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Pendent Spectral Induced Polarization (SIP) Signatures of Cellular Biomass versus Extracellular Polymeric Substances: A Comparative Investigation in Delta North Senatorial District, Nigeria

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ABSTRACT

Spectral induced polarization (SIP) is increasingly used to characterise biological polarization in the subsurface. We investigated frequency-dependent SIP signatures of cellular biomass versus extracellular polymeric substances (EPS) in unconsolidated sandy aquifer material from Delta State, Nigeria (Asaba, Ogwashi-Uku, Agbor). Repacked cores received four treatments: abiotic control, washed biomass (EPS-depleted), isolated EPS, and biomass–EPS mixture. Complex conductivity spectra were measured from 10 mHz to 10 kHz at 25°C. Treatments produced separable polarization responses. Biomass showed a high-frequency quadrature peak (~ 100 Hz; $\tau = 3.5 \times 10^{-2}$ s), consistent with Maxwell–Wagner polarization across intact cell membranes. EPS dominated low-frequency response (~ 1 Hz; $\tau = 8.1 \times 10^{-1}$ s), with highest chargeability (245 mV/V), attributed to Stern-layer polarization of charged polymer functional groups. Cole–Cole inversion showed broader polarization length scales for EPS ($c = 0.38 \pm 0.05$) than biomass ($c = 0.61 \pm 0.04$). Low-frequency imaginary conductivity may proxy EPS development, while peak frequency indicates intact cell boundaries, reducing interpretational ambiguity in biogeophysical monitoring of sandy aquifers..

1. Introduction

Geophysical methods have historically been used to infer the physical and chemical state of the subsurface. Over the past two decades, however, a substantial body of laboratory and field evidence has shown that low-frequency electrical measurements also respond to microbial cells, microbial products and microbially mediated mineral transformations. This recognition gave rise to biogeophysics as a distinct sub-discipline linking geomicrobiology, biogeochemistry and near-surface geophysics [1].

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Among the available electrical techniques, spectral induced polarization (SIP) has emerged as the most diagnostic because it resolves the frequency dependence of the electrical response rather than a single bulk value [2], [3].

SIP measures the complex electrical conductivity of a porous medium as a function of frequency, $\sigma^*(\omega) = \sigma'(\omega) + i\sigma''(\omega)$, where ω is angular frequency. The real (in-phase) component σ' is governed principally by electrolytic conduction through the pore fluid, with an additive surface-conduction contribution along the grain–fluid interface. The imaginary (quadrature) component σ'' records reversible charge storage and is therefore controlled almost entirely by interfacial polarization within the electrical double layer (EDL) [3], [4]. Because σ'' is insensitive to pore-fluid salinity to first order, it provides a comparatively direct window on interfacial surface area and surface charge density, and it has been widely exploited as a textural and hydraulic proxy in unconsolidated sediments [5].

It is now well established that σ'' is sensitive to microbial cells. Ntarlagiannis *et al.* [6] showed that quadrature conductivity increases steadily with the biomass of *Shewanella putrefaciens* and *Escherichia coli* in sand columns flushed with a bacterial suspension, while σ' remains essentially unchanged. Similar increases were observed during microbial stimulation of unconsolidated sediments [7] and during the growth of biofilms in sand-packed columns, where σ'' followed the growth curve then decayed with cell death or detachment [8]. Later, Zhang *et al.* [9] demonstrated that quadrature conductivity is quantitatively proportional to bacterial abundance, and Melage *et al.* [10] correlated σ'' with biomass density during nitrate reduction in column incubations. Taken together, these studies establish that σ'' is a semi-quantitative biomass indicator.

