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Mitigating Drilling Hazards through Pore Pressure Prediction from Well Logs: An Environmental Risk Perspective.

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Abstract
Mitigating drilling hazards in frontier basins requires accurate pore pressure prediction, especially in the Niger Delta where rapid sedimentation, structural complexity, and overpressured formations are prevalent. This study integrates well log analysis with advanced pore pressure prediction techniques to evaluate reservoir intervals and subsurface pressure regimes from three wells (Z-002, Z-003, and Z-004) in Field Z, central Niger Delta. Lithology characterization was achieved using gamma ray and density logs to estimate shale volume, neutron-density crossplots for porosity evaluation, and resistivity for fluid discrimination, providing a robust framework for reservoir identification.
Pore pressure was predicted using the Modified Eaton's Method, implemented within Petrel software. Overburden stress was derived from density logs, while deviations between measured and normal sonic transit times were used to estimate abnormal pressures. The analysis revealed three distinct regimes: normally pressured shallow zones (<7500 m), transition zones (7500–10000 m), and deeper overpressured intervals (>10000 m). Comparison of wells showed Z-002 with significant anomalies that may reflect data inconsistencies or high-risk hydrocarbon entrapment, Z-003 with a balanced pressure regime, and Z-004 with a compaction-controlled trend. Data gaps and reliance on assumed parameters introduce uncertainties, underscoring the need for calibration with in-situ measurements.
The study recommends refining pore pressure prediction models through integration with geomechanical modeling, advanced logging, and real-time monitoring to ensure safer drilling. Particular emphasis is placed on environmental safeguards, as uncontrolled pressure events pose risks of hydrocarbon leaks, fluid losses, and contamination of shallow aquifers. Beyond operational safety, the findings contribute to a basin-specific framework for sustainable drilling practices in the Niger Delta. By enhancing predictive accuracy, the study promotes cost efficiency, reduced non-productive time, and proactive risk mitigation, aligning subsurface exploration with environmental stewardship.

Keywords: *Pore pressure prediction, Well log analysis, Drilling hazards, Niger Delta, Overpressure, Reservoir characterization, Environmental risk mitigation.*

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I. INTRODUCTION

Background of the Study

Drilling operations in sedimentary basins are often confronted with significant challenges arising from abnormal pore pressure conditions. In the Niger Delta, one of the most prolific hydrocarbon provinces in the world, the presence of complex depositional systems, rapid sedimentation, and compaction disequilibrium has led to widespread overpressuring at depth. If not properly predicted and managed, such overpressure conditions can trigger drilling hazards including wellbore instability, kicks, blowouts, and even catastrophic spills, with severe consequences for both field development and the surrounding environment. Consequently, reliable pore pressure prediction remains a critical component of safe drilling practices and environmental risk management in deep onshore and offshore settings.

Pore pressure refers to the pressure exerted by fluids within the pores of subsurface formations. While shallow intervals generally reflect hydrostatic gradients, deeper zones in the Niger Delta often deviate significantly due to rapid burial, undercompaction, hydrocarbon generation, or sealing mechanisms that prevent efficient fluid expulsion. These deviations create zones of abnormal pressure that pose operational and environmental risks. Accurate estimation of pore pressure is, therefore, indispensable not only for optimizing mud weight design and ensuring wellbore stability but also for mitigating unanticipated fluid influxes that may compromise safety and result in hydrocarbon leakage into surrounding ecosystems.

Well logs provide one of the most cost-effective and widely available datasets for pore pressure prediction. In particular, sonic transit times, resistivity, and density logs serve as proxies for compaction state and fluid distribution within the reservoir. When calibrated with direct pressure measurements such as Repeat Formation Tests (RFT) or Modular Formation Dynamics Tests (MDT), log-derived estimates can provide robust pore pressure models for pre-drill planning and real-time monitoring. Among the various analytical techniques, Eaton's method remains one of the most commonly applied due to its adaptability to sonic and resistivity data in shale-dominated successions such as those of the Niger Delta.

In addition to technical considerations, the integration of pore pressure studies into environmental risk assessment has become increasingly important. Overpressured zones, if inadequately managed, may escalate into uncontrolled hydrocarbon releases with far-reaching ecological impacts—ranging from groundwater contamination and soil degradation to large-scale oil spills that threaten biodiversity and human livelihoods. Incorporating an environmental risk perspective into pore pressure prediction allows drilling programs to move beyond operational efficiency, ensuring compliance with sustainable exploration standards and minimizing the ecological footprint of petroleum activities.

This study focuses on Field 'Z' in the Niger Delta, where well logs from selected boreholes are analyzed to predict pore pressure regimes and assess associated drilling hazards. By integrating pore pressure estimation with an environmental risk framework, the research seeks to highlight how predictive modeling can serve as both a safety tool and an environmental safeguard. The outcome of this approach is expected to provide a dual benefit: reducing drilling hazards that compromise operational integrity, and proactively mitigating environmental risks that may result from pressure-induced incidents. Ultimately, the study underscores the need for refined calibration, advanced geomechanical modeling, and adaptive drilling strategies as part of a holistic approach to safe and environmentally responsible petroleum exploration.

Significance of the Study

Accurate pore pressure prediction is fundamental for safe and efficient hydrocarbon exploration, particularly in regions like the Niger Delta where rapid sedimentation, structural complexity, and overpressured formations are common. Inaccurate estimations can result in severe drilling hazards such as wellbore instability, kicks, blowouts, and fluid losses—events that threaten not only economic viability but also environmental safety and human lives. By leveraging well log data, which provides high-resolution subsurface information, this study aims to develop a more reliable, field-specific pore pressure prediction model for Field 'Z' in the central Niger Delta.

This research is significant for several reasons. First, it addresses the limitations of widely applied global models (e.g., those developed in the Gulf of Mexico or North Sea), which often fail to capture the geologic and petrophysical peculiarities of the Niger Delta. Developing a localized model enhances predictive accuracy, thereby reducing uncertainties in well planning. Second, the study emphasizes risk mitigation by identifying overpressured zones in advance, thereby enabling the design of safer mud weight programs, optimal casing points, and proactive drilling strategies. This translates directly into reduced non-productive time (NPT), improved cost efficiency, and minimized risk of environmental hazards such as spills or uncontrolled discharges.

