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Integrated GPR and electrical resistivity imaging for shallow fault detection in a tectonically active region: A case study in Bali, Indonesia

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ABSTRACT

Bali Island is located within a tectonically active region influenced by the convergence of the Indo-Australian and Eurasian plates, making it highly susceptible to seismic hazards. One area with potential fault activity is Bangli Regency. This study aims to identify subsurface fault structures using an integrated geophysical approach combining Ground Penetrating Radar (GPR) and dipole–dipole electrical resistivity methods. Data were acquired along four survey lines in Lembean, Tembuku, Belantih, and Sukawana villages. Secondary geological data from the Geological Survey Center were also incorporated. The resistivity data were processed using RES2DINV, while GPR data were analyzed using ReflexW 7.1. The results reveal indications of fault-related anomalies in Belantih, Lembean, and Sukawana. In Belantih, GPR detected anomalies at a distance of 301 m with depths ranging from 1–6 m, while resistivity results indicated anomalies at 51 m with a depth of 20.2 m. In Lembean, anomalies were identified at 290 m with depths of 1–5 m from GPR data and at 144 m with a depth of 11.8 m from resistivity analysis. In Sukawana, GPR results showed a potential fault structure at 590 m with depths up to 8 m; however, this could not be validated by resistivity data due to acquisition errors. No significant fault-related anomalies were detected in Tembuku. These findings demonstrate the effectiveness of integrating GPR and electrical resistivity methods for shallow subsurface fault identification and provide important insights into local seismic risk assessment in Bangli Regency.

1. Introduction

Indonesia is situated within one of the most tectonically active regions in the world, characterized by complex interactions among several major lithospheric plates, including the Indo-Australian, Eurasian, and Pacific plates. This tectonic configuration forms part of the Pacific Ring of Fire and results in frequent seismic and volcanic activities across the archipelago. Bali Island, located in the central part of Indonesia, lies along the Sunda Arc, where the Indo-Australian Plate subducts beneath the Eurasian Plate. This geodynamic setting makes Bali particularly vulnerable to seismic hazards, including earthquakes associated with both subduction zones and crustal fault systems [1, 2].

While subduction-related earthquakes are often well recognized due to their large magnitudes and regional impacts, shallow crustal faults pose a different but equally important hazard. These faults can generate localized but destructive earthquakes, often with limited warning and significant ground shaking intensity. In many cases, such faults are not well mapped, particularly in regions where surface expressions are subtle or obscured by vegetation and human activities. Therefore, identifying and characterizing shallow subsurface fault structures is crucial for improving seismic hazard assessment and supporting disaster risk reduction strategies [3–5].

Bangli Regency, located in the central part of Bali Island, represents one of the regions with potential tectonic activity that has not been comprehensively investigated. Geological maps indicate the presence of structural lineaments that may correspond to fault zones; however, their precise locations, geometries, and depths remain poorly constrained. Given the increasing population density and infrastructure development in this region, understanding the subsurface fault distribution becomes increasingly important [6, 7]. Conventional geological mapping alone is often insufficient to detect buried or inactive faults, particularly in areas covered by volcanic deposits or thick soil layers [8–10].

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Geophysical methods provide an effective and non-invasive approach for investigating subsurface structures. Among these, Ground Penetrating Radar (GPR) and electrical resistivity methods are widely used for near-surface imaging due to their high resolution and sensitivity to subsurface contrasts. GPR is particularly effective in detecting shallow discontinuities and stratigraphic variations by analyzing the propagation and reflection of high-frequency electromagnetic waves. It is capable of providing detailed images of subsurface features at depths typically up to several meters, depending on the subsurface conditions [3, 11].

On the other hand, electrical resistivity methods, especially the dipole–dipole configuration, are well suited for mapping variations in subsurface electrical properties, which can be related to lithological changes, fractures, and fluid content. Resistivity imaging can penetrate deeper than GPR and is effective in identifying structural features such as faults, fractures, and zones of weakness. The dipole–dipole array, in particular, offers good lateral resolution and is sensitive to vertical structures, making it suitable for fault detection studies [12, 13].