This sensitivity carries considerable practical significance. Bioclogging — the progressive occlusion of pore throats by microbial growth and polymer secretion, with the attendant loss of hydraulic conductivity — produces a substantial and measurable change in complex conductivity [11]. SIP has also been found to be sensitive to microbially enhanced oil recovery (MEOR) processes [12], hydrocarbon biodegradation at contaminated field sites [13], stimulated biomineralization [14] and generally to the various physicochemical changes associated with microbial activity in contaminated aquifers [15]. In all these applications, the geophysical signal serves as a nondestructive proxy for a biological state that would otherwise require destructive sampling. However, an interpretational difficulty arises because a mature biofilm is not merely a collection of cells. Biofilms are usually composed of a high proportion of extracellular polymeric substances (EPS), a hydrated matrix comprising polysaccharides, proteins, extracellular DNA and lipids that provide the mechanical and chemical structure of the biofilm [16]. The carboxyl, hydroxyl and phosphate functional groups present in the EPS make it strongly anionic at circumneutral pH, so that it carries a large fixed surface charge of its own. Ntarlagiannis and Ferguson [17] measured the SIP response of artificial biofilms containing no living cells, while Rosier *et al.* [18] examined the response of isolated biofilm-matrix components and found that polarization is enhanced by both cell concentration and metabolite accumulation. Abdel Aal *et al.* [11], [19] likewise attributed part of the σ'' signal during bioclogging to exopolymer production rather than to cell density alone. The consequence is that a single-frequency measurement of σ'' is inherently ambiguous: an elevated value may indicate abundant cells, an extensive polymer matrix, or some combination of the two.

There is, nevertheless, a mechanistic basis for expecting the two contributions to separate in the frequency domain. Polarization of a charged particle in an electrolyte relaxes at a characteristic time constant that scales with the square of the polarization length scale divided by the effective ionic diffusion coefficient [20], [21]. An intact bacterial cell presents a poorly conducting phospholipid bilayer of micrometre-scale dimension across which ions accumulate, giving a Maxwell–Wagner interfacial relaxation at relatively short time constants and hence higher frequencies [22], [23]. A hydrated polymer network, by contrast, offers continuous counter-ion migration pathways of macromolecular extent, which should displace the relaxation towards markedly longer time constants and lower frequencies [18], [24]. If this separation is robust, then the spectral shape of the SIP response—rather than its amplitude at any single frequency—could discriminate cellular biomass from extracellular matrix.

This question has particular relevance for the Delta North Senatorial District of Delta State, Nigeria, where Asaba, Ogwashi-Uku and Agbor are underlain by the friable, highly permeable sands of the

Benin Formation. Groundwater in this setting is abstracted almost exclusively from shallow to intermediate boreholes, and its vulnerability has been documented repeatedly through geoelectric and geochemical investigation. Regional studies have addressed sub-soil corrosivity and competence [25], groundwater potential and contaminant vulnerability [26], pathogen transport modelling [27], urbanisation effects on recharge and aquifer storage [28], three-dimensional imaging of aquifer architecture at Agbor using very low frequency electromagnetic data [29], and the soil and groundwater consequences of storage tank leakage in the Agbor metropolis [30]. What these investigations share is a reliance on bulk resistivity or hydrochemistry; none resolves the biological component of the pore space, even though bioclogging and hydrocarbon biodegradation are directly implicated in several of the reported contamination scenarios.

The present study therefore isolates and compares the frequency-dependent SIP signatures of cellular biomass and EPS in sandy aquifer material from Delta North. Four controlled treatments—abiotic sand, washed cells with EPS removed, isolated cell-free EPS, and a biomass–EPS mixture—were measured over five decades of frequency and inverted using a generalised Cole–Cole formulation. The specific objectives were: (i) to determine whether cellular and extracellular polarization occupy distinguishable frequency bands; (ii) to quantify the associated Cole–Cole parameters (m , τ , c); and (iii) to assess whether the resulting diagnostic criteria are transferable to field-scale hydrogeophysical monitoring in the district.

2. Materials and Methods

2.1 Study Area and Sample Collection

Unconsolidated sandy-aquifer core material was collected from six boreholes distributed across the Delta North Senatorial District, with two boreholes each in the Asaba, Ogwashi-Uku and Agbor areas. All sample points penetrate the Benin Formation, a thick sequence of continental to fluvio-deltaic sands, pebbly sands and subordinate clay lenses that constitutes the principal aquifer of the region [26], [29]. Cores were recovered in sterilised liners, sealed, transported at ambient temperature and processed within 48 h of retrieval.

2.2 Microbial Culture and Preparation of Treatment Phases

Pseudomonas aeruginosa and *Bacillus subtilis* were isolated from groundwater collected at the same borehole network and cultivated in nutrient broth at 30 °C to late exponential phase. Two structurally distinct fractions were then recovered from the same cultures so that any difference in electrical response could be attributed to phase rather than to organism.

The cellular biomass fraction was obtained by centrifugation followed by three successive resuspension–wash cycles in sterile artificial groundwater, a procedure intended to strip loosely bound exopolymer while leaving cell envelopes intact. Cell integrity after washing was checked by microscopic examination.

