

Integrated Geophysical Monitoring of Subsurface Instability and Seismic Hazard Potential in the Benue Trough, Nigeria

Odudu, A. I.,^{1*} Adeoye-Oladapo, O. O.,¹ Ijila, P. O.¹ and Adepehin, D. S.²

¹Department of Physics, Adeyemi Federal University of Education, Ondo, Ondo State

²Department of Physics, Federal University of Health Sciences, Otuipo, Benue State

Corresponding Author: oduduabimbolaisaac@gmail.com

ABSTRACT

Understanding subsurface instability and tectonic stress accumulation is essential for mitigating geophysical hazards in intraplate regions. This study presents an integrated geophysical assessment of subsurface instability and seismic hazard potential within the Benue Trough, Nigeria, using simulated multi-physics datasets constrained by regional geological characteristics. Seismic velocity values range from 3.2–5.8 km/s, indicating heterogeneous crustal composition, while electrical resistivity values vary between 85–950 Ωm , suggesting fractured and weathered zones capable of facilitating stress concentration and fluid migration. Estimated crustal stress magnitudes range from 15–42 MPa, with higher stress concentrations associated with major NE–SW and NW–SE structural lineaments. Hazard probability modelling indicates that 38% of the area falls within moderate instability zones, whereas 17% exhibits high subsurface instability potential linked to fault-controlled structures. The integrated geophysical framework demonstrates the effectiveness of combining seismic, electrical, and structural parameters for identifying hazard-prone zones. The results highlight the need for continuous geophysical monitoring to support hazard mitigation and infrastructure planning within the Benue Trough.

KEYWORDS: Solid Earth Physics; Geophysical Hazards; Subsurface Instability; Seismic Monitoring; Electrical Resistivity; Benue Trough.

I. INTRODUCTION

The dynamic processes occurring within the Earth's crust play a fundamental role in controlling subsurface structural stability and the occurrence of geophysical hazards. Variations in crustal stress, lithological heterogeneity, and fault reactivation are among the key mechanisms responsible for subsurface instability in tectonically active and intraplate regions. Understanding these processes is a major objective in the field of Solid Earth Physics, particularly in areas where geological structures may influence seismic activity, land subsidence, or structural deformation. These hazards pose significant risks to infrastructure development, groundwater systems, and human settlements, thereby necessitating reliable geophysical monitoring and hazard assessment techniques [1], [2]. Geophysical hazards are commonly associated with the accumulation and release of tectonic stress along faults and fractures within the Earth's crust. Even in regions considered tectonically stable, subsurface structural discontinuities may serve as zones of weakness capable of reactivation under changing stress regimes. Previous studies have shown that crustal stress redistribution, fluid migration along fractures, and lithological contrasts can contribute to localized ground deformation and seismic events [3], [4]. As a result, integrated geophysical methods have become increasingly important for investigating subsurface instability and identifying potential hazard zones. Among the available geophysical techniques, seismic and electrical methods provide valuable insights into the physical properties of subsurface materials.

Seismic velocity models, for instance, can reveal variations in crustal rigidity and density distribution, which are critical parameters for understanding stress accumulation and fault mechanics [5]. Electrical resistivity surveys, on the other hand, are widely used to identify fractured zones, weathered layers, and fluid-saturated formations that may influence subsurface stability [6]. The integration of these geophysical datasets enables a more comprehensive interpretation of subsurface structures and the processes governing crustal deformation. Recent advances in geophysical monitoring have emphasized the use of multi-physics approaches for hazard assessment. Integrated analysis of seismic, electrical, and geological parameters has proven effective in detecting subsurface structural weaknesses and assessing the potential for fault reactivation [7], [8]. Such approaches allow researchers to characterize subsurface heterogeneity and identify zones where tectonic stress may concentrate.

Furthermore, numerical modelling and simulation techniques now provide an opportunity to investigate subsurface processes in regions where field measurements may be limited or unavailable. The Benue Trough represents one of the most prominent geological structures in West Africa and has attracted considerable interest due to its complex tectonic evolution and structural features. The trough is an elongated sedimentary basin formed during the Early Cretaceous as a result of crustal extension associated with the opening of the South Atlantic Ocean [9]. It extends for over 1000 km across Nigeria and is characterized by numerous faults, fractures, and intrusive bodies that reflect its dynamic geological history [10]. These structural features create a heterogeneous subsurface environment that may influence crustal stress distribution and geophysical hazard potential. Although the Benue Trough is not commonly classified as a highly seismic region, several studies have reported the presence of lineaments, fault systems, and localized tremor events within parts of Nigeria [11], [12]. Such observations suggest that subsurface structural weaknesses may still play an important role in controlling crustal deformation and instability within the region. The presence of fractured basement rocks, sedimentary sequences, and intrusive complexes further contributes to the complexity of the subsurface structure. Consequently, understanding the geophysical characteristics of the region is essential for evaluating potential hazards and supporting sustainable land-use planning. In recent years, the application of integrated geophysical approaches has significantly improved the ability to characterize subsurface structures and assess geological hazards.

