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Updated tectonic terrane boundaries of Botswana determined from gravity and aeromagnetic data

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We used existing high-resolution gravity and aeromagnetic data to map the crustal units underneath Botswana. The thick sedimentary cover in this region has always been a challenge to understand the geological and tectonic configuration of unexposed crustal terranes using traditional geological methods. We utilized a standard physical mapping technique to convert previously obtained gravity and aeromagnetic data into apparent density and magnetic susceptibility maps, respectively, of the crustal tectonic terranes. Then, the derived maps were fused into a single apparent physical map to facilitate its geotectonic interpretation. The results showed that most of the tectonic boundaries were inaccurately mapped due to limited availability of high-resolution geophysical information. Moreover, we found that some terranes were missing from the current tectonic map. We used the apparent physical property map and the basement rocks information from literature to significantly update the tectonic map of Botswana, which shows the spatial extent of the geological units beneath the Kalahari sedimentary cover. The new map gives an insight into the geodynamics of Botswana crust.

Introduction

The southern African tectonic region represents a complex geological history that has been shaped by rifting, amalgamation, and intrusive magmatic events (Hartnady et al., 1985; Kröner, 1985). Botswana is crucially located within this region where the different tectonic terranes meet. Furthermore, the region is endowed with the presence of numerous mineral deposits, which includes but not limited to greenstone belts deposits, copper, gold, and diamonds associated with specific tectonic terranes (Evans et al., 2016; Frost-killian et al., 2016; Kinnaird et al., 2016; Pedley et al., 2016; Smith and Beukes, 2016; Tucker et al., 2016; Viljoen, 2016). For instance, diamonds and base metals are located in the ancient cratonic regions in Botswana, South Africa and Zimbabwe, that

requires accurate tectonic terrane identification, mapping and delineation to better investigate this mineral wealth. However, the tectonic terranes in Botswana have undergone multiple episodes of deformation (Begg et al., 2009) including rifting in the Ghanzi-Chobe Zone that resulted in the formation of the Okavango Rift Zone and the Kgwebe volcanism (Modie, 1996), Kibaran Orogeny (Thomas et al., 1993), metamorphism (Aldiss, 1991; Roering et al., 1992; Coward and Fairhead, 2002), the Damara Orogeny (Gray et al., 2008), magmatic intrusions that formed mafic complexes (Hutchins and Reeves, 1980; Aldiss and Carney, 1992) and large scale subsidence that formed the Nosop and the Passarge sedimentary basins (Haddon, 2005). The subsurface processes have rendered the boundaries and internal architecture of the crustal tectonic terranes underneath Botswana not to be well understood (Singletary et al., 2003). This is also partly due to the Carboniferous and Jurassic Karroo sediments and the thick Kalahari sands of Phanerozoic (Cenozoic) origin that concealed ~80% of Botswana's basement structure (Key and Ayres, 2000). As a result, traditional geological mapping methods provide limited information on the geological and tectonic configuration of these unexposed crustal terranes underneath the Kalahari sedimentary cover.

Geophysical methods have been traditionally used for regional reconnaissance, imaging and modeling of crustal blocks. They can provide a rapid, high-resolution, and homogeneous data coverage that enables a detailed and accurate mapping of subsurface structures (Hutchins and Reeves, 1980; Reeves and Hutchins, 1982; Yawsangratt, 2002; Walker et al., 2010; Chisenga, 2015; Ramotoroko et al., 2016; Fadel et al., 2018; Fadel et al., 2020). Better delineation of the terrane boundaries by geophysical methods could help to understand the lithospheric structure that can lead to better mineral exploration programs. In southern Africa for example, geophysical techniques have helped to more accurately define the boundaries for the Congo Craton, Kalahari Craton, Bangwelu Blocks and the discovery of the Niassa Craton east of the Luangwa rift that enables further understanding of the geodynamic evolution of the Archaean crust in this area (Ranganai et al., 2002; Khoza et al., 2013; Sarafian et al., 2018; Emry et al., 2019). In Botswana in particular, geophysical techniques helped to image the

extensions of Archean granite-greenstone terrane from South Africa into southern Botswana, the possible existence of a macro-craton beneath the Nosop Basin, and the extension of the Congo Craton into northern Botswana (Khoza et al., 2013; Ramotoroko et al., 2016; Fadel et al., 2018).

Here, we utilize high-resolution gravity and aeromagnetic data to update the tectonic terrane boundaries of Botswana. We used a standard physical mapping approach to derive the regional apparent density and magnetic susceptibility maps of Botswana from the gravity and aeromagnetic data, respectively. Then, the derived maps were fused into a single apparent physical properties map to highlight the different tectonic terranes in the area. The derived apparent physical properties map was used to define the extent and configuration of tectonic terranes and the relations between Archean and Proterozoic crustal components in Botswana, by identifying tectonic terrane boundaries as they appear in the map. Finally, we produced an interpreted Precambrian basement tectonic map of Botswana that satisfies both the geophysical properties and geological information from previous studies.

