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FAST TRACK PAPER

Gravity evidence for a larger Limpopo Belt in southern Africa and geodynamic implications

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SUMMARY

The Limpopo Belt of southern Africa is a Neoarchean orogenic belt located between two older Archean provinces, the Zimbabwe craton to the north and the Kaapvaal craton to the south. Previous studies considered the Limpopo Belt to be a linearly trending east-northeast belt with a width of ~250 km and ~600 km long. We provide evidence from gravity data constrained by seismic and geochronologic data suggesting that the Limpopo Belt is much larger than previously assumed and includes the Shashe Belt in Botswana, thus defining a southward convex orogenic arc sandwiched between the two cratons. The 2 Ga Magondi orogenic belt truncates the Limpopo–Shahse Belt to the west. The northern marginal, central and southern marginal tectonic zones define a single gravity anomaly on upward continued maps, indicating that they had the same exhumation history. This interpretation requires a tectonic model involving convergence between the Kaapvaal and Zimbabwe cratons during a Neoarchean orogeny that preserved the thick cratonic keel that has been imaged in tomographic models.

Key words: craton, gravity, Limpopo Belt, southern Africa.

INTRODUCTION AND GEOLOGICAL BACKGROUND

The Limpopo Belt of southern Africa is considered to be a ~250 km wide and ~600 km long linear belt trending east-northeast (e.g. Roering *et al.* 1992; Holzer *et al.* 1999) and made of granulites exposed between the Zimbabwe craton to the north and the Kaapvaal craton to the south (Fig. 1). On the basis of structural, lithological and metamorphic arguments (e.g. McCourt & Vearncombe 1992), the Belt has been divided into three tectonic domains bounded by ductile shear zones: Northern Marginal Zone (NMZ), Central Zone (CZ) and Southern Marginal Zone (SMZ). The SMZ is exposed in South Africa and is predominantly made of tonalite-trondhjemite-granite assemblages and granulites. The NMZ lies mainly in Zimbabwe and comprises granulite-facies gneisses and charnockites. Supracrustal metasedimentary assemblages represent a minor lithological component in the marginal zones but are more prominent in the central zone. The CZ assemblages, which are mainly granodioritic to granitic gneisses, tonalite-trondhjemite-granites and metamorphosed mafic and ultramafic rocks, are complexly folded and most structures cannot be traced across the bounding shear zones into the adjacent marginal zones.

The relationship between the Limpopo Belt and the adjacent medium-grade terrane named the ‘Shashe Belt’ in NE Botswana is unknown, although Bennet (1970) suggested that there is a gradual metamorphic transition between them. The Shashe Belt is a northwest-southeast-trending structure located northwest of the Magogaphate shear zone (Fig. 1). It is made of tonalite-trondhjemite-granites and related orthogneisses, migmatites and supracrustal meta-sedimentary assemblages, metamorphosed mafic and ultramafic rocks, and metavolcanic rocks affected by greenschist to amphibolite facies metamorphism (Aldiss 1991). The absence of granulite facies assemblage in the Shashe Belt, coupled with its northwest-southeast trend, has resulted in its exclusion as part of the Limpopo Belt. Information on the regional subsurface structures to constrain these relationships has not previously been available. Other arguments supporting a linear shape of the Limpopo Belt include aeromagnetic data displaying a consistent NE–SW trend for the Magogaphate shear zone (Fig. 1), inferred to be the northern boundary of the Limpopo Belt in Botswana (e.g. Key & Hutton

