GEOPHYSICAL MODELLING OF THE MOLOPO FARMS COMPLEX IN SOUTHERN BOTSWANA: IMPLICATIONS FOR ITS EMPLACEMENT WITHIN THE ~2 GA LARGE IGNEOUS PROVINCES OF SOUTHERN AND CENTRAL AFRICA

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ABSTRACT

The Molopo Farms Complex is an extremely poorly exposed, major, ultramafic-mafic layered intrusion straddling the southern border of Botswana with South Africa. It lies within the south-western part of the ~2.0 Ga large igneous province of southern and central Africa that includes the better known Bushveld Complex. Integrated interpretation of regional gravity data and new high-resolution airborne magnetic data have constrained the geometry of the Molopo Farms Complex in southern Botswana as a strongly faulted, polyphase intrusion compartmentalised by regional ductile shear zones. Previous models showing that the Complex was emplaced in at least two discrete stages are supported. Ultramafic rocks were initially emplaced as a semi-coherent lopolithic sheet up to about 4 km in thickness cutting across Transvaal Supergroup strata that had already been folded into open eastwest trending dome and basin structures with wavelengths of about 4 km. Steeply dipping, dyke-like ultramafic bodies adjacent to, and within major shears are inferred to be solidified feeders to the main lopolithic part of the MFC. It is likely that the initial ultramafic sheet was emplaced at a high crustal level (<3 km depth) into an attenuated Transvaal Supergroup sequence. This lack of a thick hanging wall sequence is thought to be significant for the emplacement of the succeeding mafic sheets. The ultramafic sheet thermally altered its wall rock and also created a complex fracture system in its hanging wall rocks. Differentiation within the ultramafic sheet produced basal harzburgites overlain by bronzites and possibly mafic sheets. Later mafic/basic sheets and dykes, again fed along shear-controlled, steeply dipping zones, spread into the fracture network created by the initial emplacement of the ultramafic lopolith to form a distinctive spider's-web pattern on high-resolution airborne magnetic maps. It is proposed that either post-emplacement regional folding or gravitational collapse of the basal ultramafic lopolith produced a major basin with a ~40 km eastwest diameter, north of the Jwaneng-Makopong Shear Zone and smaller basin to the southeast. The newly postulated, steeply dipping ultramafic/mafic feeders, as well as the ultramafic lopolith and areas with anomalous nickel values in soils are considered to be prospective for PGE-bearing magmatic nickel-copper sulphide mineralisation. Magmatic rocks dated at about 2.0 Ga are a common feature, not only of the Kaapvaal Craton, but of all the African cratonic blocks south of the Equator. Reactivated intracratonic faults and shears appear to control emplacement of individual magmatic complexes although a sub continental thermal anomaly unconfined by lithospheric plate boundaries is a likely driving force for the widespread magmatism.

Introduction

The Molopo Farms Complex (MFC) is a layered ultramafic-mafic intrusion, straddling the southern border of Botswana with South Africa, that is part of a major magmatic and thermal event dated between about 2.0 and 2.1 Ga, referred to as a Large Igneous Province by Hanson (2003) and Hanson et al. (2004). This province comprises large granitic and ultramafic/mafic intrusions (including the Bushveld Complex) and less common extrusive volcanic complexes into/onto the Kalahari and Congo Cratons (e.g. Carney et al., 1994; Key and Ayres, 2000; Singletary et al., 2003). The associated thermal anomaly is recorded in widespread rock and mineral ages of about 2000 Ma in Palaeoproterozoic and Archaean rocks of southern Africa, including the Limpopo Belt (van Breemen and Dodson, 1972; Hanson, 2003). The MFC has been dated at 2044 ± 24 Ma (Coetzee and Kruger, 1989), which is a similar age to other Palaeoproterozoic intrusions and lavas of southern Botswana such as the Moshaneng Complex (Figure 1; Key and Ayres, 2000; Hanson, 2003). The MFC underlies an area of about 13,000 km^2 of southernmost Botswana and adjacent parts of South Africa across the Molopo River (Gabrielli, 2003; Prinsloo, 1994; Figures 1 and 2). For the most part, the MFC is completely unexposed with a cover of Kalahari beds that varies in thickness: commonly exceeding 100 m in the west and south (and almost 200 m in proto-Molopo palaeo-valleys infilled by Karoo strata (e.g. at Bray, labelled B in Figure 2; Gould et al., 1987; Key and Ayres, 2000); 25 to 50 m over the eastern sector; and thinning to almost nothing locally in the north. Small exposures of asbestos-bearing basic rocks (Lamont, 1950; Wayland, 1951), and ultrabasic rocks recognised in well spoil at Keng Pan (Boocock, 1963, KP in Figure 2) are the only surface showings of the intrusion.

Regional aeromagnetic and reconnaissance gravity surveys conducted from 1962 to 1965 indicated that the basic/ultrabasic rocks might form part of a large complex (Gerrard, 1964). Behr (1987) suggested from the results of exploration drilling for asbestos that the concealed MFC was similar in its lithology, geological setting and probably in its age to the Bushveld Complex found several hundred kilometres to the east. (More specifically the MFC is geologically similar to the Rustenburg Layered Suite - Cawthorn et al., 2008). The full extent of the MFC in Botswana only became apparent following the interpretation of the results of the Reconnaissance Aeromagnetic survey of Botswana, which was flown in 1976 (Reeves, 1978).

Previous geological, geophysical and exploration surveys in Botswana (Behr, 1974 and 1987; Reeves and Hutchins, 1976; Reeves, 1978; Mallick et al., 1981; Kimbell et al., 1984; Meixner and Peart, 1984; Mitchell, 1985; Gould et al., 1987; McGeorge, 1989; 1991; 1992; Reichhardt, 1992; 1994; Sharrock, 1992; Reunion Mining (Botswana), 1998; Chatupa, 1994; Lock, 1996; Cominco, 1998) were hampered by the lack of exposure and the low resolution of the available geophysical data. This meant that only the gross internal configuration of the MFC could be elucidated. The previous studies (notably Gould et al., 1987) deduced, from an interpretation of regional gravity and aeromagnetic data backed up by ground geophysics and drilling, that the MFC is a strongly faulted, large, layered intrusion comprising a lower ultramafic sequence (the Lower Molopo Farms Complex, LMFC) of harzburgites and subordinate pyroxenites with a known thickness exceeding 1300 m. This is overlain by a predominantly mafic sequence (the Upper Molopo Farms Complex, UMFC), 1400 to 1500 m thick, comprising norites, gabbros and subordinate pyroxenites. In general the mafic rocks are thinner in the northern sector of the MFC, where the ultramafic rocks are correspondingly thicker. In plan-view, the MFC was shown to comprise a northern basin-shaped lopolith and a strongly faulted, west-northwest-dipping southeastern unit with rocks of the LMFC discontinuously forming the margins of the northern basin and a wedge-shaped basal unit in the southeast.