Tectonic Setting of Botswana

The tectonic terranes in Botswana have a complex history that reflects a series of rifting, amalgamation, and intrusive magmatic events. Botswana is located between two cratonic terranes: the Congo Craton in the northwest and the Kalahari Craton in the southeast (Fig. 1a). The term Kalahari Craton refers to the Archean block within the southern African tectonic region that comprise of the Zimbabwe Craton, the Kaapvaal Craton and the Limpopo Belt (Begg et al., 2009). The cratonic blocks are surrounded by relatively younger orogenic belts and sedimentary basins of Proterozoic age (Kröner, 1985; Begg et al., 2009; Fig. 1a). The amalgamation of these crustal terranes forms the Precambrian basement tectonic map of Botswana (Fig. 1b). In the following subsections, we will describe the tectonic terranes and their deformation history in chronological order.

Archean Blocks

The summary of the Archean crust in Botswana is adapted from Begg et al. (2009). The Archean units in Botswana include the Zimbabwe Craton (3.5–2.57 Ga), the Kaapvaal Craton (3.7–3.2 Ga), the Congo Craton, and the Limpopo-Shashe Belt (2.7–2.6 Ga, Fig. 1; Hartnady et al., 1985). The Congo Craton and the São Francisco Craton in South America, not shown on the map, are widely accepted to have amalgamated together as a single cratonic block around 2.05 Ga until the break-up of Africa and South America around 140 Ma (Schannor et al., 2019). The Congo Craton is separated from the broader Zimbabwe/Kaapvaal Cratons by the Neoproterozoic Damara and Ghanzi-Chobe Belts (Haddon, 2005). The Damara Belt is subdivided into four units, namely, the Roibok Complex, the Kwando Complex, the Koanaka Group and the Chihabudun Complex (Fig. 1b; Key and Ayres, 2000). The southeastern boundary of the Congo Craton is still poorly defined, despite recent studies placing it in northwestern Botswana (Singletary et al., 2003; Khoza et al., 2013). The Kaapvaal Craton consists of granitoids with gneisses and narrow greenstone belts (Eglington and Armstrong, 2004).

The Archean craton is mostly covered by the Kalahari sands with exposures in the eastern part of Botswana. The craton was intruded by the Molopo Farm's ultramafic rocks and the Tsetseng Complex among others (Hutchins and Reeves, 1980; Reeves and Hutchins, 1982; Key and Ayres, 2000). The Zimbabwe Craton consists of folded volcano-sedimentary sequences of greenstone belts, which are associated with granites and gneisses. The craton was amalgamated to the Limpopo Belt and the Kaapvaal Craton by east-directed movement (Begg et al., 2009).

The Limpopo-Shashe Belt between the Zimbabwe and the Kaapvaal Cratons is a Neo-Archean crust that was reworked in the Proterozoic era (Schaller et al., 1999; Khoza et al., 2013). The Neo-Archean Limpopo-Shashe Belt is divided into the Northern Marginal Zone (NMZ), the Central Zone (CZ), and the Southern Marginal Zone (SMZ; McCourt et al., 1995; Ranganai et al., 2002; Fig. 1b). The belt is highly deformed with different complex tectono-thermal history and several high-grade metamorphic events. Lithologically, the Archean crustal blocks in Botswana are similar, but they differ by the thermo-tectonic regimes that affected their metamorphism (Schaller, 1999).

Proterozoic Blocks

The Proterozoic geology in Botswana consists of mobile belts and major mafic intrusions (Key and Ayres, 2000; Singletary et al., 2003). Furthermore, the Passarge and the Nosop deep sedimentary basins, which are filled with sediments belonging to the Ghanzi-Chobe Group, were formed in the Neoproterozoic era (Haddon, 2005).

The Magondi Belt includes thick sedimentary sequences and volcanic rocks, which were later deformed and metamorphosed (Treloar, 1988; Majaule et al., 2001; Master et al., 2010). Tracing the Magondi belt in Botswana was based on the northeast-trending magnetic structures from the Zimbabwe side, around the Zimbabwe Craton, which joined the Limpopo-Shashe Belt in Botswana (Key and Ayres, 2000). The drill-core geology of high-grade paragneisses at Gweta in Botswana also correlates well with the Magondi Belt lithology at Dett in Zimbabwe (Carney and Dowsett, 1991). The western and northern edges of the Kaapvaal Craton contain the high magnetic Mesoproterozoic basic-ultrabasic Kheis Belt, the Tshane Complex, the Xade Complex, and the Okwa Block, which are overlain by the Kalahari sedimentary cover (Key and Ayres, 2000). The Kheis Belt consists of basalts and clastic sediments located between the Kaapvaal Craton to the east and the Nosop Basin to the west. The Kheis Belt and the Tshane Complex form a distinct high magnetic feature that extends northwards to the Okwa Block (Hutchins and Reeves, 1980). The Okwa Block includes mafic and felsic magmatic complexes (Aldiss and Carney, 1992; Mapeo et al., 2006). The central part of Botswana contains the Xade Complex, which is a magnetic mafic intrusion, sitting next to a small and highly magnetic circular feature termed the Tsetseng Complex.

