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Geopressured-Geothermal System Potential of the Nigerian Chad Basin, Northeastern Nigeria: Implications for Deep Sedimentary Basin Energy Resources

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Abstract

The geopressured-geothermal potential of the Nigerian sector of the Chad Basin remains largely unexplored despite its favourable geological setting. This study evaluates the basin's suitability for geopressured-geothermal energy development through an integrated assessment of its thermal regime, sedimentary architecture, reservoir characteristics, sealing formations, and structural framework. Available geothermal datasets indicate thermal gradients ranging from approximately 24 to 61 °C/km and heat-flow values between 60 and 156 mW/m², reflecting significant spatial variability and localized thermal anomalies. Stratigraphic analysis reveals sedimentary successions exceeding 5 km in thickness, comprising laterally extensive sandstone reservoirs within the Bima and Gongila formations overlain by regionally continuous shale units capable of functioning as effective thermal and hydraulic seals. Structural analysis further indicates that basement-rooted faults and fracture networks may facilitate upward heat transfer, fluid migration, and pressure communication, thereby enhancing geothermal circulation within the basin. The central and eastern sectors exhibit the most favourable combination of elevated thermal gradients, substantial sediment thickness, well-developed reservoir intervals, competent sealing lithologies, and structurally controlled permeability, making them the most prospective targets for future exploration. Comparative evaluation with established geopressured-geothermal provinces, including the Gulf Coast Basin (USA), the North German Basin, and the Pannonian Basin, demonstrates that the Nigerian Chad Basin possesses many of the critical geological attributes required for commercial geopressured-geothermal exploitation. These findings identify the basin as a promising but underexplored renewable energy resource with considerable potential to diversify Nigeria's energy portfolio, enhance long-term energy security, and support sustainable low-carbon energy development through future exploration and resource appraisal.

Keywords

Geopressured-geothermal Systems;
Bornu Basin;
Geothermal Gradient;
Deep Sedimentary Aquifers;
Renewable Energy;
Nigeria.

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1. Introduction

The global transition towards cleaner and more sustainable energy sources has renewed interest in geothermal energy as a reliable source of low-carbon power. Unlike solar and wind energy, geothermal resources can provide continuous base-load electricity generation independent of weather and seasonal variations, making them an important component of future energy systems (Lund and Toth, 2021; IEA, 2024). While geothermal development has traditionally focused on volcanic and hydrothermal settings, recent advances in exploration and drilling technologies have expanded interest in deep sedimentary basins and geopressured-geothermal systems, where elevated temperatures, high fluid pressures and suitable reservoir formations occur at depth (Moeck, 2014; Limberger et al., 2021).

These systems have been successfully investigated in several sedimentary basins worldwide, including the Gulf Coast Basin, North German Basin and Pannonian Basin, highlighting their potential as significant renewable energy resources (Bebout et al., 1982; Limberger et al., 2021).

Despite possessing abundant fossil fuel resources, Nigeria continues to face significant energy deficits arising from increasing population growth, industrialization and inadequate electricity generation capacity (World Bank, 2023). Although renewable energy development has largely focused on solar and hydropower, several Nigerian sedimentary basins exhibit thermal characteristics favourable for geothermal development. Among these, the Chad Basin has attracted considerable attention due to reported geothermal gradients that exceed global continental averages and evidence of elevated subsurface heat flow (Anakwuba and Chinwuko, 2015; Kwaya et al., 2016). Previous studies have mainly concentrated on geothermal gradient estimation, bottom-hole temperature analysis and Curie point depth investigations, while the possibility of geopressured-geothermal systems within the basin has received relatively little attention.

The Nigerian sector of the Chad Basin possesses several geological attributes that favour the development of geopressured-geothermal resources, including sediment thicknesses exceeding 5 km, extensive sandstone reservoirs within the Bima and Gongila formations, regionally developed Fika Shale seals, and basement-controlled fault systems capable of enhancing heat and fluid migration (Genik, 1992; Obaje, 2009). These characteristics suggest that the basin may host geothermal systems comparable to those developed in other sedimentary basins worldwide.

