Shallow seismic refraction and magnetic studies at Lake Ngami, The Okavango Delta, Northwest Botswana

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Abstract

A seismic refraction analysis was carried out on data acquired on an 8.5 km profile at Lake Ngami, NW Botswana, to determine the structure and stratigraphy underlying the lake. The seismic spread comprised a 48-channel seismograph with a 9.5 m receiver and source spacing. The seismic source comprised 10 hammer blows on an aluminum plate, from which a vertical stack was recorded. The data were processed with WinSism™ version 10 program using the intercept time method. A total field magnetic survey was also carried out along the same line.

The seismic refraction profile shows a low velocity layer (400–1600 m/s) extending from the surface at the southern end of the line to a maximum depth of 30 m in the middle of the profile, returning to a depth of 20 m from 4.5 km to the northern end of the line. The low velocity layer consists of the unconsolidated sediments and is underlain by more compact and saturated material with seismic velocities of 1600–3600 m/s. This material is interpreted to comprise semi- to fully consolidated sandstone. The base of these sandstones, however, could only be mapped near the southern end of the line out to 2 km. High seismic velocity rocks (3600–5000 m/s), interpreted to be weathered to fresh basement, were mapped below the sandstones at the southern end of the line.

The magnetic profile shows a high at the beginning of the line which progressively declines to a low at 3 km. The field strength increases rapidly over the next 1.5 km to reach a plateau level at 4.5 km. The magnetic high at the beginning of the line corresponds to shallow basement which is mapped in the refraction profile. The magnetic low at 3 km is indicative of a thickened sediment section at this location.

The southern end of the line with high seismic velocities comprises basement rocks located in the footwall block of the Kunyere Border Fault of the Okavango Rift. The step-wise downthrown hanging wall block consists of the low to intermediate velocity basin deposits in the northern part of the profile.

Keywords: Lake Ngami; Okavango rift; Stratigraphy; Seismic velocity; Magnetic profile

1. Introduction

The northeast trending Okavango rift (Reeves, 1972), covering some 36000 km^2 in northwestern Botswana, is part of the southwestern branch of the East African Rift System (EARS) (Modisi et al., 2000; Fig. 1). It occupies a subtle topographic depression with a relief of less than 100 m. The Okavango River within this rift flows from Angola in the north and splays into a bird-foot delta upon entering the rift basin, with a subtle gradient of 1:3600 (McCarthy et al., 1993). The delta terminates in the south-east against scarps of the northeast trending Kunyere and Thamalakane faults (Fig. 2). Relief on the fault scarps is only a few meters and up to 25 m at Lake Ngami. Remote sensing and high resolution geophysics are the main tools that have been used to map the geological structure of the Okavango rift (Greenwood and Carruthers, 1973; Scholz, 1975; Hutchins et al., 1976; Hutchins et al., 1977; Mallick et al., 1981; Laletsang, 1995). Geological mapping

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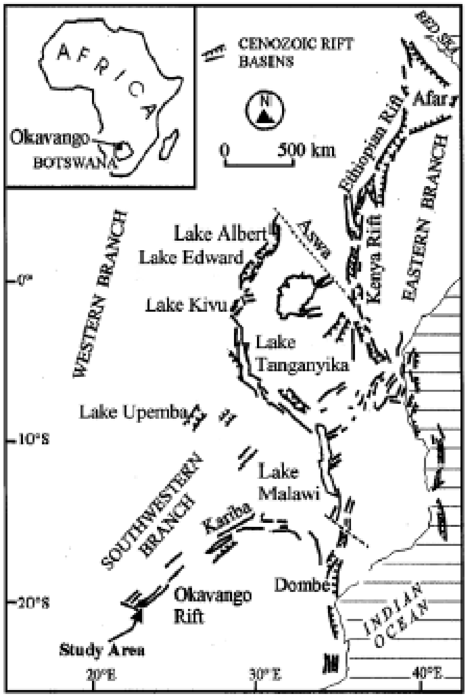

Fig. 1. Map of the East African Rift System. The inset is a map of Africa showing the position of the Okavango Rift Basin in Northwest Botswana (modified from Modisi et al., 2000).

