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3D Geometry of the Xade Complex inferred from Gravity and Magnetic Data

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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 geology or to fully assess its mineral potential (Meixner & 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 with a potential feeder zone along a major fault that defines the western margin of the Kaapvaal craton.

INTRODUCTION

The Xade Complex generates a series of pronounced concentric magnetic anomalies (Figure 1) and a positive gravity anomaly (Figure 2). Based on the XH1 borehole (see location on Figure 1), it is assumed that the sources of these anomalies are likely to be interleaved mafic basaltic sheets, about 500 meters thick, which were extruded during the Mesoproterozoic (~1.1 Ga, Hanson, 2003) and are now preserved within a sub-Karoo NW-SE trending syncline. The aim of the 3D modelling described here was to confirm the synclinal nature of the complex and to better quantify its vertical dimensions and lithological composition. Due to the complexity of the magnetic anomalies over the Xade Complex, the structural inversion was initially conducted using the gravity anomaly only, as this provided the most stable means of resolving the overall geometry. An attempt was then made to subdivide a magnetic model in 2D and 3D, in order to elucidate the finer structure of the magnetic anomaly. However, this could only be successfully achieved in 2D.

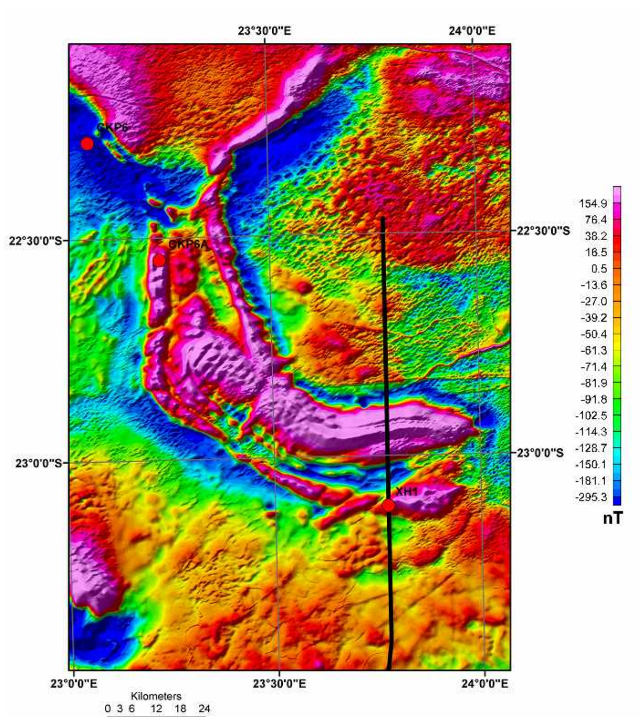

Figure 1: Total Magnetic Intensity over the Xade complex. Seismic line boreholes referred in the text are indicated.

GRAVITY AND MAGNETIC FIELDS

The magnetic anomaly was provided as a 60 m grid of Total Magnetic Intensity (TMI; Figure 1) and the Bouguer gravity anomaly (Figure 2) as a 1 km grid (using a reduction density of

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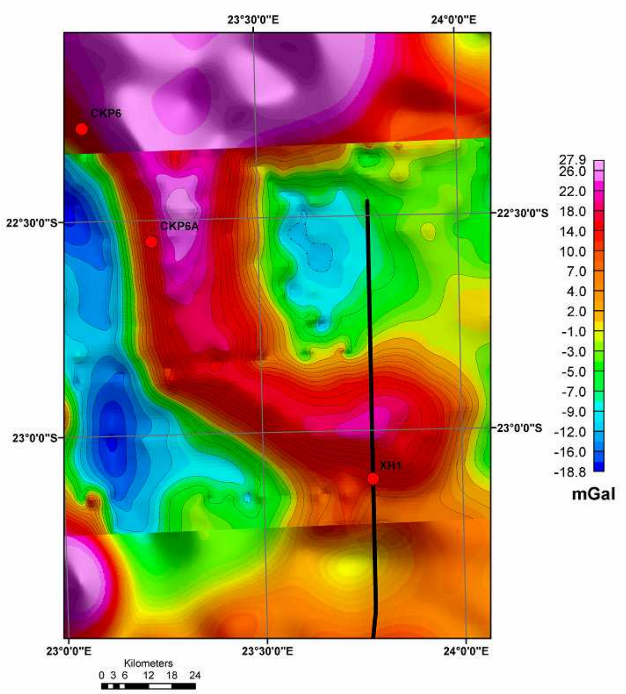

Figure 2. Bouguer gravity anomaly (Left; mGal). The contours of the anomaly are displayed only in the area used for the inversion.

