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MORALITY BEFORE KNOWLEDGE

A python-based application for automated very low frequency-electromagnetic data processing and subsurface interpretation

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ABSTRACT

Background: Very Low Frequency Electromagnetic (VLF-EM) method is widely applied in near-surface geophysical investigations for identifying subsurface structures such as fractures, faults, and conductive zones. However, the interpretation of VLF-EM data often requires complex processing steps and specialized software, which may limit efficiency and accessibility for field-based analysis. This study presents the development of a Python-based application designed for automated processing and interpretation of VLF-EM data to support subsurface structure identification. The application integrates several essential VLF-EM data processing stages, including data input, signal filtering, Fraser and Karous–Hjelt transformations, profile visualization, and subsurface pseudo-section generation. The system was developed using Python programming language and graphical user interface (GUI) components to enable user-friendly interaction and efficient data handling. Field VLF-EM data collected from Neheun area, Aceh Besar, were used to evaluate the performance of the proposed application. The processed data were analyzed to identify subsurface conductive anomalies associated with geological structures. The results demonstrate that the developed application is capable of producing clear and interpretable VLF-EM profiles and pseudo-sections, allowing effective identification of subsurface conductive zones. Automated processing significantly reduces manual interpretation time while maintaining consistency and reliability of results. The visualization outputs enhance the understanding of subsurface structures and support preliminary geological interpretation. In conclusion, the proposed Python-based application provides an effective and accessible tool for automated VLF-EM data processing and subsurface interpretation. Its flexibility, open-source environment, and integrated visualization features make it suitable for geophysical surveys and educational purposes. The novelty of this study lies in the integration of automated VLF-EM data processing and interpretation within a standalone Python-based application that simplifies analysis while preserving essential geophysical principles.

KEYWORDS: automated data processing; python-based application geophysic; very low frequency.

1. Introduction

Near-surface subsurface investigations play a critical role in a wide range of geoscientific applications, including geological mapping, groundwater exploration, environmental assessment, geotechnical engineering, and natural hazard mitigation.

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Accurate characterization of subsurface structures is essential for understanding geological processes and supporting safe infrastructure development, particularly in regions prone to seismic activity (Kearey et al., 2013; Reynolds, 2011). In tectonically active environments, subsurface heterogeneity associated with faults, fractures, and lithological contrasts can significantly influence ground stability and fluid migration, thereby increasing vulnerability to geological hazards (Telford et al., 1990).

Indonesia is recognized as one of the most seismically active regions in the world due to its location at the convergent boundary between the Indo-Australian Plate and the Eurasian Plate. This tectonic configuration results in intense deformation, frequent earthquakes, and complex geological structures along the Sunda subduction zone and associated strike-slip fault systems (Handayani & Harjono, 2020). The northern part of Sumatra, including the Aceh region, is strongly affected by these tectonic processes and has experienced numerous damaging earthquakes in both historical and recent times (Muzli et al., 2018; Idris et al., 2019).

Aceh Besar Regency represents a critical area within this tectonic framework due to the presence of active fault systems, particularly the Seulimeum Fault. Seismological investigations indicate that this fault is capable of generating shallow earthquakes that pose significant risks to local communities and infrastructure (Muksin et al., 2022). In addition to active tectonics, the geological setting of Aceh Besar is characterized by diverse lithological units, including sedimentary formations, volcanic rocks, limestone, and weathered materials of varying electrical properties (Bennet et al., 1982; Ploethner & Siemon, 2005). These conditions contribute to strong lateral and vertical heterogeneity in subsurface electrical conductivity, making geophysical investigation both challenging and necessary.

Among various near-surface geophysical techniques, the Very Low Frequency Electromagnetic (VLF-EM) method has been widely applied as an effective reconnaissance tool for identifying shallow conductive structures. The VLF-EM method utilizes electromagnetic waves transmitted by powerful radio transmitters operating in the very low frequency range, typically between 15 and 30 kHz (Cheng, 1989). When these waves interact with the subsurface, they induce secondary electrical currents within conductive bodies such as fault zones, fracture networks, clay-rich layers, and water-saturated rocks (McNeill & Labson, 1991). The resulting electromagnetic response is measured at the surface in the form of in-phase and quadrature components, which reflect variations in subsurface conductivity (Reynolds, 2011).

Due to its passive operation, rapid data acquisition, and minimal logistical requirements, the VLF-EM method is particularly suitable for surveys conducted in areas with difficult access, dense vegetation, or rugged topography (Bosch & Müller, 2001). Consequently, VLF-EM has been successfully applied in a wide range of studies, including fault and fracture detection, groundwater exploration, karst investigations, environmental monitoring, and archaeological surveys (Rajab, 2020; Yadi et al., 2017). Despite these advantages, VLF-EM data interpretation remains challenging because raw measurements are often affected by cultural noise, topographic effects, and complex subsurface conditions that can obscure geological signals (Telford et al., 1990).

To improve the interpretability of VLF-EM data, several filtering and transformation techniques have been developed. One of the most widely used methods is the Fraser filter, which enhances lateral conductivity contrasts by transforming in-phase data and emphasizing anomaly locations along survey profiles (Fraser, 1969). Building upon this approach, the Karous–Hjelt transformation provides a more advanced technique for converting filtered VLF-EM data into pseudo-sections that approximate the subsurface distribution of equivalent current density or conductivity with depth (Karous & Hjelt, 1983). These pseudo-sections enable qualitative interpretation by visualizing conductive and resistive zones in a two-dimensional framework that is intuitive and informative for geological analysis (Rajab, 2020).

