GEOPHYSICS — YOUR KEY TO SUCCESS IN AFRICA

D.B. Farquhar-Smith*, C. Ecorcheville⦿ and S. Kilty*
*Geoterrex-Dighem Pty Ltd, 7-9 George Place, Artarmon, NSW, 2064, Australia
⦿Compagnie Generale de Geophysique 1, Rue Leon Migaux, 91341, Massy, CEDEX France

ABSTRACT

"One of the principal problems which faces the geologist in Botswana is that exposure of pre-Tertiary formations is restricted to about 25 per cent of the country" (Carney et al., 1994). The Kalahari sands cover about 1 million square kilometres of Africa, extending from the northern Cape Province of South Africa to the Zaire River in central Africa. The problem of mapping the geology through significant cover is restricted to neither Botswana, nor other countries throughout Africa — it is prevalent on other continents, such as in southwestern United States of America, Brazil and the Yilgarn of Western Australia.

In response to the difficulties that geologists have in such areas of cover, alternative methods such as airborne geophysics have been successfully initiated. Aeromagnetic surveys have proved to be the most cost-effective tool available in mapping complex geology and sporadic outcrops in remote regions. Consequently, more line kilometres of airborne magnetic surveys are flown each year throughout the world than any other technique. It is the most common geophysical technique because of its the greatest depth penetration, being known to detect features as deep as 20 kilometres below the surface.

Twenty years after Terra Surveys and Kenting Earth Sciences flew a reconnaissance aeromagnetic survey with four kilometre line spacing over 500 000 km^2 of Botswana, France's Compagnie Generale de Geophysique returned to fly a detailed aeromagnetic survey with 250 metre line spacing over the Western Ngamiland District of Botswana for the Department of Geological Survey. The objectives of the project were to provide incentives to the private sector for mineral exploration, and to provide methodical mapping of groundwater-related structures, thus assisting in the long-term development of Botswana.

Aeromagnetic surveys have limitations: they can only locate stratigraphy and structures which have a magnetic signature or have a magnetic contrast to their surroundings. Once regions of suitable character have been selected, alternative airborne geophysical methods, such as fixed-wing TEM and frequency domain helicopter systems, can be applied with great success, as has been demonstrated in Namibia and Ethiopia.

INTRODUCTION

During 1975 and 1976 Terra Surveys and Kenting Earth Sciences flew 150 000 line km of reconnaissance airborne magnetic surveys over some 500 000 km^2 of Botswana with a 4 km line spacing, at a mean terrain clearance of 300 m. That survey was funded by the Canadian Government, through its International Development Agency (CIDA), to enable the Government of Botswana to extend exploration of the country's geology into the Kalahari region.

Twenty years later (during 1996 and 1997), Compagnie Generale de Geophysique (CGG) flew a detailed airborne geophysical survey over 56 000 km^2 of the Western Ngamiland District of Botswana, on behalf of the Department of Geological Survey of the Ministry of Mineral Resources and Water Affairs. The airborne magnetic survey consisted of 280 000 line km with a line spacing of 250 m, at a mean terrain clearance of 80 m. This survey was funded by the European Union to assist Botswana in its long-term development. The primary goals of the project were to provide incentives to the private sector for mineral exploration, and to provide methodical mapping of groundwater-related structures and potential freshwater aquifers to be utilised by the Department of Water Affairs.

An integral component of each of the surveys was a geological interpretation. The detail of the resultant geological maps is indicative of the difference in the spatial resolution between the two surveys.

Aeromagnetic surveying is an ideal exploration tool, as it is relatively unaffected by the presence of surficial material, such as weathering or overburden. It suffers only from a reduction in the amplitude of response and some loss of resolution as the depth of overburden increases (for a constant ground clearance).