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 & 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 (see Figure 2). To the west, this complex is bordered by a north-south elongated negative anomaly that defines the edge of the Kaapvaal craton.

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. 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.

BOREHOLE DATA

Only 2 boreholes have been drilled to intersect this body. 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, a remanent intensity of 0.6 up to 64 A/m and densities of 2.7 gcm-3 - 3.0 gcm-3.

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.

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

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 extrusive units are the main source of the gravity and magnetic anomalies.

2D MODELLING

A SEGY file has been provided of the N-S seismic line KG-01 which crosses the south-eastern part of the Xade Complex (Figure 1). The seismic section has been depth converted 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 3). 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 see further discussion below).

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. In order to match the fine structures of the magnetic anomaly we have subdivided the syncline and introduced susceptibility variations (Figure 3; susceptibilities range from 0.16 SI to 0.06 SI). 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.

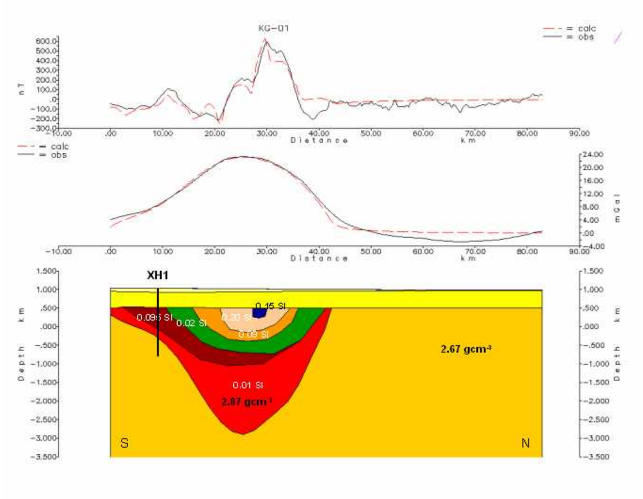

Figure 3: 2D gravity and magnetic modelling across the Xade complex (along line KG-01).

3D MODELLING

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. The base Karoo 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 Waterberg sediments 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.

Once the initial model had been built, we ran a structural inversion of the Bouguer anomaly (using a 5 km low-pass filtered anomaly as an input) that only allowed the base of the complex to be modified. The following workflow was applied:

1. The input grids were resampled to 200 meters and a regional gravity field (linear trend) was removed.
2. The Bouguer anomaly was computed and the residual anomaly inverted to define a new top surface for the complex.
3. The total magnetic intensity was computed using the new model, to see if the gravity interpretation was consistent with the magnetic data.
4. Further trials were conducted to investigate whether the introduction of magnetic susceptibility variations within the complex (subdividing the syncline into a series of interleaved magnetized layers) improved the match between the observed and calculated magnetic anomalies.

RESULTS

The 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 4 and 5. 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.

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

Model	Density (gcm-3) Model 1 (ρ=0.1)	Model 2 (ρ=0.2)	Model 3 (ρ=0.3)
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

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, which the 2D modelling (Figure 3) has suggested is due to magnetic property variations within the complex. An attempt was made to divide the complex into differently magnetized layers in 3D but this proved difficult and the initial results do not represent a significant advance on the single layer model.

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).