Borehole intersections showed that minor intrusions are a common feature of the MFC and its surrounding Transvaal Supergroup country rocks, and range in composition from gabbronorite to melagranodiorite with an isolated granite intrusion (Gould et al., 1987). These minor intrusions are mostly concordant sheets (to bedding in the Transvaal Supergroup) and are tens to hundreds of metres in thickness. There is a concentration of sub-horizontal mafic sheets in the centre of the northern lopolith. Gould et al. (1987) concluded that some of the minor intrusions are genetically related to the MFC although others are later intrusions.

A second national airborne geophysical survey of Botswana completed in the 1990s (flown by Fugro Airborne Surveys for the Government of Botswana) provided much higher resolution magnetic data (Figure 3) that the authors have interpreted in order to better elucidate the regional geology of southern Botswana (Figure 2) and the internal structure of the MFC (Wellfield Consulting Services, 2004). In addition, a considerable amount of new geological information derived from about 300 groundwater and about 150 mineral exploration boreholes has become available since the study of Gould et al. (1987). The locations of the boreholes are shown on Figure 4, and also on the Botswana Geological Survey 1:250,000 Mabutsane (33), Kanye (34), Molopo (38), and Lobatse (39) geological maps prepared by the authors (Central Kalahari Aeromagnetic Interpretation Project, 2005a-d). The current interpretation, whilst providing more detail on the geology of the MFC, has shown that the previous pioneering attempts were broadly correct.

The purpose of the present paper is to describe in more detail the internal geology of the MFC and to offer a new model for its emplacement. The work was funded by the Botswana Government with a view to encouraging further mineral exploration work on the MFC following earlier unsuccessful attempts to discover PGE mineralization similar to that found in the Bushveld Complex (Wellfield Consulting Services, 2004).

Geological Setting of the MFC in Botswana

Almost 3000 million years of sedimentation, igneous activity, metamorphism and deformation are recorded in the rocks that now underlie the Kalahari beds of southern Botswana (Table 1; Crockett and Jones, 1975; Gould et al., 1987; Carney et al., 1994; Key et al., 1996; Key and Ayres, 2000; Mapeo et al., 2004). Three major periods of post-

Archaean folding have eastwest axes which suggest re-activation of older crustal structures throughout the recorded post-Archaean geological record (Silver et al., 2004). Previous authors (Tinker et al., 2002; Silver et al., 2004; De Wit and Tinker, 2004) identify a distinct eastwest structural grain to the Kaapvaal Craton in southern Botswana based on subcontinental geophysical data. The eastwest long axis of the MFC in Botswana may therefore be controlled in part by the grain of the underlying cratonic rocks.

Ductile shears and brittle faults, irrespective of their age, mostly trend east-northeast to northeast and westnorthwest to northwest. For example, Cullen (1958) concluded that northwesterly trending faulting accompanied folding of Transvaal Supergroup strata prior to emplacement of the MFC. The sub-continental trend of kimberlites in the Kaapvaal Craton is northeast to southwest (Jelsma et al., 2004) although the kimberlite fields in southern Botswana (Jwaneng and Kokong, shown on Figure 3) are also aligned as an east to west trending belt. However, northwest to southeast trending faults locally control the emplacement of individual kimberlites in southern Botswana.

On the larger sub-continental scale it has already been noted that the MFC is part of major Palaeoproterozoic igneous event (Hanson, 2003; Hanson et al., 2004). This Large Igneous Province, defined by the ~2.0 Ga magmatic rocks (and associated thermal anomalies identified by K-Ar mineral and rock ages) is not confined to a single craton, although the major ultramafic/mafic intrusions are best seen in the Kaapvaal Craton (Figure 1).

Geophysical Investigation

Rock properties

The primary objective has been to elucidate the structure of the MFC, largely by means of gravity and magnetic surveys. In order to assess the results of these surveys properly, it is important to have information on the density and magnetic properties of the various rock types likely to be present. For this purpose, a summary of the physical properties of rocks encountered in the Molopo Farms Project exploration boreholes is given here (adapted from Gould et al., 1987).

Density and magnetic susceptibility measurements were made on over 500 core samples from Molopo Farms Project exploration boreholes. Measurements of magnetic susceptibility were made using a Bison 3101A meter and directions and intensities of magnetisation of specimens were obtained by means of a Princeton Applied Research SMI spinner magnetometer. Individual measurements are summarised in Table 2. Some rock types are not represented in these data but occur in the project area and Table 3 gives values for analogous rocks elsewhere in Botswana or the Republic of South Africa.

The ultrabasic rocks show the greatest variation in density, which is dependent upon the degree of alteration (most commonly serpentinisation). For the samples collected, the overall mean is 2.83 Mg/m^3 but individual values range from 2.52 Mg/m^3 for a serpentinite to 3.30 Mg/m^3 for a fresh pyroxenite. In Table 2, samples from the ultrabasic series are subdivided into those from relatively less serpentinised regions and those from highly serpentinised zones in the vicinity of known faults. This is not a precise division, but it does give an indication of the range of mean densities to be expected. Mean densities for the Layered Basic Series and Minor Intrusive Suite are 2.98 Mg/m^3 and 2.94 Mg/m^3, respectively. The following rocks were identified as the principal sources of magnetic anomalies within the project area.

Ultrabasic rocks

The magnetic susceptibility of the ultrabasic rocks varies greatly with the degree of serpentinisation: relatively fresh rocks have values of less than 1×10^{-3} SI units, while the strongly serpentinised varieties have values of 100×10^{-3} to 200×10^{-3} SI units.

Basic and intermediate rocks

Rocks of the Minor Intrusive Suite generally have fairly low susceptibilities although more magnetic gabbros with susceptibilities of 30×10^{-3} SI units were found in some boreholes. Diorites displayed susceptibilities in the range 40×10^{-3} to 100×10^{-3} SI units. Rocks of the Layered Basic Series exhibited low mean susceptibilities.

Banded Iron-Formation (BIF)

This rock type was not intersected in any project borehole, but is known to be responsible for the very intense magnetic anomalies in the southeast corner of the survey area (in the vicinity of label B' on Figures 4, 5 and 6).

Remanent magnetisation

Knowledge of remanent magnetisation is important in the interpretation of magnetic anomalies. If such magnetisation is weak compared with the induced magnetisation, or in the same direction, it is acceptable to make an 'induced only' assumption in the interpretation. However, if there is a strong remanent component in a direction different to that of the Earth's present field this should be allowed for if the geometry of the causative bodies is not be misinterpreted. Measurements of the natural remanent magnetisation (NRM) of igneous rock samples from Molopo Farms project boreholes showed that the vast majority of ultrabasic rock samples exhibited normal (negative or upward) inclinations, grouped around the inclination of the Earth's present field (-60°). Some (albeit very few) samples were found to exhibit reversed magnetisation, however. In contrast, all rock samples of the Layered basic series displayed a marked reverse magnetisation with near-vertical positive (or downward) inclinations.