This study therefore evaluates the geopressured-geothermal potential of the Nigerian Chad Basin through an integrated assessment of its thermal regime, stratigraphic architecture, reservoir-seal relationships and structural framework. The results provide new insights into the renewable energy potential of the basin and contribute to the growing understanding of sedimentary geothermal resources in Africa.

2. Geological Setting

The Chad Basin is one of the largest intracontinental sedimentary basins in Africa, occupying an area of approximately 2.3 million km^2 across Nigeria, Niger, Chad, Cameroon and the Central African Republic. The Nigerian sector, commonly referred to as the Bornu Basin, forms the southwestern margin of this extensive depression and represents one of the country's most important frontier sedimentary basins (Obaje, 2009; Olugbemiro et al., 1997). The stratigraphy of the Nigerian Chad Basin comprises a thick succession of Cretaceous to Recent sediments resting unconformably on Precambrian crystalline basement rocks.

The sedimentary fill exceeds 5 km in several depocentres and locally approaches 7 km, providing sufficient burial depth for the development of elevated formation temperatures (Obaje, 2009). The oldest sedimentary unit is the Aptian–Albian Bima Sandstone, which consists predominantly of continental fluvial and alluvial deposits. The formation is composed mainly of coarse- to medium-grained feldspathic sandstones interbedded with mudstones and siltstones. Previous petroleum and hydrogeological investigations have demonstrated that the Bima Sandstone possesses favourable reservoir characteristics, including significant thickness, relatively high porosity and widespread lateral continuity (Carter et al., 1963; Olugbemiro et al., 1997).

From the standpoint of geothermal resource development, the Bima Formation represents the most promising deep geothermal reservoir in the basin. Its considerable thickness allows for large thermal storage capacity, while its sandstone-dominated lithology provides the permeability required for fluid circulation and heat extraction. Similar sandstone reservoirs constitute the primary geothermal targets in sedimentary geothermal systems of the North German Basin, the Paris Basin and the Alberta Basin (Majorowicz and Grasby, 2010; Limberger et al., 2021).

Overlying the Bima Sandstone is the Gongila Formation, which consists of alternating sandstone, limestone and shale deposited during a major Cenomanian marine transgression. Although traditionally regarded as a hydrocarbon-bearing unit, the formation may also possess geothermal significance where porous sandstone intervals occur. In many sedimentary geothermal systems, stacked reservoir configurations provide multiple targets for geothermal exploitation and improve the long-term sustainability of production operations.

The Turonian–Santonian Fika Shale represents one of the most important formations in the context of geopressured geothermal systems. The unit consists predominantly of thick marine shale sequences deposited under relatively quiet offshore conditions. In several parts of the basin, the formation exceeds 2 km in thickness and exhibits low permeability characteristics that favour the preservation of abnormal pore pressures (Adegoke et al., 2014). The presence of such a regionally extensive sealing unit is critical for the formation of geopressured geothermal systems.

Thick shale formations reduce vertical fluid escape, inhibit heat loss and facilitate the long-term preservation of elevated temperatures and pressures within underlying reservoirs (Bebout et al., 1982; McKenna and Blackwell, 2005). Consequently, the stratigraphic relationship between the Bima Sandstone and the Fika Shale closely resembles the reservoir-seal architecture observed in several producing sedimentary geothermal provinces worldwide.

The Maastrichtian Gombe Formation and the overlying Tertiary Kerri-Kerri Formation consist largely of sandstone, siltstone and claystone deposited in fluvial, deltaic and lacustrine environments. These younger formations host important groundwater aquifers but are generally too shallow to serve as major geothermal reservoirs for electricity generation. Nevertheless, they may play an important role in the migration and discharge of thermal waters along fault-controlled pathways.

