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DETERMINING GEOTHERMAL RESOURCES IN RIFTED BASINS: PRELIMINARY ANALYSIS OF THE BORNO BASIN, NIGERIA

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ABSTRACT

The Borno Basin is a Cretaceous rifted basin that holds potential for geothermal energy development. Determining the extent and nature of Borno Basin's geothermal resources require investigation of the interplay between the basin's extensional tectonic framework, thick sedimentary successions, and igneous intrusions. Borehole data from within the basin report bottom-hole temperatures of approximately 171°C at a depth of 3.5 km providing a geothermal gradient ranging from 2.81–5.88 °C/100 m, an average thermal conductivity of 2.35 W/mK, and a heat flow value of mean 80.6 mW/m^2. The existing conceptual geothermal model of the region proposes that dispersed igneous intrusions within the sedimentary infill may serve as localized geothermal heat sources, while the Gongila and lower Fika sandstone units act as hot fluid reservoirs, and the younger Fika Shale provides a low-permeability seal. Here we report on preliminary seismic-wireline integration using the Bornu Basin Albarka-1 borehole and on how this will assist upcoming characterization and evaluation of the basin architecture to assist its development as a geothermal resource.

1 INTRODUCTION

The Borno Basin (spelled Bornu Basin in earlier literature), also known as the Nigerian sector of the Chad Basin, is in the northeastern part of Nigeria and forms part of a series of Cretaceous and post-Cretaceous rift basins across Central and West Africa (Fig.1b). The Borno Basin occupies an estimated 152,000 km^2 across northeastern Nigeria (Fig.1a). This represents approximately 10% of the total 2.38 million km^2 area of Chad Basin, which extends beyond Nigeria into Chad, Niger, Cameroon, and the Central African Republic. The Borno Basin forms an east–west trending inland sub-basin along the southwestern margin of the Chad Basin, located between latitudes 11°00'–13°45'N and longitudes 8°21'–14°40'E (Olugbemiro, 1997).

The Nigerian sector of the Chad Basin, a rifted basin, may host geothermal energy potential like that discovered in other such geological settings. The Borno Basin (Fig.1a) is characterized by a complex interplay of sedimentary formations, tectonic structures, and geothermal gradients that hold potential for geothermal energy development. Nwankwo and Ekine (2009) reported heat flow measurements within the basin ranging from 63.6 to 105.6 mW/m^2 with an average of 80.6 mW/m^2,and data from borehole temperature measurement were used for gradient calculations by Kwaya et al. (2016) and recorded geothermal gradients of 2.81–5.88 °C/100 m (average: 3.71 °C/100 m), thermal conductivities of 0.58–4.21 W/mK (mean 1.63 W/mK), and heat flow measurements of 45–90 mW/m^2.

The Borno Basin is a rift basin belonging to the West African Rift Subsystem (WARS), which is part of the larger West and Central African Rift System (WCARS). (Genik, 1992, 1993). The tectonic history of the Borno Basin reflects its position within the larger WCARS framework, where phases of extension, compression, and relative stability were driven by the breakup of Gondwana and the opening of the South Atlantic (Fig. 1b). These tectonic processes not only influenced basin morphology but also left behind structural and magmatic imprints that continue to define its geological character. The tectonic evolution of the Borno Basin is interpreted to have occurred in five stages (Genik, 1992, 1993): (1) Pan-African Crustal Consolidation (750–550 Ma): Formation of basement lineaments and fault systems that later controlled rift development. (2). Paleozoic–Jurassic Platform Development (550–130 Ma): A tectonically stable period characterized by cratonic sagging and sediment accumulation. (3) Cretaceous Rifting (130–75 Ma): The main rift phase, associated with Gondwana fragmentation, block faulting, transtensional tectonics, basin segmentation, inversion, and magmatism. (4) Maastrichtian–Paleogene (75–30 Ma): Renewed rifting and deposition of thick continental clastics, although several basins became emergent during this phase. (5) Neogene–Recent (30–0 Ma): Diminished rifting activity, regional uplift (e.g., Cameroon Volcanic Line), and sedimentation in Lake Chad.