However, the immediate objective of the Western Ngamiland project was the identification and subsequent delineation of lead, zinc, copper, nickel and gold mineralisation. This is not an easy task for an aeromagnetic survey, which maps the relative abundances of magnetite. However, throughout Africa airborne electromagnetic (EM) systems, either fixed-wing (such as GEOTEM®) or helicopter-borne (such as DIGHEM®) have shown that conductive base metal targets are identifiable. Two examples of airborne EM surveys are presented to demonstrate the success of airborne EM in Africa.

WESTERN NGAMILAND DISTRICT, BOTSWANA

Pre-1990s mapping

In 1977, as a sequel to the 1975-1976 airborne survey, a separate CIDA-assisted contract was signed to undertake the geological interpretation of the survey.

There were several objectives for the interpretation. These were:

- calculate depths to magnetic bodies and, where possible, prepare depth contours for the base of the Kalahari sand and also the top of the pre-Karoo (Precambrian) basement;
- map regional basement and surficial geological provinces for the purpose of identifying favourable environments for economic minerals; and
- delineate important regional tectonic units in the Karoo and basement rocks, and further assist in the identification of prospective areas for future mineral exploration.

The interpretation of this reconnaissance aeromagnetic survey yielded new geological information in areas of Kalahari sand cover. For the first time estimates were available for the thickness and extent of the Kalahari sand. A swarm of west-northwest–east-southeast striking post-Karoo dolerite dykes was identified. The extent of the Stormberg basalts was delineated, and estimates of the total thickness of the Karoo succession were made over much of the country.

The pre-Karoo (or basement) geology was divided into several large areas of distinct tectonic style. In the northwest of the country, in the region of the Western Ngamiland survey and the Ghanzi–Chobe survey, the geology appeared to be an extrapolation of the northeast-trending Damaran province of northern Namibia.

Recently, with new image processing techniques, the reconnaissance aeromagnetic surveys across Botswana to be recompiled (Prakla-Seismos, 1987), thus revealing features never seen before which have led to a new, more detailed, geological interpretation (Figure 1).

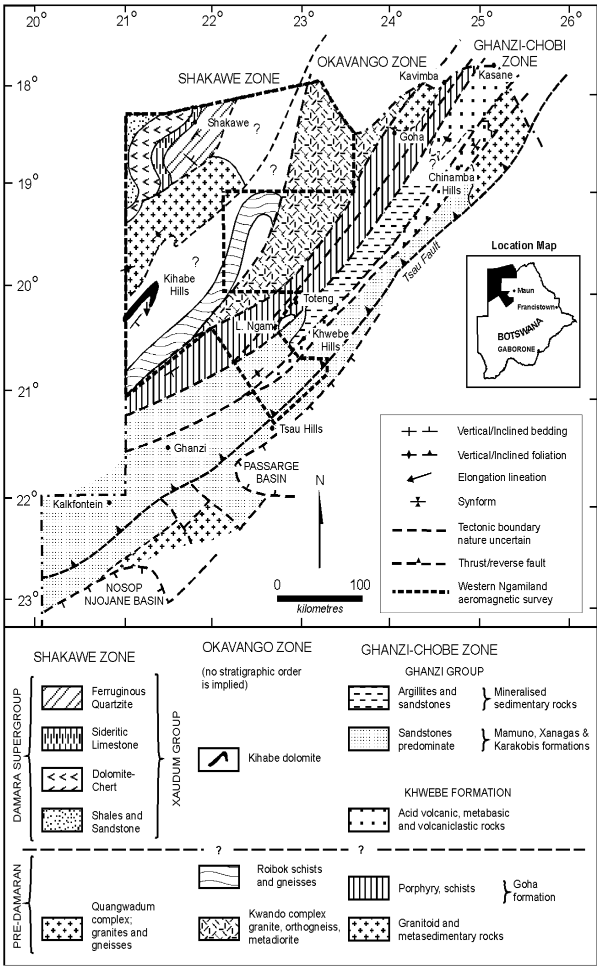

Figure 1. Map of the Botswana Orogenic Belt, Western Ngamiland, in part based on an interpretation of aeromagnetic data by Terra Surveys (1978) (from Carney et al., 1994).