Although Fraser and Karous–Hjelt filtering techniques are well established in the literature, practical implementation of VLF-EM data processing often relies on manual workflows or proprietary software. Such workflows typically involve multiple processing stages, including data formatting, filtering, interpolation, visualization, and interpretation, often using separate software packages (Bosch & Müller, 2001). This fragmented approach can be time-consuming, susceptible to user-dependent errors, and difficult to apply consistently, particularly for users with limited experience in geophysical data analysis.

Recent developments in open-source scientific computing environments have created new opportunities for improving geophysical data processing workflows. Python, in particular, has become increasingly popular in the geosciences due to its extensive ecosystem of numerical, visualization, and data analysis libraries, as well as its support for graphical user interface development (Van Rossum & Drake, 2009). Python-based tools promote transparency, reproducibility, and adaptability, which are essential attributes in modern scientific research and education. However, despite the growing use of Python in geophysical modeling and data analysis, dedicated applications for automated VLF-EM data processing and interpretation remain relatively limited.

In the context of Aceh Besar, most previous studies have focused on seismological analysis and regional tectonic characterization, while near-surface electromagnetic investigations are still scarce. Furthermore, existing VLF-EM studies often prioritize interpretation results without addressing the efficiency and accessibility of the data processing workflow itself. This gap highlights the need for an integrated, user-friendly, and automated solution that can streamline VLF-EM data processing while maintaining adherence to established geophysical principles.

Therefore, this study aims to develop a Python-based application for automated Very Low Frequency Electromagnetic (VLF-EM) data processing and subsurface interpretation. The proposed application integrates essential processing steps within a single platform, including CSV data input, signal filtering using Moving Average, Fraser, and Karous–Hjelt methods, data interpolation, two-dimensional pseudo-section visualization, and automated preliminary interpretation based on average conductivity values at different depth zones. The system is designed with a graphical user interface to enhance usability and reduce technical barriers associated with conventional data processing workflows.

Field VLF-EM data acquired from the Neheun area, Aceh Besar, are used to evaluate the performance of the developed application. The study assesses the capability of the application to generate clear and interpretable pseudo-sections that reveal subsurface conductive anomalies associated with geological features such as fractures, fault zones, and water-saturated materials. By automating the processing and interpretation stages, this approach aims to reduce analysis time, improve consistency, and minimize subjective bias in VLF-EM data interpretation (Kearey et al., 2013).

The novelty of this research lies in the integration of automated VLF-EM data processing and preliminary subsurface interpretation within a standalone, open-source Python-based application. Unlike conventional workflows that rely on multiple software tools and extensive manual intervention, the proposed system offers an end-to-end solution that simplifies analysis while preserving scientific rigor. This study is expected to contribute to the development of more efficient and accessible geophysical tools for near-surface investigations, particularly in tectonically active regions.

2. Methods

2.1 Study area and data acquisition

The VLF-EM dataset utilized in this study was acquired in the Neheun area, Aceh Besar Regency, Aceh Province, Indonesia. This region is situated within a highly active tectonic setting governed by the interaction of major strike-slip and secondary fault systems associated with the Great Sumatran Fault. One of the most significant geological structures influencing the study area is the Seulimeum Fault, a northwest–southeast trending active fault that has been identified through geological mapping, geomorphological observations, and seismological analysis (Muksin et al., 2018; Muzli et al., 2018). The presence of this fault system has resulted in intense deformation, fracture development, and heterogeneous subsurface conditions that are particularly favorable for electromagnetic investigations.

Recent tectonic studies indicate that active fault zones in Aceh are characterized by increased fracture density, enhanced porosity, and elevated groundwater circulation, all of which contribute to distinct electrical conductivity contrasts detectable by electromagnetic methods (Muksin et al., 2022; Idris et al., 2019). Lithologically, the Neheun area comprises a complex assemblage of volcanic rocks, altered volcanic deposits, sedimentary units, and unconsolidated alluvial materials. These lithologies exhibit diverse electromagnetic responses depending on mineral composition, degree of weathering, and fluid content (Reynolds, 2011). In particular, weathered volcanic rocks and water-saturated alluvial deposits are expected to exhibit higher conductivity relative to unaltered bedrock units.

The selection of the Neheun area as the study site is therefore justified by both its geological complexity and its relevance to seismic hazard mitigation and near-surface subsurface characterization. Recent geophysical investigations emphasize that tectonically active environments provide an ideal testbed for evaluating automated processing and interpretation frameworks, as they present realistic challenges such as strong lateral heterogeneity and noise-prone datasets (Alao et al., 2024; Zhang et al., 2025). Consequently, this area offers an appropriate context for assessing the performance and robustness of the proposed Python-based automated VLF-EM data processing system.

