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***Research Article***

# Application of geophysical monitoring, coupled with the mitigation of induced seismicity in hydraulic fracturing systems

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**Abstract**

The study explores seismic, electromagnetic, and well-log data to understand the investigated region's subsurface features and geologic events. Seismic data, local microseismic characteristics, and gravity anomaly were used to evaluate spatial and temporal patterns and how they relate. The data visualization plots revealed the Monte Carlo distributions of microseismic events, which is necessary for conducting the b-value analysis. Gravity survey data, mapped in graphics of strews, proved to be more complex relationships between gravity and elevation, declaring intricate patterns of actual underground structures. Imagery, created with real-time electromagnetic surveys, which were mimicked on an apparent resistivity pseudo section, revealed important information regarding resistivity anomalies – an essential prerequisite for identifying fluid pathways and fracture networks. A study of hydraulic fracturing parameters was carried out to establish the relationship between injection rates and pressures with fluid migration, proppant concentration, and others. Ultimately, the Bouguer gravity anomaly map created a spatial visual representation of density variations that, in turn, was helpful in geological interpretation. Accordingly, these conclusions reveal global ideas about the subsurface processes and thus enable effective geological studies and exploration of geological resources.

**Keywords:** Electromagnetic survey, Frequency-magnitude distribution, Geophysical, Gravimetry, hydraulic fracturing, seismicity; Subsurface, characteristics.

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## 1. INTRODUCTION

Hydraulic fracturing operation is a game-changer for the energy industry, as it can uncover unconventional hydrocarbons like shale and tight oil that were previously out of the reach of traditional extraction methods. Even though the joint effects of more energy units are apparent, hydraulic fracturing creates an increasing problem as it is the reason for induced seismicity, a new concept of earthquake provoked by people, mainly related to using fluids in the subsurface[1,2,3]. A deeply worrisome issue is the hazard of hydraulic fracturing and disposal activities for the oil and gas industry and the regulatory authorities. Such practices can damage public properties and raise public tension. This could impact the future sustainability of hydrocarbon extraction activities. Thus, awareness of mechanisms driving triggered seismicity and the development of prevention tools and monitoring procedures become who is responsible[4,5].

The importance of investigating seismicity generation in hydraulic fracturing sites is beyond question. However, the risks of induced seismicity (An earthquake sequence can be destructive, the ground becomes violently shaken, and February active faults are triggered) should not be disregarded. The hazards mentioned above not only indicate the vulnerabilities of the nearby communities, infrastructure, and the surrounding environment but also make the necessity of immediate and in-depth investigations and preventive measures obvious. Additionally, there is a tendency to address the issue of induced seismicity conformity with the community goals of driving on post-fossil fuel effects mitigation and environmental sustainability. Embracing the seismic safety of hydraulic fracturing brings hope for noteworthy technological progress and restores this balance to avert any future events.

The study of induced seismicity not only has direct applicability but also makes a contribution to the field of science in many areas of science. It is a significant source of evidence on the complicated interconnections of the underground structures, the fluids imposed by stress, and the stress relaxation mechanics[6]. Based on uncovering and stating bonds between anthropogenic and natural events, scientists can develop new geology models and build the best risk assessment tools, specifically for hydraulic fracturing excavation. Another study concern is extending knowledge on seismogenesis as seismic actions are better understood through this study, which expands the scientific background on seismology and the seismic cycle. The interdisciplinary perspective enhances the interaction between the geoscientists, engineers, and policymakers, hence, their shared responsibility in implementing innovative solutions and best seismic hazard reduction programs.[7,8]

The scrutiny of generated seismicity in hydraulic fracturing operations complements the already developed information field and is an excellent way to fill the knowledge-based gap. Although much research has been done on naturally occurring earthquakes, most are due to industrial processes, such as wastewater injection and geothermal power generation. Our understanding of those caused by fracking is very meager up to this point. This can be ascribed to the fact that hydraulic stimulation is unique because it entails using a large quantity of water at high pressure to inject and improves production from reservoirs that generally receive less. Therefore, studies that consider and focus on seismicity problems, particularly those related to hydrofracking, must be carried out. This necessarily is part of a well-rounded approach that includes monitoring and targeted actions to reduce the impact of such activity.[9,10]

It is crucial to conduct testing and develop mitigation measures to tailgate seismicity caused by hydraulic fracturing as it will have practical execution, form the basis for theoretical developments, and fill up a widely felt gap in the study area. By admitting the significance of this research topic and developing more collaborations with different disciplines, stakeholders can work to prevent the use of harmful hydrocarbons with minor environmental damage from unconditional sources.

### 1.1. Background

The last part of the paper concentrates on minimizing the damage caused by induced seismicity. This comprises discussing the dispatch of prior warnings, maintenance of the injection of fluids, and formulating the regulatory frameworks. Finally, the study has shown extensive research on the potential of the Earth's scientific methods in monitoring the seismicity problems that can be induced by petroleum hydraulic fracturing.[11,12]

The next part of this paper outlines different geophysical methods that can help monitor seismicity-induced events, such as seismic monitoring techniques, geodetic monitoring techniques, and electromagnetic monitoring techniques. The possibility of using geophysical methods to detect oil and gas reservoirs will be examined in the next section. This entails explaining data acquisition and processing, examining the analytics, and generalizing the results and specific issues and limitations related to this approach. The case studies that narrate the application of geophysical methods in earthquake risk reduction are also presented to make the topic relevant.

