wrapped by the D_3 shear fabric. *Star* = location of sample JC1.

gneisses. The eastern part is characterized by a discrete shear zone (fig. 4*b*) that wraps the kilometer-scale outcrops of metaquartzite that define an older fold pattern, interpreted as D_2 (figs. 2, 3).

***D_3* Shear System.** Different structural patterns can be recognized within the Baklykraal shear zone (figs. 2, 3). (1) The western part of the shear zone is a prominent, N-S-trending, nearly vertical strike-slip structure (fig. 2; fig. 4*c*–4*e*). Reorientation of the D_2 gneissic fabric of rocks of the Messina Suite into the shear zone indicates a sinistral displacement and a N-S movement direction (fig. 2). (2) In the north, the N-S-trending, nearly vertical foliation of the shear zone changes strike to an E-W orientation where it deviates around more competent blocks of Alldays and Singelele-type gneiss (fig. 2). As a result, the shear zone changes attitude to become south-dipping and subhorizontal (figs. 4*f*, 5*a*). (3) A younger age for the Baklykraal shear zone is confirmed by the truncation of the D_2 sheath fold (*A* in fig. 2) by the E-W-trending shear fabric.

Structural measurements taken from sheared rocks throughout the Baklykraal shear zone (fig. 5*a*) show that the N-S-trending structures are nearly vertical ductile shear zones with a nearly horizontal sense of movement (e.g., fig. 4*c*–4*e*; *A* in fig. 5*a*). Structural measurements taken from the northern parts of the Baklykraal shear zone (fig. 4*f*; *B*, *C* in fig. 5*a*) show that the foliation defining the shear zone changes orientation from N-S and subvertical to NE-SW-striking and SE-dipping. It is important to note that this SE-dipping foliation is still characterized by an oblique, shallow, south-plunging lineation (fig. 4*f*) such that the overall movement direction to the north along the shear zone remains the same (fig. 5*a*). The N-S subvertically oriented and E-W subhorizontally oriented foliations thus are strike-slip and dip-slip components of the same shear zone (frontal and lateral ramp portions). This observation excludes the possibility of the D_3 shear plane being folded. Apparent fold closures reflected by the map pattern (fig. 2) resulted in the previous interpretation (Pienaar 1985; Van Reenen et al. 2004) of this major shear zone being a N-S-trending fold (fig. 2).

D_2 Fold Event. Completely unsheared outcrops of massive metaquartzite partly or completely wrapped by D_3 shear zones within the northern and eastern part of the Baklykraal shear zone preserve evidence of an older fold event, termed "D_2." The large folded outcrop of metaquartzite in the eastern part of the shear zone is closely associated with outcrops of completely unsheared paragneiss and garnet-bearing Singelele-type gneiss (figs. 2, 6). The paragneiss has a banded gneissic fabric (fig. 6*a*) and moderately plunging lineation (fig. 6*b*), similar to the regional S_2 foliation and moderately plunging lineations developed in high-grade gneisses external to the Baklykraal shear zone (Pienaar 1985; Brandl and Pretorius 2000). Precursors to the Singelele-type gneiss were emplaced during the D_2 deformation event and often show cuspate contact relationships with the closely associated paragneisses (fig. 6*c*). Slivers of paragneissic gneiss within the Singelele-type gneiss confirm an intrusive relationship (fig. 6*d*). Similar relationships involving Singelele-type gneisses and paragneisses in the Musina area (fig. 1) have also been interpreted (Hofmann et al. 1998; Kröner et al. 1998, 1999) as reflecting the main neo-Archean D_2 deformation event.

Structural measurements of linear elements taken from D_2 outcrops within the Baklykraal shear zone are plotted in figure 5*b*. That figure shows the scatter of D_2 lineations and D_2 fold axis that show no relationship with the D_3 elements. The average linear elements measured from D_2 sheath folds that occur throughout the cross-folded Central Zone (*X* in fig. 5*b*; Roering et al. 1992) also differ markedly from the D_2 structural elements measured from outcrops within the Baklykraal shear zone and from the mean linear element population measured from D_3 shear zones (*Y* in fig. 5*b*). The scatter of D_2 structural data plotted on figure 5*b* is to be expected, given the fact that these older dismembered fold closures should reflect varying degrees of rotation during the superimposed D_3 shear event.

M_3 Metamorphic Event. Van Reenen et al. (2004) discussed the metamorphic evolution of three highly sheared metapelitic gneisses (T18, T20, and T73; fig. 2) sampled from the N-S-trending shear zone in the west (fig. 2). Their study showed that the mineral paragenesis of garnet-cordierite-sillimanite-biotite-quartz that defines the D_3 shear fabric was produced by synkinematic crystallization and documents a single decompression-cooling *PT* path that traverses from 780°C at 5.7 kbar to 600°C at 3.3 kbar (fig. 7, path *C*). The three straight gneisses (Smit and Van Reenen 1997; Smit et al. 2001) studied in detail by Van Reenen et al. (2004) thus preserve no petrographic evidence of earlier fabrics or petrographic and petrologic evidence of earlier relict minerals (Van Reenen et al. 2004). The studied gneisses document the complete reworking of D_2/M_2 gneisses as the result of the superimposed D_3 shear deformational event. The *PT* path on figure 7 (path *C*) reflects this dynamic process.

M_2 Metamorphic Event. Evidence for an early high-grade metamorphic event is demonstrated by the completely unsheared outcrops (fig. 6) of garnet-bearing Singelele-type gneiss (sample RB38), together with lesser amounts of garnet-biotite gneiss (sample RB1) and, rarely, massive metapelitic gneiss (sample JC1) that occur just south of the large folded (D_2) outcrops of metaquartzite in the eastern part of the Baklykraal shear zone (fig. 2).