1997 geological mapping

CGG's Western Ngamiland aeromagnetic survey of northwestern Botswana also had a geological interpretation as an integral part of the project. The 250 m line spacing for the survey meant that the resulting geological interpretation was significantly more detailed than previous interpretations in the region. The survey covered the northwestern half of Figure 1.

Very little was known about the area other than from the previous reconnaissance aeromagnetic survey, as there were only three significant outcrops in the area north of the Ghanzi–Chobe fold belt and only three deep drillholes.

The geological interpretation of the 1996-1997 aeromagnetic survey was accomplished using enhanced ER Mapper® images produced at scales of 1:125 000 and 1:500 000. The images used were: residual magnetic intensity; first vertical derivative; and the residual magnetic intensity reduced to the pole.

This new aeromagnetic survey (Figure 2) has enabled progress to be made towards the detailed delineation and characterisation of geological units beneath the Phanerozoic cover. The structural interpretation has identified lineaments, faults and other structures and will form the foundation for geological map products that will directly aid in identifying regions and zones of favourable mineral and groundwater potential.

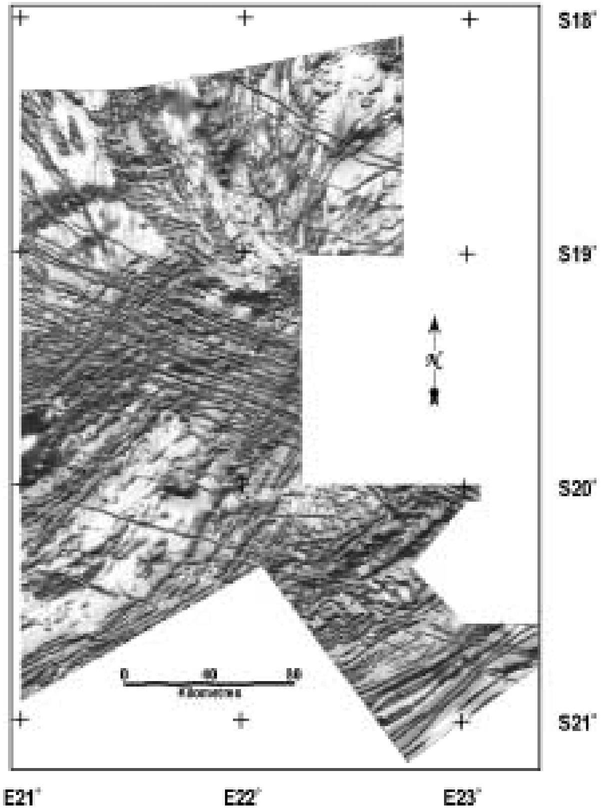

Figure 2. Residual magnetic image of part of the 1996-1997 Western Ngamiland aeromagnetic survey.

GEOTEM®

GEOTEM is a fixed wing time domain EM system that is mounted in a CASA. In 1992 a survey was flown with a base operating frequency of 75 Hz with a 1.76 msec pulse width. There were 15 off time channels ranging from 0.1 msec to 4.7 msec.

Today's GEOTEM deep system operates with a pulse width of 4 msec. This allows the generating of a much larger dipole moment, putting more energy into the ground. With a new lower base frequency of 25 Hz there is a much longer off time allowing responses to be measured as late as 16 msec, enabling the recording of subtle responses from very deep targets beneath conductive cover.

NAMIBIA

In 1992, Geoterrex Pty Ltd flew a GEOTEM II electromagnetic and magnetic survey for Erongo Exploration and Mining Company Limited. The area flown, known as the Ruacana grants area, is located in the relatively unexplored northwestern part of Namibia.