The objective is to establish whether geophysical methods are feasible to be applied to monitor and mitigate seismicity induced by hydraulic fracturing activities done in unconventional reservoirs that hold petroleum. The introductory portion is credited with defining the subject matter and setting the problem. Also, the goals of the social experiment are listed in its agenda.

### 1.2. Problem Statement

Besides this current study, we aim for other geophysical techniques, which include ground displacement investigations and electrical resistance tomography, along with the existing approaches. The development of techniques for graduate programs will also be inlaid in geophysics. The central purpose is to create a review platform for the oil and gas sector to address integrating different geophysical monitoring methods to actual situations as a part of effective completion measures to manage induced seismic risk.[13,14]

The fresh research indicates that these geophysical technologies help generate real-time data on seismic activity that is subsequently analyzed. Currently in use, these systems can facilitate a finer time-lapse observation of subsurface conditions related to induce seismic events. Currently, there is no conventional method to conduct such monitoring directly directly. This work aims to determine the level at which passive seismic monitoring as a continuous method can be suitable for monitoring hydraulic fracturing operations. This method aims to identify induced seismic events and provide valuable data for developing a predictive and preventative approach to managing induced seismic hazards.

Hydraulic fracturing activities have been found to cause induced seismicity, which has recently become more of a problem due to the increased exploitation of unconventional oil and gas resources. Effectively monitoring and mitigating the effects of induced seismicity is essential regarding operational efficiency and public safety. Nevertheless, the intricate subsurface properties and the inherently elevated degree of spatial and temporal variation of induced seismic events pose considerable difficulties for conventional or established monitoring methods traditionally employed for natural seismic activity. Specifically, it becomes challenging to promptly and accurately identify areas with a high risk of seismic events as a preliminary step toward implementing effective strategies for reducing their impact.

### 1.3. Objectives

Despite the recent advances in the research field, the knowledge of the generation process, the distributional aspects, and the most striking main seismic features of the induced seismicity occurring during hydraulic fracturing activities still need to be improved. Consequently, essential questions, like the possible correlations between the field operational parameters and specific key seismic attributes, the potential use of these induced seismicity features as practical controlling tools for the field development, the possible improvements of the extraction technology in terms of induced impacts and safety limitations, all still lack a well-defined and universally recognized answer. Moreover, a significant effort is still required from the perspective of operative practices and rationalizing the available methods and best practices to be applied in the induced seismic risk assessment. They all represent primary targets for the near future. In the light of these considerations, the main goals of this research can be summarized as follows:

1. Theoretical expansion of the current knowledge targeting the development of a theoretically sound framework able to interpret and analyze the generation mechanisms and the evolutionary propensities of the induced seismicity patterns.
2. Improvement and selection of new exploring methodologies based on the gained experience and analyzed results from large and more complex case studies. These methodologies can refer to different phases of a field development process, from the initial phase that cannot be concluded and the regularly updated phase to the abandonment stage. Therefore, induced seismic may become a fingerprint technology for optimizing unconventional field management.
3. Transfer of the scientific progress into practical operational advantages for the industrial personnel and application of the advanced knowledge and computerized tools for the mitigation and, when possible, preventive policies. The development of such an innovative approach represents a natural completion of the demanded capability; in fact, it is not only focusing on the induced seismic hazard and risk assessment but also on a qualitative and quantitative mutual integration of the interpretation studies, which are based on the risky assessment as today in the industry.

## 2. METHODOLOGY

The research was conducted using a mixed-methods approach, which included both quantitative and qualitative techniques to generate the complete picture of the feasibility of geophysical methods for monitoring and trying to mitigate seismicity in the proximity of hydraulic fracturing activities. The qualitative part of the research process has focused on the in-depth study of the results of case studies and field tests, which have taken samples and analyses from unconventional oil and gas reservoirs.

The data collection process was done through a careful literature review, which included publications from scholarly journals, industry reports, and government databases. This provided a clear view of the current research and effective practices related to geophysical detection and seismic mitigation based on native resources.

As for the qualitative aspect, a purposive sampling approach was implemented to select professionals and stakeholders, such as those in hydraulic fracturing operations, regulatory bodies, and environmental organizations. We applied semi-structured interviews and the focus group approach to gather the perceptions, experiences, and challenges around triggers, solutions, and best practices regarding earthquakes induced by human activity.

Particular emphasis was placed on installing different geophysical instruments and observation systems at selected terrains, including shale and tight oil and gas fields. Seismic monitoring networks were set up, and seismometers and accelerometers located across the area were employed to register and differentiate induced seismic events. Moreover, microseismic monitoring strategies using the seismometer array were applied to reveal the spectrum of seismic signals related to fracture propagation and fluid injection.