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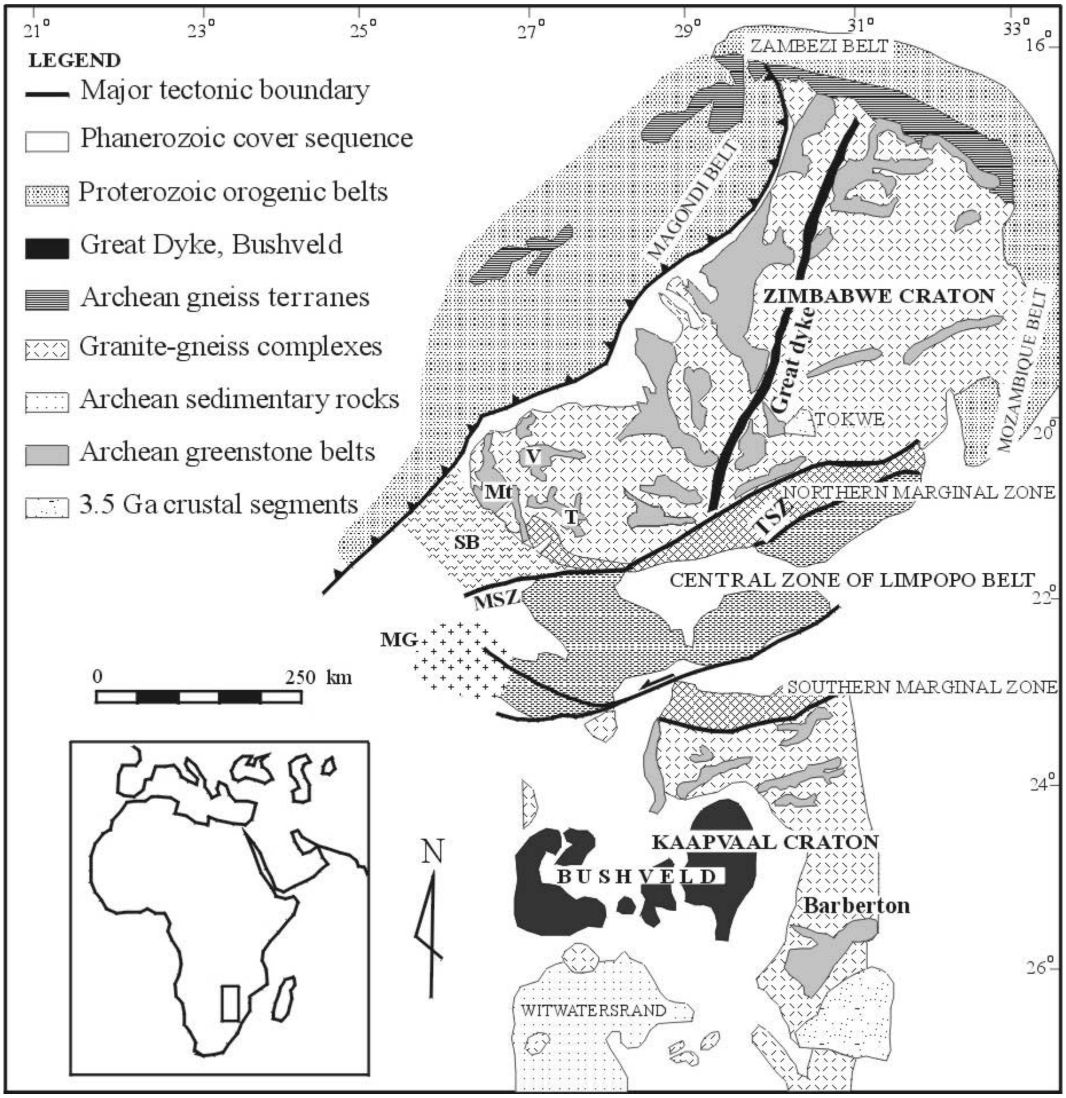

Figure 1. Simplified geological map of the Limpopo–Shashe Belt and adjacent cratons. The main locations and features quoted in the text are shown. SB = Shashe Belt, MG = Mahalapye Granite Complex, MSZ = Magogaphate shear zone, TSZ = Triangle shear zone. Greenstone belts in northeast Botswana are: Mt = Matsitama, T = Tati, V = Vumba.