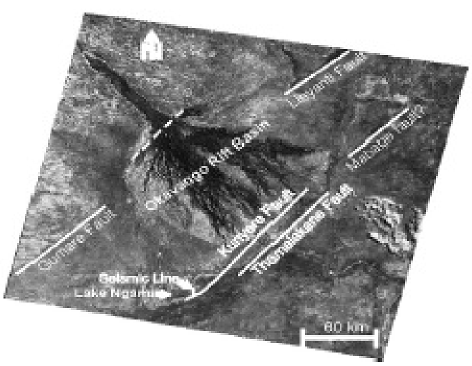

Fig. 2. Landsat Thematic Mapper image showing the main faults of the Okavango Rift Basin.

is inhibited by the mantling unconsolidated Kalahari Group sediments.

Notwithstanding the results, little is known about the sediment infill within the delta in terms of the geometry and detailed stratigraphy. Cenozoic deposits are characterized by a variety of continental sedimentary deposits consisting of unconsolidated sand, sandstones, siltstones, minor clay, calcrete and diatomaceous earth. Depositional environments include aeolian, pan, and fluvio-lacustrine. The vertical, lateral, and temporal variation of these deposits in northwest Botswana is poorly understood due to the lack of outcrop, unavailability of core samples, and other pertinent information. Climatic conditions and changes in both space and time have played a significant role in controlling the deposition of the sediments. The EARS transcends a variety of climatic areas, including very dry and arid environments at Afar, through subtropical and tropical regions in East and Central Africa, and semi-arid to arid regions in its southwestern branch at the Okavango Delta and beyond into Namibia. Comparative studies of the embryonic Okavango rift with the more mature rifts in East and Central Africa are necessary in order to understand the inherent processes, mechanisms, dynamics, and their implications on the physical environment. The role of geological structures and the influence of tectonics on the deposition of the sediments is also a knowledge gap that needs to be filled.

During this study, shallow seismic refraction and magnetic surveys were undertaken to determine the structure and shallow stratigraphy at the southeastern edge of Lake Ngami, Northwest Botswana. The objective was to compare the results with those obtained from the interpretation of aeromagnetic data, in order to determine vertical fault displacement at the border fault of the Okavango basin. Geological mapping, pit logging, and shallow seismic surveys, were undertaken to establish the lithostratigraphy and geological structures of the rocks within and adjacent to the Okavango Delta.

2. Geological setting

Mesoproterozoic rocks are exposed in isolated outcrops along the southeastern flank of Lake Ngami and further to the east-south-east at the Kgwebe Hills (Fig. 3). The metavolcanic rocks forming the Kgwebe Formation occur in the core of anticlines with northeast trending shallow plunging fold axes (Schwartz and Akanyang, 1994). The Ghanzi Group consists of folded metasediments and minor metavolcanics (Thomas, 1973; Modie, 1996; Akanyang, 1997). These Mesoproterozoic rocks display a strongly developed steep foliation, trending 060°, and medium to low grade metamorphism (Schwartz and Akanyang, 1994).

Unconformably overlying the basement are Palaeozoic to Mesozoic clastic sedimentary rocks belonging to the Karoo Supergroup (Smith, 1984). These rocks consist of conglomerates and gritty to coarse-grained sandstones. Compositions range from impure sandstones, calcareous sandstones, to quartz arenites. Jurassic basaltic rocks are interpreted from aeromagnetic anomaly patterns (Modisi, 2000). Dolerite dykes trend N110° and were mapped mainly from aeromagnetic anomalies.

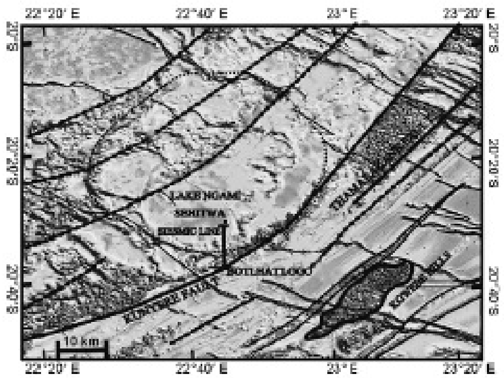

Fig. 3. Geological structure underlying the Lake Ngami area derived from high resolution aeromagnetic data. Note the prevalence of NE-SW trending faults parallel to the major rift bounding faults, the Kunyere and the Thamalakane. The outline of Lake Ngami, which is itself a magnetic anomaly, is shown in hachure. The seismic and magnetic line is also shown.