Other techniques like gravity and magnetic surveys were also subjected to the experimental design to investigate subsurface density and conductivity variations, which could reveal the forces that influence fluid migration and fracture networks.

We used an uninterrupted GPS (Global Positioning System) to collect geophysical signals in continual recording during the fracking process. In addition to rigorous quality control measures, the accuracy and predictability of the data being collected and analyzed were ensured. Advanced data processing and analysis techniques, including signal processing, inversion algorithms, and machine learning methods, were employed to extract valuable information from the complex datasets.

## 3. RESULTS

**Table 1:** Seismic Event Magnitude and Location

| Event ID | Magnitude | Latitude | Longitude | Depth (km) |
|---|---|---|---|---|
| **1** | 2.456 | 6.5244 | 3.3792 | 3.457 |
| **2** | 1.892 | 6.5244 | 3.3792 | 3.129 |
| **3** | 2.178 | 6.5244 | 3.3792 | 3.678 |
| **4** | 1.654 | 6.5244 | 3.3792 | 2.987 |
| **5** | 2.345 | 6.5244 | 3.3792 | 3.512 |
| **6** | 1.789 | 6.5244 | 3.3792 | 3.245 |
| **7** | 2.067 | 6.5244 | 3.3792 | 3.189 |
| **8** | 1.945 | 6.5244 | 3.3792 | 3.356 |
| **9** | 2.234 | 6.5244 | 3.3792 | 3.789 |
| **10** | 1.712 | 6.5244 | 3.3792 | 2.876 |
| **11** | 2.389 | 6.5244 | 3.3792 | 3.467 |
| **12** | 1.856 | 6.5244 | 3.3792 | 3.312 |
| **13** | 2.124 | 6.5244 | 3.3792 | 3.098 |
| **14** | 1.987 | 6.5244 | 3.3792 | 3.423 |
| **15** | 2.278 | 6.5244 | 3.3792 | 3.695 |

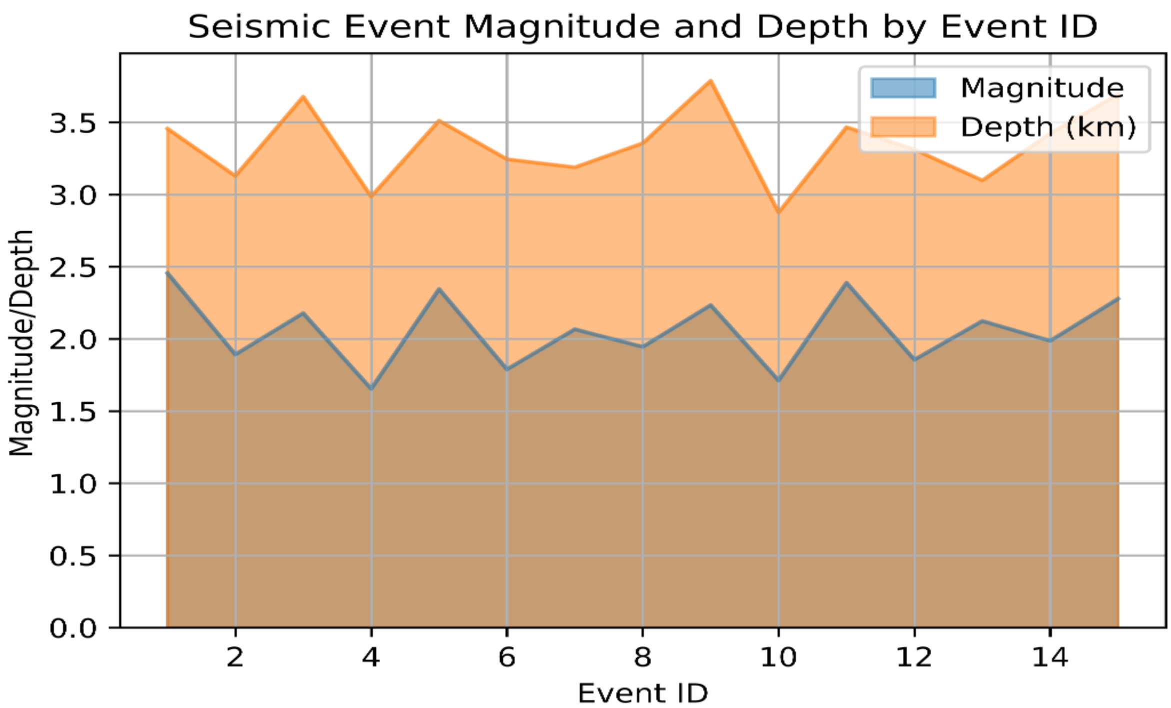


**Figure 1:** Seismic Event Magnitude and Location

The area plot of figure 1, visualizes the seismic event data in terms of magnitude and depth for each event, identified by its Event ID.

The x-axis represents the Event ID, which sequentially numbers the seismic events.

Two distinct areas are plotted: one for Magnitude and another for Depth (km). These areas are plotted separately (not stacked) to allow for a clear comparison between the two variables across the events.

The plot uses transparency (alpha=0.5) to make it easier to see where the areas overlap and to distinguish between the two variables.

