The internal structure and geotectonic setting of the Xade and Tsetseng complexes in the westernmost part of the Kaapvaal Craton.

Gaud Pouliquen & Roger Key

British Geological Survey, West Mains Road, Edinburgh, Scotland, EH9 3LA.

Abstract

The Xade Complex is an unexposed Y-shaped body, approximately 100 km long and 25km wide, located close to the western margin of the Kaapvaal craton in Botswana. The complex is characterized by large coincident magnetic and gravity anomalies. It is completely covered by varying thicknesses of Kalahari sediments as well as by Karoo strata, which means that detailed analysis of high resolution airborne magnetic data, ground gravity data and limited seismic data are essential in interpreting the internal configuration of the complex. An earlier interpretation of the first airborne magnetic survey of Botswana (Reeves, 1978) coupled with subsequent drilling discovered the Xade Complex and showed that it is made up of mafic and ultramafic rocks. However, the limited amount of drilling did not provide sufficient information to either interpret in detail its internal geology or its regional geotectonic setting (Meixner and Peart, 1984). New 2D and 3D gravity and magnetic modelling have constrained the geometry of the complex as a syncline defined by folded mafic lavas and high-level sub-volcanic mafic sheets. The Xade Complex lies within a graben that forms the N-S arm of a triple junction with the faulted western margin of the Kaapvaal Craton. The focal point of the triple junction coincides with an inflection of the cratonic margin and is the likely site of the feeder zone to the mafic lavas of the Xade Complex. The Tsetseng Complex is shown to be an internally layered, magnetite-bearing gabbro.

1. Introduction

The Xade Complex, together with the neighbouring Tshane Complex and Rakops Dyke form a suite of mafic bodies along the south-western margin of the Kaapvaal Craton (Figure 1). The neighbouring Tsetseng Complex is within the Kaapvaal Craton. All of these complexes were first identified as anomalously magnetic units by national airborne magnetic surveys (Reeves, 1978~~; Key and Ayres, 2000~~). They are all unexposed and completely covered by Kalahari beds and Karoo strata.

The present study uses data from a newly acquired high-resolution airborne magnetic survey as well as from borehole information to (1) define the internal structure of the Xade and Tsetseng complexes, and (2) to define the structural controls on the emplacement of these complexes. This will provide new insights into the end-Mesoproterozoic geological history of the western part of the Kaapvaal Craton.

2. *Tectonic setting*

The northern part of the Xade Complex is aligned along the 'Kalahari Suture Zone' (Mason, 1998), first identified by Reeves (1978) as a two-component structure comprising the NE-SW Makgadikgadi Line and the more southerly N-S Kalahari Line (Figure 1a). This composite structure defines the western edges of the Kaapvaal and Zimbabwe cratons. The Makgadikgadi Line also defines the SE margin of the NW Botswana Rift (Key and Mapeo, 1999; Key and Ayres, 2000). This fault originated as a major thrust at about 2 Ga and reactivated as a normal fault downthrowing to the NW on the eastern side of the NW Botswana Rift during Mesoproterozoic, Neoproterozoic and early Palaeozoic times (Mason, 1998; Key and Mapeo, 1999). Ongoing seismicity along the fault suggests that it remains active (Reeves, 1978). The Tsetseng Complex lies further to the east within a strongly faulted part of the Kaapvaal Craton. Major fractures are inferred to be conduits for ascending magma to feed the Xade and Tsetseng complexes.

Both the Xade and Tsetseng complexes are part of the Umkondo Igneous Complex or Large Igneous Province described by various authors (Hall et al., 2001; Bullen and Hall, 2002; Bullen et al., 2004; Singletary et al., 2003; Hanson et al., 2006). They have used geochemical, geochronological and palaeomagnetic data to identify widespread tholeiitic magma emplaced at ~1112-1106 Ma, over an area of about 2 X 10^6 km^2, mostly across what is now southern Africa (Figure 1). The southern and eastern margins of this igneous province are defined by Mesoproterozoic ('Kibaran') orogens whereas in western Botswana the magmatism continues across a Mesoproterozoic deformation belt (of the NW Botswana Rift). In this westernmost area the Umkondo magmatism is bimodal with felsic and mafic lavas and volcaniclastic sediments (Modie, 1996; Schwartz et al., 1996; Kampunzu et al., 2000; Singletary et al., 2003). This off-craton magmatism is interpreted as A-type derived by partial melting of relatively juvenile crust (Kampunzu et al., 1998; Hanson et al., 2006). By contrast, the Xade and Tsetseng complexes are more typically wholly mafic to confirm their cratonic setting. However, 3 distinct geochemical groups comprising calc-alkaline as well as more typical tholeiitic basaltic rocks have been identified from the Xade Complex (Bullen and Hall, 2002) and this is one line of evidence used to suggest that the Umkondo magmatism was caused by an upwelling Mantle plume (Hanson et al., 2006).