Gravity Survey

During 1980 and 1981, a regional gravity survey was carried out over the MFC in southern Botswana. An area of 17 000 km^2 was covered with approximately 4800 uniformly distributed gravity stations. Bouguer anomalies were calculated against the International Gravity Formula, 1967 and referred to the International Gravity Standardisation Net, 1971 (Morelli et al., 1974). Data were reduced using a Bouguer correction density of 2.67 Mg/m^3. Terrain corrections were estimated to be small and were not applied (Gould et al, 1987).

Second Airborne Magnetic Survey

All data from the Central Kalahari Aeromagnetic Survey undertaken by Fugro Airborne Surveys (Pty) Ltd were made available to the project (flight-line separation 250 m, mean ground clearance 80 m). Total magnetic Intensity (TMI) data were gridded at a spacing of 60 m. In addition, gridded aeromagnetic data (grid spacing 250 m) were purchased from the South African Council for Geoscience, covering the area immediately to the south of the project area in South Africa. The latter data are of lower resolution than the Botswana dataset but are of benefit in that regional cross border anomalies associated with the MFC could be identified.

Gravity and Magnetic anomalies

The Bouguer anomaly map

The Bouguer gravity anomaly data for the Molopo Farms area are presented in Figure 4. Bouguer anomalies lay in the range -150 m Gal to -75 m Gal, the overall negative bias resulting from isostatic compensation for terrain elevation by crustal thickening. The overall form of the MFC Bouguer anomaly high is indicative of a lopolithic structure, elongated from southwest to northeast and with a width of up to 100 km. Drilling evidence (Gould et al., 1987) has suggested that, rather than being a simple lopolith, the intrusion is of a compound or cedar tree nature with Transvaal rocks inter-layered with the igneous rocks. The precise limits of the MFC cannot be accurately defined by the gravity survey, especially where the ultrabasic rocks may be strongly serpentinised. As a very approximate guide, it can be suggested that these limits lie in the vicinity of the -115 m Gal to -120 m Gal zone encircling the central high. An extension into the Republic of South Africa in indicated.

The Magnetic anomaly map

Total Magnetic Intensity (TMI) data for the Central Kalahari project region (Figure 3) displays the complexity of the magnetic field in the Molopo Farms area in contrast to the more clearly defined magnetic signature of the Xade Complex to the north (Pouliquen et al., 2008).

Figure 5 displays TMI data covering the Molopo Farms area. Unfortunately, as with all images of TMI data, the distribution of causative magnetic bodies is confused by the dipolar nature of the Earth's magnetic field. A clearer picture of pre-Kalahari structural (magnetic) grain is achieved thorough application of the Analytic Signal derivative transform (AS, or total gradient) (Figure 6). This image highlights shallow magnetic sources and clearly shows prominent northwest to southeast oriented dyke anomalies cut, in the centre of the region, by a belt of northeast to southwest oriented anomalies. This belt appears to separate the MFC into northern and southern lobes, within which complex networks of concentric anomalies can be observed. Variably serpentinised ultramafic rocks also show up clearly in this image (labelled, A, C and D), identified as reddish-brown zones indicative of strong magnetic gradients.

The concept of analytic signal of magnetic anomalies was developed by Nabighian (1972; 1974). The analytic signal is calculated by taking the square root of the sum of the squares of each of the three directional first derivatives of the magnetic field as follows:

$$|AS(x,y)|=((d\,T/dx)^2+(d\,T/dy)^2+(d\,T/dz)^2)^{1/2}$$

The resulting shape of the analytic signal is independent of the orientation of the magnetization of the source and is centred over the structure giving rise to the anomaly. Thus the effect is one of transforming the shape of the magnetic anomaly from any magnetic inclination to a single positive anomaly (or peak). This is demonstrated in Figure 7, a schematic representation of internal Upper MFC-type structures (layered ultramafic sheets and sub-vertical 'feeder' zone that may be likened to the appearance of a cedar tree) together with their computed magnetic responses (TMI and AS). It should be observed especially for the tabular bodies that a magnetic anomaly is associated with each lateral 'edge' or (boundary/contact), the magnetic anomaly decreasing in amplitude as an 'edge' becomes more deeply buried. Each of these anomalies is transformed into a single positive AS peak, the amplitude of the peak reflecting depth of burial. A partial line-work interpretation of the TMI and AS data is shown in Figure 8. Given a vertical stack of sill-like bodies, each of finite strike extent and approximately circular plan, we may thus expect a neat pattern of concentric AS anomalies. In the case of the MFC, however, we observe more of a broken spider's web, suggestive of intensive fracturing and multiple dyke intrusion.

2.5D gravity and magnetic modelling

Figures 4 through to 6 identify three regional transects selected for 2.5D gravity and magnetic modelling. Two profiles cross the MFC from north to south (A-A' and B-B') with one directed west to east across the northern lobe of the MFC (C-C'). Given the relative simplicity of the regional gravity field over the MFC in contrast with the complex pattern of anomalies revealed by the airborne magnetic data, it was decided to focus initially on quantitative interpretation of the gravity data. At a later stage, magnetic properties would be incorporated into the modelling. A final stage would then involve adjustment of model properties and geometry in order to attain a reasonable (calculated) fit to the observed data.

To interpret the gravity data quantitatively, a density for the host rock is required. In this study, detailed gravity interpretation concerns areas where the complex is mapped as intruding Transvaal Supergroup siltstones and quartzites, and it is these rocks that are therefore treated as the host. The average density of the Transvaal siltstone and quartzite depends on the relative proportions of the two rock types: samples collected from the Lobatse area (Table 3) indicate a range of 2.66 Mg/m^3 (all quartzite) to 2.77 Mg/m^3 (all siltstone). whilst a figure of 2.75 Mg/m^3 is recorded for the Transvaal metasediments which form the floor rocks of the Bushveld Complex in the Kashane area, Western Transvaal (Biesheuval, 1970).

Prior to model construction, a fixed 'regional gravity' field of -125 m Gal was subtracted from each gravity profile. The rationale behind this decision is pictured in Figure 9, which shows each of the original gravity profiles. At the northern limit of profiles A–A' and, B–B', a figure of -125 mGal appears justified in order to isolate the positive gravity feature defining the MFC. At the southern end of these profiles (and in the case of profile C–C'), others may disagree. However, the author's preference has been to account for any discrepancies through modelling, rather than by removal at the outset.

Each starting model had 4 horizons:

1. digital terrain (SRTM data – Farr and Kobrick, 2000);
2. the base of the Kalahari beds (interpolated from available borehole data);
3. the base of the Upper Molopo Farms Complex (UMFC); and
4. the base of a 2 km thick Lower Molopo Farms Complex (LMFC).

