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Configuration of late Archaean Chilimanzi and Razi suites of granites, south-central Zimbabwe craton, from gravity modelling: geotectonic implications

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Abstract The subsurface geometry of five representative late Archaean 'Chilimanzi and Razi' suite plutons in the Zimbabwe craton (ZC) has been investigated by gravity modelling constrained in part by surface geology, density measurements and seismic information, to determine their 3D configuration and infer tectonic context of emplacement. The generally K-rich, massive, homogeneous monzogranites are characterised by large Bouguer gravity lows (up to -30 mGal amplitude) whose gradients outline their spatial extent well. The southernmost plutons and their anomalies have general trends paralleling the North Marginal Zone (NMZ) of the Limpopo orogenic belt (LB).

Predictive gravity models indicate that the density contrast of the Chivi batholith (CB) adjacent to the 'volcanic arc-like' Belingwe greenstone belt extends to a depth of about 13 km. The nearby Razi pluton (RP) which intrudes the ZC-LB boundary appears to have been emplaced at shallower depths/levels. The gravity model suggests a thickness of about 5 to 6 km, and a moderate to shallow dip to the southeast under the NMZ, compatible with syn-kinematic intrusion during overthrust of the LB over the ZC. The smallest Nalatale granite (Ng) is on average 2.5 km thick under the Fort Rixon greenstone belt but includes a root up to 4.5 km thick under the anomaly peak, and a steep contact with the tonalite/gneiss to the east. These granites follow the general power-law for pluton dimension and are similar in this respect to the classical wedge-shaped plutons, extending largely in one direction, with large aspect ratios (Length(L)/Thickness(T)>7). However, the overall shape of the RP is typical of a diapir (Width(W)<T), although it may have been affected by the LB deformation.

Gravity modelling along a NS traverse crossing the Chilimanzi batholith (ChB), the Masvingo greenstone belt (MGB) and the Zimbabwe granite (ZG) indicate a thickness of around 6 km for the dense greenstone belt with a thickness of about 8.5 km for the adjacent ZG. The 'complex' shaped ChB shows a 2 km thick tabular body with a root zone extending to ~4.5 km depth on the south end, adjacent to the greenstone belt; typical of the so-called flat-floored plutons with a gently dipping floor towards the root zone. These two plutons roughly follow the power-law for laccolith/batholith dimensions (W/T>5; L/T>15). Overall, the CB and the ZG are interpreted as massive, deep-rooted batholithic intrusions (L/T≅10), contrary to some geological interpretations of these late, post-kinematic intrusions as sheet-like bodies emplaced at relatively shallow levels in the crust. On the other hand, the ChB appears to be a tabular intrusion, probably fed by dykes; it exhibits a lateral extent much greater than the vertical one, outlining a sheeted geometry (W/T>7; L/T>18).

The geophysical evidence, together with geological and fabric data, support and/or confirm the two main granite configurations: sheets and batholith; and thus also confirm the two main modes of emplacement: dyke and diapirism or ballooning plutonism. This is consistent with other known batholiths on the ZC but considered unusual for plutons of the same age and spatially close when compared to other Archaean cratons.

Keywords: Zimbabwe craton; late Archaean pluton; gravity modeling; depth extent; emplacement mechanism

1 Introduction

The intrusion of volumetrically large Late Archaean granites (Sylvester 1994; Moyen et al. 2003) is important for a number of reasons; for example, Archaean tectonics (e.g., Zegers 2004; Lopez et al. 2006; Liodas et al. 2013; Laurent et al. 2014; Halla et al. 2017), crust-mantle coupling (e.g., Berger and Rollinson 1997; Zeh et al. 2009), local and regional seismicity (Singh et al., 2004), and mineralisation control (e.g., Cassidy et al. 1998; Duuring et al. 2007; Lin and Beakhouse 2013; Yang 2014). In the Zimbabwe craton (ZC), the intrusion of the ~2.6 Ga Chilimanzi and Razi suites represent the stabilisation of the Zimbabwe craton (e.g., Jelsma et al. 1996; Horstwood et al. 1999; Jelsma and Dirks 2002; Oberthur et al. 2002; Siegesmund et al. 2002). The granitic plutons occupy >50% of the craton (Blenkinsop et al. 1997; Frei et al., 1999; Blenkinsop and Treloar 2001) making them socio-economcally important for groundwater supply (e.g., Owen et al. 2002, Ranganai and Ebinger 2008). Gold mineralization in many greenstone belts may be linked to mobilisation of ore-forming fluids by these internally and externally emplaced granitoids during deformation (e.g., Campbell and Pitfield 1994; Blenkinsop et al. 2000).

There is also a close temporal link between intrusion of the Great Dyke and the emplacement of these plutons (e.g., Frei et al. 1999; Oberthur et al. 2002; Siegesmund et al. 2002). The K-rich porphyritic monzogranite intrusions also document widespread lower crustal melting and reworking/recycling (e.g., Hickman 1978; Jelsma et al. 1996; Berger and Rollinson 1997; Frei et al. 1999; Oberthur et al. 2002; Zeh et al. 2009; Blenkinsop 2011).

The emplacement mechanism for these granites intruding and deforming both the older tonalitic gneisses and the greenstone belts has long formed the focus of a debate (e.g., Snowden 1984; Ramsay 1989; Wilson 1990; Jelsma et al. 1993; Blenkinsop et al. 1997; Becker et al. 2000; Jelsma and Dirks 2000, 2002; Blenkinsop and Treloar 2001; Hofmann et al. 2002; Siegesmund et al. 2002; Ranganai et al. 2008; Gwavava and Ranganai 2009; Blenkinsop 2011; Ferre´ et al. 2012; Ranganai 2012, 2013). Many of the granites have contacts which are grossly discordant to the greenstones sequences, as exemplified by the Shangani batholith or Nalatale granite (Ng, Fig. 1) (Ridley et al. 1997). Generally, the discordant or concordant nature of contacts has significance in relation to the mode of emplacement and/or level of exposure (e.g., Castro 1987; Cruden 1998; Cruden and McCaffrey 2001; Galadi-Enriquez et al. 2003; Ferre´ et al. 2012).

From field geological and geophysical data (e.g., Ramsay 1989; Ridley et al. 1997; Becker et al. 2000; Blenkinsop and Treloar 2001; Moyen et al. 2003; Flecha et al. 2006), experimental, numerical and theoretical considerations (e.g., Ramberg 1981; Clemens 2005; Lopez et al. 2006; Rey and Houseman 2006; Dietl and Koyi 2008; Ferre´ et al. 2012) it can be deduced that granitoid magmas ascend and are emplaced under a complex interaction of gravitational processes due to density inversion (Rayleigh-Taylor instability) and horizontal (plate/micro-plate) tectonics (e.g., Castro 1987; Paterson and Vermon 1995; Petford et al. 2000; Vigneresse and Clemens 2000; Pawley et al. 2004; Clemens 2005; Ferre´ et al. 2012; Laurent et al. 2014). It is now generally accepted that these magmas ascend via diapirism and dyking (e.g., Petford and Clemens 2000; Vigneresse and Clemens 2000; Clemens 2005; though see Weinberg 1999). Further, diapirism can also be considered as both an ascent and an emplacement mechanism for large plutons (Blenkinsop and Treloar 2001; Clemens 2005; see also McCaffrey and Petford 1997). Although ascent and emplacement are intimately linked, the present shapes of granitic intrusions at depth generally reflect the emplacement modes of the magmas rather than their ascent styles (Vigneresse and Clemens 2000). However, the active processes determine the final geometries of the bodies, and in favourable cases, the inverse problem of deducing mechanisms can be undertaken by relying on the geometry of the plutons (Galadi-Enriquez et al. ~~2002~~2003). Thus establishing the 3D shape of plutons is helpful for understanding not only magma emplacement but also its ascent in some cases (e.g., Ameglio et al. 1997; Dehls et al.

~~1999~~1998; Goulty et al. 2001; Haederle and Atherton 2002; Galadi-Enriquez et al. 2003; Peschler et al. 2004; Tahiri et al. 2007).

Among the geophysical techniques, the gravity method is particularly suited to determination of the bulk geometries of plutons as they invariably show a strong density contrast with the surrounding rocks (e.g., Fig. 2) and are, therefore, associated with moderate to large (negative) gravity anomalies (-10 to -30 mGal amplitude) (e.g., Stettler et al. 1990; Ameglio et al. 1997; Ameglio and Vigneresse 1999; Kurian et al. 2001; Haederle and Atherton 2002; McLean and Betts 2003; Peschler et al. 2004; Flecha et al. 2006; Tahiri et al. 2007; Oliveira et al. 2008; Ranganai et al. 2008; Gwavava and Ranganai 2009; Ranganai 2012, 2013; Fig. 3). Despite the problem of non-uniquness and low resolution (e.g., Blakely 1995; Stettler et al. 1997; Wellman 2000), these gravity anomalies can be used to rule out certain mass distributions and the accompanying hypotheses for pluton emplacement (e.g., Vigneresse 1990; Ameglio and Vigneresse 1999; McLean and Betts 2003). Several authors have noted that important information on the emplacement mechanism of granitic magmas is preserved in the 3D shape/characteristics of the plutons, and that both are controlled by regional tectonics/deformation (Ameglio et al. 1997; Cruden 1998; Dehls et al. 1998; Vigneresse et al. 1999; Vigneresse and Clemens 2000). Gravity determined proportions of intrusive bodies (length L vs. thickness T) can be used to distinguish between plutons and laccoliths as they follow the general power-law: $T = c \times L^a$ (McCaffrey and Petford 1997; Petford and Clemens 2000; Petford et al. 2000), where exponent a is the slope of the regression line and c is the intercept. Granite plutons may also produce scattered discontinuous magnetic anomalies due to their variable composition and inhomogeneous distribution of magnetic minerals within them (Singh et al., 2004; Gwavava and Ranganai, 2009; Ranganai et al., 2015; Fig. 4).

While relatively extensive geological, structural and geochronological work has been carried out to study the evolution of the plutons in the ZC (e.g., Robertson 1973; Snowden 1984; Ramsay 1989; Wilson 1990; Jelsma et al. 1993, 1996; Wilson et al. 1995; Blenkinsop et al. 1997; Ridley et al. 1997; Frei et al. 1999; Horstwood et al. 1999; Becker et al. 2000; Jelsma and Dirks 2000; Blenkinsop and Treloar 2001; Hofmann et al. 2002; Jelsma and Dirks 2002; Siegesmund et al. 2002; Ferre´ et al. 2012), until recently, scant attention has been paid to geophysical investigations of the 3D configuration of greenstone belts, the mode and extent of granite emplacement, and related problems (e.g., Ranganai 1995, 2012, 2013; Ranganai et al. 2008;

Gwavava and Ranganai 2009). Indeed, geophysical aspects of granite-greenstone terranes are grossly understudied when compared to the voluminous geological accounts of these regions worldwide (Anhaeusser 2014). However, this is changing due to increased avalaibility of various geophysical data sets. We have selected five (5) representative plutons (Chilimanzi batholith, Chivi batholith, Nalatale granite, Razi pluton, Zimbabwe granite) for gravity and magnetic investigations, all located in the south-central part of the Zimbabwe craton (Fig. 1) where there are type areas for studying Archaean granite-greenstone relationships and Archaean crustal evolution (e.g., Bickle and Nisbet 1993; Wilson et al. 1995; Jelsma and Dirks 2002).