Sample JC1 is composed of garnet-orthopyroxene/sillimanite-cordierite-biotite-quartz-plagioclase, with no K-feldspar. The massive melanocratic rock has a granoblastic texture and is characterized by the complete absence of leucosomes, which are commonly developed within most gneissic rocks in the west Alldays area (fig. 6*a*, 6*b*). The complete absence of leucosomes suggests that sample JC1 represents a restite formed after separation of a granitic melt most likely represented by the Singelele-

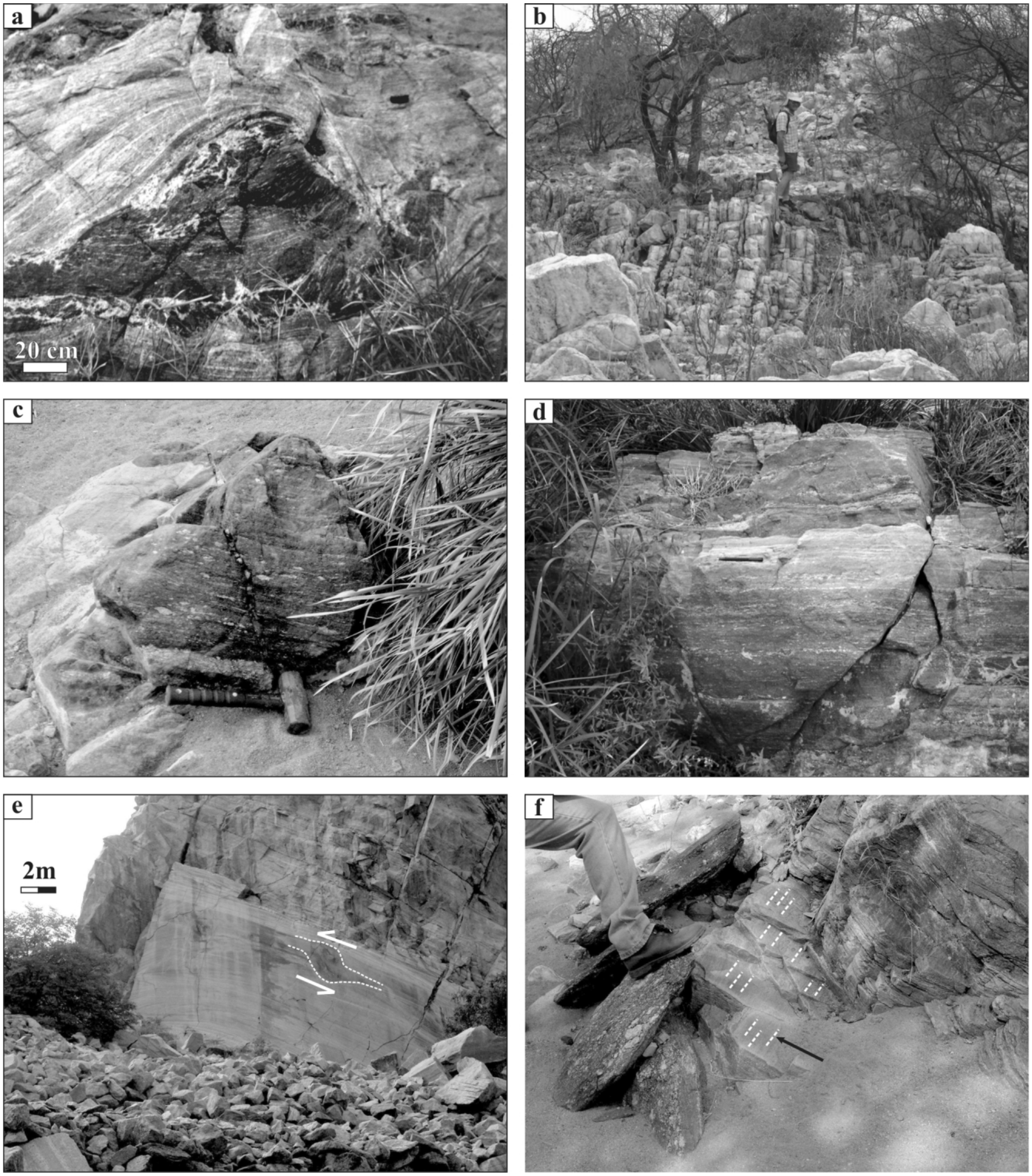


Figure 4. Examples of the D_3 shear fabric. The locations of the photographs are shown on figure 2. *a*, Mafic lens in sheared Alldays gneiss. Note the discordant relationship of the gneissic fabric (D_2) of the mafic lens and the shear fabric (D_3) of the Alldays gneiss. View is toward the east. *b*, Highly sheared metaquartzite from a shear zone that wraps the large folded outcrop of metaquartzite near the eastern contact of the shear zone (fig. 2). View is toward the south. *c*, N-S-trending, nearly vertical shear fabric with nearly horizontal lineations developed within a garnet-biotite paragneiss. Winged feldspar porphyroblasts suggest a sinistral sense of movement along the shear plane. View is toward the east. *d*, N-S-trending, nearly vertical shear fabric with nearly horizontal lineations developed within

type gneiss. Sample JC1 is highly complex and records petrographic and petrologic evidence for distinct mineral assemblages and reaction textures that reflect evidence for two high-grade metamorphic events (Perchuk 2005; Perchuk et al. 2006). The uplift of the rocks from the lower crust levels, termed "M_2," documents a retrograde decompression-cooling *PT* path (fig. 7, path *A*) from ~850°C at ~8.5 kbar to ~675°C at 6 kbar. This path is interpreted as reflecting the uplift of the high-grade rocks to midcrustal levels (Perchuk et al. 2006). In the Central Zone, rims of large garnet porphyroblasts (garnet$_2$) are being replaced by cordierite$_2$ and orthopyroxene$_2$, as is reflected by the presence of classic symplectic textures in which completely disoriented wormlike orthopyroxene$_2$ is intergrown with cordierite$_2$. This reaction texture records not only decompression cooling of the rock (e.g., Harley 1989; Perchuk 1989) but also, in some cases, evidence for a prograde reaction (Perchuk et al. 2006) that describes an isobaric (~6 kbar) *PT* path (fig. 7, path *B*) from ~675° to ~770°C. The Z-like shape of the three distinct *PT* paths shown in figure 7 has also been described for other high-temperature polymetamorphic complexes (Perchuk 2005; Perchuk et al. 2006).