1976; Aldiss 1991). However, the Limpopo Belt lithologies underwent granulite facies metamorphism (>600°C) at 2 Ga (e.g. Kamber *et al.* 1995) and therefore their magnetic properties were reset. In contrast, gravity anomalies reflect the lateral variation of density and are an excellent tool for mapping terrane boundaries (e.g. Emenike 1986). The boundaries of the Limpopo Belt are well defined in South Africa and Zimbabwe but it is not known how far the Limpopo Belt extends west into Botswana. Furthermore, the Kaapvaal craton–Limpopo Belt–Zimbabwe craton boundaries are ill defined in Botswana and the relationship between the Shashe Belt, the Limpopo Belt and the Zimbabwe craton is still controversial. These are key issues in any interpretation of the geotectonic evolution of the Kaapvaal and Zimbabwe cratons and the Limpopo Belt during the Neoarchean.

In this paper, we use a newly compiled gravity data set covering the Limpopo Belt and adjacent cratons in Botswana, northern South Africa, Mozambique, and Zimbabwe to: 1) delineate the boundaries between the Limpopo Belt and the adjacent Kaapvaal and Zimbabwe cratons, 2) define the relationship between the Shashe and Limpopo Belts, and 3) constrain the deep structure of both belts. We also consider the implications of geophysical, geochronological, and petrological data on the geotectonic evolution of the Limpopo Belt. We interpret the data in terms of Archean accretion and consider the implications for the transition from Archean to post-Archean plate tectonics.

GRAVITY DATA

The gravity data used in this study includes two major sets. The first set corresponds to data used in previous publications and acquired during the past four decades of gravity surveys in Botswana, Mozambique, South Africa, and Zimbabwe (e.g. Gwavava *et al.* 1992; Fisk & Hawadi 1996). Although variable, the total accuracy of the calculated gravity anomalies in this set is placed at ±2 mGal, being the accuracy of the least precise older surveys. The second set of data is unpublished and was acquired by the Botswana Geological Survey during 1998 and 1999 in the northern part of the country. They comprise 4000 points acquired with helicopter

