Petrophysical study of the eastern interior of central Kongo and the southwest surroundings of Kinshasa in the Inkisi formation

Étude pétrophysique de l'intérieur oriental du centre du Kongo et des environs sud-ouest de Kinshasa dans la formation d'Inkisi

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ABSTRACT: The purpose of this study is to assess the petrophysical potential of this Inkisi geological formation. By analyzing key parameters such as porosity and permeability, it provides a better understanding of the geological dynamics of the region. This study also aims to identify areas likely to yield natural resources, particularly hydrocarbons, in order to guide future research and exploitation. This assessment therefore contributes to a better understanding of the physical properties of the formation and its potential economic value.

KEYWORDS: Porosity, Permeability, Geological dynamics, Hydrocarbons, and Economic potential.

RÉSUMÉ: L'objectif de cette étude est d'évaluer le potentiel pétrophysique de cette formation géologique de l'Inkisi. En analysant des paramètres clés tels que la porosité et la perméabilité, elle permet de mieux comprendre la dynamique géologique de la région. Cette étude vise également à identifier les zones susceptibles de receler des ressources naturelles, en particulier des hydrocarbures, afin d'orienter les recherches et l'exploitation futures. Cette évaluation contribue donc à une meilleure compréhension des propriétés physiques de la formation et de sa valeur économique potentielle.

MOTS CLÉS: Porosité, Perméabilité, Dynamique géologique, Hydrocarbures et Potentiel économique.

1. Introduction

The Inkisi Formation is a large quartz-feldspar sandstone complex of ochre color, resting on units of the West Congo Supergroup within the Niari Basin (Affaton and al., 2016). Located in Central Africa, it extends from Congo to Angola, crossing the Democratic Republic of Congo (DRC) (Figure 1). Tectonic and structural research on this formation remains limited and, for the most part, outdated (Stanton & Schermerhorn, 1960; Cornet & Pourret, 1982). More recent work, carried out between 1990 and 2014 (Alvarez and al., 1995; Tack and al., 2001; Delvaux and al., 2014), indicates that the Inkisi sandstones are marked by brittle tectonics. However, the study by (Alvarez and al.1995), which indirectly addresses the structures, suggests that the faults observed are of synsedimentary origin and therefore concludes that the Formation has not undergone major tectonic deformation.

In Angola, the Inkisi Formation is covered by Karoo deposits, which exhibit deformations that are widely recognized in southern and central Africa. It is therefore conceivable that the Inkisi sandstones recorded either the tectonic stresses affecting the Karoo deposits (Catuneanu and al., 2005; Daly and al., 1991, 1992; Delvaux and al., 2012), or those related to the opening of the central Atlantic Ocean (Maurin & Guiraud, 1993). These episodes would have imprinted characteristic structures that clearly reflect the tectonic style of the formation.

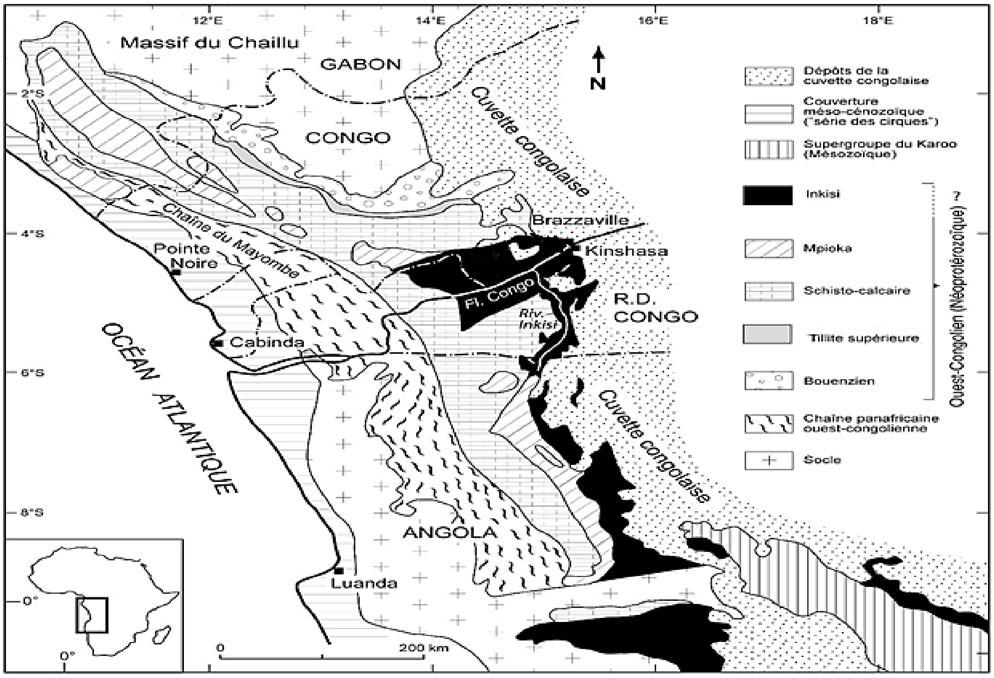


Figure 1 Synthesis geological map of the Inkisi Formation. Based on Sounga, Affaton, Noack & Mialoundama (2012).