Although both GPR and resistivity methods have been widely applied independently in geophysical investigations, each method has its own limitations. GPR performance is highly dependent on the electrical conductivity of the subsurface; in highly conductive materials, signal attenuation can significantly reduce penetration depth. Conversely, resistivity methods may suffer from lower resolution in very shallow layers and ambiguities in interpretation due to non-uniqueness of inversion results [6, 14, 15]. Therefore, integrating these two methods can provide complementary information, combining the high-resolution imaging capability of GPR with the deeper penetration and structural sensitivity of resistivity measurements [4, 16].

Several previous studies have demonstrated the effectiveness of integrated geophysical approaches for fault detection and subsurface characterization. However, such integrated studies remain limited in the context of Bali Island, particularly in Bangli Regency. Most existing studies in the region have focused on volcanic processes or regional tectonics, with relatively little emphasis on shallow fault identification using high-resolution geophysical techniques. This gap highlights the need for detailed, site-specific investigations that can reveal hidden fault structures and contribute to local-scale seismic hazard assessments [17, 18].

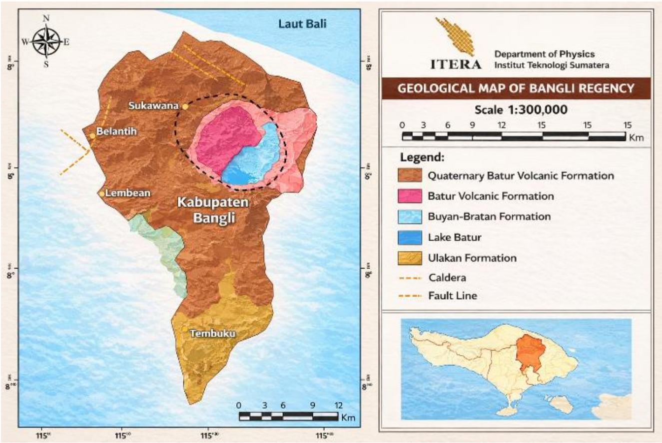

Fig. 1. Geological map of Bali Island, Indonesia.

The present study aims to address this gap by applying an integrated geophysical approach combining GPR and dipole–dipole electrical resistivity methods to identify shallow subsurface fault structures in Bangli Regency, Bali. Data acquisition was conducted along four survey lines located in Lembean, Tembuku, Belantih, and Sukawana villages. These locations were selected based on geological indications of potential structural features and accessibility for field measurements. In addition, secondary geological data from the Geological Survey Center were incorporated to support interpretation and validation [19–21].

The specific objectives of this study are: (1) to image the shallow subsurface structure using GPR and resistivity methods, (2) to identify and characterize anomalies that may indicate the presence of fault structures, and (3) to evaluate the effectiveness of integrating these methods for fault detection in a tectonically active volcanic region. The resistivity data were processed using RES2DINV to obtain two-dimensional subsurface resistivity models, while GPR data were processed using ReflexW 7.1 to enhance signal clarity and interpret subsurface reflections [3, 6, 16].

The novelty of this research lies in the integration of high-resolution GPR data with dipole–dipole resistivity imaging in a relatively underexplored tectonic setting. By combining these complementary methods, this study provides a more comprehensive understanding of shallow fault structures compared to single-method approaches. Furthermore, the results contribute to improving the geological knowledge of Bangli Regency and offer valuable insights for local seismic hazard assessment and land-use planning [3, 11].

Ultimately, this study is expected to demonstrate that integrated geophysical methods can serve as a reliable and efficient tool for detecting shallow subsurface faults in complex geological environments. The findings not only have implications for the study area but also provide a methodological framework that can be applied to similar tectonically active regions worldwide [6, 14, 15].

Recent seismic records from the Meteorology, Climatology, and Geophysics Agency (BMKG) Region III indicate that Bali and its surrounding areas experienced significant seismic activity during 2020. A total of 5,840 earthquake events were recorded, with the majority characterized by low magnitudes (M < 3) and shallow focal depths (h ≤ 60 km), accounting for 3,478 events. The highest frequency of seismic activity occurred in August, with 942 recorded events, predominantly located in the Sumba region. Overall, low-magnitude earthquakes (M ≤ 3) dominated the seismicity pattern, reaching 4,060 events, while shallow earthquakes (h ≤ 60 km) accounted for 4,999 events [4, 16]. These data highlight the high level of microseismic activity in the region, which may reflect ongoing tectonic deformation and stress accumulation.