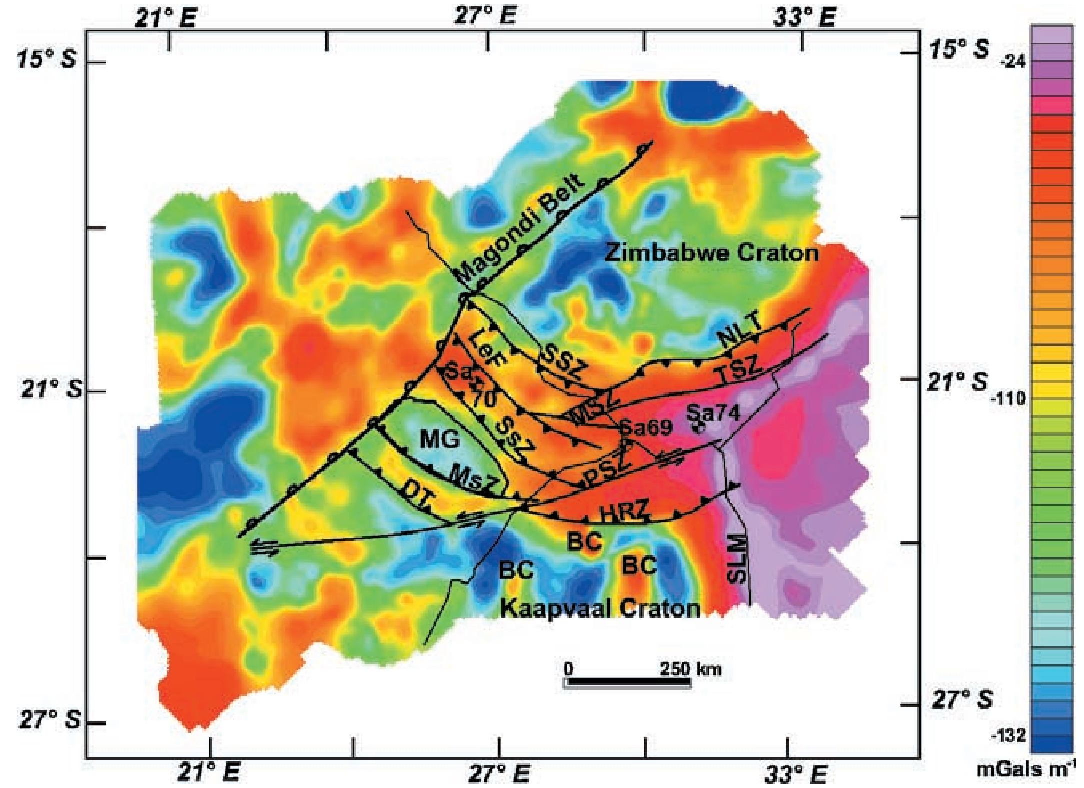

Figure 2. Bouguer anomaly map of the Limpopo–Shashe Belt and adjacent cratons upward continued to 10 km, with tectonic interpretation overlay based on surface geology and gravity data. BC = Bushveld Complex; DT = Dinokwe Thrust; HRZ = Hout River Shear Zone; LeF = Lechana Fault; MSZ = Magogaphate Shear Zone; MsZ = Mahalapye Shear Zone; NLT = Northern Limpopo Thrust Zone; PSZ = Palala Shear Zone; SLM = Sabi-Lebombo Monocline; SSZ = Shashe Shear Zone; SsZ = Sunny Side Shear Zone. PSZ is not an accretionary tectonic boundary. The gravity anomaly of the Limpopo Belt is intersected in the east by a north-south short-wavelength high (SLM) marking the western edge of the Indian Ocean extensional province. Sa69, Sa70 and Sa74 are selected seismic stations giving crustal thickness of 51, 54 and 43 km respectively in the Limpopo–Shashe Belt.

support using differential GPS for positioning and altitude, and the anomalies are considered accurate to ±0.5 mGal.

The irregularly spaced data were gridded at a 5 km cell size using a minimum curvature technique (Smith & Wessel 1990). To clearly isolate anomalies with different wavelengths, various filters (e.g. Blakely 1995) were applied on the gridded data. The Bouguer anomaly and 10 km upward continued grids were selected to illustrate the main gravity field and geological features of the study area. Upward continuation of the data enables suppression of short-wavelength, shallow sources and emphasizes deeper, medium- to long-wavelength structures.

RESULTS

Four first-order results can be drawn from the gravity maps (e.g. Fig. 2): (i) The Limpopo Belt stands out as a major gravity high between the two cratons as previously suggested (e.g. Emenike 1986; Gwavava *et al.* 1992). On the Bouguer anomaly map, the cratons are characterised by regional negative Bouguer anomalies in the range −130 to −90 mGal due to predominantly igneous felsic to intermediate crustal rocks. The gravity lows characterizing the cratons are emphasized on the 10 km upward continued map (Fig. 2), where the boundaries between the cratons and the Limpopo Belt are further accentuated. Short wavelength lows coincident with mainly post-tectonic plutons, and highs associated with greenstone belts and layered mafic-ultramafic complexes (e.g. Bushveld complex, Fig. 2) are superimposed on the regional gravity anomalies. (ii) The gravity high associated with the Limpopo Belt defines a southward convex arc with an east–northeast trend in the east, swinging to become east–west in the centre (between 28° and 31°E) and then northwest–southeast in the west (west of 28°E) over the 'Shashe Belt'. The anomaly decreases progressively in amplitude from ~90 mGal over the Limpopo Belt in the east to ~50 mGal in the west over the Shashe Belt. South of the 'Shashe Belt' gravity high, the Limpopo gravity high is split by a low coincident with the Mahalapye granite complex west of 27°E (Fig. 2). This arc shape of the Limpopo gravity high correlates with the lateral variation of structural trends and thickness of the crust within the Limpopo–Shashe Belt. Receiver function analysis of broad-band seismic records (Nguuri *et al.* 2001, Gore, unpublished data) show crustal thicknesses of ca. 40–45 km beneath the Limpopo Belt central zone (e.g. station 74, Fig. 2), ca. 48–51 at the junction of the Limpopo and Shashe belts (e.g. station 69, Fig. 2), and ca. 50–54 km beneath the Shashe Belt central zone (e.g. station 70, Fig. 2). The lower crust is laminated and the Moho poorly defined beneath the Limpopo–Shashe Belt central zone (*cf.* Nguuri *et al.* 2001). *P–T* estimates based on metamorphic minerals indicate that the present erosional levels were overlain by a lithostatic load of ~25 km and ~15 km in the Limpopo and Shashe Belts, respectively. Therefore, the pre-exhumation crustal thickness was ~70 km in both belts, supporting their linkage and the arc shape of the thickened crust. (iii) The arcuate-shaped structural trends of the Limpopo–Shashe Belt are well defined on the vertical derivative map and coincide with a belt of parallel to subparallel shear zones including the Dinokwe thrust, the Mahalapye shear zone, the