The objectives of this paper are to (i) present gravity models of some of the representative late Archaean plutons showing their present 3D configurations and subsurface relation with the adjacent greenstone belts and tonalitic gneisses, (ii) infer their mode of emplacement, (iii) where possible, infer magma plumbing systems by analogy to modern volcanic arc and rift magma systems, and (iv) extend interpretation to geologically and geophysically similar late Archaean plutons in the craton. The relation of the plutons to the NMZ and therefore late Archaean tectonics of the ZC and LB (see Frei et al. 1999; Blenkinsop 2011 and references therein) is also assessed. Further, we make comparisons with other plutons in similar cratons elsewhere. These are emplaced along major lineaments as narrow bands and veins as shown on aeromagnetic data (Singh et al. 2004; Yang, 2014; Ranganai et al. 2015; Fig. 4). The present gravity studies reveal whether the younger granites intruding both the greenstone belts and the surrounding tonalitic gneisses are sheet-like bodies or deep-rooted batholithic intrusions, an aspect which is also significant in understanding the evolution and tectonic behaviour of the Archaean crust in general (Mareschal and West 1980; Wellman 2000; Kurian et al. 2001; Peschler et al. 2004; Zegers 2004; Lopez et al. 2006; Rey and Houseman 2006; Zeh et al. 2009; Blenkinsop 2011; Laurent et al. 2014).

2 Regional Geological Setting

The ZC contains many of the ‘typical’ Archaean elements: ‘ancient’ gneisses and tonalites (~3.5 Ga), high-grade metamorphic belts, folded low-grade greenstone belts (~3.5-2.7 Ga), syn-volcanic granites (2.9-2.7 Ga), layered mafic-ultramafic complexes including the Great Dyke (2.7-2.5 Ga), post-volcanic granite plutons (2.65-2.55 Ga), and Proterozoic mafic dyke swarms and sills (e.g., Wilson 1990; Blenkinsop et al. 1997; Horstwood et al. 1999; Jelsma and Dirks 2002). The 'young' granites have been locally divided into the 2.7 Ga Sesombi and Wedza suites and the 2.6 Ga Chilimanzi and Razi suites (e.g., Wilson et al. 1995; Jelsma et al. 1996; Blenkinsop et al.,1997; Frei et al. 1999; Horstwood et al. 1999; Jelsma and Dirks 2002). The Chilimanzi and Razi suites are closely related to the final stages of the stabilisation of the craton and late Archaean tectonics of the Limpopo orogenic belt (e.g., Frei et al. 1999; Jelsma and Dirks 2002; Oberthur et al. 2002; Blenkinsop 2011).

The study area is the south-central ZC between latitudes 19.5°S and 21.25°S and longitudes 29°E and 32°E, and includes a portion of the NMZ and Triangle shear zone in the SE part (Fig. 1). The region includes the ~3.5 Ga Tokwe Segment (TS) of highly deformed and banded tonalitic gneisses, whose ~NS trend also defines the >3.1 Ga tectonic grain of the craton (Wilson 1990; Wilson et al. 1995; Jelsma and Dirks 2002). This unique terrain is considered to be a nucleus, from where the craton grew westwards and northwards by crustal accretion (Wilson 1990; Wilson et al. 1995; Horstwood et al. 1999; Jelsma and Dirks 2002). The granite plutons under study include the Chilimanzi batholith (ChB) and Zimbabwe granite/batholith (ZG) around Masvingo, the Chivi granite/batholith (CB) and Razi pluton (RP) around Buhwa, and the Nalatale granite (Ng) (the Shangani monzogranite of Ridley et al. 1997) near Fort Rixon (Fig. 1). They basically correspond to the generally massive potash and porphyritic granites described by Robertson (1973, 1974). A brief summary of the three different areas where the plutons occur and their geological significance follows.

The CB is best known for its relation to the 'archetypal' Belingwe (Mberengwa) greenstone belt (BGB) and the NMZ of the Limpopo orogenic belt (e.g., Robertson 1973, 1974; Hickman 1978; Bickle and Nisbet 1993; Frei et al. 1999; Ranganai et al., 2008), as well as its large size (~150 km long and up to 35 km wide). It parallels the ENE-trending Buhwa (Mweza) greenstone belt (B) and the adjacent south-dipping porphyritic Razi pluton (RP) intruding the ZC-NMZ boundary (Fig. 1; Robertson 1973, 1974; Hickman 1978; Fedo et al. 1995; Mkweli et al. 1995; Rollinson and Blenkinsop 1995; Frei et al. 1999). Within the region, Razi-type porphyritic granites are found throughout the NMZ and in the Triangle shear zone (Rollinson and Blenkinsop 1995; Berger and Rollinson 1997; Zeh et al. 2009; Blenkinsop 2011). Although a number of geological studies have been undertaken (e.g., Fedo et al. 1995; Mkweli et al. 1995; Frei et al. 1999), this is the first geophysical investigation of subsurface relationships between the Razi pluton and the NMZ. The Chivi batholith hosts the diamondiferous Murowa kimberlite (Smith et al. 2004) while the Buhwa belt is known for iron ore deposits and Sandawana emeralds (Fedo et al. 1995; Zwaan et al. 1997).

The Nalatale pluton is the smallest pluton studied but one of the clearest examples of deformation of greenstone belts by these units (e.g., Ranganai 2013). It intrudes, and almost bisects, the Fort Rixon-Shangani (FRSh) greenstone belt, leaving only a narrow neck in the west linking the FR and Sh sections (Fig. 1). According to Harrison (1969), intrusion of granites has domed up the greenstones, causing them to dip away from the granite at steep angles. The Nalatale pluton is also referred to as the Shangani monzogranite by Ridley et al. (1997) who see it as typical example of a discordant pluton against greenstones. These plutons tend to form stocks and small batholiths cross-cutting greenstone structures due to "rapid", forceful emplacement (Ridley et al. 1997).

The Chilimanzi batholith and the Zimbabwe granite are found in the Masvingo granite-greenstone terrain which includes the type-area for the Chilimanzi suite plutons, Chirumanzu (Fig. 1; Wilson et al. 1995; Jelsma and Dirks 2002). The area also records the oldest pluton age of 2634 Ma (Jelsma and Dirks 2002). ZG includes porphyritic varieties of Razi type around Lake Mutirikwi (Fig. 1; Robertson 1973). The two granite plutons sandwich the Masvingo greenstone belt (MGB), and extend for large distances (cf ZGS 1994; Gwavava and Ranganai 2009). However, deformation of the MGB is considered to be related mainly to events associated with the adjacent Limpopo orogenic belt (Coward and James 1974; Wilson 1990; Campbell et al. 1992), with local pluton emplacement playing a minor role. The Zimbabwe granite trends broadly parallel to the nearby NMZ. It hosts the diamondiferous Sese kimberlite at its southeast edge (Smith et al. 2004), while the ChB could be associated with the Bikita tinfield and several agrominerals (Wilson 1964; Van Straaten 2002).

3 Gravity Data and Rock Densities

The gravity data used in this study can be broadly grouped into two sets acquired during the past two decades of surveys using LaCoste & Romberg gravimeters and covering the various granite-greenstone terranes. Both sets used a network of primary base stations tied to the IGSN71 fundamental points that had previously been established throughout the country and therefore adequate base stations existed in the area (see Fisk and Hawadi 1996). Several bench marks and other old stations were re-occupied to better tie the new and old surveys together. The first set corresponds to data used in previous publications and acquired with station elevations determined predominantly by barometric altimeters (e.g., Gwavava et al. 1992; Fisk and Hawadi 1996). Height network closure errors were adjusted by the method of least squares, resulting in a precision ranging from ±5 m to ±2 m (e.g. Gwavava et al. 1992) for the individual heights along traverses. The second set includes more recently acquired data, both published and unpublished profiles across selected plutons and adjacent gneisses and greenstones. These data were acquired using a combination of satellite positioning systems (GPS) and barometric leap-frogging, controlled by trigonometric beacons, bench marks and differential GPS points at approximately 10 km intervals (e.g., Ranganai et al. 2008), resulting in an estimated precision of ±1 m in altitude. In both cases, the final simple Bouguer anomaly values are based on the 1967 International Gravity Formula and a reduction density of 2670 kg m^{-3}. Terrain corrections were applied where the topography was deemed very rugged (e.g., Gwavava et al. 1992; Ranganai et al. 2008; Gwavava and Ranganai 2009). Although variable, the total accuracy of the calculated gravity anomalies is placed at ±2 mGal, being the accuracy of the least precise older surveys and the estimated terrain contributions. The combined observations were gridded at 6.0 km interval (Fig. 3) using a minimum curvature algorithm with tension (Smith and Wessel 1990).

During the various gravity surveys representative rock samples were collected for density measurements which were then combined with existing densities from previous surveys and others from the ZGS database (Phaup 1973; Gwavava et al. 1992; Ranganai et al. 2008; Gwavava and Ranganai 2009; Ranganai 2013). The average densities of the various formations were determined to be: old granites 2670 kg m^{-3}, young granitic plutons (our present targets) 2550-2600 kg m^{-3} and greenstones 2900 - 3000 kg m^{-3} (Table 1 and Fig. 2). The densities are estimated to be accurate to within ± 50 kg m^{-3}.

The range of densities obtained for the granitic rocks is 2500 to 2700 kg/m^3 with a mean of 2630 ± 20 kg/m^3. Generally, the lowest values correspond to weathered gneisses but a few seem to be associated with the late (2.6 Ga Chilimanzi suite) granitic plutons, particularly the porphyritic types. Diorites and granodiorites yield the highest densities. Excluding these extreme values, the range becomes very small, with a mean of 2660 kg/m^3, a value closer to the histogram concentration at 2650-2700 kg/m^3. The histogram shows a simple unimodal distribution, which suggests that the rocks are fairly homogeneous in composition (c.f. Subrahmanyam and Verma 1981).

The amount of mafic minerals controls the density of acid plutonic rocks while plagioclase is important in basic rocks, respectively (e.g. Henkel 1991, 1994). These attributes also play important, but not exclusive, roles in determining the names by which rocks are identified in the field, and have been used to divide granites into I- and S-types or magnetite- and ilmenite series (e.g., Ishihara 1977, Clark 1997; Table 2); although there is significant overlap as granitic rocks crystallize into a broad spectrum of compositions (e.g., Frost et al. 2001).

4 Regional Gravity (and Aeromagnetic) Maps and Interpretation

A simple Bouguer gravity anomaly map for the south-central Zimbabwe craton showing outlines of the plutons and the location of the modelled profiles is presented in Figure 3. Details of the Bouguer anomalies and their geological significance have been given by Ranganai et al. (2008), Gwavava and Ranganai (2009) and Ranganai (2013), and only a summary is given here, with more information under the selected plutons below. An even broader context can be found in Braitenberg (2015) who compares satellite and terrestrial gravity data for the whole craton, while Gwavava et al. (1996) discuss isostatic compensation of the region. Generally the map is mainly dominated by short wavelength anomalies due to supracrustal features; in particular gravity lows over granite plutons and highs over greenstone volcanics and mafic-ultramafic intrusions, typical of most Archaean granite-greenstone terrains world-wide (e.g., Gupta et al. 1982; Subrahmanyam and Verma 1982; Stettler et al. 1997; Wellman 2000; Peschler et al. 2004). Notable examples include a large amplitude N-S gravity anomaly high of the Belingwe greenstone belt (BGB), large gravity anomaly lows over the Chivi granite and Zimbabwe granite adjacent and parallel to an ENE-trending large gravity high encompassing the Buhwa greenstone belt (B) and NMZ of the Limpopo belt (with the Razi pluton indistinguishable within this broad high), and finally, discontinuous highs over the NNE-trending mafic/ultramafic Great Dyke (GD) (Fig. 3). The main exception to relatively shallow sources is the long wavelength Bouguer gravity high over the

NMZ that extends into the CZ and is related to crustal thinning based on seismic evidence (e.g., Stuart and Zengeni 1987; Gwavava et al. 1992, 1996; Gore et al. 2009). In Figure 3, it is also worth noting that the Nalatale granite (Ng) has no obvious associated gravity low at this regional scale as it is obscured by the flanking Fort Rixon and Shangani greenstone belts, and is barely indicated on the derivative map (Fig. 5). However to the northeast of the Fort-Rixon-Shangani greenstone belt granite, a poorly constrained large low is located over the Shangani-Somabhula granite, suggesting a subsurface link with the Nalatale pluton. The gravity low zones imply that the granitic plutons are of much lower density compared to the dense greenstone belt and ultramafic complexes.