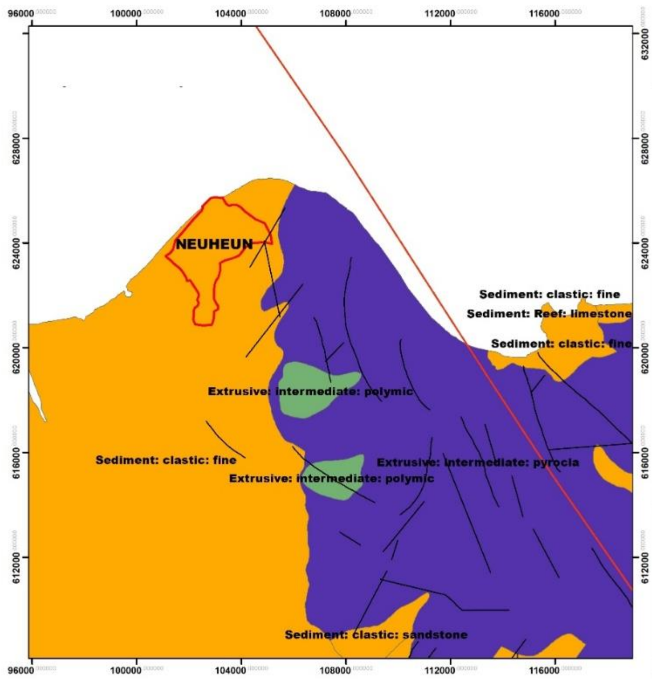

Fig. 1. Research location

The geological framework of the Neuheun area in Mesjid Raya, Aceh Besar, is characterized by a complex interplay of tectonic activity and diverse lithological formations, primarily influenced by its proximity to the Sumatran Fault Zone (SFZ). Strategically located within the Banda Aceh Geological Sheet, the region's stratigraphy is dominated by two major units: Quaternary Alluvium (Qh) and the Lam Kabeue Formation. The lower-lying coastal areas consist of Alluvium deposits, which include unconsolidated materials such as gravel, sand, and silt, often associated with high groundwater potential but prone to seismic amplification. Conversely, the hilly topography surrounding the Neuheun housing complexes is composed of older, more competent rocks, including tuffaceous sandstone, calcareous shale, and localized limestone outcrops, which provide a distinct geophysical signature compared to the surrounding sediments.

From a structural perspective, Neuheun is geologically significant due to the influence of the Seulimeum Segment, one of the active branches of the Sumatran Fault. This tectonic setting has resulted in a high density of secondary structures, such as fractures, joints, and minor fault splays, which significantly alter the subsurface resistivity and conductivity. These structural features act as primary conduits for fluid migration or as accumulation zones for conductive minerals, making the area an ideal natural laboratory for VLF-EM surveys. The undulating terrain, ranging from coastal flats to steep volcanic-sedimentary hills, creates a varied overburden thickness that requires the precise filtering and depth-estimation techniques such as those described in Figure 3 to accurately map the underlying geological hazards or natural resources.

2.2 VLF-EM data acquisition strategy

The Very Low Frequency Electromagnetic (VLF-EM) method exploits electromagnetic signals transmitted by powerful radio transmitters operating in the very low frequency range, typically between 15 and 30 kHz. These signals propagate through the Earth and induce secondary electrical currents within conductive subsurface structures. The interaction between the primary electromagnetic field and these induced currents generates secondary magnetic fields, which can be measured at the surface to infer subsurface conductivity variations (McNeill & Labson, 1991; Reynolds, 2011).

In this study, VLF-EM data were collected using a portable VLF-EM receiver capable of recording both the in-phase and quadrature components of the electromagnetic field. The survey design prioritized profile orientations that intersect suspected geological structures, such as faults and fracture zones, at angles close to perpendicular. This acquisition geometry maximizes anomaly amplitude and enhances the detectability of conductive features, as demonstrated in recent VLF-EM field studies conducted in structurally complex terrains (Alao et al., 2024; Desifatma et al., 2024).

Measurements were acquired at regular station intervals along each survey line to ensure adequate spatial sampling and resolution. Station spacing was selected based on expected target depth and the wavelength of the transmitted signal, following established VLF-EM survey design principles (Telford et al., 1990). To reduce the influence of cultural noise, measurements were conducted away from major infrastructure such as power lines and metallic structures whenever possible. Field protocols were standardized to maintain consistent sensor orientation, measurement timing, and environmental conditions. All acquired data were stored digitally and exported in tabular format, subsequently converted into CSV files to facilitate seamless integration with the automated Python-based processing system.

2.3 Data preprocessing and quality control

Raw VLF-EM data are inherently susceptible to various sources of noise and uncertainty, including cultural electromagnetic interference, instrument instability, and environmental effects. As a result, data preprocessing and quality control constitute essential components of the methodological framework. Within the developed application, preprocessing routines are automatically executed upon data import to ensure numerical consistency and reliability prior to filtering and interpretation. The preprocessing workflow includes completeness verification, station spacing validation, and statistical outlier detection. Missing values and irregular station intervals are automatically identified and flagged. Depending on the severity of the issue, incomplete datasets may either be corrected through interpolation or excluded from subsequent processing stages. Outlier detection is performed using threshold-based statistical criteria derived from the mean and standard deviation of the dataset, allowing identification of anomalous values that may result from transient electromagnetic disturbances or measurement errors (Akin & Arisoy, 2025)

Recent methodological studies emphasize that systematic preprocessing significantly improves the reliability and interpretability of VLF-EM data, particularly when advanced transformations such as pseudo-section modeling are applied (Desifatma et al., 2024; Mendoza Veirana et al., 2024). By embedding these quality control procedures within an automated workflow, the developed application ensures consistent treatment of all datasets while minimizing subjective user intervention. This approach enhances reproducibility and reduces the likelihood of interpretation bias.

2.4 Application development and automation framework

The automated VLF-EM data processing system was developed using the Python programming language, selected for its flexibility, open-source nature, and extensive ecosystem of scientific computing libraries. Numerical operations are handled using NumPy, while data management and manipulation are performed using Pandas. Visualization of processed data is implemented using Matplotlib, which enables the generation of high-quality two-dimensional profiles and pseudo-sections suitable for publication (Hunter, 2007). A graphical user interface (GUI) was developed to facilitate user interaction with the application. The GUI allows users to import data, select processing parameters, apply filters, and visualize results without requiring direct interaction with the underlying code. This design significantly lowers the technical barrier for users with limited programming experience and supports efficient field-based or educational applications (Fauzi, 2017).