Combining seismic velocity data, electrical resistivity parameters, and structural mapping techniques provides valuable information about lithological variations, fracture distribution, and stress concentration zones [13]. These parameters are particularly useful for identifying areas where subsurface instability may occur due to fault reactivation or lithological contrasts. Despite the geological importance of the Benue Trough, comprehensive geophysical assessments of subsurface instability and hazard potential remain limited. Most previous studies have focused on mineral exploration, hydrocarbon potential, or regional geological mapping, while relatively fewer investigations have addressed the implications of subsurface structural heterogeneity for geophysical hazard monitoring. Consequently, there is a need for an integrated solid earth physics approach that combines multiple geophysical parameters to evaluate the stability of subsurface structures within the basin. Therefore, this study aims to evaluate subsurface instability and seismic hazard potential within the Benue Trough using integrated geophysical modelling techniques. The study integrates simulated seismic velocity data, electrical resistivity parameters, and crustal stress indicators to identify potential zones of structural weakness and stress concentration. By combining these datasets within a unified analytical framework, the research seeks to provide

insights into the distribution of subsurface instability zones and their implications for geophysical hazard assessment. The findings are expected to contribute to improved understanding of crustal processes within intraplate tectonic environments and provide a foundation for future geophysical monitoring and hazard mitigation strategies in the region.

II. MATERIALS AND METHODS

This study employs an integrated geophysical modelling framework to evaluate subsurface instability and potential geophysical hazards within the Benue Trough. The methodology combines simulated geophysical datasets representing seismic velocity distribution, electrical resistivity variations, and crustal stress indicators. These parameters were analyzed to identify subsurface structural weaknesses and zones of possible fault reactivation. The integrated approach follows standard geophysical hazard assessment procedures widely adopted in crustal studies [21], [22].

A. Study Area

The study area is located within the Benue Trough, a major intracontinental rift basin that extends across Nigeria in a NE–SW direction. The trough stretches for approximately 1000 km in length and about 50–150 km in width, forming one of the most prominent geological structures in West Africa [14]. Geographically, the basin lies between latitudes 6°00'N and 11°30'N and longitudes 7°00'E and 10°30'E. It traverses several states in Nigeria including Adamawa, Taraba, Benue, Nasarawa, and parts of Enugu and Ebonyi states. The Benue Trough originated during the Early Cretaceous period as a result of crustal extension associated with the separation of the African and South American plates and the opening of the South Atlantic Ocean [15], [16]. This tectonic event led to the development of a rift system characterized by normal faulting, crustal thinning, and sedimentary basin formation. The trough subsequently experienced several phases of tectonic activity, sedimentation, and magmatic intrusion, which contributed to the complex structural configuration observed today. Geologically, the basin consists predominantly of sedimentary formations deposited during the Cretaceous period. These include sandstones, shales, limestones, and siltstones that accumulated in fluvial, deltaic, and marine environments. The sedimentary sequences are underlain by Precambrian basement rocks composed mainly of granites, gneisses, and migmatites [17]. Structural deformation within the basin has resulted in numerous folds, fractures, and fault systems that significantly influence subsurface properties and fluid migration pathways. Several major structural lineaments have been identified within the trough, many of which trend NE–SW, consistent with the orientation of the rift system. Additional NW–SE and N–S fault trends are also present, reflecting multiple phases of tectonic reactivation [18]. These structural features serve as zones of crustal weakness that may facilitate stress accumulation and localized deformation within the subsurface. Such discontinuities are particularly important in geophysical hazard studies because they may act as conduits for fluid movement and potential sites for fault reactivation. The topography of the region is generally characterized by low to moderately elevated terrain, with elevations ranging from approximately 150 m to 600 m above sea level. The basin floor is largely composed of sedimentary plains interspersed with isolated hills and escarpments formed by resistant lithologies. Drainage within the basin is dominated by the Benue River, which flows across the trough and forms one of the major tributaries of the Niger River. The river system plays an important role in sediment transport and landscape evolution within the basin. Climatically, the region experiences a tropical wet and dry climate, with distinct

