Petrophysical Characterization and Lithological Mapping of the Ikole–Itapaji Basement Complex, Southwestern Nigeria

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ABSTRACT

The Ikole–Itapaji area forms part of the Precambrian Basement Complex of southwestern Nigeria and comprises diverse crystalline rocks whose lithological and structural characteristics influence their inferred petrophysical behaviour. This study focuses on the petrophysical characterization and lithological mapping of the Ikole–Itapaji Basement Complex using detailed field geological investigations, structural measurements, rock sampling and lithological interpretation. Geological mapping was conducted across accessible exposures, while lithological characteristics, weathering conditions and structural features were systematically documented. Thirty-five representative rock samples were collected from the major lithological units to support lithological characterization. The mapped basement comprises gneiss, migmatite, granite, pegmatite and charnockite, distinguished based on their mineralogical, textural and field characteristics. Structural features, including foliation, joints, fractures, folds, quartz veins, and shear zones, were also identified and measured. The petrophysical characterization was qualitative and geologically constrained because direct measurements of porosity, permeability, density and electrical resistivity were not undertaken. The results indicate that the inferred petrophysical behaviour of the basement is primarily controlled by lithology, weathering and structural discontinuities. Fresh, massive crystalline rocks are expected to have very low primary porosity, whereas weathered, fractured, and jointed zones may develop enhanced secondary porosity and permeability. Gneiss and migmatite exhibit relatively greater potential for secondary fluid movement where structural discontinuities and weathering are well developed, while granite, pegmatite and charnockite are comparatively massive and have limited primary pore space. The study demonstrates that lithological mapping integrated with structural and weathering characteristics provides a useful basis for qualitative assessment of the petrophysical behaviour of crystalline basement rocks in the Ikole–Itapaji area.

Keywords: Basement Complex; lithological mapping; petrophysical characterization; secondary porosity; secondary permeability; weathering; Ikole–Itapaji; southwestern Nigeria.

INTRODUCTION

The Basement Complex of Nigeria constitutes a major component of the Precambrian crust of West Africa and comprises diverse lithological assemblages that have undergone complex episodes of deformation, metamorphism and magmatic activity. Southwestern Nigeria exposes extensive basement rocks including gneisses, migmatites, schists, quartzites and granitoids, reflecting a complex history of crustal development associated with the Pan-African tectonothermal event (Ajibade et al., 1987; Rahaman, 1988; Oyinloye, 2011). The variations in lithology, mineral composition, texture and structural features exert important controls on the physical behaviour of these crystalline rocks.

Previous studies have demonstrated the usefulness of geological, remote sensing and geophysical approaches for basement lithological and structural characterization in southwestern Nigeria. Ojo et al. (2024) applied aeromagnetic and remote sensing data to basement classification in Ekiti State, while Adetunla et al. (2025) integrated geological, aeromagnetic and remote sensing datasets for litho-structural mapping of basement rocks in southwestern Nigeria. Studies by Ayuba et al. (2024), Ogah and Abubakar (2024), and Salako et al. (2024) further demonstrated the importance of structural and integrated geophysical interpretation in characterizing basement terrains and identifying zones of geological significance. At the regional scale, the geological framework and evolution of the Nigerian Basement Complex have been extensively discussed by Ajibade et al. (1987), Rahaman (1988) and Oyinloye (2011).

Despite these studies, detailed lithological characterization of specific basement localities remains necessary because lithological contacts, weathering intensity, fractures, joints and other structural features may vary considerably across short distances. In addition, the relationship between lithological and structural characteristics and the inferred petrophysical behaviour of basement rocks remains insufficiently documented in the Ikole–Itapaji area. Since crystalline basement rocks generally have limited primary porosity, geological features such as weathering, fracturing, jointing and shearing may be particularly important in generating secondary porosity and permeability. Consequently, detailed lithological mapping provides an essential basis for understanding the geological controls on the potential petrophysical behaviour of the basement.

This study aims to characterize the petrophysical behaviour of the basement rocks and produce a detailed lithological map of the Ikole–Itapaji area, southwestern Nigeria, based on geological observations and interpretation of the identified lithological and structural characteristics.

Specifically, the study seeks to:

1. identify and characterize the major lithological units exposed within the Ikole–Itapaji Basement Complex;
2. delineate and map the spatial distribution and contacts of the identified lithological units;
3. characterize the weathering, fracturing, jointing, alteration and other structural features affecting the basement rocks;
4. assess the geological controls on the inferred petrophysical behaviour of the basement rocks, particularly with respect to secondary porosity and permeability;
5. establish the relationship between lithological and structural characteristics and the potential pathways for fluid movement within the basement; and
6. develop an integrated lithological and petrophysical interpretation of the Ikole–Itapaji Basement Complex.

The Study Area

Figure 1 shows the location of the Ikole–Itapaji–Ake-Ako area in Ekiti State, southwestern Nigeria. The area is situated within the Precambrian Basement Complex of southwestern Nigeria, which forms part of the Pan-African mobile belt. The basement terrain comprises migmatite–gneiss complexes, Pan-African granitoids, charnockites, pegmatites, and minor metasedimentary rocks that have experienced multiple episodes of deformation, metamorphism, and magmatism (Rahaman, 1988; Oyinloye, 2011).

The study area extends approximately between latitudes 7°47′N and 8°05′N and longitudes 5°26′E and 5°34′E, covering about 590 km². The terrain is rugged and undulating, with hills, ridges, and valleys characteristic of crystalline basement environments. The topographic variations primarily reflect differences in lithology, weathering resistance, and structural deformation of the basement rocks (Ojo et al., 2024).

The drainage pattern is predominantly dendritic, although local changes in stream orientation suggest structural control by fractures, joints, and faults. These structural discontinuities commonly influence surface drainage and provide pathways for groundwater flow and hydrothermal fluid migration within basement terrains (Adetunla et al., 2025).

The study area is readily accessible through a network of major and minor roads connecting Ikole-Ekiti, Itapaji, and Ake-Ako, facilitating geological investigations and field observations. Overall, the geological setting, topography, and structural characteristics make the area suitable for aeromagnetic investigation and structural interpretation aimed at improving the understanding of the basement framework and its mineral exploration potential.