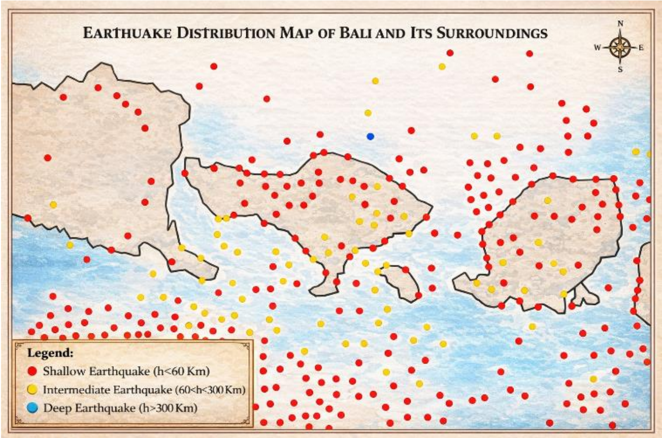

Fig. 2. The spatial distribution of earthquake occurrences around Bali.

Fig. 2 Illustrate the spatial distribution of earthquake occurrences in Bali and its surrounding regions, providing insight into the regional seismicity pattern. Although many of these earthquakes are small in magnitude, their frequency indicates active tectonic processes that may be associated with both regional subduction dynamics and local crustal fault systems. Earthquakes are natural phenomena that occur due to the sudden release of energy within the Earth's crust, generating seismic waves that propagate to the surface. They are most commonly associated with tectonic processes, particularly in regions located along the so-called "Ring of Fire," where intense interactions between tectonic plates take place. Indonesia, extending from Sumatra to Papua, lies within this seismically active belt, making it highly vulnerable to earthquake hazards [17, 18].

In general, earthquakes are primarily caused by the sudden movement of the Earth's crust along fault planes, where accumulated stress exceeds the strength of rocks, resulting in rupture and displacement. This process generates seismic waves that can cause ground shaking and potential damage at the surface. Although tectonic faulting is the dominant mechanism, earthquakes can also be triggered by other natural processes such as volcanic eruptions, landslides, and, in rare cases, meteor impacts or anthropogenic activities. However, most destructive earthquakes are related to tectonic movements along active fault systems.

Understanding the distribution and characteristics of seismic activity is therefore essential for identifying active fault zones and assessing seismic hazards. In regions such as Bali, where both subduction-related and crustal earthquakes coexist, distinguishing between these sources becomes particularly important. High-frequency, low-magnitude, and shallow-depth earthquakes may serve as indicators of near-surface fault activity that is not always visible at the surface.

2. Method

2.1. Study area and data acquisition

This study was conducted between January 2021 and August 2022 using secondary geophysical data provided by the Geological Survey Center, Ministry of Energy and Mineral Resources, Indonesia. The dataset was originally acquired during field surveys conducted between May and July 2014 in Bangli Regency, Bali.

Geographically, Bangli Regency is located at coordinates 08°03′40″–08°50′48″ S and 114°25′53″–115°42′40″ E. The study area is characterized by complex geological conditions influenced by volcanic activity and tectonic deformation associated with the Sunda Arc system. Four survey lines were selected across different locations, namely Belantih, Lembean, Sukawana, and Tembuku, based on geological indications of potential structural features. The spatial distribution of the survey lines is presented in Fig. 1.

This study utilized two types of geophysical data: First, ground penetrating radar (GPR) data, consisting of radargram recordings that represent electromagnetic wave reflections in the subsurface. The second method is electrical resistivity data, obtained using a dipole–dipole array configuration, representing subsurface resistivity variations. Both datasets were obtained as secondary data from the Geological Survey Center (2014) and reprocessed in this study to identify potential fault structures in the study area.