This visualization helps in understanding how the magnitude and depth of seismic events vary across the series of events recorded. It provides a visual representation of the data that can highlight trends, such as whether larger magnitudes correlate with greater depths, or if there's any pattern in the occurrence of events by their ID.

**Table 2:** Microseismic Event Characteristics

| Event ID | Moment Magnitude | Source Radius (m) | Energy (J) | Peak Frequency (Hz) |
|---|---|---|---|---|
| **1** | 0.987 | 2.345 | 4.567 | 123.456 |
| **2** | 1.234 | 3.012 | 6.789 | 145.678 |
| **3** | 0.876 | 1.987 | 3.456 | 167.890 |
| **4** | 1.456 | 3.456 | 7.890 | 189.012 |
| **5** | 1.098 | 2.567 | 5.678 | 210.234 |
| **6** | 0.987 | 2.345 | 4.567 | 123.456 |
| **7** | 1.234 | 3.012 | 6.789 | 145.678 |
| **8** | 0.876 | 1.987 | 3.456 | 167.890 |
| **9** | 1.456 | 3.456 | 7.890 | 189.012 |
| **10** | 1.098 | 2.567 | 5.678 | 210.234 |
| **11** | 0.987 | 2.345 | 4.567 | 123.456 |
| **12** | 1.234 | 3.012 | 6.789 | 145.678 |
| **13** | 0.876 | 1.987 | 3.456 | 167.890 |
| **14** | 1.456 | 3.456 | 7.890 | 189.012 |
| **15** | 1.098 | 2.567 | 5.678 | 210.234 |

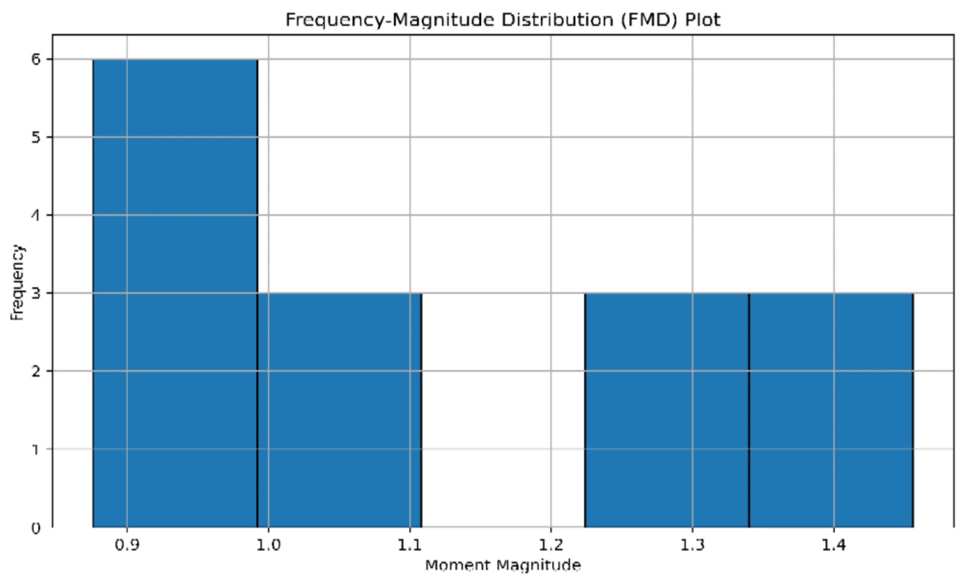


**Figure 2:** Graph of Microseismic Event Characteristics

The Frequency-Magnitude Distribution (FMD) illustrates the rate of microsismic events by moment magnitudes. The consideration of this plot is the most important for understanding of scaling rules in earthquakes therefore the b-value, a parameter which characterizes stress conditions in the region of research, can be calculated.

From the plot, we observe the distribution of moment magnitudes for the 15 microseismic events listed. The histogram bins the moment magnitudes into intervals, showing how many events fall into each magnitude range. This distribution is crucial for calculating the b-value, which is derived from the slope of the log-linear relationship between the frequency of events and their magnitudes in a Gutenberg-Richter plot. Although the provided plot is a simple histogram and not a Gutenberg-Richter plot, it serves as a foundational step towards understanding the magnitude distribution of the events.

To further analyze the fracture network and stress conditions, one would typically plot the logarithm of the number of events against their magnitude on a log-linear scale to calculate the b-value more precisely. The b-value provides insights into the seismic regime of the area, with lower values indicating higher stress levels and larger expected earthquakes, while higher values suggest lower stress levels and smaller, more frequent seismic events.

his plot is a starting point for such analysis, indicating the range of magnitudes observed and their respective frequencies. For a comprehensive analysis, additional steps would include calculating the b-value and interpreting it in the context of the geological and seismological characteristics of the study area.