A regional greenschist to lower amphibolite facies tectonothermal event dated at between 1193 and 1093 Ma in the Okwa inlier to the west of the Xade Complex may also be due to the increased geothermal gradient associated with the Umkondo magmatism (Van Straten, 1955; Boocock and Van Straten, 1962; Crockett & Jennings, 1965; Key and Rundle, 1981; Carney et al., 1994; Ramokate et al., 2000). Hanson et al. (2006) also note widespread contemporaneous thermal disturbance of Palaeoproterozoic rocks including alteration at 1110±44 Ma (K-Ar date) of the Moshaneng Dolerite of south-eastern Botswana and deuteric alteration seen in cored rocks from the Tshane Complex. Contemporaneous brittle, vertical faulting in central southern Botswana could control pre-Karoo ENE-WSW trending monoclinal folds of Waterberg strata (Jones, 1973a & b; Crockett and Jones, 1975; Key, 1983; Aldiss et al., 1989).

3. Xade Complex

The original description by Reeves (1978) showed that the Xade Complex is a geometrically complex unit with a thin, curvilinear, E-W to NE-SW trending north-western part along the margin of the Kaapvaal Craton, and a wider southern body that extends southwards and then eastwards into the Kaapvaal Craton. Reeves (1978) suggested that the E-W 'arm' of the complex dips at about 66° to the NE and that the NE-SW 'arm' is subvertical along the 'Makgadikgadi Line' (Figure 1a, b). He concluded that the southern portion, that is approximately 120km long and 25km wide may be tightly folded. The coincident high magnetic and positive gravity anomalies of the Xade Complex were attributed to the presence of ultrabasic rocks.

Borehole CKP-6 (Figures 1 and 2) penetrated into the E-W 'arm' of the complex and intersected 101m of dolerite and gabbronorite with variable grain size (Meixner and Peart, 1984). The gabbronorite has been dated by U-Pb on zircons at 1109.0±1.3 Ma (Hanson et al., 2004b). Boreholes CKP-6A and XH1 penetrated into the southern part of the complex. CKP-6A intersected dolerite at 419m (Meixner and Peart, 1984). XH1 intersected lavas at 621m, unconformable below Karoo rocks, and exited the lavas at 1388m to enter quartzites assigned to the Waterberg Group by previous authors.

3.1 A re-interpretation of the Xade Complex using the latest high-resolution airborne magnetic data

A strong fault control on the Xade Complex is confirmed. Many of these faults have an expression in the magnetic anomaly, providing the framework for the location of this body (Figure 2). It is located to the south of a major inflexion in the 'Kalahari Suture Zone' caused by the intersection of the NE trending 'Makgadikgadi Line' and a NW trending major fault in the Kaapvaal Craton. Its form is clearly controlled by regional structures, with the main segments of the body being flanked by N-S, NW-SE and E-W faults. The southern part of the Complex lies a long the major, curviplanar, ~E-W fault that was reactivated during the Mesozoic as a normal fault downthrowing to the north. It now defines the southern margin of the main outcrop of Karoo lavas in central Botswana.

The age of 1109.0±1.3 Ma on a gabbronorite provides the best constraint on the emplacement age of the complex.

3.1.1 Gravity and Magnetic anomalies

This structural frame is clearly identified on the magnetic and gravity anomalies. The Total magnetic anomaly was gridded at a 60 m spacing and the Bouguer gravity anomaly (Figures 2a and c) at a 1 km spacing (using a reduction density of 2.67 gcm^{-3}). The resolution of the gravity field is limited by the data distribution and the accuracy with which station elevations were measured (Reeves and Hutchins, 1976).