The automation framework integrates multiple processing stages into a unified workflow, including data import, preprocessing, Fraser filtering, Karous–Hjelt transformation, smoothing, interpolation, and visualization. Automation reduces manual intervention, minimizes processing time, and ensures consistent application of algorithms across multiple datasets. The modular architecture of the application allows individual processing components to be modified or expanded, enabling future integration of advanced techniques such as quantitative inversion or machine-learning-assisted interpretation (Zhang et al., 2025).

2.5 Karous–Hjelt Pseudo-Section modeling

Following application of the Fraser filter, the Karous–Hjelt (K–H) transformation is employed to generate two-dimensional pseudo-sections that approximate the subsurface distribution of equivalent current density with depth. The K–H method redistributes surface electromagnetic anomalies into a series of depth levels using weighted summation, producing a qualitative image of subsurface conductive structures (Karous & Hjelt, 1983).
Although pseudo-sections do not represent true depth inversions, they remain a widely accepted interpretative tool for reconnaissance-level investigations. Recent studies reaffirm that K–H pseudo-sections provide valuable insights into the geometry, continuity, and relative depth extent of conductive features, particularly in environments where data density or survey constraints limit the application of full inversion techniques (Alao et al., 2024; Zhang et al., 2025). In this study, the K–H transformation is discretized into multiple depth levels corresponding to increasing penetration depth. The resulting pseudo-section matrices are stored and visualized using consistent scaling and color mapping to facilitate comparison across survey lines. While full electromagnetic inversion is beyond the scope of this research, the adopted K–H framework provides a robust qualitative foundation compatible with future methodological enhancements.

2.6 Noise reduction and moving average smoothing

To further enhance data interpretability, a moving average smoothing filter is optionally applied to both filtered VLF-EM profiles and pseudo-section data. This technique reduces high-frequency noise by averaging values within a user-defined window, thereby emphasizing coherent geological features while suppressing random fluctuations. The selection of smoothing window size represents a balance between noise reduction and spatial resolution preservation. Excessive smoothing may obscure narrow conductive features, whereas insufficient smoothing may fail to suppress noise. Recent computational geophysics research advocates adaptive and user-controlled smoothing strategies, particularly when processing heterogeneous datasets with variable noise characteristics (Mendoza Veirana et al., 2024). In the developed application, smoothing parameters can be adjusted interactively through the GUI, allowing users to tailor processing to specific survey conditions and objectives.

2.7 Interpretation and validation

Discrete VLF-EM measurements must be interpolated to generate continuous profiles and pseudo-sections suitable for interpretation. Spatial interpolation estimates intermediate values between measurement points, enhancing the visual coherence of subsurface features. In this study, interpolation and visualization are performed using Matplotlib, enabling generation of publication-quality figures with customizable color scales, annotations, and legends. Recent visualization studies highlight the importance of consistent color mapping and scale normalization to avoid misinterpretation of electromagnetic anomalies (Mendoza Veirana et al., 2024). Accordingly, standardized visualization parameters are implemented within the application to ensure comparability across datasets and survey lines.

2.8 Interpretation and validation

Processed VLF-EM profiles and pseudo-sections are interpreted to identify subsurface conductive anomalies. Anomalies characterized by significant amplitude contrasts, spatial coherence, and continuity across depth levels are interpreted as potential geological structures such as fracture zones, fault planes, or water-saturated materials. Interpretation follows established VLF-EM principles emphasizing anomaly symmetry, lateral extent, and correlation between filtered profiles and pseudo-sections (Reynolds, 2011). Validation of the automated processing results is conducted through qualitative comparison with theoretical expectations of VLF-EM responses and consistency across survey lines. The agreement between Fraser-filtered profiles and K–H pseudo-sections provides confidence in the reliability of the automated workflow.

2.9 Interpretation and validation

A key contribution of this study is the integration of an automated qualitative interpretation framework within the processing workflow. The framework computes average conductivity values within predefined depth intervals extracted from K–H pseudo-sections. Based on empirically established conductivity ranges, subsurface zones are classified into conductive, moderately conductive, and resistive categories (Palacky, 1988). ecent trends in electromagnetic data analysis emphasize the growing role of semi-automated and machine-assisted interpretation approaches, particularly for preliminary assessment of large datasets (Zhang et al., 2025). While the present framework remains qualitative, it provides a systematic and reproducible means of initial interpretation that supports objective decision-making and guides further detailed investigations.

3. Results and Discussion

3.1 Software development and functionality results

The processed VLF-EM profiles obtained from the Neheun survey area reveal significant lateral variations in the in-phase component, indicating strong contrasts in subsurface electrical conductivity. After preprocessing and filtering, the profiles exhibit distinct anomalies characterized by both positive and negative peaks, which are commonly associated with conductive geological structures such as fracture zones, faults, and water-saturated materials (Fraser, 1969; Reynolds, 2011). The Fraser-filtered profiles show enhanced anomaly localization compared to the raw in-phase data. Several prominent anomalies are consistently observed along the survey lines, suggesting the presence of laterally continuous conductive zones. These anomalies are particularly pronounced in sections where abrupt changes in signal amplitude occur over short distances, a characteristic often attributed to fault-controlled fracture systems (Bosch & Müller, 2001; Alao et al., 2024). The spatial consistency of these anomalies across adjacent profiles indicates that they are unlikely to be artifacts of noise or cultural interference, but rather reflect genuine subsurface features.