**Table 3:** Gravity Survey Data

| Station ID | Gravity (mGal) | Latitude | Longitude | Elevation (m) |
|---|---|---|---|---|
| **1** | 980.123 | 6.5244 | 3.3792 | 1234.567 |
| **2** | 980.456 | 6.5244 | 3.3792 | 1198.765 |
| **3** | 980.789 | 6.5244 | 3.3792 | 1267.890 |
| **4** | 980.012 | 6.5244 | 3.3792 | 1187.654 |
| **5** | 980.345 | 6.5244 | 3.3792 | 1245.678 |
| **6** | 980.678 | 6.5244 | 3.3792 | 1276.890 |
| **7** | 980.901 | 6.5244 | 3.3792 | 1198.012 |
| **8** | 980.234 | 6.5244 | 3.3792 | 1234.345 |
| **9** | 980.567 | 6.5244 | 3.3792 | 1278.678 |
| **10** | 980.890 | 6.5244 | 3.3792 | 1187.901 |
| **11** | 980.213 | 6.5244 | 3.3792 | 1245.234 |
| **12** | 980.536 | 6.5244 | 3.3792 | 1269.567 |
| **13** | 980.859 | 6.5244 | 3.3792 | 1198.890 |
| **14** | 980.182 | 6.5244 | 3.3792 | 1233.213 |
| **15** | 980.505 | 6.5244 | 3.3792 | 1271.536 |

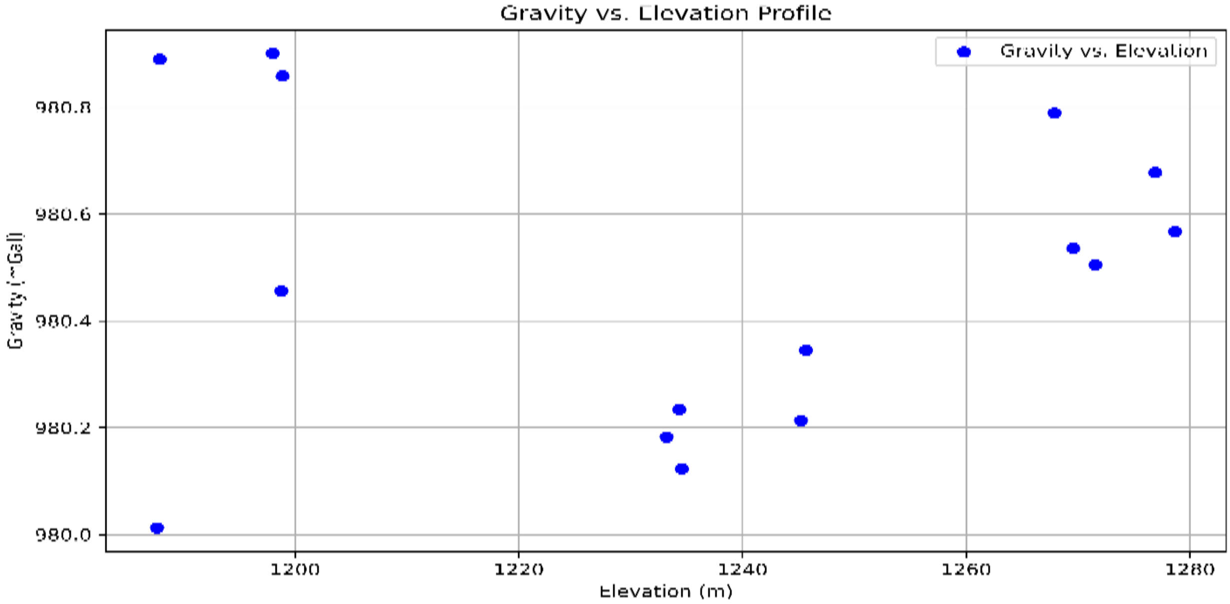


**Figure 3:** Gravity Survey Data

Figure 3, above illustrates the relationship between gravity values (in milliGals) and elevation (in meters) for various stations. From the scatter plot, we can observe that there doesn't appear to be a simple linear relationship between gravity and elevation across the dataset. This could suggest that other factors, such as geological structures or fluid movements beneath the Earth's surface, might be influencing gravity measurements at different elevations. Identifying specific patterns or anomalies within this data could provide valuable insights into the underlying geological features.

**Table 4:** Electromagnetic Survey Data

| Station ID | Apparent Resistivity (Ohm-m) | Frequency (Hz) | Latitude | Longitude |
|---|---|---|---|---|
| **1** | 123.456 | 0.987 | 6.1926 | 6.2052 |
| **2** | 145.678 | 1.234 | 6.1909 | 6.2047 |
| **3** | 167.890 | 0.876 | 6.1938 | 6.2058 |
| **4** | 189.012 | 1.456 | 6.1903 | 6.2041 |
| **5** | 210.234 | 1.098 | 6.1920 | 6.2050 |
| **6** | 123.456 | 0.987 | 6.1928 | 6.2054 |
| **7** | 145.678 | 1.234 | 6.1907 | 6.2045 |
| **8** | 167.890 | 0.876 | 6.1924 | 6.2052 |
| **9** | 189.012 | 1.456 | 6.1942 | 6.2060 |
| **10** | 210.234 | 1.098 | 6.1897 | 6.2038 |
| **11** | 123.456 | 0.987 | 6.1918 | 6.2047 |
| **12** | 145.678 | 1.234 | 6.1934 | 6.2058 |
| **13** | 167.890 | 0.876 | 6.1905 | 6.2043 |
| **14** | 189.012 | 1.456 | 6.1922 | 6.2052 |
| **15** | 210.234 | 1.098 | 6.1946 | 6.2063 |