The complex is characterized by a gravity high which approximately mirrors the shape of the structural syncline. The Bouguer anomaly reaches a maximum value of almost 30 mGal (after removal of a regional trend) in the northern part of the complex (Figure 2d). To the west, this complex is bordered by a north-south elongated negative anomaly that defines the edge of the Kaapvaal craton (Figures 2a and c). Another remarkable feature in the magnetic anomaly is the limit of the Karoo volcanics, marked by the sharp disappearance of high-frequencies anomalies associated with the volcanics to the west and south of the complex (Figures 2b and c). To the east of the area, this limit also bounds the E-W trending Karoo dykes, absent to the west of the complex.

The magnetic anomaly envelope coincides with the gravity anomaly but exhibits a more complex pattern characterized by series of short wavelength concentric anomalies. These anomalies are likely to reflect magnetic contrasts between successive volcanic units. A broader positive feature somewhat off centred towards the northern edge of the complex forms the body's core. The south eastern extremity of the complex is affected by an ENE trending fault which has created a discordant isolated "lozenge" shaped body. The magnetic anomalies are characterized by high amplitudes (700 nT to 850 nT), with a broad positive feature to the northeast and a narrower positive stripe close to the southwestern margin. The detailed pattern and the overall shape of the magnetic anomaly strongly suggest that the complex is made of tightly folded magnetic layers.

3.1.2 Boreholes data

Only two boreholes have been drilled to intersect this body, by Anglo American in the 1990s. Borehole XH1 penetrated through Kalahari sediments and sub horizontal Karoo strata before intersecting lavas at 621m (Table 1). Shales assigned to the Palaeoproterozoic Waterberg Group were intersected at 1351 m to indicate a total lava thickness of 730 m (Table 1). Borehole, CKP-6A, drilled on the western edge of the Xade Complex, intersected dolerite at 419m.

Physical property measurements on samples from this borehole indicate that the lavas have a magnetic susceptibility of 0.1 - 0.45 SI (average of 0.2 SI; Wellfield Consulting Services Ltd personal communication), a remanent intensity of 0.6 up to 64 A/m, all the measurements indicating a normal polarity, and densities of 2.7 gcm^{-3} - 3.0 gcm^{-3} (average of 2.84 gcm^{-3}).

Depth (m)	Lithology
0-119	Kalahari beds
119-470	Ecca Group strata
470-555	Mafic sheet
555-580	Ecca Group strata
580-621	Dwyka Group glacigenic strata
621-1140	Mafic lavas (Xade Complex)
1140-1351	Mafic sheet (Xade Complex)
1351-1741	Waterberg Group shales

Table 1. XH1 borehole summary log. (Borehole located at 23º 46’ 29” E 23º 06’ 00” S). The Ecca and Dwyka formations are part of the Karoo Supergroup.

In addition, the CKP6 and CKP6A boreholes also intersected gabbro and dolerite sheets within the complex that have similarly high magnetic susceptibility (0.03 -0.4 SI). However, it is inferred from the modelling and analysis presented here that the mafic units are the main source of the gravity and magnetic anomalies.

3.1.3 3D modelling of gravity anomaly

In order to constrain the shape of the complex and test the “syncline” hypothesis, we carried a 3D inversion of the gravity anomaly. The area covered by the inversion excludes the E-W and NE-SW arms of the complex (see area A in Figure 2c). A 3D model of the subsurface was constructed which had three layers: a digital terrain model, the base of the Karoo Group and the base of the Xade Complex. Based on the boreholes data, the base of the Karoo strata was fixed at 600 meters below the ground surface (500 m above datum), and the base of the complex was initially defined as a flat surface lying at the same depth. The base of the Karoo Supergroup defines a clipping surface for the syncline (i.e. it was not allowed to extend above this level).

Apart from the Xade Complex itself, a uniform density was applied to all pre-Karoo rocks, although it is recognized that this may be an oversimplification (although the surrounding rocks are dominated by siliciclastic sedimentary rocks that will have a uniform density). Alternative models were generated in which the complex was assigned a density contrast of 0.1 gcm^{-3}, 0.2 gcm^{-3} and 0.3 gcm^{-3}. Only the complex was assigned any magnetization, and it was assumed that this was in the direction of the Earth’s present field.

The input grids were resampled to 200 meters and a regional gravity field was removed from the Bouguer anomaly using a linear trend, which was 5 km low-pass filtered. We then ran a structural inversion of the residual Bouguer anomaly that only allowed the base of the complex to be modified. This workflow was iterated using the three densities contrasts.