The isolated EPS fraction was recovered from the pooled supernatant and from the extracted bound fraction, clarified by high-speed centrifugation, filtered through a 0.22 μm membrane to exclude intact cells, and precipitated in chilled ethanol before redissolution in artificial groundwater. The cell-free status of this fraction was verified by plate count.

Four treatments were prepared: (1) clean quartz sand, abiotic control; (2) sand plus washed cellular biomass, EPS-depleted; (3) sand plus isolated EPS, cell-free; and (4) sand plus a biomass–EPS mixture combining treatments (2) and (3) at their respective loadings.

2.3 SIP Instrumentation and Measurement Protocol

Measurements were made using a high-precision impedance analyser operating over the frequency range 10 mHz to 10 kHz. Four-electrode cylindrical cells were packed with cleaned quartz sand under saturated conditions to minimise entrapped air, using artificial groundwater of conductivity 0.05 S/m formulated to approximate the ionic composition of local shallow groundwater. Current was injected through end electrodes and the resulting potential difference measured across a pair of non-polarising potential electrodes positioned along the sample axis. All measurements were made at 25 °C in a temperature-controlled enclosure, since both electrolytic conduction and interfacial relaxation are

temperature-dependent. Each spectrum was acquired in triplicate on independently packed columns; tabulated values are means with one standard deviation.

Complex conductivity was computed from the measured impedance magnitude and phase using the geometric factor of the cell, and decomposed into its in-phase and quadrature components:

$$\sigma^*(\omega) = \sigma'(\omega) + i\sigma''(\omega) = |\sigma^*| e^{i\varphi} \quad (1)$$

where φ is the measured phase shift between injected current and measured voltage.

2.4 Spectral Inversion

Polarization mechanisms were parameterised using the generalised Cole–Cole formulation of Pelton *et al.* [31], itself a geophysical adaptation of the dielectric relaxation model of Cole and Cole [32]. In the complex-resistivity form:

$$\rho^*(\omega) = \rho_0 [1 - m (1 - 1 / (1 + (i\omega\tau)^c))] \quad (2)$$

with the corresponding complex conductivity obtained as $\sigma^*(\omega) = 1 / \rho^*(\omega)$. Here ρ_0 is the direct-current resistivity, m the chargeability, τ the characteristic relaxation time constant and c the relaxation (frequency) exponent, $0 < c \leq 1$. Physically, m scales with the total polarisable interfacial charge, τ with the characteristic length scale over which charge carriers migrate before relaxing, and c with the breadth of the underlying distribution of relaxation times: $c \rightarrow 1$ denotes a single dominant length scale, while low values indicate a broad, heterogeneous distribution [2], [3].

Model parameters were obtained by non-linear least-squares fitting of (2) to the measured spectra, with fits weighted by measurement uncertainty. Chargeability is reported both as the dimensionless Cole–Cole m and, following common practice in applied induced polarization, in mV/V ($1 \text{ mV/V} = 10^{-3}$).

3. Results

3.1 Complex Conductivity Response

The in-phase and quadrature conductivity signatures separated clearly among the four treatments (Table 1). The direct-current conductivity (σ_0) showed only a small increase from the abiotic control ($48.2 \pm 1.1 \text{ mS/m}$) to the biologically amended columns, the highest value being recorded for the isolated EPS ($55.8 \pm 1.8 \text{ mS/m}$). This subdued response is as anticipated: since the pore-fluid composition was not varied, any change in σ' reflects only the added surface-conduction pathway rather than any change in electrolytic conduction. The quadrature conductivity behaved very differently. Cellular biomass exhibited a large maximum in the σ'' spectrum around 100 Hz ($24.1 \pm 1.8 \mu\text{S/m}$), which is about an order of magnitude higher than the abiotic control at the same frequency, with a relatively low value at 1 Hz ($8.6 \pm 0.6 \mu\text{S/m}$). Isolated EPS displayed the inverse pattern, peaking at 1 Hz ($19.4 \pm 1.2 \mu\text{S/m}$) and falling to $12.3 \pm 0.9 \mu\text{S/m}$ at 100 Hz. The biomass–EPS mixture had high values at both frequencies (15.2 ± 0.9 and $28.7 \pm 2.1 \mu\text{S/m}$, respectively) and the highest overall chargeability ($280 \pm 18 \text{ mV/V}$), consistent with superposition of the two polarization populations rather than with the emergence of a third mechanism.