Exposures of dolerites show a medium grained basic rock consisting of plagioclase with intergranular augite and minor amounts of opaque minerals. These intrusive rocks have been dated using the $^{40}Ar/^{39}Ar$ method at 178 to 179 Ma in the Francistown area, further to the east along the strike of the dykes (LeGall et al., 2002). The dykes form a west-northwest swarm, 70 km wide, with a dyke spacing of about 2.3 km, as mapped with high resolution aeromagnetic data (Modisi, 2000). Kalahari Group sediments consist of unconsolidated to semi-consolidated sedimentary deposits. The top 3.8 m of the unconsolidated sediments are described in Fig. 4. Aeolian deposition is evidenced by fossil dune morphologies to the south and north of Lake Ngami and to the west and east of the Okavango Delta. Within the rift basin, deposits are fluvial and include sand, silt and clayey sands. Sand, mud, and diatomaceous earth deposits occur in the fluvio-lacustrine environment of the Lake Ngami area. On the scarps of the Kunyere Fault along the edge of Lake Ngami, calcrete deposits are exposed. These calcretes probably resulted from alternating wet and dry periods and fluctuations of the water table.

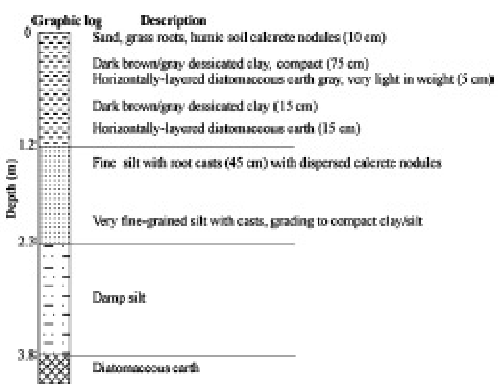

Fig. 4. Detailed log description for a pit excavated on the bed of Lake Ngami. The location of the pit is shown on the seismic profile in Fig. 5a.

3. Seismic refraction and magnetic profiles

Seismic data were recorded along a south–north profile across the southern edge of Lake Ngami (Fig. 3). The objective was to map the stratigraphy comprising the lake sediments and the basement structure using seismic reflection profiling. However, the field conditions and available instrumentation only allowed the recording of data which were found to be inadequate for seismic reflection processing. These data, nevertheless, were of sufficient quality for seismic refraction inversion since they showed clearly visible first breaks. These data were thus processed for seismic refraction profiling which produced the profile (Fig. 5a) discussed in this paper.

Seismic data were acquired with a 48 channel Bison™ 9000A signal enhancement digital seismograph and 48 high resolution Mark Products geophones, along a south to north line laid out perpendicular to the edge of the lake. The 48 single geophones (no groups) were planted at 9.5 m intervals. The source of seismic energy used in this survey was a 14 lb steel hammer hitting on an aluminum plate. The hammer source is particularly suited for high resolution seismic work since it produces a wide bandwidth of frequencies (Sheriff and Geldart, 1995). Although a surface source was not ideal, it was found at the beginning of the survey that the surface clay layer, which was decoupled

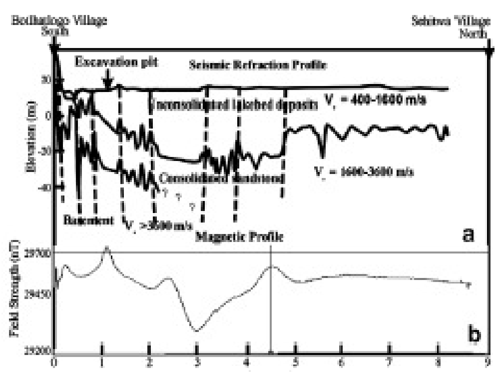

Fig. 5. (a) An interpreted seismic refraction profile across Lake Ngami running S–N from Botlhatlogo to just south of Sehitwa village. The profile consists of 20–30 m of unconsolidated lakebed clay deposits underlain by consolidated sandstone. (b) Total field magnetic profile recorded alongside the seismic refraction profile. Note the pick in the profile from 0–2.5 km and the low at 3 km, followed by the plateau at 4.5–8.5 km.

from the underlying material, prevented penetration of the seismic energy from a Betsy seismic gun. The acquisition geometry adopted in this survey was such that all the 48 geophones were planted and the source was fired at every geophone from 1 to 48, and there was no roll-along. This geometry is suitable for reflection surveys when there is little labour available to move the geophones, but a large number of recording channels is available. In this case a reasonable amount of fold can still be attained for stacking. The shot-point was fired 10 times at each receiver and the records stacked vertically. After complete recording of one spread, the entire set-up was moved forward and the recording process repeated. This was continued until 8.5 km of line was recorded covering the southern edge of Lake Ngami towards the north.