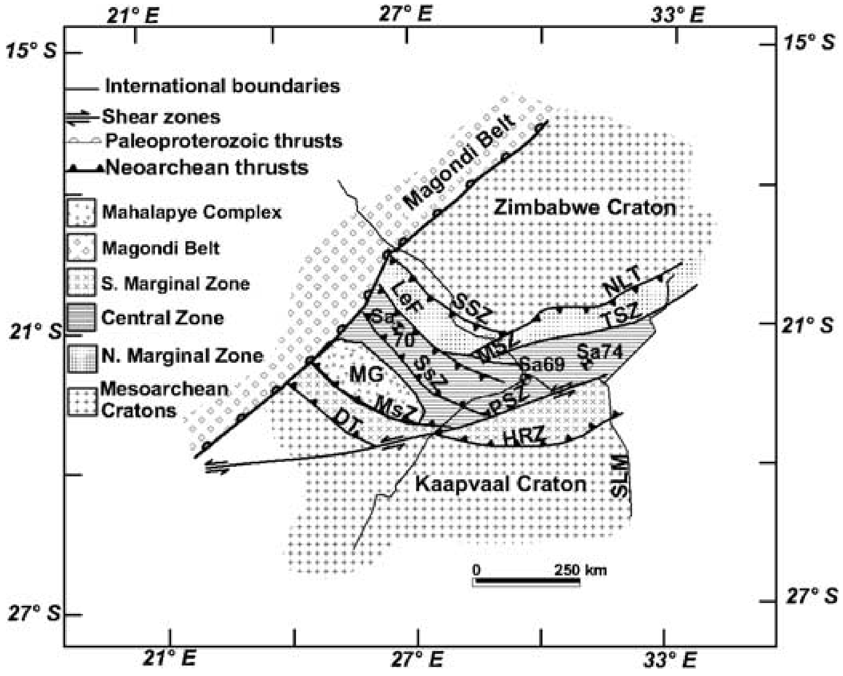

Figure 3. Distribution of the three tectonic zones of the Archean Limpopo–Shashe Belt and relations with the Zimbabwe and Kaapvaal cratons and the Paleoproterozoic Magondi Belt interpreted from gravity data and previous geology. Abbreviations as in Fig. 2.

