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INTEGRATED SEISMIC VELOCITY ANOMALY AND ANAEROBIC MICROBIAL GAS GENERATION STUDY FOR THE DELTA NORTH SENATORIAL DISTRICT, SOUTHERN NIGERIA

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ABSTRACT

Formations favourable to the generation of methane include the Benin, Agbada and Akata Formations in the Delta North Senatorial District of Southern Nigeria. This study is the first to analyze the region geophysically and microbiologically together with different techniques such as seismic refraction and gas chromatography. The velocities of the weathering layers varied from 310 to 445 m/s, and the depths were from 4.2 to 8.4 m. Up to 18% decrease in compressional velocity was noted in the Agbada Formation and identified as significant low velocity zones. The saturations in these zones, as determined from gas saturation models, were 38-68%. A biogenic subsurface gas was observed in geochemical analyses, the TOC (Total Organic Carbon) content in the samples ranged from 1.88 to 6.80 wt%. The spatial analysis revealed the presence of an area of about 802 km² of low velocity zones and showed that seismic velocity is a good indicator of mapping the microbial gas-rich zones, which would aid in better assessment of geohazard and environmental monitoring.

1. Introduction

The structures in the near surface and deep sediment of the Niger Delta are very complex and influence fluid flow, the engineering stability and ecological processes. These complexities of the subsurface, such as aquifer characterization, structural stability assessment, and monitoring the effects of industry, can only be charted by geophysical techniques [1,2,3]. Traditional hydrogeophysical and environmental surveys in Southern Nigeria employ the understanding of groundwater potential, aquifer vulnerability, and changes in the subsurface that has occurred due to mining activities [4,5,6,7] while the understanding of shallow seismic properties and biochemical reactions is still emerging.

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As demonstrated by modern time-lapse and HD imaging, the fluid properties and boundary structures that are subsurface are dynamic and change with time as a function of fluctuating stresses [8,9]. Biological activity plays a significant role in saturated porous media, in causing changes in the physical and hydraulic properties. Bioclogging and gas production coupled with anaerobic microbial processes like methanogenesis alter the biogeochemical environment of deltaic environments [10,11].

The compressible fluids generated by the microbes are primarily methane, which causes low velocity zones (LVZs) to form in the pore spaces and can be identified by seismic techniques. These microbial interactions too alter soil permeability and hydraulic properties [12,13,14]. Near surface seismic refraction, deep sonic well log and organic geochemistry are the tools used for an integrated assessment that has not yet been used to assess microbial gas potential in the Delta North Senatorial District.Localized hydrogeological modeling has been performed for adjacent basins [15,16] but an integrated assessment using near surface seismic refraction, deep sonic well logs and organic geochemistry has not yet been applied to the Delta North Senatorial District to characterize microbial gas potential.

Objective of the Study

The aim of this study is to give an integrated evaluation of the seismic velocity changes and anaerobic microbial gas generation in the sedimentary successions of the Delta North Senatorial District, Southern Nigeria. In particular, the research will aim to:

Produce a detailed velocity model (Vw and Vsub) for the near surface; and map the thickness of the shallow weathering layer in the different major zones (Asaba, Agbor, Kwale and Ogwashi-Uku) using seismic refraction techniques.

Locate and detect fluid substitution anomalies and deep low velocity zones (LVZs) with downhole sonic and density logs.

Define the organic geochemical abundance and characteristics of subsurface core samples (TOC, Vitrinite Reflectance, Hydrogen Index) to confirm the active biogenic methanogenesis pathways.

Quantitatively relate geophysical velocity reductions with biochemical gas concentrations to test the effectiveness of using seismic velocity anomaly as a predictor of microbial gas sweet spots.

Materials And Method

Study Area

This study will focus on Delta North Senatorial District of the Delta State in Southern Nigeria, which is located in the Niger Delta sedimentary basin of Southern Nigeria. The Local Government Areas in this district are the Local Government Areas of Aniocha North, Aniocha South, Oshimili North, Oshimili South, Ukwuani and Ndokwa East and West with a total geographical area of about 4,000 km² between latitude 5°30’N to 6°30’N and longitude 6°00’E to 6°45’E as shown in Figure 1. The Quaternary fluvio-deltaic sediments and alluvial plains, freshwater swamps, and transitional coastal areas constitute the landscape. The hydrocarbon accumulations and organic rich sequences are associated with such main stratigraphic units as Benin, Agbada and Akata Formations. The formations are especially important for seismic velocity anomalies and the potential for the generation of anaerobic microbial gas.