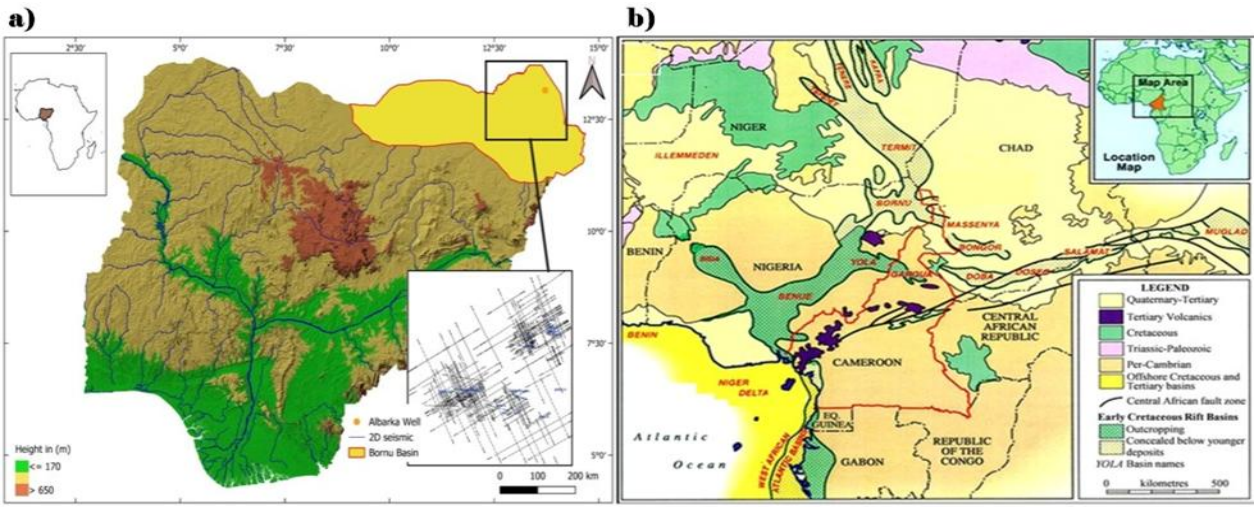


Figure 1. (a) location of the Borno Basin in Nigeria showing study area, (b) Map of the West and central African rift system (Genik, 1993).

The structural features of the Borno Basin are attributable to Late Cretaceous tectonic processes. Geophysical studies reveal an ovoid gravity anomaly and the Maiduguri Trough, which contains approximately 3000 m of Cretaceous and Quaternary sediments, linking the basin structurally to the Termit Rift (Crachtley, 1984). Odusina (1983) further suggests that the Borno Basin is genetically connected to the Upper Benue Trough and the Manga structural unit of Niger Republic, implying a common tectonic origin. Seismic surveys identified several structural elements within the Borno Basin which can be broadly classified into two categories: fault-related structures and fold-related structures. Within the Maiduguri sub-basin, northeast–southwest trending faults and folds predominate, and structural analysis of the Basin indicates structures are dominantly the result of faulting given the simple, symmetrical geometries of the present folds that are largely confined to the deeper stratigraphic levels of the basins (Avbovbo et al., 1986; Didi et al., 2020; Okosun, 1995).

Within the Borno Basin, dolerite intrusions were confirmed by well cuttings from the Albarka 1 borehole, where an ~150 m thick sill was encountered during drilling. Such igneous bodies are considered to occur as strata-concordant and discordant intrusions, expressed as laterally discontinuous high-amplitude anomalies (Suleiman et al., 2017). Using a range of seismic attributes, including reflection intensity, relative acoustic impedance, and instantaneous frequency, up to 53 igneous bodies were identified. Seismic survey data shows most intrusions are confined to the Cretaceous units—the Fika Shale, Gongila Formation and Bima Sandstone, though some extend into the Kerri-Kerri Formation (Suleiman et al., 2017). The stratigraphy of the Borno Basin begins with the feldspathic Bima Sandstone, overlain by the calcareous Gongila Formation deposited during early marine incursions. This is succeeded by the Fika Shale, consisting of gypsiferous blue-grey shale with thin, discontinuous limestones (Okosun, 1995). The overlying Gombe Sandstone comprises estuarine–deltaic sandstones, siltstones, and minor shales, with local coal seams and ferruginised horizons forming low-grade ironstones (Carter, 1963). The Kerri-Kerri Formation overlies this succession and is composed of loosely cemented sandstones, claystones, and siltstones with local ironstone and conglomerate; these deposits are lacustrine–deltaic in origin and exceed 200 m in thickness. The youngest unit, the Chad Formation, is a sequence of yellow and grey clays, sands, sandy clays, and diatomite (Carter, 1963).