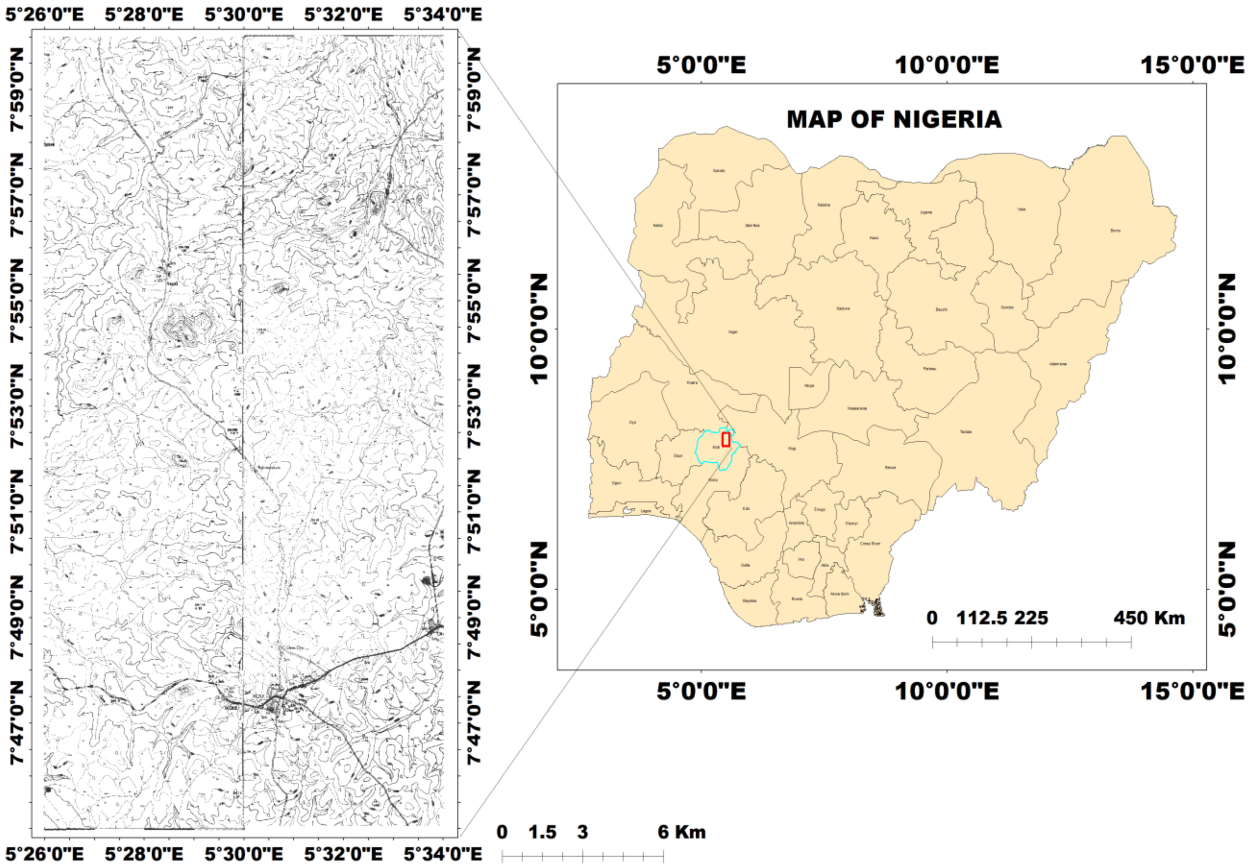

Figure 1. Location and topographic map of the Ikole–Itapaji–Ake-Ako area, Ekiti State, southwestern Nigeria, illustrating the geographical extent, drainage network, road accessibility, and topographic relief of the study area.

GEOLOGICAL SETTING

The study area is located within southwestern Nigeria, forming part of the Precambrian Basement Complex of the West African Craton. This crystalline basement terrain is distinct from the surrounding sedimentary basins, including the Sokoto Basin, Chad Basin, Bida Basin, and the Benue Trough, which are largely composed of Cretaceous-to-Tertiary sediments (Ojo et al., 2024). The southwestern region, including the Ikole–Itapaji axis, is dominated by crystalline rocks that have undergone extensive tectono-metamorphic evolution. The Nigerian Basement Complex evolved through multiple orogenic events, notably the Liberian, Eburnean, and Pan-African cycles, which resulted in widespread deformation, metamorphism, and granitoid emplacement (Adetunla et al., 2025). These processes led to the development of major lithological units, including the migmatite–gneiss complex, schist belts, and Pan-African granitoids.

In the study area, migmatite–gneiss and granitic rocks are predominant, with minor metasedimentary occurrences. Structurally, the area is characterized by well-developed faults, fractures, and foliations, predominantly trending NE–SW and NW–SE, reflecting the imprint of Pan-African deformation (Ogah & Abubakar, 2024). These structures are critical in controlling hydrothermal fluid flow and mineral deposition. Mineralization within the Basement Complex is commonly associated with quartz veins, pegmatites, and shear zones. The presence of granitic and pegmatitic intrusions within the Ikole–Itapaji area further suggests favourable conditions for mineralization. Recent studies have demonstrated the effectiveness of integrated geophysical methods in delineating such structurally controlled mineralized zones (Salako et al., 2024). The geological framework of the study area reflects a complex interplay of lithology and structure, providing a suitable environment for mineralization and justifying integrated geophysical and remote sensing investigations (Fig. 2)