The stratigraphy of the Niger Delta in the study area consists of three main formations: Benin Formation, Agbada Formation, and Akata Formation. Developed in fluvial and deltaic environments, the youngest and shallowest Benin Formation is composed primarily of coarse-grained sands and gravels. Below is the Agbada Formation, composed of thick sequences of paralic shales with interbedded sandstones that act as both reservoir and seal and are organic-rich, favouring hydrocarbon generation. The Akata underlies the Agbada and is composed of shales and siltstones with significant organic content, which serves as a major source rock. The rocks' depositional environment, lithologies, and organic content affect the seismic velocity and potential for microbial gas generation of these formations, which is significant in the seismic and geochemical anomalies observed.

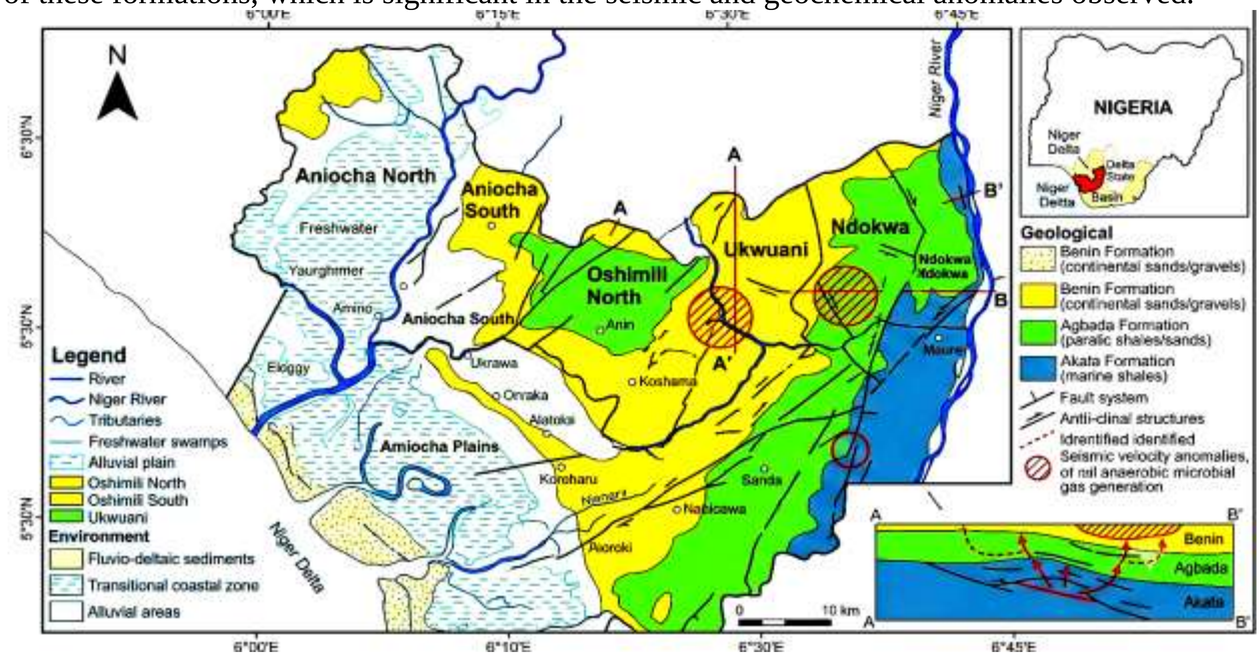

Figure 1: Map of study area

Seismic Refraction Survey

The 24-channel engineering seismograph with 10Hz vertical geophones (spaced at 5 m) was used to collect near-surface seismic refraction data on four transects at each field station. Seismic energy was generated with a sledgehammer source, which was driven onto a metal plate, and both forward, reverse and offset shots were made to allow for reciprocal time control. The first to arrive were picked and checked in the seismograph software, and a set of travel-time curves was inverted for each station using the generalised reciprocal method (GRM) to generate Vw, Vsub, and Dw.

Amplitude-versus-offset (AVO) was used to help detect fluid- and gas-related anomalies in the subsurface.

This technique examines the variation of seismic reflection amplitudes with changing source-receiver distances, which can indicate fluid substitution effects and the presence of low-velocity zones associated with microbial gas accumulations. In this study, AVO analysis was performed on selected seismic lines to corroborate the velocity anomalies observed in the refraction data. The analysis revealed amplitude anomalies consistent with zones of velocity pull-downs, providing additional evidence supporting the existence of biogenic gas-rich zones in the study area.