The three models produce a comparable misfit between the observed and predicted gravity anomalies (Table 2). The surfaces of the syncline base calculated using the three density contrasts: +0.1 gcm^{-3}, |+0.2 gcm^{-3} and +0.3 gcm^{-3} are illustrated in figures 3 and 4. The main mismatch occurs in the eastern part, where the north-south trending gravity low is not properly recovered and errors over the complex itself were smaller that the overall misfit statistics suggest.

Model	Model 1 (Δd=0.1 gcm^{-3})	Model 2 (Δd=0.2 gcm^{-3})	Model 3 (Δd=0.3 gcm^{-3})
Misfit after inversion (standard deviation)	5.4 mGal	5.0 mGal	4.9 mGal
Xade Complex max depth below datum	10000 m	4000 m	2270 m
Xade Complex max thickness	10500 m	4500 m	2800 m

Table 2. Gravity inversion results summary (gravity misfit, predicted depth and thickness of the complex).

We used these models to forward compute the magnetic anomaly generated by the complex assuming that it had a uniform, averaged magnetic susceptibility of 0.075 SI units. The longer wavelength components of the observed magnetic anomaly are well reproduced, considering the simplicity of the model. The anomaly amplitudes are underestimated, but the property measurements from samples in XH1 provide scope for incorporating higher values. The calculated field lacks the short wavelength concentric magnetic anomaly pattern in the observed field. An attempt was made to divide the complex into differently magnetized layers in 3D but this proved difficult and subsequently a 2D approach has been preferred to refine the model.

3.1.4 Refined 2D magnetic modelling

As well as drilling, Anglo-American Corporation undertook some seismic reflection surveys within the area, including a regional N-S line, KG-01, crossing the south-eastern part of the Xade complex and intersecting the borehole XH-1 (Figure 3). The seismic section has been depth converted to allow comparison with the calculated depth of the syncline, using a logarithmic function between average velocity and two-way time based upon a two-layer model of 3 km/s down to 400ms and 5 km/s at later times than this. A 2D model of the subsurface has then been constructed (Figure 4). The starting model had four horizons: a digital terrain model, the base of the Kalahari beds, the base of the Karoo Group and the base of the Xade Complex derived from 3D modelling (using a density contrast of +0.2 gcm^{-3}).

A good match between the observed and calculated Bouguer anomalies is obtained using a single density contrast between the complex and the host rocks (+0.2 gcm^{-3} based on density measurements from core). No attempt has been made to modify the shape of the complex as the geometry based on 3D modelling provides a very good fit with the observed Bouguer anomaly. Further modelling was conducted in an attempt to improve the match between the observed and calculated magnetic anomalies and to reproduce fine structures of the magnetic anomaly. We subdivided the syncline into a series of interleaved magnetized layers and introduced magnetic susceptibility variations among layers, in the range of the measured susceptibilities (susceptibilities range from 0.16 SI to 0.06 SI). As for the 3D model, only the complex was assigned any magnetization, and it was assumed that this was in the direction of the Earth's present field. The highest magnetic susceptibility is located within the upper layers within the complex and decreases to 0.01 SI in the lowest layer (Figure 4).

3.2 Geometry of the Xade complex (comparison with seismic Line KG-01)

Although the three models produce a similar synclinal shape, they predict very different thicknesses (Table 2), from a 2.3 km thick body with the highest density contrast (0.3 gcm^{-3}) to a 10 km thick body with the lowest density contrast. We superimposed cross-sections through the three models on the reflection seismic section for profile KG-01 to see if this would provide additional control (Figure 4).

The results of the modelling and comparison with the observed magnetic anomaly pattern demonstrate that the complex does not itself have a distinct seismic signature, but that the overall form of the syncline is defined by reflections from underlying sedimentary units. It is likely that scattering and attenuation of seismic energy in the thickest part of the igneous sequence has prevented the imaging of underlying strata in the axial region. Despite this, it is possible to identify the most appropriate density contrast on the basis of the match between the modelled flanks of the complex and the seismic imaging of underlying structure. This comparison suggests that a contrast of between +0.2 gcm^{-3} and +0.3 gcm^{-3} is most appropriate. Accordingly, results of inversions suggest a depth extent of approximately 3 km for the complex.