Half-strike extents for the UMFC and LMFC were set to 25 km. Initial rock properties were set as follows: Kalahari beds (ρ = 2.1 Mg/m^3, magnetic susceptibility 0.00 SI);

UMFC (ρ = 2.85 Mg/m^3, magnetic susceptibility 0.00 SI) (cf. ultrabasic series – overall, Table 2);

LMFC (ρ = 3.05 Mg/m^3, magnetic susceptibility 0.00 SI)\(cf. ultrabasic series – unserpentinised, Table 2);

Host Rock (ρ = 2.75 Mg/m^3, magnetic susceptibility 0.00 SI) (cf. Biesheuval, 1970).

Initially, all magnetic anomalies were assumed to be due to local induction by the Earth's magnetic field (D = –13 degrees, I = –63 degrees, H = 29000 nT). The results of modelling are shown in Figures 10a (A–A'), 10b (B–B') and 10c (C–C'). Whilst accepting the non-uniqueness associated with the (gravity and magnetic) modelling process, every effort was made to create a series of models not inconsistent with existing ideas of the structure of the MFC. Thickness and depth estimates are necessarily approximate because of the lack of information on the density of the rocks of the igneous complex at depth and the difficulty in accurately separating the gravitational effects of these rocks from those due to changes in Transvaal and Waterberg lithology, and/or basement depth and composition.

Regional Geophysical Structure

The new high-resolution airborne geophysical data shows that major, bifurcating east-northeast to westsouthwest trending shear zones (the Jwaneng- Makopong and Werda-Kgare Shear Zones, Figure 2) cut across southern Botswana and split the MFC into northern and southern lobes (Figures 5 and 6, and see Figure 13 of Cawthorn and Walraven, 1998). Thus the two ultramafic lopoliths recognised in the MFC in southern Botswana by Gould et al. (1987) are separated by this shearing. The shear zones define a strong magnetic anomaly and are also located along a marked junction between higher gravity to the south and lower to the north (see Figure 10a). The magnetic anomaly is attributed to steeply-dipping, strongly magnetic dykelike bodies modelled at depths of between 300 m and 600 m in the shear zones. The east-northeast trending shear zones are now considered to have provided conduits for the emplacement of the MFC magma with the steeply dipping magnetic sheets in the shear zones interpreted as solidified parts of the feeder material.

The northern lobe

A sub-circular intricate pattern of high-frequency magnetic anomalies in the northern basin (Figures 5 and 6) is considered to be generated by a series of interrelated discordant UMFC mafic sills and cross-cutting dykes intruded into previously fractured Upper Transvaal sedimentary rocks. These mafic bodies may be in contact with the LMFC lopolith, but permeate throughout the sedimentary sequence. This zone is bordered to the north and east by shallow, highly magnetic, extensively serpentinised ultramafic rocks of the LMFC (zones A, C and D, Figure 6). Drilling (Gould et al., 1987) indicates the thickness of the LMFC in the Tubane area (T, Figure 2) to be in the order of 2 km. Modelling suggests that in the centre of the northern lobe the LMFC is approximately 3 to 4 km deep (Figures 10a, 10b and 10c).

The southern lobe

South of the Jwaneng-Makopong Shear Zone, the southern lobe can be split into two parts. A southeastern part comprises strongly faulted LMFC ultramafic rocks that define the southern and eastern, outer margins of a tight basin (Figures 2, 5 and 6) as well as interconnected mafic sheets considered to be part of the UMFC within Transvaal Supergroup sedimentary rocks. Due to the complex faulting, the sub-cropping LMFC is interspersed with blocks of UMFC, Transvaal strata and in places Waterberg rocks. The form of the magnetic anomaly over the ultrabasic block that extends to the northeast from Bray (B on Figure 2, corresponding approximately to the position of label A' on Figures 4, 5 and 6) indicates that its LMFC rocks have reversed remanent magnetisation (i.e. magnetisation approximately antiparallel to the Earth's present field) at depths of approximately 2 km. Magnetic susceptibilities of the order of 0.2 SI indicate a substantial proportion of magnetite in this unit, 5 to 10%, which may be caused by the extensive serpentinisation of the ultramafic rocks (seen in boreholes), and/or by engulfment and assimilation of the Masoke Banded Iron Formation (part of the Archaean basement, see Figure 2).

A major southwestern extension of the MFC in the area immediately north (and south) of the Molopo River and west of the southeastern MFC basin is characterised by isolated mafic sheets at or near subcrop, which are assumed to be UMFC. Regional gravity data (Fourie and Cole, 2000) indicate a mushroom shaped body for the MFC, with a head straddling the Molopo River and a stem trending south-southwest immediately east of the Molopo River in RSA (see also Figure 13 of Cawthorn and Walraven, 1998). The northern edge of the head aligns with the Jwaneng-Makopong Shear Zone. The stem, which is approximately 25 km wide, extends at least 100 km to the south-southwest, representing the south-western component of the MFC.

Figure 10b (lower) provides a section of the conceptual model along model profile B-B'. This builds on a previous cross section of Gould et al. (1987). The added detail of the network of Upper Molopo Farms Complex sheets cutting into Transvaal Supergroup strata is based on the spider's web pattern defined by the high resolution magnetic data (Figures 5 and 6). The steep feeders of MFC rocks along the Jwaneng-Makopong and Werda-Kgare Shear Zones and to the south of Keng Pan are also based on the plan view of the high-resolution magnetic data (Figure 5) and supported by available borehole data, including that of Gould et al. (1987). The lenticular aspect of the various intrusive sheets again reflects the lateral discontinuity of layers within the MFC recorded in the borehole data.

Emplacement Mechanism

Previous work, based on detailed examination of borehole cores established that the MFC was emplaced in at least two discrete stages (Gould et al., 1987; Reichhardt, 1994). The new high resolution magnetic data confirm that the first-stage ultramafic rocks partly define the outer (basal) margins of the MFCs main northern lobe as well as the more faulted south-eastern lobe (Figure 5). However, these ultramafic rocks along with the later (second-stage) mafic rocks also form steeply dipping, dyke-like bodies locally aligned along major, steeply dipping shear zones**.** It is proposed that these steeply dipping bodies represent solidified feeders to the lobate or lopolithic parts of the MFC, analogous for example, to the model for the emplacement of the Rum Central Complex (Emeleus et al., 1996). There has/have to be steeply dipping feeder(s) to allow magma to access into high crustal levels so it is logical to infer that the steeply dipping bodies interpreted from the geophysical data do represent feeder zones. It is also considered likely that different sectors of the MFC may have been emplaced along separate discreet feeder zones.