The granitic plutons surrounding the Masvingo greenstone belt (MGB) are characterised by broad and low Bouguer gravity zones; with three major lows over the Zimbabwe granite (ZG), the northeastern end of the Chivi granite (CB), and southern parts of the Chilimanzi batholith (ChB). The largest gravity low zone, about 160 km long and 60 km wide and up to 25 mGal amplitude, is over the ZG; followed by the CB which is ~130 km long, about 20 km wide and up to 20 mGal amplitude. There is a slight indication that the ZG has subsurface links to both the CB and ChB southwest and east of the MGB, respectively, further supported by the upward continued data (not shown; Ranganai et al. 2002). A significant anomaly also occurs over the southern parts of the ChB; ~60 km long and 15 km wide and up to 10 mGal amplitude. The large negative anomalies are interpreted to reflect large areal and depth extents for the plutons, although the anomalies could be constrained by better gravity station coverage in some places (Fig. 3). We also note that the ZG gravity anomaly is much wider than the mapped outcrop, extending into (i.e. encompassing) the tonalitic gneiss area next to the NMZ and suggesting a possible subsurface presence. Several mapped small and isolated outcrops of enclosed plutons could be shallow and extensive below surface (Gwavava and Ranganai 2009). On the other hand, the Bouguer gravity anomalies over the arc-type ChB is smaller than the mapped outcrop, with elevated values in the north and lower values in the south. The northern part of the ChB was probably intruded by dolerite sills as large sheets (small sills mapped on the geology and seen on aeromagnetic maps (Figs. 3 and 4; Wilson 1964; Gwavava and Ranganai 2009)) and this could explain the unexpected relative gravity high compared to the south. Alternatively, the pattern could reflect/represent different phases of intrusion resulting in different densities. The gravity anomaly shapes of these plutons suggest their emplacement as ENE-WSW elongate batholiths (cf. Ridley et al. 1997; Ameglio and Vigneresse 1999; Tahiri et al. 2007), an idea tested by modelling below, where details of the profiles across the five plutons under study are given.

The regional aeromagnetic structural interpretation and tectonic implications are detailed by Ranganai et al. (2015) and only anomaly aspects relevant to the current study are highlighted. The residual aeromagnetic anomaly map (Fig. 4) shows conspicuous highs over the granites and genisses largely reflecting magnetic mineralogy and correlating with the I-type and S-type classification (Table 2). Pluton/batholith anomaly trends are consistent with the gravity anomalies and suggest emplacement along lineaments. The Chivi and Chilimanzi batholiths have similar signatures while the Razi pluton and Zimbabwe granite signatures are also similar and higher, with that over the Razi pluton suggesting it is much larger than the mapped outcrop (Fig. 4). Both the signature and enlarged size of the Razi pluton are partly supported by observations by Mkweli et al. (1995) of syn-kinematic intrusion under granulite facies metamorphism (cf Clark, 997) and deformation together with the NMZ. However, the magnetic anomalies are not used to determine the spatial dimensions of the plutons due to the heterogeneous distribution of magnetic minerals and variable metamorphic grade.

In order to improve the mapping of the plutons, several data processing and anomaly enhancement techniques were applied to the gravity data. This information is important in determining the spatial dimensions of the plutons used later. In particular, derivatives (horizontal and/or vertical; e.g., Fig. 5) are routinely used to map edges of anomalous bodies as they remove or suppress the regional trends in the data, (e.g., Gupta and Grant 1985; Boschetti 2005; Li et al. 2010; Cooper and Cowan 2011; Ma et al. 2016). The gradient method detects the edges by looking for the maxima and minima in the initial spatial derivative of the image. The improvement is possible because the rate of change of gravity with elevation is much more sensitive to changes in rock densities occurring near the ground surface than to changes occurring at depth (Gupta and Grant 1985). The effect is to sharpen anomalies caused by abrupt lateral changes in near-surface densities at the expense of broader anomalies caused by deeper or more gradual density changes (Simpson et al. 1986). The improvement is clear, with the Chivi batholiths, Zimbabwe granite and Chilimanzi batholith all now well-mapped and the Nalatale pluton boundaries slightly improved (Fig. 5). In addition, due to the significant density differences between greenstones, old gneisses/granites and young plutons, this physical property can be exploited to map the different rock types (e.g., Cordell and McCafferty 1989). Figure 6 shows the apparent density (Gupta and Grant 1985) determined using an average thickness of the major dense bodies, i.e. greenstone belts, of 6.0 km (cf Ranganai et al. 2008). The map is generally similar to the Bouguer anomaly map (Fig. 3) but there is better resolution of margins. Lateral dimensions of the plutons from all these maps are averaged for analysis later.

5 2¾D Gravity Modelling

The field traverse locations were partly dictated by available roads and tracks across the plutons. Suitable gravity profiles (L1 to L5) were selected perpendicular to the mapped geological contacts and covering the peak Bouguer anomaly and thus the thickest part of the plutons. The modelled profiles used either data along the traverses or from stations projected onto a best straight line through the traverse, and long enough to define the regional field (Fig. 3).

A versatile interactive software using algorithms for 2½D or 2¾D polygonal bodies was used to calculate the gravity model responses along the selected profiles (Won and Bevis 1987). 2¾D is the same as 2½D but one end correction is "longer" than the other, *i.e.*, it is assumed that the profile does not pass through the middle of the body. Further, the angle of the body with respect to the plane of the model can be varied, and the body asymmetrically positioned about the profile, thus providing a quasi-3D model. Based on geological information, a simplifying assumption that the greenstone belts and the plutons overlie a granitic gneiss base of average density 2670 kg m^{-3} has been made. Assuming the lower crust to be uniform helps to focus the near surface rocks with density variations more clearly. In each case, the observed anomalies were reasonably reproduced using simple models and these broadly satisfy the surface geology, the rock densities and the gravity field. A regional field of -120 ± 5 mGal (Fig. 3) was used as DC shift while previous gravity modeling and seismic studies (Gwavava et al. 1996; Gwavava and Ranganai 2009; Gore et al. 2009) have been used to constrain depths to the lower crust and upper mantle where necessary/appropriate (see below).

6 Results

6.1 Nalatale granite (Ng): Fort Rixon-Shangani (FRSh) Granite-Greenstone Terrain

Figure 7a is the Bouguer gravity anomaly map over the Nalatale granite (Ng) and adjacent Shangani (Sh) and Fort Rixon (FR) greenstone belts, which clearly shows a pronounced gravity low over the pluton. The Bouguer gravity high over the adjacent Shangani greenstone belt is considerably shifted to the north, suggesting that the pluton underlies the southern part of the belt. The pluton is mapped better at this local scale than in Figure 3 (L1) at regional scale.

Gravity profile L1 (Fig. 7a) was originally designed to investigate the configuration of the Fort Rixon greenstone belt (Ranganai 2013) but it also allows us to determine the shape of the pluton, as it passes along its southern edge. There were access problems preventing a better traverse location. The gravity anomaly along L1 is asymmetric and shows an increase to a small positive peak of about 25 mGal on the western half of the greenstone outcrop, with a more gradual fall eastwards (Fig. 7b). It is probable that this granite underlies much of the eastern parts of the Fort Rixon greenstone belt. The pluton produces a relatively small negative anomaly of about -7 mGal. The greenstone belt model shows a direct shallow contact to the pluton in the east and a ~45° south-easterly dipping contact with background gneisses in the west (Fig. 7b). The shallow eastern contact is somewhat domal in shape but steep at depth, consistent with an intrusive relationship between greenstones and the adjacent subsurface granite. The short wavelength relative positive Bouguer anomaly can be fit with a belt of basaltic extrusive lavas with contrast ~0.3 kg/m^3 that is about 3.5 km beneath the peak, and thinning eastward. The resultant inverted and 'side-crunched' triangular model of the volcanics (Fig. 7b) may be a result of the intrusion and granitisation of the greenstone belt by the pluton (cf. Harrison 1969; Gupta et al. 1982; Stettler et al. 1997). The granite pluton is on average 1.5 km thick under the greenstone belt but includes a root up to 4.5 km thick under the outcrop and anomaly peak, and a vertical contact with the tonalite/gneiss in the east. Our model is similar to that of Dehls et al. (1998) for the Ulu pluton, Slave Province, Canada that showed a ~2 km depth extent with several plug-like roots extending to 7 km that may have fed the relatively thin tabular body.

6.2 Chivi Granite/Batholith (CB) and Razi Pluton (RP): Belingwe (Mberengwa)-Buhwa Granite-Greenstone Terrain

Although Ranganai (1995) evaluated the depth extent of the Buhwa greenstone belt and the nature of the Chivi granite contacts with it, the 3D geometry of the Chivi granite and Razi pluton remained weakly constrained. A complicating factor on profile L2 through them (Figs. 3 and 8a) is its position relative to the Limpopo Belt, where previous studies have shown that crustal thinning contributes significantly to the regional Bouguer gravity anomalies in the region (Gwavava et al. 1992). Although the profile is not very long (<60 km), it extends into the NMZ of the Limpopo Belt for about 20 km and, therefore, the Moho has been included in the model. In accordance with seismic data and previous gravity modelling, the crust was taken as 34 km thick, shallowing southwards at about 5° (Stuart and Zengeni 1987; Gwavava et al. 1992; Gore et al. 2009). A density of 3000 kg/m^3 for the upper mantle was used (cf Gwavava and Ranganai, 2009), while the pluton was modelled with a density of 2550 kg/m^3 compared to a background of 2660 kg/m^3. Only a uniform density (2960 kg/m^3) for the greenstone belts is considered. This is thought to be slightly lower than the density of the Buhwa belt which is dominated by denser iron formation and magnetite quartzite (average ~3000 kg/m^3) (Ranganai, 1995). Use of the higher density for the greenstone belt does not affect the overall shape of the models, but as density contrast is increased, then thinner bodies result.

The geological cross-section, the Bouguer anomaly and the derived models are shown in Fig. 8b. The profile is dominated by the broad negative anomaly associated with the Chivi granite, and a narrow but sharp positive anomaly over the Buhwa greenstone belt. The BGB has a relatively small amplitude Bouguer high, while the RP only causes a small depression of the Buhwa-NMZ positive anomaly. A peak to peak fit between the observed and calculated gravity anomalies requires that the Chivi granite extends to a depth of about 13 km. A thinning of the batholith on the northwest part is indicated in the model, with a tongue-like subsurface extension under the BGB. This section is up to 5 km thick, resulting in a sheet-like tabular body with a 13 km thick diapir. Significantly, small granite stocks/cupolas outcrop within the greenstone belt in this area. It is, therefore, probable that the Chivi granite is in fact in contact with the Mberengwa belt at depth. The belt itself has been modelled as only 1 km thick in this area, compared to ~5 km in the central part (Ranganai et al. 2008). The overall shape of the pluton suggests that the major conduit for the intrusion was located near the Buhwa greenstone belt where the pluton is thickest, spreading horizontally northwards.