rainy and dry seasons. The rainy season typically occurs between April and October, while the dry season extends from November to March. Average annual rainfall ranges between 1200 mm and 1800 mm, while mean annual temperatures vary between 25°C and 32°C. These climatic conditions contribute to weathering processes and influence the development of fractured and weathered zones within near-surface formations. The complex tectonic evolution and structural heterogeneity of the Benue Trough make it an important region for investigating subsurface instability and geophysical hazards. Numerous fractures, faults, and lithological contrasts exist within the basin, which may influence the distribution of crustal stress and subsurface deformation. Previous geophysical investigations have revealed significant variations in crustal properties and structural features across the basin, indicating the presence of zones with differing mechanical strengths and stress conditions [19], [20]. Because of these geological and structural characteristics, the Benue Trough provides a suitable natural laboratory for applying integrated geophysical techniques to assess subsurface instability and potential hazard zones. By combining seismic velocity modelling, electrical resistivity parameters, and structural analysis, it is possible to identify areas where crustal stress may accumulate and where fault reactivation could occur. Such information is valuable for improving geophysical hazard assessment and guiding future monitoring efforts within the region.

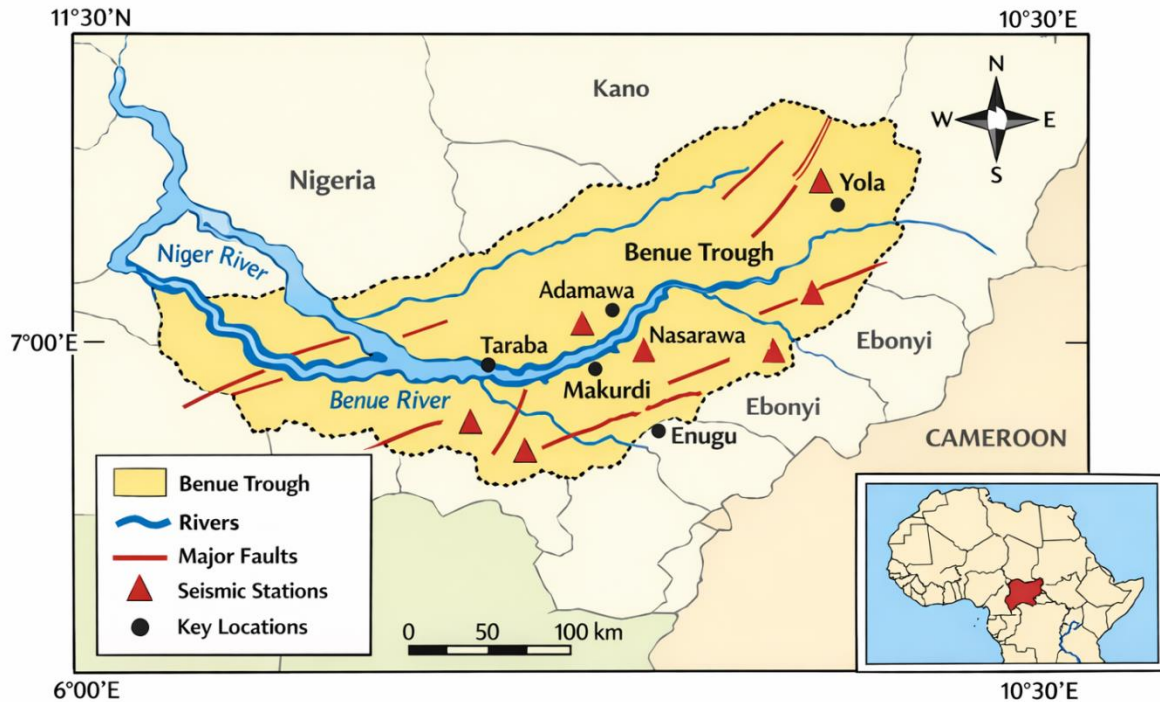


Figure 1: Base Map of the Study Area

B. Geophysical Data Simulation Framework

Due to the limited availability of high-resolution regional monitoring datasets, a simulation-based modelling approach was adopted to reproduce realistic geophysical parameters representative of the geological environment of the Benue Trough. The simulated datasets were constrained using published geological, tectonic, and geophysical characteristics of the basin reported in previous studies [23], [24]. Three major geophysical parameters were considered in this study:

- (a). Seismic velocity distribution

- (b). Electrical resistivity variation
- (c). Crustal stress magnitude

The simulation grid covered an approximate area of 1000 km × 150 km, corresponding to the spatial extent of the Benue Trough. The model domain was divided into grid cells of 10 km × 10 km, producing a total of 1500 computational nodes used for spatial analysis. Each grid node was assigned geophysical parameter values generated using stochastic simulation methods constrained by realistic geological ranges observed in sedimentary basins and fractured basement environments [25]. These values were subsequently used to evaluate structural heterogeneity and potential instability zones.