The exact temporal relationships between the major shears and emplacement of the MFC are not unravelled due to the complete lack of exposure. Some shearing took place after emplacement as there is borehole evidence for sheared MFC rocks with chlorite ± talc and calcite veining and extensive serpentinisation e.g. in boreholes MF16, 17 and 27 in Gould et al., 1987). However, the extreme mismatch on the shapes of the MFC on opposite sides of the Jwaneng-Makopong Shear Zone suggests that these shears were already present prior to the Complex's emplacement, as the mismatch cannot readily be explained by post-emplacement shearing. As noted in the Introduction, certain structural trends recurred throughout the entire geological history of southern Botswana and the east-northeast to northeast trending shears through the MFC could well be reactivated faults.

The ultramafic magma spread laterally into the surrounding Transvaal strata that had already been folded into east-west rending dome and basin structures with wavelengths of about 4 km (Cullen, 1958). This magma intruded into basal Transvaal Supergroup dolomites of the Taupone Group in the north (fed from the feeder south of Keng Pan and into higher units towards the south (next to the Werda-Kgare Shear Zone in Figure 10). Differentiation of the early ultramafic sheet produced basal harzburgites overlain by bronzites and possibly immediately overlying mafic sheets (previous studies of Gould et al., 1987; von Gruenewaldt et al., 1985; Reichhardt, 1994).

Borehole data indicate that the laterally spreading magma sheet thinned and thickened as individual layers are discontinuous over horizontal distances of less than several hundred metres (Gould et al., 1987). The ultramafic sheet thermally altered its wall rock (as noted in footwall recrystallised quartzites at 24º 01' 43" E, 25º 20' 29" S in the Moselebe Valley). It is likely that the ultramafic sheet was emplaced at a high crustal level (<3 km depth), as only an attenuated Transvaal Supergroup sequence was present in this part of southern Botswana (Cullen, 1958). This suggestion corresponds to the findings of Cawthorn and Walraven (1998) that the Bushveld Complex (intruded into a fuller succession in the Transvaal basin) was initially emplaced at a depth of only about 3 km below surface.

As a result of this high crustal level emplacement it is suggested that the emplacement of the ultramafic rocks created an extensional, brittle fracture system in its hanging wall Transvaal Supergroup rocks. This network of open brittle fractures mainly within Upper Transvaal (Segwagwa Group) strata was infilled by subsequent injections of the second magma pulses of mafic material to create the spider's web pattern on plan views of the high-resolution airborne magnetic data (Figures 5and 6). As noted by Gould et al. (1987) there are widespread sheets of basic to intermediate rocks cutting through the MFC and its surrounding country rocks. At least some of these sheets of the Minor Intrusive Suite were believed to be more or less coeval with, and genetically related to the MFC by Gould et al. (1987).

The main spread of magma from the conduit zones was to the north of the Jwaneng-Makopong Shear Zone (Figure 2). Gravitational collapse of the magma, after cooling produced a major basin-shaped lopolith with a ~40 km east-west diameter. This northern lobe has centripetal dips of <30º, proved by the attitude of layering observed in cored boreholes (Gould et al., 1987). A smaller, gently to moderately dipping (≤40°; borehole data in Gould et al., 1987) south-eastern lobe was created to the south of the major shear zones.

After the emplacement of the MFC, steeply dipping (westwards) shears cut across southern Botswana, possibly related to the Kheis orogeny (Cawthorn et al., 2008). Numerous shears are present in the cored boreholes (Gould et al., 1987 and the authors' examination of the core). A mylonite zone at a depth of 271 m in Borehole MF9A (at 23° 46' 54" E 25° 21' 58" S) has a pronounced down-dip lineation to indicate downdip tectonic transport.

A network of late brittle fractures cuts through southern Botswana (Figure 2) to further complicate the geology of the MFC. Micro-fractures in borehole cores notably from the main northern lopolith show that tectonic disruption is intense with common secondary alteration of the magmatic rocks. In the southern sector of the MFC, in the Bray and Moselebe Valley areas, there is less disruption by post-emplacement faulting and the rocks are less altered (Gould et al., 1987). The northeast trending Werda-Kgare Shear Zone can be traced as a lineament to an origin splaying off the Palala Shear Zone at the northern edge of the Bushveld Complex (Figure 9 of Carney et al., 1994). Any westward projection into Botswana of the Thabazimbi-Murchison Line (TML), which is considered to have had a great influence on the emplacement of the Bushveld Complex (Good and De Wit, 1997), would lie to the north of the MFC. Perhaps more intriguingly the Mololeme and Jwaneng- Kokotsha Faults appear to connect with an arcuate magnetic lineament which swings easterly and then south-easterly to finally join the TML where it exits the Bushveld Complex (Figure 13, Cawthorn and Walraven, 1998; Cawthorn et al., 2008).

Earlier studies (Gould et al., 1987; Reichhardt, 1992; 1994) suggested that mixing of the old and new magma took place, with the mixing zone forming the focus of previous mineral exploration. However, the highresolution airborne magnetic data (supported by borehole evidence) show that any zone of mixing is clearly not as uniformly developed in the MFC as it is in the Bushveld Complex.

Mineralisation

Previous mineral exploration (Behr, 1974 and 1987; Gould et al., 1987, Reichhardt, 1994) focused on finding PGE mineralization comparable to that found in the Bushveld Complex. Efforts were made to establish a complete igneous stratigraphy for the MFC and to identify the ultramafic-mafic contact. PGE mineralization was discovered but found to be laterally discontinuous, even between closely spaced exploration drillholes and therefore of no economic value. The laterally discontinuous nature of platinum mineralization noted by previous exploration (notably by Reichhardt, 1994) may now be attributed to the laterally discontinuous nature of the host rocks.

It is suggested that an alternative exploration target are the steeply dipping, dyke-like ultramafic and mafic bodies parallel to major shears interpreted as solidified feeder zones. According to models developed for the genesis of magmatic Ni-Cu ± PGE sulphide deposits in Voisey's Bay, Labrador, at Nor'ilsk in Russia and elsewhere, the feeder conduit is regarded as a particularly favourable site for mineralisation (Evans- Lamswood et al., 2000; Naldrett, 1999; Naldrett, 2007). Interaction of the magma with country rocks, possibly associated with the addition of sulphur, is also an important genetic control although there is no evidence for this in the MFC. Repeated magma flow within the feeder zones can give rise to massive sulphide mineralisation, which is preferentially developed where physical traps exist for the concentration of sulphide droplets, either in structural embayments or irregularities, or at the point where the feeder enters a high-level magma chamber. On this basis, future exploration should be focused along the postulated MFC feeder zones (zones E and F in Figure 6). However, given the inferred complexity of the intrusive plumbing in the central internal sector of the MFC and the lack of exposure, it is not possible to predict the precise locations of targets in this part of the MFC.

Minor Ni-Cu mineralization was found in exploration boreholes by Molopo Botswana in the Keng Pan area between 1987 and 1991. It is suggested that the best target for this type of mineralization is in the basal harzburgites of the thick ultramafic sheet where average nickel values are about 2000 ppm (Reichhardt, 1994; zones A, C and D of Figure 6). Anomalous nickel values in soils in the north-western part of the MFC (Zone B of Figure 6) should also be followed up.