Sunny Side shear zone, the Lechana fault and the Shashe shear zone (Fig. 2). These shear zones are major accretionary boundaries (e.g. Holzer *et al.* 1999) allowing us to further correlate the two belts. The southwest-verging Dinokwe thrust and Mahalapye shear zone bound the southwestern marginal zone of the Shashe Belt, a correlative of the SMZ of the Limpopo Belt (Fig. 3). The northeast-verging Shashe shear zone and Lechana fault bound the northeastern marginal zone of the Shashe Belt, a correlative of the NMZ of the Limpopo Belt (Fig. 3). The gravity data suggest that the northeast-verging Shashe thrust in eastern Botswana is a continuation of the northern Limpopo thrust zone, defining an arcuate tectonic boundary between the Zimbabwe craton and the Limpopo–Shashe Belt. Geochronological data show that both thrust zones developed between 2.68–2.65 Ga (Mkweli *et al.* 1995; Bagai *et al.* 2002). The central zone of the Shashe Belt is separated from the marginal zones by tectonic breaks and correlates with the CZ of the Limpopo Belt (Fig. 3). Opposite vergence in the marginal zones bounding the central zone of the Shashe Belt indicates a 'pop-up' structure similar to that documented in the Limpopo Belt (e.g. Roering *et al.* 1992). (iv) The Limpopo–Shashe Belt gravity high is truncated to the northwest by another high over the northeast-trending Magondi Belt. Gravity structural trends of the 2 Ga Magondi Belt are predominantly northeast in contrast to the west-north-westerly trends of the Shashe Belt. In the east, the gravity anomaly of the Limpopo–Shashe Belt is intersected by a north-south short-wavelength high over the Sabi-Lebombo monocline (SLM, Fig. 2), marking the western edge of the Indian Ocean extensional province (e.g. Gwavava *et al.* 1992).

DISCUSSION AND CONCLUSIONS

We have provided evidence suggesting that the continental crust in this part of southern Africa is characterized by an arcuate-shaped gravity high, which encompasses both the Limpopo and Shashe Belts. The continuity between the Limpopo Belt and the Shashe Belt that was a matter of controversy for many years (Bennet 1970; Key & Hutton 1976; Aldiss 1991) is resolved by the gravity data in this paper. The gravity high marking the NMZ of the Limpopo Belt continues without a break into the Shashe Belt, indicating that the Magogaphate shear zone (Fig. 1) does not represent the Zimbabwe craton–Limpopo Belt boundary as previously suggested (Key & Hutton 1976; Aldiss 1991). The typical gravity low marking boundaries between cratons and orogenic belts do not exist along the Magogaphate shear zone. Instead the data support the interpretation that the Magogaphate shear zone was superimposed on the Limpopo–Shashe Belt structures during a younger event, presumably the major 2 Ga event recorded by mineral ages (e.g. Kamber *et al.* 1995). In Botswana, the boundary between the Limpopo–Shashe Belt and the Zimbabwe craton is the Shashe shear/thrust zone (Fig. 3).

Our observations invalidate a number of geotectonic models of the Limpopo Belt. The CZ of the Limpopo Belt has been interpreted as an exotic crustal block bounded by the Magogaphate–Triangle shear zones and the Palala shear zone (Fig. 1) and inserted sideways as a tectonic terrane between the southern and northern marginal zones during the Neoarchean (e.g. McCourt & Vearncombe 1992; Treloar *et al.* 1992). The arc shape of the central zones of the Limpopo and Shashe Belts and the tectonic 'pop-up' structures in both belts do not support this interpretation. Some workers (Barton *et al.* 1994; Kamber *et al.* 1995; Holzer *et al.* 1999) emphasize the large set of Ar-Ar and Pb-Pb mineral ages indicating that the Magogaphate–Triangle shear zone was mainly active at 2 Ga, and suggest a Paleoproterozoic suturing of the Kaapvaal and Zimbabwe cratons along the Limpopo Belt. The gravity signature of the Archean Shashe Belt is similar to that of the Limpopo Belt, despite an estimated 10 km depth difference between the exposed units in the two belts. This indicates a limited differential uplift/exhumation during the Paleoproterozoic reactivation of the

Limpopo Belt. This is supported by upper-mantle tomography data indicating a continuous ∼200–250 km thick Archean-type high-velocity cratonic keel beneath the Shashe and Limpopo Belts (James *et al.* 2001). Further, Re/Os dating of mantle nodules from the Venitia kimberlite pipe in the Limpopo Belt yielded a Neoarchean age (Carlson *et al.* 2000). Thus, the Paleoproterozoic tectonometamorphic event did not significantly disturb the structure of the Archean Limpopo continental lithosphere, which offers a unique opportunity of constraining the Neoarchean accretion processes.