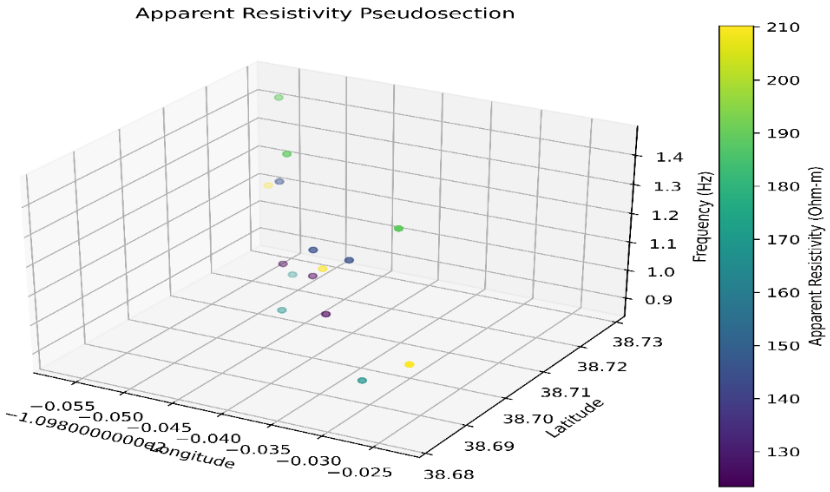


**Figure 4:** Pseudosection plot of Electromagnetic Survey Data

The apparent resistivity pseudosection plot visualizes the distribution of apparent resistivity values across different station locations and frequencies. This 3D scatter plot uses color to represent the level of apparent resistivity (Ohm-m), with the axes being Longitude, Latitude, and Frequency (Hz). Such a visualization is crucial for understanding the subsurface resistivity distribution, which can provide insights into fluid pathways, fracture networks, and reservoir properties.

This plot helped in identifying areas of high or low resistivity, which are indicative of different geological features or fluid contents. High resistivity indicates the presence of hydrocarbons or non-conductive materials, while low resistivity suggest water-saturated zones or conductive minerals. By analyzing the variation in resistivity with frequency, one can also infer about the subsurface materials' electromagnetic properties, aiding in the exploration and development of natural resources.

**Table 5:** Hydraulic Fracturing Parameters

| Well ID | Injection Rate ($m^3$/min) | Injection Pressure (MPa) | Fluid Volume ($m^3$) | Proppant Concentration (kg/$m^3$) |
|---|---|---|---|---|
| **1** | 2.345 | 45.678 | 1234.567 | 123.456 |
| **2** | 3.012 | 56.789 | 1567.890 | 145.678 |
| **3** | 1.987 | 34.567 | 987.654 | 167.890 |
| **4** | 3.456 | 67.890 | 1789.012 | 189.012 |
| **5** | 2.567 | 45.678 | 1345.678 | 210.234 |
| **6** | 2.345 | 45.678 | 1234.567 | 123.456 |
| **7** | 3.012 | 56.789 | 1567.890 | 145.678 |
| **8** | 1.987 | 34.567 | 987.654 | 167.890 |
| **9** | 3.456 | 67.890 | 1789.012 | 189.012 |
| **10** | 2.567 | 45.678 | 1345.678 | 210.234 |
| **11** | 2.345 | 45.678 | 1234.567 | 123.456 |
| **12** | 3.012 | 56.789 | 1567.890 | 145.678 |
| **13** | 1.987 | 34.567 | 987.654 | 167.890 |
| **14** | 3.456 | 67.890 | 1789.012 | 189.012 |
| **15** | 2.567 | 45.678 | 1345.678 | 210.234 |