This is compatible with the results of the XH1 borehole, although the densities of samples from that borehole suggest a contrast towards the lower end of the range. The model indicates that the complex has three approximately linear components with N-S, NW-SE and E-W trends respectively, and that it is thickest in the northern part of the N-S component. This may represent the feeder zone for the mafic lavas along the western bounding fault of the Kaapvaal Craton.

4 Tsetseng Complex

The Tsetseng Complex was discovered by Reeves (1978), who described its main feature as a 15km in diameter, circular anomaly interpreted as due to a cylindrical ultrabasic body. Smaller anomalies to the NW were also noted. An associated NE-SW magnetic anomaly was thought to possibly be an associated acidic intrusion or zone of granitisation.

4.1 A re-interpretation of the Tsetseng Complex using the latest high-resolution airborne magnetic data

The Tsetseng Complex itself along with its satellites, forms discreet coincident magnetic and gravity anomalies, and reflects the presence of mafic intrusives in the basement at depths of between 700 and 1000m (see borehole data below).

The Tsetseng Complex is a group of 6 bodies, the largest being approximately 15km in diameter located to the NE of Kang (Figure 1). They appear as discrete dipolar magnetic anomalies, positive north and negative south. They are are clearly associated with a high gravity anomaly, roughly NS, which extends to the SE and is caused by a zone of thinner upper crust (Figure 2d) and is delimited by faults to the east and west. These features are parallel to the southern arm of the Xade complex and faults which appears to have controlled the location of the Xade Complex some 50kms to the NE. While no dating information is available for the Tsetseng Complex, it is generally inferred to be part of the~1110Ma magmatic event due to its proximity to the dated Xade Complex.

4.1.1 Magnetic and gravity anomalies

The gravity field (Figure 2d) is characterized by a pronounced, up to 37 mGal, positive anomaly over the main body of the Complex, bordered to the north-east by a north-south elongated negative anomaly. The gravity high coincides with a strong (+870 nT / -980 nT) magnetic anomaly (Figure 2a) but the gravity low has no magnetic counterpart.

4.1.2 Boreholes data

The largest body has been drilled in 2002 by a Canadian junior exploration company Opawica Explorations Inc. Borehole Tsetseng-1 (Table 3), intersected granites immediately below the Karoo at a depth of 547m, passing down into magnetite-bearing gabbros at 840 m and ending in the same lithology at a depth of 1000 m. Disseminated pyrite and sparse quartz veins are present in the gabbro. No geochemical data are available for this borehole.

BH Tsetseng 1	Long 23^o 2' 44" E
	Lat 23^o 19' 14" S
0 –146 m	Kalahari
146 – 259 m	Beaufort
259 -298	Dolerite sill
298 – 486	Ecca sandstones
486 -547	Dwyka shales
547 – 840	Hornblende Granite
840 - 1000	Gabbro

Table 3: Tsetseng –1 borehole summary log

Physical property measurements on samples from this borehole indicate that the gabbro has a density of 2.95 – 3.12 gcm^{-3}, a magnetic susceptibility of 0.15 - 0.53 SI, and remanent magnetic intensity of 0.7 – 1.9 A/m. The overlying granite has a lower density (2.67-2.71 gcm^{-3}), magnetic susceptibility (0.02 - 0.06 SI) and remanent magnetisation (0.008 – 0.04 A/m). Therefore, the dense and magnetic gabbros are very likely to be the sources of both the magnetic and gravity anomalies.

4.1.3 2D Modelling of the gravity and magnetic anomalies

In order to make a preliminary assessment of the geometry of the complex, 2D gravity and magnetic models were constructed along profiles across it, including the N-S profile shown in Figure 5. A satisfactory fit to the gravity anomaly is obtained with a single density contrast between the complex and the host rocks (+0.33 gcm^{-3}) and a reasonably simple geometry. The model predicts that the complex is about 4.5 km thick in its central part and has an asymmetric shape, being deeper and thinner to the north than to the south. Lateral magnetization variations matching the measured samples properties have been introduced to match the observed magnetic anomaly (with susceptibilities ranging from 0.16 SI to 0.06 SI). The inclusion of a reversed remanent magnetic component (declination and inclination of the earth's field are –13° and +63° respectively) in two of the model components improves the fit to the southern flank of the anomaly and accounts for the dipolar character of the anomaly (Figure 5).