For GPR data were processed using ReflexW 7.1 software to obtain high-resolution subsurface images. The processing workflow included several standard steps:

1. Time-zero correction, to align the first arrival of the electromagnetic wave.
2. Dewow filtering, to remove low-frequency noise components.
3. Gain application (energy decay correction), to compensate for signal attenuation with depth.
4. Bandpass filtering, to eliminate high-frequency noise and enhance signal clarity.

These processing steps were applied sequentially to improve signal-to-noise ratio and to produce clear radargram sections suitable for interpretation. The processed radargrams represent subsurface reflection patterns associated with stratigraphic boundaries and structural discontinuities.

While the electrical resistivity data were initially provided in .stg format and converted into .dat format using EarthImager 2D software to ensure compatibility with RES2DINV. The processed data were then inverted using a least-squares inversion algorithm implemented in RES2DINV to generate two-dimensional subsurface resistivity models.

To improve data quality, noisy or inconsistent data points were identified and removed prior to inversion. The inversion process was iteratively performed until the root mean square (RMS) error was reduced to below 5%, ensuring reliable model convergence. Additionally, logarithmic transformation of apparent resistivity values was applied to enhance model stability and resolution. The final output consists of resistivity sections representing subsurface structures and lithological contrasts.

2.2. Data integration and interpretation

Interpretation of subsurface structures was carried out using both qualitative and quantitative approaches by integrating GPR and resistivity results with regional geological information. GPR data were interpreted based on reflection patterns, signal discontinuities, and amplitude variations, which may indicate subsurface structural features such as fractures or faults.

Resistivity data were analyzed based on contrasts in resistivity values, which are associated with changes in lithology, porosity, and fluid content. Potential fault structures were identified by correlating anomalies observed in both datasets. Structural features were interpreted where consistent anomalies appeared across multiple datasets and aligned with regional geological trends. The integration of both methods allowed for improved confidence in identifying shallow subsurface fault structures [14, 22, 23].

3. Results and discussion

3.1. Fault identification in the study area

Geophysical surveys were conducted in Bangli Regency, Bali, using two complementary methods: Ground Penetrating Radar (GPR) and electrical resistivity with a dipole–dipole configuration. The acquired datasets were processed using ReflexW 7.1 for GPR data and RES2DINV for resistivity data to generate subsurface images in the form of radargrams and resistivity sections, respectively. The processed results were subsequently analyzed to identify potential fault structures by integrating geophysical anomalies with the regional geological framework. Particular attention was given to discontinuities in reflection patterns (GPR) and contrasts in resistivity values, which may indicate structural features such as fractures or fault zones.

Table 1
Stratigraphy of the study area

Age	Sub-Age	Formation	Lithological Column	Geological Description
Quaternary	Holocene	Buyan–Bratan and Batur Volcanic Group	■	Lava, tuff, and volcanic breccia
Quaternary	Holocene	Batur Volcanic Formation	■	Agglomerate, lava, tuff, and minor lava from ongoing Batur volcanic activity
Quaternary	Pleistocene	Ancient Buyan–Bratan Volcanic Group	■	Breccia, lava, and tuff
Tertiary	Early Miocene	Ulakan Formation	■	Breccia, lava, tuff, and intercalated carbonate sedimentary rocks

The geological setting of the study area plays a crucial role in supporting the interpretation. Based on regional stratigraphic information (Table 1), the study area is dominated by Quaternary (Holocene) volcanic deposits. These deposits are primarily associated with the Buyan–Bratan and Batur volcanic systems, consisting of lava, tuff, and volcanic breccia. Such lithological compositions are known to exhibit heterogeneous physical properties, which can significantly influence geophysical responses. The identification of fault structures was therefore carried out by correlating geophysical anomalies with the expected geological conditions. Potential fault zones are interpreted where consistent anomalies are observed in both GPR and resistivity data, particularly in areas showing disrupted stratification, abrupt lateral changes, or zones of contrasting resistivity. This integrated approach enhances the reliability of fault detection and reduces interpretation ambiguity associated with single-method analysis.