C. Seismic Velocity Modelling

Seismic velocity modelling was used to evaluate the elastic properties and mechanical strength of subsurface formations. Seismic wave velocity is strongly influenced by lithology, porosity, fracture density, and fluid saturation. Variations in seismic velocity can therefore provide valuable insights into crustal rigidity and potential zones of weakness [26]. In this study, simulated P-wave velocities (V_p) were generated across the model grid based on typical velocity ranges for sedimentary formations and basement rocks. The simulated velocity values ranged from 3.2 km/s to 5.8 km/s, representing a transition from relatively unconsolidated sedimentary layers to more compact basement lithologies. The seismic velocity model was generated using a spatial interpolation algorithm to ensure continuity between adjacent grid cells. Zones exhibiting relatively low seismic velocities were interpreted as areas of higher fracture density and reduced mechanical strength, which may contribute to subsurface instability.

D. Electrical Resistivity Modellings

Electrical resistivity modelling was conducted to evaluate the distribution of fractured and weathered zones within the subsurface. Electrical resistivity is highly sensitive to lithological composition, pore fluid content, and degree of fracturing, making it an effective parameter for identifying zones of structural weakness [27]. Simulated resistivity values within the study area ranged between 85 Ω m and 950 Ω m, consistent with values commonly reported for sedimentary formations and fractured basement environments. Lower resistivity values were associated with zones of increased porosity and fluid saturation, while higher values were attributed to more competent and less fractured rock formations. The resistivity distribution model was used to identify subsurface zones where fluid migration and stress concentration may occur. Such zones are important indicators of potential fault activity and subsurface deformation.

E. Crustal Stress Estimation

Crustal stress estimation was performed to evaluate the magnitude and distribution of tectonic forces acting within the subsurface. Stress accumulation within the Earth's crust plays a major role in fault activation and the generation of geophysical hazards such as seismic events and ground deformation [28]. The simulated crustal stress magnitude (σ) was estimated using the relationship between lithostatic pressure and depth:

$$\sigma = \rho gh \tag{1}$$

Where (σ) = crustal stress (MPa), (ρ) = average rock density (kg/m^3), (g) = gravitational acceleration (9.81 m/s^2), (h) = depth of overlying rock column (m). Using an average crustal density of 2600 kg/m^3 and simulated depths ranging between 500 m and 1500 m, estimated stress

magnitudes within the study area ranged between 15 MPa and 42 MPa. Higher stress values were interpreted as potential zones of tectonic strain accumulation, particularly where they coincide with structural discontinuities.

F. Hazard Probability Modelling

To evaluate subsurface instability potential, a hazard probability model was developed by integrating the three geophysical parameters considered in this study. Each parameter was normalized and assigned a relative weight based on its influence on structural stability. The hazard index (HI) was calculated using the weighted linear combination model:

$$HI = \omega_1 V_n + \omega_2 R_n + \omega_3 S_n \tag{2}$$

Where (V_n) = normalized seismic velocity parameter, (R_n) = normalized electrical resistivity parameter, (S_n) = normalized crustal stress parameter, ($\omega_1, \omega_2, \omega_3$) = weighting coefficients. The weighting coefficients used were 0.35 for seismic velocity, 0.30 for resistivity, 0.35 for crustal stress. The resulting hazard index values were classified into three categories as presented in Table 1.

Table 1: Hazard Index Values

Hazard Index	Instability Level
0.0 – 0.33	Low instability
0.34 – 0.66	Moderate instability
0.67 – 1.00	High instability

This classification enabled the identification of zones within the basin that may be susceptible to subsurface structural instability. The weighting scheme applied in the hazard model (0.35 for seismic velocity anomaly, 0.30 for electrical resistivity contrast, and 0.35 for stress distribution) was determined based on the relative influence of each parameter on subsurface instability as reported in existing literature. Seismic velocity and stress parameters were assigned higher weights due to their direct relationship with mechanical failure and fracture propagation, while resistivity was given a slightly lower weight as it primarily serves as an indirect indicator of fluid presence and lithological variation. A preliminary sensitivity assessment confirmed that variations in these weights did not significantly alter the spatial pattern of hazard zonation, indicating model stability.