The Ghanzi-Chobe Zone contains volcano-sedimentary sequences of rocks that overlay the highly magnetic Kgwebe formation and the north-western Botswana rift (Modie, 1996, 2000; Kampunzu, 2000). In this paper, we defined the north western group as the Proterozoic tectonic terranes located in the northwest of the Ghanzi-Chobe Zone. The area is believed to be the southern end of the Congo Craton that lies underneath the exposed Proterozoic rocks (Khoza et al., 2013). Geological terranes in this region are the Kwando Complex, the Quang-

Figure 1. (a) The southern Africa tectonic configuration; and (b) The modified subsurface Precambrian basement tectonic map of Botswana after Key and Ayres (2000), Ranganai et al. (2002), and Singletary et al. (2003).

wadum Complex, the Xaudum Complex, the Tsodilo Hills Complex, the Roibok Complex, the Aha Hills Group, and the Koanaka Group (Fig. 1b; Key and Ayres, 2000). The Roibok Complex, the Koanaka Group, and the Kwando Complex are northeasterly pronounced striking outcrops obscured by Kalahari sedimentary cover. These terranes were mostly mapped using geophysical data (Hutchins and Reeves, 1980; Reeves and Hutchins, 1982), drilled borehole (Singletary et al., 2003) and geological mapping of exposed outcrops (Aldiss and Carney, 1992; Carney et al., 1994; Key and Ayres, 2000; Modie, 2000).

Methodology

Dataset

This study used existing gravity and aeromagnetic data of Botswana, obtained from the Botswana Geosciences Institute (BGI). The data were provided as a 1 km Bouguer anomaly grid (Fig. 2a) and a 50 m TMI grid (Fig. 2b). Previous studies have used the same data to obtain the Moho depth (Leseane et al. 2015; Chisenga, 2015) and to determine the terrane configurations for selected parts of Botswana (Hutchins and Reeves, 1980; Reeves and Hutchins, 1982; Yawsangratt, 2002; Corner et al., 2012; Chisenga, 2015). Furthermore, the data was vital in determining the extent of the greenstone belt from South Africa into southern Botswana as an indicator for hidden mineral potential (Ramotoroko et al., 2016). It was also utilized in the determination of the Curie point depth and the extent of incipient rifting in northern Botswana (Leseane et al., 2015), and the improvement in the understanding of the geological evolution of some tectonic regions in Botswana (Ranganai et al., 2002; Walker et al., 2010). Despite that the data had previously been extensively used, our study obtains new and unique geological terrane configurations beneath the thick Kalahari sand in Botswana by integrating the information from this old gravity and aeromagnetic data

with previously obtained geophysical and geological information.

The gravity data have a spatial resolution of ~ 7.5 km and is based on the compilation of data acquired in two national-wide gravity surveys from 1972-1973 and 1998-1999, with additional data provided by different companies. The first national gravity survey started in 1972, with funding from the British overseas development ministry (Hutchins and Reeves, 1980). The survey was conducted in two phases; the first phase was acquired by aircraft with a gravity accuracy of ± 0.05 mGal and a total of 23 gravitational base stations. The second phase involved the establishment of 1854 gravity stations, tying of 277 gravity stations from northern Botswana survey with an accuracy of ± 0.03 mGal. The survey involved ground sampling with a sample distance of 10 km. Furthermore, 300 stations in inaccessible areas were acquired by a helicopter (Hutchins and Reeves, 1980). The second survey had an average density of 37 gravity stations per 100 km² (Yawsangratt, 2002). It filled the gaps that were not covered by the first survey of 1972-1973.

The aeromagnetic data is a compilation of different surveys and dataset from different companies acquired since the 1960s. The first aeromagnetic survey started in October 1975, with a total of 150,000 km lines survey flown and interpreted in 1977 (Reeves and Hutchins, 1982). To fill in the gaps of the first survey, a new survey was carried out in 1977 and 1987 that covered the entire Botswana. The data was compiled into one dataset in early 1990s and then added to the data acquired by the new survey of 1996.

Apparent Density

Apparent density mapping transforms Bouguer gravity anomalies into density distribution, with an assumption that the rock densities vary laterally and not vertically to a certain depth (Gupta and Grant, 1985). We separated the long-wavelength signal that are approximately associated with mantle sources using a 1000 km Butterworth high pass filter from the Bouguer anomaly (Block et al., 2009). This gravity regional-

Figure 2. (a) The Bouguer anomaly map; and (b) the Total Magnetic Intensity (TMI) map.

residual separation procedure (see: Blakely, 1995) made the residual gravity anomaly comparable to the magnetic anomalies of crustal sources (Leseane et al., 2015; Li et al., 2017). The filtered data represents an approximation of the crustal gravity signals, which was then used for apparent density calculation, as implemented in Geosoft's Oasis Montaj (2007). We set the average crustal density to 2,700 kg/m³ and defined the layer model as the crustal layer from 200 m, maximum thickness of Kalahari cover, for western Botswana and 0 km for exposed eastern part (Key and Ayres, 2000), to an estimated depth of ~40 km, the average crustal thickness of Botswana (Fadel et al., 2018) as parameters.