1.1. Geographical contexts of inkisi formation

The Inkisi Formation mainly outcrops in the province of Kongo-Central and in the southwestern part of the city-province of Kinshasa, in the Democratic Republic of Congo. It owes its name to the Inkisi River, a tributary of the right bank of the Congo River, which crosses a large part of its characteristic outcrops. Geographically, the main outcrop sites are located in the localities of Kimwenza, Madimba, Mbanza-Ngungu, Kisantu, and Songololo. To the north, it extends to the outskirts of Kinshasa (Mont Ngafula and Kinsuka areas), while to the south it extends towards the Kongo-Central plateaus. Its lateral extension suggests a large sedimentary cover, evidence of ancient fluvial or deltaic deposits.

1.1.1. Location of Inkisi

The Inkisi formation is located in the west of the Democratic Republic of Congo (DRC) and in the northwest of Angola, between 14°53' and 15°36' east longitude and 4°57' and 7°41' south latitude. It originates in northwestern Angola, in the Mucaba region of Uige Province, at an estimated altitude of 900 m (Deceunink, 1952). It flows from south to north, where it empties into the Congo River (in the Cataractes and Lukaya district of Kongo Central Province).

1.1.2. Geomorphology

The Inkisi Formation has a geomorphology characterized by an extensive basin between the Mbanza-Ngungu Ridge (Thysville) and the Kwango Plateau, with gently rolling hills and moderate topography. This region forms a vast territory where the sediments of the formation consist mainly of arkosic sandstones (arkoses) associated with conglomerates, deposited in a mega-fan type alluvial environment, under the influence of an intertwined river system, indicating a poorly developed floodplain environment with sedimentary dynamics mainly concentrated on lateral and downstream migratory channels (M.L. Assine, 2005). The sediments that make up the Inkisi Formation originate from erosion of the mountains and surrounding regions, notably the ancient Pan-African Mayombe Massif and the Congo Craton. These sediments consist mainly of grains of quartz, feldspar (a type of mineral), and small rock fragments. They were deposited a very long time ago, during the Paleozoic era, in a basin that was gradually expanding. This basin received these materials transported by a complex network of rivers and streams, creating a vast accumulation of sediments that later formed the rock known today as the Inkisi Formation (T. Chakraborty et al. 2010; Mashala and al, 2024).

1.1.3. Climate

The climate is characterized by tropical humidity, marked by a long rainy season from September to May, peaking in March-April, and a shorter dry season from June to August, but mitigated by sporadic rainfall. Average temperatures range between 26 and 28°C, with daytime highs close to 30°C and cooler nights. The dynamics of the intertropical convergence zone are closely linked to annual rainfall, which generally varies between 1,500 and 2,000 mm, resulting in persistent atmospheric humidity that is conducive to the development of dense and diverse vegetation (J. DE PLOEY, 1963).

1.1.4. Hydrography

The region features gently rolling plateaus carved by deep valleys, whose morphology derives from the interaction between lithology, fluvial erosion, and ancient tectonic legacies (Tack et al., 2010; De Wit & Tinker, 2004).

The hydrographic network, dominated by the Inkisi River and its tributaries, is mainly located in fracture zones, promoting active erosion and the deposition of fine sediments in the alluvial plains. This dynamic controls soil distribution, with hydromorphic soils rich in organic matter in low-lying and marshy areas, and ferralitic soils on better-drained slopes.

1.1.5. Pedology

The formation is characterized by soil heterogeneity directly linked to lithology, the humid tropical climate, and local ecological conditions. Three main soil types have been identified (FAO, 2015): (i) ferralitic soils, which are widespread, clayey in texture, highly acidic and characterized by a high concentration of iron and aluminum oxides, giving them red-brown to yellow-brown hues and sometimes limited drainage; (ii) hydromorphic and alluvial soils, developed in floodplains and marshy areas, rich in organic matter, with a clay-loam texture, offering high fertility but constrained by poor drainage; and (iii) red tropical ferralitic soils, which are better drained and characteristic of drier or higher altitude areas, whose average fertility can be improved by organic or mineral inputs (FAO, 2015).