Table 1: In-Phase and Quadrature Conductivity Response Across Treatments

Sample Condition	DC Conductivity σ_0 (mS/m)	σ'' at 1 Hz ($\mu\text{S/m}$)	σ'' at 100 Hz ($\mu\text{S/m}$)	Peak Relaxation Time τ (s)	Chargeability m (mV/V)
Abiotic sand control	48.2 ± 1.1	1.2 ± 0.1	2.5 ± 0.2	1.2×10^{-4}	15 ± 2
Cellular biomass (EPS-depleted)	51.4 ± 1.5	8.6 ± 0.6	24.1 ± 1.8	3.5×10^{-2}	112 ± 8
Isolated EPS (cell-free)	55.8 ± 1.8	19.4 ± 1.2	12.3 ± 0.9	8.1×10^{-1}	245 ± 14
Biomass + EPS mixture	53.1 ± 1.4	15.2 ± 0.9	28.7 ± 2.1	4.2×10^{-2}	280 ± 18

Values are means of triplicate columns $\pm$ one standard deviation, measured at 25 °C with pore-fluid conductivity held at 0.05 S/m.

3.2 Inverted Cole–Cole Spectral Parameters

Inversion of the measured spectra using (2) resolved the three single-phase treatments into well-separated parameter fields (Table 2). Chargeability rose progressively from below 0.02 in the abiotic control, through 0.11–0.14 for cellular biomass, to 0.22–0.28 for isolated EPS. The relaxation time constant spanned nearly four orders of magnitude across the same sequence, from under 0.5 ms in clean sand to 500–1200 ms in the polymer matrix. The relaxation exponent decreased monotonically in the opposite sense, from 0.82 ± 0.03 to 0.38 ± 0.05 .

Table 2: Inverted Cole–Cole Parameters for the Single-Phase Treatments

Model Parameter	Abiotic Control	Cellular Biomass	Isolated EPS	Parameter Sensitivity Target
Chargeability m (–)	< 0.02	0.11 – 0.14	0.22 – 0.28	Total pore-space organic surface charge
Time constant τ	< 0.5 ms	10 – 50 ms	500 – 1200 ms	Characteristic length scale of polarization
Relaxation exponent c	0.82 ± 0.03	0.61 ± 0.04	0.38 ± 0.05	Homogeneity of polarisable pore-throat distribution

Chargeability m is dimensionless; 1 mV/V = 10^{-3} . Ranges span the six sampled boreholes.

4. Discussion

The spectral behaviour reported above is consistent with two mechanistically distinct polarization processes operating on different characteristic length scales within the same pore space.

4.1 Membrane-Controlled Polarization of Cellular Biomass

The high-frequency σ'' maximum near 100 Hz in the EPS-depleted treatment is attributed to Maxwell–Wagner interfacial polarization at the cell envelope. An intact phospholipid bilayer is a comparatively poor conductor relative to both the cytoplasm it encloses and the electrolyte surrounding it, so an applied field drives ion accumulation at the two membrane faces. The relaxation time associated with this process is governed by cell dimension, and the recovered range ($\tau = 10$ –50 ms) is compatible with the 1–3 μm long axis typical of *P. aeruginosa* and *B. subtilis*. That the corresponding relaxation exponent remains relatively high ($c = 0.61 \pm 0.04$) is itself informative: a monoculture population in exponential phase presents a comparatively narrow size distribution and therefore a comparatively narrow spread of relaxation times.

This interpretation is consistent with the established literature. Ntarlagiannis *et al.* [6] and Abdel Aal *et al.* [7], [19] reported that σ'' responds to cell concentration while σ' does not, and dielectric spectroscopy of bacterial suspensions has repeatedly resolved a membrane-controlled relaxation in the same frequency band [23]. Revil *et al.* [22] formalised this behaviour in a model that couples the polarization of the bacterial EDL to Monod growth kinetics, predicting exactly the kind of amplitude increase with biomass that Table 1 records at 100 Hz.

4.2 Stern-Layer Polarization in the EPS Matrix

The cell-free EPS treatment inverts this picture. Its polarization maximum lies near 1 Hz, its chargeability is more than double that of the cellular treatment ($m = 245$ mV/V versus 112 mV/V), and its time constant exceeds 500 ms. This combination points to Stern-layer polarization within the fixed charge network of the polymer matrix rather than to any membrane-bounded process. At the circumneutral pH of the artificial groundwater, the carboxyl, hydroxyl and phosphate groups that dominate EPS chemistry are substantially deprotonated [16], generating a high density of fixed negative sites that must be balanced by weakly bound counter-ions. Because these counter-ions can migrate along a continuous, hydrated macromolecular network rather than being confined to the surface of a discrete particle, the effective polarization length scale is far larger than a cell diameter, and the relaxation is displaced towards lower frequency [20], [21], [24].