The terrain is predominantly flat, with a very rugged section in the north, and smaller rugged sections in the west. Overall it is sparsely vegetated, with pockets of cultivated and densely vegetated land, particularly in the central section of the survey area. An electricity transmission line runs north–south through the east of the survey area, giving a very strong, noisy, response on the magnetic and GEOTEM images.

Eighty percent of the survey area is underlain by platform carbonates of the Tsumeb and Abenab Subgroups of the Damara Sequence, a potential host for Mississippi Valley-type mineralisation. The remaining area is underlain by Nosib Group sandstone, which locally hosts stratabound copper mineralisation.

Consequently Erongo employed GEOTEM as a method that would directly detect discrete conductors that could be attributable to base metal mineralisation (Erongo, 1992). 13 000 line km of GEOTEM II data were collected with a line spacing of 250 m. A caesium vapour magnetometer was mounted in a second bird at a nominal terrain clearance of 70 m, allowing aeromagnetic data to be collected concurrently with the GEOTEM. The sample rate of 10 samples per second corresponded to a 7 m sample interval.

GEOTEM electromagnetic data proved a very useful tool for mapping distinct geological units as there are significant differences in the conductive properties of the rocks. Hence, apart from being used as a target selection method, the GEOTEM system is capable of mapping surface geology. Major structural features associated with the northwest-trending synclines and anticlines are evident in both the GEOTEM and magnetic datasets (Jagger and Ravier, 1992).

Interpretation of the GEOTEM delineated six conductivity terrains, varying from the resistive areas within the Nosib sandstone overlain by Kalahari sands to the very conductive portions of the Abenab Formation. Individual anomalies were also identified for follow-up work, based on criteria such as:

- geological environment;
- strike length and degree of isolation of the conductor;
- shape and size of the anomaly; and

- association with the magnetic data.

All conductors were then ranked, priority 1 anomalies being those conductors that satisfied most of the criteria for the target of interest and therefore the highest priority for follow up. These conductors typically had a small to moderate strike length, sharp, well-defined EM response, and a wide range of conductivity. 218 anomalies were picked, of which 6 were ranked as priority 1, 22 priority 2, 71 priority 3 and 119 priority 4.

There was little correlation between the GEOTEM anomalies and the magnetic data. The most diagnostic anomaly characteristic was the rate of decay. Typically, the anomalies had no distinct response on the first four channels, becoming better defined at mid channels with a slow decay. No early time response and a smooth rather than sharp response at late time confirmed that the anomalies were likely to be due to a bedrock source.

After the initial follow up of six priority 1 anomalies with soil geochemistry and ground EM, three anomalies were percussion drilled. The drilling showed that these anomalies and probably many other GEOTEM targets were graphitic shales within the carbonate successions. These results led to a complete reassessment and reinterpretation of the GEOTEM data in combination with all the data that were available at the time, including geochemistry, Landsat TM, geology and structural data. This integrated interpretation led to a revised list of GEOTEM anomalies, of which 66 were followed up on the ground, with 21 being drilled. Two of these targets were proved to be associated with breccia-hosted semi-massive to massive sulphides in quartzite, one with Zn–Pb–Cu but of limited width (K-P Knupp, personal communication, 1997).

The GEOTEM survey proved to be an invaluable tool for sub-outcrop mapping, especially in areas of poor outcrop due to a blanket of old Kalahari aeolian sand and pervasive calcrete. The target generation for Mississippi Valley-type massive sulphides was difficult due to the abundance of graphitic shales within the carbonates. However, by integrating the GEOTEM data with other datasets the success rate improved significantly.

ETHIOPIA

DIGHEM

The third airborne geophysical method that has been successfully applied in Africa is DIGHEM. DIGHEM^{V} is a multi-frequency electromagnetic system that is contained within a 9 m bird towed beneath a helicopter. The bird contains five stand-alone transmitting–receiving coil pairs. Two coil pairs are orientated in the coaxial direction (ie, with the axes in the flight direction) and three coil pairs in the horizontal coplanar direction (axes vertical).