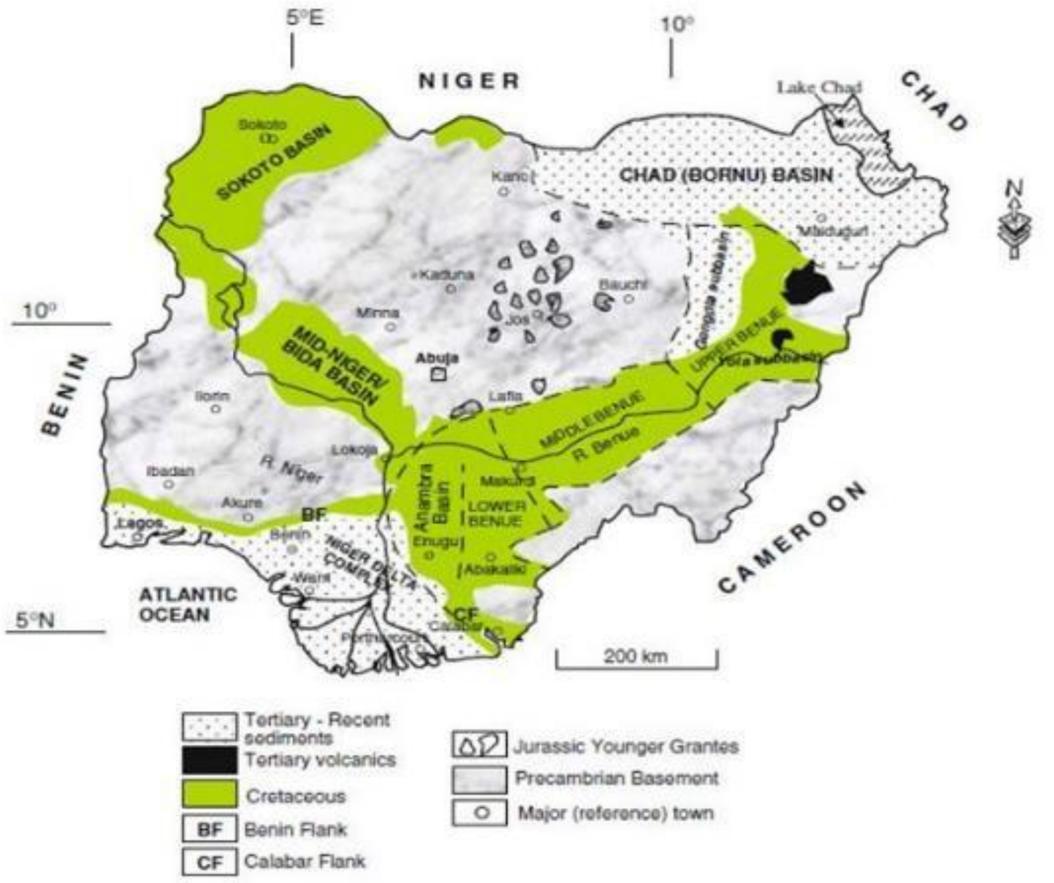

Figure 2: Geological map of Nigeria showing the distribution of major lithological units, including the Precambrian Basement Complex and surrounding sedimentary basins (Sokoto, Chad, Bida, and Benue Trough).

The geological cross-section along A–B in Fig. 3 illustrates the subsurface relationships between the major lithological units. Granite gneiss occupies most of the intermediate crustal section and overlies a broad migmatitic basement. The undulating contact between granite gneiss and migmatite suggests an irregular basement surface produced by differential melting, metamorphic segregation, and prolonged crustal evolution. The continuity of the migmatite beneath much of the section indicates that it forms the oldest exposed basement unit within the area.

The cross-section further demonstrates that the granodiorite intrusion cuts the surrounding granite gneiss in the northeastern segment of the profile. This intrusive relationship indicates that the granodiorite is younger than the host granite gneiss. The pegmatite body shown within the granodiorite represents a later magmatic phase formed by crystallization of residual silica-rich melts. Such pegmatitic intrusions are common products of highly evolved granitic systems and frequently host economically important rare-element minerals (Adetunla et al., 2025).

From a geological evolution perspective, the study area records multiple stages of crustal development. The migmatites represent the oldest basement components formed through high-grade metamorphism and partial melting. These were subsequently reworked and transformed into granite gneiss during regional metamorphic events. Charnockitic bodies were emplaced or developed under high-temperature conditions, while granodioritic magmatism and pegmatitic intrusions represent younger intrusive phases associated with crustal melting and magmatic differentiation. Collectively, these lithological relationships indicate prolonged Precambrian crustal evolution culminating in widespread Pan-African tectono-metamorphism (Rahaman, 1988; Oyinloye, 2011).

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The geological architecture depicted by the map and cross-section demonstrates that the Ikole–Itapaji–Ake-Ako area forms part of a deeply reworked basement terrane characterized by extensive migmatization, granitoid emplacement, and localized charnockitic development. The intimate association of these lithologies provides evidence of repeated episodes of metamorphism, partial melting, magmatism, and crustal stabilization within the southwestern Nigerian Basement Complex.

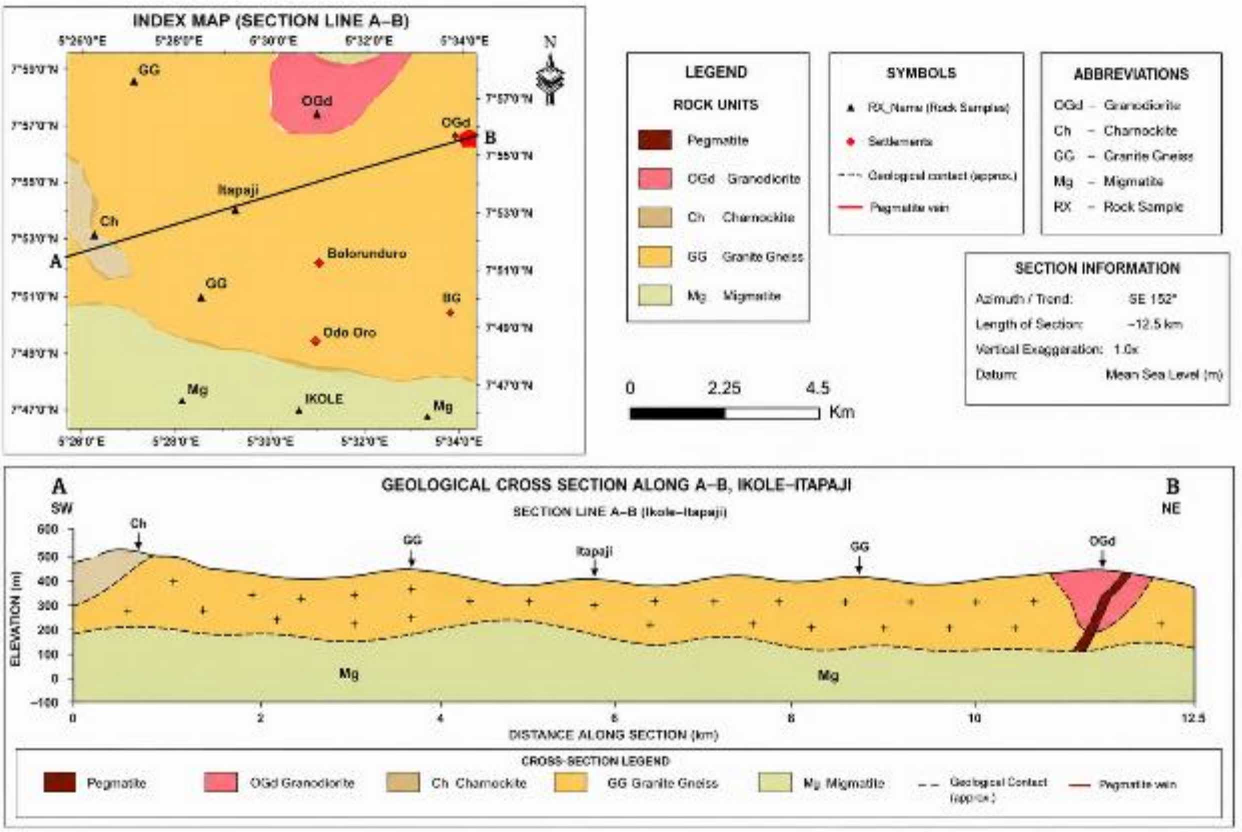

Figure 3. Geological cross-section along A–B across the Ikole-Itapaji area, showing the subsurface relationships between migmatite, granite gneiss, charnockite, granodiorite, and pegmatite units.