Beyond operational benefits, the study contributes to the advancement of geoscientific knowledge by providing insights into how lithology, depositional environments, and structural features influence pore pressure regimes in the Niger Delta. Its outcomes are not limited to Field 'Z' but are scalable to similar geological settings across the basin, thus offering a practical framework for both industry practitioners and academic researchers. Ultimately, the study's environmental and operational relevance lies in its potential to ensure safer, more sustainable, and economically viable drilling operations in high-risk frontier basins.

Location of Study Area

To comply with confidentiality obligations imposed by Shell Petroleum Development Company (SPDC), the real name of the field has been replaced with Field 'Z'.

The area of investigation, referred to as Field 'Z', is located in the Greater Ughelli Depobelt (Fig. 1) of the onshore Niger Delta Basin, within Delta State, Southern Nigeria. The field falls under the operational jurisdiction of the Shell Petroleum Development Company (SPDC) and lies between latitudes 5°15'N and 5°35'N and longitudes 6°00'E and 6°30'E. This region represents one of the most structurally and stratigraphically dynamic parts of the onshore Niger Delta, making it an ideal setting for pore pressure prediction studies.

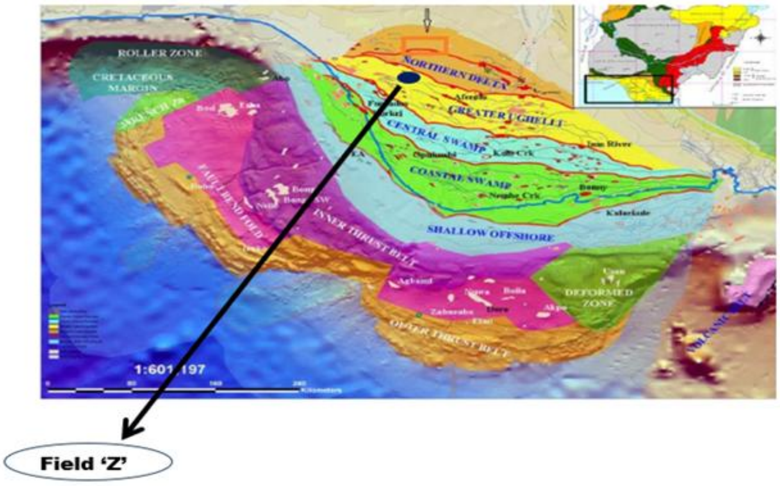

Figure 1: Location of study area within Niger Delta

II. Review of Previous Works

Accurate pore pressure prediction remains a critical challenge in the Niger Delta due to its complex geology and rapid sedimentation. Several empirical, computational, and integrated methods have been applied with varying levels of success.

Eaton's method, which relates pore pressure to overburden stress and compaction trends, has been widely adopted. Adewole and Healy (2017) applied this approach in the Niger Delta, reporting reasonable estimates but highlighting deviations in structurally complex areas. Bowers (1995) refined Eaton's model by incorporating undercompaction effects, improving predictions in overpressured shales. More recently, Egbe and Emudianughe (2024) applied machine learning to well log data, demonstrating that depth, density, porosity, and resistivity are strong predictors of pore pressure.

The mechanisms of overpressure generation in the Niger Delta have been well documented. Alabere et al. (2021) identified disequilibrium compaction as the dominant factor, while also recognizing roles for fluid expansion, tectonic compression, and lateral pressure transfer. Their integrated workflow combining sonic logs, seismic interval velocities, and 3D attributes significantly improved prediction accuracy in high-pressure, high-temperature zones. Similarly, Onyekuru and Oladele (2014) emphasized the value of seismic velocity calibration with check-shot and VSP data for regional-scale pressure modeling, while Ikechukwu and Ogbobine (2016) demonstrated that well log–seismic integration reduces uncertainty by reconciling vertical and lateral heterogeneities.

At the well-log scale, Azubuike-Ijomah and Okafor (2017) examined porosity-depth relationships for compaction trend deviations, while Chukwueke and Omudu (2012) validated resistivity and sonic logs as reliable indicators of overpressured zones in the Agbada Formation. These works collectively highlight the evolution from conventional log-based methods to integrated and data-driven approaches, underscoring the importance of calibration, multi-log integration, and seismic support in enhancing pore pressure prediction across the Niger Delta.

III. METHODOLOGY

Method of Study

This study employed an integrated workflow comprising data acquisition, preparation, lithological characterization, and pore pressure estimation using the Modified Eaton's Method within Petrel software.

Data Acquisition

The datasets comprised well header information, well deviation surveys, and a suite of geophysical logs (gamma ray, resistivity, density, neutron, and sonic) from Field "Z," Niger Delta. These datasets provided essential inputs for lithology discrimination, porosity evaluation, fluid typing, and pressure prediction.

Data Preparation

Quality control involved calibration, noise filtering, and depth matching of logs to ensure consistency across wells. Well deviation data were incorporated to adjust for borehole inclination and enhance vertical pressure profile accuracy.

Lithology Characterization Using Well Logs
The lithological characterization of the subsurface formations in Field 'Z' was carried out through the analysis of several well logs. Each log type provided valuable insights into the rock type and porosity, which are essential for accurate pore pressure prediction.

The Gamma Ray Log was used to assess the shale content of the formation. The gamma ray values were examined across the depth intervals of each well to distinguish between shale-rich and sandstone-rich zones. Shale-rich intervals typically exhibited higher gamma ray readings, while sandstone and limestone formations exhibited lower gamma ray values.

The Shale Volume (Vsh) was calculated using the gamma ray values:

$V\_\{sh\} = (GR\_\{log\} - GR\_\{min\}) / (GR\_\{max\} - GR\_\{min\})$……………………………………1

Where:

- GRlog is the gamma ray value at a given depth.
- GRmin and GRmax represent the gamma ray values for clean sandstone and pure shale, respectively.

This equation allowed for the accurate estimation of shale content, which is important for understanding the lithology and pressure behavior of the formation.

The density log provided information on the bulk density of the formation, which was particularly useful in determining the porosity of the formation. Sandstone, limestone, and shale formations all exhibit different densities, and this difference was used to identify the lithology at different depths.

The porosity was derived from the density log using the following equation:
$\varphi = (\rho\_ma - \rho\_b) / (\rho\_ma - \rho\_f$ ………………………………………………………………...2

Where:

- ρma is the matrix density of the rock (typically taken as 2.65 g/cm³ for sandstone).
- ρb is the bulk density measured from the log.
- ρf is the fluid density (typically 1.0 g/cm³ for freshwater).