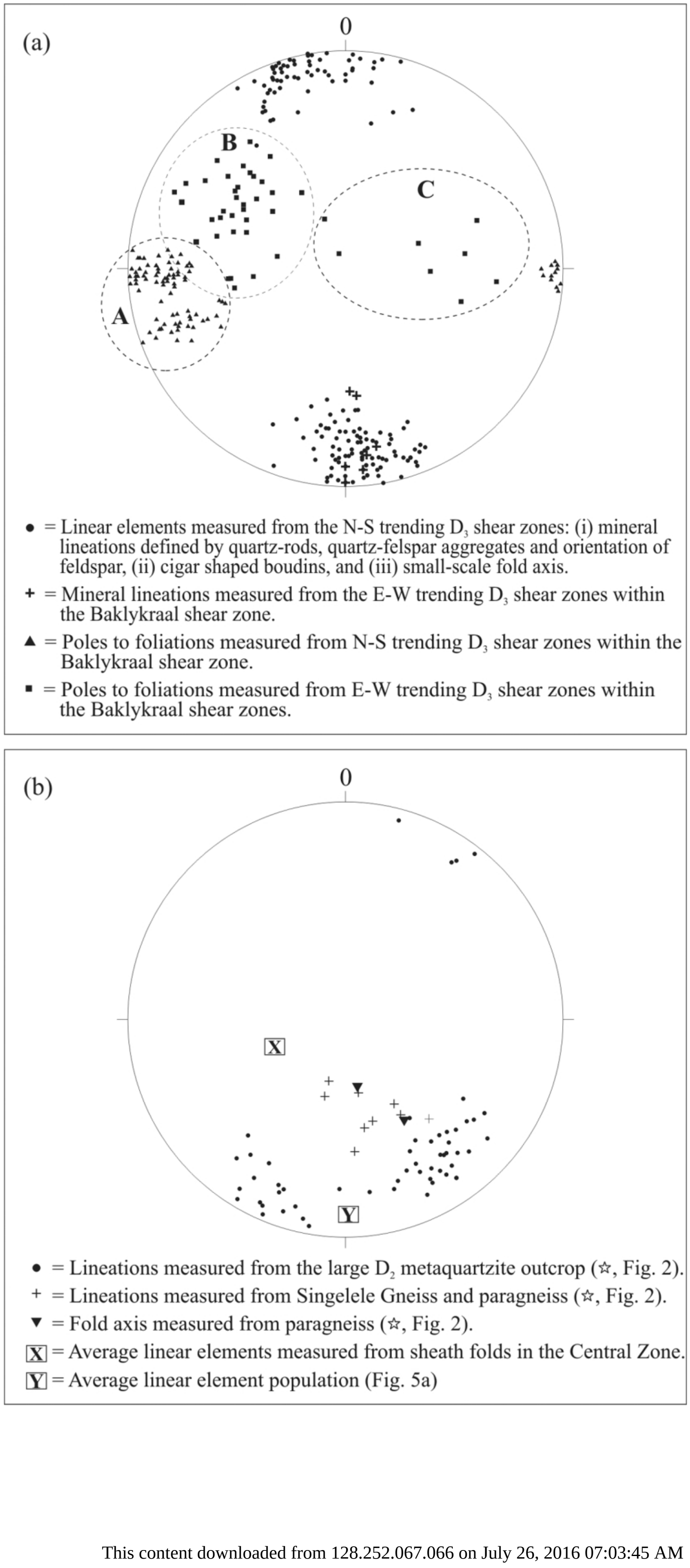
Geochronology

Introduction. Two different approaches were used to date the D_2/M_2 (fig. 7, path *A*) and D_3/M_3 (fig. 7, path *C*) tectonometamorphic events that affected the West Alldays area. First, the Pb-Pb stepwise leaching (PbSL) method developed at the University of Bern in Switzerland (Frei and Kamber 1995) was used to directly date garnet from three samples from the same outcrop area (fig. 2, *star*): samples JC1 (metapelitic gneiss), RB1 (garnet-biotite paragneiss; fig. 6*a*, 6*b*), and RB38 (garnet-bearing Singelele-type gneiss; fig. 6*c*, 6*d*). Sample T73 (sheared metapelitic gneiss) was collected from a D_3 shear zone in the western part of the Baklykraal shear zone (fig. 2, *circle*; Van Reenen et al. 2004). Second, U-Pb zircon SHRIMP data were used to date the time of crystallization of the igneous protolith to the garnet-bearing Singelele-type gneiss (sample RB38) to constrain the age of the S_2 gneissic fabric (fig. 6*c*). The techniques are described in appendix A, available in the online edition or from the *Journal of Geology* office.

PbSL Data. Garnet grains from D_2 sample JC1 are light purple and clear and contain microinclusions of mainly quartz and biotite. The results are plotted in figure 8*a* (uranogenic diagram) and figure 8*b* (thorogenic diagram) and listed in table B1 (tables B1 and B2 are available in the online edition or from the *Journal of Geology* office). The first short leaching step with 4 N HNO_3 recovered more-radiogenic Pb ($^{206}Pb/^{204}Pb \sim 39$) than steps 2 and 3, in which nearly identical Pb components were released ($^{206}Pb/^{204}Pb = 27.902$ for step 2 and $^{206}Pb/^{204}Pb = 27.924$, for step 3), after which generally increasingly radiogenic Pb was recovered from step 3 to step 5. The last step (JP1 residue) is characterized by the highest $^{206}Pb/^{204}Pb$ ratio, ~76. All stepwise leaching data define an isochron of 2094 ± 150 Ma (MSWD = 170; fig. 8*a*). Step 2 is offset from the linear array in figure 8*a*, and if this fraction is excluded, a slightly better linear correlation (MSWD = 42) defined by steps 1, 3, 4, and 5 yields an isochron date of 2120 ± 110 Ma. In the thorogenic diagram (fig. 8*b*), steps 1–4 do not reveal much, while step 5 shows a low Th/U ratio that probably points to zircon micro-inclusions in this step. The intermediate age of ~2120 Ma, between the neo-Archean and ~2000 Ma, can be explained by the presence of two (optically not resolved) generations of garnet or by incomplete site remixing, during the 2000-Ma event, of radiogenic Pb accumulated since the earlier event. The first possibility is strongly supported by the fact that JC1 is a polymetamorphic granulite with petrologic evidence for two discrete high-grade metamorphic events (fig. 7, paths *A*, *B*; Perchuk 2005; Perchuk et al. 2006). In either case, the age can be characterized as a mixed age reflecting both neo-Archean and Paleoproterozoic events; thus, the considerable scatter seen in figure 8*c* is to be expected.

D_2 sample RB1 (Boshoff 2004) is composed of large subhedral porphyroblasts of garnet occurring in a matrix composed mainly of quartz, plagioclase, and biotite. Two optically distinct generations of

calc-silicate gneisses. View is toward the west. *e*, Marble quarry on the farm Kairo. The quarry faces toward the northeast. The large rotated calc-silicate boudin (outlined in white stipples) indicates a sinistral sense of movement. *f*, Shallow, SE-dipping foliation in the northern part of the Baklykraal shear zone. The oblique, shallow, south-plunging lineations (*white stipples*) are oriented parallel to the lineations developed within N-S-trending strike-slip shear zones (*c*, *d*; fig. 5*a*). See text for discussion.