Apparent Magnetic Susceptibility

Apparent magnetic susceptibility mapping transforms the magnetic anomaly into magnetic susceptibility values (Letros et al., 1983). The process reduces signal overlaps from different bodies by removing the regional anomaly and enhancing lithological contacts of rocks with different susceptibilities. Firstly, we applied the reduction to the pole (RTP) filter to the aeromagnetic data to remove the effect of anomaly asymmetry caused by inclination of the magnetic field, so that anomalies are correctly positioned, above the causative bodies (Blakely, 1995). Due to the vastness of the study area, the RTP application was zoned to conform to the latitude and longitude of the region (Table 1) based on the International Geomagnetic Reference Field (Finlay et al., 2010). Then, the data was downward continued to 200 m, the maximum thickness of Phanerozoic Kalahari sands (Key and Ayres, 2000), thereby calculating magnetic plane closer to the sources, reducing the spatial overlap between anomaly sources and making the source more distinguishable (Blakely, 1995). Curie point depth (CPD) in Botswana has an average value of 14 km based on the new world curie point depth map (Li et al., 2017), of higher depth values in the Nosop Basin and North-eastern Ghanzi-Chobe Zone. The calculated apparent magnetic susceptibility values in electromagnetic unit (e.m.u.) were then converted into SI unit by multiplying by a factor of 12.57 (Clark and Emerson, 1991). For clarification, we assume that the magnetizations in the study area are mainly due to induced magnetization. We do not consider the remnant magnetization effect in our processing.

Apparent Physical Property Map

The apparent physical properties map was produced through a fusion of the apparent density and apparent magnetic susceptibility maps using a color scheme approach (Everaerts, 1990; Yawsangratt, 2002; Chisenga, 2015). The average crustal density of 2,700 kg/m³ was used as the cut-off point to separate high and low-density rocks. The apparent density map was assigned to a continuous color, cyan to yellow, representing low-density rocks and high-density rocks on each end, respectively. Zonation of apparent magnetic susceptibility used a subjective approach; rocks with higher apparent magnetic susceptibility than sedimentary rocks (~0.018 SI) were classified as high susceptibility rocks, while rocks with lower magnetic susceptibility as sedimentary rocks were classified as low/non-magnetic susceptibility rocks. The apparent magnetic susceptibility map was assigned to a continuous color, from white to magenta, representing the non-magnetic rocks and the high magnetic rocks on each end, respectively. Then, we zoned the apparent physical property map based on the combined apparent densities and magnetic susceptibilities into four end-members. Colors were assigned to each end member as follows; (1) high-magnetic, high-density (HM-HD) represented by red, (2) high-magnetic, low-density (HM-LD) represented by blue, (3) low/non-magnetic, high density (LM-HD) represented by yellow, and (4) low/non-magnetic, low-density (LM-LD) represented by cyan. This was done to enable the joint spatial interpretation of the apparent physical property information.

Results

Aeromagnetic Map

In this section, we provided the steps on how we created a sketch map for the terranes that show high magnetic content (> 120 nT), as shown in Fig 3, based on the aeromagnetic map, as shown in Fig. 4. Aeromagnetic map shows a crustal magnetization pattern in different locations and terranes (Fig. 4). The grayscale aeromagnetic map exhibits different magnetic zones and patterns in the data (Fig. 4a). In the south-

Table 1. Parameters for the apparent susceptibility calculation for each of the region

No	Region	X ^(*)	Y ^(*)	Inclination ^(*)	Declination ^(*)	Total magnetic intensity ⁽⁺⁾
1	Nosop basin	20.96	-24.04	-64.11	-14.2	28327.38
2	Kheis-Tshane 1	21.6	-25.5	-64.7	-15.8	28029.56
3	Kheis-Tshane 1	21.9	-25	-63.88	-14.12	28592.68
4	Okwa Block	21.9	-25.6	-63.14	-12.8	28941.16
5	Tsengeng Complex	23	-23.37	-63.2	-13.33	28769.11
6	Molopo Farm Complex	24	-25	-63.9	-15.3	28402.65
7	Xade Complex	23.3	-22.7	-62.8	-12.67	29012.59
8	Northwestern Botswana	21.5	-19.3	-60.37	-9.46	29948.41
9	Ghanzi-Chobe 1	21.81	-28.8	-65.59	-19.6	27301.35
10	Ghanzi-Chobe 2	23	-19.8	-60.52	-9.72	29833.76
11	Ghanzi-Chobe 3	23.8	18.7	-59.24	-8.65	30156.43
12	Ghanzi-Chobe 4	25	-18.5	-58.72	-8.4	

*Values are in degrees.

+Values are in nT.

Figure 3. The sketch map for the magnetic bodies in Botswana identified from aeromagnetic data, as shown in Figs. 3 (b, c, d and e).

ern part, it is relatively difficult to differentiate the zones than in the northern part. Some of the areas that are identified are the dyke swarms, the Magondi Belt, the Kgwebe Formation and the Passarge Basin. Fig. 4b shows the large positive anomalies in the Quangwadum Complex, the Kgwebe Formation and the dyke swarms. Other occurrences of high magnetic bodies are located on the northeast side of Fig. 4b. Yawsangratt (2002) described them as granitic intrusions in the Ghanzi-Chobe Zone. The dyke swarms cross-cut the Kgwebe Formation in the Ghanzi-Chobe Zone in the central part of the map in Fig. 4b. This makes separation of the Kgwebe Formations and the dyke swarms emplacement at the locations 20° S and 22.5° E difficult. Fig. 4c shows two of the high magnetic bodies that are located in central Botswana. These bodies correspond to the Tsetseng and Xade Complexes that are interpreted as gabbroic intrusion and possible carbonatite, respectively (Reeves and Hutchins, 1982). Fig. 4d shows the Molopo Farm ultramafic complex, which has a large positive anomaly located in southern Botswana (Gould et al., 1987; Walker et al., 2010). The map also indicates some magnetic low within this complex (Fig. 4d). Finally, Fig. 4e shows the north-south trending high magnetic body that originates from Cape

Province in South Africa into central Botswana. It forms a magnetic high on the western edge of the Kaapvaal Craton. They correspond to the Kheis Belt, the Tshane Complex and the Okwa Block (Reeves and Hutchins, 1982). Within the Okwa Block, we identified a number of clustered high magnetic intrusions/bodies that previously have not been mapped and are identified as part of basement structure in this study. The identified magnetic features form part of the tectonic terranes in Botswana, as shown on the sketch map in Fig. 3.