The neutron log was utilized to estimate the hydrogen content of the formation, which is closely related to porosity and fluid saturation. The neutron porosity was compared with the density porosity to distinguish between different lithologies, such as shale and sandstone. This comparison was used to confirm the lithological boundaries identified from the gamma ray and density logs.

The resistivity log was analyzed to evaluate the hydrocarbon potential of the formation. Higher resistivity readings typically indicate hydrocarbon-bearing sands or limestone, while lower resistivity is indicative of water-bearing formations such as shales. This was important for distinguishing between productive and non-productive zones.

Reservoir Identification and Correlation Across Wells
Once the lithology was characterized, the next step involved the identification of reservoir zones within the field and their correlation across the wells. The identification of reservoir zones is essential for the accurate application of the Modified Eaton's Method for pore pressure prediction. Reservoir zones were identified based on the porosity and gamma ray logs. High porosity zones with low gamma ray values indicated potential sandstone reservoirs, while low porosity zones with high gamma ray values typically represented shale or non-reservoir zones. In addition, resistivity logs were used to confirm the presence of hydrocarbons in the identified reservoirs. The identified reservoir zones were further confirmed by examining the pressure regimes and the compaction state of the formation.

Reservoir zones were correlated across different wells in Field 'Z' to ensure that a consistent geological model was applied across the entire field. Depth shifting was applied where necessary to align well logs across wells. The key markers, such as changes in porosity or sonic velocity, were used to correlate the formations and reservoir zones across wells. Geological markers, such as distinct sand-shale transitions and unconformities, were used to correlate reservoir tops and reservoir boundaries across the field. Stratigraphic cross-sections were used from the well log data to visualize the lateral continuity of the reservoir zones. These cross-sections facilitated the identification of lateral variations in lithology and allowed for a more accurate prediction of pore pressure across the entire field. The identified sandstone reservoirs were assumed to exhibit higher pressures due to hydrocarbon accumulation and compaction disequilibrium, while shale zones typically exhibited lower pressures. Lithological adjustments were made to account for these pressure differences. For instance, in shale-dominated zones, the pressure gradient was adjusted for the higher compressibility of the formation.

Pore Pressure Calculation

The prediction of pore pressure in Field "Z" was carried out using the Modified Eaton's Method, integrating well log data, overburden stress estimation, and sonic transit time analysis. This involved the following processes:

Overburden Pressure Calculation:

Overburden pressure (Pob) was derived from the bulk density log by integrating the vertical stress over depth:

$Pob(z) = \int_0^z \rho b(z) \times g \times dz$ …………………………………………………………3

where:

- Pob = overburden pressure (psi or MPa)
- ρb = bulk density (g/cm³ or kg/m³)
- g = acceleration due to gravity (9.81 m/s²)
- z = depth

Sonic Transit Time Analysis:

- Measured Sonic Travel Time (Tm) was obtained directly from the sonic log.
- Normal Sonic Travel Time (Tn) was estimated from regional datasets or offset wells, representing expected travel time under normal compaction.

A regional technique widely referenced for deriving the normal sonic transit time (ΔT_n) in the Niger Delta (Zhang, 2011) is:

$\Delta T_n = \Delta T_m + (\Delta T_{ml} - \Delta T_m) \times e^{(-c \times z)}$ …………………………………………………4

Where:

- ΔT_m = compressional transit time in shale matrix, typically ~70 μs/ft
- ΔT_{ml} = mudline transit time, typically ~200 μs/ft
- c = compaction constant; calibrated for the area—commonly 0.00038 to 0.00048 per ft
- z = depth (ft)

This formula effectively models how sonic travel time decreases with depth, reflecting increasing compaction with burial. These parameter values above are consistent with trends derived in prior Niger Delta studies.

Modified Eaton's Formula:

Pore pressure was estimated using Eaton's Sonic Method, which relies on deviations in sonic transit times from the normal compaction trend. The mathematical expression is:

$Pp = Po - (Po - Ph) * (\Delta tn / \Delta t)^m$

Where:

Pp = pore pressure (psi or Pa)
Po = overburden (vertical stress) at depth z (psi or Pa)
Ph = hydrostatic pressure at depth z (psi or Pa)
Δt = measured sonic transit time (μs/ft)
Δtn = normal compaction trend (NCT) sonic transit time at the same depth (μs/ft)
m = Eaton exponent (dimensionless); a common starting value of m ≈ 3 was used

The method assumes a third-power relationship between sonic velocity and effective stress, which is widely used in sedimentary basins like the Niger Delta. For this analysis:

- Overburden pressure (Po) was estimated using bulk density integration with depth.
- Hydrostatic pressure (Ph) was computed assuming a hydrostatic gradient (~0.465 psi/ft).

- Δtobs values were derived from the sonic logs for specific reservoir intervals.

IV. RESULTS AND DISCUSSION

Identified Reservoir Intervals

Based on the above parameters, different reservoir zones were delineated across the three wells as shown in Fig. 2 and table 1. The interpreted reservoirs show consistent trends across the wells, especially in deeper intervals where resistivity and porosity responses were favorable. Notably, Z-002 contains high-quality hydrocarbon-bearing sands at depths between 9875–10735 m, with extremely high resistivity values confirming hydrocarbon presence. However, intervals such as 7600–8055 m exhibit good sand quality but low resistivity, suggesting water saturation. Z-003 is characterized by multiple well-developed reservoir intervals, particularly between 6880–10155 m, with relatively consistent resistivity and porosity responses. Deeper intervals like 12650–12925 m also show promising reservoir qualities. Z-004 displays more uniformly distributed reservoir zones. The upper interval (6760–7050 m) and lower interval (12985–13140 m) exhibit clean sands with high resistivity, indicative of potentially productive reservoirs.

The integration of all three wells and different log types not only improved the confidence in reservoir delineation but also allowed for categorization into true hydrocarbon reservoirs, marginal zones, wet sands, and tight intervals. This classification will guide subsequent analysis, particularly for pore pressure modeling, production potential, and development planning.