(a)
0
A
B
C
● = Linear elements measured from the N-S trending D_3 shear zones: (i) mineral lineations defined by quartz-rods, quartz-felspar aggregates and orientation of feldspar, (ii) cigar shaped boudins, and (iii) small-scale fold axis.
+ = Mineral lineations measured from the E-W trending D_3 shear zones within the Baklykraal shear zone.
▲ = Poles to foliations measured from N-S trending D_3 shear zones within the Baklykraal shear zone.
■ = Poles to foliations measured from E-W trending D_3 shear zones within the Baklykraal shear zones.
(b)
0
X
Y
● = Lineations measured from the large D_2 metaquartzite outcrop (☆, Fig. 2).
+ = Lineations measured from Singelele Gneiss and paragneiss (☆, Fig. 2).
▼ = Fold axis measured from paragneiss (☆, Fig. 2).
X = Average linear elements measured from sheath folds in the Central Zone.
Y = Average linear element population (Fig. 5a)

garnet, reflected by inclusion-rich cores with inclusion-free rims (Boshoff 2004), characterize the garnet porphyroblasts of this completely unsheared gneiss. Garnet fragments of metapelite RB1 are purple and contain micro-inclusions of quartz, biotite, and chlorite. No visible zircon inclusions (potential contaminants) are present in the garnets. Pb leaching data are plotted in figure 8*c*, 8*d* and listed in table B1. Increasingly radiogenic Pb was recovered for steps 1–4 (table B1), but the residual (step 5) yield is less radiogenic ($^{206}Pb/^{204}Pb \sim 91$) than that of leaching step 4 ($^{206}Pb/^{204}Pb \sim 340$); nevertheless, its low $^{208}Pb/^{206}Pb$ (i.e., Th/U) ratio, apparent in figure 8*d*, indicates that this Pb may be affected by zircon micro-inclusions. All steps together yield an isochron age of 2173 ± 79 Ma (fig. 8*c*), with a large MSWD value of 1150. Similar to the case of JC1, this result is interpreted as a mixed age, whereby two generations of garnet are represented by the inclusion-rich cores and the inclusion-free rims (Boshoff 2004).

D_2 sample RB38 is mainly composed of quartz, microcline perthite, and plagioclase, with garnet and biotite present in small amounts. Subhedral garnet grains are optically homogenous and often characterized by quartz inclusions that occur throughout the grains. Evidence that this rock could have experienced more than one event is suggested by the presence of two generations of biotite, namely, a greenish-brown variety that occurs as small grains in the matrix and a reddish-brown variety that is closely associated with intergrowths of fibrolite (sillimanite) with quartz that define narrow shear planes that transect the sample. The PbSL data from this sample are plotted in figure 9*a*, 9*b* and listed in table B1. The Pb released is increasingly radiogenic from step to step. The least-radiogenic Pb ($^{206}Pb/^{204}Pb \sim 81$) was released by the short leaching step 1 with 4 N HNO_3, whereas the most-radiogenic Pb ($^{206}Pb/^{204}Pb \sim 636$) was measured in the final step (step 5). This highly radiogenic Pb shows low apparent Th/U (fig. 9*b*), probably reflecting admixture of Pb from microscopic zircon inclusions. If included in the regression, it dominates the result: all PbSL data together define a date of 2443 ± 34 Ma (fig. 9*a*) with a very high MSWD value of 17,500. If step 5 is excluded, a better linear correlation results (MSWD = 230; fig. 9*b*), which yield a much younger but poorly defined regression age of 2254 ± 220 Ma. As in the above cases, this latter date is considered a mixed garnet age. The zircon micro-inclusions may be more predominantly neo-Archean in age.

The garnet grains of D_3 sample T73 are pale purple, clear, and inclusion free. Leaching protocols and analytical results are given in table B1 (see app. A). For this sample, the complete procedure was done twice, using different leaching protocols (see table B1). All leaching steps from both PbSL procedures together display a linear arrangement of data points defining an isochron of 2023 ± 11 Ma (fig. 9*c*). The residues (step 5s) are probably affected by zircon microcrysts, as shown by the low $^{208}Pb/^{206}Pb$ ratios in figure 9*d*, which reflect low Th/U ratios. Since only one generation of garnet is present in this sheared metapelite (Van Reenen et al. 2004), the date of 2023 ± 11 Ma is interpreted as the age of the high-grade shear deformational event that resulted in the formation of the N-S-trending Baklykraal D_3 shear zone.

Zircon SHRIMP Data. Thirty-eight SHRIMP U-Pb analyses were obtained on zircons from the garnet-bearing Singelele-type gneiss (sample RB38). The data are plotted on a conventional concordia diagram (fig. 10) and presented in table B2.

The data show a wide range in U (134–4524 ppm), Th (18–1235 ppm), and Th/U in these zircons (table B2). Some data plot close to the concordia, but most are significantly discordant. Two analyses (spots 1.1 and 21.1) indicate distinctly older ages (3296 ± 6.3 and 3009 ± 10 Ma, respectively) and are interpreted as representing xenocrysts. The remaining analyses are mainly intermediate between 2600 and 2000 Ma, with Pb loss apparently at ~500 Ma

Figure 5. Lower hemispherical projection of structural elements associated with the D_2 and D_3 deformational events preserved within the Baklykraal shear zone. Data obtained from Pienaar (1985), Feldtmann (1996), and this study. *a*, Subpopulation A represents poles to planes within nearly vertical N-S-trending strike-slip shear zones (fig. 2). Subpopulation B represents poles to shear planes that are trending in a northeasterly direction close to the northern part of the shear zone (fig. 2). Subpopulation C represents poles to shear planes that are trending E-W in the northern part of the Baklykraal shear zone (fig. 2). All shear planes coincide with the nearly horizontal population of lineations. See text for discussion. *b*, Linear structural elements measured from D_2 outcrops that are wrapped by D_3 shear zones within the Baklykraal shear zone (e.g., fig. 6*b*; see also the inset map). The D_2 lineations show no relationship with D_3 linear elements represented by *Y* or with D_2 lineations (*X*) associated with sheath folds external to the Baklykraal shear zone. See text for discussion.