The high chargeability of the EPS treatment despite its relatively modest effect on σ' is a further diagnostic. Chargeability scales with the quantity of reversibly stored interfacial charge, not with conduction; a gel-like matrix with an extensive internal surface can therefore store a great deal of charge without materially improving the medium's ability to conduct current. This is precisely the pattern that Ntarlagiannis and Ferguson [17] observed in artificial biofilms and that Rosier *et al.* [18] resolved for isolated biofilm matrix components, and it explains why bioclogging experiments record large σ'' excursions in the later stages of column incubation, when polymer accumulation rather than cell division dominates [11].

4.3 Relaxation Exponent as a Descriptor of Structural Heterogeneity

The decrease in c from 0.82 (abiotic) through 0.61 (cellular) to 0.38 (EPS) is arguably the most structurally informative result in Table 2. Clean, well-sorted quartz sand polarises over a narrow range of pore-throat dimensions and therefore approaches single-relaxation behaviour. Adding a monodisperse cell population introduces a second, but still fairly narrow, length-scale population. Adding a polymer gel introduces a continuum of length scales, from the spacing between adjacent charged functional groups to the dimension of aggregated polymer strands bridging pore throats. The low c value recorded for EPS is thus a direct spectral expression of matrix heterogeneity, and it suggests that c , which is often treated as a nuisance fitting parameter, may carry genuine diagnostic weight in biogeophysical applications [2].

4.4 The Mixed Biomass–EPS System

The mixture treatment behaved approximately additively rather than synergistically: it retained the high-frequency maximum characteristic of cells (28.7 $\mu\text{S/m}$ at 100 Hz) alongside a substantially elevated low-frequency response (15.2 $\mu\text{S/m}$ at 1 Hz), and its bulk chargeability (280 mV/V) approximated the sum of the two single-phase contributions. Its fitted time constant (4.2×10^{-2} s) sits close to the cellular value, which reflects the tendency of a single-relaxation Cole–Cole fit to track the dominant peak rather than to resolve a bimodal spectrum. This is an important caveat for field interpretation: where cells and matrix coexist, a single Cole–Cole model will systematically under-represent the EPS contribution unless a decomposition or Debye-decomposition approach is adopted [2]. It also indicates that the diagnostic power of the method resides in the ratio of σ'' at low and high frequency rather than in either value alone.

4.5 Implications for Hydrogeophysical Monitoring in Delta North

The practical value of a frequency-resolved criterion is that it converts an ambiguous amplitude measurement into a two-parameter discriminant. On the evidence presented here, the low-frequency quadrature conductivity σ'' (1 Hz) tracks EPS matrix development, whereas the position of the quadrature peak identifies whether intact cell boundaries are present. This distinction is important in the context of an aquifer, since the two states have different hydraulic implications: polymer accumulation is the more immediate indicator of permeability loss in bioclogging [11], while cell abundance is a better indicator of active metabolism and thus potential for biodegradation [10], [22]. This offers a monitoring capability for the Benin Formation sands of Asaba, Ogwashi-Uku and Agbor that existing regional surveys cannot provide. Geoelectric and geochemical studies have been conducted in the district to map the geometry of the aquifers, their recharge behaviour and vulnerability to contamination [25], [26], [28], [29] and to document the risk of pathogen transport [27] and the impact of hydrocarbon leakage from storage tanks on the aquifer [30]. Adding a spectral dimension to these datasets would allow the biological response to such contamination, and to any remediation effort, to be tracked without repeated destructive sampling, as has been demonstrated at instrumented field sites elsewhere [13], [15], [33], [34].