The similarity of the gravity anomaly pattern (Fig. 2) of the central and marginal zones of the Limpopo Belt at depth, and continuity with the Archean Shashe Belt, suggest that the NMZ, CZ, SMZ, and Shashe Belt represented a single geotectonic entity during exhumation. The somewhat reduced gravity anomaly over presently thicker crust in the Shashe Belt is consistent with it representing a somewhat shallower exhumed crustal section of the Archean Limpopo–Shashe Belt. The main exhumation event occurred during the Archean because there is no major 2 Ga igneous and high-grade metamorphic event in the Shashe Belt and the SMZ of the Limpopo Belt. U-Pb zircon ages from the Shashe Belt are in the range 2.7–2.6 Ga and are similar to the common crystallization age of granitoids in the Limpopo Belt (Mkweli *et al.* 1995; McCourt & Armstrong 1998; Bagai *et al.* 2002).

The gravity, seismic and geochronological data discussed above indicate that the accretionary tectonics in the Shashe and Limpopo Belts and the amalgamation of the Kaapvaal and Zimbabwe cratons happened during the Neoarchean, with limited lateral transport during overprinting by the 2 Ga strike-slip tectonics. If the final collision between the Kaapvaal and Zimbabwe cratons was at 2 Ga as postulated by some workers, the southern gravity boundary between the Kaapvaal craton and the Limpopo Belt would occur at the southern margin of the central zone along the Palala shear zone. Our data show that this boundary is the Hout River shear zone (Figs 2 and 3), separating the SMZ and the Kaapvaal craton. Similarly, the northern boundary of the Belt is the Northern Limpopo thrust and Shashe thrust zones, at the contact between the Limpopo–Shashe Belt and the Zimbabwe craton.

One of the most controversial topics in geology relates to Archean continental accretion processes (e.g. De Wit 1998; Hamilton 1998). Meso- and Neo-archean cratons (∼4.0–2.5 Ga) have a thick high-velocity mantle keel (tectosphere) and relatively thin (∼30–35 km) crust. Proterozoic and younger belts commonly do not have such high velocity keels (although they show coupling between mantle and crust: Carlson *et al.* 2000), and their crust is thicker, up to 70–80 km thick in Cenozoic continental collisional orogens, e.g. Himalayas. The central zones of the Archean Limpopo and Shashe Belts present Himalaya-belt-type crustal features, i.e. a pre-exhumation crustal thickness of ∼70 km, a poorly defined Moho, and laminated lower crust, overlying a 200–250 km thick Archean-like mantle keel. We infer that, as for most Archean cratons, the presence of this keel explains the good preservation of Archean crustal structures in the Limpopo Belt, despite a substantial tectonothermal reworking at 2 Ga. The over thickened Archean crust in the Limpopo–Shashe Belt represents a Phanerozoic-like tectonic pop-up structure (this paper and, e.g. Roering *et al.* 1992).

The Limpopo–Shashe Belt has crustal thickness, tectonic, and geophysical features of modern continental collisional orogens versus Archean-type igneous rock association (*cf.* tonalite-trondjemite-granites) and an Archean-type high-velocity mantle keel. Therefore, the continental lithosphere beneath the Limpopo–Shashe Belt preserves features marking the transition between Archean and post-Archean plate tectonic processes.

SUPPLEMENTARY MATERIAL

A Bouguer anomaly map of the Limpopo–Shashe belt can be found online at http:\\www.blackwellscience.com/products/journals/suppmat/GJI/GJI1703/GJI1703SmA.htm. A first vertical derivative gravity map can be found at http:\\www.blackwellscience.com/products/journals/suppmat/GJI/GJI1703/GJI1703SmB.htm.

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