Recent VLF-EM studies conducted in tectonically active environments demonstrate that fault-related conductive anomalies commonly manifest as narrow, high-amplitude features aligned with known or inferred fault traces (Desifatma et al., 2024). The observed anomaly patterns in the Neheun area exhibit similar characteristics, supporting their interpretation as zones of enhanced conductivity associated with structural discontinuities. The ability of the automated Python-based system to clearly delineate these features confirms the effectiveness of the preprocessing and filtering framework applied in this study.

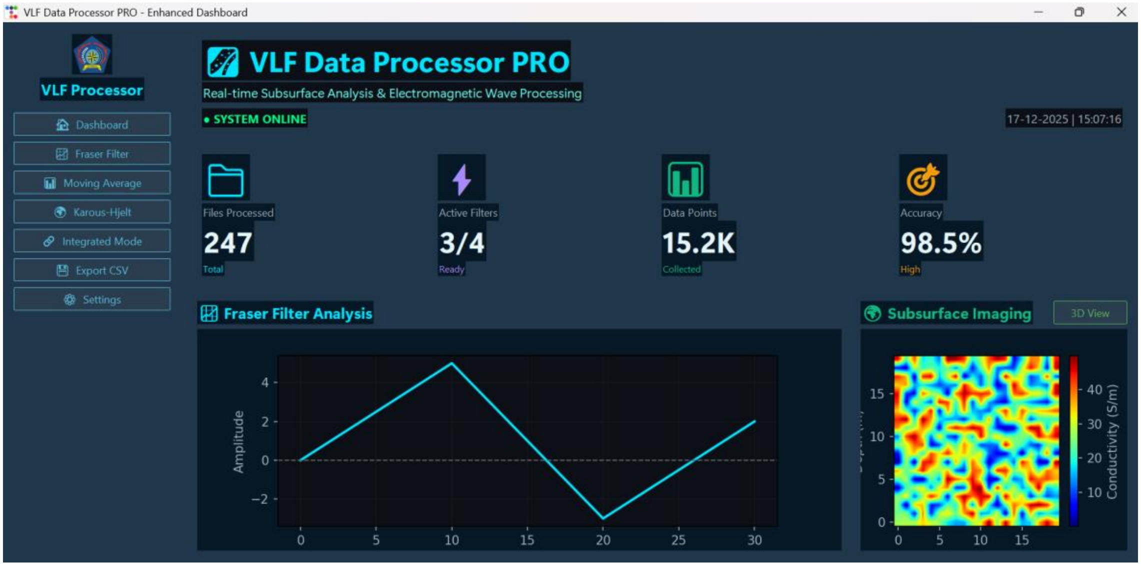

Fig. 2. Graphical user interface (GUI)

Figure 2 illustrates the Enhanced Dashboard interface of the VLF Data Processor PRO, which serves as the main graphical user interface (GUI) for automated processing and interpretation of Very Low Frequency Electromagnetic (VLF-EM) data. The dashboard is designed to provide users with real-time system status monitoring, processing summaries, and preliminary visualization of electromagnetic responses in a single integrated environment. At the top of the interface, the application title *"VLF Data Processor PRO – Enhanced Dashboard"* is displayed along with the subtitle *"Real-time Subsurface Analysis & Electromagnetic Wave Processing"*. This section emphasizes the system's capability to perform near-real-time processing and analysis of VLF-EM data. The "SYSTEM ONLINE" indicator confirms that all core processing modules and dependencies are functioning properly at the time of operation. Additionally, the timestamp displayed on the upper-right corner provides a record of the system's operational time, supporting traceability and reproducibility during data analysis sessions.

The left-side navigation panel provides structured access to the main functional modules of the application. These include:

- Dashboard, which displays overall system performance and data summaries;
- Fraser Filter, dedicated to lateral anomaly enhancement of VLF-EM data;
- Moving Average, which applies noise reduction through smoothing operations;
- Karous–Hjelt, used for generating subsurface pseudo-sections;

- Integrated Mode, which combines multiple filters and transformations in a single workflow;
- Export CSV, allowing processed data to be saved for external analysis;
- Settings, where users can configure processing parameters.

This modular design improves usability and allows users to execute specific processing tasks efficiently without navigating complex workflows. The Fraser Filter Analysis panel presents a line plot illustrating the filtered VLF-EM response along a survey profile. The horizontal axis represents station positions, while the vertical axis indicates signal amplitude after Fraser filtering. This visualization highlights lateral conductivity contrasts and facilitates the identification of anomalous zones commonly associated with faults, fractures, or conductive lithologies. The clear presentation of positive and negative peaks supports rapid qualitative interpretation and comparison with subsurface pseudo-sections.

On the right side of the dashboard, the Subsurface Imaging panel displays a color-coded two-dimensional conductivity map derived from processed VLF-EM data. The color scale represents variations in electrical conductivity (S/m), with warmer colors indicating more conductive zones and cooler colors representing resistive materials. This visualization provides an intuitive overview of subsurface heterogeneity and complements the profile-based analysis shown in the Fraser Filter panel. The option for 3D View further suggests extensibility toward more advanced visualization techniques.

Overall, the dashboard demonstrates the effectiveness of integrating data processing, visualization, and preliminary interpretation within a single automated platform. By presenting key metrics, filtered profiles, and subsurface images simultaneously, the VLF Data Processor PRO enhances processing efficiency, reduces user-dependent bias, and supports reproducible electromagnetic data analysis. This integrated interface represents a significant improvement over traditional multi-software workflows commonly used in VLF-EM studies.