Discussion and Conclusion

The emplacement of the MFC is inferred to be controlled by magma ascent up steeply dipping east-northeast and northeast trending feeders that are structurally controlled. Regional shear zones identified by the high resolution airborne magnetic data (and confirmed by shears identified in borehole cores) at least in part, postdate emplacement of the MFC but may also utilise older structures that controlled the location of the feeder channels. The overall gently to moderately dipping lopolithic shape of the MFC in southern Botswana identified by previous workers with steeply dipping feeders is typical of layered ultramafic/mafic complexes (e.g. Emeleus et al., 1996).

Reactivated large-scale faults and shears within Archaean cratons, caused by stresses associated with both extensional and compressional plate tectonic events along cratonic margins, may have acted as conduits for lower crust/mantle-derived magmatism. A thermal anomaly with a radius of at least several thousand kilometres, underlying the various Archaean plates may have been the heat engine driving the magmatism. Upper crustal evidence for the thermal anomaly is provided locally by contact metamorphic aureoles around the Bushveld Igneous Complex and the re-crystallised quartzites of the Moselebe Valley; and regionally by c. 2.0 Ga K-Ar mineral ages (e.g. Van Breemen and Dodson, 1972).

The discontinuous nature of layering within the MFC, in part due to faulting and shearing, coupled with the almost complete absence of exposure means that it is unlikely that laterally extensive PGE mineralization similar to that found in the contemporaneous Bushveld Complex will be found in the MFC. Rather the postulated, dyke-like feeder bodies are suggested as the principal targets for PGE-bearing magmatic nickelcopper sulphide mineralisation.

Acknowledgements

The Central Kalahari Project (CKP) was financed by the Botswana Government and supervised by a project group comprising officials from the Department of the Geological Survey, Botswana. We thank the Geological Survey of Botswana for providing us with the magnetic and gravity data. David Gould, Susan Webb, Detlef Eberle and Grant Cawthorn are sincerely thanked for their constructive criticisms of the original manuscript. The unpublished commercial material referred to in this paper is available from the Botswana Geological Survey in Lobatse. This paper is published with the permission of the Executive Director, BGS (NERC).

References

Anhaeusser, C.R. and Walraven, F., 1999. Episodic Granitoid Emplacement in the Western Kaapvaal Craton: evidence from the Archean Kraaipan granite-greenstone terrain, South Africa. *Journal of African Earth Sciences*, 28, 289–309.

Behr, S.H., 1974. The geology of State Grants 11/72 and 12/72 (and the western parts of 13/72) in southern Botswana. Cyril Hurvitz Exploration Company (Pty) Ltd. Unpublished Report, *Geological Survey of Botswana*, 23pp.

Behr, S.H., 1987. The Keng Pan Ultrabasic Complex and its asbestos mineralization. Cyril Hurvitz Exploration company (Pty) Ltd. Unpublished Report, *Geological Survey of Botswana*.

Biesheuval, K., 1970. An interpretation of a gravimetric survey in the area west of Pilanesberg in the Western Transvaal. *Special Publication of the- Geological Society of South Africa*, 1, 266–282.

Boocock, C., 1963. *Geological Survey of Bechuanaland*, Annual Report for 1962, 11–12.

Carney, J.N., Aldiss, D.T. and Lock, N.P., 1994. The geology of Botswana. *Bulletin of the Geological Survey of Botswana*, 37, 113pp.

Cawthorn, R.G., Eales, H.V., Walraven, F., Uken, R. and Watkeys, M.K., 2008. The Bushveld Complex. In: M.R. Johnson, C.R., Anhaeusser and R.J. Thomas (Editors), The Geology of South Africa. *Geological Society of South Africa/Council for Geosciences*, 261–282.

Cawthorn, R.G. and Walraven, F., 1998. Emplacement and Crystallization Time for the Bushveld Complex. *Journal of Petrology*, 39, 1669–1687.

Central Kalahari Aeromagnetic Interpretation Project, 2005a. 1:250,000 Geological map of Mabutsane (33). *Botswana Geological Survey*.

Central Kalahari Aeromagnetic Interpretation Project, 2005b. 1:250,000 Geological map of Kanye (34). *Botswana Geological Survey*.

Central Kalahari Aeromagnetic Interpretation Project, 2005c. 1:250,000 Geological map of Molopo (38). *Botswana Geological Survey*.

Central Kalahari Aeromagnetic Interpretation Project, 2005d. 1:250,000 Geological map of Lobatse (39). *Botswana Geological Survey*.

Chatupa, J.C., 1994. Review of the geology and Ni-Cu-PGE mineralisation of the Molopo Farm Complex, Botswana. Unpublished Report, *Geological Survey of Botswana*, 6pp.

Coates, J.N.M, Davies, J., Gould, D., Hutchins, D.G., Jones, C.R., Key, R.M., Massey, N.W.D., Reeves, C.V., Stansfield, G. and Walker, I.R., 1979. The Kalatraverse One report. *Bulletin of the Geological Survey of Botswana*, 21, 421pp.

Coetzee, H. and Kruger, F.J., 1989. The geochronology, Sr- and Pb- isotope geochemistry of the Losberg Complex, and the southern limit of Bushveld Complex magmatism. *South African Journal of Geology*, 92, 37–41.

Cominco Resources Botswana (Pty) Ltd., 1998. Report on Reconnaissance Permit No. 3/87. Confidential Report, *Geological Survey of Botswana*, 9pp.

Crockett, R.N. and Jones, M.T., 1975. Some aspects of the geology of the Waterberg System in eastern Botswana. *Transactions of the Geological Society of South Africa*, 78, 1–10. Cullen, D.J., 1958.

The Geology of the Dikgomodikae Area. *Geological Survey of Bechuanaland Protectorate*, Records for 1956, 5–11.

De Wit, M. and Tinker, J., 2004. Crustal structures across the central Kaapvaal Craton from deep-seismic reflection data. *South African Journal of Geology*, 107, 185–206.

Eglington, B.M. and Armstrong, R.A., 2004. The Kaapvaal Craton and adjacent orogens, southern Africa: a geochronological database and overview of the geological development of the craton. *South African Journal of Geology*, 107, 13–32.

Emeleus, C.H., Cheadle, M.J., Hunter, R.H., Upton, B.G.J. and Wadsworth, W.J., 1996. The Rum layered suite. In: R. G. Cawthorn (Editor), Layered Intrusions. *Developments in Petrology*, 15, 403–439.

Evans-Lamswood, D.M., Butt, D.P., Jackson, R.S., Lee, D.V., Muggridge, M.G., Wheeler, R.I. and Wilton, D.H.C., 2000. Physical controls associated with the distribution of sulphides in the Voisey's Bay Ni-Cu-Co deposit, Labrador. *Economic Geology*, 95, 749–769.