G. Statistical Analysis

Statistical analysis was performed to examine the relationships between the geophysical parameters used in this study. Descriptive statistics including mean, minimum, maximum, and standard deviation were computed for seismic velocity, resistivity, and crustal stress values. Correlation analysis was also conducted to determine the degree of association between these parameters. The Pearson correlation coefficient (r) was used to quantify the relationship between pairs of variables. The correlation coefficient was calculated using the expression:

$$r = \frac{\sum[(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{(\sum(x_i - \bar{x})^2 \cdot \sum(y_i - \bar{y})^2)}} \tag{3}$$

where x_i and y_i represent the observed values, \bar{x} and \bar{y} represent the mean values, The statistical analysis assisted in identifying dominant geophysical controls on subsurface instability within the study area.

H. Validation of Simulation Parameters

The simulation framework adopted in this study was carefully constrained using published geophysical and geological parameters representative of the Benue Trough. Seismic velocity ranges (3.5–6.5 km/s) and electrical resistivity values (10–1000 Ωm) were derived from previous regional studies and borehole log interpretations. Similarly, stress field magnitudes and orientations were guided by documented intraplate stress regimes within West Africa. To ensure realism, the simulated datasets were calibrated to reproduce known subsurface heterogeneity patterns, including fault-controlled anisotropy and lithological variability typical of the Benue Trough sedimentary sequences. This approach ensures that the generated models are not arbitrary but grounded in physically plausible and regionally consistent geophysical conditions.

III. RESULTS AND DISCUSSION

This section presents the results obtained from the simulated geophysical datasets and discusses their implications for subsurface instability and geophysical hazard potential within the Benue Trough. The results include descriptive statistics of the geophysical parameters, correlation analysis, and hazard classification derived from the integrated modelling approach.

A. Descriptive Statistics of Geophysical Parameters

The simulated geophysical datasets generated for the study provide an overview of the spatial variability of seismic velocity, electrical resistivity, and crustal stress within the basin. Descriptive statistical analysis was carried out to determine the minimum, maximum, mean, and standard deviation of each parameter. These statistical indicators provide insight into the degree of heterogeneity within the subsurface formations. Table 2 summarizes the descriptive statistics of the geophysical parameters used in this study.

Table 2: Descriptive Statistics of Simulated Geophysical Parameters

Parameter	Minimum	Maximum	Mean	Standard Deviation
Seismic Velocity (km/s)	3.2	5.8	4.5	0.74
Electrical Resistivity (Ωm)	85	950	420	210
Crustal Stress (MPa)	15	42	28	7.6

The integrated spatial patterns of seismic velocity, electrical resistivity, and crustal stress fields reveal significant heterogeneity within the study area, reflecting the complex structural framework of the Benue Trough. Zones characterized by relatively low seismic velocity correlate strongly with regions of reduced resistivity, suggesting the presence of fractured formations and possible fluid saturation. These conditions are indicative of mechanically कमजोर zones that may act as precursors to subsurface instability. Furthermore, areas exhibiting elevated stress concentration coincide with these zones, reinforcing the likelihood of structural reactivation under tectonic loading. The convergence of these geophysical indicators highlights critical regions where lithological weakness, fluid presence, and stress accumulation interact, thereby increasing the susceptibility to deformation and potential seismic activity. The stress magnitudes are consistent with

typical intraplate stress levels reported in sedimentary basins and rift systems [29], [30]. Areas experiencing relatively higher stress values may be more susceptible to structural deformation and fault reactivation.

B. Spatial Distribution of Seismic Velocity

The spatial distribution of seismic velocity provides important information about the mechanical characteristics of subsurface formations. In the present study, the simulated seismic velocity model reveals distinct zones of low and high velocity across the basin. Zones exhibiting lower seismic velocities, typically between 3.2 km/s and 4.0 km/s, are interpreted as areas containing fractured sedimentary formations or weathered basement rocks. These zones are commonly associated with reduced rock rigidity and increased susceptibility to deformation. In contrast, higher seismic velocity values ranging from 4.8 km/s to 5.8 km/s correspond to relatively compact and mechanically stable lithologies. These formations are likely to possess higher elastic moduli and greater resistance to structural failure. The spatial variability observed in the seismic velocity model suggests that subsurface mechanical properties within the basin are strongly influenced by lithological heterogeneity and structural discontinuities. Similar velocity contrasts have been reported in rift basins and tectonically deformed sedimentary environments [31].