The Buhwa greenstone belt model shows a narrow body extending to approximately 2.5 km depth, possibly reaching 3.0 km. The adjacent Razi pluton, which intrudes the Craton-Limpopo Belt boundary (e.g. Robertson 1973; Mkweli et al. 1995; Frei et al. 1999), appears to have been emplaced at relatively shallow depths. The model suggests a 6 km wide rectangular body about 6 to 7 km thick, and a moderate to shallow dip to the southeast. It slopes to the SE at shallow angles until almost flat at a depth of about 3.5 km, resulting in a tilted diapir. Elliptical charnoenderbites and plutons in the NMZ have been interpreted as diapirs (Rollinson and Blenkinsop 1995; Blenkinsop 2011). Attempts to model a second profile (L4, Figs. 2 and 7a) for comparison proved difficult due to the small anomaly amplitude and interference from the NMZ. It was also difficult to define the regional in this case.

6.3 Chilimanzi Batholith (ChB) (Chikwanda Pluton) and Zimbabwe Granite (ZG) (Charumbira pluton): Masvingo Granite-Greenstone Terrain

The regional MGB Bouguer gravity anomaly map (Fig. 9a) shows a high over the greenstone belt and a large low over the Zimbabwe granite, with the Chilimanzi batholith surprisingly associated with background gravity levels. One profile from the study of Gwavava and Ranganai (2009) is considered (L3, Fig. 3, 9a) that passes through the centre of the MGB. The profile (Fig. 9b) has a conspicuous narrow Bouguer gravity anomaly high over the Masvingo greenstone belt and a relatively wide gravity low over the Zimbabwe granite. A small ‘hump’ within this low is interpreted to be basement high as there is no evidence of (ultra-)mafic intrusions. The Chilimanzi batholith only appears as a small gravity low (Fig. 9b). Like profile L2 through the Chivi and Razi plutons, this profile runs into the NMZ in the south, and seismic information on the deep crustal structure of the area was again used to constrain the lower crust of the models. A 40 km thick crustal model was adopted made up of an 8 km top layer of granites, greenstones and metasediments followed by a middle layer 27 km thick of density 2800 kg m^{-3} and a base layer 5 km thick of density 3400 kg m^{-3} (Gwavava et al. 1996; Gwavava and Ranganai, 2009). Top and middle layer thickness variations of ± 2 km did not produce significant changes in the configuration of the greenstone belt and the plutons.

The 2¾D model (Fig. 9b) shows that at the location of the profile the Chilimanzi batholith has an approximately right-angled triangular shape (wedge) comprising a 5.0 km-thick tabular body in the south, with a gradual tapering to the north (over a 55 km horizontal distance) up to a 1.5 km thick root zone or dyke feeder. The Masvingo greenstone belt is about 17.0 km wide and 5.8 km thick, with sub-vertical edges. The Zimbabwe granite is an almost 55 km wide and 8 km thick tabular body with a narrow subsurface inclusion of granite gneiss in the northern part. The pluton extends below the surface beyond the mapped exposure to the south. It is worth noting that the gravity profile passes towards the edge of the Zimbabwe granite and therefore this 8 km depth extent may be less than its greatest thickness. As for the Chivi granite cross-sections, attempts to model a second profile (L5, Figs 2 and 8a) ideally bi-secting the pluton proved difficult due to high interference from the NMZ and the small anomaly amplitude relative to the gneisses along this traverse.

7 Discussion

The main features of the studied granites are the large negative anomalies (-25 mGal) over the linear Chivi granite (CB) and Zimbabwe granite (ZG) (Fig. 3), and their ENE-trend parallel to NMZ which is significant with respect to the late Archaean tectonics (thrusting?) between the Zimbabwe craton and Limpopo belt. A -10 mGal anomaly also occurs over the Chilimanzi batholith (ChB); but E-W trending adjacent/near to the MGB rather than ENE-trending as for the others. The general NE/SW to EW trend of gravity lows associated with the plutons (Fig. 3) may indicate either a tectonic stress field or pre-existing crust or lithospheric-scale weakness around the time of the intrusions. This is thought to be due to effects of the NW-directed thrusting onto the craton that formed the Limpopo Belt, particularly in the vicinity of the Limpopo Belt margin (e.g., Robertson 1973, 1974; Coward et al. 1976; Wilson 1990; Mkweli et al. 1995; Frei et al. 1999). It’s also a conspicuous trend on the GOCE Bouguer residual of Braitenberg (2015), and the craton as a whole (Fig. 1), reflecting lower crustal origin. Gwavava and Ranganai (2009) interpret the ~E-W trend for the ChB as due to decreasing influence of NMZ compression with distance from the frontal thrust contact. Deformation in the Zimbabwe craton is generally less pervasive than in the NMZ, implying a comparatively strong craton (Blenkinsop 2011). The elongate sub-oval gravity lows corresponding to the plutons, and the best-fitting gravity models from constrained cross-sections, are consistent with shallow and deep-rooted batholiths as the main mode of their emplacement (e.g., Mareschal and West 1980; Subrahmanyam and Verma 1982; Stettler et al. 1997). On the basis of their evolved geochemical and isotope characteristics, they have been interpreted as crustal melts, and may have been a product of loading following accretion (Jelsma et al. 1996; Jelsma and Dirks 2002).

The three large plutons flanking the MGB show contrasting geophysical and morphological features. Gravity models indicate that the density contrast of the Chivi granite may extend to a depth of up to 13 km; its contact with gneisses is vertical in the south but domal in the north. Similarly, the Zimbabwe granite is a large block at least 8 km thick, and possibly up to 10 km under the anomaly peak in the central part. The northern contact of the Zimbabwe granite with the greenstone belt is almost vertical, while its southern contact with the older gneisses is very shallow and domal in shape but with steep walls at depth, consistent with ballooning plutonism or partial convective overturn (e.g., Mareschal and West 1980; Minnitt and Anhaeusser 1992; Jelsma et al. 1993, 1996; Collins et al. 1998; Nelson 1998; Becker et al. 2000; Goulty et al. 2001; Galadi-Enriquez et al. 2003; Pawley et al. 2004; Tahiri et al. 2007). This pluton has a relatively deep root and is generally oval in shape; the resulting overall picture resembles the typical post-kinematic granite (Ridley et al. 1997). Pluton thicknesses of between 10 and 15 km have been reported in other Archaean terrains (e.g., Peschler et al. 2004, and references therein), and magma bodies of similar dimensions have been geophysically imaged in active arc settings (e.g., Comeau et al. 2015; Pritchard and Gregg 2016). The Chilimanzi batholith, on the other hand, appears to be a shallow sheet-like or tabular body at most 2 km thick with a 5 km root zone in the southern end. According to Vigneresse et al. (1999), the deepest zones calculated from gravity data, provided they show vertical lineations in outcrop, are feeder channels that fed the pluton. Unfortunately, such information is unavailable as there is no recent mapping.

The other two plutons show different features. The Razi pluton model is a 6 km wide rectangular body about 6 to 7 km thick, with a moderate to shallow dip to the southeast, consistent with LB deformation. The Razi granites intruded the NMZ syn-kinematically (Mkweli et al. 1995), and they are likely to dip moderately SE for two reasons: 1) They have been deformed into parallelism with the shear zone boundaries, and 2) They were intruded with a sheet like-geometry initially into the shear zone. In the model, they slope to the SE at shallow angles until almost flat at a depth of about 3.5 km. The profile for the Nalatale granite passes on the edge of the pluton and yields a 1.5 km thick body under the Fort Rixon greenstone belt but includes a root up to 4.5 km thick under the outcrop and anomaly peak (Fig. 7). Ranganai (2013) reports another less reliable model along a profile across both the Shangani and Fort Rixon greenstone belts, with the pluton almost halfway between the two (L0, Fig. 7a). On average, the two greenstone belts are depicted as shallow (~6 km) volcanic piles while the pluton is a narrow diapir 7 km wide and about 12 km thick, resulting in an approximate symmetry about the pluton.

Below, we discuss further the various characteristics to determine the nature of the plutons.

7.1 Nature of contacts

Gravity investigations have suggested that the typical post-kinematic granite consists of a relatively flat-lying roof region, commonly showing outward dips and walls which slope steeply outward (Ridley et al. 1997). Several techniques have been developed to determine the nature of geological contacts from gravity data (see Blakely 1995). Horizontal derivatives, which can easily be computed in the space domain, thus lowering the noise effect, are some of the most common methods for detecting target edges (e.g., Li et al. 2010; Ma et al. 2016). The location of an inflection point on a gravity anomaly, i.e. the position where the horizontal gravity gradient changes most rapidly, can provide information on the nature of the edge of an anomalous body (Kearey et al. 2002). Alternatively, Kearey et al. (2002) show that the inflection points on a gravity profile lie near the uppermost edges of an outward dipping body but near the base of the anomaly for an inward dipping body. Over a tabular body, the inflection points delineate the body (edges). This test was problematic in this study due to interference from the adjacent greenstone belts (e.g., Fig. 10), making it difficult to locate the inflection points. However, the gravity models controlled by field mapping/observations generally support these findings. Figures 7b, 8b and 9b invariably show that the contacts of most exposed granite plutons are sub-vertical or slope outward, consistent with an intrusive nature (cf roof of the plutons).

7.2 Tridimensional shape of the plutons

Gravity modelling suggests the approximate 3D shape of the plutons. The general power-law for intrusive bodies (length L vs. thickness T): $T = c \times L^a$ (McCaffrey and Petford 1997; Petford and

Clemens 2000; Petford et al. 2000), is used to distinguish between plutons and laccoliths in this study (Table 3). For laccoliths, $T = 0.12L^{0.88}$ while for plutons, $T = 0.29L^{0.8}$ (McCaffrey and Petford 1997; Cruden 1998), and $T = 0.29L^{0.6}$ for plutons/batholiths (Petford and Clemens 2000; Petford et al. 2000). The line *a* = 1 (self-similar growth) defines the critical divide between predominantly vertical inflation (a>1) and predominantly horizontal elongation (*a*<1) during intrusion growth (McCaffrey and Petford 1997; Petford et al. 2000). Diapirs, being thicker than they are wide (i.e. W/T < 1), would plot above the line *a* =1 (Petford and Clemens 2000). According to Dietl and Koyi (2008) differences in values for *a* and *c* partly reflect that only two (thickness and width) of the three available dimensions are taken into account; but in all cases, the power law exponent *a* is always less than one (*a* < 1), indicating the tabular shape of granitoid bodies. Alternatively, *a* < 1 means that pluton lengths exceed their thickness (Petford and Clemens 2000); the intrusions lengthen more rapidly than they thicken, maintaining an overall tabular body. A modified version of the power-law, based on gravity studies and a larger number of field observations, is given by Cruden and McCaffrey (2001) as: $T = 0.6(\pm 0.15)L^{0.6(\pm 0.1)}$, but defines L differently. The results from this do not make any difference to the final classification in our results (Table 3).