Farr, T. G. and Kobrick, M., 2000. Shuttle Radar Topography Mission produces a wealth of data. *EOS Transactions of the American Geophysical Union*, 81, 583–585.

Fourie, C.S.J. and Cole, P., 2000. 1:1 000 000 Gravity Map of the Republic of South Africa. *Council for Geoscience, South Africa*.

Gabrielli, F. (2003). The Geology of the Bray area. Council for Geoscience, South Africa. ISBN 1-875061-97-5. 1:250 000, Geological Series, Explanation Sheet 2522, 42pp. Pretoria, South Africa: *Council for Geoscience*.

Gerrard, I., 1964. The solid geology of the area covered by the airborne magnetometry survey. *Geological Survey of Botswana*, unpublished Report, No. IG/23/65, 29pp.

Good, N. and De Wit, M.J., 1997. The Thabazimbi-Murchison Lineament of the Kaapvaal Craton, South Africa: 2700 Ma of episodic deformation. *Journal of the Geological Society, London*, 154, 93–97.

Gould D., Rathbone, P.A. and Kimbell, G.S., 1987. The Geology of the Molopo Farms Complex, Southern Botswana. *Bulletin of the Geological Survey of Botswana*, 23, 178pp.

Hanson, R.E., 2003. Proterozoic geochronology and tectonic evolution of southern Africa. In: *M.* Yoshida, B.F. Windley and S. Dasgupta (Editors), Proterozoic East Gondwana: Supercontinent assembly and break-up. *Special Publication of the Geological Society, London*, 206, 427–463.

Hanson, R.E., Gose, W.A., Crowley, J.L., Ramezani, J., Bowring, S.A., Bullen, D.S., Hall, R.P., Pancake, J. and Mukwakwami, J., 2004. Paleoproterozoic intraplate magmatism and basin development on the Kaapvaal Craton. Age, paleomagnetism and geochemistry of ~1.93 to ~1.87 Ga post- Waterberg dolerites. *South African Journal of Geology*, 107, 233–254.

Jelsma, H.A., de Wit, M.J., Thiart, C., Dirks, P.H.G.M, Viola, G., Basson, I.J. and Anckar, E., 2004. Preferential distribution along transcontinental corridors of kimberlites and related rocks of Southern Africa. *South African Journal of Geology*, 107, 301–324.

Key, R.M. and Ayres, N., 2000. The 1998 edition of the National Geological Map of Botswana. *Journal of African Earth Sciences*, 30, 427–451.

Key, R.M., Mapeo, R.B.M. and Corfu, F., 1996. Widespread Palaeoproterozoic magmatism and deformation in south-east Botswana. Abstract Volume, *IGCP 363 Conference*, September 1996, Zambia-Zimbabwe, 2–3.

Kimbell, G.S., Burley, A.J., Parker, M.E., Pease, S.F. and Barton, K.T., 1984. The Gravity Survey of the Molopo Farms Area, Southern Botswana, *Bulletin of the Geological Survey of Botswana*, 30, 101pp.

Lamont, G.T., 1950. Preliminary report on the Kakia asbestos occurrence. Unpublished Report, Geological *Survey of Bechuanaland Protectorate*, GTL/G/50, 5pp.

Lock, N.P., 1996. Final Report on Prospecting Licences 40-49/90, Mokatse Mining (Pty) Ltd. Confidential Report, *Geological Survey of Botswana*.

Mallick, D.I.J., Habgood, F. and Skinner, A.C., 1981. A geological interpretation of Landsat imagery and air photography of Botswana. *Institute of Geological Sciences*, Overseas Geology and Mineral Resources, 56, 35pp.

Mapeo, R.B.M, Armstrong, R.A., Kampunzu, A.B. and Ramokate, L.V., 2004. **S**HRIMP U-Pb zircon ages of granitoids from the Western Domain of the Kaapvaal Craton, Southeastern Botswana: implications for crustal evolution**.** *South African Journal of Geology*, 107, 159–172.

Mare, L.P. and Cole, J., 2006. The Trompsburg Complex, South Africa: A preliminary three dimensional model. *Journal of African Earth Sciences,* 44, 314–330.

Mare, L.P. and Tabane, L.R., 2004. Physical properties of South African rocks: South African Geophysical atlas, vol. IV, 5th edition, *Council for Geoscience*, South Africa, 37pp.

McGeorge, I.B., 1989. Molopo Botswana (Pty) Ltd, Reconnaissance Permit 4/87. Statement of Direct Costs. Confidential Report, *Geological Survey of Botswana*, 6pp.

McGeorge, I.B., 1991. Final Report for PL 12/87, Southern District. Confidential Report, *Geological Survey of Botswana*, 5pp.

McGeorge, I.B., 1992. Final Report PL 14/87, Southern District. Molopo Botswana (Pty) Ltd. Confidential Report, *Geological Survey of Botswana*, 6pp.

Meixner, H.M. and Peart, R.J., 1984. The Kalahari Drilling Project. *Bulletin of the Geological Survey of Botswana*, 27, 224pp.

Mitchell, A.A., 1985. Report on the Geology of the Keng Pan, Sekoma Pan and Tubane Areas, and on the Drilling Programme at Keng Pan. Confidential Report, *Geological Survey of Botswana*.

Morelli, C., Gantar, C., Honkasalo, T., McConnell, R.K., Tanner, J.G., Szabo, B., Uotila, U. and Whalen, C.T., 1974. The International Gravity Standardization Net 1971 (I.G.S.N. 71). *International Association of Geodesy, Special Publication*, 4, 194pp.

Nabighian, M.N., 1972. The Analytic Signal of Two-Dimensional Magnetic Bodies with Polygonal Cross-Section: It's Properties and Use for Automated Anomaly Interpretation. *Geophysics*, 37, 507–517.

Nabighian, M.N., 1974. Additional comments on the analytic signal of two-dimensional magnetic bodies with polygonal cross-section. *Geophysics*, 39, 85–92.

Naldrett, A.J., 1999. World-class Ni-Cu-PGE deposits: key factors in their genesis. *Mineralium Deposita*, 34, 227–240.

Naldrett, A.J., 2007. Fifty years of progress in the understanding of magmatic Ni-Cu±PGE sulphide deposits. *Proceedings of the Ninth Biennial SGA Meeting*, Dublin, Ireland, 971–973.

Pouliquen, G., Key, R.M. and Walker, A., 2008. The internal structure and geotectonic setting of the Xade and Tsetseng complexes in the western most part of the Kaapvaal Craton. *South African Journal of Geology*, 111, 345–356.

Prinsloo, J., (1994). Geophysical Interpretation of the Bray 2522 Area. Council for Geoscience, South Africa. *Council for Geoscience*, Internal Report 1994-0076, 27pp.