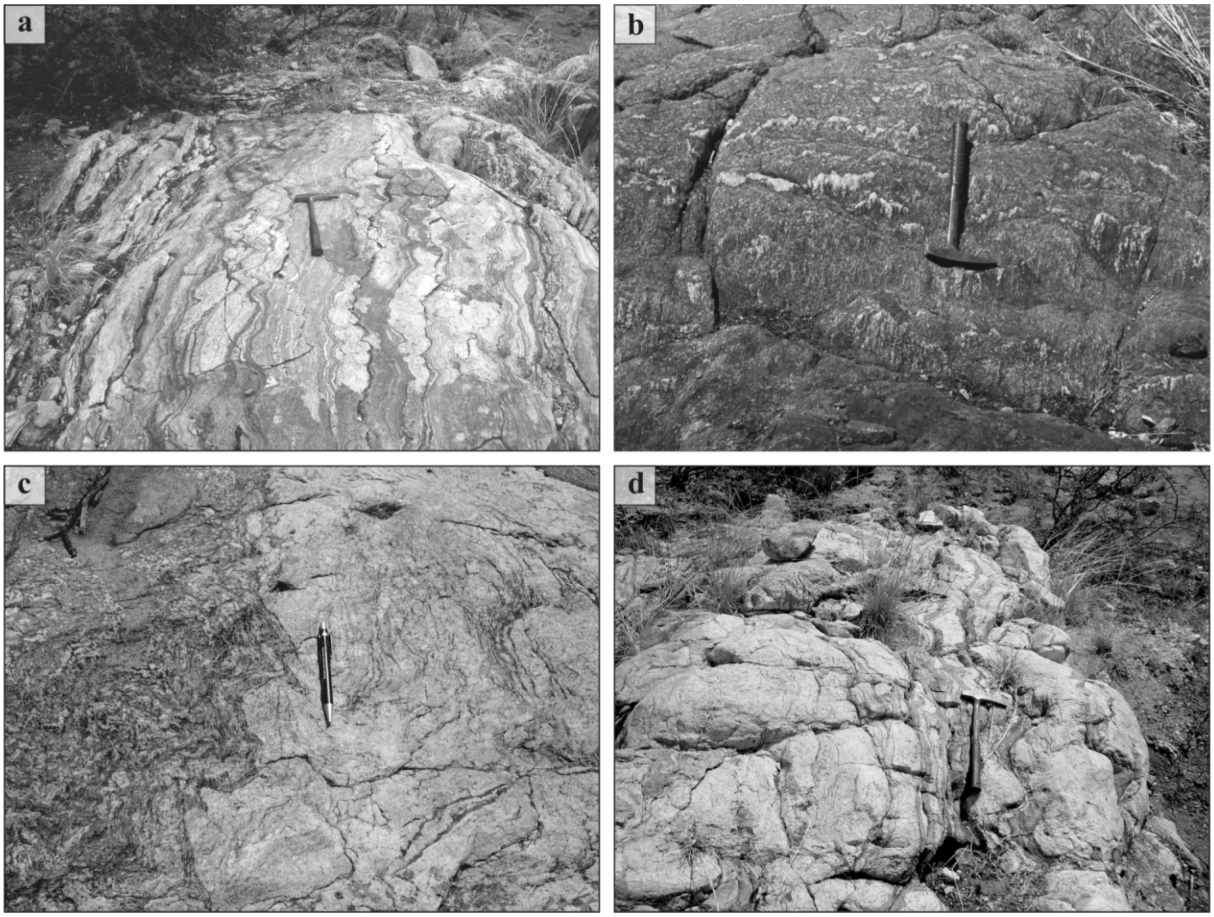


Figure 6. The D_2 gneissic outcrop preserved within the Baklykraal shear zone (fig. 2). *a*, Example of S_2 gneissic fabric developed within banded garnet-biotite paragneiss. *b*, Steeply SSW-plunging D_2 lineation associated with the S_2 gneissic fabric. Hammer is oriented parallel to the lineation. *c*, Cuspate structures developed at the contact between garnet-biotite gneiss (*left*) and Singelele-type gneiss (*right*). *d*, Slivers of garnet-biotite gneiss (*hammer*) trapped within the Singelele-type gneiss. See text for discussion.

(fig. 10*b*). In detailed zircon studies (e.g., Vavra et al. 1999), it has been shown that such intermediate, or mixed, ages are due mostly to growth of new domains, or overgrowths, during a younger metamorphic or igneous event rather than to loss of radiogenic Pb from the zircons (which occurs in weathering). The mixed-age populations, therefore, show that the second metamorphism, in this case at ~2000 Ma, was sufficiently intense to allow such renewed zircon crystallization.

Discussion

The published geological map of the West Alldays area (fig. 2) clearly reflects two distinctly different styles of deformation that, supported by field, structural, petrologic, and age data, can be linked to two distinct geologic events.

The Neo-Archean Event (D_2/M_2). The D_2 map pattern in the West Alldays area (fig. 2) comprises a regionally developed high-grade (S_2) gneissic fabric that evolved into a regional (D_2) system of sheath folds mapped as nearly circular to oval-shaped structures characterized by lineations that consistently plunge steeply WSW (Roering et al. 1992; Van Kal 2004). This event is termed "D_2/M_2." From similarities between steeply dipping structural domains in the West Alldays area and those elsewhere in the Central Zone, we consider that the D_2/M_2 event is constrained to ~2600 Ma. This is also the time of crystallization of precursors to syn- and late-tectonic Singelele-type quartzofeldspathic gneisses that accurately constrain the age