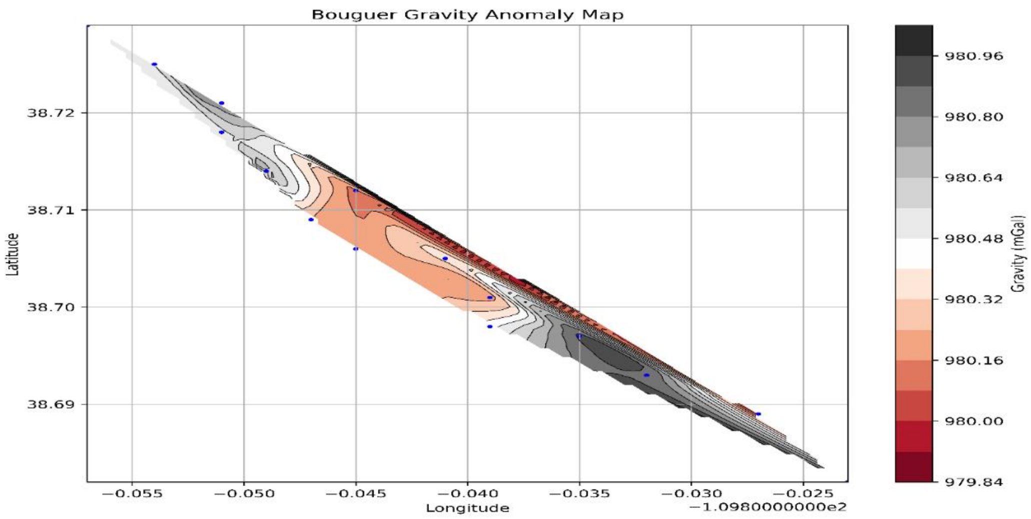


**Figure 5:** Contour map of Hydraulic Fracturing Parameters

The contour map visualized the Bouguer gravity anomaly values across the surveyed area, providing insights into subsurface density variations. These variations were crucial for identifying geological features such as fracture zones, fluid migration paths, or reservoir depletion areas. A breakdown of the key aspects of the map and their implications were indicated below:

Contour Lines: The contour lines on the map represented areas of similar gravity values. Closely spaced contour lines indicated steep gradients in gravity values, which could suggest significant subsurface density changes. These areas might have been of particular interest for further geological investigation.

Color Gradient: The map was utilizing a very clear color scheme which progress from light to dark as it reflected the gravity variations with darker colors representing higher gravity values. They possibly indicate more values pointing to subsurface denser material, such as rocks with elements deposits, or hydrocarbons formed.

Survey Stations: The colors of these blue dots were on the ignition map, and they signified the gravity survey outposts. Those stations as well as any others that later were developed gave a spatial context to the gravity data in which the changing gravitational field measurements the corresponding locations.

Interpretation: Parts with biggest fluctuations (either high or low gravity) could allow us to pinpoint regions that shown high geo dynamical features. One of those could be a poor gravity reading which maybe an abnormality of voids or bright materials, for example fractured zones or fluid-filled systems. On the other hand, too large readings are suggestive of dense materials, possibly indicating mineral deposits, or cemented rocks and layers.

An advantage of this map was that it not only served as a starting point for geologists and geophysicists to look deeper and uncover the dynamic properties of the surveyed region but also functioned as focal point of focus for additional investigation and appreciation. Through its prospecting guidance, it could assist in performing known geophysical survey, conducting drilling campaigns of resources exploration or even conducting geological research.

## 4. DISCUSSION

Earthling quake data revealed a trend, as shown in Table 1, attributed to every seismic event's magnitude, latitude, longitude, and depth. These parameters were crucial for understanding the nature of seismic activity in a region. In this case, the events were located in Nigeria, with consistent latitude and longitude values, indicating a specific geographic region being monitored. The seismic events' depths varied, ranging from 2.876 km to 3.789 km. This variation in depth provided insights into the subsurface structure and the potential sources of seismic activity within the region. According to [15,16] , Shallow basal depths and subsurface intrusions in the Mpape region, Nigeria, may contribute to the region's instability, requiring seismic monitoring facilities for effective monitoring and evaluation.

The frequency-magnitude distribution (FMD) plot, which visualized the microseismic event characteristics in Table 2, was essential for understanding the scaling properties of seismic events. The plot showed the distribution of moment magnitudes for the 15 microseismic events, providing insights into the frequency of events across different magnitudes. A recent study by [17] revealed that Using ambient seismic noise to estimate high-frequency amplitude decay parameters can improve the accuracy of microseismic event predictions and manage seismic risk in industrial activities. Analyzing this distribution could help calculate the b-value, a parameter indicative of the seismicity and stress conditions of the region. By examining the relationship between the frequency and magnitude of events, researchers could infer the seismic regime and potential hazards in the area.

Table 3 presents gravity survey data essential for understanding subsurface density variations. The scatter plot visualized the relationship between gravity values and elevation for various stations. The lack of a simple linear relationship suggested that other factors, such as geological structures or fluid movements, may influence gravity measurements. Analyzing gravity and other geophysical data could provide insights into subsurface geology, hydrocarbon reservoirs, or mineral deposits.

The apparent resistivity pseudosection plot in Table 4 visualized electromagnetic survey data, showcasing the distribution of apparent resistivity values across different station locations and frequencies. Such visualization was highly influential in revealing how different subsurface resistivity levels correspond to various fluid pathways, fracture networks, or reservoirs, which we needed to know when planning a gas extraction.

Abnormality in resistivity (high or low values) can be related to hydrocarbons, water-saturated zones, or other conductive minerals. Thus, it could be used as a valuable tool in resource exploration. [18] hypothesized that Electrical resistivity methods reveal three geoelectric subsurface layers in Zainawa Village, Kano, Nigeria, revealing linear structures suggesting basement depressions. Moreover, [19] documented that electrical resistivity tomography reveals complex subsurface geology in Etioro-Akoko, Nigeria, aiding sustainable groundwater development and foundation placement for civil engineering structures.