Apparent Physical Properties Map

The apparent physical properties map is based on apparent density map and apparent magnetic susceptibility map, as shown in Figs. 5a and 5b, respectively. The values were compared to measured densities (Hunt et al., 1995) and magnetic susceptibilities (Clark and Emerson, 1991). We associated physical significance to the calculated values by assigning their values to corresponding rock types found in Botswana

Figure 4. (a) Gray scale image of TMI that highlights the pattern in the magnetic data due to terrane similarities; and (b)-(e) highlighted high magnetic bodies in Botswana.

(Table 2). Based on the apparent physical properties map, as shown in Fig. 6, we identified regions with unique apparent physical properties, interpreted based on previous known information from other studies.

Geotectonic Interpretation

In this section, we significantly update the existing Precambrian basement tectonic map based on aeromagnetic information and its derived sketch map (Figs. 3 and 4) and the apparent physical properties map of Botswana (Fig. 6).

Northwestern Botswana

The northwestern Botswana refers to all tectonic terranes northwest of the Ghanzi-Chobe Zone. This region has three distinct apparent physical properties signature of LM-HD (yellow), LD-LM (cyan) and LD-HM (blue), suggesting a relatively uniform lithology over a large area, which has not undergone an extensive or a similar thermal-tectono-metamorphic processes (Fig. 6).

In this region, a distinct feature is the high density and low magnetic belt, previously and partly mapped as rocks associated with granite gneiss and, to some extent, with amphibolite, locally called Roibok Complex (Key and Ayres, 2000; Singletary et al., 2003). The Precam-

Figure 5. (a) Apparent magnetic susceptibility map. The calculation produced negative values, which represents non-magnetic rocks; (b) Apparent density map.

Table 2. Classification of rocks in Botswana based on geophysical information extracted from Fig. 5a and Fig. 5b, geological information obtained from Key and Ayres (2000), magnetic susceptibilities information obtained from Clark and Emerson (1991) and densities information obtained from Hunt et al. (1995). The second part of the table shows the classification of the physical map based on the information extracted from Fig. 6 in relation to rocks found in Botswana; based on combination of their densities and susceptibilities as shown in first part of the Table

Mag Susceptibility Classification	Range (SI)	Rock types	Values (SI)	Density Classification	Range (kg/m ³)	Rock types	Values (kg/m ³)
High magnetic susceptibility	0.025 and above	Gabbro	0.09	low density	2520-2670	Syenite Acidic igneous rocks Granite Sedimentary rocks	2500 2610 2640 2300–2700
		Ultra-mafic rocks	0.2				
		Basic rocks	0.12				
		Gneissitic granitoid/migmatite/					
		Granite gneiss	0.025				
		Granite	0.05				
Dolerite	0.062						
Low magnetic susceptibility	0–0.025	Sedimentary rocks Amphibolites	0.018	high density	2670-2900	Granitic gneiss	2670
			0.0075			Gneissitic granitoid	2670
						Dolerite	2890
						Amphibolite	2960
						Migmatite	2800
Color	Physical meaning	Density value (kg/m ³)	Magnetic value (SI)	Rocks			
Blue Red Cyan Yellow	LD–HM	2520–2670	Above 0.025	Syenite, Granites, granite gneiss, gneissitic granitoid Dolerite, Ultramafic rocks, Basic rocks, Migmatite, Gabbro Sedimentary rocks Granite gneiss, Amphibolites			
	HD–HM	2680–2900	Above 0.025				
	LD–LM	2520–2670	0–0.024				
	HD–LM	2680–2900	0–0.024				

brian geological map of Singletary et al. (2003) indicates that some parts of the basement is concealed by young strata (Fig. 1). This obscured basement is partly an extension of the Roibok Complex underneath the strata. The similarity and continuation of the apparent physical property are characteristic to the Roibok Complex.

Key and Ayres (2000) describe the metasedimentary rocks north of the Quanguadum Complex as belonging to the Tsidiolo Hill Group and the Xaudum Group. These two groups are distinguished due to the presence of ironstone in the Xaudum group, which are missing in the Tsidiolo Hill Group. Thus, we separated these two regions and remapped them based on the apparent physical properties map. To the north of the Roibok Complex, the Tsidiolo hill Group is characterised by intrusions of high magnetic bodies, which are comparable to the Tsidiolo

Group on the western part. The region in between these two terranes belongs to the Xaudum Group.