The dimensions and their proportions (ratios) for the studied plutons based on field (outcrop), gravity anomalies and numerical models are summarised in Table 3, including the 'arc-type' discordant Nalatale granite. However, the lateral dimensions should be considered minimum estimates because the exposed width and length of the plutons have been reduced through erosion (Blenkinsop and Treloar 2001). Their uncertainties are considered particularly significant for the Zimbabwe granite whose extent is not shown on any geological map. Further, variable thickness using irregular floor as base is noted for all the plutons. Gravity resolution is generally the lowest among all the geophysical methods (e.g., Blakely 1995; Stettler et al. 1997; Wellman 2000) but products such as derivatives, analytic signal, and apparent density can be helpful (cf Blakely 1995; Boschetti 2005; Cooper and Cowan 2011; Ma et al. 2016). The first vertical derivative constrains the edges of the Chivi batholith (Fig. 5), with the others not very clear. On the other hand, the apparent density map (Fig. 6) appears to delineate the three major botholiths: Chilimanzi, Chivi, and Zimbabwe. The smaller plutons/batholiths may be poorly constrained by existing gravity coverage. In nearly all cases, lateral extensions (extent) are substantially larger than the vertical ones; they have large cross sectional aspect ratios with horizontal major axes >7 times the vertical one (i.e. L/T > 7; Tables 3 and 4), outlining a tabular or sheeted geometry.

Length-thickness plots (Fig. 11) show that the Nalatale granite and Razi pluton plot very close to the pluton regression line (a = 0.8), the Chivi occurs slightly below this line but the Zimbabwe granite plots just below the laccolith regression line (a = 0.88). The ChB plots very close to the pluton/batholith line. The power-law exponent of a = 0.6 for plutons and batholiths (Petford and Clemens 2000; Petford et al. 2000) does not fit the plutons in this study. Using the modified pluton power-law, the Razi pluton and Nalatale granite still plot very close to the pluton line but the CB now above and slightly further away (Fig. 11).

7.3 Tectonic setting and emplacement of the plutons

The 3D shape of plutons can also indicate their tectonic setting. For example, the length/width (L/W) vs. width/thickness (W/T) diagram discriminates the 3D characteristics of intrusive plutons (Ameglio et al. 1997; McCaffrey and Petford 1997), and reflects the control of the emplacement mechanism and shape of the plutons by regional tectonics/deformation (Vigneresse et al. 1999; Petford and Clemens 2000; Petford et al. 2000; Dietl and Koyi 2008; Oliveira et al. 2008). Ameglio et al. (1997) and Vigneresse et al. (1999) have identified two types of granite plutons based on magmatic fabric and gravity data: thin (3-4 km), flat-floored (tablet-shaped) plutons, extending roughly equally in every horizontal direction, typically with several root/feeder zones; and thick (>10 km), wedge-shaped plutons, extending predominantly in one horizontal direction along which one or a few root/feeder zones appear. Root zone(s) may be elongated and may align parallel to the bulk elongation of the pluton (e.g., Dehls et al. 1998). According to Ameglio et al. (1997) and Vigneresse et al. (1999) the tectonic settings of these pluton types can be summarised as follows. Flat-floored plutons spread parallel to a tectonically layered (plastic?) crust and are emplaced during large-scale extension (extensional tectonic environment) while wedge-shaped plutons infill more-or-less vertical fractures (dilatant volumes) in the brittle crust (undergoing deformation?), under both conditions of compression and extension.

More recently, Peschler et al. (2004) have proposed the use of batholith shape/geometry as indicators of transition from crustal-scale diapirism-type tectonics prior to 2.8 Ga to more plate tectonic-like tectonics thereafter. Batholiths dated 2.8-2.7 Ga have predominantly tabular shapes, about 3 km thick, and lack the large, deeply extending root zones that are more evident for the older batholiths. The rarity of deep roots and a thickness of 5-6 km are characteristics of the ca. 2.7 Ga batholiths, resembling batholiths in many Phanerozoic terranes fed by dykes. (Peschler et al. 2004).

The relation between (L/W) and (W/T) ratios for the plutons in this study (Table 4 and Fig. 12) clearly separates wedge-shaped plutons (L/W > W/T) from flat-floored ones (L/W < W/T). The analysis of dimensions shows that the Nalatale granite, the Chivi batholith and the Razi pluton are wedge-shaped (with the latter having diapir features, W/T < 1) while the Zimbabwe granite and the ChB are flat-floored. The former have V-shaped or carrot cross-sections with steep walls, steepening with depth. However, the flat-floored ChB gravity model also depicts this shape- some plutons have both wedge and tabular characteristics (e.g., Cruden and McCaffrey 2001). ZG displays a flat-floored geometry, with the horizontal dimension to thickness ratios of more than 15 and 5, parallel and perpendicular to the longest horizontal dimension, respectively (Table 4). Both Ng and ZG plot relatively close to the dividing line, L/W = W/T = 1 (Fig. 12); thus they may have characteristics of both types, especially considering the uncertainties in the dimensions. However, in another possible but less constrained gravity model (Ranganai 2013) the Nalatale pluton appears as a typical diapir with thickness (~12 km) greater than width (7 km); T>W or W/T<1. It is noted that the volume of magma has been linked to space-making processes such as floor subsidence and/or roof lifting (cf 3-stage process; Cruden 1998; Pet ford et al 2000; Cruden and McCaffrey 2001). A preliminary length vs volume plot for all the plutons is approximately linear (Fig. 13), suggesting that the derived dimensions are relatively correct (cf Soesoo and Bons, 2015).

According to the interpretation of Petford et al. (2000) the Razi and Chivi plutons should be regarded as lopoliths emplaced by floor depression; and the Zimbabwe granite as a laccolith emplaced by roof-uplift. In this context, dykes (as opposed to diapirs) are the most probable way to feed them (Petford and Clemens 2000; Vigneresse and Clemens 2000). Similarly, the model of Peschler et al. (2004) would require that these 2.6 Ga plutons be emplaced under modern day plate-tectonic settings, rather than diapiric. This would require clear structural and petrologic supporting evidence of in-situ expansion from dykes or narrow channel-ways (Johnson et al. 2001), which is currently unavailable. On the other hand, Blenkinsop (2011) argues that several

Razi type plutons in the NMZ have structural features that are diapiric in origin. The review of Laurent et al. (2014) points to global Wilson subduction-collision cycles since 3.0 Ga, with the Chilimanzi granites mentioned as examples.

The general shape of the Chivi batholith is similar to that of the Zimbabwe granite, but they differ in thickness, and hence dimensional analysis (Tables 3 and 4; Figs 9 and 10; McCaffrey and Petford 1997; Petford et al. 2000) puts them into different categories- wedge and flat, respectively. It should be noted that the Zimbabwe granite covers a large expanse east of the study area and it is difficult to map its margins in that direction. In this larger outcrop picture (i.e. longer length), it would fit the flat category, extending horizontally in every direction. However, we interpret both the Chivi batholith and the Zimbabwe granite (at least the section studied) as massive, deep-rooted batholithic intrusions, generally oval in shape. These results contradict some geological interpretations of these late, post-kinematic intrusions as sheet-like bodies emplaced at relatively shallow levels in the crust.

The Chilimanzi batholith is equally problematic; the gravity model suggests a wedge shape but the areal extent (dimensional analysis) places it into the flat-floored type. Further, the gravity anomaly is much smaller than the mapped outcrop. However, considering the ‘low density’ section only it appears to be a shallow sheet-like or tabular body at most 2 km thick with a 5 km root zone at its southern end: typical of the thin, flat-floored granite (Ameglio et al. 1997; Ameglio and Vigneresse 1999; Vigneresse et al. 1999; Kurian et al. 2001), with the thick end interpreted as a root zone. This may be consistent with emplacement along narrow channelways, possibly as dykes or sheets that may have exploited shear zones and faults (e.g., Stettler et al. 1990; Dehls et al. ~~1999~~1998; Petford et al. 2000; Blenkinsop and Treloar 2001; Haederle and Atherton 2002; McLean and Betts 2003; Peschler et al. 2004; Ferre´ et al. 2012). The presence of differentiated, late-magmatic granite types (further) attests to the presence of a feeder zone. However, it is also possible that pluton emplacement may be a combination of processes (e.g., Kisters and Anhaeusser 1995; Paterson and Vermon 1995; Ridley et al. 1997; Jelsma and Dirks 2002).

Although diapirism has been invoked as an important process in both the ZC (e.g., Jelsma et al. 1993; Becker et al. 2000; Jelsma and Dirks 2000) and the NMZ (e.g., Rollinson and Blenkinsop 1995; Blenkinsop 2011), this model of emplacement receives little support from our data and analysis.

8 Conclusions

Despite the noted uncertainties in the spatial dimensions of the plutons, it seems likely that there are different geometries in the different granites. The studied plutons follow the general power-law for pluton/batholith dimension and are similar in this respect to the wedge-shaped plutons 6-10 km thick and the classical tabular plutons <5 km thick. In particular:

We interpret both the Chivi batholith and the Zimbabwe granite (at least the section studied) as massive, deep-rooted batholithic intrusions, generally oval in shape.

The Chilimanzi batholith displays an overall sloping floor with the southern end interpreted as a feeder zone, typical of the so-called flat-floored plutons with a gently dipping floor towards the root zone (and irregular shape?).

At the location of the gravity profile, the Nalatale granite fits a wedge model, with a pronounced single feeder zone corresponding to the thickest part extending to 5 km.

The Razi pluton appears to be unique: its overall shape more like a diapir than either a wedge or a tabular body. The configuration is consistent with NMZ overthrust onto the ZC at moderate to shallow angles.

Two of the five studied plutons appear to be tabular, adding to the growing list of such plutons in the Zimbabwe craton, contrary to some established ideas. This emphasises the need for more detailed comparative studies as previously advocated by Blenkinsop and Treloar (2001), and using different techniques (e.g., Vigneresse 1990; Flecha et al. 2006).

Overall, the results confirm the two main granite configurations: sheets/tabular and batholith/wedge; and thus also confirm the two main modes of emplacement: dyke and diapirism or ballooning plutonism. However, this does not rule out a combination of processes for magma emplacement (e.g., Ridley et al. 1997; Becker et al. 2000; Jelsma and Dirks 2002; Zegers 2004; Laurent et al., 2014). Further work in the central and northern parts of the craton is planned.

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References

Ameglio, L., & Vigneresse, J.L. (1999). Geophysical imaging of the shape of granitic intrusions at depth: a review. *Geological Society of London Special Publication, 168*, 39-54.

Ameglio, L., Vigneresse, J.L., & Bouchez, J.L. (1997). Granite pluton geometry and emplacement mode inferred from combined fabric and gravity data. In J.L. Bouchez, D.H.W. Hutton & W.E. Stephens (Eds.), *Granite: From Segregation of Melt to Emplacement Fabrics* (pp. 199-214). Kluwer Academic Publishers, Dordrecht.

Anhaeusser, C.R. (2014). Archaean greenstone belts and associated granitic rocks – A review. *Journal of African Earth Sciences, 100*, 684-732.

Becker, J.K., Siegesmund, S., & Jelsma, H.A, (2000). The Chinamora batholith, Zimbabwe: structure and emplacement-related magnetic rock fabric. *Journal of Structural Geology, 22*, 1837-1853.

Berger, M., & Rollinson, H. (1997). Isotopic and geochemical evidence for crust-mantle interaction during late Archaean crustal growth. *Geochemica et Cosmochimica Acta, 61(22)*, 4809-4829.

Bickle, M.J., & Nisbet, E.G. (Eds.) (1993). *The geology of the Belingwe greenstone belt, Zimbabwe: A study of the evolution of Archaean continental crust*. Geological Society of Zimbabwe Special Publication 2, A.A. Balkema, Rotterdam. p 239.

Blakely, R.J. (1995). *Potential Theory in Gravity and Magnetic Applications*. Cambridge University Press, Cambridge. p 441.

Blenkinsop, T.G. (2011). Archean magmatic granulites, diapirism, and Proterozoic reworking in the Northern Marginal Zone of the Limpopo Belt. In D.D. van Reenen, J.D. Kramers, S. McCourt & L.L. Perchuk (Eds.), *Origin and Evolution of Precambrian High-Grade Gneiss Terranes, with Special Emphasis on the Limpopo Complex of Southern Africa* (pp. 1–24). Geological Society of America Memoir 207. doi:10.1130/2011.1207(13).