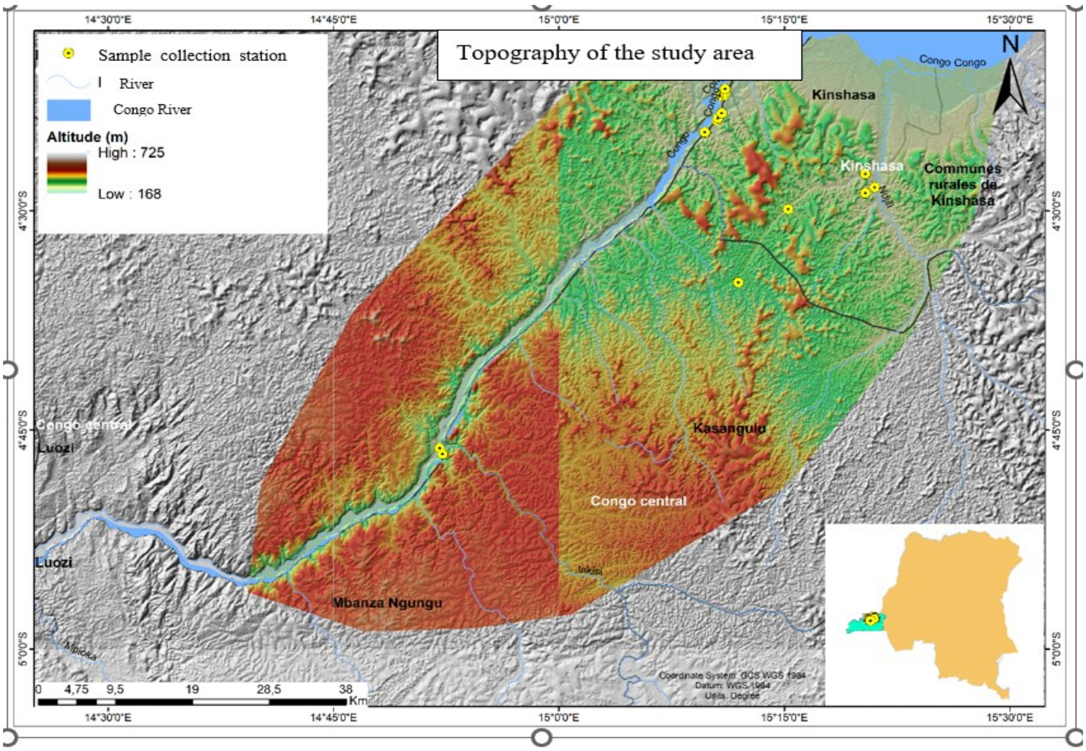


Figure 2 Topographic map of the study area.

1.2. Geological context of Inkisi formation

1.2.1. Lithostratigraphy

The Inkisi Formation, belonging to the West Congolese Supergroup in Central Africa (Congo), is a Paleozoic lithostratigraphic formation characterized mainly by a sedimentary body of sandstone and arkose, wine-red in color, with a few rare greenish passages. This formation is voluminous and is divided into a lower member comprising white mica arkoses with flat pebbles (quartz, sandstone, psammites, and claystones), and an upper member composed mainly of fine siliceous, feldspathic, or micaceous sandstones with some intercalations of claystones (P. Alvarez; J.-C, 1991).