The coaxial transmitting–receiving coil pairs are ideal for locating steeply dipping conductive bodies. This is because the primary field is essentially horizontal beneath the bird and hence provides excellent coupling to bodies that strike across the flight path.

When the response of the coplanar coil pair is compared to that of the coaxial coil pair, important geometric information about conductors, such as their strike, dip and thickness can be determined (Dighem/I*Power, 1995).

Adola area

An example of using DIGHEM in Africa is 16 000 line km survey that Dighem/I*Power flew in Ethiopia in 1993 and 1994. The survey was located in the Adola area of southern Ethiopia. In the north of the survey area the terrain is covered in rainforest while to the south the country is moderately arid. The depth of weathering is as great as 30 metres. The terrain is variable, with up to 300 m of vertical relief across the survey area.

There were several reasons why DIGHEM was chosen to fly the survey. Firstly, the terrain in much of the area is very steep. This makes it impossible for a conventional fixed wing aircraft to maintain a consistent mean terrain clearance. Electromagnetic systems are active systems that generate a field and then measure the resultant field, and consequently the quality of the data is much reduced if the distance between the transmitter and the target is increased. The second reason why DIGHEM was chosen was that the magnetic field in the equatorial latitudes of Africa is very flat. Within the Ethiopian survey area, the inclination of the magnetic field is only 8º. At this inclination a north–south vertical dyke (which can be simulated by a monopole at each end of the body) is represented as a small magnetic small high at either end of the body where the monopole is situated and very little response over the centre of the body. Consequently, if a profile is flown east–west across the centre of the dyke no response is measured. Hence at this magnetic inclination it can be very difficult to interpret the magnetic data (Breiner, 1973; Roux, 1978).

The 16 000 line km Ethiopian survey was paid for by the United Nations Development Programme on behalf of the Ethiopian Institute of Geological Surveys. The goal of the survey was to provide information on the geology and structure of the Adola area for the purposes of mineral exploration and geological mapping. Data collected included multi-frequency EM, total field magnetic and multi-channel radiometric.

The survey area was selected for its high gold potential. The West Adola block consists mainly of greenschist facies, basic to ultrabasic rocks and metasediments in the north, which host the Lega Dembi, Sakaro and Digati gold deposits. The southern part has similar geology, with the addition of radioactive granitic gneisses of the Burjiji type which are potential sources of rare metals. The East Adola block covers the most prospective parts of the eastern metavolcanic–sedimentary belt. In addition to its gold potential, the belt includes the Kenticha-type radioactive pegmatites, currently being exploited for rare metals.

The survey was flown east–west, with a line spacing of 200 m. The terrain clearance for the helicopter was 60 m. The magnetic images of the Adola survey show that east–west structures can be seen but due to the magnetic inclination north–south features are poorly defined. West-northwest faulting is prominent in the magnetic data, with the Kenticha rare metal mine being located on one such prominent, broad west-northwest-trending fault zone.

Such matters as varying inclinations of the Earth's magnetic field, however, do not affect the EM data. The 480 Hz resistivity delineates areas of high conductivity such as the graphitic schists. The 7200 Hz resistivity shows more detail, particularly the less-conductive smaller amplitude anomalies. This is because the 480 Hz resistivity has a maximum dynamic range of 500 ohm m. Consequently the weaker conductors are not being energised by this lower frequency. The 7200 Hz resistivity is mapping up to 8000 ohm m and is responding to the weakly conductive ultramafic bodies and fractured fault zones.

Enormous geological detail can be seen, such as the folding of the graphitic schists and the cross-cutting faults that divide the graphitic schists. These are not as apparent in the low frequency data. Lithological boundaries and units could easily be mapped from both the EM and the radiometric data. Many of the lithological units in the survey area yield consistent geophysical signatures that are useful when extrapolating the results of the survey to areas with no geological mapping.