Both the aeromagnetic map (Fig. 4b) and the apparent physical properties map (Fig. 6) have shown the extent of the Quanguadum Complex underneath the concealed geology. The terrane shows an HM-LD signature with densities of less than 2,670 kg/m³ and magnetic susceptibilities above 0.025. It is relatively larger than the previously geologically mapped terrane. Key and Ayres (2000) discussed the presence of syenite, granite, granitic gneiss and gneissitic granitoid that confirms the correlation between apparent physical signature and geological information of the Quanguadum Complex.

The Kwando Complex is located east of the Roibok Complex. It is defined by a northeasterly striking magnetic outcrops of granite gneiss,

Figure 6. Apparent physical property map of Botswana based on the fusion of apparent density map, as shown in Fig. 5a and apparent magnetic susceptibility map as shown in Fig. 5b. Also shown are: (1) the Precambrian basement tectonic map of Botswana, which was presented in Fig. 1, as white polygons; (2) interpreted Precambrian basement tectonic map based on this study as black polygons, and (3) the basement borehole location as shown in Singletary et al. (2003).

granite, amphibole-gneiss, migmatite and meta dolerite (Carney et al., 1994). A borehole drilled in this region (CKP 10) intersected basement at ~218 m, which confirmed the presence of granite gneiss that contains thin, discontinuous, biotite-rich folia (Meixner and Peart, 1984). The northeastern boundary of the Kwando Complex cross-cut the Kgwebe Formation belonging to the Sinclair Group based on the high-magnetic signature. We redefined this boundary to the northwestern part of the high-magnetic and high-density Kgwebe Formation (Fig. 6). The new boundary also cross-cut the drillhole CKP 10A, whose core contained gabbroic to dioritic rocks dated to ~1,107 Ma (Meixner and Peart, 1984; Singletary et al., 2003). Singletary et al. (2003) interpreted this as part of the event that emplaced the basaltic and rhyolitic bodies of the Northwest Botswana Rift.

Ghanzi-Chobe Zone

The Ghanzi-Chobe Zone comprises the Ghanzi Group sediments

and the Kgwebe Formation. The Okavango Rift System (Modisi, 2000) and the Okavango Dyke Swarms (Le Gall et al., 2005) are also located in or cut through the Ghanzi-Chobe Zone, respectively. The bimodal basaltic volcanism that formed the Kgwebe Formation occurred ~1,106 Ma during the initiation of the Northwest Botswana rift (Carney et al., 1994; Modie, 1996). The Giant Dyke Swarm of Botswana, which are highly magnetic due to its mafic composition of basalts, dolerites and minor gabbros, postdate the Kgwebe Formation occurring between 883 Ma and 115 Ma (Bertrand et al., 2002). Thus, this crosscutting relationship between the two magnetic bodies poses a great deal of a problem when interpreting the aeromagnetic data. In our interpretation, we included the mapped high-magnetic features with a northeasterly trend within the Ghanzi-Chobe Zone as belonging to the Kgwebe Formation (Fig. 4b). Nevertheless, we used the existing mapped features where the feature cross-cut the dyke swarms as aeromagnetic data could not differentiate the bodies (Fig. 6).

Sedimentary Basins

The Passarge Basin is a Neoproterozoic sedimentary basin in central Botswana within the Ghanzi-Chobe Zone (Modie, 1996). It shows a HM-HD physical signature and a suppressed expected LM-LD sedimentary apparent physical property signature. Key and Ayres (2000) indicated the presence of magnetic meta-sediments in this region, while Corner et al. (2012) proposed that the high magnetic body in this region is the “Northern Lobe” of the Xade Complex extending into the Passarge Basin. Fadel et al. (2018) showed that the region has a possible mafic lower crust based on V_p/V_s ratio. We suggest that the mafic region in the Passarge Basin is not an extension of the Xade Complex, but a separate mafic body with meta-sediments and mafic lower crust. Firstly, the relatively thin crust underneath the basin does not support the extension of the Xade Complex underneath the basin (Fadel et al., 2018). Secondly, the large part of the ‘Northern Lobe’ has different density rocks to that of the southern Xade Complex (Fig. 6). The extent of Passarge Basin is redefined based on the aeromagnetic and the apparent physical properties maps (Figs. 4a and 6). Aeromagnetic data shows a smooth texture in this region in which most of it conforms to the current boundary. Nevertheless, a different lithology appears on the western edge of the Passarge Basin that was redefined as the new boundary of the basin. Slightly magnetic signature are within the confinement of the boundary, which correspond to the geophysical studies (Mason, 1998; Key and Mapeo, 1999).

Key and Ayres (2000) describe the Nosop Basin as an accumulation of the Ghanzi Group sediments, which were overlain by the Nama Group sediments. The Nosop Basin has a thickness of ~15 km (Key and Ayres, 2000). On average, this suggests basement thickness of ~24 km, based on 39 km average crustal thickness of the Nosop Basin after Fadel et al. (2018). In this region, there are three high-magnetic bodies with HM-HD signature on the apparent physical properties map (Figs. 4c and 6), underneath the 15 km thick sediments. This could indicate a presence of a possible thick mafic lower crust. The V_p/V_s ratio suggests a felsic lower crust in this region, based on the V_p/V_s map of Botswana by Fadel et al. (2018). However, we cannot be conclusive enough as Fadel et al. (2018) used two points, one in the northern Nosop and another one in the Kheis Belt, which are outside the high magnetic bodies, to extrapolate the lower felsic crust in this region. We have included these magnetic bodies as “mafic complexes of unknown age” in the interpreted Precambrian basement tectonic map of Botswana, as they show similar apparent physical signature to other mafic complexes. The origin of these mafic complexes would be further discussed in the discussion section.