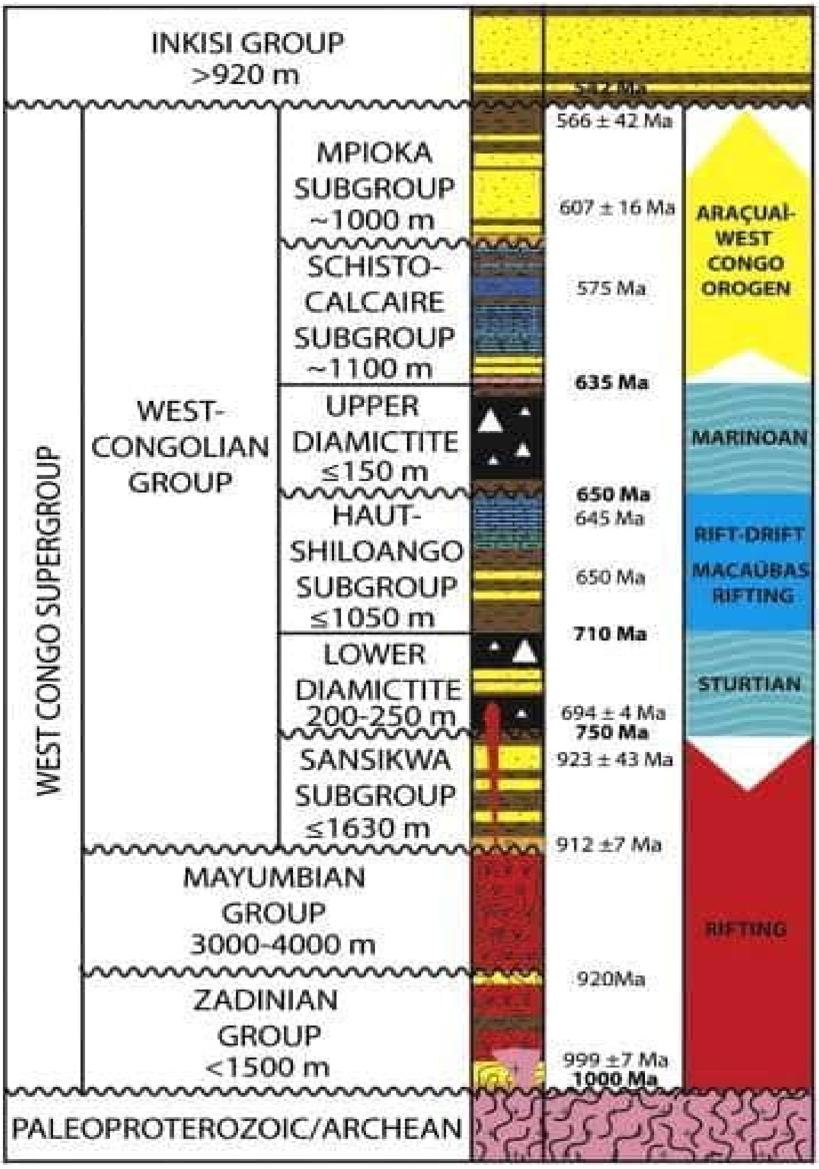


Figure 3 Lithostratigraphic column of the Inkisi Formation (Tack et al, 2010).

1.2.2. Mineral structure and resources

The Inkisi Formation is a geological formation consisting mainly of arkosic sandstone (feldspathic arenite) dating from the Paleozoic era, with overlying loose material composed of sand grains and iron oxides acting as binders. It includes minerals such as quartz, feldspars, micas, and tourmaline, as well as rock fragments. These mineralogical characteristics indicate a siliceous composition with some opaque heavy minerals present (Schermerhorn L.J.G. 1961). In terms of mineral resources, the region around Inkisi, within the broader context of the geological basin, is known for its varied deposits, including cobalt, copper, and iron. For example, there are iron-rich laterite zones (iron hats) and cobalt deposits associated with silicified dolomites. The copper deposit in the Mbanza-Ngungu region (near Inkisi) also attests to the local mineral wealth. The minerals mined are both oxides and sulfides, which contain significant metal resources present in the formation and its surroundings (Trompette, R. 1994; Ngakosso and al, 2001).

1.2.3. Oil system

- **Bedrock**

The bedrock of the Inkisi Formation refers to the underlying sedimentary rock, a red to purplish-red feldspathic arkose, forming the basement of the Inkisi sandstone basin around Kinshasa. It consists mainly of coarse siliceous or arkosic sandstone, with feldspars, quartz, mica, and lithic fragments, sometimes conglomeratic at the base, cemented by silica or iron oxides. The facies indicate a post-Pan-African fluvial-deltaic deposit in a Paleozoic extension basin, with current alteration to kaolinite and ferruginous concretions Affaton et all, (2016). This formation lies unconformably on the Mpioka molasse or Precambrian basement and is covered by ochre sands, laterites, or formations such as Bucomasi. It outcrops in quarries near Kinshasa, at approximately 5°S and 15°E, contributing to the plateaus of the Congo Basin.

- **Rock reservoir**

The Inkisi formation's petroleum system is part of the geological context of the West Congolese Supergroup, where red arkosic deposits (sands and sandstones) from the Paleozoic era form a sedimentary basin conducive to the accumulation of potential reservoirs. The Inkisi formation, deposited in a post-Pan-African extension basin, has lithological and structural characteristics that may favor the presence of hydrocarbon reservoirs, particularly due to its moderately porous sandstones, the presence of secondary fractures, and variable intergranular connectivity (Alvarez P, Maurin J-C, Vicat J-P. 1995). Overall, the Inkisi formation can be considered a significant component of a larger petroleum system in the Congo Basin, where it represents reservoir potential due to its petrophysical properties and geological setting. This potential can be explored both for hydrocarbon exploration and for understanding hydrodynamic flows in the region, paving the way for energy and hydrogeological exploitation prospects.

1.2. History of geological research on the Inkisi Formation

The first descriptions of the Inkisi Formation date back to the work of Belgian geologists in the early 20th century (Cornet, 1914; Cahen, 1954). These pioneering studies focused mainly on the general stratigraphy of the Congo Basin and lithological classification. Subsequently, the work of (Lepersonne 1974) clarified the stratigraphic succession of the Inkisi Group, placing it at the top of the region's shale series. More recently, (Daly 1991, 1992) proposed a structural and tectonic synthesis of the Congo Basin and its margins, highlighting the importance of the Inkisi Formation in understanding post-Pan-African evolution. Despite these contributions, few studies have addressed petrophysical aspects in detail, which justifies the present research.

The objective of this study is to analyze the physical properties of the rocks in the Inkisi formation in order to determine their capacity to contain hydrocarbons. This analysis is based primarily on the petrophysical characterization of the rocks, which includes the study of several key parameters (Bussac G and al, 1960). First, the porosity of the rocks must be assessed, i.e., the amount of void space that can accommodate fluids, and their permeability, which corresponds to the ease with which these fluids can flow through the porous network. High porosity combined with sufficient permeability is essential for a rock to serve as a hydrocarbon reservoir.

2. Methodology

Methodological steps

To meet the objectives of our study, we adopted a rigorous, multidisciplinary methodology incorporating documentary research, data analysis, and field investigations. Initially, a thorough bibliographic analysis of previous work was carried out, supplemented by a study of the archives of the Center for Geological and Mining Research.