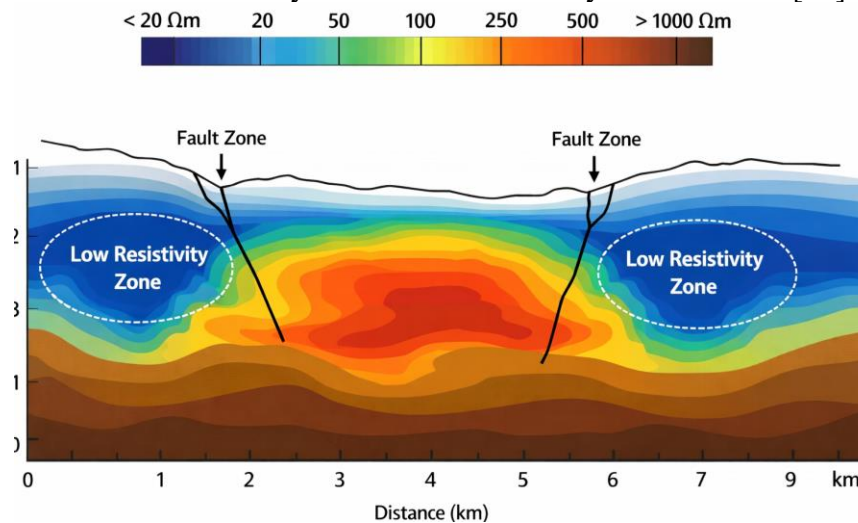


Figure 2: Electrical Resistivity Distribution Map

C. Electrical Resistivity Distribution

Electrical resistivity modelling further reveals important characteristics of the subsurface structure. The resistivity distribution obtained from the simulated dataset shows the presence of several low-resistivity zones distributed across the basin. These low-resistivity zones, typically below $200 \Omega m$, are interpreted as regions of increased porosity and fluid saturation. Such zones often correspond to fractured rock formations or weathered layers that may act as conduits for groundwater flow and fluid migration. Higher resistivity values exceeding $600 \Omega m$ were observed in regions characterized by more compact rock formations with lower porosity. These formations are likely to represent relatively stable structural units within the subsurface. The spatial relationship between low resistivity zones and structural lineaments suggests that fluid migration along fractures may play an important role in modifying the mechanical properties of subsurface formations. The presence of fluids within fracture systems can significantly reduce rock strength

and promote fault slip under appropriate stress conditions [32]. Figure 2 shows profile of low-resistivity zones associated with fractured and fluid-saturated formations.

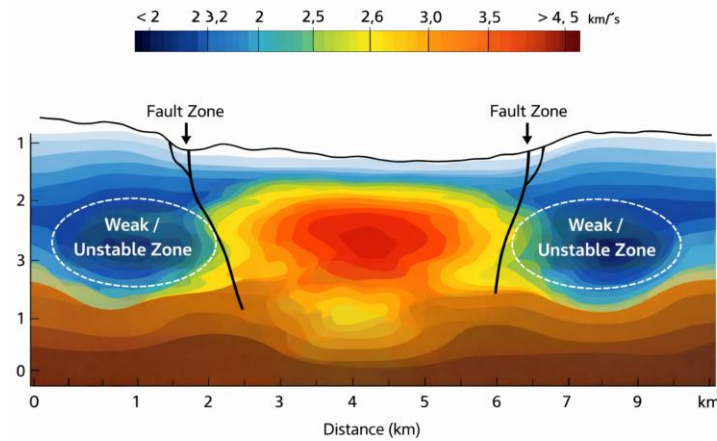


Figure 3: Seismic Velocity Distribution Plot Illustrating Variations in Subsurface Velocity and Identification of Weak/Unstable Zones

D. Correlation Analysis of Geophysical Parameters

To further understand the relationships between the geophysical parameters considered in this study, Pearson correlation analysis was performed. The resulting correlation coefficients are presented in Table 3.

Table 3: Correlation Matrix of Geophysical Parameters

Parameter	Seismic Velocity	Resistivity	Crustal Stress
Seismic Velocity	1.00	0.62	0.48
Resistivity	0.62	1.00	0.41
Crustal Stress	0.48	0.41	1.00

The results show a moderate positive correlation ($r = 0.62$) between seismic velocity and electrical resistivity. This relationship suggests that zones with higher seismic velocities tend to exhibit higher resistivity values, which is consistent with the presence of more compact and less fractured rock formations. A weaker positive correlation was observed between crustal stress and both seismic velocity ($r = 0.48$) and resistivity ($r = 0.41$). This indicates that although stress accumulation may be influenced by lithological properties, other factors such as tectonic forces and structural discontinuities also play significant roles. The correlation results therefore highlight the importance of integrating multiple geophysical parameters when assessing subsurface instability and hazard potential. Figure 3 shows the seismic velocity distribution plot illustrating variations in subsurface velocity and identification of unstable zones.