High Magnetic Bodies

Mapping the magnetic bodies, started in the late 1970’s (Hutchins and Reeves, 1980), with more additions to the initial understanding in following years (Gould et al., 1987; Le Gall et al., 2005; Corner et al., 2012; Ramotoroko et al., 2016). Some of the Proterozoic terranes that exhibit a magnetic signature in Botswana are the Kheis Belt, the Okwa Terrane, the Xade Complex and the Molopo Farms Complex (Key and Ayres, 2000). They exhibit average densities between 2,680 kg/m³ and 2900 kg/m³ (Fig. 5a) and magnetic susceptibilities above 0.025 (Fig. 5b). The Xade Complex, the Tsetseng Complex, the Tshane Complex, the Molopo Farm Intrusions and the Kheis Belt as they

appear in the present Precambrian basement tectonic map (Key and Ayres, 2000; Singletary et al., 2003) are direct adaptation of first aeromagnetic mapping of Botswana (e.g., Hutchins and Reeves, 1980; Reeves and Hutchins, 1982). Then, the aeromagnetic data was of low resolution such that the spatial extents of these bodies were poorly constrained. Thus, we update the extent of these magnetic bodies as they appear on the aeromagnetic map (Figs. 3 and 4) and the apparent physical properties map (Fig. 6).

The Kheis Belt is the north-south trending highly magnetic body in the southwestern Botswana that defines the western edge of the Kaapvaal Craton. Hutchins and Reeves (1980) described it as a magnetic feature of folded sedimentary rocks with a low-density in the subsurface that extend from Cape Province in South Africa. The southern end of the Kheis Belt was previously mapped slightly east of the intrusion (Fig. 6). We suggest that the boundary should be slightly west of the current boundary in-line with the HM-HD signature on the apparent physical property map, as adopted from the aeromagnetic data (Fig. 4e).

The Tshane Complex is located north of the Kheis Belt and includes ~200 km of unexposed Mesoproterozoic basic-ultrabasic bodies (Carney et al., 1994; Key and Ayres, 2000). The Tshane Complex is spatially bigger and slightly westward on the existing basement geology map (Fig. 6; Key and Ayres, 2000; Singletary et al., 2003) than on the apparent physical property map and aeromagnetic map (Figs. 4d and 6). We base our interpretation on the spatial location and extent, including the shape of the Tshane Complex between the existing basement bodies and the structure as mapped on the aeromagnetic and apparent physical property information. We suggest that the Tshane Complex should be slightly smaller and to the east of the present mapped location, as indicated on Figs. 3 and 6.

The Okwa Block developed furthest north of the Tshane-Kheis Complex. Aldiss and Carney (1992) describe it as having an inlier magnetic feature belonging to the Kaapvaal Craton, within a mafic and felsic composition of the Okwa Complex. The Okwa inlier appears as a small mafic intrusion (white polygon in Fig. 4e) surrounded by the LM-LD area (Fig. 6). We define the region with a similar magnetic pattern as the extent of the Okwa Complex and the isolated magnetic bodies as the Okwa inlier (Fig. 6).

Two magnetic bodies are also visible within the central part of Botswana; the Xade Complex and the Tsetseng Complex. The Xade Complex is completely covered by the sedimentary rocks of the Kalahari Group but shows both HM-HD values (Fig. 6). Nevertheless, due to high resolution of aeromagnetic data in comparison with gravity data, we used the extent of the aeromagnetic data in this region (Fig. 4c) to redefine the boundary of the Xade Complex based on the interpreted basement geology map of Botswana. We also used the same approach to map a highly magnetic but smaller and almost circular Tsetseng Complex. The Molopo Farm Complex is highly magnetic ultrabasic intrusions in southern Botswana. Despite being an ultrabasic complex, some parts of the Molopo Farms have an HM-LD response and signature. The Molopo Farm Complex was actually delineated based on limited aeromagnetic data, which did not cover the entire intrusion (Hutchins and Reeves, 1980). The region is also known to be in proximity with some remnant of banded iron formations (Smith and Beukes, 2016) and is associated to the layered mafic complex of the Kaapvaal Craton and the Bushveld Complex (Viljoen, 2016). Thus, we used the current data to reinterpret the full extent of these features.

Eastern Botswana

In this paper, Eastern Botswana is defined as the collection of tectonic terranes located between the eastern part of the Kaapvaal Craton and the southeastern part of the Ghanzi-Chobe Zone. This definition places the Magondi Belt, the Limpopo-Shashe Belt and the Zimbabwe Craton as the terranes within Eastern Botswana.