Next, a geological survey of the outcrops in the field was carried out (a total of 38 samples were taken) using equipment such as:

-GPS: for geolocation,
-Geological hammers: for taking samples,
-Geological compass: for structural measurements (dip and strike),
- Magnifying glass: for detailed observations.

Finally, the samples were analyzed at the Kinshasa Road Authority laboratory for petrophysical analyses (porosity and permeability).

We therefore used the mercury porosimetry method: the sample is placed in a vacuum chamber and then immersed in mercury. Gradual pressure (from 0.1 to 400 MPa) is applied, forcing the mercury to penetrate the pores according to Washburn's equation: $r = 2\lambda COS\Theta/P$ where r is the pore radius, λ is the surface tension of mercury, θ is the contact angle (typically 140°), and P is the pressure.

For permeability, we used the stationary permeametry method, in which the sample is placed in a sealed cell, saturated with water, and then subjected to a hydraulic head difference between the inlet and outlet. We measure the steady flow Q through the sample; Darcy's law $Q=kA\Delta P/L$ then allows us to calculate the permeability coefficient k, where A is the cross-sectional area and L is the length of the sample.

3. Results and discussion

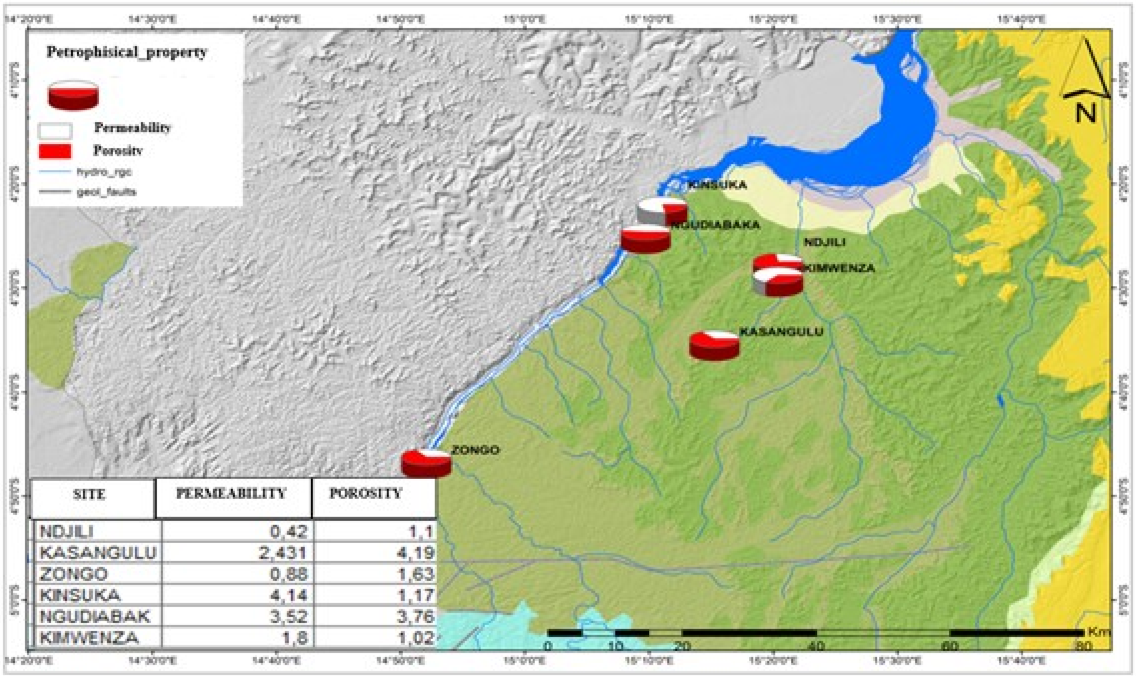
Table 1 Table summarizing the calculations of the porosity result (Road office/DRC; 2025).

SITE	Dry cylinder mass (dm) (g)	Wet cylinder mass (wm) (g)	Bulk density (ρ) g/cm³	Porosity (Φ) (%)	Cylinder volume (V) (cm³)	Pore volume (Vp) (cm³)	Bulk density (ρa) g/cm³
NDJILI	45,8	46	2,54	1,1	0,078740157	0,000866142	581,66
KASANGULU	43,7	44,4	2,66	4,19	0,263157895	0,011026316	166,06
ZONGO	33,1	33,3	2,7	1,63	0,074074074	0,001207407	446,85
KINSUKA	68,2	68,5	2,66	1,17	0,112781955	0,001319549	604,7066667
NGUDIABAKA	39,7	40,3	2,49	3,76	0,240963855	0,009060241	164,755
KIMWENZA	77,7	78	2,66	1,027	0,112781955	0,001158271	688,94

The map shown below (Figure 1) presents the petrophysical properties of six sites located in the southwestern part of the city-province of Kinshasa and Kongo-Central, highlighting the permeability (K) and porosity of local geological formations. The data show significant variation between sites: KINSUKA and NGUDIABAKA have high permeability (4.14 and 3.52, respectively), indicating good fluid transmission capacity, while KASANGULU has the highest porosity (4.19%), suggesting significant storage potential. Conversely, NDJILI has the lowest values, revealing an environment less favorable to water circulation or storage. This map, combining geographic, hydrological, and geological data, is a useful tool for assessing groundwater resources and managing aquifers in the region.