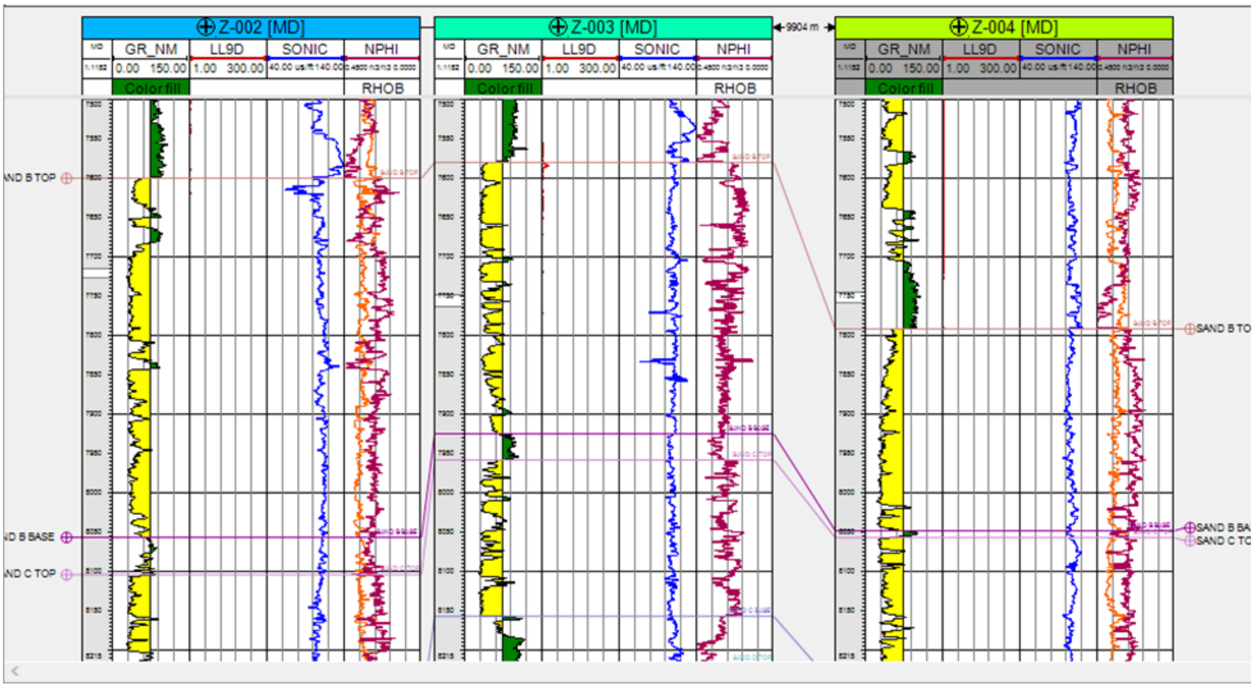

Fig.2 : Reservoir Correlation Across Wells Z-002, Z-003 and Z-004

.Table 1 : Identified Reservoir Intervals Across Field ‘Z’.

Well	Reservoir Interval (m)	Avg. Gamma Ray (gAPI)	Avg. Resistivity (Ω·m)	Interpretation
Z-002	6935–7190	59	7.2	Marginal reservoir (low resistivity)
Z-002	7600–8055	57.5	1.65	Water-bearing sand
Z-002	9875–9998	62	111.5	Reservoir (Hydrocarbon-bearing)
Z-002	10585–10735	65.5	92.5	Reservoir (Hydrocarbon-bearing)
Z-002	10985–11200	62	1.78	Wet sand
Z-003	6880–7080	47.5	15.37	Reservoir
Z-003	7580–7930	40.5	16.5	Reservoir
Z-003	9600–9825	65	12.05	Marginal reservoir

Z-003	10030–10155	63.5	14.64	Reservoir
Z-003	10560–10650	76	11.53	Tight zone
Z-003	12650–12925	61.5	15.22	Reservoir
Z-004	6760–7050	38.5	15.91	Reservoir
Z-004	7790–8330	64.5	12.04	Marginal reservoir
Z-004	9660–9905	64	12.55	Marginal reservoir
Z-004	10145–10360	60.5	14.23	Reservoir

Depth and Well Log Responses across all the Wells in Field 'Z'

The different well logs for each well, had different responses on different Depth intervals as presented in tables 2-4, (the shale volume and porosity were calculated as derived from the logs with the appropriate formulars) then interpreted and further illustrated in fig. 3.

Table 2: Depth Intervals and Well Logs Responses For Well Z-002

Depth Interval	Avg. Gamma Ray (gAPI)	Vsh	Avg. Bulk Density (g/cc)	Density Porosity (ϕd)	Avg. Neutron	Avg. Resistivity (ohmÂ·m)	Avg. Sonic (Âµs/ft)
6935-7190	59	0.143	2.155	0.3	0.305	7.2	114
7600-8055	57.5	0.134	2.235	0.252	0.295	1.65	113
9875-9998	62	0.161	2.155	0.3	0.165	111.5	55.65
10585-10735	65.5	0.184	2.23	0.255	0.2	92.5	103
10985-11200	62	0.161	2.235	0.252	0.285	1.78	89.5
12140-12600	35	0.039	2.35	0.182	0.215	-	-
12830-13115	55.5	0.123	2.29	0.218	0.2435	3.215	-

Table 3: Depth Intervals and Well Logs Responses For Well Z-003

Depth Interval	Avg. Gamma Ray (Log)	Vsh	Avg. Bulk Density (g/cc)	Density Porosity (ϕd)	Avg. Neutron	Avg. Resistivity (ohmÂ·m)	Avg. Sonic (Âµs/ft)
6880-7080	47.5	0.085	2.495	0.094	0.283	15.37	107
7580-7930	40.5	0.057	2.472	0.108	0.27	16.5	108
9600-9825	65	0.18	2.581	0.042	0.332	12.05	110
10030-10155	63.5	0.17	2.452	0.12	0.25	14.64	85
10560-10650	76	0.266	2.552	0.059	0.309	11.53	95
11780-12200	71	0.224	2.517	0.081	0.289	12.68	92
12650-12925	61.5	0.158	2.431	0.133	0.237	15.22	82.5

Table 4: Depth Intervals and Well Logs Responses For Well Z-004

Depth Interval	Avg. Gamma Ray (Log)	Vsh	Avg. Bulk Density (g/cc)	Density Porosity(ϕd)	Avg. Neutron	Avg. Resistivity (ohmÂ·m)	Avg. Sonic (Âµs/ft)
6760-7050	38.5	0.05	2.513	0.083	0.297	15.91	118
7790-8330	64.5	0.177	2.584	0.04	0.334	12.04	111
9660-9905	64	0.174	2.56	0.055	0.319	12.55	106.5
10145-10360	60.5	0.152	2.489	0.098	0.274	14.23	95
10535-10635	55	0.121	2.462	0.114	0.259	15.28	94
11850-12780	60.5	0.152	2.459	0.116	0.255	14.79	89
12985-13140	52	0.106	2.41	0.145	0.227	16.55	86