During refraction processing, 9 shots were chosen at every 6th station (47.5 m) on each spread. The density of the shots was chosen to increase the accuracy of mapping in the faulted areas. Only two spreads were combined in each run due to limitations in software capability, so that the total spread length was 893 m. The data were inspected and edited for bad traces using the commercial software package Winsism™ version 10 (W_Geosoft, 2004), after which the first breaks were picked interactively on the screen. The first breaks were inverted for interpretation using the intercept time method described in Redpath (1973).

In addition to the seismic refraction survey, a total field magnetic profile was recorded along the same transect using a GSM-19™ proton precession magnetometer. The objective of the magnetic survey was to map basement structure to corroborate the observations made on the seismic profile. The data were recorded at 20 m intervals in a south to north direction.

4. Results

The seismic refraction and magnetic profiles are presented in Fig. 5. The seismic refraction profile shows a low velocity layer (400–1600 m/s) extending from the surface at the southern end of the line to a maximum depth of 30 m in the middle of the profile (0–4.5 km), and returning to a constant but shallower depth of 20 m from 4.5 km to the northern end of the line. The low velocity layer is underlain by more compact and saturated material with seismic velocities of 1600–3600 m/s. Also, very high seismic velocity rocks (3600–5000 m/s) were mapped below the sandstones at the southern end of the line.

The magnetic profile in Fig. 5b shows a magnetic high at the beginning of the line, which progressively declines to a magnetic low at 3 km. The field strength increases rapidly over the next 1.5 km to reach a plateau level at 4.5 km.

5. Interpretation

The low velocity layer (400–1600 m/s) is interpreted to comprise unsaturated and unconsolidated lake bed sediments such as black clay which was observed on the lake surface, and silt, sand, clay and diatomaceous earth observed in a pit logged near the beginning of the line (Fig. 5a).

The material underlying the low velocity layer is interpreted to comprise semi- to fully consolidated sandstone. Consolidated sandstones have been mapped in the vicinity of the seismic line. The base of these sandstones, however, could only be mapped near the southern end of the line out to 2 km, where they are lost in a downward trend. The rocks below the sandstones are interpreted to be basement, which is juxtaposed against the sediments by faulting on the southern edge of Lake Ngami.

The abrupt increase or decrease in thickness of the lake bed sediments was used to infer fault locations along the seismic profile. Eight such faults were identified and are indicated in Fig. 5a. These faults are high angle and progressively displace the basement downward from the south end of the line out to 2 km, after which the displacement direction is reversed, thus forming a small graben on the lake-bed, in which the sediments have become thickened. Fault plane solutions computed by Scholz (1975) indicate that the Kunyere border fault, which clearly affects the rocks near the beginning of the line, dips at 60° to the northwest. Evidence of extensive faulting is abundantly shown by the aeromagnetic data interpretation shown in Fig. 3.

The magnetic high at the beginning of the line, (Fig. 5b) in the magnetic profile, corresponds to shallow basement, which is mapped in the refraction profile. The magnetic low at 3 km is indicative of a thickened sediment section at this location. This finding is corroborated by the seismic refraction profile as the middle of the small "graben". An estimate of the depth to basement using the straight-slope method described in Ram Babu et al. (1986) gives ~400 m. Indeed, Greenwood and Carruthers (1973) interpreted ~300 m of Karoo age sediments at Lake Nagmi from seismic refraction data, and Laletsang (1995) interpreted ~300 m of Karoo sandstone from seismic reflection data to the north of the Kunyere Fault near Maun. The plateau at the northern end of the line corresponds to reduced sediment thickness, which is also indicated by the refraction survey.

6. Conclusions

The seismic refraction profile shows that Lake Ngami is underlain by a thin layer (20–30 m) of sediments resting on faulted basement and more competent sediments. The investigation has established clearly that the Kunyere Fault comprises a fault zone with a number of synthetic faults. The antithetic faults are small in scale and occur towards the centre of Lake Ngami. The problems experienced with recording seismic reflection data at Lake Ngami have shown that in the future one requires deep shot holes to place the source below the expansive surface clay layer.

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