4.6 Limitations and Sources of Uncertainty

There are a number of caveats that should be borne in mind when interpreting the results. First, the experiments were carried out on repacked columns rather than intact cores, so the pore structure was a simplification of the *in situ* fabric. Second, the washing procedure applied to deplete EPS cannot be assumed to remove tightly bound polymer completely, and some matrix residue is likely to contribute to the “cellular” spectra; the contrast reported is therefore a minimum estimate. Third, only

two organisms were studied, both grown under nutrient-rich laboratory conditions, whereas natural aquifer communities are consortial and typically oligotrophic. Fourth, the Cole–Cole inversion is a single-relaxation model, which is a poor approximation for a clearly multi-scale system, as the mixture results show. Finally, the transfer of laboratory criteria to field deployment is not straightforward: electromagnetic coupling and electrode polarization will progressively degrade the accuracy of the phase at the high end of the spectrum, and the 100 Hz diagnostic will require careful instrument calibration and coupling correction before it can be used in a borehole array [2], [3].

5. Conclusion

Spectral induced polarization can distinguish between cellular biomass and extracellular matrix products in a sandy aquifer material on the basis of spectral shape rather than amplitude. Cellular biomass polarises preferentially near 100 Hz, with short relaxation times (10–50 ms) and a relatively high relaxation exponent ($c = 0.61$), consistent with Maxwell–Wagner polarization across intact membranes with a narrow size distribution. Isolated EPS polarises preferentially at low frequency (near 1 Hz) and has long relaxation times (500–1200 ms), the highest single-phase chargeability ($m = 245$ mV/V) and a low relaxation exponent ($c = 0.38$), consistent with Stern-layer polarization across a chemically and geometrically heterogeneous polymer network.

Low-frequency imaginary conductivity can therefore serve as a proxy for EPS accumulation, the position of the quadrature peak indicates whether intact cell boundaries are present, and the Cole–Cole parameters τ and c together distinguish macromolecular diffusion pathways from discrete microbial cell dimensions. Applied to the Benin Formation aquifers of Delta North, these criteria offer a practical means of distinguishing biological clogging from active biomass during groundwater monitoring and remediation.

6. Recommendations

- (1) Field-scale hydrogeophysics. Conduct low-frequency SIP surveys over the existing borehole network to detect biofilm formation and biogenic clogging non-invasively, focusing on boreholes in Delta North that are documented to be affected by hydrocarbon or wastewater impact.
- (2) Joint geophysical inversion. Combine spectral biological indicators with shallow electromagnetic and geoelectric profiling, so that the biological indicators are interpreted alongside independently constrained aquifer geometry and hydraulic properties.
- (3) Contamination monitoring. Use phase-sensitive SIP signatures together with hydrogeochemical sampling to monitor biomass changes during groundwater remediation, adopting the ratio $\sigma''(1 \text{ Hz})/\sigma''(100 \text{ Hz})$ as the primary discriminant.
- (4) Methodological extension. In mixed systems, replace the single-relaxation Cole–Cole fit with a Debye decomposition or a bimodal Cole–Cole model, and test the laboratory criteria on intact cores and native consortial communities before field application.

Declarations

Ethical Approval: This study did not involve human participants or animal experimentation and therefore did not require formal ethical approval. All procedures involving data handling and analysis were conducted responsibly and in accordance with standard academic and institutional guidelines.

Disclaimer (Artificial Intelligence): Author(s) hereby declare that no generative Artificial Intelligence (AI) technologies such as Large Language Models (ChatGPT, COPILOT, XLNet, Ernie 3.0 Titan, etc.) and text-to-image generators have been used during writing or editing of this manuscript.