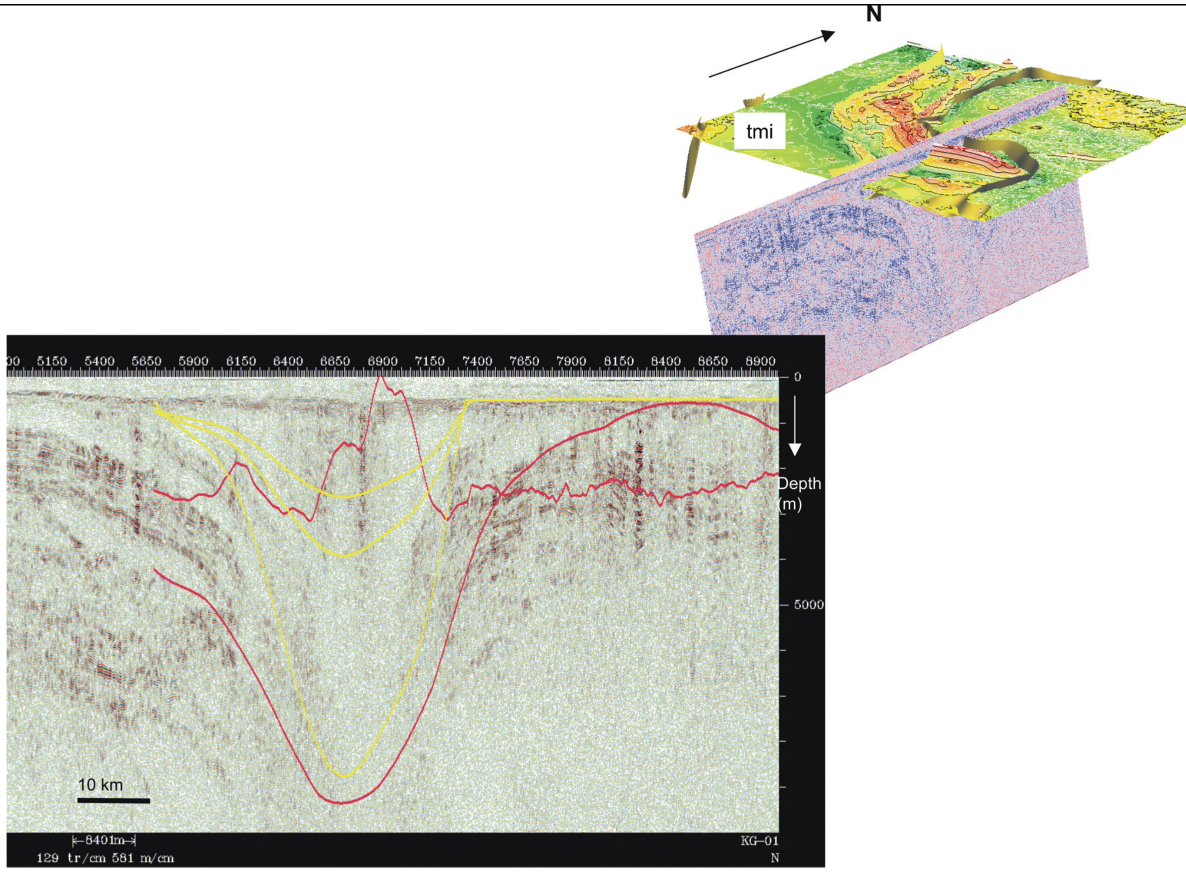

Figure 4: Syncline shape from Bouguer anomaly structural inversion (in yellow). Increasing depths are obtained for decreasing density contrast (respectively for 0.3, 0.2 and 0.1 gcm-3 from top to bottom). The TMI and Bouguer anomaly (inverted in the figure) have been overlaid in red. Top right corner: location plot of the KG-01 section below the magnetic anomaly.

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 (Figure 5). Results of inversions suggest a depth extent of approximately 3 kms for the complex.

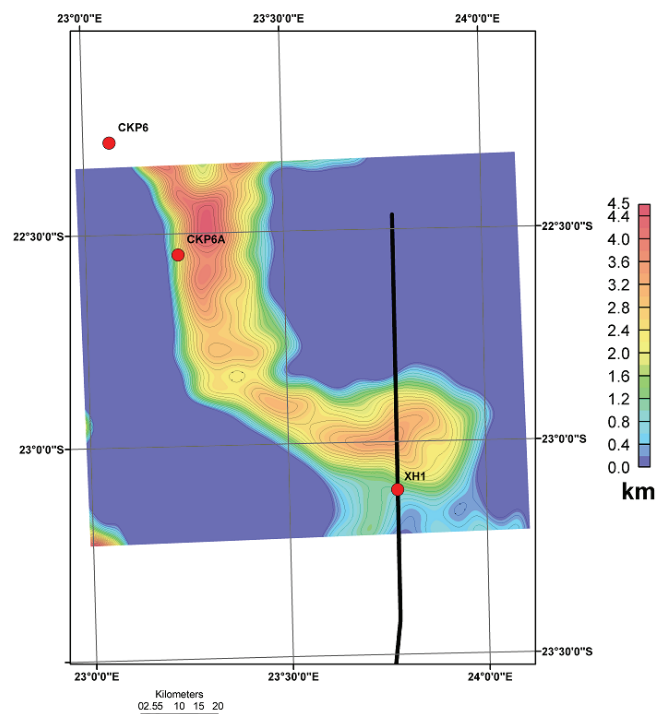

Figure 5: Depth of the Xade complex below datum (in km, positive down) using a density contrast of + 0.2 gcm-3 for the gravity inversion.). The top of the complex lies at 500 m above datum.

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.

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