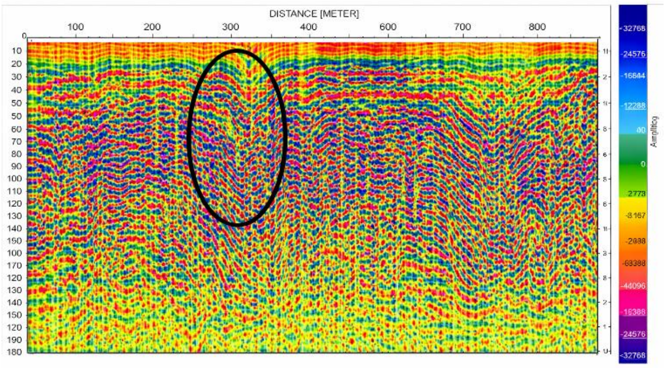

Fig. 3. Subsurface cross-section using the GPR method in Belantih village.

Geophysical measurements in Belantih Village, Kintamani District, were conducted along a survey line extending from coordinates 8°13′52.6″ S, 115°15′33.7″ E to 8°13′42.1″ S, 115°15′33.2″ E. The total survey length for the Ground Penetrating Radar (GPR) profile was approximately 900 m, while the electrical resistivity survey covered a shorter profile of 150 m using a dipole–dipole configuration with an electrode spacing of 3 m.

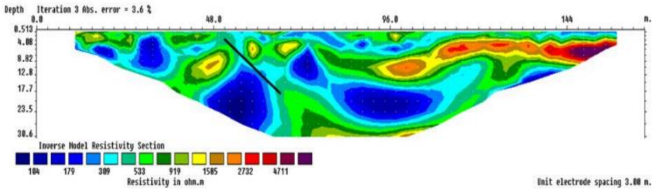

Fig. 4. Subsurface cross-section using geophysical methods Belantih village.

The subsurface imaging results were obtained through the processing of GPR data using ReflexW 7.1, producing radargram sections that reveal shallow subsurface features (Fig. 3). In addition, the resistivity data were processed using RES2DINV to generate two-dimensional resistivity sections representing deeper subsurface conditions (Fig. 4). These complementary datasets provide detailed information on subsurface structures, enabling the identification of potential discontinuities and anomalies associated with fault zones in the study area [24].

Based on the processed GPR data in Belantih Village (Fig. 3), a clear subsurface discontinuity is observed at approximately 301 m along the survey line, with depths ranging from 1 to 6 m. This feature is characterized by disrupted reflection patterns and contrast variations, which are indicative of a potential fault structure. To verify this interpretation, an electrical resistivity survey was conducted across the suspected zone. The resistivity profile was positioned starting at approximately 250 m along the GPR line, corresponding to the location where the anomaly was identified.

The resistivity section (Fig. 4) reveals significant variations in subsurface resistivity values. Low-resistivity zones range from approximately 104 to 1,584 Ωm, while high-resistivity zones range from 1,585 to 4,711 Ωm. Based on regional geological information, the low-resistivity values are interpreted as tuff and volcanic breccia, whereas the high-resistivity values are associated with more compact volcanic rocks, such as lava flows. This interpretation is consistent with the regional stratigraphy of Belantih, which is dominated by Quaternary (Holocene) volcanic deposits.

A distinct anomaly interpreted as a fault structure is identified at a distance of approximately 51 m along the resistivity profile, extending to a depth of about 20.2 m. This feature is characterized by a sharp resistivity contrast between zones of 309–919 Ωm and 1,585–2,732 Ωm. Such a contrast suggests the presence of a structural discontinuity, where a relatively weak, low-resistivity zone intersects and disrupts higher-resistivity layers. The consistency between the shallow anomaly detected by GPR and the deeper resistivity contrast strengthens the interpretation of a fault zone in this area. This integrated geophysical evidence indicates the presence of a subsurface structural feature that may play a role in local tectonic activity.

The second survey line is located in Lembean village, Kintamani District, Bangli Regency, extending from coordinates 8°17′25.0″ S, 115°16′23.3″ E to 8°17′22.1″ S, 115°16′16.5″ E. The GPR survey was conducted along a profile length of approximately 850 m, while the electrical resistivity survey covered a 200 m profile using a dipole–dipole configuration with an electrode spacing of 4 m.