MATERIALS AND METHODS

Materials

The materials used for the study included a 1:25,000-scale topographic map, Brunton compass clinometer, Garmin GPSMAP 64s GPS receiver, geological hammer, hand lens, measuring tape, sample bags, field notebook, digital camera, and personal protective equipment. These materials were used for geological mapping, lithological identification, structural measurements, outcrop documentation, and rock-sample collection.

Methods

A reconnaissance survey of the Ikole–Itapaji area was first undertaken using the topographic base map to establish accessibility, drainage patterns, topography, and distribution of rock exposures. Detailed geological mapping was subsequently conducted along roads, footpaths, stream channels, farm tracks, and natural exposures.

At each outcrop, lithological characteristics including rock colour, grain size, mineral composition, texture, fabric, weathering condition, alteration, and contact relationships were recorded. Major lithological units were identified and their geographical coordinates and elevations were obtained using a handheld GPS receiver. Representative field photographs were also taken. A total of thirty-five (35) fresh rock samples were collected from the major lithological units to support lithological identification and characterization.

Structural features including foliation, joints, fractures, folds, quartz veins, shear zones, and mineral lineations were identified and measured using a Brunton compass clinometer. Planar structures were recorded as strike and dip, while linear structures were recorded as trend and plunge. The structural measurements were compiled and analysed using rose diagrams and lower-hemisphere stereographic projections to establish the dominant structural orientations.

The lithological map was prepared by integrating field observations, GPS locations, lithological characteristics, contact relationships, and structural information. The mapped lithological units were differentiated based on their diagnostic field characteristics and spatial relationships.

Petrophysical Interpretation

Petrophysical characterization was carried out qualitatively from the geological characteristics of the basement rocks because direct measurements of porosity, permeability, density, and electrical resistivity were not undertaken. The interpretation focused on the geological factors capable of controlling the physical behaviour of crystalline basement rocks, particularly lithology, weathering, fracturing, jointing, faulting, shearing, and alteration.

Fresh and massive basement rocks were interpreted as having low primary porosity and permeability, whereas intensely weathered, fractured, jointed, sheared, and altered zones were considered potential sites of enhanced secondary porosity and permeability. The distribution and intensity of these features were evaluated in relation to the mapped lithological units to establish their potential influence on fluid movement and the inferred petrophysical behaviour of the basement.

Integrated Interpretation

The geological and structural observations were integrated to produce the final lithological map and establish the relationship between lithology, structural features, weathering, and inferred petrophysical behaviour. This integration provided the basis for identifying geological zones with potentially enhanced secondary porosity and permeability within the Ikole–Itapaji Basement Complex.

RESULTS AND DISCUSSION

Lithological Mapping

Gneiss

Gneiss Fig. 4 is one of the dominant lithological units within the Ikole–Itapaji Basement Complex. It is characterized by well-developed alternating felsic and mafic bands produced during high-grade regional metamorphism, reflecting prolonged tectonothermal evolution and crustal reworking (Rahaman, 1988; Oyinloye, 2011). The rock is generally medium- to coarse-grained, with foliation defined by the preferred orientation of biotite, hornblende, and feldspar. The mineralogical and textural variations observed within the gneiss provide important criteria for distinguishing the unit during lithological mapping and reflect the effects of metamorphic recrystallization and deformation (Winter, 2014; Vernon, 2004).

The gneiss preserves evidence of three deformation phases. The D_1 event is represented by the original compositional banding; D_2 produced the dominant regional foliation through intense ductile deformation; while D_3 is expressed by localized folding, fractures, and shear zones that overprint the earlier fabrics (Rahaman, 1988; Oyinloye, 2011). These structural features indicate that the gneiss forms part of the Migmatite–Gneiss Complex and records the polyphase tectono-metamorphic evolution associated with the Pan-African Orogeny. The occurrence of fractures, joints and localized shear zones within the gneiss is also significant to its inferred petrophysical behaviour, as such discontinuities may provide secondary pore spaces and preferential pathways for fluid movement within the crystalline basement. Consequently, zones where fracturing and weathering are more pronounced may possess greater potential for secondary permeability than relatively fresh and massive portions of the gneiss (Gabrielsen, 2024). Fig. 9 illustrates the representative occurrence and structural characteristics of the gneiss within the study area.

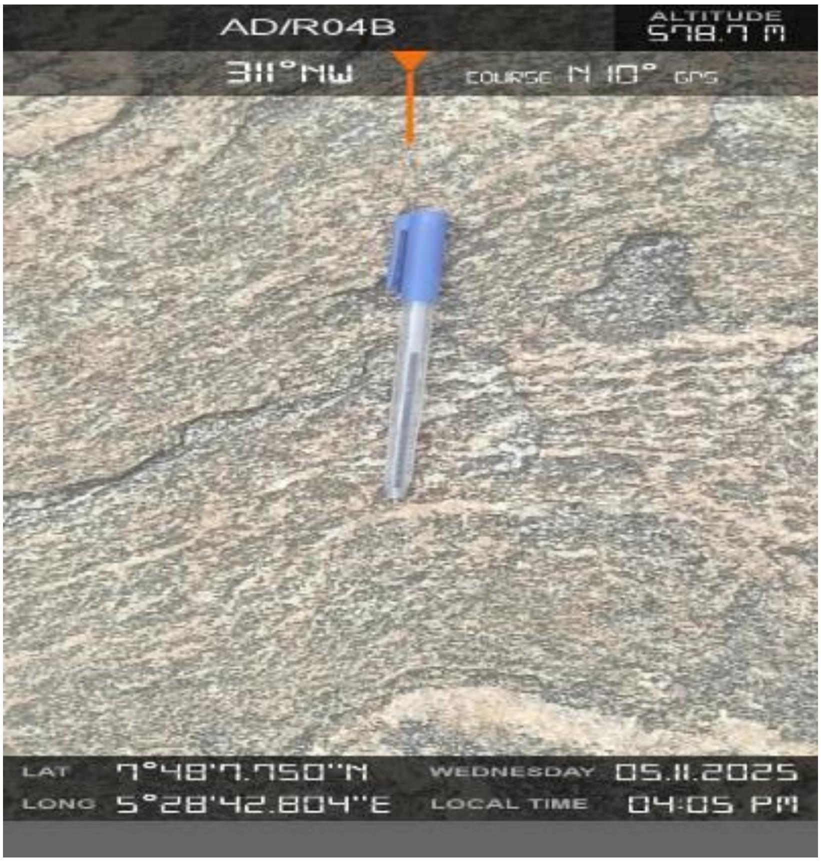

Figure 4. A gneiss outcrop showing well-developed gneissic banding defined by alternating felsic and mafic mineral layers.