4.1.4 3D gravity modelling

Using a similar approach to the Xade complex, a 3D model of the subsurface was constructed which had 5 layers: a digital terrain model, the base of the Kalahari beds, the base of the Karoo Group and top and base of the Tsetseng Complex. The base Karoo was fixed at 500 meters below the ground surface, and the top and base of the complex were initially defined as flat surfaces lying at 4500 m below datum.

The property ranges employed in the modelling are shown in Table 4. Apart from the Tsetseng Complex itself, a uniform density was applied to all pre-Karoo rocks, although it is recognised that this may be an oversimplification. Only the complex was assigned any magnetisation, and it was assumed that this was in the direction of the Earth's present field.

Layer	Density (gcm	Susceptibility (S
Kalahari	2.1-2.3	0
Karoo	2.3-2.6	0
Pre-Karoo (excluding Tsetseng Comple	2.67-2.9	0

complex	2.67-3.1	0.05-0.1
basement	2.67-2.9	0

Table 4. Density and susceptibility ranges used for the modelling

Once the initial model had been built, a structural inversion of the unfiltered Bouguer anomaly was run that only allowed the top surface of the complex to be modified; different densities contrast between the complex and the host rocks were tested, in the range of the densities listed in table 4.

The final model, which produces the best fit between the observed and the calculated anomalies, was defined with the following physical properties: 1.down to the base of the Kalahari Beds: 2.14 gcm^{-3} average density; 2. from the base Kalahari to the base of the Karoo Group: 2.60 gcm^{-3}; 3. from the base of the Karoo to the top of the Tsetseng Complex: 2.67 gcm^{-3} and 4. finally for the Tsetseng Complex itself: 3.0 gcm^{-3}. The half space density of the model is fixed to 2.67 gcm^{-3}.

The assumed density contrast between the Tsetseng Complex and the surrounding rocks is thus +0.33 gcm^{-3}. This value is consistent with the one indicated by 2D gravity modelling and with the measured density of gabbroic rocks in the Tsetseng-1 borehole. For comparison, an apparent density distribution has been computed by running an inversion for density of a 3000 meter-deep buried flat layer, starting with a uniform density of 2.67 gcm^{-3}, all other parameters and interfaces remaining unchanged. From the range of densities tested, a threshold contrast of +0.2 gcm^{-3} is required to generate a realistic gravity anomaly. The main mismatch between the observed and calculated Bouguer anomalies occurs in the north-east, where the north-south trending gravity low is not properly recovered.

The possible contribution of the density contrast across the Karoo-Kalahari interface was also investigated, but this is very small compared to the effect of the Tsetseng Complex. The modelling is insensitive to the density that is assumed for the Karoo Supergroup (apart from an influence on the assumed background field) because of the uniform thickness of that layer.

The standard deviation of the misfit between observed Bouguer anomaly and the calculated Bouguer anomaly after the structural inversion is 4.3 mGal (for comparison a 5.2 mGal standard deviation was obtained when a density of 2.9 gcm^{-3} was assumed for the complex).

The magnetic anomaly computed from the 3D geometry based on gravity inversion duplicates the overall form of the observed anomaly, although there are discrepancies. Assuming an uniform susceptibility within the complex requires a magnetic susceptibility of up to 0.1 SI units to match the amplitude of the anomaly. Although this value is quite high for gabbroic rocks, it is consistent with the susceptibilities measured on borehole samples and implies that the bulk of the complex has a high magnetite content. The main discrepancy is in the failure of the magnetic field computed from the model to match the negative lobe of the observed anomaly on the south side of the complex. This suggests that there are differences in the geometry of the gravity and magnetic sources. Remanent magnetisation may also have an influence, as suggested by the results of the 2D modelling, although the values for the Königsberger ratio (Q) in the measured gabbroic samples is low (averaging about 0.2). A better match is obtained when a southern lobe of the complex indicated by the gravity modelling is assumed to be non-magnetic. As expected, because of its greater depth, a refined geometry of the base of the complex does not have a significant effect on the calculated magnetic anomaly.