The youngest stratigraphic unit, the Quaternary Chad Formation, comprises unconsolidated sands, silts and clays deposited in lacustrine and fluvial environments. Although geothermal temperatures are unlikely to be encountered within this unit, its extensive aquifer systems may provide valuable information regarding regional groundwater circulation and potential hydraulic connectivity with deeper formations.

The structural framework of the Nigerian Chad Basin is dominated by basement-controlled fault systems inherited from Cretaceous rifting events. Regional geophysical investigations reveal that the principal structural trends are oriented NE–SW, NW–SE and locally E–W, reflecting multiple phases of tectonic deformation during basin evolution (Avbovbo et al., 1986; Obaje, 2009). These structures are significant not only because they controlled sedimentation patterns during basin development but also because they continue to influence present-day subsurface fluid flow. In sedimentary geothermal systems, faults commonly act as preferential pathways for the upward migration of deep thermal fluids and the redistribution of heat within the basin (Moeck, 2014).

Numerous studies have demonstrated that geothermal anomalies are frequently concentrated near fault intersections, relay zones and fractured basement highs where permeability is enhanced (Siler et al., 2019; Limberger et al., 2021). Similar conditions may exist within the Chad Basin, where inherited basement structures provide hydraulic connections between deep sedimentary reservoirs and the underlying crystalline basement.

The interaction between fault-controlled permeability, thick sedimentary insulation and elevated geothermal gradients is therefore likely to play a fundamental role in determining the distribution and quality of geothermal resources within the basin. Areas where major fault systems intersect thick sedimentary depocentres may represent particularly favourable targets for future geothermal exploration.

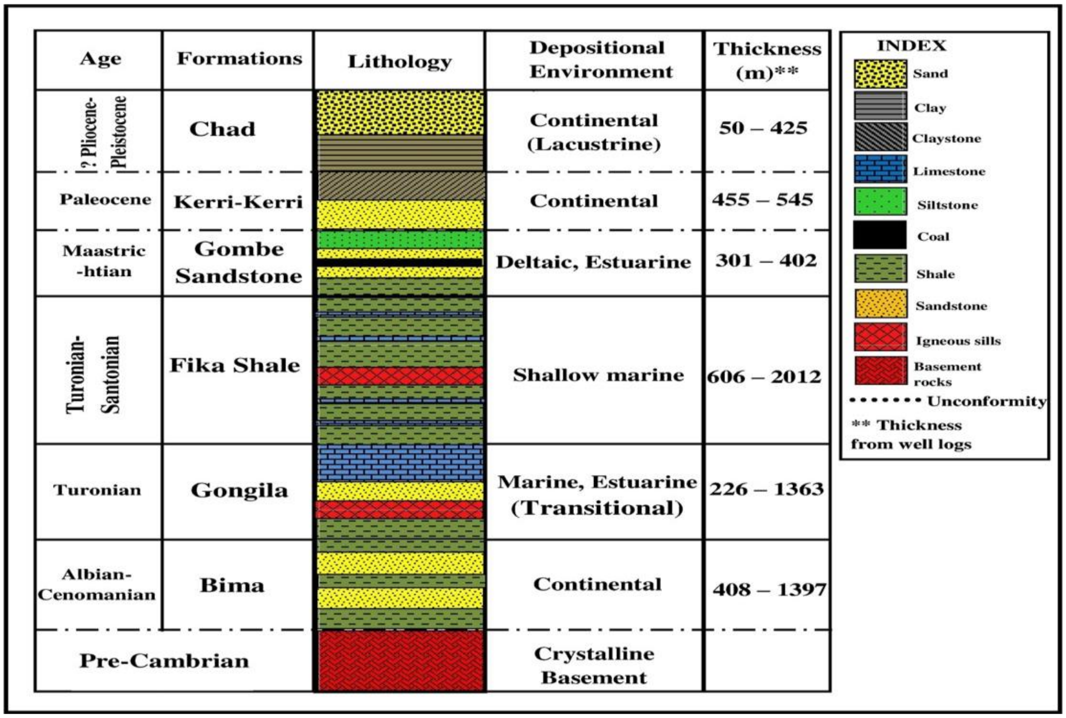

Figure 1: Stratigraphic succession in the Nigerian sector of the Chad Basin adopted from (Adegoke et al., 2014).