Migmatite

Migmatite Fig. 5 is one of the major lithological units in the study area and is characterized by alternating light-coloured leucocratic bands and dark melanocratic layers formed through partial melting (anatexis) during high-grade metamorphism. The leucocratic bands are composed mainly of quartz and feldspar, whereas the melanocratic layers are rich in biotite and hornblende, reflecting melt segregation, mineral recrystallization and compositional differentiation during high-grade metamorphism (Rahaman, 1988; Oyinloye, 2011). The distinct contrast between the leucocratic and melanocratic components provides a useful field criterion for distinguishing the migmatite from other basement lithologies during lithological mapping. The mineralogical and textural characteristics of the rock are also consistent with the complex metamorphic and magmatic processes that characterize high-grade basement terrains (Winter, 2014; Vernon, 2004).

The migmatite preserves evidence of three deformation phases. The primary compositional layering represents D_1, D_2 produced the dominant foliation through intense ductile deformation, while D_3 is expressed by localized folding and fractures that overprint the earlier fabrics (Rahaman, 1988; Oyinloye, 2011). These features indicate that the migmatite forms part of the Migmatite–Gneiss Complex and records the polyphase tectono-metamorphic evolution associated with the Pan-African Orogeny in the Southwestern Nigerian Basement Complex. The presence of fractures and localized structural discontinuities may also influence the inferred petrophysical behaviour of the migmatite by providing potential pathways for fluid movement and contributing to secondary porosity and permeability. Where such fractures are interconnected and associated with weathering or alteration, their influence on fluid movement may be enhanced (Gabrielsen, 2024). Fig. 10 illustrates the representative field occurrence and structural characteristics of the migmatite within the study area.

Figure 5. Migmatite field photograph showing well-developed migmatitic banding with alternating leucocratic and melanocratic layers.

Pegmatite

Pegmatite Fig. 6 is an important intrusive lithological unit in the study area, characterized by a very coarse-grained, leucocratic texture dominated by quartz and feldspar. Its conspicuous coarse crystal size, massive character, and generally weakly developed foliation distinguish it from the surrounding migmatitic and gneissic rocks, making it readily identifiable during lithological mapping. Pegmatites commonly represent highly evolved magmatic products formed from residual melts enriched in volatile components and incompatible elements, and their mineralogical and textural characteristics provide evidence of advanced magmatic differentiation (Černý et al., 2012; London, 2024).

The pegmatite is interpreted as a late-stage product of Pan-African granitic magmatism and was emplaced after or during the waning stages of the major regional tectono-magmatic activity. Its relatively massive character and weak deformation suggest limited subsequent ductile deformation compared with the surrounding gneisses and migmatites, although minor fractures may reflect later brittle deformation. The occurrence of pegmatite veins and bodies cutting or occurring within older basement lithologies provides evidence of intrusive relationships and contributes to understanding the late-stage magmatic evolution of the Ikole–Itapaji Basement Complex (Rahaman, 1988; Oyinloye, 2011; Adetunla et al., 2025).

From a petrophysical perspective, the generally massive and crystalline nature of the pegmatite suggests limited primary porosity. However, fractures and joints developed within the pegmatite may provide localized secondary pathways for fluid movement, particularly where the discontinuities are interconnected or associated with weathering. Thus, the occurrence and structural condition of pegmatite bodies are relevant to the qualitative assessment of secondary porosity and permeability within the mapped basement terrain (Gabrielsen, 2024). Fig. 11 shows the representative field occurrence of pegmatite in the study area.

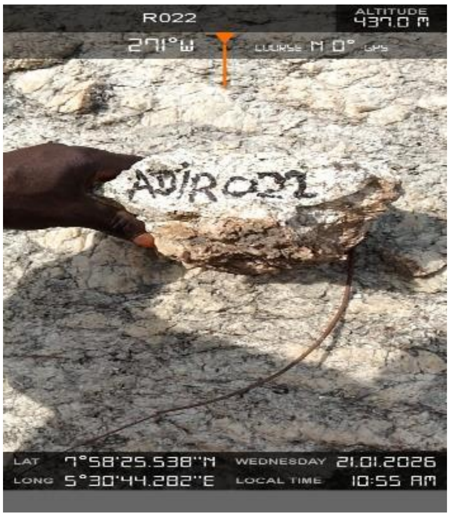

Figure 6. Pegmatite outcrop showing a predominantly leucocratic appearance and coarse-grained crystalline texture.

Granite

Granite Fig. 7 occurs as coarse-grained, leucocratic intrusive bodies composed predominantly of quartz and feldspar, with subordinate biotite and hornblende. The rocks generally preserve their characteristic igneous texture, although locally developed weak foliation and preferred mineral alignment indicate limited post-emplacement deformation. The mineralogical and textural characteristics provide useful criteria for distinguishing the granite from the surrounding gneissic and migmatitic rocks during lithological mapping (Rahaman, 1988; Oyinloye, 2011; Winter, 2014).

The granites are interpreted as products of Pan-African magmatism within the Southwestern Nigerian Basement Complex. Their relatively massive character, preservation of igneous textures, and limited development of tectonic fabrics suggest that they experienced comparatively less ductile deformation than the surrounding metamorphic rocks. Minor joints and fractures are interpreted as evidence of later brittle deformation and may locally influence the inferred petrophysical behaviour of the granite by providing secondary discontinuities and potential pathways for fluid movement. Where these fractures are sufficiently interconnected or affected by weathering, they may contribute to enhanced secondary porosity and permeability within otherwise crystalline and relatively impermeable granite (Gabrielsen, 2024). The occurrence of the granite therefore contributes to understanding the magmatic and tectonic evolution of the Ikole–Itapaji Basement Complex (Rahaman, 1988; Adetunla et al., 2025). Fig. 12 shows the representative field occurrence of granite in the study area.