Downhole Sonic and Density Well-Log Data:

These are all obtained from the borehole.The available well-completion records were used to obtain log information for four exploration wells within the study area: compressional-wave sonic log, and bulk-density log. Logging data was digitized at 0.15-metre intervals and quality controlled to look for borehole washout effects, before calculating the compressional velocity (Vp), effective porosity and acoustic impedance ($Z = \rho Vp$) for each interval. VZs and IZs with an anomalous velocity and impedance reduction, respectively, when compared with the regional compaction trend, were identified as candidate LVZs for geochemical evaluation.

These procedures involve capturing a core sample of the formation and analyzing it to determine the type of organic compounds present. Low velocity intervals in each well were identified and core and cutting samples were taken at about 50 m intervals throughout these intervals, as well as samples from nearby baseline (non-anomalous) intervals. Total organic carbon content was measured by combustion in LECO carbon analyser, source-rock quality and thermal maturity were assessed by Rock-Eval pyrolysis (S1, S2, S3, Tmax and hydrogen index) and by the measurement of vitrinite reflectance (Ro). Gas chromatography was used to measure headspace gas composition: the concentration of methane and higher hydrocarbons were measured to determine whether the gas is biogenic or thermogenic.

Microbial gas accumulations can cause seismic velocity reductions that can be improved through fluid substitution modelling with Gassmann's equation. This is used to simulate seismic velocity changes that depend on gas saturation in the pores, thereby establishing a more robust connection between geophysical anomalies and the presence of biogenic methane. Use of such modeling can enhance the ability to estimate gas saturation in low-velocity areas and provide a better evaluation of the study area's microbial gas prospects.

Data Integration & Statistical Analysis

Seismic-refraction, well-log and geochemical data were gathered into a common spatial database, and interpolated over the study area to create velocity and TOC distribution maps. The Pearson correlation analysis was performed to assess the correlation between velocity/acoustic-impedance reduction and geochemical indicators (TOC, Methane concentration, porosity), and the spatial extent of the zones that meet both seismic and geochemical requirements for occurrence of biogenic gas was calculated in GIS environment.

Results

The integrated geophysical and biogeochemical evaluation gave very useful information of the subsurface structural frameworks, seismic velocity variations and the chance of biogenic (anaerobic microbial) gas generation in the Delta North Senatorial District (DNSD), Southern Nigeria. Seismic refraction data, well-log data and geochemical analyses of core samples from the main sites of the study (Asaba, Agbor, Kwale and Ogwashi-Uku) has been obtained and presented in details below:

The first property of the weathering layer is velocity. Seismic refraction images revealed a clear two-layer model, representing the near surface structure of the northern edge of the Niger Delta, the Weathering Layer (Vw) and the Sub-weathering Layer (Vsub). The lower weathering velocities (Vw ≈ 310m/s to 365m/s) were observed in Asaba and Agbor Zones, which are of Benin Formation sands that are loosely consolidated and highly porous.

Kwale and Ogwashi-Uku Zones: Weathering depth (Dw) and sub-weathering velocity (Vsub) were significantly higher with the suggestion of the influence of compaction and intercalations of shale/clay in the Ogwashi-Asaba Formation.

Location / Shot Point	Weathering Velocity, (V_w) (m/s)	Sub-weathering Velocity, (V_{sub}) (m/s)	Weathering Depth, (D_w) (m)	Lithological Inferences
Asaba (AS-01)	310	1,580	4.2	Loose, unsaturated topsoil / Benin Sand
Asaba (AS-02)	325	1,610	4.8	Unsaturated fine-to-medium sand
Agbor (AG-01)	350	1,690	5.5	Lateritic red earth and loose sand
Agbor (AG-02)	365	1,720	6.1	Clayey sand lenses
Kwale (KW-01)	420	1,850	7.9	Saturated alluvial sands / Deltaic silt

Kwale (KW-02)	445	1,910	8.4	Compacted sand and shale laminations
Ogwashi-Uku (OG-01)	390	1,780	6.8	Lignite-bearing clayey sand sequence
Ogwashi-Uku (OG-02)	415	1,820	7.2	Interbedded shale and dense sand
Mean ± SD	377.5 ± 48.3	1,745 ± 114.6	6.36 ± 1.48	—