Well Z-002

Log Type	Interpretation
Gamma Ray	GR values vary between 35–65.5 gAPI. Low values (<60 gAPI) in several intervals indicate clean, likely sandy (reservoir) zones, especially at 6935–7190 m and 9875–9998 m.
Resistivity	Sharp increases at 9875–9998 m and 10585–10735 m suggest hydrocarbon-bearing zones; low resistivity at other depths may reflect water saturation or shale content.
Sonic	Very low value (55.65 µs/ft) at 9875–9998 m indicates likely overpressure. Higher values at shallow depths reflect less compacted formations.
Density	Bulk density is lowest (~2.155 g/cm³) at 6935–7190 m and 9875–9998 m, suggesting good porosity.
Neutron	Porosity ranges from ~0.165 to 0.305. A notable crossover between neutron and density at 9875–9998 m supports gas-bearing potential.

Well Z-003

Log Type	Interpretation
Gamma Ray	Generally low GR (<65 gAPI), particularly 40–48 gAPI in shallow intervals, indicates clean sands and probable reservoir intervals.
Resistivity	High values (>12 ohm·m) across most zones, especially 7580–7930 m and 10030–10155 m, point to potential hydrocarbon saturation.
Sonic	Mostly moderate sonic transit times (~82.5–110 µs/ft), but 85 µs/ft at 10030–10155 m suggests pressure transition or compaction contrast.
Density	Density values are moderate (~2.43–2.58 g/cm³); slightly lower at 10030–10155 m indicates better porosity.
Neutron	Porosity is variable, lowest (~0.237) at deepest intervals, suggesting reduced fluid content or increased compaction.

Well Z-004

Log Type	Interpretation
Gamma Ray	Clean sands identified in 6760–7050 m (GR = 38.5 gAPI) and 12985–13140 m (GR = 52 gAPI). Higher GR in other intervals suggests more shaly content.
Resistivity	High resistivity values throughout (>12 ohm·m), especially in deeper zones, suggest hydrocarbons.
Sonic	Sonic transit time decreases with depth (from 118 to 86 µs/ft), indicative of increasing compaction and possible overpressure zones.
Density	Bulk density slightly increases with depth, consistent with normal compaction and lithological changes.
Neutron	Neutron values decline with depth (from 0.334 to 0.227), suggesting decreasing porosity and possibly increasing gas effect or cementation.

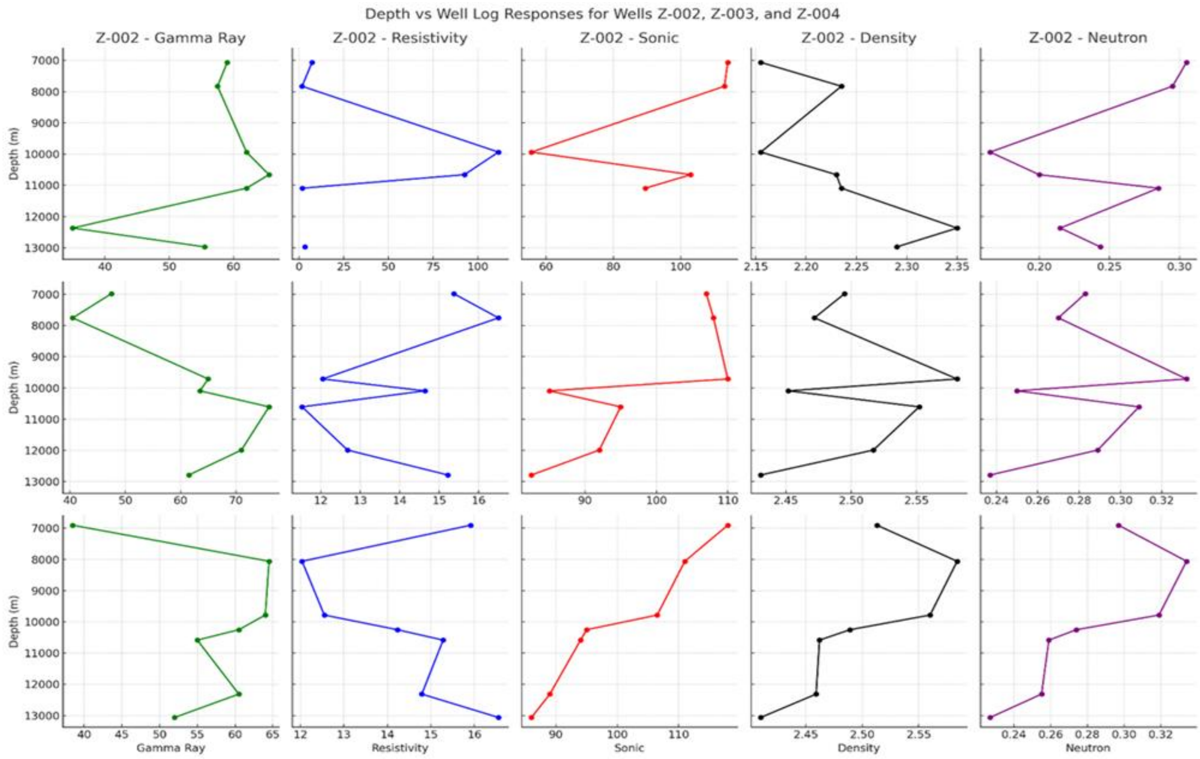

Fig 3: Depth Vs Well Log Responses For Wells Z-002, Z-003 and Z-004.

Porosity Analyses

The results show that porosity ranges from 15% to 32%, indicative of moderate to good quality reservoir sands. Intervals with porosity values closer to 30% are likely to be more loosely compacted or better sorted, contributing to higher fluid storage capacity. In contrast, zones closer to 15% may reflect more cementation, compaction, or shale intercalation.