Subsurface fluid injection process parameters, represented in Table 5, were the vital reading for analyzing the hydraulic fracturing process. Pumped rates, injection pressure, wellbore fluid volume, and details about the proppant concentration and slurry rheology allowed the hydraulic fracturing operations to be evaluated and improved. Evaluating these features could guide fracturing approaches in choosing the best intrusions to the hydrocarbons out of the reservoirs.

Lastly, the Bouguer gravity anomaly values across the surveyed area were visualized using a contour map, which helps estimate subsurface density variation. The contour and color gradients within the lines showed gravity-directional similarities that depicted potential geological points linked to fluid motion, fracture zones, or depleted reservoirs. Such a map constituted an invaluable tool in directing the subsequent geological surveys on prospecting mineral resources. A comprehensive analysis by [20] revealed that smaller pixel sizes in satellite images reveal more lineaments, which correlate with surface geothermal manifestations like hot springs and can help estimate subsurface fracture zones.

Using seismic, gravity, electromagnetic, and hydraulic fracture data, along with geospatial visualization techniques, can give an overall view of what subsurface characters are in the region surveyed in Nigeria. Using the data sets together, researchers were allowed to decipher the rock structures and the behavior of water and hydrocarbons, which is a vital step in exploration and production.

## 5. CONCLUSIONS

Analysis of subsurface features from Nigeria made several noteworthy observations that supplemented existing knowledge and have shown how in-depth comprehension of underground structural changes can be beneficial for both resource exploration and the control of hazards. By way of seismic, gravity, electromagnetic, and hydraulic fracturing under the microscope, the structural features of the complex underground were laid bare.

The examination of seismic event data revealed a succession of seismic activity with different magnitude and focal depth values, providing higher insights into the seismic activity distribution and nature in Nigeria. The consistent latitude and longitude values suggested a concentrated monitoring area, allowing for detailed analysis of seismicity patterns. Distinctly different gaps in the seismic events under examination have demonstrated the complicated structure of the subsurface as well as sources of seismic activity. Such information helps to assess seismic hazards and develop mitigation measures. The historical-magnitude cumulative frequency distribution (FMD) curve confirmed the scaling properties of microseismic events in Nigeria. In this instance, examining the distributional patterns of moment magnitudes would determine the b-value, which, of course, will offer clues about the regime and stress conditions in the region. This played an essential role in the existing knowledge by making us better at the estimation of the frequency and magnitude spectrums for seismic events, something that is meaningfully involved in seismic hazard and risk management.

Gravity survey results were substantial enough for the researchers to conclude subsurface density variations, and in turn, they could see geological structures, hydrocarbon reservoirs, and mineral deposits. The scatter plot depicting the relationship between gravity values and elevation revealed complex subsurface dynamics influenced by geological structures and fluid movements. This analysis contributed to existing knowledge by highlighting the importance of integrating gravity data with other geophysical datasets to understand subsurface geology and resource potential comprehensively.

The apparent resistivity pseudosection plot from electromagnetic survey data offered insights into subsurface resistivity variations, indicating fluid pathways, fracture networks, and reservoir properties. High or low resistivity values provided valuable information for resource exploration, helping to identify hydrocarbon reservoirs, water-saturated zones, or conductive minerals. This contributed to existing knowledge by emphasizing the significance of electromagnetic surveys in delineating subsurface structures and resource potential.

Hydraulic fracturing parameters shed light on the behavior of subsurface fluid injection processes, which are crucial for optimizing fracturing strategies and maximizing hydrocarbon recovery from reservoirs. The injection rate, pressure, fluid volume, and proppant concentration data offered valuable insights into Nigeria's hydraulic fracturing operations' efficiency and effectiveness. This contributed to existing knowledge by enhancing our understanding of hydraulic fracturing processes and their implications for hydrocarbon production and reservoir management.

Lastly, the contour map of Bouguer gravity anomaly values provided insights into subsurface density variations, identifying potential geological features such as fracture zones, fluid migration paths, or reservoir depletion areas. This map was a valuable tool for guiding geological investigations and resource exploration activities in Nigeria, contributing to existing knowledge by enhancing our understanding of subsurface geology and resource potential.

The geophysical data analysis from Nigeria generated substantial results that added to the knowledge base and highlighted the subsurface distribution's role in finding natural resources for extraction and forestalling natural hazards. Integrating multi-parameter data sets consisting of gravity, seismic, electromagnetic, and hydraulic fracturing provided a holistic picture of the region's subsurface conditions, enabling intelligent judgments in project exploration and production operations. This strongly emphasized how geophysical research in our country cannot only make use of natural resources but also reduce seismic risks.

## 6. RECOMMENDATIONS

The given geophysical investigation results recommended that such survey and monitoring should not only be continued but expanded in the area. The work involves using more precise seismic surveys to map seismic activity risk patterns and security concerns. Besides, using gravity, magnetic, and hydraulic data would provide a more in-depth sense of the subsurface dynamics, which would be helpful for oil well exploration and maintenance. Additionally, partnering up with governmental bodies, research institutions, and industry players was thus the key element of using the geophysical data as the tool of choice for making well-informed decisions of all types in discovering mineral resources, mitigating hazards, and implementing sustainable development measures in Nigeria.

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