3.2 VLF-EM data processing and interpretation results

The Karous–Hjelt (K–H) pseudo-sections generated from the filtered VLF-EM data provide a two-dimensional qualitative representation of subsurface conductivity distribution with depth. The pseudo-sections reveal several vertically and laterally coherent conductive zones extending from near-surface levels to greater pseudo-depths. These conductive features are represented by high equivalent current density values and are spatially correlated with anomalies identified in the Fraser-filtered profiles. In the shallow depth levels, conductive zones are interpreted as weathered or unconsolidated materials with elevated moisture content, consistent with the geological setting of the Neheun area (Reynolds, 2011). At greater pseudo-depths, vertically elongated conductive anomalies suggest the presence of fracture or fault zones that facilitate groundwater circulation. Such features are commonly identified in VLF-EM pseudo-sections as sub-vertical conductive structures extending across multiple depth levels (Karous & Hjelt, 1983; Rajab, 2020).

Recent studies emphasize that while K–H pseudo-sections do not represent true depth inversions, they remain highly effective for reconnaissance-level investigations and preliminary structural interpretation (Alao et al., 2024; Zhang et al., 2025). In this study, the consistency between surface profile anomalies and subsurface pseudo-section features enhances confidence in the reliability of the results. The automated generation of pseudo-sections ensures uniform processing parameters across datasets, reducing subjective bias and improving interpretational consistency. between the filtered profiles and pseudo-section patterns supports the reliability of the automated data processing and interpretation results.

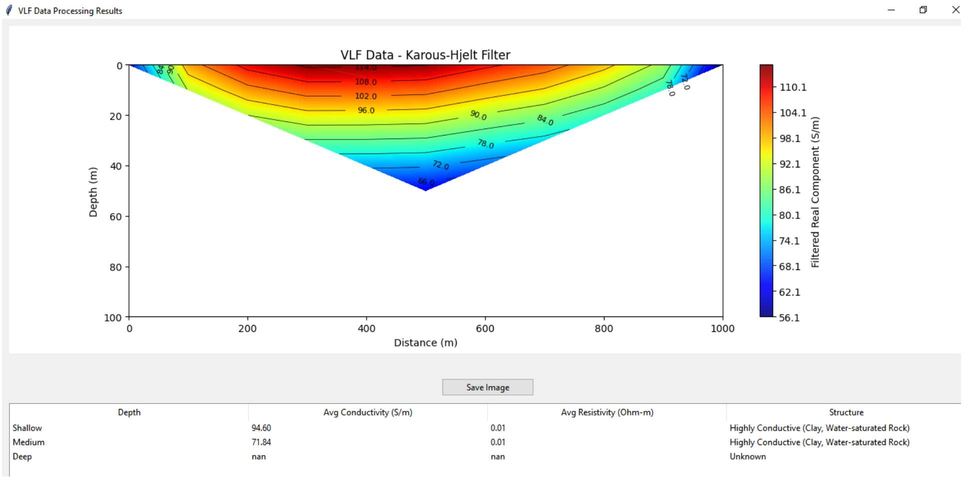

Fig. 3. Results of Karous-Hjelt filter contour visualization

Figure 3 illustrates the operational workflow of the developed Python-based application for VLF-EM data processing, structured as a systematic flowchart. The process begins with the Start node, leading into the Input Data stage where users upload raw field measurements, including distance, in-phase, and quadrature components. The core of the application lies in the subsequent processing sequence, which starts with a Moving Average Filter to suppress high-frequency noise and smooth the signal. This is followed by two critical geophysical transformations: the Fraser Filter, which converts zero-crossing anomalies into peak values for easier identification of conductive structures, and the Karous-Hjelt Filter, which calculates the equivalent current density distribution to provide depth information.

The final stages of the flowchart focus on visualization and data management. Once the mathematical transformations are complete, the system generates a Profile Visualization to display 2D graphs of the filtered data and a Pseudo-section to map the subsurface conductivity variations. The workflow concludes with a Save Result option, allowing users to export the processed plots and numerical data for further geological interpretation, before reaching the End of the operation. This structured approach highlights the application's ability to automate complex manual calculations into a streamlined, user-friendly graphical interface.

3.3 Effectiveness of noise reduction and smoothing

The application of moving average smoothing significantly improves the clarity of both VLF-EM profiles and pseudo-sections. Prior to smoothing, high-frequency fluctuations attributable to environmental noise and instrumental variability are evident in certain sections of the data. After smoothing, coherent geological features become more prominent, while random noise is effectively suppressed. However, careful selection of smoothing parameters is crucial to avoid excessive attenuation of narrow conductive features. In this study, moderate smoothing windows were found to provide an optimal balance between noise reduction and spatial resolution preservation. This finding aligns with recent research highlighting the importance of adaptive smoothing strategies in near-surface electromagnetic data processing (Mendoza Veirana et al., 2024).

The interactive control of smoothing parameters within the developed application allows users to visually assess the impact of filtering in real time. This capability represents a significant advantage over conventional static processing workflows and supports informed decision-making during interpretation. The results demonstrate that smoothing, when applied judiciously, enhances interpretability without compromising geological fidelity.

3.4 Geological implications of interpreted conductive anomalies

A distinctive feature of this study is the implementation of an automated qualitative interpretation framework based on average conductivity values extracted from K–H pseudo-sections. The framework classifies subsurface zones into conductive, moderately conductive, and resistive categories according to empirically established conductivity ranges (Palacky, 1988). This classification provides a systematic basis for preliminary interpretation and reduces reliance on subjective visual assessment alone.