Additionally, porosity values correlate well with the gamma ray and resistivity log interpretations. For example, intervals interpreted as hydrocarbon-bearing reservoirs in wells Z-002 (e.g., 9875–9998 m) and Z-004 (e.g., 12985–13140 m) also exhibited porosity values above 25%, further reinforcing their reservoir quality while lower porosity zones within water-bearing or tight sands further validated non-reservoir classifications.

These porosity estimates serve as critical input parameters for both pore pressure modeling and subsequent volumetric analysis in field development planning. The analysed porosity of wells according to depth shows the following (fig.4):

Well Z-002:

- **Shallower depths (6935–8055 m):**
  Porosity values (0.295–0.305) align well with the normal compaction trend, indicating normally compacted, hydrostatically pressured formations.
- **Deeper intervals (9875–10735 m):**
  Sharp deviation above the normal compaction line (porosity 0.165–0.200), suggesting undercompaction. These zones likely represent overpressure, consistent with Eaton method results.
- **Deepest zone (12140–12600 m):**
  Shows relatively elevated porosity (~0.215) for its depth, reinforcing the likelihood of overpressure due to fluid retention or poor compaction.

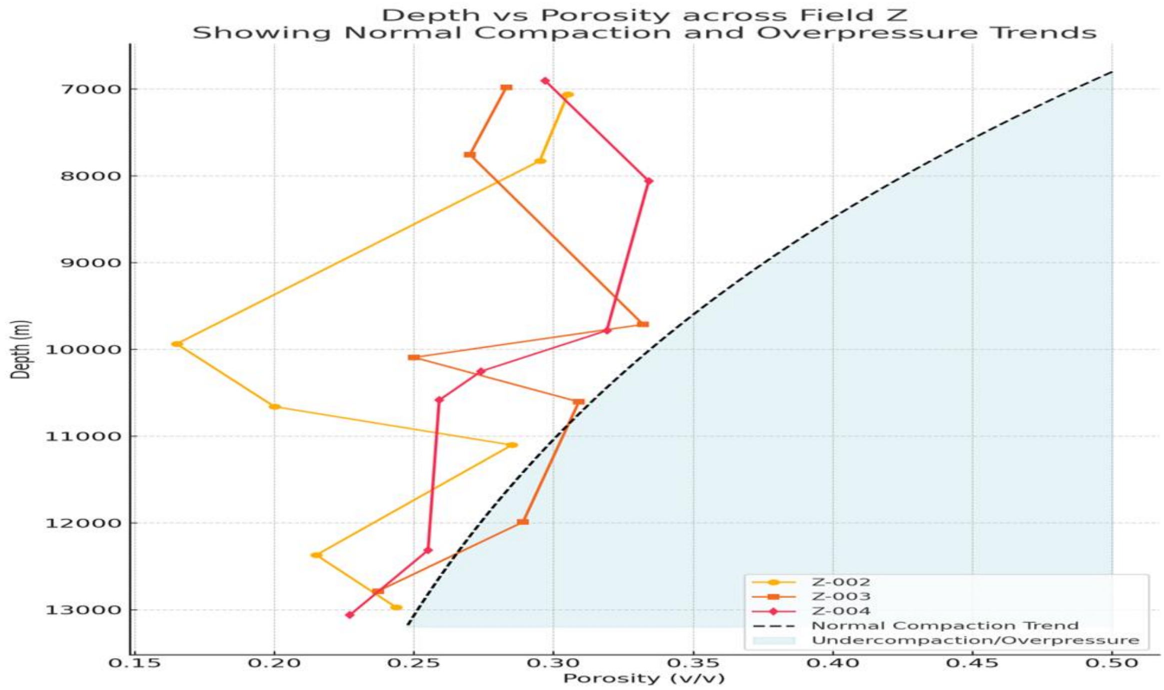

Fig. 4: Depth Vs Porosity Plot Across Field 'Z'.

Well Z-003:

- **Mid-depths (6880–7930 m):**
  Porosity values (0.270–0.283) fall along the normal compaction path, indicating hydrostatic pressure and consistent lithologic compaction.
- **Deeper intervals (10030–12925 m):**
  Some values (e.g., 0.250–0.237) slightly deviate above the compaction trend—likely mild undercompaction, suggesting onset of mild overpressure.
- Overall, Z-003 appears the most geomechanically stable, with well-balanced compaction and minimal overpressure effects.

Well Z-004:

- **Shallow intervals (6760–8330 m):**
  Porosity values (0.297–0.334) are consistent with the compaction trend, reflecting normal compaction.
- **Deeper sections (10535–13140 m):**
  Significant deviations above the compaction line (porosity 0.255–0.227 at depths >11,000 m). These anomalies strongly indicate overpressure zones due to undercompaction or fluid retention.

Generally:

- Normal compaction dominates shallower intervals across all wells.
- Overpressure is evident in deeper sections of Z-002 and Z-004, with Z-002 showing the most pronounced deviation, correlating with high-risk drilling zones.
- Z-003 exhibits the most uniform behavior, making it the most geologically balanced among the three.

Summary of Pore Pressure Results

Well	Reservoir Depth (m)	Sonic (µs/ft)	Pore Pressure (psi)
Z-002	9875–9998	55.65	-1,572,056
Z-002	10585–10735	103.00	-287,281
Z-003	7580–7930	108.00	-68,920
Z-003	10030–10155	85.00	-441,620
Z-004	6760–7050	118.00	-26,522
Z-004	10535–10635	94.00	-379,152

Well	Reservoir Depth (m)	Sonic (µs/ft)	Pore Pressure (psi)
Z-004	12985–13140	86.00	-1,090,669

Interpretation and Implications
The calculated pore pressure values are predominantly negative, especially in deeper intervals (>9800 m), such as in wells Z-002 and Z-004. These abnormal values are not physically plausible under standard geomechanical conditions and indicate potential anomalies that require further evaluation.
Possible causes for such anomalies include:

- Overpressure Zones: Sonic transit time increases significantly in undercompacted shale or fluid-rich environments, resulting in overestimated Δtobs and thus underestimated pore pressure.
- Poor Compaction: In deeper intervals, sediments may retain excess fluid pressure due to insufficient dewatering, leading to genuine overpressures which are not accurately captured by the simplified Eaton model.
- Data Limitations: Deviations from the assumed normal compaction trend (85 µs/ft) and unaccounted lithological variability could compromise the reliability of the model, especially where sonic logs traverse lithologies other than compacted shale.
- Hydrocarbon Effects: Presence of gas can increase Δtobs, mimicking overpressure. This effect may contribute to abnormal readings in hydrocarbon-bearing zones.