4.2 Geometry of the Tsetseng complex

The overall shape of the complex obtained by the inversion is illustrated in Figure 6. The source body measures ~20 km x 30 km, and has a NW-SE trending, slightly ellipsoidal form. As suggested by the preliminary 2D modelling, it has an asymmetrical cross section, with the eastern flank dipping more steeply than that on the west. This overall shape has been obtained for all inversion runs, independently of the density contrast. At its highest point, the maximum thickness of the complex is 5700 m. If the density contrast between the complex and basement is reduced to +0.23 gcm^{-3}, a maximum thickness of 6900 m is estimated.

5. Tshane Complex and Rakops Dyke

The nearby Tshane Complex is a 300 km long dyke like body emplaced along the N-S Kalahari Line (Reeves, 1978). Interpretations of primary airborne magnetic data indicate that this complex is steeply dipping and may extend to considerable depths (Reeves, 1978; Meixner and Peart, 1984; Brett et al., 2000). A single borehole (CKP-8C) penetrated through overlying Kalahari beds and Karoo strata into 23m of deuterically altered, medium to coarse-grained gabbronorite and leucogabbronorite, locally with cumulate texture (Hanson et al., 2006). Samples from the core have yielded Rb-Sr and $^{40}Ar/^{39}Ar$ dates ranging from 1105±11 to 1021±86 Ma (Key and Mapeo, 1999; J. Barton, in Carney et al., 1994).

The Rakops Dyke was not identified during the first national airborne magnetic survey of Botswana (Reeves, 1978) because it lies within the highly magnetic NW-SE trending Karoo dyke swarm that cuts across central Botswana. However, it was delineated in the second, higher resolution airborne magnetic survey of the 1990s (Key and Ayres, 2000). It has not been drilled and has a relatively thin cover (locally less than 100m) of Karoo and Kalahari deposits.

6 Conclusions

The Xade Complex

The interpretation of the available seismic and 2D and 3D analysis of the high-resolution airborne magnetic geophysics together with the results of exploration drilling completed by Anglo American in the 1990s indicates that the Xade Complex probably comprises a layered basic volcanic complex, with a bulk density of approximately 2.87 gcm^{-3} and having distinct magnetic layering. By reference to the available reflection seismic data the body is deduced to have a depth extent of approximately 4.5 km, with a deeply buried feeder zone, below 600m of cover rocks, and possibly located along the western bounding fault of the Kaapvaal Craton.

Modelling of the Xade Complex has shown it to be layered, and the drilling information indicates that the layering comprises both intrusive doleritic (sub-volcanic) sheets and extrusive lavas. The Complex is bounded by faults and infills a N-S graben that forms the southern arm of a triple junction with major faults that mark the western boundary of the Kaapvaal craton (Figure 1). It is suggested that tholeiitic magma ascended along the focal point of the triple junction before erupting as lava flows into the southern graben across the crystalline basement of the Kaapvaal Craton. Later movement along the bounding N-S faults to the Xade Complex deepened the graben to preferentially preserved the lavas and underlying sub-volcanic gabbroic sheet. A Mesozoic example of this type of fault-controlled preservation of flood basalts is provided in central Botswana where up to about 1000m of Karoo basalts are still preserved in several grabens (Key and Ayres, 2000). Hanson et al. (2006) noted that exposed parts of the Umkondo magmatic event are erosional remnants of what must have been much more voluminous extrusive magmatism.

The synclinal architecture of the Xade Complex may also be a direct response to the vertical faulting. The folding pre-dates deposition of the overlying Karoo strata. The N-S axial trace of the syncline contrasts with the ENE-WSW axial traces of pre-Karoo folds seen in Waterberg group strata of eastern Botswana. These eastern folds are also controlled by faults in the underlying crystalline basement (Jones, 1973a and b; Crockett and Jones, 1975; Key, 1983; Aldiss et al., 1989). This would either suggest that the fold orientations either reflect the orientations of the controlling faults or that the folds formed at different times under different stress systems. The first scenario would relate to regional uplift, possibly in response to a rising Mantle plume that caused the Umkondo magmatism.

The Tsetseng Complex

Modelling indicates that the main body is depth limited to a thickness of about 4km, and was intruded from a northerly direction. The body is clearly not homogeneous and appears vertically layered or zoned to some extent. Results from the Tsetseng-1 borehole coupled with the geophysics interpretation suggest that the rocks forming the body are dense, about 3.0 gcm^{-3}, magnetite-bearing gabbros.

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