3. Materials and Methods

This study adopted an integrated basin-analysis approach that combines geological, geothermal, stratigraphic and structural information to evaluate the geopressured-geothermal potential of the Nigerian Chad Basin. Similar basin-scale approaches have been widely applied in the assessment of sedimentary geothermal systems in Europe, North America and Australia, where geothermal prospectivity is controlled by the interaction of heat flow, reservoir quality, sealing capacity and structural architecture (Moeck, 2014; Limberger et al., 2021; Agemar et al., 2014).

The assessment considered six principal geological parameters that are widely recognized as critical controls on geopressured-geothermal systems (Bebout et al., 1982; McKenna and Blackwell, 2005):

- Basin thickness.
- Geothermal gradient.
- Heat flow.
- Reservoir occurrence and quality.
- Seal distribution and effectiveness.
- Structural controls on fluid migration.

To facilitate basin-scale evaluation, a Geopressured Geothermal Favorability Index (GGFI) was developed. Similar multi-criteria ranking approaches have been successfully used in geothermal resource assessments in sedimentary basins where exploration data remain limited (Moeck, 2014; Limberger et al., 2021). Each parameter was assigned a score between 1 and 5 according to its relative contribution to geothermal system development. The weighted scores were subsequently combined to generate a qualitative geothermal favourability ranking. Unlike conventional geothermal studies that focus primarily on thermal anomalies, the present methodology emphasizes the complete geothermal play system, including heat source, reservoir quality, sealing mechanisms and fluid pathways, consistent with the geothermal play concept proposed by Moeck (2014).

Table 1: Parameters used in assessing the geothermal potential

Parameter	**Weight (%)**
Geothermal Gradient	25
Heat Flow	15
Reservoir Development	20
Sediment Thickness	15
Seal Effectiveness	10
Structural Controls	15

4. Results

4.1 Basin Architecture and Reservoir Distribution

Analysis of available geological and geophysical information indicates that the central and eastern sectors of the Nigerian Chad Basin contain the greatest sediment thicknesses, locally exceeding 5 km. These regions correspond to major depocentres formed during Cretaceous extension and subsequent thermal subsidence associated with the evolution of the West and Central African Rift System (Genik, 1992; Obaje, 2009). The Bima Sandstone forms the principal geothermal reservoir unit within the basin.

Its regional extent, significant thickness and documented porosity make it the most prospective target for geothermal fluid storage and production. Previous hydrogeological and petroleum studies have similarly recognized the Bima Formation as an important reservoir unit within the basin (Carter et al., 1963; Olugbemiro et al., 1997).

The Gongila Formation provides additional reservoir intervals, particularly where sandstone-rich facies are developed. The occurrence of multiple stacked reservoir units may improve the sustainability of geothermal production by increasing the volume of recoverable thermal fluids, a feature commonly observed in productive sedimentary geothermal provinces (Majorowicz and Grasby, 2010).

4.2 Thermal Regime

The basin exhibits geothermal gradients ranging from approximately 24 to 61 °C/km and heat-flow values ranging between approximately 60 and 156 mW/m². These values are considerably higher than the average continental geothermal gradient of approximately 25–30 °C/km and average continental heat flow of about 65 mW/m² (Turcotte and Schubert, 2014; Majorowicz and Grasby, 2010; Figure 2).

The elevated geothermal gradients indicate the existence of localized thermal anomalies within parts of the basin. Similar thermal conditions have been reported in several sedimentary geothermal provinces including the Pannonian Basin, North German Basin and Gulf Coast Basin, where geothermal energy is currently exploited or actively investigated (Limberger et al., 2021; Agemar et al., 2014).