2 MATERIALS AND METHODS

This study integrates 2D seismic reflection data, wireline log analysis, and synthetic seismogram modelling from the Albarka-1 well to analyze the preliminary geothermal system architecture of the Bornu Basin. The 2D seismic dataset covers approximately 12,000 km^2 of the Borno Basin. Individual seismic lines range from 13 to 92 km in length (Fig. 1a) and image the subsurface to approximately 6 seconds two-way travel time (TWT) with an estimated vertical resolution of ~30 m (average velocities of 2800-3200 m/s). The data are zero-phase, SEG normal polarity, with peaks representing increases and troughs decreases in acoustic impedance. Synthetic seismograms were generated using a zero-phase Ricker wavelet (with a dominant frequency of 20–25 Hz) and 6-second, 8-bit digitization, providing high fidelity for small-throw faults and deeper reflectors. Synthetic seismograms were generated using the corrected sonic and density curves with a zero-phase, positive-polarity Ricker wavelet. No bulk time shift(+0ms) was required to

achieve optimal correlation between the synthetic and field seismic data, enabling reflector alignment across Fika, Gongila, and Bima Formations. Reflectors were continuous to about 1600 m, beyond which volcanic intrusions disrupted seismic continuity. Well control was provided by Albarka-1, located about 209 m from seismic line CHD-89-944B, with a total depth of 3477.6m. Wireline data obtained from the NNPC archive were processed in Techlog™ for environmental correction and petrophysical interpretation. Sonic and density logs were quality-controlled and validated with checkshot data to refine the velocity–depth relationship. Where density values were missing, Gardner's equation was used to estimate substitutes. The well-to-seismic tie was implemented in 2024 Petrel™ for horizon picking, fault interpretation, and structural framework construction. Seismic attribute analysis further refined structural and stratigraphic features relevant to geothermal circulation. Published temperature data were incorporated to constrain the geothermal gradient and evaluate the subsurface thermal regime.

3 RESULTS

3.1 Preliminary seismic interpretation and synthetic seismogram

The synthetic seismogram tied to the Albarka-1 well was analyzed within the context of the basin's regional lithostratigraphic framework (Fig.3b). Preliminary interpretation of the synthetic seismogram and the corresponding seismic sections (Fig. 3a) reveals strong, laterally continuous reflectors at depths coinciding with the wireline logs defined lithostratigraphic boundaries, particularly at the base of the Fika (~2400-2500 m) and upper igneous intrusion zones (~1500 –1800m). On seismic profiles, the Fika interval presents as a uniform, low-amplitude reflector; the reservoir sandstones of the Gongila and Bima Formations show moderately bright reflections; and igneous layers produce sharp, high-amplitude events consistent with strong acoustic impedance contrasts. Preliminary structural interpretation of the Albarka-1 seismic line suggests several through-going faults appear to offset major stratigraphic boundaries (Fika, Gongila, and Bima formations), forming tilted fault blocks and localized reflectors warping above intrusive bodies (Fig.3a). These seismic features appear as discrete, high angle breaks occasionally associated with small-scale folding.