Reeves, C.V., 1973. A gravity determined density value for Kalahari sediments at Jwaneng. *Geological Survey of Botswana*, Report CVR/11/73 (unpublished), 2pp.

Reeves, C.V., 1978. The reconnaissance aeromagnetic survey of Botswana: 1975–1977. Final interpretation report. Terra Surveys Ltd. (Canadian International Development Agency), *Geological Survey of Botswana*, 315pp.

Reeves, C.V. and Hutchins, D.G., 1976. The National Gravity Survey of Botswana: 1972–1973. *Bulletin of the Geological Survey of Botswana*, 5, 44pp.

Reichhardt, F. J., 1992. Relinquishment Report for Prospecting Licence 1/84 (Bray). Gold Fields (Botswana) (Pty) Ltd. Confidential Report, *Geological Survey of Botswana*.

Reichhardt, F.J., 1994. The Molopo Farms Complex, Botswana: History, Stratigraphy, Petrography, Petrochemistry and Ni-Cu-PGE Mineralization. *Exploration Mining Geology*, 3, 263–284.

Reunion Mining Botswana (Pty) Ltd., 1998. Prospecting License 57/96. Phitshane Molopo, Southern Botswana. Report for the 1st quarter, third year 1st June 1998-31 August 1998. Confidential Report, *Geological Survey of Botswana*, 12pp.

Sharrock, J.M., 1992. Relinquishment Report for Prospecting Licenses 37/88 and 38/88. Tinto Botswana Exploration (Pty) Ltd. Confidential Report, *Geological Survey of Botswana*, 5pp.

Silver, P.G., Fouch, M.J., Gao, S.S., Schmitz, M. and Kaapvaal Seismic Group, 2004. Seismic anisotropy, mantle fabric, and the magmatic evolution of Precambrian southern Africa. *South African Journal of Geology*, 107, 45–58.

Singletary, S.J., Hanson, R.E., Martin, M.W., Crowley, J.L. Bowring, S.A., Key, R.M., Ramokate, L.V., Direng, B.B. and Krol, M.A., 2003. Geochronology of Basement Rocks in the Kalahari Desert, Botswana, and implications for Regional Proterozoic tectonics. *Precambrian Research*, 121, 47–71.

Smit, P.J. and Maree, B.D., 1966. Densities of South African rocks for the interpretation of gravity anomalies. *Bulletin of the Geological Survey of South Africa*, 48, 37pp.

Tinker, J., De Wit, M. and Grotzinger, J., 2002. Seismic Stratigraphic Constraints on Neoarchean - Paleoproterozoic Evolution of the Western Margin of the Kaapvaal Craton, South Africa. *South African Journal of Geology*, 105, 107–134.

Tombale, A.R., 1986. 1:125,000 Geological Map of the Jwaneng area. *Geological Survey of Botswana*.

Van Breemen, O. and Dodson, M.H., 1972. Metamorphic chronology of the Limpopo Belt, Southern Africa. *Geological Society of America Bulletin*, 83, 2005–2018.

Von Gruenwaldt, G., Sharpe M.R. and Hatton C.J., 1985. The Bushveld Complex: Introduction and Review. *Economic Geology*, 80, 803–812.

Wayland, E.J., 1951. Asbestos in the Bechuanaland Protectorate. Unpublished Report, *Geological Survey of Bechuanaland Protectorate*, EJW/14, 4pp.

Wellfield Consulting Services (Pty) Ltd., 2004. Interpretation of Aeromagnetic Data of Central Kalahari Project. Final Report, February - 2006. *Geological Survey of Botswana*, 68pp.

TABLES

Table 1: A summary of the major (pre-Kalahari beds) geological events in the Molopo Farms area (taken from brief explanations to 1:250,000 geology maps of the area: Central Kalahari Aeromagnetic Interpretation Project, 2005a-d).

Table 2: Densities and magnetic susceptibilities of rock samples from the Molopo Farms project boreholes. (Modified from Gould et al., 1987).

Table 3: Densities and magnetic susceptibilities for rocks analogous to those found in the Molopo Farms project area. (Modified from Gould et al., 1987).

Source 1: Reeves (1973) Source 2: Coates et al. (1979)

Source 3: Gould et al. (1987) Source 4: Smit and Maree (1966)

Source 5: Mare and Tabane (2004)

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Complex (Werde-Kgare and Jwaneng-Makopong) are marked as blue lines (refer to Figure 2). Additional features (outlined in red) labelled A though to F, indicate preferred targets for follow-up mineral exploration (see the section on mineralisation for a description of these sites).

Figure 7: A schematic representation of internal Upper MFC-type structures (layered ultramafic sheets and sub-vertical 'feeder' zone) (below), together with their computed magnetic responses – Total Magnetic Intensity (TMI) and Analytic Signal (AS) (above). In this computation, the N-S oriented geological model is strictly 2-D and all magnetic anomalies have been computed assuming induced magnetisation only (D = -15, I = -64). Magnetic susceptibility for all 'magnetic' sources was set to an arbitrary level of 0.2 SI.

Figure 8: A partial line-work interpretation (black solid lines) of the Total Magnetic Intensity (TMI) data covering the Molopo Farms study area. The subsurface extent of the Molopo Farms Complex (as inferred from available gravity and magnetic data) is marked as a dashed line. The interpreted line-work represents a complex pattern of faulting/shearing, dyke (or feeder) intrusion and sill emplacement.

Figure 9: Regional gravity profiles (A-A'), (B-B') and (C-C'), used to guide the selection of a regional background field for removal prior to 2.5D modelling.

Figures 10a, 10b (upper) & 10c: Gravity and magnetic models along transects (A-A'), (B-B') and (C-C'). Figure 10b (lower) presents a schematic N-S cross-section of the Molopo Farms Complex (along transect B-B'), based on borehole logs.

Data profiles: Red – observed; black – calculated

UMFC Upper MFC layered mafic rocks

(density 2.85 Mg/m^3; magnetic susceptibility 0.02 SI)

LMFC Lower MFC ultramafic rocks
(density 2.95 – 3.05 Mg/m^3; magnetic susceptibility 0.02 – 0.2 SI)
(note: within shear zones, density values in the range 2.75 – 2.85 Mg/m^3 were introduced to reflect the likely effects of serpentinisation)

LMFC – R Lower MFC ultramafic rocks attributed with 'reversed' magnetisation
(density 3.00 Mg/m^3; magnetic susceptibility 0.02 – 0.2 SI)

Archaean ‘basement’	(density 2.75 Mg/m^3; magnetic susceptibility 0.00 SI)
G	Felsic intrusive
	(density 2.62 Mg/m^3; magnetic susceptibility 0.00 SI)
V	Mafic extrusive
	(density 2.80 Mg/m^3; magnetic susceptibility 0.20 SI)

Intersections of other modelled transects are indicated (e.g. C-C').

JK: Jwaneng-Makopong shear zone