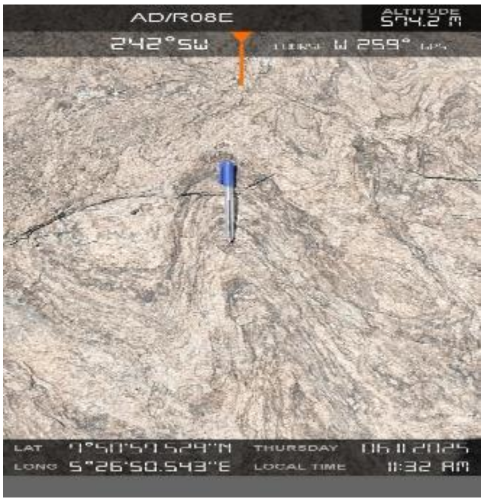

Figure 7. Granite outcrop Sample showing a coarse-grained crystalline texture with weak foliation and

locally developed mineral alignment.

Charnockite

Charnockite Fig. 8 occurs as medium- to coarse-grained, greyish to greenish-grey crystalline rocks with a massive to weakly foliated fabric. The rocks are composed mainly of quartz and feldspar with subordinate ferromagnesian minerals, and their mineralogical and textural characteristics are consistent with high-temperature igneous crystallization within the deep crustal environment (Rahaman, 1988; Oyinloye, 2011). The distinctive colour, texture and mineral assemblage provide useful criteria for differentiating the charnockite from the other basement lithologies during lithological mapping (Winter, 2014).

The charnockites preserve evidence of subsequent tectonic reworking, with the primary igneous fabric locally modified by weak foliation associated with ductile deformation, while joints and fractures represent later brittle deformation. These features indicate that the charnockites record an episode of high-temperature magmatism followed by tectonic modification within the polyphase geological history of the Southwestern Nigerian Basement Complex (Rahaman, 1988; Adetunla et al., 2025). The generally massive nature of the charnockite suggests limited primary porosity; however, joints, fractures and zones of weathering may locally enhance secondary porosity and provide potential pathways for fluid movement. The distribution and intensity of these discontinuities are therefore relevant to the qualitative assessment of the inferred petrophysical behaviour of the charnockite within the study area (Gabrielsen, 2024). Fig. 13 illustrates the representative field occurrence of charnockite in the Ikole–Itapaji area.

Figure 8. Charnockite outcrop Sample showing a massive crystalline texture with weak foliation and evidence of deep-crustal recrystallization.

Qualitative Petrophysical Characterization of the Basement Rocks

Lithological Controls on Petrophysical Behaviour

The petrophysical behaviour of the Ikole–Itapaji Basement Complex is strongly influenced by variations in lithology, mineral composition, texture, grain arrangement and structural fabric. The mapped basement assemblage comprises gneiss, migmatite, pegmatite, granite and charnockite, each exhibiting distinct mineralogical and textural characteristics that may influence their capacity for fluid storage and movement. In crystalline basement terrains, primary pore spaces are generally limited; consequently, variations in petrophysical behaviour are expected to be controlled largely by secondary features such as weathering, fractures, joints, foliation and other structural discontinuities (Rahaman, 1988; Oyinloye, 2011; Winter, 2014).

The gneisses and migmatites, characterized by pronounced mineralogical banding and tectonic fabrics, may exhibit greater potential for secondary porosity and permeability where foliation is intersected by fractures and joints. Their heterogeneous mineralogical and textural characteristics reflect prolonged metamorphic and deformational processes, which may produce zones of mechanical weakness that are subsequently exploited by brittle structures and weathering (Rahaman, 1988; Oyinloye, 2011; Vernon, 2004). Consequently, intensely fractured or weathered portions of these rocks may provide preferential pathways for fluid movement.

Granite and pegmatite are generally more massive and possess relatively well-preserved crystalline textures. Their primary porosity is therefore expected to be very low. Nevertheless, joints, fractures and weathering may generate localized secondary porosity and permeability. In pegmatite, the coarse-grained nature and dominance of quartz and feldspar reflect crystallization from evolved residual melts and provide distinctive lithological characteristics for mapping, while the development of fractures may locally modify its otherwise massive character (Černý et al., 2012; London, 2024).

Charnockite similarly exhibits a predominantly crystalline and massive fabric, suggesting limited primary pore space. However, its petrophysical behaviour may be modified where joints, fractures and weathering are developed. The occurrence and intensity of these discontinuities therefore become more important than primary textural characteristics in assessing its potential for secondary fluid storage and movement (Oyinloye, 2011; Winter, 2014).

Overall, the lithological variations observed in the Ikole–Itapaji Basement Complex suggest that the potential for secondary porosity and permeability is not uniform across the mapped rock units. Rather, it is expected to be controlled by the interaction between lithology and subsequent geological processes, particularly fracturing, jointing, weathering and alteration. The more intensely fractured, weathered or structurally disrupted portions of the basement are therefore considered more favourable for secondary fluid movement than fresh, massive and relatively unfractured rocks. This qualitative interpretation provides the basis for assessing the weathering and structural controls on the inferred petrophysical behaviour of the basement rocks in subsequent sections.

Weathering and Secondary Porosity

Weathering is an important control on the inferred petrophysical behaviour of the Ikole–Itapaji Basement Complex. Progressive alteration and breakdown of crystalline rocks can modify their mineralogical, textural and structural characteristics and generate secondary pore spaces. Unlike primary porosity, which is generally limited in fresh crystalline basement, secondary porosity may develop through weathering, fracturing, jointing and alteration. The extent of these processes is influenced by lithology, mineral composition, texture and structural condition (Rahaman, 1988; Oyinloye, 2011; Winter, 2014; Vernon, 2004).

The variable lithological and structural characteristics of the study area may result in differential weathering of the basement units. Gneiss and migmatite, with their compositional banding, mineralogical heterogeneity and tectonic fabrics, may develop localized secondary pore spaces where weathering acts along foliation, fractures and joints. Granite, pegmatite and charnockite generally have massive crystalline fabrics and limited primary pore space, but weathering along pre-existing fractures and joints may locally enhance secondary pore development (Černý et al., 2012; London, 2024).

Structural discontinuities are particularly important because fractures, joints, faults and shear zones can facilitate fluid penetration and promote deeper weathering. Their distribution therefore provides an important basis for interpreting variations in weathering and potential secondary porosity within basement terrains (Gabrielsen, 2024; Adetunla et al., 2025). However, intense alteration may also produce fine-grained materials that reduce pore connectivity and restrict fluid movement. Thus, the inferred petrophysical effect of weathering depends on its intensity, lithological setting and relationship with structural discontinuities (Ojo et al., 2024; Ogah & Abubakar, 2024).

Overall, zones where intense weathering coincides with interconnected fractures and joints are interpreted as having greater potential for secondary porosity and fluid movement, whereas fresh, massive and weakly fractured basement is expected to exhibit comparatively limited secondary pore development. This provides a basis for assessing the structural controls on secondary permeability in the Ikole–Itapaji Basement Complex.