Following problems within Ethiopia the Lega Dembi mine was closed. A Saudi company with the intention of reopening it has recently purchased it. There has been very little follow up to the survey and consequently there is still a great deal of potential for further discoveries.

CONCLUSIONS

The 250 m line spaced 1996-1997, CGG Western Ngamiland aeromagnetic survey for the Botswana Department of Geological Survey has delineated geological details that were impossible to map in the previous reconnaissance survey of the 1970s. However, aeromagnetic data cannot be expected to directly identify or delineate lead, zinc, copper, nickel and gold mineralisation. Consequently, throughout Africa, CGG have been flying airborne electromagnetic (EM) systems, both fixed wing- (such as GEOTEM®) or helicopter-borne (such as DIGHEM). Those techniques are better-suited to distinguishing economic mineralisation on the basis of conductivity.

Geophysics can be used to explore areas of Africa that are remote, have difficult terrain, are under tertiary cover such as the Kalahari sands or in low magnetic latitudes. The systems are very useful for geological mapping in such areas and allow direct detection of anomalous conductive bodies in a most cost effective manner.

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REFERENCES (and SELECTED BIBLIOGRAPHY)

Breiner, S., 1973. Applications manual for portable magnetometers. GeoMetrics (unpublished).

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

CGG, 1997. Geological interpretation of the aeromagnetic survey of Western Ngamiland, Botswana 1:500 000 map. Department of Geological Survey, Botswana.

Cowan, D.R. and Crabb, T.N., 1981. Airborne magnetic and radiometric surveys in sequential exploration, pp.127-143. *In* Doyle, H.A., Glover, J.E. and Groves, D.I., *Geophysical prospecting in deeply weathered terrains*, 179pp.

Dighem/I*Power 1995, Technical Report, Ministry of Mines and Energy, Ethiopian Institute of Geological Surveys, Project ETH/90/009, Mineral exploration and training, helicopter electromagnetic, magnetic and radiometric survey, Adola Area Ethiopia (unpublished).

Dighem/I*Power 1996. Geological applications of airborne electromagnetic systems, the DIGHEM system. Geoterrex Pty Ltd. (unpublished).

Erongo Exploration and Mining Company Limited 1992. Ombarundu Grant Renewal Report, Erongo Exploration and Mining Company Limited (unpublished).

Jagger, S. and Ravier, P. 1992. Logistics and interpretation report — airborne electromagnetic survey, Ruacana Grants, Namibia for Erongo Exploration and Mining Company Ltd. Geoterrex Pty Ltd, (unpublished).

Mortimer, C., 1984. Geological map of Botswana 1:1 000 000 map. Geological Survey Department, Botswana.

Paterson, N.R., Reford, M.S. and Reeves, C.V., 1979. The reconnaissance aeromagnetic survey of Botswana — I: Some novel techniques of survey execution, data compilation and interpretation, pp. 31-65 *In* McEwen, G.E. (ed.), Geophysics and the exploration of the Kalahari. *Geological Survey of Botswana, Bulletin* **22**, 423 pp.

Prakla-Seismos 1987. Anomalies of the magnetic total intensity of Botswana 1:1,000,000 map. Geological Survey of Botswana.

Reeves, C.V., 1978. The reconnaissance aeromagnetic survey of Botswana — II: its contribution to the geology of the Kalahari. *In* McEwen, G.E. (ed.), Geophysics and the exploration of the Kalahari. *Geological Survey of Botswana Bulletin* **22**, 423 pp.

Roux, A.T., 1978. Geophysical field manual for technicians No.1. The magnetic method. SAGA. (unpublished).

Worku, H. and Yifa, K. 1990. The tectonic evolution of the Precambrian metamorphic rocks of the Adola Belt (southern Ethiopia). *Journal of South African Earth Sciences*, **12** (4), 1191.