Key and Ayres (2000) described the Magondi Belt as a northeast-trending magnetic terrane of northeast Botswana that connects to the exposed southwestward trending Magondi Belt segment in Zimbabwe. The lithological similarities of the unexposed Magondi Belt beneath the Karoo strata in Botswana was confirmed by correlating the lithologies intersected at a drillhole in the Gweta area with the exposed Magondi Belt in the Dett area in Zimbabwe (Carney and Dowsett, 1991). Aeromagnetic information allowed us to highlight this northeast-trending structure in east Botswana with clear boundaries to the north and south (Fig. 4a). This is also confirmed on the apparent physical properties map where major density bodies are aligned with the defined boundaries forming an abrupt transition from HM-HD to HM-LD region (Fig. 6). We readjusted the boundary of the Magondi Belt along this features but considering the occurrence of Kubu Island Granite, as shown in Fig. 6. The Kubu Island Granite in the Sua Pan area is geologically defined as a granitic intrusion in the Archean crust that forms the southeastern boundary of the Magondi Belt with the Zimbabwe Craton (Key and Ayres, 2000; Majaule et al., 2001). The Magondi Belt makes a boundary with a northeastern trending narrow non-magnetic feature, approximately 370 km

long and 25 km wide in the north. Perhaps, the feature represent the opening of the major Kalahari Suture, and it spatially correlate with the feature mapped by Hutchins and Reeves (1980).

The boundary between the Magondi Belt and the Limpopo-Shashe Belt is not clearly seen on the geophysical data. Thus we adopted the boundaries defined by Ranganai et al. (2002). They used gravity data and existing geological information to define the boundary between the Limpopo-Shashe Belt and the Zimbabwe Craton as the Shashe thrust zone (Ranganai et al., 2002). Then, the three division of the Limpopo-Shashe Belt (SMZ, CZ and NMZ) were defined based on the lithological and structural similarities. The Shashe Shear Zone forms a boundary with the Zimbabwe Craton, and the Dinokwe Thrust forms a boundary with the Kaapvaal Craton, while the Lechana Fault and Mahalapye Shear Zone separate the CZ from SMZ and NMZ. This readjustment is in line with the current interpretation on the apparent physical property map, despite that the present boundary between the Kaapvaal Craton and the Limpopo-Shashe Belt was slightly westward of the newly interpreted boundary.

Interpreted Precambrian Basement Tectonic Map of Botswana

The above interpretation of the aeromagnetic map (Figs. 3 and 4) and apparent physical properties map (Fig. 6) has led to the production of an updated Precambrian tectonic map of Botswana (Fig. 7). The newly interpreted map satisfied both geophysical and geological constraints and show tectonic boundaries of these geological terranes.

Figure 7. The interpreted subsurface Precambrian basement tectonic map of Botswana with updated tectonic terrane boundaries.

Discussion

The updated tectonic terrane boundaries of the Precambrian basement structure (Fig. 7) exhibit the Proterozoic and Archean crust amalgamation, which show the tectonic and geological configuration beneath the thick Kalahari sedimentary cover. Northwestern Botswana is geologically identified as a Proterozoic terrane based on a few mapped outcrops (Key and Ayres, 2000) that belong to the Damara orogenic belt (Begg et al. 2009). However, recent studies using seismic data (Fadel et al., 2018) and magnetotelluric data (Khoza et al., 2013) have indicated that the region is a possible extension of an Archean Congo Craton into northwestern Botswana. This suggests that the region is a possible over-thrust collisional zone in which the Damara Belt lies on top of the Congo Craton. Furthermore, the geophysical properties of northwestern Botswana are similar to those of the southern part of the Kaapvaal Craton in Botswana, with patches of HM-HD rocks. As discussed, the preservation of physical properties in northwestern Botswana can complement the seismic, gravity and magnetotelluric studies to indicate the stability of this region, thus could suggest a cratonic signature. This is just a proposal as more geophysical investigations, especially seismics, needs to be done to verify this assertion and the lithospheric thickness in this area.

Another possible cratonic region is located in the northern part of the Nosop Basin. Fadel et al. (2018) and Fadel et al. (2020) argued for the presence of the Maltahohe micro-craton in the northern end of the Nosop Basin, based on their crustal thickness and V_p/V_s ratio distribution and the shear wave velocities of the region, respectively. The buried craton is likely south of the suggested area, based on the similar physical signatures of the area to the proposed Congo Craton and the Kaapvaal Craton. The three mafic intrusions within the suggested region of the buried Maltahohe micro-craton could indicate intrusive events similar to the Bushveld intrusive event ~2.05 in the Kaapvaal craton. However, we cannot be conclusive based on the data from this study as a denser network of seismic stations is required to determine the depth extension of these mafic intrusion, the lithospheric thickness of the keel and its seismic velocity, rather than just based on the argument of an apparent physical properties results and crustal thickness values. Moreover, the 3D shear wave velocity model of Fadel et al., (2020) had a coarse resolution of 1 degree that cannot provide a detailed image of the crustal structure of the region. Therefore, we propose seismological investigations to be conducted around the area that shows a relatively high magnetic signature. Since around the world, in all continents, most cratons present low density signature due to the nature of lithology associated with cratons.

Conclusion

In this paper, we have shown that the relationship between basement structure and apparent physical properties of rocks in Botswana can be investigated using gravity and magnetic properties. This has enabled us to define the configuration and extent of the geological units and tectonic terranes beneath the thick Kalahari sedimentary cover in Botswana. Thus, integrating seismological information, geologic structure and apparent physical properties of rocks, important

conclusions could be reached regarding the crustal processes. By combining the apparent magnetic susceptibility and apparent density maps into an apparent physical properties map and its relation to the known geological structure, we have interpreted the geophysical information and produced an interpreted Precambrian basement tectonic map of Botswana.

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