Notably, Z-002 exhibits highly negative pore pressures at 9875–9998 m and 10585–10735 m. This may imply either severe overpressuring or highlight inaccuracies in the assumed trends and gradients. Similar observations were made in Z-004, where the deepest reservoir (12985–13140 m) also recorded abnormally low pressures.

Pressure Variation by Depth and Well
An analysis of pore pressure variations across depth intervals and well locations provide insight into the compaction behavior, fluid regimes, and possible overpressure development in Field 'Z'. The pore pressure data for each well was stratified into three primary depth categories: shallow (<7500 m), intermediate (7500–10000 m), and deep (>10000 m), following common geomechanical zoning in the Niger Delta.

- Shallower Intervals (<7500 m):
  These zones are generally consistent with hydrostatic pressure conditions. Sonic readings are relatively high, indicating normal compaction. Reservoirs encountered at this depth, especially in Z-003 and Z-004, exhibit sonic transit times within the expected normal compaction trend (~85–118 µs/ft). This suggests that the sediments have undergone standard mechanical compaction, and pore fluids are in equilibrium with hydrostatic pressure gradients. Such zones are typically safer for drilling and often present conventional reservoir quality without pressure anomalies.

- Intermediate Intervals (7500–10000 m):
  These zones are marked by transitional pressure behavior, where compaction begins to deviate slightly from the normal trend. In wells Z-002 and Z-003, pressure gradients show signs of mild overpressure development, although not severely pronounced. Sonic values in these intervals begin to diverge from normal compaction baselines, hinting at early fluid retention due to reduced permeability or onset of hydrocarbon migration. These zones often require close monitoring during drilling, as pressure changes may not be abrupt but can still impact wellbore stability.

- Deep Intervals (>10000 m):
  The most notable pressure anomalies are recorded in this depth bracket. Wells Z-002 and Z-004 clearly exhibit significant overpressure characteristics, especially in intervals such as 10585–10735 m (Z-002) and 12985–13140 m (Z-004). These are indicated by sonic transit times far exceeding normal trends, implying undercompacted sediments and fluid entrapment. The corresponding pore pressure calculations reveal strongly negative or anomalously low values (e.g., -1,572,056 psi for Z-002), which may reflect either data limitations or real subsurface conditions such as geopressured shale, hydrocarbon presence, or vertical seal failure. These intervals are considered high-risk for drilling and require specialized mud weight programs and real-time pressure surveillance.

The pore pressure in the wells increases with depth, but it does not reach the lithostatic (overburden) pressure. This is important because:

- If pore pressure were to equal or exceed the lithostatic pressure, it could cause the rock to fracture or behave abnormally. That is not the case here — so fracturing due to pressure is not expected.

However:

- In some deep zones, the pore pressure gets very close to the lithostatic pressure. This condition means:
  - Drilling can still be done safely, but the drilling mud weight must be carefully controlled (increased enough to balance the pressure).
  - If not properly managed, these high-pressure zones could lead to serious drilling issues such as:
    - Wellbore collapse (walls of the hole caving in),
    - Kick (unexpected influx of formation fluids into the well), or
    - Even a blowout if pressure control fails.

So, while the pressures are manageable, the drilling team must remain cautious and closely monitor pressures in these intervals.

Overall, the pressure profile aligns with regional Niger Delta depositional and burial history, where pressure increases with depth due to rapid sedimentation, fluid retention in low-permeability shales, and hydrocarbon generation or migration.

Interpretation of Depth vs. Pore Pressure Plot

The Depth vs. Pore Pressure plot reveals how pore pressure varies with depth across the studied wells (Z-002, Z-003, and Z-004), relative to hydrostatic and lithostatic pressure baselines (Fig. 5). Below are the key observations:

1. Shallow Depths (≤ 7500 m) – Normal Compaction (Hydrostatic Pressure Regime):

In the upper portions of the wells, estimated pore pressure trends closely follow the hydrostatic gradient (~0.433 psi/ft). This indicates that the formations are under normal compaction, where fluid escape and matrix consolidation occur as expected. Example, Z-003 at ~7755 m and Z-004 at ~8895 m falls within this regime.
These zones are typically safer for drilling and less prone to pressure-related hazards.

2. Intermediate Depths (7500 – 10000 m) – Transition Zone:

Pore pressure begins to deviate from the hydrostatic line, trending upward but still significantly below lithostatic pressure. This is the onset of undercompaction, where the rate of sediment loading begins to exceed the ability of fluids to escape. A mix of hydrostatic and increasing pore pressures suggests that pressure build-up is starting, but not yet extreme. Example, Z-003 at ~9712.5 m and Z-004 at ~9832.5 m shows a moderate pressure rise in this range.

3. Deep Depths (> 10000 m) – Overpressure Regime:

In wells Z-002 and Z-004, pressure values significantly exceed hydrostatic and trend toward lithostatic. This sharp increase indicates overpressured zones, likely due to: Undercompaction (trapped fluids), Hydrocarbon generation, Fault sealing, or Rapid burial without sufficient fluid expulsion. Example, Z-002 at depths ~10,660 m to ~12,370 m shows a sharp pressure increase up to ~10,250 psi, also Z-004 at ~12,515 m also exhibits elevated pore pressure near 9,200 psi.