3.1. Porosity analysis

The graph (Figure 2) illustrates the porosity of rocks at different sites in Kinshasa and Kongo-Central. Kasangulu has the highest porosity (4.19%), reflecting well-sorted, loosely compacted, and probably coarse sediments typical of recent fluvial or alluvial deposits with high permeability. Ngudiabaka (3.76%) and Zongo (1.63%) show intermediate values, corresponding to mixed deposits alternating between permeable and impermeable layers. Kimwenza (1.02%), Ndjili (1.1%) and Kinsuka (1.17%) show low porosities, linked to significant compaction, the presence of fines or advanced cementation, suggesting calm or ancient environments. From a petroleum perspective, only Kasangulu and Ngudiabaka could represent marginal reservoir potential, while the other sites, with porosity <2%, are not very favorable for hydrocarbon circulation, except in the presence of fractures or special matrices. These analyses are based on porosity (Boggs, 2006).



SITE	PERMEABILITY	POROSITY
NDJILI	0,42	1,1
KASANGULU	2,431	4,19
ZONGO	0,88	1,63
KINSUKA	4,14	1,17
NGUDIABAK	3,52	3,76
KIMWENZA	1,8	1,02

Figure 4 Porosity and permeability diagram map.

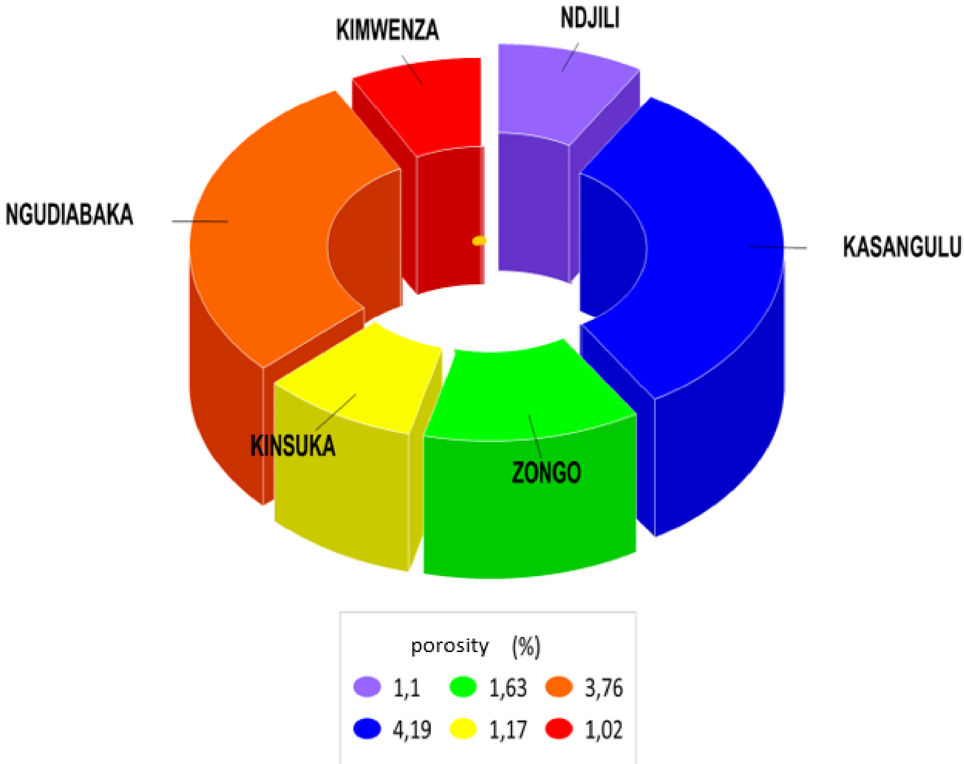


Figure 3 3D diagram of porosity.

3.2. Permeability analysis

Table 2 below shows the relative permeability, absolute permeability, and effective permeability values measured at the various sites.

Table 2 Permeability result calculations.

Site	PERMEABILITY RELATIVE Kr	PERMEABILITY ABSOLUTE Kv (md)	PERMEABILITY K
NDJILI	1,4	0,3	0,42
KASANGULU	1,3	1,87	2,431
ZONGO	1,1	k0,8	0,88
KINSUKA	2,3	1,8	4,14
NGUDIABAKA	1,6	2,2	3,52
KIMWENZA	1,5	1,2	1,8

Analysis of sandstone permeability at the sites studied (Figure 40) shows that Kinsuka has the highest permeability (4.14 mD), despite modest porosity (1.17%), suggesting good flow potential due to effective sorting or fractures. Kimwenza (3.52 mD) and Ngudiabaka (2.43 mD) also exhibit high permeability, reinforcing their potential as reservoirs, even with low porosity, typical of weakly cemented or fractured rocks. Zongo (1.8 mD) and Kasangulu (2.43 mD), the latter with the best porosity (4.19%), show interesting overall potential for low-viscosity petroleum systems. In contrast, Ndjili (0.42 mD) is distinguished by very low permeability, which severely limits its reservoir potential (Boggs, 2006).