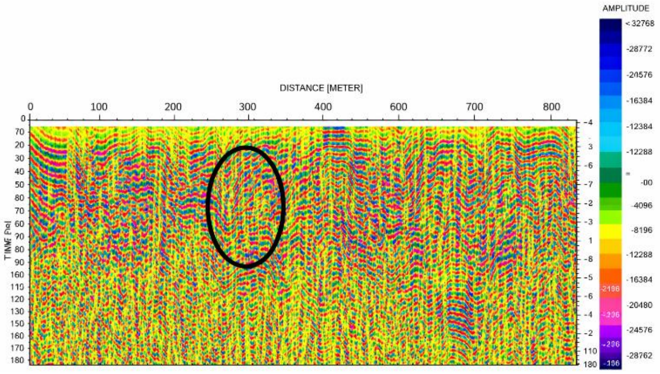

Fig. 5. Subsurface cross-section using the GPR method in Lembean village.

The GPR data, processed using ReflexW (Fig. 5), reveal a distinct subsurface discontinuity at approximately 290 m along the profile, with depths ranging from 1 to 5 m. This anomaly is characterized by disrupted reflection patterns and lateral inconsistencies, suggesting the presence of a potential shallow fault structure. To validate this interpretation, an electrical resistivity survey was conducted across the anomalous zone. The resistivity profile was initiated at approximately 146 m along the GPR line, corresponding to the location of the identified GPR anomaly.

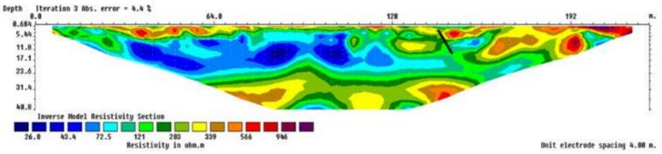

Fig. 6. Subsurface cross-section using geophysical methods Lembean village.

The resulting resistivity section (Fig. 6) shows significant variation in subsurface resistivity values. Low-resistivity zones range from approximately 26 to 338 Ωm, while higher resistivity values range from 339 to 946 Ωm. Based on regional geological conditions, the low-resistivity zones are interpreted as tuff and volcanic breccia, whereas the higher resistivity zones are associated with more consolidated volcanic materials, such as lava. This interpretation is consistent with the stratigraphy of Lembean, which is dominated by Quaternary (Holocene) volcanic deposits.

A prominent anomaly interpreted as a fault structure is identified at a distance of approximately 144 m along the resistivity profile, extending to a depth of about 11.8 m. This feature is marked by a clear resistivity contrast between zones of 203–338 Ωm and 339–566 Ωm. Such contrasts indicate the presence of a structurally weak zone with lower resistivity that disrupts adjacent higher-resistivity layers. The correlation between shallow anomalies detected by GPR and deeper resistivity contrasts provides strong evidence for the presence of a subsurface fault in the Lembean area. This integrated interpretation enhances the reliability of fault identification and highlights the effectiveness of combining GPR and resistivity methods in complex volcanic terrains.

The third survey line is located in Tembuku district, Bangli Regency, extending from coordinates 8°27′38.2″ S, 115°22′58.8″ E to 8°27′27.0″ S, 115°22′59.6″ E. The GPR survey covered a profile length of approximately 920 m, while the electrical resistivity survey extended 300 m using a dipole–dipole configuration with an electrode spacing of 6 m. The resistivity profile was initiated at approximately 420 m along the GPR line. The processed subsurface sections from GPR and resistivity data are presented in Fig. 7 and Fig. 8, respectively.

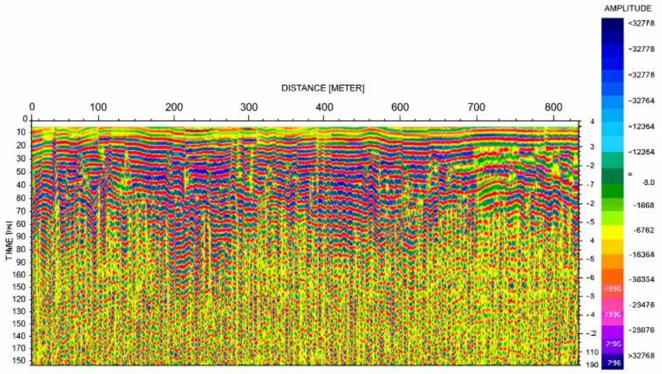

Fig. 7. Subsurface cross-section using the GPR method in Tembuku village.