Assuming average surface temperatures of approximately 28–30 °C, subsurface temperatures exceeding 120 °C may occur at depths between 2.5 and 4 km in the most favourable sectors of the basin. Such temperatures are generally considered suitable for binary-cycle geothermal power generation using Organic Rankine Cycle (ORC) technologies (DiPippo, 2016).

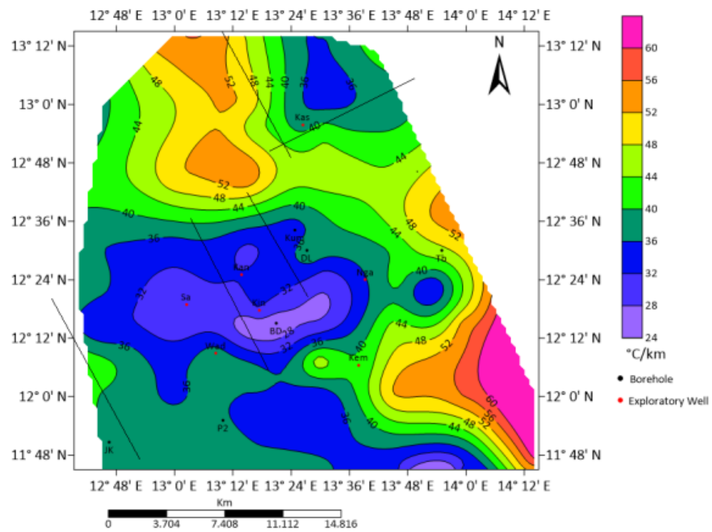

Figure 2: Map of Geothermal Gradient in Chad Basin

4.3 Seal Development

The Fika Shale represents the most important sealing formation within the basin. Its considerable thickness, regional continuity and low permeability suggest a strong capacity to preserve elevated pore pressures and reduce vertical heat dissipation. The occurrence of thick shale units overlying permeable sandstone reservoirs is one of the defining characteristics of geopressured-geothermal systems worldwide (Bebout et al., 1982; McKenna and Blackwell, 2005).

Similar reservoir-seal relationships have been documented in the Gulf Coast geopressured-geothermal province of the United States, where thick shale successions contribute significantly to pressure preservation and thermal retention (Wallace et al., 1979). Consequently, the stratigraphic relationship between the Bima Sandstone and the Fika Shale provides favourable conditions for the development of geopressured geothermal reservoirs within the Chad Basin.

4.4 Structural Controls

The structural framework of the basin is dominated by NE–SW and NW–SE trending fault systems inherited from the Cretaceous tectonic evolution of the basin (Avbovbo et al., 1986; Genik, 1992; Figure 3). Fault systems are widely recognized as fundamental controls on geothermal fluid circulation because they enhance permeability and facilitate heat transfer from deeper crustal levels (Moeck, 2014; Siler et al., 2019).

Within the Chad Basin, these structures likely serve as conduits for the upward migration of thermal fluids and heat. Areas where major faults intersect deep sedimentary depocentres appear particularly favourable for geothermal exploration because fault intersections commonly exhibit enhanced fracture permeability and increased hydraulic connectivity (Faulds et al., 2010; Siler et al., 2019). The observed association between deep depocentres, elevated thermal gradients and structurally complex zones suggests that geothermal prospectivity within the basin is controlled by the interaction between sedimentary architecture and fault-mediated fluid flow.