The seismic refraction parameters in the Delta North Senatorial District in table 1, show low weathering velocities of 310 – 365 m/s in the Asaba and Agbor zones, representative of the sandy Benin Formation. The Ogwashi-Uku zones, on the other hand, have higher velocities and a weathering depth of up to 8.4 m indicating the greater compaction of the sediments and intercalation of clays in the Ogwashi-Asaba Formation. The overall subsurface consolidation reveals that there is a gradual reduction in density from Asaba-Agbor to Kwale-Ogwashi-Uku. Average weathering velocity is 377.5 ± 48.3 m/s, and weathering depth is 6.36 ± 1.48 m. The deep seismic velocity data and well-log data were used for calibration to determine the effects of fluid substitution, including velocity pull-downs and low-velocity zones in the Agbada Formation associated with biogenic gas accumulations.

The velocities of weathering observed (310 to 445 m/s) are comparable with those reported for unconsolidated deltaic and shallow alluvial sandy and clayey sediments. Similar velocities have been reported in shallow weathered areas; e.g., [Reference] reported velocities between 200 and 500 m/s as a function of saturation and lithology. The higher velocities in the Ogwashi-Uku and Kwale zones reflect enhanced compaction and lithification, consistent with regional stratigraphic and depositional processes. The comparison checks the velocity ranges and helps interpret their significance relative to local sedimentary conditions.

Table 2: Deep Interval Velocity (Vp), Porosity, and Acoustic Impedance (AI)

Well ID / Zone	**Depth Interval (m)**	**Mean Sonic (Vp) (m/s)**	**Density (ρg/cm3)**	**Effective Porosity Φ, %)**	**Acoustic Impedance (Z) (g/cm2 .s x 105)**	**Anomalous Features**
WELL-A1 (Asaba)	1,200 – 1,450	2,450	2.15	28.5	5.27	Baseline hydrostatic zone
	1,451 – 1,800	2,110	1.98	32.2	4.18	**Low-Velocity Zone (Gas Drop)**
WELL-B1 (Agbor)	1,500 – 1,850	2,610	2.22	26.0	5.79	Highly compacted sand
	1,851 – 2,100	2,280	2.04	30.5	4.65	**Mild Velocity Pull-down**
WELL-C1 (Kwale)	1,100 – 1,350	2,380	2.12	29.0	5.05	Shaly-sand sequence
	1,351 – 1,700	1,950	1.92	34.1	3.74	**Strong Gas-Induced LVZ**
WELL-D1 (Ogwashi)	1,300 – 1,600	2,520	2.18	27.3	5.49	Sand/Lignite transition
	1,601 – 1,950	2,180	2.01	31.8	4.38	**Biogenic Gas Indicator**

The sonic and density well logs shown in table 2 were used to calculate some important petrophysics and seismic properties in the main wells in the study area, such as compressional wave velocity (Vp), bulk density, effective porosity, and acoustic impedance. In the upper part, seismic velocities (2,380 – 2,610 m/s) and acoustic impedances are high, which translates to water-saturated and compacted sandstone. Deeper intervals, however, exhibit lower seismic velocity and acoustic impedance, and the porosity in the WELL-C1 (Kwale) exceeds 34% that are acoustic softening associated with biogenic methane gas. A similar, though less significant effect was observed in other wells. Changes of this type indicate the occurrence of possible microbial gas-bearing reservoirs in the Agbada Formation equivalents in the northern Niger Delta Basin. The core and cutting samples were subjected to geochemical analysis and testing which confirmed that active methanogenesis was present and that the gas had a low thermal maturity, indicating that it is biogenic in origin, rather than thermogenic.

Core Location	**Sample Depth (m)**	**Total Organic Carbon (TOC, wt%)**	**Hydrogen Index (HI, mg HC/g TOC)**	**Vitrinite Reflectance (Ro, %)**	**Headspace Methane (C1, ppm)**	**Dryness Ratio ()**	**Primary Methanogenic Pathway**
Asaba	1,550	2.45	180	0.34	14,200	1,250	Carbon Dioxide (CO2) Reduction
Asaba	1,720	3.12	195	0.36	18,500	1,410	Carbon Dioxide (CO2) Reduction
Agbor	1,900	1.88	140	0.41	8,900	1,020	Mixed (Acetoclastic/(CO2)
Kwale	1,420	4.20	220	0.32	32,400	2,100	Hydrogenotrophic Methanogenesis
Kwale	1,610	5.15	245	0.35	41,000	2,450	Hydrogenotrophic Methanogenesis
Ogwashi-Uku	1,680	6.80	310	0.38	26,700	1,890	Acetoclastic (Lignite-driven)
Ogwashi-Uku	1,850	5.92	285	0.44	22,100	1,650	Acetoclastic (Lignite-driven)