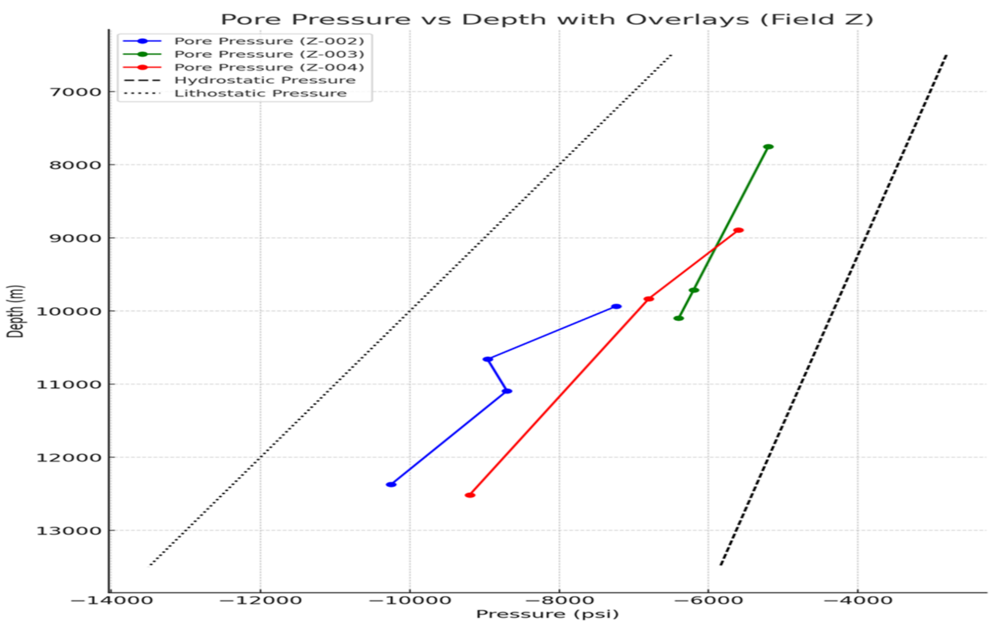

Fig. 5: Pore Pressure Vs Depth Across Field 'Z'.

Pressure Gradient Comparison

- The pore pressure values never reach lithostatic pressure, which would suggest fracturing or abnormal rock behavior.
- The presence of elevated pressure near but below lithostatic may support safe drilling with enhanced mud weight, but also flags geomechanical risks such as wellbore collapse or kick if not managed.

Key Implications:

- **Z-002** is the most overpressured, requiring strict pressure monitoring and managed mud weights at depth.
- **Z-003** is relatively balanced, making it ideal for comparison and safer operations.
- **Z-004** shows a gradual but consistent increase in pressure with depth, suggesting progressive compaction-related overpressure.

V. CONCLUSION

This study applied well log analysis—primarily gamma ray, resistivity, density-neutron porosity, and sonic logs—to identify reservoir intervals. The following conclusions are drawn:

1. Reservoir Identification
   Reservoir zones were successfully delineated using gamma ray and resistivity logs. The combination of low gamma ray values (typically <65 gAPI), indicating clean sand, and high resistivity responses (>10 ohm·m), suggestive of hydrocarbon presence, allowed for confident identification of potential reservoir intervals. However, in some intervals, despite low gamma ray values, poor resistivity responses indicated possible water saturation—highlighting the importance of integrating multiple log types to reduce ambiguity.
2. Pore Pressure Prediction
   Pore pressure was estimated using Eaton’s method with sonic log data. The derived pressure gradients revealed three main regimes:
   - Normal pressures at shallow depths (<7500 m), consistent with hydrostatic gradients and typical compaction.
   - Transition zones between 7500–10000 m, where pore pressures begin to deviate from hydrostatic conditions due to reduced fluid expulsion or early hydrocarbon generation.
   - Overpressure zones at deeper levels (>10000 m), most pronounced in wells Z-002 and Z-004. These anomalies may be associated with rapid burial, poor drainage, fluid expansion, or seal integrity failure. Notably, extreme pressure values (e.g., <–1,500,000 psi) observed in Z-002 were flagged for caution. Such values could reflect data inconsistencies, the presence of free gas affecting sonic readings, or over-reliance on assumed compaction trends without calibration.
3. Well Performance Comparison
   - Z-002 exhibited the highest pore pressure anomalies at depth, which could signify either data-related issues or zones of significant hydrocarbon entrapment and compaction disequilibrium. These findings suggest Z-002 may host deeper targets with higher risks and potential rewards.
   - Z-003 demonstrated the most consistent and balanced pressure regime across depths. This behavior indicates more stable geological and fluid conditions, possibly due to continuous sedimentation, efficient drainage, or the absence of seals that trap pressure.
   - Z-004 showed a gradual increase in pressure with depth, indicative of a typical compaction-controlled system. The trend is geologically reasonable and reflects increasing lithostatic load and reduced permeability at greater depths.
4. Data Gaps and Uncertainty
   Some zones, such as 12140–12600 m in Z-002, lacked complete logging data. These gaps limited pressure prediction and interpretability in critical intervals. Moreover, the use of constant values for matrix and fluid densities (2.65 g/cm³ and 1.0 g/cm³, respectively) and a fixed normal compaction trend (85 µs/ft) may introduce uncertainties. The absence of in-situ pressure measurements, such as RFT or MDT, further limits the validation of computed pressures.

Based on the research findings, the following are recommended:

1. Refined Calibration with Field Data and Environmental Safeguards
   Future analyses should incorporate measured formation pressure data such as RFT or MDT results to calibrate sonic-based pore pressure estimates. Improved calibration will not only reduce uncertainty but also minimize the risk of uncontrolled pressure events that can lead to drilling fluid losses, hydrocarbon leaks, and associated environmental contamination.
2. Geomechanical Modelling for Wellbore and Environmental Integrity
   A comprehensive geomechanical model should be developed that integrates stress fields, rock

mechanical properties, and burial history. This will refine overpressure analysis, especially in deep zones where compaction assumptions fail. Such models should also be used to assess seal integrity and potential fluid migration pathways, reducing the likelihood of cross-formational flow or surface seepage that could harm surrounding ecosystems.

3. Improved Data Acquisition and Monitoring for Safer Operations
Advanced re-logging or reprocessing should be applied to intervals with questionable data, using modern high-resolution tools. Ensuring more reliable pore pressure profiles will lower the probability of drilling accidents such as kicks, blowouts, or mud losses that may result in marine or soil contamination. Integration with real-time monitoring will enhance early detection of abnormal pressures, providing proactive environmental protection.
4. Environmentally Conscious Drilling Strategy
Overpressure zones—particularly in wells Z-002 and Z-004—require carefully designed drilling programs. Pre-drill pore pressure models should guide mud weight programs, while real-time MWD/LWD monitoring systems should track dynamic changes. Early detection of anomalies reduces blowout risks and prevents the uncontrolled release of hydrocarbons or drilling fluids into surrounding formations or surface environments.
5. Integrated Reservoir Characterization for Pressure and Risk Management
A multidisciplinary interpretation involving seismic inversion, velocity modeling, core analysis, and biostratigraphy should be undertaken to improve reservoir definition and better detect sealing and trapping mechanisms. A clearer understanding of pressure barriers will reduce the likelihood of fluid migration into freshwater aquifers or environmentally sensitive shallow zones.

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