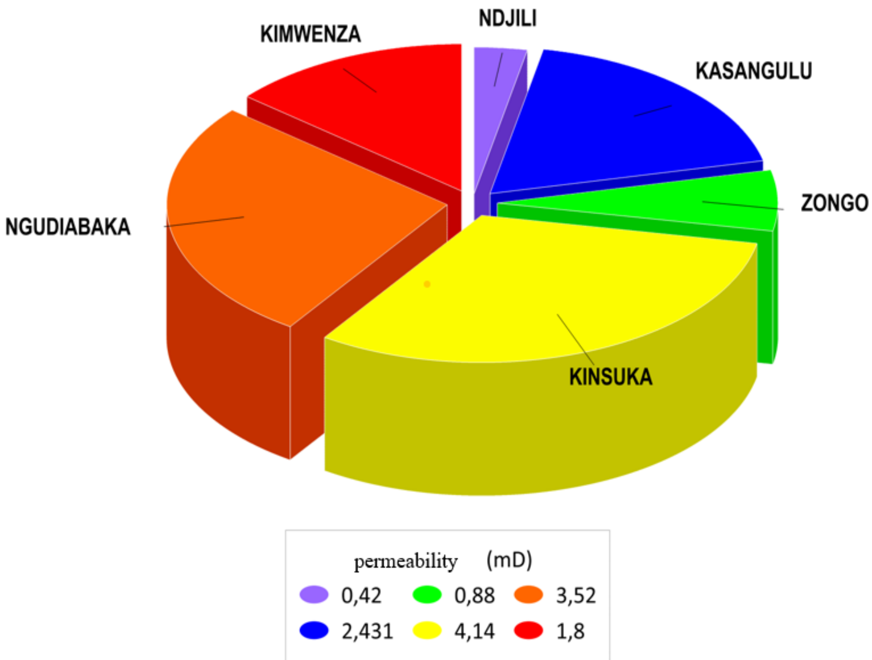


Figure 3 3D diagram of permeability.

3.3. Combined analysis

The combined porosity-permeability analysis shows that the sandstones studied have moderately to weakly porous and permeable reservoir characteristics (porosity 1.02–4.19%; permeability 0.42–4.14 mD), typical of diagenic formations. The Kasangulu site, with the best porosity (4.19%) and average permeability (2.43 mD), appears to be the most promising reservoir, while Kinsuka stands out for its high permeability (4.14 mD) despite low porosity (1.17%), suggesting a role for fractures. Kimwenza and Ngudiabaka show intermediate potential (permeability 2.4–3.5 mD; porosity <2%), reflecting partially cemented or compacted sandstones, while Ndjili, with very low porosity and permeability (1.1%; 0.42 mD), has limited reservoir potential (Levorsen, 1967; Tiab & Donaldson, 2015).

3.4. Analysis of the correlation between porosity and permeability

The linear relationship between porosity (%) and permeability (mD) of the sandstones studied is described by the equation: Permeability = 0.357 × Porosity + 1.432, indicating that a 1% increase in porosity results in an average increase of 0.357 mD, while a base permeability of approximately 1.432 mD remains even at zero porosity, reflecting the effect of secondary porosity or microfractures. However, Pearson's correlation coefficient (r = 0.35) and p-value (0.49) reveal a weak and statistically insignificant correlation, confirming that permeability variability is controlled more by texture, cementation, and fracturing than by porosity alone (Figure 4) (Bear, 1972; Tiab & Donaldson, 2015).