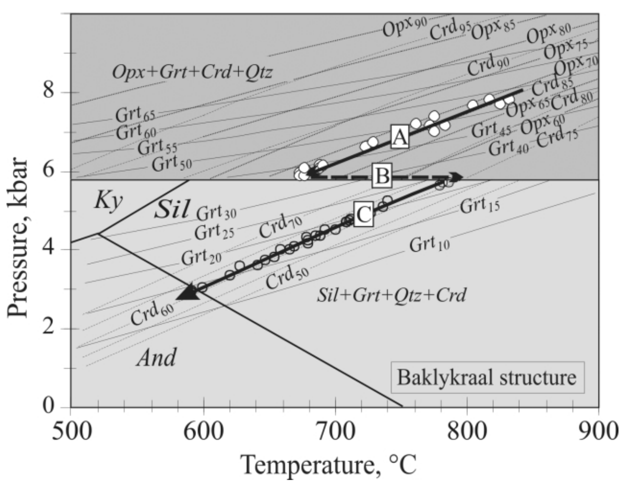


Figure 7. Integrated diagram showing *PT* paths that reflect the neo-Archean and Paleoproterozoic exhumation of the D_2/M_2 metapelitic gneisses JP1 (path *A*) and the D_3/M_3 sheared gneiss T73 (path *C*; after Perchuk et al. 2006). The diagram also shows that the minimum pressure of path *A* (~5.5 kbar) corresponds closely to the maximum pressure of path *C*. This implies that the D_2/M_2 metapelitic gneiss JP1 was overprinted by ~120°C during an isobaric heating event (path *B*) ~550 Ma after the D_2/M_2 event. Isopleths of N_{Mg} for minerals in sample JP1 (cordierite [Crd], orthopyroxene [Opx], quartz [Qtz], garnet [Grt], K-feldspar [Kfs], biotite [Bt], plagioclase [Pl], and zircon [Zrn]) are calculated for the reaction Grt + Qtz = Crd + Opx, and isopleths of NMg for minerals in sample T73 (Crd, sillimanite [Sil], Qtz, Grt, Kfs, Bt, Pl, Zrn) are calculated for the reaction $Grt_1 + Sil + Qtz \Rightarrow Crd_2$ (Van Reenen et al. 2004). Sample JP1 is from the same outcrop as sample JC1, for which Pb-Pb stepwise leaching data were obtained.

of the D_2 gneissic foliation of the Avoca sheath fold (fig. 2) to the interval between ~2651 ± 8 and ~2626 ± 5.4 Ma (Boshoff et al. 2006). Kröner et al. (1999) constrained the time of the main D_2 deformation event in the Musina area to ~2600 Ma on the basis of zircon SHRIMP age data obtained from what they interpreted as syn-D_2 Singelele-type gneisses.

A decompression-cooling *PT* path (fig. 7, path *A*) from 850°C at 8.5 kbar to 675°C at 6 kbar shows that the currently exposed surface of the Central Zone was uplifted to midcrustal levels during this neo-Archean high-grade tectonometamorphic event. Pb-Pb garnet ages determined for a metapelitic gneiss (JC1; 2094 ± 150 or 2120 ± 110 Ma), a garnet-biotite gneiss (RB1; 2173 ± 79 Ma), and a garnet-bearing Singelele-type gneiss (RB38; 2443 ± 34 or 2254 ± 220 Ma) from the same D_2 outcrops within the Baklykraal shear zone are best interpreted as representing mixed ages that reflect both a neo-Archean and a Paleoproterozoic event. This interpretation is strongly supported by the fact that polymetamorphic sample JC1 is characterized by detailed petrological studies that allow us to deduce two distinct *PT* paths (fig. 7, paths *A* and *B*).

The Paleoproterozoic Event (D_3/M_3). Our conclusion that the Baklykraal structure is a major high-grade D_3 shear zone superimposed onto the existing D_2 high-grade fold pattern of the West Alldays area is based on field, structural, metamorphic, and age data. The Baklykraal shear zone, developed mainly in metasedimentary rocks of the Beit Bridge Complex (fig. 2), is expressed as a prominent series of N-S-trending ridges within an area mainly underlain by orthogneisses that are dominated by E-W-trending structures that also include sheath folds (fig. 2). The constant shallow south-plunging lineation (fig. 5*a*) measured from both the N-S-trending strike-slip and the E-W-trending oblique-slip components (lateral and frontal ramp portions) of the Baklykraal shear zone (fig. 2) suggests an overall northward-vergent sense of thrust movement during this high-grade shear deformational event.

A decompression-cooling *PT* path that traverses from 780°C at 5.7 kbar to 600°C at 3.3 kbar (sheared sample T73; fig. 7, path *C*) reflects the uplift of the high-grade rocks of the Central Zone to the upper crustal levels during the high-grade shear event that is accurately constrained at 2023 ± 11 Ma (PbSL garnet age). The intensely sheared sample (T73) documents petrographic and petrologic evidence for complete reworking during the high-temperature shear event. This event was preceded by an isobaric (±6 kbar) heating event (from 675° to 770°C; fig. 7, path *B*) that resulted in the formation of polymetamorphic granulites not previously described in the Central Zone.

Conclusion

This study provides the following important new information that contributes to the understanding of crust formation in the Limpopo Complex:

1. The recognition of previously undocumented N-S-trending and north-verging (D_3) shear zones in the Central Zone that are characterized by high-grade tectonites ("straight gneisses") with well-developed (S_3) gneissic fabrics. In the West Alldays area, the superimposition of D_3 onto the regional D_2 fold pattern produced the kilometer-scale N-S-trending Baklykraal shear zone that, before this