The GPR results (Fig. 7) do not show significant subsurface discontinuities or reflection anomalies that would indicate the presence of a fault structure. The radargram is characterized by relatively continuous and parallel reflection patterns, suggesting a stratigraphically uniform subsurface. This condition is consistent with relatively stable geological settings, where deformation is minimal and dominated by gentle subsidence or folding rather than faulting.

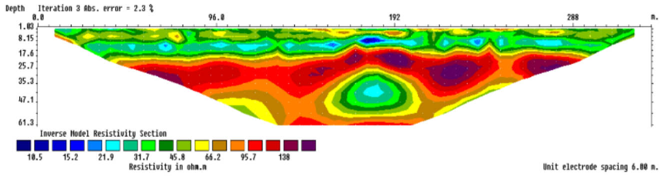

Fig. 8. Subsurface cross-section using geophysical methods Tembuku village.

Similarly, the resistivity section (Fig. 8) does not reveal any clear structural discontinuities associated with fault zones. Instead, the subsurface is characterized by gradual lateral variations in resistivity values, reflecting lithological heterogeneity rather than structural disruption. The resistivity values range from approximately 10.5 to 66.1 Ωm for low-resistivity zones and from 66.1 to 138 Ωm for higher-resistivity zones.

Based on regional geological interpretation, the low-resistivity zones are associated with tuff deposits, while the higher-resistivity zones likely correspond to volcanic breccia. These interpretations are consistent with the regional stratigraphy, which is dominated by Quaternary (Holocene) volcanic formations. The absence of consistent anomalies in both GPR and resistivity datasets indicates that no significant fault structures are present along the investigated profile in Tembuku. This result highlights the importance of integrating multiple geophysical methods to avoid misinterpretation and to confidently distinguish between structural features and lithological variations.

The fourth survey line is located in Sukawana village, Kintamani District, Bangli Regency, extending from coordinates 8°13′3.3″ S, 115°18′18.7″ E to 8°12′15.6″ S, 115°18′23.3″ E, with a total profile length of approximately 900 m. The subsurface investigation at this site was conducted using the Ground Penetrating Radar (GPR) method, and the data were processed using ReflexW 7.1. The resulting radargram section is presented in Fig. 9. The processed GPR data (Fig. 9) reveal a distinct subsurface anomaly at approximately 590 m along the profile, extending from shallow depths of around 0.5 m to approximately 8 m. This feature is characterized by disrupted and discontinuous reflection patterns, which are commonly associated with structural disturbances such as fault zones.

The interpretation is further supported by the regional geological context, where the study area is dominated by Quaternary (Holocene) volcanic deposits. In such environments, structural discontinuities observed in GPR profiles are often indicative of faulting or fracturing within heterogeneous volcanic materials. However, unlike the other survey locations, the interpretation in Sukawana is based solely on GPR data, as electrical resistivity measurements were not available due to data acquisition limitations. This absence of complementary resistivity data introduces a degree of uncertainty in confirming the identified anomaly as a fault structure. Therefore, while the GPR results strongly suggest the presence of a shallow subsurface discontinuity, further investigation using additional geophysical methods is recommended to validate this interpretation.

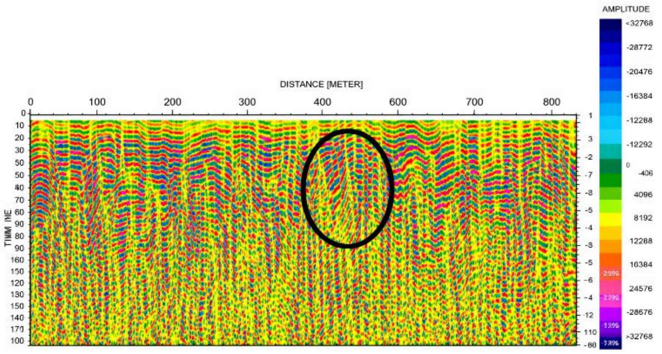

Fig. 9. Subsurface cross-section using the GPR method in Sukawana village.