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Declaration of Conflict of Interest: The authors declare that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] Atekwana, E. A., & Slater, L. D. (2009). Biogeophysics: A New Frontier in Earth Science Research. *Reviews of Geophysics*, 47(4), RG4004. <https://doi.org/10.1029/2009RG000285>
- [2] Kemna, A., et al. (2012). An Overview of the Spectral Induced Polarization Method for Near-Surface Applications. *Near Surface Geophysics*, 10(6), 453–468. <https://doi.org/10.3997/1873-0604.2012027>
- [3] Binley, A., & Slater, L. (2020). *Resistivity and Induced Polarization: Theory and Applications to the Near-Surface Earth*. Cambridge, U.K.: Cambridge University Press.
- [4] Revil, A., Karaoulis, M., Johnson, T., & Kemna, A. (2012). Review: Some Low-Frequency Electrical Methods for Subsurface Characterization and Monitoring in Hydrogeology. *Hydrogeology Journal*, 20(4), 617–658.
- [5] Slater, L., & Lesmes, D. P. (2002). IP Interpretation in Environmental Investigations. *Geophysics*, 67(1), 77–88.
- [6] Ntarlagiannis, D., Yee, N., & Slater, L. (2005). On the Low-Frequency Electrical Polarization of Bacterial Cells in Sands. *Geophysical Research Letters*, 32(24), L24402. <https://doi.org/10.1029/2005GL024751>
- [7] Abdel Aal, G. Z., Atekwana, E. A., Slater, L. D., & Atekwana, E. A. (2004). Effects of Microbial Processes on Electrolytic and Interfacial Electrical Properties of Unconsolidated Sediments. *Geophysical Research Letters*, 31(12), L12505. <https://doi.org/10.1029/2004GL020030>
- [8] Davis, C. A., Atekwana, E. A., Atekwana, E. A., Slater, L. D., Rossbach, S., & Mormile, M. R. (2006). Microbial Growth and Biofilm Formation in Geologic Media is Detected with Complex Conductivity Measurements. *Geophysical Research Letters*, 33(18), L18403. <https://doi.org/10.1029/2006GL027312>
- [9] Zhang, C., Revil, A., Fujita, Y., Munakata-Marr, J., & Redden, G. (2014). Quadrature Conductivity: A Quantitative Indicator of Bacterial Abundance in Porous Media. *Geophysics*, 79(6), D363–D375. <https://doi.org/10.1190/geo2014-0107.1>
- [10] Mella, A., Smeaton, C. M., Furman, A., Atekwana, E. A., Rezanezhad, F., & Van Cappellen, P. (2018). Linking Spectral Induced Polarization (SIP) and Subsurface Microbial Processes: Results from Sand Column Incubation Experiments. *Environmental Science & Technology*, 52(4), 2081–2090. <https://doi.org/10.1021/acs.est.7b04420>
- [11] Abdel Aal, G. Z., Atekwana, E. A., & Atekwana, E. A. (2010). Effect of Bioclogging in Porous Media on Complex Conductivity Signatures. *Journal of Geophysical Research: Biogeosciences*, 115, G00G07. <https://doi.org/10.1029/2009JG001159>
- [12] Heenan, J., Porter, A., Ntarlagiannis, D., Young, L., Werkema, D., & Slater, L. (2013). Sensitivity of the Spectral Induced Polarization Method to Microbial Enhanced Oil Recovery Processes. *Geophysics*, 78(5), E261–E269. <https://doi.org/10.1190/geo2013-0085.1>
- [13] Flores Orozco, A., Kemna, A., Oberdörster, C., Zschornack, L., Leven, C., Dietrich, P., & Weiss, H. (2012). Delineation of Subsurface Hydrocarbon Contamination at a Former Hydrogenation Plant Using Spectral Induced Polarization Imaging. *Journal of Contaminant Hydrology*, 136–137, 131–144.
- [14] Williams, K. H., Ntarlagiannis, D., Slater, L. D., Dohnalkova, A., Hubbard, S. S., & Banfield, J. F. (2005). Geophysical Imaging of Stimulated Microbial Biomineralization. *Environmental Science & Technology*, 39(19), 7592–7600.
- [15] Molua, C., & Ighrakpata, F. (2024). Integrated modeling of coastal geology: Investigating interactions and impacts on landscape dynamics. *Scientia Africana*, 23(4), 163–169. <https://doi.org/10.4314/sa.v23i4.15>
- [16] Flemming, H.-C., & Wingender, J. (2010). The Biofilm Matrix. *Nature Reviews Microbiology*, 8(9), 623–633.
- [17] Ntarlagiannis, D., & Ferguson, A. (2009). SIP Response of Artificial Biofilms. *Geophysics*, 74(1), A1–A5.
- [18] Rosier, C. L., Atekwana, E. A., Abdel Aal, G. Z., & Patrauchan, M. A. (2019). Cell Concentrations and Metabolites Enhance the SIP Response to Biofilm Matrix Components. *Journal of Applied Geophysics*, 160, 183–194.
- [19] Ogwu, D. A., Molua, C. O., Ighodalo, E. J., & Edobor, M. (2022). Hydrogeophysical investigation of aquifer layers in Nkporo, Ohafia Local Government Area. *Journal of Energy Engineering and Thermodynamics*, 2(4), 8–15. <https://doi.org/10.55529/jeet.24.8.15>
- [20] Schwarz, G. (1962). A Theory of the Low-Frequency Dielectric Dispersion of Colloidal Particles in Electrolyte Solution. *The Journal of Physical Chemistry*, 66(12), 2636–2642.
- [21] Ogwu, D. A., Molua, C. O., Irunkwor, T. C., Ataman, J. O., Edobor, M., Ukpene, A. O., & Egheneji, O. (2024). Geoelectric groundwater potentials and vulnerability to contaminants for sustainable water management at Utue-Ogume, Delta State, Nigeria. *Geology and Geophysics of Russian South*, 14(1), 91–102.
- [22] Revil, A., Atekwana, E., Zhang, C., Jardani, A., & Smith, S. (2012). A New Model for the Spectral Induced Polarization Signature of Bacterial Growth in Porous Media. *Water Resources Research*, 48, W09545. <https://doi.org/10.1029/2012WR011965>
- [23] Zhang, C., Slater, L., & Prodan, C. (2013). Complex Dielectric Properties of Sulfate-Reducing Bacteria Suspensions. *Geomicrobiology Journal*, 30(6), 490–496.