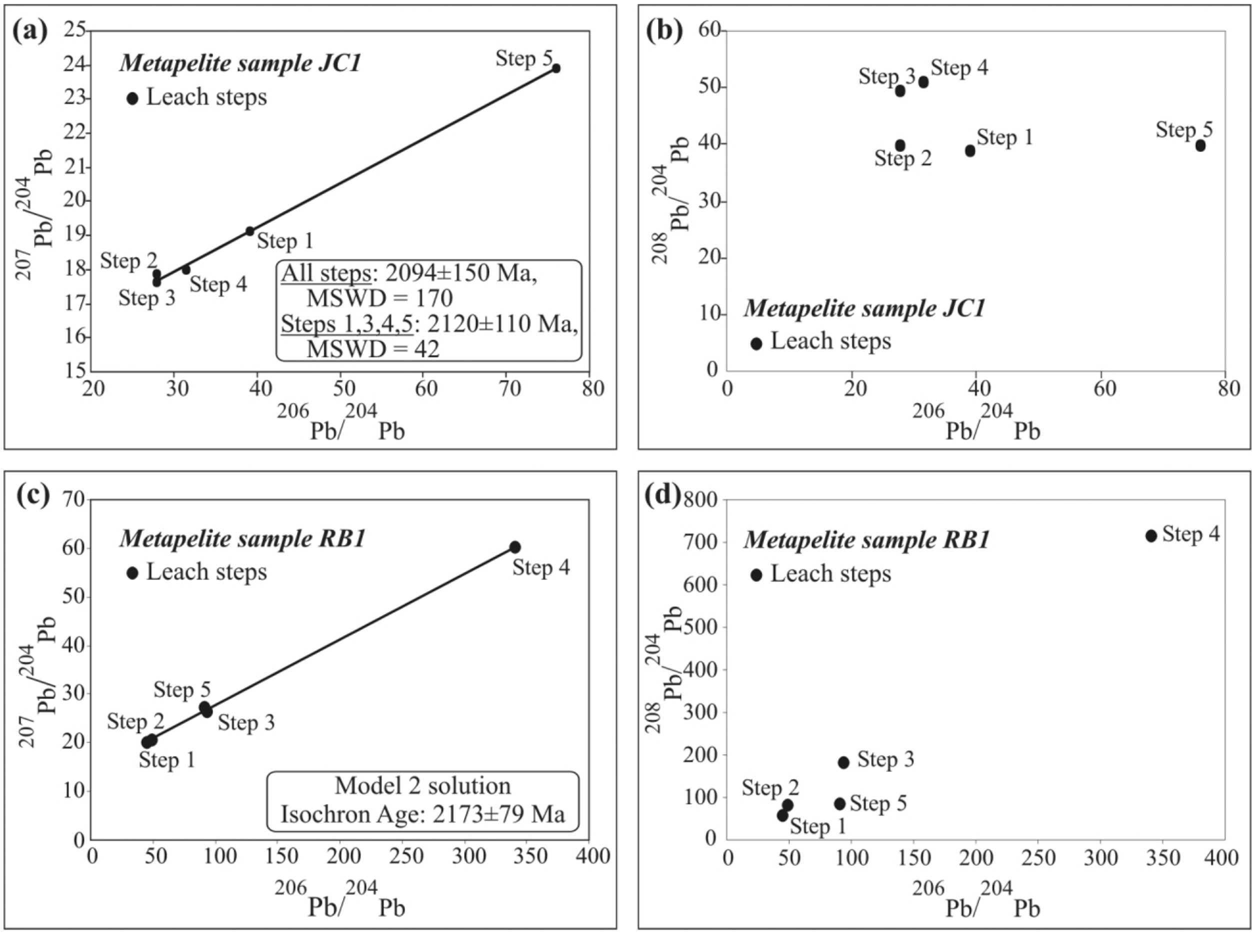


Figure 8. Pb stepwise leaching (PbSL) data of garnet from the metapelitic gneiss sample JC1 shown on (*a*) uranogenic and (*b*) thorogenic Pb isotope diagrams. An isochron age of 2120 ± 110 Ma in *a* is defined by steps 1, 3, 4, and 5, which show a better linear correlation (MSWD = 42) than all leach steps together. *b*, The arrangement of the PbSL data points indicates only minor contamination by possible zircon inclusions, as depicted by the offset of step 5. (*c*) Uranogenic and (*d*) thorogenic Pb isotope diagrams of the metapelitic gneiss sample RB1. The isochron age of 2173 ± 79 Ma in *d* includes all respective leach steps (noted in table B1) and indicates isotope equilibrium.

study, was mapped as a fold (the Baklykraal fold) and interpreted as part of the regional D_2 fold pattern in the Central Zone. The Baklykraal system of mainly N-S-trending shear zones may be linked to other large-scale ductile shear zones in the Central Zone of the Limpopo Complex (e.g., the Mahalapye, Palala, Triangle, and Tshipise shear zones) that were also active in the Paleoproterozoic (for details, see Holzer et al. 1998; Schaller et al. 1999; Kramers et al. 2006). The geometric and temporal link between these shear zones, which is a matter of some debate and the subject of our ongoing research, will be addressed in future publications.

2. New metamorphic data (Van Reenen et al. 2004; Perchuk et al. 2006) show that rocks within the Baklykraal shear zone preserve evidence for two distinct high-grade metamorphic events, reflected by three distinct *PT* paths (fig. 7, *A–C*). Two important conclusions can be drawn from these data. First, the two decompression-cooling *PT* paths (fig. 7, JC1 path *A* and T73 path *C*) reflect separate uplift stages starting from different crustal levels. Our interpretation is that the decompression-cooling *PT* path for sample JC1 (fig. 7, path *A*) reflects the uplift of the high-grade rocks from lower- to midcrustal levels during the peak metamorphic and deformational event (D_2/M_2), while the decompression-cooling *PT* path for sample T73 (fig. 7, path *C*) records the subsequent uplift of the high-grade rocks from the middle to the upper crustal levels during the D_3/M_3 shear event. Second, the maximum-pressure conditions recorded by the D_3/M_3 event