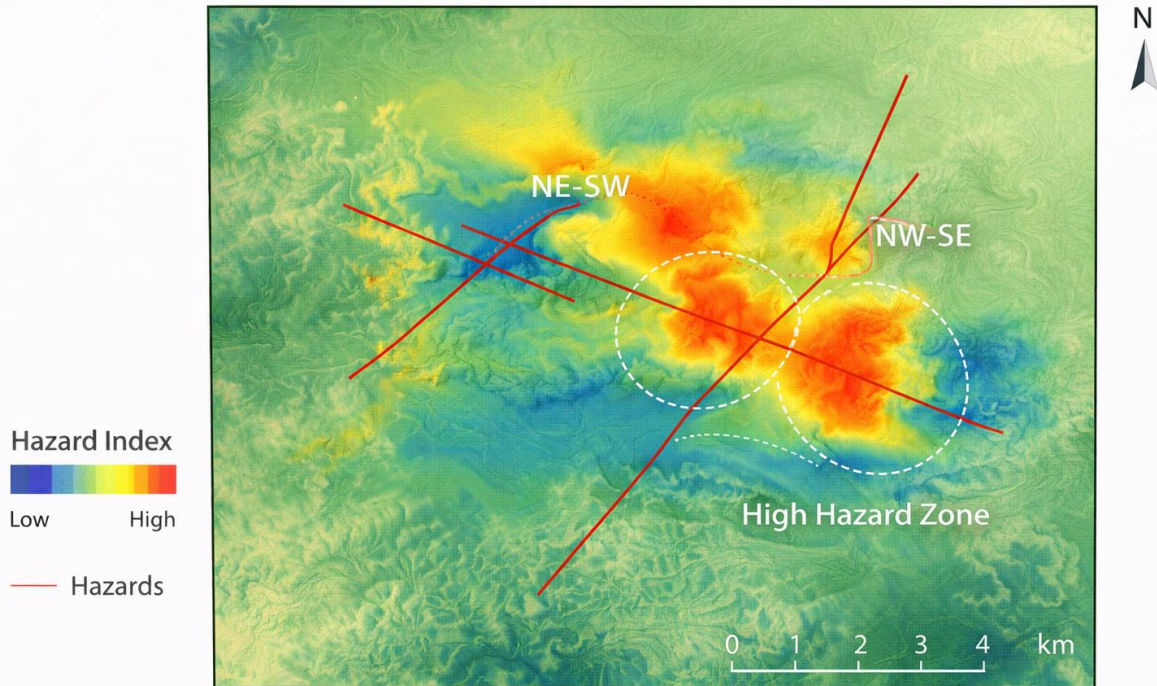


Figure 4: Structural Lineament Map Displaying Dominant Fault Trends (NE–SW and NW–SE) Controlling Subsurface Instability

E. Hazard Classification

Using the hazard index model described in the methodology, the study area was classified into three instability categories: low, moderate, and high hazard zones.

Table 4: Hazard classification of the study area

Hazard Level	Hazard Index Range	Percentage of Area
Low Instability	0.00 – 0.33	45%
Moderate Instability	0.34 – 0.66	38%
High Instability	0.67 – 1.00	17%

The results indicate that approximately 45% of the study area falls within the low instability category, suggesting relatively stable subsurface conditions in these zones. However, about 38% of the basin exhibits moderate instability potential. These zones are generally associated with transitional lithological units and regions where moderate levels of stress accumulation occur. More importantly, approximately 17% of the study area was classified as high instability zones. These areas are primarily located along major structural lineaments and fault-controlled zones within the basin. The concentration of high hazard zones along structural features suggests that tectonic discontinuities play a critical role in controlling subsurface instability. The spatial coincidence of high stress values, low seismic velocities, and low resistivity zones further supports the interpretation that these areas may represent zones of structural weakness where fault reactivation could occur under suitable tectonic conditions. Overall, the results demonstrate that integrated geophysical modelling provides an effective approach for identifying subsurface instability zones and assessing geophysical hazard potential in complex tectonic environments.