Blenkinsop, T.G., Martin, A., Jelsma, H.A., & Vinyu, M.L. (1997). The Zimbabwe Craton: summary of greenstone belt geology. In M.J. de Wit & L.D. Ashwal (Eds.), *Greenstone Belts*. Oxford monograph on geology and geophysics (pp. 567-580). Clarendon Press, Oxford.

Blenkinsop, T.G., & Oberthur, T., & Mapeto, O. (2000). Gold mineralization in the Mazowe area, Harare-Bindura-Shamva greenstone belt, Zimbabwe: I. Tectonic controls on mineralization. *Mineralium Deposita, 35*, 126-137.

Blenkinsop, T.G., & Treloar, P.J. (2001). Tabular intrusion and folding of the late Archaean Murehwa granite, Zimbabwe, during regional shortening. *Journal of the Geological Society of London, 158*, 653-664.

Boschetti, F. (2005). Improved edge detection and noise removal in gravity maps via the use of gravity gradients. *Journal of Applied Geophysics*, 57, 213-225.

Braitenberg, C. (2015). Exploration of tectonic structures with GOCE in Africa and across-continents. *International Journal of Applied Earth Observation and Geoinformation,* 35, 88-95. doi:10.1016/j.jag.2014.013.

Campbell, S.D.G., Oesterlen, P.M., Blenkinsop, T.G., Pitfield, P.E.J., & Munyanyiwa, H. (1992). A Provisional 1:2 500 000 scale Tectonic map and the tectonic evolution of Zimbabwe. *Annals of the Zimbabwe Geological Survey*, Vol. XVI (1991), 31-50.

Campbell, S.D.G., & Pitfield, P.E.J. (1994). *Structural controls of gold mineralization in the Zimbabwe Craton-Exploration Guidelines*. Zimbabwe Geological Survey Bulletin 101, Harare, 270pp.

Cassidy, K.F., Groves, D.I., & McNaughton, N.J. (1998). Late-Archean granitoid-hosted lode-gold deposits, Yilgarn Craton, Western Australia: Deposit characteristics, crustal architecture and implications for ore genesis. *Ore Geology Reviews*, 13(1-5), 65-102.

Castro, A. (1987). On granitoid emplacement and related structures: A review. *Geologische Rundschau*, 76(1), 101-124.

Clark, D.A. (1997). Magnetic petrophysics and magnetic petrology: aids to geological interpretation of magnetic surveys. *AGSO Journal of Australian Geology & Geophysics*, 17(2), 83-103.

Clemens, J.D. (2005). Granites and granitic magmas: strange phenomena and new perspectives on some old problems. *Proceedings of the Geologists' Association*, 116, 9-16.

Collins, W.J., Van Kranendonk, M.J., & Teyssier, C. (1998). Partial convective overturn of Archean crust in the East Pilbara craton, Western Australia- driving mechanisms and tectonic implications. *Journal of Structural Geology*, 20(9–10), 1405–1424.

Comeau, M.J., Unsworth, M.J., Ticona, F., & Sunagua, M. (2015). Magnetotelluric images of magma distribution beneath Volcán Uturuncu, Bolivia: Implications for magma dynamics. *Geology*, 43(3), 243-246

Cooper, G.R.J., & Cowan, D.R. (2011). A generalized derivative operator for potential field data. *Geophysical Prospecting*, 59, 188–194.

Cordell, L., & McCafferty, A.E. (1989). A terracing operator for physical property mapping with potential field data. *Geophysics*, 54, 621-634.

Coward, M.P., & James, P.R. (1974), The deformation patterns of two Archaean greenstone belts in Rhodesia and Botswana. *Precambrian Research*, 1, 235-258.

Coward, M.P., James, P.R., & ~~Wakefield~~Wright, L~~J~~. (1976). Northern margin of the Limpopo Mobile belt, southern Africa. *Geological Society of America Bulletin*, 87, 87601-87611.

Cruden, A.R. (1998). On the emplacement of tabular granites. *Journal of the Geological Society*, 155(5), 853-862.

Cruden, A.R., & McCaffrey, K.J.W. (2001). Growth of Plutons by Floor Subsidence: Implications for Rates of Emplacement, Intrusion Spacing and Melt-Extraction Mechanisms. *Physics and Chemistry of the Earth A*, 26(4-5), 303-315.

Dehls, J.F., Cruden, A.R., & Vigneresse, J.L. (1998). Fracture control of late Archean pluton emplacement in the northern Slave Province, Canada. *Journal of Structural Geology*, 20(9-10), 1145-1154.

Dietl, C., & Koyi, H. (2008). Formation of tabular plutons- results and implications of centrifuge modeling. *Journal of Geosciences*, 53(3-4), 253-261.

~~Dirks, P.H.G.M., & Jelsma, H.A. (1998). Horizontal accretion and stabilization of the Archean Zimbabwa Craton. *Geology*, 26(1), 11-14.~~

~~Dixon, J.M., & Summers, J.M. (1983). Patterns of total and incremental strain in subsiding troughs: Experimental centrifuged models of inter-diapir synclines. *Canadian Journal of Earth Sciences*, 20, 1843-1861.~~

Duuring, P., Cassidy, K.F., & Hagemann, S.G. (2007). Granitoid-associated orogenic, intrusion-related, and porphyry style metal deposits in the Archean Yilgarn Craton, Western Australia. *Ore Geology Reviews*, 32(1-2), 157-186.

Fedo, C.M., Eriksson, K.A., & Blenkinsop, T.G. (1995). Geologic history of the Archaean Buhwa greenstone belt and surrounding granite-gneiss terrain, Zimbabwe, with implications for the evolution of the Limpopo Belt. *Canadian Journal Earth Sciences*, 32, 1977-1990.

Ferre´, E.C., Galland, O., Montanari, D., & Kalakay, T.J. (2012). Granite magma migration and emplacement along thrusts. *International Journal of Earth Sciences (Geol Rundsch)*, 101, 1673–1688. DOI 10.1007/s00531-012-0747-6

Fisk, K., Hawadi, M.T. (1996). *The National Gravity Dataset of Zimbabwe*. Zimbabwe Geological Survey Bulletin 103, Harare. pp 39.

Flecha, I., Carbonell, R., Zeyen, H., Marti, D., Palomeras, I., Simancas, F., & Perez-Estaun, A, (2006), Imaging granitic plutons along the IBERSEIS profile. *Tectonophysics*, 420, 37-47.

Frei, R., Blenkinsop, T.G., & Schönberg, R. (1999). Geochronology of the late Archaean Razi and Chilimanzi suites of granites in Zimbabwe: implications for the late Archaean tectonics of the Limpopo belt and Zimbabwe craton. *South African Journal of Geology*, 102, 55-63.

Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J., & Frost, C.D. (2001). A Geochemical classification for granitic rocks. *Journal of Petrology*, 42(11), 2033-2048.

Galadi-Enriquez, E., Galindo-Zaldivar, J., Simancas, J.F., & Exposito, I. (2003). Diapiric emplacement in the upper crust of a granitic body: the La Bazana granites (SW Spain). *Tectonophysics*, 361, 83-96.

Gore, J., James, D.E., Zengeni, T.G., Gwavava, O. (2009). Crustal structure of the Zimbabwe craton and the Limpopo belt of Southern Africa: new constraints from seismic data and implications for its evolution. *South African Journal of Geology*, 112, 213–228.

Goulty, N.R., Dobson, A.J., Jones, G.D., Al-Kindi, S.A., & Holland, J.G. (2001). Gravity evidence for diapiric ascent of the Northern Arran Granite. *Journal of the Geological Society*, 158(5), 869-876.

Gupta, V.K., & Grant, F.S. (1985). Mineral-exploration aspects of gravity and aeromagnetic surveys in the Sudbury-Cobalt area, Ontario. In W. J. Hinze (Ed.) The utility of regional gravity and magnetic anomaly maps (pp 392-412), Society of Exploration Geophysicists, Tulsa.

Gupta, V.K., Thurston, P.C., & Dusanowskj, T.H. (1982). Constraints upon models of greenstone belt evolution by gravity modeling, Birch-Uchi greenstones belt, Northern Ontario. *Precambrian Research*, 16, 233-255.

Gwavava, O., & Ranganai, R.T. (2009). The geology and structure of the Masvingo greenstone belt and adjacent granite plutons from geophysical data, Zimbabwe craton. *South African Journal of Geology*, 112, 119-132. doi:10.2113/gssajg.112.2.000

Gwavava, O., Swain, C.J., & Podmore, F. (1996). Mechanisms of isostatic compensation of the Zimbabwe and Kaapvaal cratons, the Limpopo Belt and the Mozambique basin. *Geophysical Journal International*, 127, 635–650. https://doi.org/10.1111/j.1365-246X.1996.tb04044.x

Gwavava, O., Swain, C.J., Podmore, F., & Fairhead, J.D. (1992). Evidence of crustal thinning beneath the Limpopo Belt and Lebombo monocline of southern Africa based on regional gravity studies and implications for reconstruction of Gondwana. *Tectonophysics*, 212, 1-20.

Haederle, M., & Atherton, M.P. (2002). Shape and intrusion style of the Costal Batholith, Peru. *Tectonophysics*, 345, 17-28.

Halla, J., Whitehouse, M.J., Ahmad, T., & Bagai, Z. (2017). Archaean granitoids: an overview and significance from a tectonic perspective. *Geological Society London Special Publications*, 449, 1–18.

Harrison, N.M. (1969). *The geology of the country around Fort Rixon and Shangani*. Rhodesia Geological Survey Bulletin 61, pp 152.

Henkel, H. (1991). Petrophysical properties (density and magnetisation) of rocks from the northern part of the Baltic shield. *Tectonophysics*, 192, 1-19.

Henkel, H. (1994). Standard diagrams of magnetic properties and density- a tool for understanding magnetic petrology. *Journal of Applied Geophysics*, 32, 43-53.

Hickman, M.H. (1978). Isotopic evidence for crustal reworking in the Rhodesian Archaean craton, southern Africa. *Geology*, 6, 214-216.

Hofmann, A., Jagoutz, O., Kroner, A., Dirks, P.H.G.M., & Jelsma, H.A. (2002). The Chirwa dome: granite emplacement during late Archean thrusting along the northeastern margin of the Zimbabwe craton. *South African Journal of Geology*, 105, 285-300.

Horstwood, M.S.A., Nesbitt, R.W., Noble, S.R., & Wilson, J.F. (1999). U-Pb zircon evidence for an extensive early Archean craton in Zimbabwe: a reassessment of the timing of craton formation, stabilization and growth. *Geology*, 27, 707-710.

Ishihara, S. (1977). The magnetite-series and ilmenitr-series granitic rocks. *Mining geology*, 27, 293-305.

Jelsma, H.A., & Dirks, P.H.G.M. (2000). Tectonic evolution of a greenstone sequence in northern Zimbabwe: sequential early stacking and pluton diapirism. *Tectonics*, 19, 135-152.

Jelsma, H.A., & Dirks, P.H.G.M. (2002). Neoarchaean tectonic evolution of the Zimbabwe Craton. In C.M.R. Fowler, C. Ebinger & C.J. Hawkesworth (Eds.), The Early Earth: Physical, Chemical and Biological Development (pp. 183-211), Geological Society of London Special Publication 199. London.