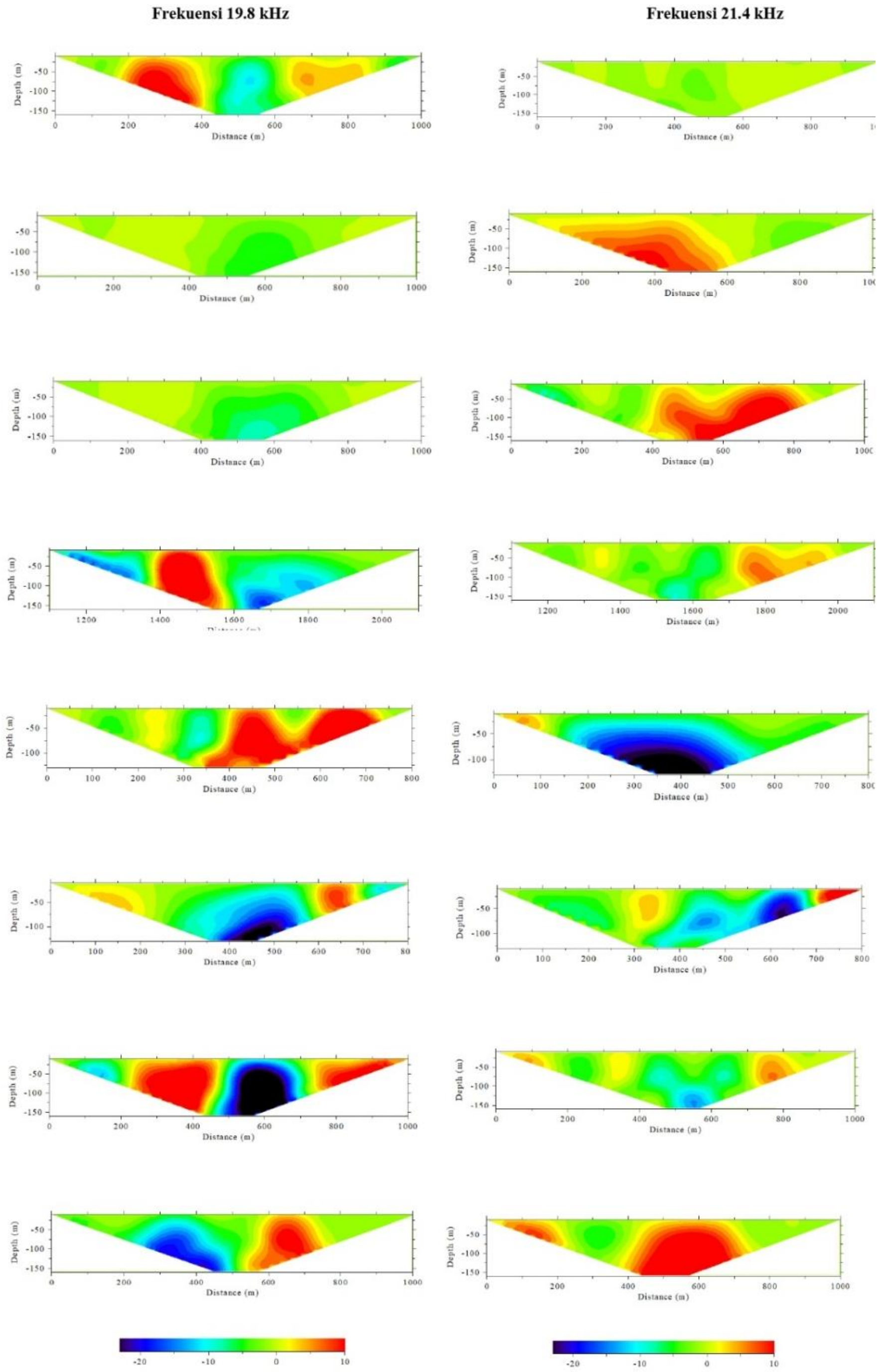

Fig. 4. Data processing using Karous-Hjelt filtering with frequencies of 19.8 kHz and 21.4 kHz for paths 1 to 8

The automated interpretation results indicate that several conductive zones are concentrated at shallow to intermediate pseudo-depths, consistent with the presence of fractured and water-saturated materials. These zones are spatially aligned with known tectonic structures in the Aceh Besar region, particularly those associated with the Seulimeum Fault system (Muksin et al., 2022). The correspondence between automated classification and geological expectations reinforces the validity of the proposed approach. Recent advancements in geophysical data analysis advocate the integration of automated or semi-automated interpretation techniques to improve efficiency and reproducibility, especially in studies involving large or complex datasets (Zhang et al., 2025). While the present framework remains qualitative, it represents an important step toward more objective and standardized VLF-EM interpretation workflows.

The VLF-EM pseudo-sections generated through the automated processing workflow (Section 3.2) reveal pronounced lateral and vertical variations in subsurface conductivity across the survey lines. High-conductivity zones, indicated by warm color anomalies, are consistently observed at intermediate distances along several profiles and extend to depths of approximately 100–150 m. These coherent and continuous anomalies are interpreted as subsurface conductive structures, most likely associated with fractured zones, fault-related features, or weathered materials with elevated fluid content. In contrast, low-conductivity regions represented by cooler color tones are interpreted as relatively resistive and more competent rock units. The sharp conductivity contrasts between conductive and resistive zones suggest the presence of subsurface structural boundaries, supporting the geological implications discussed in Section 3.4. The spatial alignment and persistence of conductive anomalies across multiple profiles further indicate that these features are structurally controlled rather than artifacts of noise or surface effects.