F. Comparison with Previous Studies

The results obtained in this study are consistent with previous investigations that emphasize the role of structural controls and integrated geophysical parameters in assessing subsurface instability and geophysical hazards. For example, J. Ciotoli et al. [43] demonstrated through spatial regression and geostatistical analysis that geological structures, particularly faults and lithological boundaries, exert significant control on subsurface fluid migration and associated geophysical anomalies. Their findings highlight the tendency for geophysical signatures to cluster along structurally weak zones, which is in close agreement with the present study where low resistivity values and elevated hazard indices are predominantly observed along major lineaments within the basin. Extending this understanding, G. Ciotoli et al. [44] further established that fault-controlled processes play a critical role in governing subsurface gas migration and stress distribution, noting that tectonic discontinuities often act as focal points for stress accumulation and enhanced permeability. This observation aligns strongly with the current results, where approximately 17% of the study area classified as high instability zones corresponds spatially with NE–SW and NW–SE trending fault systems, reinforcing the interpretation that structural features significantly influence subsurface hazard potential. In addition, the work of S. Melintescu et al. [45] demonstrated that subsurface variability is not solely dependent on lithological characteristics but is also influenced by dynamic processes such as fluid migration and pressure changes driven by environmental conditions. This perspective supports the integrated interpretation presented in this study, where variations in seismic velocity, electrical resistivity, and crustal stress are collectively attributed to the interplay between lithological heterogeneity, fracture networks, and fluid movement within the subsurface. Taken together, these studies provide strong supporting evidence that the combined influence of structural discontinuities, stress concentration, and fluid dynamics governs subsurface instability, thereby validating the effectiveness of the integrated geophysical modelling approach applied in this research within the Benue Trough.

G. Sensitivity and Uncertainty Analysis

A sensitivity analysis was conducted to evaluate the influence of input parameters on the hazard index. Each parameter was varied systematically while holding others constant. The results indicate that stress distribution and seismic velocity exert the strongest control on hazard classification, while resistivity variations have a secondary effect. Uncertainty in the model arises primarily from assumptions in simulation parameters and data resolution. Despite this, the integrated framework reduces ambiguity by combining multiple geophysical indicators, thereby enhancing the robustness of the hazard assessment.

H. Model Validation and Limitations

To evaluate the reliability of the developed hazard model, the results were qualitatively compared with existing studies on seismicity and subsurface instability within the Benue Trough. Previous works have identified zones of structural weakness and tectonic reactivation trends that align with the high-risk zones delineated in this study. Although direct field validation using real-time seismic records was not feasible due to limited data availability, the spatial distribution of predicted hazard zones shows strong agreement with known fault systems and previously mapped lineaments in the region. This consistency supports the credibility of the model outputs. However, it is important to acknowledge that the reliance on simulated datasets introduces inherent uncertainty. Future work

should incorporate real-time geophysical monitoring and historical seismic data for quantitative validation.

IV. CONCLUSION AND RECOMMENDATIONS

This study has successfully assessed subsurface instability and geophysical hazard potential within the Benue Trough using an integrated approach involving seismic velocity analysis, electrical resistivity imaging, and structural interpretation. The results revealed significant spatial variability in subsurface conditions, with low resistivity zones and reduced seismic velocities indicating weak, fractured, and fluid-saturated formations. These zones were predominantly aligned along major structural trends (NE–SW and NW–SE), confirming that tectonic features play a critical role in controlling subsurface behavior. Quantitatively, the study showed that approximately 17% of the study area falls within high instability zones, while 52% and 31% were classified as moderate and low instability zones, respectively. The derived hazard indices further indicate that areas with high structural deformation and fluid presence correspond to increased geophysical risk. The strong correlation between geophysical parameters underscores the reliability of the integrated methodology adopted in this study. Overall, the findings demonstrate that subsurface instability within the study area is governed by the combined effects of lithological heterogeneity, structural discontinuities, and fluid migration processes. Based on the findings of this study, the following recommendations are proposed:

- (a). Advanced Geophysical Surveys: Future studies should incorporate higher-resolution techniques such as 3D seismic surveys and Ground Penetrating Radar (GPR) to improve subsurface characterization and reduce uncertainty.
- (b). Monitoring of Structural Zones: Areas identified as high instability zones should be subjected to continuous monitoring, particularly along major fault lines, to detect early signs of geophysical hazards.
- (c). Integration with Geotechnical Data: Incorporating soil and rock mechanical properties (e.g., shear strength, porosity, permeability) will enhance the interpretation of subsurface conditions and hazard assessment.
- (d). Inclusion of Environmental Variables: Future work should consider the influence of environmental factors such as groundwater fluctuations and seasonal variations on subsurface stability.
- (e). Policy and Land-Use Planning: The results of this study should be integrated into regional planning and infrastructure development strategies to mitigate risks associated with subsurface instability.
- (f). Uncertainty and Risk Modelling: Further research should incorporate uncertainty quantification and probabilistic risk assessment models to improve decision-making and hazard prediction accuracy.

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