Jelsma, H.A., van der Beek, P.A., & Vinyu, M.L. (1993). Tectonic evolution of the Bindura-Shamva greenstone belt (northern Zimbabwe): progressive deformation around diapiric batholiths. *Journal of Structural Geology*, 15, 163-176.

Jelsma, H.A., Vinyu, M.L., Valbracht, P.J., Davies, G.R., Wijbrans, J.R., & Verdurmen, E.A.T. (1996). Constraints on Archaean crustal evolution of the Zimbabwe craton: a U-Pb zircon, Sm-Nd and Pb-Pb whole-rock isotope study. *Contributions to Mineralogy and Petrology*, 124, 55-70.

Johnson, S.E., Albertz, M., & Paterson, S.R., (2001). Growth rates of dike-fed plutons: Are they compatible with observations in the middle and upper crust? *Geology*, 29(8), 727-730.

Kearey, P., Brooks, M., & Hill, I. (2002). *An Introduction to Geophysical Exploration*, 3rd Edition, Blackwell Science, Blackwell Publishing. pp 262.

Kisters, A.F.M., & Anhaeusser, C.R. (1995). Emplacement features of Archaean TTG plutons along the southern margin of the Barberton greenstone belt, South Africa. *Precambrian Research*, 75, 1-15.

Kurian, P.J., Krishna, M.R., Nambiar, C.G., & Murthy, B.V.S. (2001). Gravity field and subsurface geometry of the Kalpatta granite, south India and tectonic significance. *Gondwana Research* ,4(1), 105-111.

Laurent, O., Martin, H., Moyen, J.F., & Doucelance, R. (2014). The diversity and evolution of late-Archean granitoids: Evidence for the onset of “modern-style” plate tectonics between 3.0 and 2.5 Ga. *Lithos*, 205, 208–235.

Li, Y., Yang, Y., & Liu, T. (2010). Derivative-based techniques for geological contact mapping from gravity data. *Journal of Earth Science*, 21(3), 358-364. DOI: 10.1007/s12583-010-0099-8

Lin, S., & Beakhouse, G.P. (2013). Synchronous vertical and horizontal tectonism at late stages of Archean cratonization and genesis of Hemlo gold deposit, Superior craton, Ontario, Canada. *Geology*, 41(3), 359–362.

Liodas, N.T., Gébelin, A., Ferré, E.C., & Misgna, G.M. (2013). Deformation coupling between the Archean Pukaskwa intrusive complex and the Hemlo shear zone, Superior Province, Canada. *Tectonophysics*, 608, 1226–1237. http://dx.doi.org/10.1016/j.tecto.2013.06.022

Lopez, S., Fernandez, C., & Castro, A. (2006). Evolution of the Archaean continental crust: Insights from the experimental study of Archaean granitoids. *Current Science*, 91(5), 607-621.

Ma, G., Huang, D., Liu, C. (2016). Step-edge detection filters for the interpretation of potential field data. *Pure and Applied Geophysics*, 173, 795–803, doi: 10.1007/s00024-015-1053-6.

Mareschal, J.C., & West, G.F. (1980). A model for Archean tectonism. Part 2: Numerical models for vertical tectonism in greenstone belts. *Canadian Journal of Earth Sciences*, 17, 60-71

McCaffrey, K.J.W., & Petford, N. 1997). Are granitic intrusions scale invariant? *Journal of the Geological Society*, 154, 1-4.

McLean, M.A., & Betts, P.G. (2003). Geophysical constraints of shear zones and geometry of the Hiltaba Suite granites in the western Gawler Craton, Australia. *Australian Journal of Earth Sciences*, 50(4), 525-541.

Minnitt, R.C.A., & Anhaeusser, C.R. (1992). Gravitational and diapiric structural history of the eastern portion of the Archean Murchison greenstone belt, South Africa. *Journal of African Earth Sciences*, 15, 429-440.

Mkweli, S., Kamber, B., & Berger, M. (1995). Westward continuation of the craton-Limpopo Belt tectonic break in Zimbabwe and new age constraints on the timing of the thrusting. *Journal of Geological Society London*, 152, 77-83.

Moyen, J.F., Martin, H., Jayananda, M., & Auvray, B. (2003). Late Archaean granites: a typology based on the Dharwar Craton (India). *Precambrian Research*, 127, 103-123.

Nelson, D.R. (1998). Granite-greenstone crust formation on the Archaean Earth: a consequence of two superimposed processes. *Earth and Planetary Science Letters*, 158, 109-119.

Oberthür, T., Davis, D.W., Blenkinsop, T.G., & Höhndorf, A. (2002). Precise U-Pb mineral ages, Rb-Sr and Sm-Nd systematics of the Great Dyke, Zimbabwe: constraints on late Archean events in the Zimbabwe Craton and Limpopo Belt. *Precambrian Research*, 113, 293–305.

Oliveira, D.C., Aall'Agnal, R., Silva, J.B.C., & Almeida, J.A.C. (2008). Gravimetric, radiometric, and magnetic susceptibility study of the Paleoproterozoic Redencao and Bannach plutons, eastern Amazonian Craton, Brazil: Implications for architecture and zoning of A-type granites. *Journal of South American Earth Sciences*, 25, 100-115.

Owen, R., Mikailhov, A., & Maziti, A. (2002). Groundwater occurrence in crystalline basement aquifers: A GIS based study of a borehole dataset in a uniform granitic terrain in southern Zimbabwe. 3rd Waternet/Warfsa Symposium. http://www.waternetonline.ihe.nl/aboutWN/pdf/Owen&al.pdf

Paterson, S.R., & Vernon, R.H. (1995). Bursting the bubble of ballooning plutons: A return to nested diapirs emplaced by multiple processes. *Geological Society of America Bulletin*, 107, 1356–1380.

Pawley, M.J., Van Krenendonk, M.J., & Collins, W.J. (2004). Interplay between deformation and magmatism during doming of the Archaean Shaw Granitoid Complex, Pilbara Craton, Western Australia. *Precambrian Research*, 131, 213-230.

Peschler, A.P., Benn, K., & Roest, W.R. (2004). Insights on Archean continental geodynamics from gravity modelling of granite–greenstone terranes. *Journal of Geodynamics*, 38, 185–207.

Petford, N., & Clemens, J.D. (2000). Granites are not diapiric. *Geology Today*, 16(5), 180-184.

Petford, N., Cruden, A.R., McCaffrey, K.J.W., & Vigneresse, J.L. (2000). Granite magma formation, transport and emplacement in the Earth's crust. *Nature*, 408, 669–673.

Phaup, A.E. (1973). *Chemical analyses of the rocks, ores and minerals of Rhodesia*. Rhodesia Geological Survey Bulletin 71, Salisbury. pp 297.

Pritchard, M.E., & Gregg, P.M. (2016). Geophysical Evidence for Silicic Crustal Melt in the Continents: Where, What Kind, and How Much? *Elements*, 12, 121–127

Ramberg, H. (1981). *Gravity Deformation and the Earth's Crust: Theory, Experiments and Geological Applications*, 2nd edition, Academic Press, London, 452 pp.

Ramsay, J.G. (1989). Emplacement kinematics of a granite diapir: the Chindamora batholith, Zimbabwe. *Journal of Structural Geology*, 11, 191-209.

Ranganai, R.T. (1995). *Geophysical Investigations of the Granite-Greenstone Terrain in the South-Central Zimbabwe Archaean craton*. Unpublished PhD Thesis, University of Leeds, pp 288.

Ranganai, R.T. (2012). Gravity and Aeromagnetic Studies of the Filabusi Greenstone Belt, Zimbabwe Craton: Regional and Geotectonic Implications. *International Journal of Geoscences*, 3(5), 1048-1064. doi:10.4236/ijg.2012.35106

Ranganai, R.T. (2013). Structural and Subsurface Relationships between the Fort Rixon-Shangani Greenstone Belt and the Nalatale Pluton, Zimbabwe, as derived from gravity and aeromagnetic data. *South African Journal of Geology*, 116(2), 273-296.

Ranganai, R.T., & Ebinger, C.J. (2008). Aeromagnetic and LANDSAT TM Structural Interpretation for Identifying Regional Groundwater Exploration Targets, South-Central Zimbabwe Craton. *Journal of Applied Geophysics*, 65, 73-83. http://dx.doi.org/10.1016/j.jappgeo.2008.05.009

Ranganai, R.T., Kampunzu, A.B., Atekwana, E.A., Paya, B.K., King, J.G., Koosimile, D.I., & Stettler, E.H. (2002). Gravity Evidence for a Larger Limpopo Belt in Southern Africa and geodynamic implications. *Geophysical Journal International*, 149, F9-F14. https://doi.org/10.1046/j.1365-246X.2002.01703.x

Ranganai, R.T., Whaler, K.A., & Ebinger, C.E. (2008). Gravity anomaly patterns in the south-central Zimbabwe Archaean craton and their geological interpretation. *Journal of African Earth Sciences*, 51, 257-276.

Ranganai, R.T., Whaler, K.A., & Ebinger, C.E., 2015. Aeromagnetic interpretation in the south-central Zimbabwe Craton: (reappraisal of) crustal structure and tectonic implications. *International Journal of Earth Sciences*. http://dx.doi.org/10.1007/s00531-015-1279-7

Rey, P.F., & Houseman, G. (2006). Lithospheric scale gravitational flow: the impact of body forces on orogenic processes from Archaean to Phanerozoic. *Geological Society London Special Publication*, 253, 153-167.

~~Ridley, J.R., & Kramers, J.D. (1990) The evolution and tectonic consequences of a tonalitic magma layer within Archean continents. *Canadian Journal of Earth Sciences*, 27, 218-228.~~

Ridley, J.R., Vearncombe, J.R., & Jelsma, H.A. (1997). Relations between greenstone belts and associated granitoids. In M.J. de Wit & L.D. Ashwal (Eds.), *Greenstone Belts* (pp. 376-397). Clarendon Press, Oxford.

Robertson, I.D.M. (1973). Potash granites of the southern edge of the Rhodesian craton and the northern granulite zone of the Limpopo belt. In L.A. Lister (Ed.), *Symposium on Granites, Gneisses and Related Rocks* (pp. 265-276). Geological Society of South Africa Special Publication 3.

Robertson, I.D.M. (1974). *Explanation of the geology south of Chibi*. Rhodesia Geological Survey Short Report 41, Salisbury. pp 40.

Rollinson, H.R., & Blenkinsop, T.G. (1995). The magmatic, metamorphic and tectonic evolution of the Northern Marginal Zone of the Limpopo Belt in Zimbabwe. *Journal of the Geological Society of London*, 152, 65-75.

Siegesmund, S., Jelsma, H., Becker, J., Davies, G., Layer, P., van Dijk, E., Kater, L., & Vinyu, M. (2002). Constraints on the timing of granite emplacement, deformation and metamorphism in the Shamva area, Zimbabwe. *International Journal of Earth Sciences*, 91, 20-34.

Simpson, R.W., Jachens, R.C., Blakely, R.J., & Saltus, R.W., (1986). A new isostatic residual gravity map of the conterminous United States with a discussion on the significance of isostatic residual anomalies. *Journal of Geophysical Research*, 91 (B8), 8348-8372.

Singh, A.P., Kumar, V.V., & Mishra, D.C. (2004). Subsurface geometry of Hyderabad granite pluton from gravity and magnetic anomalies and its role in the seismicity around Hyderabad. *Current Science*, 86(4), 580-586.

Smith, C.B., Sims, K., Chimuka, L., Duffin, A., Beard, A.D., & Townend, R. (2004). Kimberlite metasomatism at Murowa and Sese pipes, Zimbabwe. *Lithos*, 76, 219-232.