Variations in anomaly geometry observed at different operating frequencies reflect changes in depth of investigation, where lower frequencies exhibit deeper and broader responses, while higher frequencies emphasize shallower and more localized features. This behavior is consistent with the theoretical characteristics of the VLF-EM method and confirms the reliability of the automated data processing approach implemented in the developed application. Overall, the integration of automated VLF-EM data processing with subsurface interpretation enhances the clarity and consistency of anomaly identification. The results demonstrate that the developed Python-based application effectively supports the detection of geologically meaningful conductive structures, providing valuable preliminary insights into the subsurface conditions of the study area.

3.5 Geological implications

The results of this study provide valuable insights into the subsurface structure of the Neheun area. The identified conductive anomalies are interpreted as fracture and fault-related zones that likely play a critical role in groundwater flow and mechanical weakness within the subsurface. In tectonically active regions, such zones are commonly associated with increased seismic hazard and ground instability (Handayani & Harjono, 2020). The alignment of conductive anomalies with regional tectonic trends supports the interpretation that the observed features are structurally controlled rather than purely lithological.

Similar relationships between VLF-EM anomalies and active fault systems have been reported in recent studies conducted in comparable geological settings (Desifatma et al., 2024; Alao et al., 2024). These findings highlight the utility of VLF-EM methods for rapid structural mapping in seismic-prone regions. Furthermore, the identification of shallow conductive zones has implications for groundwater exploration and environmental assessment. Fractured and water-bearing zones detected through VLF-EM surveys may serve as potential groundwater pathways or reservoirs, underscoring the multi-disciplinary relevance of the method (Rajab, 2020).

3.6 Performance of the automated Python-Based system

The developed Python-based application demonstrates strong performance in terms of processing efficiency, usability, and interpretational clarity. By integrating data import, preprocessing, filtering, visualization, and interpretation within a single platform, the system significantly reduces analysis time compared to traditional multi-software workflows. The graphical user interface enhances accessibility for users with limited programming expertise, facilitating broader adoption in academic, educational, and field-based contexts. The automation of key processing steps ensures consistent application of algorithms and parameters, thereby improving reproducibility. These advantages align with recent trends in geophysical research emphasizing open-source, transparent, and reproducible computational frameworks (Hunter, 2007; Zhang et al., 2025). Despite these strengths, certain limitations should be acknowledged. The interpretation remains qualitative and relies on pseudo-section approximations rather than full electromagnetic inversion. Future studies may address this limitation by incorporating quantitative inversion algorithms or machine-learning-assisted interpretation modules to further enhance analytical rigor.

3.7 Comparison with previous studies

When compared with previous VLF-EM investigations in similar tectonic environments, the results of this study exhibit strong methodological and interpretational consistency. Studies conducted in faulted terrains consistently report conductive anomalies associated with fracture zones and groundwater pathways, as observed in the Neheun area (Bosch & Müller, 2001; Alao et al., 2024). However, the primary distinction of this study lies in its emphasis on automation and integration. Unlike many prior investigations that rely on manual or proprietary processing tools, the proposed approach offers an end-to-end, open-source solution that enhances efficiency and accessibility. This contribution addresses a recognized gap in the current VLF-EM literature and aligns with contemporary directions in computational geophysics (Zhang et al., 2025).

4. Conclusions

This study successfully developed and implemented an automated Python-based application for Very Low Frequency Electromagnetic (VLF-EM) data processing and qualitative subsurface interpretation. By integrating data preprocessing, Fraser filtering, Karous–Hjelt pseudo-section modeling, noise reduction, visualization, and automated interpretation within a single graphical user interface, the proposed system significantly improves processing efficiency, consistency, and accessibility. The application effectively addresses limitations of conventional VLF-EM workflows that rely on fragmented, manual, or proprietary software tools.

Application of the developed system to VLF-EM data from the Neheun area, Aceh Besar, demonstrates its capability to clearly identify lateral and vertical conductivity anomalies associated with near-surface geological structures. Fraser-filtered profiles successfully highlight lateral conductivity contrasts, while Karous–Hjelt pseudo-sections provide coherent qualitative representations of subsurface conductive zones. These results suggest the presence of fracture- and fault-related structures, consistent with the known tectonic framework of the Seulimeum Fault system and previous geophysical investigations in the region.

The automated qualitative interpretation framework further enhances objectivity by classifying subsurface zones based on average conductivity values extracted from pseudo-sections. This approach reduces user-dependent bias and supports reproducible preliminary interpretation, making the system particularly suitable for reconnaissance surveys, educational purposes, and rapid field-based assessments in tectonically active environments. The high level of automation and user-friendly interface enables efficient analysis even for users with limited geophysical or programming experience.

Despite its demonstrated effectiveness, the present study remains limited to qualitative interpretation based on pseudo-section analysis. Future research should focus on integrating quantitative electromagnetic inversion techniques, multi-method geophysical data fusion, and machine-learning-assisted interpretation to further enhance analytical rigor and interpretational accuracy. Nevertheless, the proposed VLF Data Processor PRO represents a practical and robust contribution to near-surface electromagnetic investigations, offering an open, flexible, and reproducible platform for VLF-EM data analysis in complex geological settings.

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Author Contribution

The author made substantial contributions to the conception and design of the work, the acquisition, analysis, and interpretation of the VLF-EM data, the development of the Python-based application, and the drafting and substantive revision of the manuscript. The supervisor contributed to the scientific guidance, critical review, and direction of the research. All contributors approved the final version of the manuscript submitted for publication and agree to be accountable for all aspects of the work.

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Not applicable.

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Not applicable.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available due to their use in an ongoing academic research project.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Declaration of Generative AI Use

During the preparation of this work, the author used generative artificial intelligence tools to help slightly improve the software being developed.

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