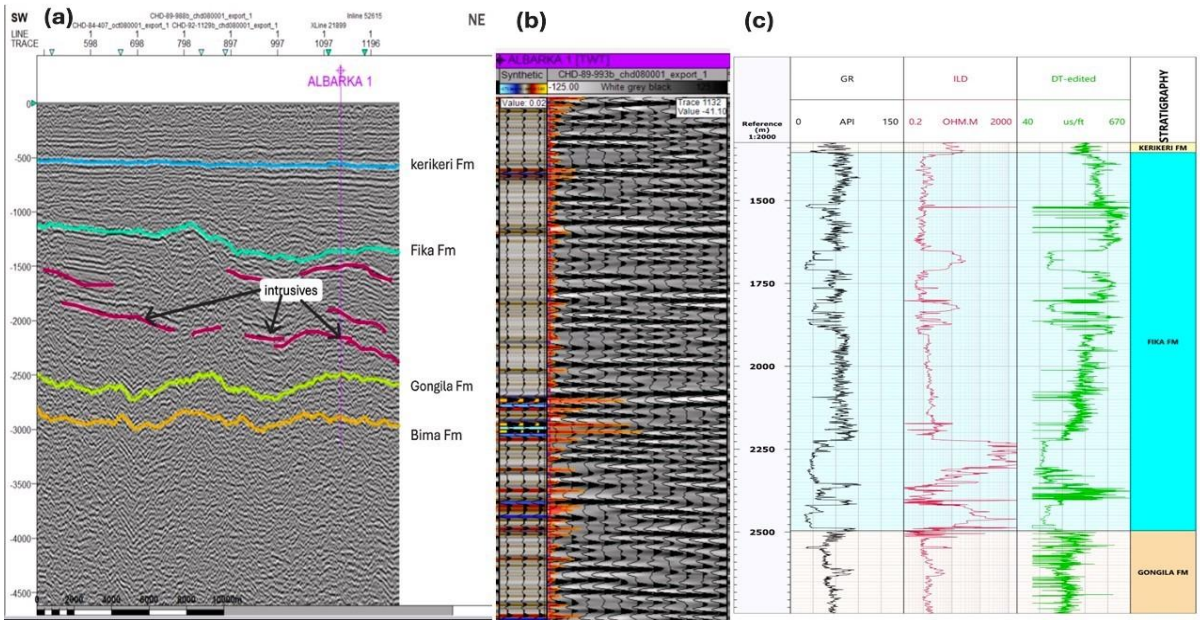


Figure 3 (a) Interpreted seismic section showing possible intrusives and structural discontinuities), (b) Synthetic seismogram tied to Albarka-1 well, (c) wireline log suite from Albarka-1 well showing Fika and upper Gongila Formations.

3.2 Wireline Signals of geothermal resource components

Using the Albarka-1 wireline dataset (Fig. 3c); gamma-ray (GR), resistivity (ILD), sonic (DT), and effective porosity (Φ_e), a preliminary petrophysical characterization of the three main geothermal resource components (heat source, reservoir, caprock) are presented here (Table 1). The Fika Formation (1355–2496 m) displays elevated gamma-ray values (~48 API), moderate resistivity (~10.8 Ω·m), and sonic transit

times near 151 µs/ft, reflecting a thick, fine-grained shale sequence of low permeability with effective porosity of ~0.14. These petrophysical characteristics are consistent with a shale unit in the Albarka-1 lithological log (N.N.P.C.L, 2006). The Gongila Formation (2496–2860 m) records lower gamma-ray values (~37 API), higher resistivity (~13.9 Ω·m), and shorter sonic transit times (~115 µs/ft) with relatively high porosity (~0.16). These petrophysical values are indicative of a moderately porous sandstone. The Bima Formation (2860–3477 m) exhibits moderate gamma-ray readings (~57 API), high resistivity (~19.8 Ω·m), and shorter sonic transit times (~104 µs/ft) with low to moderate porosity (~0.07). These features are consistent with compacted sandstones capable of storing fluids.

The presence of interbedded igneous intervals has been used to suggest the presence of localized geothermal heat anomalies within the Bornu Basin. At multiple stratigraphic levels within the Albarka-1 well, possible igneous intrusions are identified. At shallow depths (1800-2700m) within the lower Fika and upper Gongila formations, igneous units are petrophysically characterized by elevated resistivity (20–500 Ω·m; avg. 180 Ω·m), reduced sonic transit times (45–55 µs/ft; avg. 50 µs/ft), low porosity (< 0.05; avg. 0.02), and moderate to high GR (55–120 API; avg. 90 API). At deeper levels (>2860 m) a thicker igneous unit is encountered within the Bima Formation. This deeper intrusion exhibits GR 55–125 API (avg. 90 API), resistivity 100–500 Ω·m (avg. 250 Ω·m), DT 45–55 µs/ft (avg. 50 µs/ft), and very low porosity (< 0.05; avg. 0.02). These properties are consistent with a dense, regional magmatic intrusion.