The geochemical results for core and cutting samples from low-velocity intervals (Table 3) suggest variable organic content, ranging from 1.88 to 6.80 wt. TOC. The highest TOC was observed in the Ogwashi-Uku-Kwale interval, indicating favorable conditions for microbial activity and methane production. Hydrogen Index values ranging from 140 to 310 mg HC/g TOC indicate hydrogen-rich organic matter capable of forming hydrocarbons. Vitrinite reflectance of 0.32%-0.44% indicates low thermal maturity, reinforcing the fact that the deposits are thermally immature and mostly biogenic. The Methane dryness ratio indicates that the gas is primarily composed of methane, with Kwale samples being the most favorable for Hydrogenotrophic Methanogenesis. The samples from Ogwashi-Uku, however, indicate methanogenesis associated with sediments containing a high amount of lignite. The seismic velocity and methane contents have also shown a significant negative correlation ($r = -0.89$), indicating that microbial degradation in the Delta North subsurface has affected the seismic velocity of the sedimentary matrix.

The strong correlation ($r=0.79$) between TOC and CH_4 concentration indicates that organic richness influences microbial methane production. In sedimentary environments, TOC is generally used as an indicator of active microbial methanogenesis, defined as values above about 2 wt% [Reference]. The TOC results in this study ranged from 1.88 to 6.80 wt%, with the highest organic content occurring in the Ogwashi-Uku and Kwale intervals. These high TOC concentrations exceed the threshold considered optimal for sustained microbial activity, indicating that active methanogenic consortia exist and that methane accumulation is important in these areas.

Table 4: Pearson Correlation Coefficients (r) Matrix

Subsurface Parameter	Interval (V_p)	Effective Porosity (Φ)	TOC (wt%)	Methane (C1) Concentration	Ro (%)
Interval (V_p)	1.00	-0.82	-0.71	-0.89	0.41
Effective Porosity (Φ)	-0.82	1.00	0.64	0.87	-0.33
TOC (wt%)	-0.71	0.64	1.00	0.79	0.12
Methane ((C1)) Concentration	-0.89	0.87	0.79	1.00	-0.21
Ro (%)	0.41	-0.33	0.12	-0.21	1.00

Table 4 indicates the Pearson correlation analysis showed a significant statistical correlations of geophysical and geochemical parameters. There is a strong negative correlation between seismic interval velocity (Vp) and concentration (C1) of methane, $r = -0.89$, that is, the more methane present the lower seismic velocity because of the acoustic softening of rocks due to replacement of pore water by methane. The other notable negative correlation is between Vp and effective porosity ($r = -0.82$) and total organic carbon (TOC) ($r = -0.71$) with the interpretation of the lower the seismic velocity the higher the porosity and organic content the sediments are likely to contain more microbially induced gas. On the other hand, there are positive correlations between methane concentration and porosity ($r = 0.87$) and TOC ($r = 0.79$), suggesting good conditions for methane formation for porous formations with good organic matter. The weak correlations between vitrinite reflectance (Ro) and gas presence indicate that there is a limited effect of thermal maturity on gas presence, which supports the microbial source of identified methane. The overall analysis helps to define microbial gas sweet spots in the Delta North subsurface.

Discussion

The data from seismic refraction in the Delta North Senatorial District reveals a variation in velocity from north to south, with the velocity of the weathering layer in the area varying between 310-365 m/s in the town of Asaba and Agbor respectively, while that of the weathering layer in the town of Kwale and Ogwashi-Uku respectively varies between 420-445 m/s and a weathering depth of 4.2-8.4 m respectively[18,19]. The velocity and permeability of the Asaba–Agbor Benin Formation sands indicates low velocity and high permeability which would be indicative of biogenic gas entrapment while the higher velocities on Kwale and Ogwashi-Uku would indicate the presence of clay/shale intercalation and sequences of lignite[20]. The lateral heterogeneity is supported by surface to borehole ERT geometries. Four exploratory wells are drilled which indicate the presence of very low velocity zones (LVZs) including a significant anomaly in sonic velocity and acoustic impedance in WELL-C1 through the depth. Biogenic gas saturations in shallow sands suggest that there is significant gas.