Smith, W.H.F., & Wessel, P. (1990). Gridding with continuous curvature splines in tension. *Geophysics*, 16, 222-227.

Snowden, P.A. (1984). Non-diapiric batholiths in the north of the Zimbabwe Shield. In A. Kröner & R. Greiling (Eds.), *Precambrian Tectonics Illustrated* (pp. 135−145). E. Schweizerbarts'che Verlagsbuchhandlung, Stuttgart.

Soesoo, A., & Bons., P.D. (2015). From Migmatites to Plutons: Power Law Relationships in the Evolution of Magmatic Bodies. *Pure and Applied Geophysics*, 172, 1787-1801.

Stettler, E.H., de Beer, J.H., & Kleywegt, R.J. (1990). The structure of the Palmietfontein and Entabeni granite plutons as derived from geophysical data. *South African Journal of Geology*, 93(4), 676-682.

Stettler, E.H., de Beer, J.H., Eberle, D., Ludden, J., & Mareschal, M. (1997). Geophysics and Deep Structures. In M.J. de Wit & L.D. Ashwal (Eds.), *Greenstone Belts*, Oxford monograph on geology and geophysics (pp 339-375). Clarendon Press, Oxford.

Stuart, G.W., & Zengeni, T.G. (1987). Seismic crustal structure of the Limpopo mobile belt, Zimbabwe. *Tectonophysics*, 144, 323-335.

Subrahmanyam, C., & Verma, R.K. (1981). Densities and magnetic susceptibilities of Precambrian Rocks of Different Metamorphic Grade (Southern Indian Shield). *Journal of Geophysics*, 49, 101-107.

Subrahmanyam, C., & Verma, R.K. (1982). Gravity interpretation of the Dharwar greenstone-gneiss-granite terrain in the southern Indian Shield and its geological implications. *Tectonophysics*, 84, 225-245.

Sylvester, P.J. (1994). Archean granite plutons. In K.C. Kondie (Ed.), *Archean crustal evolution* (pp 261-314). Elsevier.

Tahiri, A., Simancas, J.F., Azor, A., Galindo-Zaldivar, J., Lodeiro, F.G., El Hadi, H., Poyatos, D.M., & Ruiz-Constan, A. (2007). Emplacement of ellipsoid-shaped (diapiric?) granite: Structural and gravimetric analysis of the Oulmes granite (Variscan Meseta, Morocco). *Journal of African Earth Sciences*, 48, 301-313.

Van Straaten, P. (2002). *Rocks for Crops: Agrominerals of sub-Saharan Africa*. International Council for Research in Agroforestry (ICRAF), Nairobi, Kenya, pp 338.

Vigneresse, J.L. (1990). Use and misuse of geophysical data to determine the shape at depth of granitic intrusions. *Geological Journal*, 25(3/4), 249-260.

Vigneresse, J.L., & Clemens, J.D. (2000). Granitic magma ascent and emplacement: neither diapirism nor neutral buoyancy. *Geological Society Special Publication*, 174, 1-19.

Vigneresse, J.L., Tikoff, B., & Ameglio, L. (1999). Modification of the regional stress field by magma intrusion and formation of tabular granitic plutons. *Tectonophysics*, 302(3-4), 203-224.

Weinberg, R.F. (1999). Mesoscale pervasive felsic magma migration: alternatives to dyking. *Lithos*, 46, 393-410.

Wellman, P. (2000). Upper crust of the Pilbara Craton, Australia: 3D geometry of a granite/greenstone terrain. *Precambrian Research*, 104, 175-186.

Wilson, J.F. (1964). *The geology of the country around Fort Victoria and the Bikita Tinfield*. Southern Rhodesia Geological Survey Bulletin 58, Salisbury. pp 147.

Wilson, J.F. (1990). A craton and its cracks: some of the behaviour of the Zimbabwe block from the Late Archaean to the Mesozoic in response to horizontal movements, and the significance of some of its mafic dyke fracture patterns. *Journal of African Earth Sciences*, 10, 483-501.

Wilson, J.F., Nesbitt, R.W., & Fanning, C.M. (1995). Zircon geochronology of Archaean felsic sequences in the Zimbabwe craton: a revision of greenstone stratigraphy and a model for crustal growth. In M.P. Coward & A.C. Ries (Eds.), *Early Precambrian Processes* (pp. 109-126), Geological Society Special Publication 95.

Won, I.J., & Bevis, M. (1987). Computing the gravitational and magnetic anomalies due to a polygon: algorithms and FORTRAN subroutines. *Geophysics*, 52, 232-238.

Yang, X.M. (2014). Granitoid rocks in southeastern Manitoba: preliminary results of reconnaissance mapping and sampling. *Report of Activities 2014* (pp 49–63). Manitoba Mineral Resources, Manitoba Geological Survey.

Zegers, T.E. (2004). Granite formation and emplacement as indicators of Archaean tectonic processes. In P.G. Eriksson, W. Altermann, D.R. Nelson, W.U. Mueller & O. Catuneanu (Eds.), *The Precambrian Earth: Tempos and Events* (pp 103-118). Elsevier, Amsterdam.

Zeh, A., Gerdes, A., Barton, J.M. (Jr) (2009). Archean Accretion and Crustal Evolution of the Kalahari Craton- the Zircon age and Hf isotope record of granitic rocks from Barberton/Swaziland to the Francistown Arc. *Journal of Petrology*, 50(5), 933-966. doi:10.1093/petrology/egp027

ZGS (1994). Zimbabwe Geological 1:1000 000, 7th Edition (Reprinted), Zimbabwe Geological Survey, Harare. Zimbabwe

Zwaan, J.C., Kanis, J., & Petsch, E.J. (1997). Update on emeralds from the Sandawana Mines, Zimbabwe. Gems & *Gemology*, 33, 80-100.

Figure Captions

Fig. 1 Simplified geology of the south-central Zimbabwe craton showing the major granite-greenstone terrains and the studied plutons. Greenstone belts and granite plutons named after their places of occurrence. Other geological units: TS = Tokwe segment (~3.5 Ga), BGB = Belingwe greenstone belt. (Modified after ZGS 1994, Ranganai et al. 2008 (western part), Gwavava and Ranganai 2009 (eastern part)).

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Fig. 2 Density histogram of rocks (granites and greenstones) from the south-central Zimbabwe craton (Ranganai 1995). The figures at the top of bars are the number of samples in that density range (cf. Table 1).

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Fig. 3 Simple Bouguer gravity anomaly map for the south-central Zimbabwe craton with gravity station distribution and outlines of major geological units. White triangles are stations for the southern Africa seismic experiment (Gore et al. 2009). The positions of the profiles are shown (L1, L2 & L3; L4 & L5 not modeled due to small amplitudes and interference); X-Y is approximate location of seismic traverse (Stuart and Zengeni 1987). Note Bouguer gravity anomaly highs over the greenstone belts and mafic-ultramafic intrusions (Buhwa, B; Gwanda, Gw; Filabusi, FGB; Fort Rixon-Shangani, FRSh; Belingwe, BGB; Masvingo, MGB; MUC, Mashava ultramafic complex; Great Dyke, GD) and lows over the granite plutons (Chivi; Chilimanzi; Zimbabwe; Shangani-Somabhula) as discussed in the text

(Ng = Nalatale granite pluton). DS = mapped dolerite sill. The large ENE-trending high in the SE corner of the map over the northern marginal zone (NMZ) of the Limpopo orogenic belt is related to crustal thinning. The white lines over the Zimbabwe Granite indicate positions for length and width measurements.

Fig. 4 Residual regional aeromagnetic anomaly map for the south-central Zimbabwe craton with outlines of major geological units. DS = inferred dolerite sill. Note the high magnetic signatures over the Razi pluton and the Zimbabwe granite just north of the northern marginal zone (NMZ), Limpopo belt. The white dashed line outlines the enlarged size of the Razi pluton.

Fig. 5 First vertical gravity gradient map for the south-central Zimbabwe craton with gravity station distribution and outlines of major geological units. Geological unit labels (abbreviations) and lines as in Figure 3.

Fig. 6 Apparent Density (g cm^{-3}) map for the south-central Zimbabwe craton with gravity station distribution and outlines of major geological units. Geological unit labels (abbreviations) as in Figure 3. The white lines over the Zimbabwe Granite indicate positions for length and width measurements.

Fig. 7 (a) Regional Bouguer gravity anomaly map and station distribution over the Nalatale granite (Ng) and adjacent greenstone belts, showing location of modelled profile and outlines of major geological units; Byo = Bulawayo greenstone belt; FR = Fort Rixon greenstone belt; Ng = Nalatale granite pluton; Sh = Shangani greenstone belt. (b) Geological cross-section, Bouguer gravity anomaly and 2¾D density model for profile L1, Fort Rixon greenstone belt and Nalatale pluton. Numbers refer to densities in kg/m^3. VE = Vertical Exaggeration (4). The surface of the model relates to the topography while the model cross-section is at sea-level.

Fig. 8 (a) Regional Bouguer gravity anomaly map and station distribution over the Chivi granite/batholith and adjacent greenstone belts, showing outlines of major geological units and location of the modelled profile; GD = Great Dyke; ~~MGB~~ BGB = ~~Mberengwa~~ Belingwe greenstone belt; ZG = Zimbabwe granite; X-Y is approximate location of seismic traverse (Stuart and Zengeni 1987) used as modeling constraint; (b) Chivi granite/batholith, Buhwa (Mweza) greenstone belt and Razi pluton gravity models for L2. The numbers inside the model bodies are densities in kg m^{-3}. The model surface follows the topography. Vertical exaggeration is 1.5 (i.e. vertical to horizontal ratio of 1 to 1.5).

Fig. 9 (a) Regional Bouguer gravity anomaly map and station distribution over the Chilimanzi batholith, Masvingo greenstone belt and Zimbabwe granite, showing outlines (white) of major geological units and location of the modelled profile; X-Y is approximate location of seismic traverse (Stuart and Zengeni 1987) used as modeling constraint; (b) Chilimanzi pluton, Masvingo greenstone belt and Zimbabwe ganite gravity models for Line 3. The numbers inside the model bodies are densities in kg m^{-3}. Other densities: serpentinites 2700 kg m^{-3}, metasediments 2500 kg m^{-3}, phyllites 2580 kg m^{-3}. The model surface follows the topography. Vertical exaggeration is 5 (i.e. vertical to horizontal ratio of 1 to 5).

Fig. 10 Bouguer anomaly profiles (red) and horizontal derivatives (green) across (a) the Chivi batholith (L4, Figure 8a), and (b) the Zimbabwe granite (L5, Figure 9a). MGB = Masvingo greenstone belt; NMZ = North marginal zone (Limpopo belt); ZUCext = Zvishavane Ultramafic Complex extension.

Fig. 11 Length vs Thickness plot for pluton/laccolith models (McCaffrey and Petford 1997; Cruden 1998; Petford and Clemens 2000; Cruden and McCaffrey 2001) and for plutons in this study.

Fig. 12 Field and computed W/T vs L/W ratios for the studied plutons (based on Ameglio et al. 1997; Vigneresse et al. 1999).

Fig. 13 Log volume versus log length for the five granite plutons studied showing an approximate linear trend.

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Table 1 Densities of major rock types of the granite-greenstone terrain, south-central Zimbabwe Craton (After Gwavava and Ranganai, 2009 and references therein).

Table 2. Classification of Late Granites in the south-central Zimbabwe craton according to I-type and S-type (After Ranganai, 1995).

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Table 4 Pluton Tectonic Environment based on analysis of dimensions from outcrop and gravity data (Ameglio et al., 1997; Vigneresse et al., 1999; see also Figs 1 and 2)