Fracturing, Jointing and Secondary Permeability

Fractures and joints constitute important geological controls on the inferred secondary permeability of the Ikole–Itapaji Basement Complex. Unlike fresh crystalline basement, where primary pore spaces are generally limited, interconnected fractures and joints can provide preferential pathways for fluid movement. Their influence depends on their orientation, density, aperture, continuity and degree of interconnection, as well as their relationship with lithology and weathering (Rahaman, 1988; Oyinloye, 2011; Gabrielsen, 2024).

The mapped basement lithologies exhibit varying degrees of structural discontinuity. Gneiss and migmatite commonly contain foliation, joints and fractures that may be exploited by later brittle deformation, while granite, pegmatite and charnockite may develop localized fracture and joint networks within otherwise massive crystalline fabrics. Where these discontinuities are open and interconnected, they may enhance secondary permeability and provide potential pathways for fluid migration. Conversely, sealed fractures or fractures filled by secondary minerals may have limited permeability significance (Vernon, 2004; Winter, 2014).

The orientation and spatial distribution of fractures and joints are also important in assessing their potential connectivity. Structural lineaments and fracture systems may reflect zones of deformation and weakness within the basement and can influence the distribution of weathering and fluid movement (Gabrielsen, 2024). Previous integrated geological and geophysical studies in southwestern Nigeria have similarly demonstrated the importance of structural patterns in understanding basement architecture and identifying zones of enhanced geological significance (Adetunla et al., 2025; Ojo et al., 2024).

In the Ikole–Itapaji area, therefore, zones characterized by closely spaced, interconnected and relatively open fractures and joints are interpreted as having greater potential for secondary permeability than massive, unfractured basement. The combination of fracturing with weathering is particularly significant because fractures may facilitate fluid penetration and promote further alteration of the surrounding rock. Consequently, the spatial relationship between fracture intensity, lithology and weathering provides an important basis for evaluating the inferred permeability characteristics of the basement rocks.

Structural Control of Petrophysical Behaviour

Structural features exert an important control on the inferred petrophysical behaviour of the Ikole–Itapaji Basement Complex. Foliation, fractures, joints, faults, shear zones and quartz veins represent discontinuities that can modify the otherwise compact nature of crystalline basement rocks. Their orientation, density, continuity and degree of interconnection influence the potential development of secondary porosity and permeability and may determine preferential pathways for fluid movement (Rahaman, 1988; Oyinloye, 2011; Gabrielsen, 2024).

The gneiss and migmatite, which commonly preserve well-developed foliation and compositional banding, may exhibit structural anisotropy in their physical behaviour. Fractures and joints that intersect or follow these fabrics can provide interconnected pathways, particularly where they are enhanced by weathering. In contrast, the relatively massive granite, pegmatite and charnockite are expected to have limited primary pore space, with their potential permeability being controlled mainly by the development and connectivity of fractures and joints.

Shear zones and major structural discontinuities may represent zones of enhanced deformation and rock weakening. Such features can facilitate fluid penetration and promote localized weathering, thereby increasing the potential for secondary pore development. Conversely, mineral-filled fractures and quartz veins may reduce fracture connectivity and consequently restrict fluid movement (Vernon, 2004; Winter, 2014).

The structural information obtained from field mapping therefore provides an important basis for interpreting spatial variations in the inferred petrophysical behaviour of the basement. Integration of structural orientation and distribution with lithological and weathering characteristics can help identify portions of the Ikole–Itapaji Basement Complex that are potentially more favourable for secondary porosity, permeability and fluid movement. This approach is consistent with previous basement studies in southwestern Nigeria, which emphasize the significance of structural patterns and lithological relationships in understanding basement architecture (Adetunla et al., 2025; Ojo et al., 2024).

Comparative Petrophysical Behaviour of the Lithological Units

The mapped lithological units of the Ikole–Itapaji Basement Complex exhibit different potential petrophysical behaviours as a consequence of variations in mineral composition, texture, fabric, weathering and structural characteristics. Because direct measurements of porosity and permeability were not undertaken, the comparison presented here is qualitative and based on the observed geological characteristics of the rocks. Fresh crystalline rocks are generally expected to have limited primary porosity, whereas secondary porosity and permeability are more likely to develop where weathering, fracturing and jointing are pronounced (Rahaman, 1988; Oyinloye, 2011; Winter, 2014).

Gneiss and migmatite are considered to have relatively higher potential for secondary porosity and permeability because of their pronounced foliation, compositional heterogeneity and susceptibility to structural modification. Where fractures and joints intersect these fabrics and are associated with weathering, they may provide interconnected pathways for fluid movement. Granite and pegmatite are generally more massive and therefore have very low primary porosity, although localized fractures and weathering may enhance their secondary permeability (Černý et al., 2012; London, 2024). Charnockite similarly has limited primary pore space, with its potential permeability expected to depend mainly on the intensity and connectivity of fractures, joints and weathering.

Table 1. Qualitative petrophysical behaviour of the mapped lithological units in the Ikole–Itapaji Basement Complex.

Lithological unit	Primary porosity potential	Secondary porosity potential	Secondary permeability potential	Principal geological controls
Gneiss	Very low	Moderate–high locally	Moderate–high locally	Foliation, fractures, joints and weathering
Migmatite	Very low	Moderate–high locally	Moderate–high locally	Compositional banding, fractures and weathering
Granite	Very low	Low–moderate locally	Low–moderate locally	Joints, fractures and weathering
Pegmatite	Very low	Low–moderate locally	Low–moderate locally	Fractures, joints and weathering
Charnockite	Very low	Low–moderate locally	Low–moderate locally	Fractures, joints and weathering

The comparison indicates that the petrophysical behaviour of the basement is controlled less by primary pore space than by secondary geological features. Gneiss and migmatite may provide greater potential for secondary fluid movement where structural discontinuities and weathering are well developed, whereas granite, pegmatite and charnockite are expected to remain relatively impermeable where they occur as fresh and massive rocks. However, this interpretation is qualitative, and the actual degree of porosity and permeability variation would require direct petrophysical measurements for quantitative confirmation (Gabrielsen, 2024; Adetunla et al., 2025).

Overall, the comparative assessment demonstrates that lithology, structural fabric and weathering must be considered together when evaluating the inferred petrophysical behaviour of the Ikole–Itapaji Basement Complex. Zones where lithological susceptibility to weathering coincides with interconnected fractures and joints are considered the most favourable for enhanced secondary porosity and permeability.