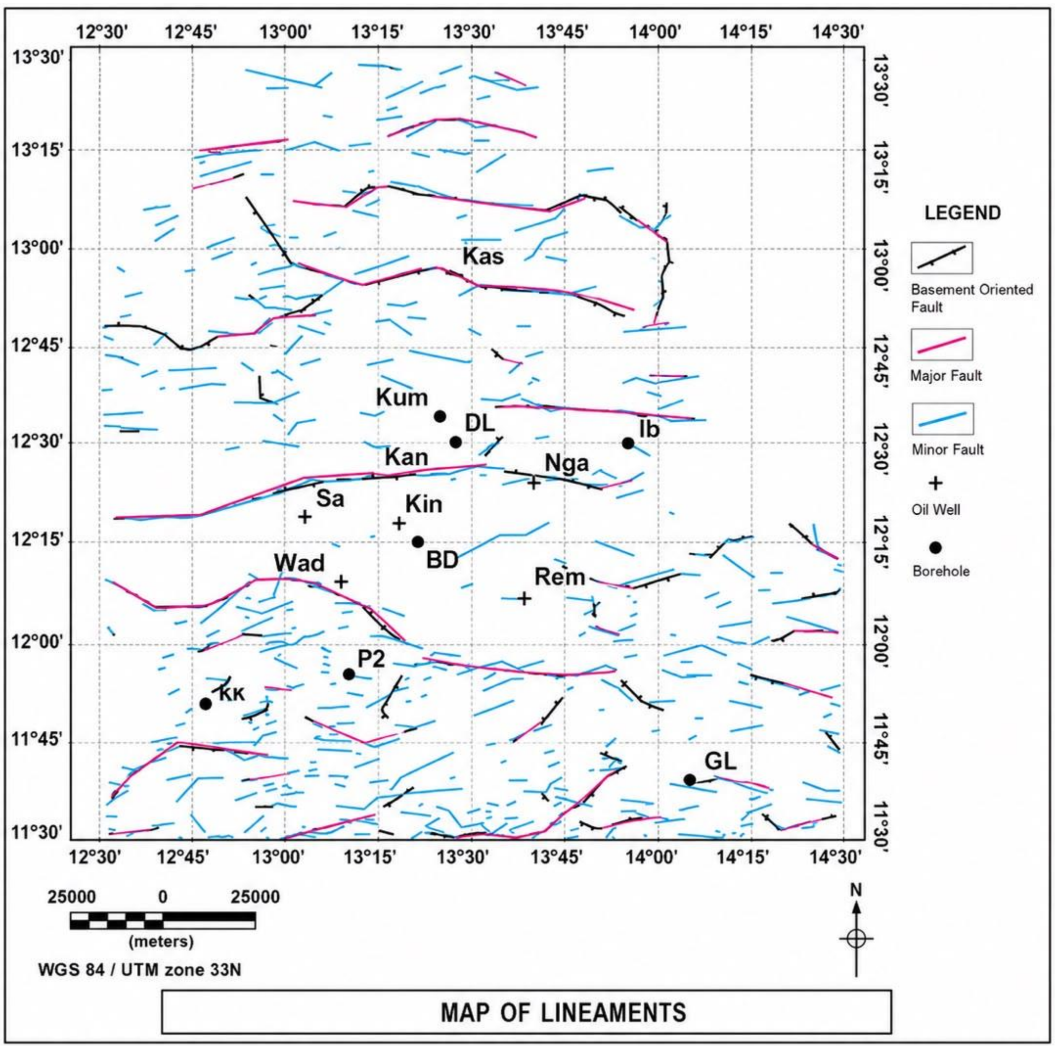

Figure 3: Lineaments Map of the Study Area

5. Discussion

5.1 Evidence for Geopressured-Geothermal Systems

Several geological indicators collectively suggest that geopressured-geothermal systems may occur within the Nigerian Chad Basin. In particular, the sedimentary thicknesses exceeding 5 km provide the burial conditions necessary for significant thermal maturation and pressure development. Similar sediment thicknesses characterize productive geothermal provinces in the Gulf Coast Basin and North German Basin (Bebout et al., 1982; Limberger et al., 2021). Moreover, geothermal gradients reaching 61 °C/km are substantially higher than average continental values and indicate the presence of localized thermal anomalies capable of generating economically attractive geothermal resources (Majorowicz and Grasby, 2010). In addition, the basin contains extensive sandstone reservoirs represented by the Bima and Gongila formations, which are overlain by thick shale units of the Fika Formation. Such reservoir-seal configurations are considered fundamental requirements for geopressured geothermal development (McKenna and Blackwell, 2005; Wallace et al., 1979).