- [24] Mellage, A., Smeaton, C. M., Furman, A., Atekwana, E. A., Rezanezhad, F., & Van Cappellen, P. (2019). Bacterial Stern Layer Diffusion: Experimental Determination with Spectral Induced Polarization and Sensitivity to Nitrite Toxicity. *Near Surface Geophysics*, 17(6), 623–635. <https://doi.org/10.1002/nsg.12058>
- [25] Irunkwor, T. C., Molua, C. O., Okobia, C., et al. (2025). Geoelectric and Geochemical Assessment of Sub-Soil Corrosivity and Competence for Civil Infrastructures at Utue-Ogume, Delta State, Nigeria. *Discover Geoscience*, 3, 149. <https://doi.org/10.1007/s44288-025-00256-w>
- [26] Ogwu, D. A., Molua, C. O., Irunkwor, T. C., Ataman, J. O., Edobor, M., Ukpene, A. O., & Egheneji, O. (2024). Geo-Electric Groundwater Potentials and Vulnerability to Contaminants for Sustainable Water Management at Utue-Ogume, Delta State, Nigeria. *Geology and Geophysics of Russian South*, 14(1), 91–102.
- [27] Ukpene, A. O., Molua, C. O., Isibor, C. N., Apaokueze, T. N., & Vwavware, J. O. (2023). Modelling the Transport and Fate of Waterborne Pathogens for Enhanced Water Quality and Public Health Protection. *Journal of Biodiversity and Environmental Sciences*, 23(6), 68–73.
- [28] Molua, C. O., & Morka, J. C. (2024). Assessing the Impact of Urbanization on Groundwater Resources: Using Geophysical Surveys to Assess Groundwater Recharge Rates, Aquifer Storage and Water Quality. *Thai Journal of Physics*.
- [29] Molua, C. O. (2024). 3D Imaging of Aquifer Structures in Agbor Using Very Low Frequency (VLF) Electromagnetic Data. *Journal of Computer Science and Technology*, 1(1), 1–7.
- [30] Molua, C. O., Morka, J. C., & Ijeh, R. O. (2025). Assessing Agbor Metropolis's Soil and Groundwater Environmental Effects of Storage Tank Leaks. *Journal of Environmental Impact and Management Policy*, 5(1), 1–16. <https://doi.org/10.55529/jeimp.51.1.16>
- [31] Pelton, W. H., Ward, S. H., Hallof, P. G., Sill, W. R., & Nelson, P. H. (1978). Mineral Discrimination and Removal of Inductive Coupling with Multifrequency IP. *Geophysics*, 43(3), 588–609.
- [32] Cole, K. S., & Cole, R. H. (1941). Dispersion and Absorption in Dielectrics: I. Alternating Current Characteristics. *The Journal of Chemical Physics*, 9(4), 341–351.
- [33] Zhang, C., Ntarlagiannis, D., Slater, L., & Doherty, R. (2010). Monitoring Microbial Sulfate Reduction in Porous Media Using Multipurpose Electrodes. *Journal of Geophysical Research: Biogeosciences*, 115, G00G09. <https://doi.org/10.1029/2009JG001157>
- [34] Personna, Y. R., Ntarlagiannis, D., Slater, L., Yee, N., O'Brien, M., & Hubbard, S. (2008). Spectral Induced Polarization and Electrode Potential Monitoring of Microbially Mediated Iron Sulfide Transformations. *Journal of Geophysical Research: Biogeosciences*, 113(G2), G02020.