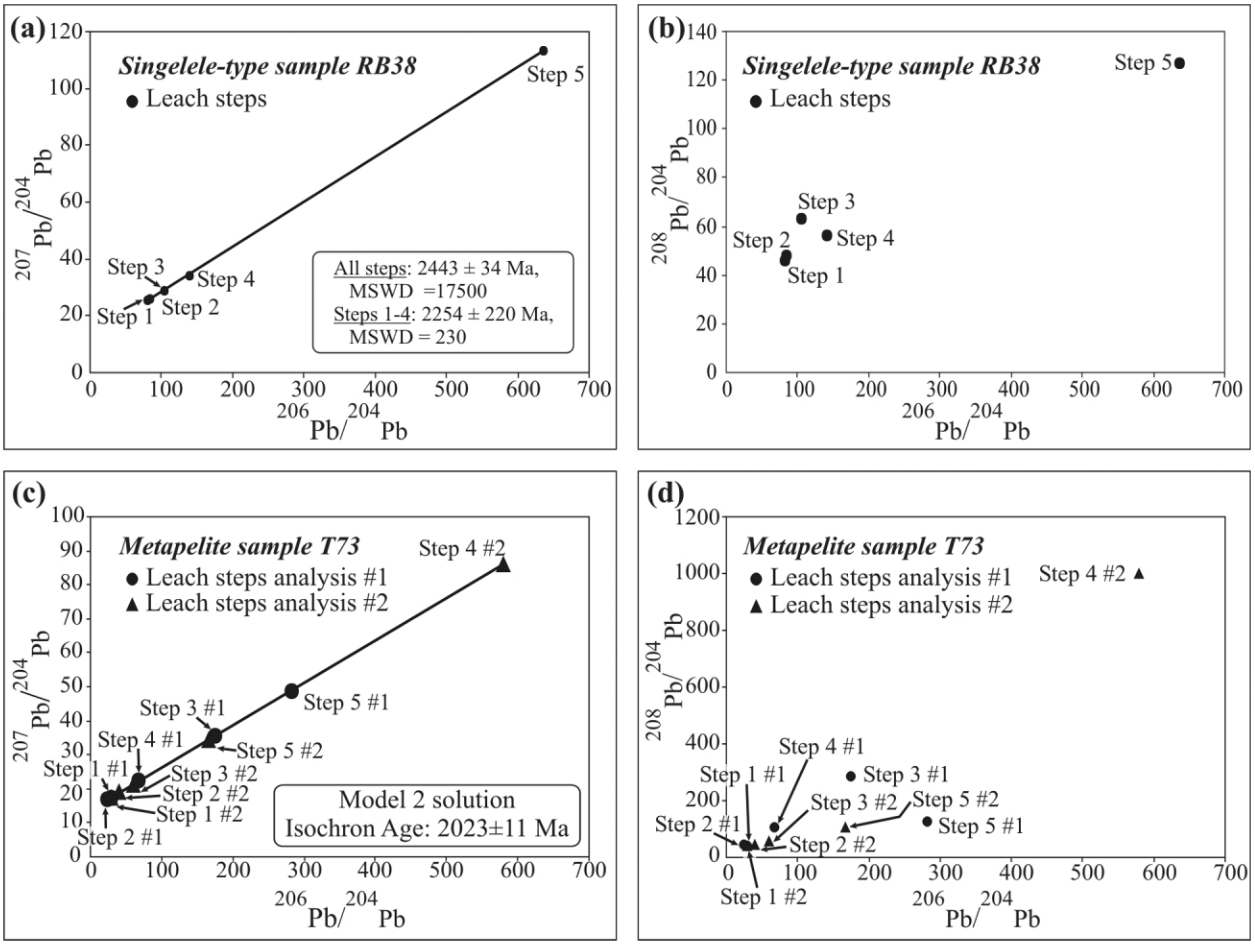


Figure 9. Pb stepwise leaching (PbSL) data of garnet from the garnet-bearing Singelele-type gneiss sample RB38 shown on (*a*) uranogenic and (*b*) thorogenic Pb isotope diagrams. An isochron age of 2254 ± 220 Ma in *a* is defined by steps 1–4, which show a better linear correlation (MSWD = 230) than all leach steps together. *b*, The arrangement of the PbSL data points indicates only minor contamination by possible zircon inclusions, as depicted by the offset of step 5. (*c*) Uranogenic and (*d*) thorogenic Pb isotope diagrams of metapelitic gneiss sample T73. The accurate isochron age of 2023 ± 11 Ma in *c*, including all respective leach steps (noted in table B1); indicates isotope equilibrium.

are exactly the same as the minimum-pressure conditions recorded by the D_2/M_2 event (compare paths *A* and *C* in fig. 7), suggesting that final uplift of the high-grade rocks was preceded by an isobaric heating event. The nearly isobaric (5–6 kbar) prograde (from 675° to 770°C) *PT* path of figure 7 (JC1 path *B*) confirms this suggestion.

3. New geochronologic data support field, structural, and metamorphic evidence for two discrete high-grade events in the West Alldays area. The PbSL leaching process yields a precise and accurate age (2023 ± 11 Ma) for garnet from a sheared (D_3) metapelitic sample, T73, that accurately reflects the syntectonic crystallization (Van Reenen et al. 2004) of a new mineral assemblage formed during the high-temperature D_3 shear event. On the other hand, all efforts to unravel precise age data from D_2 high-grade gneisses preserved within the Baklykraal shear zone proved to be unsuccessful. The PbSL of garnet (JC1, RB1, and RB38) and U-Pb zircon SHRIMP data (RB38) yield ages intermediate between ~2000 and ~2600 Ma, best interpreted as mixed ages that reflect evidence for two high-grade events. The presence of polymetamorphic granulites suggests that great care should be taken to unravel protolith and metamorphic ages from high-grade gneisses in the Central Zone of the Limpopo Complex.

The suggestion (e.g., Buick et al. 2003; Zeh et al. 2005) that the Central Zone of the Limpopo Complex preserves no unequivocal evidence for a granulite facies event before ~2000 Ma is clearly not

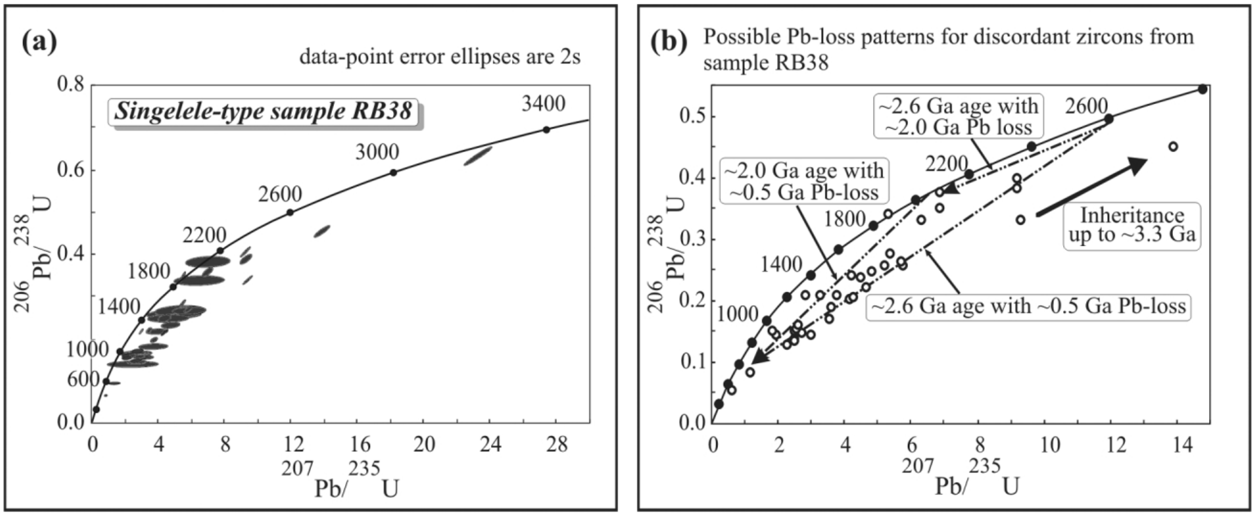


Figure 10. *a*, U-Pb concordia plot of SHRIMP analyses for the garnet-bearing Singelele-type gneiss sample RB38. *b*, Enlarged view of the U-Pb concordia plot to show the possible Pb loss patterns for the discordant zircons.

supported by our data. Published models (e.g., Roering et al. 1992; Schaller et al. 1999) for crust formation in this complexly deformed polymetamorphic high-grade gneiss terrain thus must be reinterpreted.

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