Integrated Petrophysical Interpretation and Qualitative Petrophysical Characterization

The integrated interpretation indicates that the inferred petrophysical behaviour of the Ikole–Itapaji Basement Complex is primarily controlled by lithology, weathering and structural discontinuities rather than by primary pore spaces. The mapped gneiss and migmatite, characterized by pronounced foliation, compositional banding and deformation fabrics, have relatively greater potential for secondary porosity and permeability where fractures, joints and weathering are well developed. Granite, pegmatite and charnockite, which generally exhibit more massive crystalline fabrics, are expected to possess very low primary porosity, with their potential fluid-flow characteristics controlled mainly by fractures, joints and weathering (Rahaman, 1988; Oyinloye, 2011; Winter, 2014).

Structural discontinuities constitute important controls on the development and connectivity of secondary pore spaces. Fractures, joints, shear zones and other lineaments may provide preferential pathways for fluid penetration and movement, while their intersection with weathered zones may further enhance secondary permeability (Gabrielsen, 2024). The integration of lithological and structural characteristics is therefore important for identifying portions of the basement where secondary fluid movement may be more favourable. Similar integrated approaches have been applied in basement terrains of southwestern Nigeria to establish relationships between lithology, structural architecture and subsurface geological characteristics (Adetunla et al., 2025; Ojo et al., 2024).

The qualitative characterization suggests that fresh, massive and weakly fractured basement units have limited potential for fluid storage and movement, whereas weathered and structurally disrupted zones may possess comparatively greater secondary porosity and permeability. However, fracture sealing, mineral infilling and intense alteration may locally reduce fracture connectivity and restrict fluid movement (Vernon, 2004; Winter, 2014). Thus, the inferred petrophysical behaviour varies spatially according to the interaction between lithology, degree of weathering and structural development.

Overall, the Ikole–Itapaji Basement Complex can be regarded as a heterogeneous crystalline system in which secondary geological features exert greater control on potential fluid movement than primary pore characteristics. The integrated lithological and structural interpretation therefore provides a qualitative basis for distinguishing relatively competent basement from zones with potentially enhanced secondary porosity and permeability. These findings demonstrate the importance of combining lithological mapping with structural and weathering characteristics when evaluating the petrophysical behaviour of crystalline basement rocks (Ogah & Abubakar, 2024; Salako et al., 2024).

CONCLUSION

This study provides an integrated lithological mapping and qualitative petrophysical characterization of the Ikole–Itapaji Basement Complex, southwestern Nigeria. The study area comprises diverse basement lithologies, including gneiss, migmatite, granite, pegmatite and charnockite, each exhibiting distinctive mineralogical, textural and structural characteristics that facilitate their differentiation and spatial mapping.

The geological investigation established that the basement rocks preserve evidence of polyphase deformation expressed by foliation, compositional banding, folding, joints, fractures, shear zones and quartz veins. These structural features, together with variations in lithology and weathering intensity, exert important controls on the inferred petrophysical behaviour of the basement. While the fresh crystalline rocks are expected to possess very low primary porosity, weathered and structurally disrupted zones may develop enhanced secondary porosity and permeability.

The qualitative petrophysical assessment indicates that gneiss and migmatite have relatively greater potential for secondary fluid movement where foliation, fractures, joints and weathering are well developed. Granite, pegmatite and charnockite are generally more massive and are therefore expected to have limited primary pore space, although fractures, joints and weathering may locally enhance their secondary permeability. Consequently, the petrophysical behaviour of the basement is controlled primarily by the interaction of lithology, weathering and structural discontinuities.

Overall, the study demonstrates that detailed lithological mapping provides an important geological basis for understanding the spatial variation of inferred petrophysical characteristics within crystalline basement terrains. The integration of lithological and structural information identifies weathered and fractured zones as potentially more favourable for secondary porosity, permeability and fluid movement, while fresh and massive basement represents comparatively less favourable zones. The resulting geological framework contributes to a better understanding of the lithological architecture and petrophysical behaviour of the Ikole–Itapaji Basement Complex.

LIMITATIONS OF THE STUDY

The principal limitation of this study is the absence of direct laboratory measurements of quantitative petrophysical parameters such as porosity, permeability, density and electrical resistivity. Consequently, the petrophysical characterization presented in this study is qualitative and inferred from lithological, weathering and structural characteristics of the basement rocks.

In addition, some portions of the study area have limited rock exposure due to soil cover, vegetation, weathering and accessibility constraints, which may restrict the precise delineation of certain lithological contacts and structural features. Despite these limitations, the integration of field geological observations, structural measurements and lithological mapping provides a useful basis for evaluating the geological controls on the inferred petrophysical behaviour of the Ikole–Itapaji Basement Complex.

Future studies incorporating direct laboratory petrophysical measurements and complementary geophysical techniques could provide quantitative validation of the inferred porosity, permeability and other physical properties of the mapped basement units.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made:

1. Direct laboratory measurements of porosity, permeability, density, magnetic susceptibility and electrical resistivity should be undertaken on representative samples of the mapped lithological units to quantitatively validate the inferred petrophysical characteristics.
2. Detailed geophysical investigations, particularly electrical resistivity, seismic and magnetic methods, should be integrated with the lithological map to improve the delineation of weathered and fractured basement zones.
3. Further field investigations should be conducted in areas with limited rock exposure to improve the accuracy of lithological contacts and structural mapping.
4. Fracture and joint networks should be investigated in greater detail, particularly their orientation, density, continuity and connectivity, to better evaluate their influence on secondary porosity and permeability.
5. Future studies should integrate the geological and petrophysical framework developed in this work with hydrogeological investigations to assess the potential of weathered and fractured basement zones for groundwater occurrence and movement.

DECLARATION OF COMPETING INTERESTS

Ethical Approval

This study did not involve human participants, animals, or any form of clinical or ethical experimentation. Therefore, formal ethical approval was **not required.**

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT (GPT-5-mini) to assist with language editing and content organization. After using this tool, the authors reviewed, revised, and verified all content to ensure accuracy, originality, and authenticity, and take full responsibility for the content of the published article.

Consent to Participate

As no human participants were involved in this research, obtaining consent for participation was **not applicable.** All research activities adhered to standard field and laboratory protocols without the involvement of people.

Consent to Publish

This study does not include any personal, sensitive, or identifiable information. Consequently, consent to publish was **not applicable**. All data presented are **scientific observations and analyses**, fully anonymized, and pose no ethical concerns.

Availability of Data and Materials:

The datasets used and analyzed during this study are available from the corresponding author upon reasonable request.

Authors' Contributions

Adeleke Ojo conceived and designed the study, conducted the geological field investigation and lithological mapping, acquired and documented field data, collected and characterized representative rock samples, carried out the structural analysis and qualitative petrophysical interpretation, prepared the figures and maps, interpreted the results, and wrote, reviewed, and approved the final manuscript.

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