Table 1. Wireline Parameters and Temperature Estimates for Stratigraphic Units and Igneous Intrusives in the Albarka-1 Well (Bornu Basin)

S/N	Formation/unit	Depth (m)	GR (API)	ILD (Ω·m)	DT (µS/ft)	Φ_e (v/v)	Temp (°C)*
1.	Fika	1355–2496	35–60 (~48.2)	8–15 (~10.8)	145–160 (~151.8)	0.10–0.17 (~0.14)	100–120
2.	Gongila	2496–2860	30–45 (~37)	12–17 (~13.9)	110–120 (~114.7)	0.14–0.18 (~0.16)	130–150
3.	Bima (+ below)	2860–3477	45–70 (~56.9)	15–25 (~19.8)	95–110 (~104.3)	0.05–0.09 (~0.07)	150–170
4.	Shallow Intrusives (within Fika & Gongila)	~1800–2700	55–120 (~90)	20–500 (~180)	45–55 (~50)	<0.05 (~0.02)	120–160
5.	Deep Intrusives (below Bima)	>3000	55–125 (~90)	100–500 (~250)	45–55 (~50)	<0.05 (~0.02)	>160-180

Note: Log statistics derived from cleaned Albarka-1 wireline LAS data interpreted in Techlog™ (Schlumberger). *Temperature estimates based on geothermal gradients of 2.8–5.9 °C/100 m (Kwaya et al., 2016; Nwankwo & Nwosu, 2016), Intrusive intervals inferred from high-resistivity and low-sonic responses correlated with high-impedance reflectors on the synthetic seismogram.

4 DISCUSSION AND SUMMARY

Preliminary integration of seismic, wireline and stratigraphic data from the Albarka-1 borehole provides confidence in being able to use such datasets to more accurately define key components of potential geothermal resources across the wider Borno Basin region. Preliminary analysis of seismic survey data and generation of a synthetic seismogram linking density, Gamma ray and sonic wireline data from Albarka-1 borehole, suggests there are clear seismic signals associated with the three main components of the conceptual geothermal systems in the Borno Basin, the igneous intrusion heat sources, the sandstone reservoirs, and the shale caprocks to these reservoirs. This finding is promising as it suggests that extrapolation of these geothermal component signals to the larger 2D and 3D seismic dataset available across the wider Bornu Basin will allow improved identification of potential geothermal sites and enhanced characterization of their specific architectures. Initial identification of structural influences on the seismic datasets suggests that faulting, and possibly associated small scale folding, may exert controls on heat flow and fluid migration. These structures may also control geothermal reservoir compartmentalization across the Borno Basin and will be a target of investigation in future work.

Preliminary interpretation from the Albarka-1 well suggests that analysis of petrophysical well logs effectively distinguish lithologic units that play distinct roles in the Borno Basin geothermal model. Wireline

data from Fika Formation are consistent with its potential to act as an impermeable regional cap rock over geothermal fluid reservoirs, limiting vertical fluid migration and heat loss. Estimated temperatures of 100–120°C (based on average geothermal gradients of 3.71 °C/100 m within the area) reported by (Kwaya et al., 2016; Nwankwo & Ekine, 2009) indicate an elevated geothermal gradient and potential heat retention zone, although additional well data are necessary to confirm this interpretation. The Gongila Formation wireline data indicates it may potentially serve as a reservoir capable of storing and transmitting geothermal fluids. Estimated Temperatures of 130–150 °C, based on geothermal gradients of the Bornu Basin reported by Nwankwo and Ekine (2009) suggest increased subsurface heat and possible convection zones, though the lateral extent and connectivity of these potential reservoirs remain to be tested. Igneous bodies, intruded at both shallow and deeper depths in the Borno Basin stratigraphy show marked petrophysical signatures, the characters of which can be used to explore other well datasets for similar patterns. Estimated temperatures of 150–170°C (Nwankwo & Shehu, 2015) are consistent with significant thermal gradients and conductive heat transfer to overlying units, requiring further confirmation through nearby well analysis. The occurrence of such igneous intrusions within the Fika, Gongila and Bima stratigraphic units aligns with rift-related tertiary magmatic activity. Collectively, the shallow and deep intrusions may represent heat-source components of geothermal systems, providing both localized and distributed thermal input to the overlying sandstones. Their petrophysical classification here aims to assist with mapping such intrusions distribution across the Borno Basin to assist with identification of geothermal resource sites.

Building on the work presented here, future efforts will work to expand this integrated wireline–seismic approach to additional wells located across the Borno Basin. By identifying consistent petrophysical and seismic signatures of geothermal components, we will progressively refine understanding of the basin-wide geothermal system architecture. This in turn will allow deeper insights into how rift basin processes and architecture influence magmatic processes and thus ultimately the formation and occurrence of geothermal resources in such tectonic settings.

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