Most importantly, the basement-rooted fault systems provide potential pathways for heat transfer and fluid migration. Similar structural controls have been documented in numerous sedimentary geothermal systems worldwide where faults focus fluid circulation and enhance reservoir permeability (Moeck, 2014; Siler et al., 2019). The coexistence of these geological characteristics strongly suggests that the Chad Basin possesses favorable conditions for geopressured-geothermal development.

5.2 Comparison with Global Analogues

The geological characteristics of the Chad Basin compare favourably with several established sedimentary geothermal provinces.

Table 2: Comparison of temperature vs depth in Chad Basin and global analogues

Basin	Depth (km)	Temperature (°C)
Gulf Coast Basin	3–6	120–180
North German Basin	2–5	100–160
Pannonian Basin	2–4	110–190
Chad Basin	2.5–5	100–180

The Gulf Coast Basin represents one of the best-known geopressured-geothermal provinces globally, where deep sandstone reservoirs contain elevated temperatures and abnormal fluid pressures (Bebout et al., 1982). Similarly, the North German Basin and Pannonian Basin have demonstrated the commercial viability of sedimentary geothermal systems developed within thick sedimentary successions (Agemar et al., 2014; Limberger et al., 2021). The thermal conditions inferred for the deeper sectors of the Chad Basin fall within the lower to middle range of these systems, suggesting that the basin may possess geothermal resources of comparable significance.

5.3 Geothermal Development Opportunities

The geothermal characteristics of the basin indicate several potential utilization pathways. Potential applications include:

- Binary-cycle electricity generation.
- Industrial process heating.
- Agricultural drying.
- Aquaculture.
- Greenhouse heating.
- Hybrid geothermal-solar energy systems.

Binary Organic Rankine Cycle (ORC) technology is particularly suitable for moderate-temperature geothermal resources because it can efficiently generate electricity from fluids with temperatures as low as 85–100 °C (DiPippo, 2016; Lund and Toth, 2021). Given the thermal conditions inferred for the basin, ORC systems may represent the most practical technology for future geothermal power development.

5.4. Geothermal Play Model

The most prospective geothermal play within the basin consists of crustal heat concentrated within deep sedimentary depocentres, upward heat migration through basement-rooted faults, storage of thermal fluids within the Bima Sandstone reservoir, and pressure preservation beneath the regional Fika Shale seal. This conceptual model closely resembles geopressured-geothermal systems described in the Gulf Coast Basin of the United States and sedimentary geothermal systems of the North German Basin (Bebout et al., 1982; Agemar et al., 2014). The interaction between heat source, reservoir, seal and structural permeability creates a favourable geological framework for geothermal resource development.

6. Conclusions

The Nigerian Chad Basin possesses many of the geological characteristics required for geopressured-geothermal resource development. Thick sedimentary successions, elevated geothermal gradients, extensive sandstone reservoirs and effective regional sealing formations collectively create favourable conditions for geothermal fluid accumulation and heat preservation. Deep-seated fault systems provide potential pathways for heat transfer and fluid circulation, while the Bima Sandstone and Gongila Formation offer significant reservoir potential.

The overlying Fika Shale acts as an effective regional seal capable of supporting geopressured conditions. Thermal conditions suggest that temperatures suitable for binary-cycle geothermal power generation may occur at economically drillable depths within several sectors of the basin. Among the identified geothermal plays, the Bima Sandstone beneath the Fika Shale represents the most prospective target for future exploration.

The results indicate that the Nigerian Chad Basin should be regarded as an emerging sedimentary geothermal province with significant potential to contribute to Nigeria's long-term renewable energy strategy.

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