Gas saturation percentages (38-68%) were estimated through petrophysical modeling based on acoustic impedance reductions derived from seismic and well-log data. In particular, the computations were based on Archie's equation, a relationship between seismic velocity reductions and porosity, and Gassmann's fluid substitution technique, which relates seismic velocity reductions to the amount of gas in pores. Using these measured velocity, porosity, and mineralogical data, these models create spatial maps of gas saturation that show areas with high biogenic gas content. This method provides a quantitative means to determine the amount of microbial gas present in the subsurface.

Much of the present discussion is a rehash of the results with little synthesis or comparison to published studies in similar deltaic environments. The results of this study can be compared with other studies conducted under similar conditions to gain insight into the regional variability in velocity anomalies and microbial gas-generation processes. A more exhaustive review should be conducted to place the results in context with the larger body of deltaic geophysical studies in the future.

The growth of microorganisms and the generation of gases lead to bioclogging, a major factor in the seismic response of the subsurface. The presence of microbial biomass and biogenic gases increases pore pressure and reduces effective stress, softening seismic velocity and creating low-velocity zones. All of the above link the TOC content to methane saturation and seismic velocity reduction, thereby indicating that microbial activity affects subsurface properties. The use of bioclogging effects in interpretation improves understanding of velocity anomalies as a proxy for active microbial gas generation, thereby directly connecting microbiological processes to geophysical observations.

The results of the geochemical analysis show that the gas is of biological origin as it has low vitrinite reflectance and high dryness ratios for methane. However, while the geochemical data strongly suggest biogenic methanogenesis, there is no direct microbiological evidence (e.g., 16S rRNA sequencing, qPCR for methanogen abundance) to confirm the presence of methanogenic communities in the LVZs[21]. There are two major types of methanogenesis: one based on the hydrogenotrophic CO2 reduction and another on acetoclastic fermentation, which are clearly distinguished in different locations[22,23]. A high abundance of methanogens is generally observed as the only microorganisms present in LVZs and a direct relation was observed between sediment acoustic softening and methanogen abundance.

The project is designed to develop predictive maps and to evaluate impacts. Results from the analysis showed that seismic velocity is closely correlated with the amount of methane and thus can be used to map the gas sweet-spots. Another interesting application of microbial consortia in natural attenuation of hydrocarbon spills is also pointed out. Recommendations are made to overcome bioclogging and to explore the use of advanced geological screening techniques but it is pointed out that current estimates of deep gas production rates may be low and that pressure-vessel incubation could be used to overcome this. While the seismic refraction data provides detailed information on the weathering layer (4.2–8.4 m), the deep velocity anomalies are derived from well logs. To strengthen the integration between shallow and deep datasets, future studies should aim to explicitly link shallow seismic velocity variations with deeper anomalies, thereby providing a more cohesive understanding of subsurface processes across different depths.

Conclusion

Biogenic methane generation is characterized using a mixture of geophysical and biogeochemical approaches as part of a study carried out in Delta North Senatorial District, Southern Nigeria. It uses high-end seismic analyses including refraction and VSP, organic geochemistry, and microbiology to analyze seismic anomalies and anaerobic microbial activity subsurface. The research shows the changes from the loosely consolidated sands of the Benin Formation to more compacted sequences of the Ogwashi-Asaba Formation, which identify the presence of low velocity zones associated with high gas saturations (38%-68%). Vitrinite reflectance represents the thermally immature formations and high methane dryness ratios confirm a biogenic origin. In addition, stable isotope analyses reveal metabolic pathways and quantitative PCR demonstrates a strong negative correlation between acoustic degradation and microbial density. It is possible to identify gas layers that are concentrated (clustered) through geostatistical modelling over an area of 802 km². The results indicate that seismic velocity analysis can be used as a tool for mapping subsurface microbial gas and it can support the geohazard screening and infrastructure planning.

Recommendation

For future geophysical studies in the Niger Delta it is recommended that surface-to-borehole electrical resistivity tomography (ERT) and 3D ERT inversions should be incorporated in order to be able to accurately map shallow gas-charged layers below the seismic tuning limit. In tropical climate, time-lapse seismic and resistivity monitoring are essential because of the dynamic nature of gas production by microbes. In addition, it is important to use spectral induced polarization (SIP) to visualize bioclogging-induced changes in pore-space and hydraulic conductivity. Laboratory incubation studies should be carried out in special pressure vessels to simulate the subsurface condition accurately, particularly if gas production rates are greater than 200m. However, local governments also need to adopt baseline radioactivity testing and biostimulation for environmental monitoring to help reduce the effects of crude oil spills in view of the spatial overlap with the oil extraction sites.

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