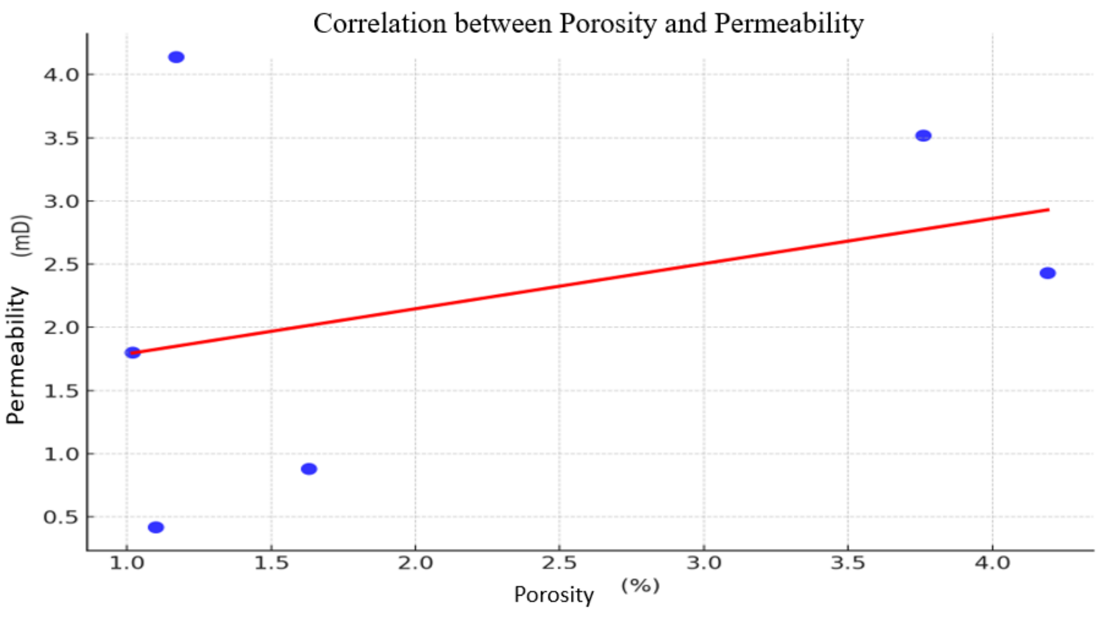


Figure 4 Correlation between porosity and permeability.

The linear regression between porosity and permeability of the sandstones studied reveals a positive but weak correlation (r = 0.35; p = 0.49), which is statistically insignificant, suggesting that the relationship between these parameters is largely controlled by petrographic and structural factors rather than by a direct link. Indeed, Kinsuka has high permeability (4.14 mD) despite very low porosity (1.17%), reflecting secondary porosity related to fractures, while Kasangulu and Ngudiabaka have relatively high porosity-permeability pairs, characteristic of well-sorted and poorly cemented sandstones. Overall, very low porosities (< 5%) limit reservoir potential, but variations in permeability show the importance of intergranular connectivity and/or fracturing in controlling reservoir quality (Bear, 1972; Tiab & Donaldson, 2015).

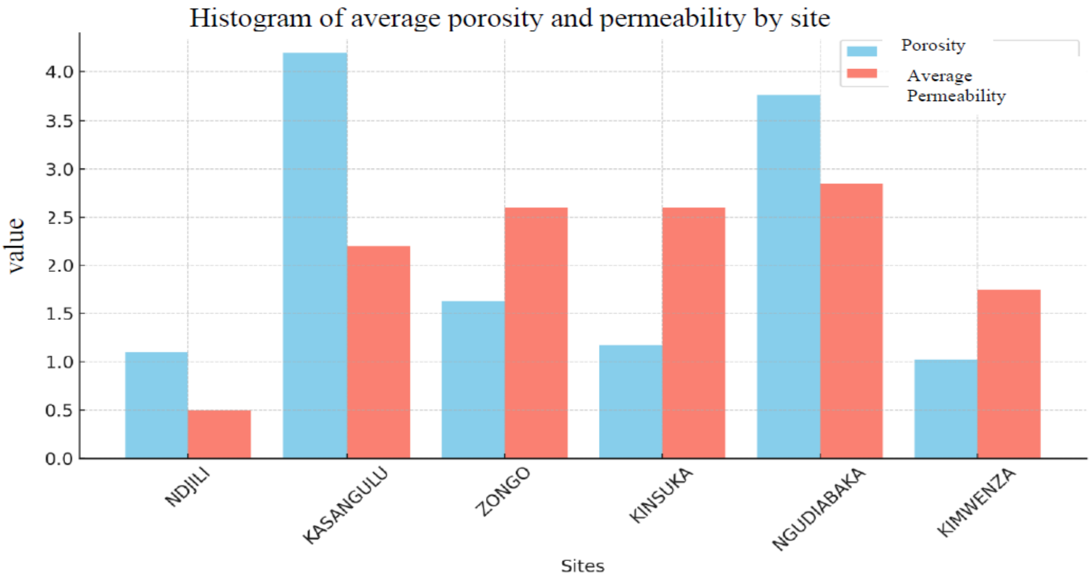


Figure 5 Histogram of average porosity and permeability by site.

4. Conclusion

The petrophysical study of samples from the Inkisi Formation, particularly at the Kasangulu, Ndjili, Zongo, Kinsuka, Ngudiabaka, and Kimwenza sites, highlights several important new findings for understanding this formation in its regional context. The analyses reveal a predominance of fine to medium-sized particles with asymmetrical and varied grain size distributions, reflecting multiple deposition events and complex transport environments. The sandstones analyzed are moderately porous (1.02–4.19%) and permeable (0.42–4.14 mD), indicative of significant diagenesis, with Kasangulu showing the highest porosity, while Kinsuka and Ngudiabaka show the highest permeabilities, suggesting that permeability is controlled more by intergranular connectivity and secondary fracturing than by simple porosity (weak correlation r = 0.35). This study, which is innovative for the area, places the Inkisi formation in a broader context of a potential petroleum system and a crucial hydrogeological setting. The presence of sandstone with moderate porosity and permeability may make these formations attractive reservoirs for hydrocarbon exploitation, particularly in areas where fractures improve permeability.

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