3.2. *Regional seismicity and tectonic implications*

Following the integration and interpretation of GPR and electrical resistivity data, the presence of subsurface structural features, interpreted as fault zones, can be identified along several survey lines in Bangli Regency, Bali. These findings are consistent with the regional tectonic setting of Bali, which is strongly influenced by the interaction between major lithospheric plates. Bali Island is located in close proximity to the convergent boundary between the Indo-Australian Plate and the Eurasian Plate. This tectonic interaction forms part of the Sunda subduction system, which is responsible for significant seismic activity in the region. In addition to subduction-related processes in the southern part of Bali, the northern region is influenced by a back-arc thrust system, which further contributes to crustal deformation and seismic hazard.

The northern part of Bali, including Bangli Regency, is therefore considered a seismically active zone. Earthquake characteristics in this region are generally dominated by shallow events with relatively high occurrence frequencies, accounting for approximately 60% of recorded seismicity. Such shallow earthquakes are often associated with crustal faulting, which aligns with the subsurface anomalies identified in this study.

Historical earthquake records further support the high seismic vulnerability of the Bangli region. One of the most significant events is the "Gejer Bali" earthquake in 1815, which resulted in approximately 10,253 fatalities. More recent events include earthquakes recorded in 1981 and 1986 in the northwestern area near Banjar Wangsian, both with magnitudes of approximately 4.3. Additional seismic activity was recorded on March 11, 2011 (M 4.9), located approximately 24 km east of Munduk, followed by another event on March 21, 2017 with a magnitude of 4.0.

These historical and instrumental records indicate that Bangli Regency experiences recurring seismic activity, reinforcing its classification as a high-risk area. The spatial distribution of past earthquake events is illustrated in Fig. 10. The consistency between regional seismicity patterns, geological conditions, and geophysical anomalies identified in this study suggests that the detected subsurface structures may represent active or potentially active fault systems. These findings highlight the importance of detailed subsurface investigations for improving seismic hazard assessment and supporting risk mitigation strategies in tectonically active regions such as Bali. [20, 21, 25].

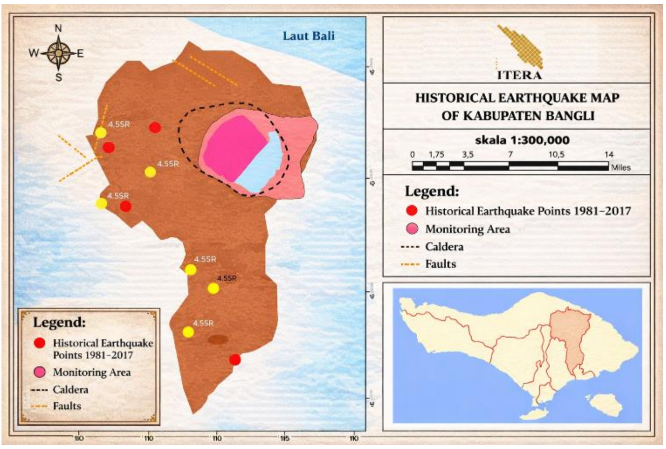

Fig. 10. Spatial distribution of recorded earthquakes distribution in Bangli Regency (1981–2017).

The regional geological evolution of Bali began during the Early Miocene, characterized by marine depositional environments that produced breccia interbedded with limestone and pillow lava. In the southern part of the island, carbonate deposition dominated, forming the Southern Formation, while finer-grained sediments accumulated along its northern margins. By the late Pliocene, these depositional sequences were uplifted above sea level due to regional tectonic activity, accompanied by the development of fault structures.

Subsequent tectonic processes resulted in deformation and faulting of relatively younger sedimentary and volcanic deposits. In the northern offshore region, additional sedimentation during the Pliocene led to the formation of the Asah Formation. Uplift and tectonic activity continued, shaping the present-day geological configuration of Bali. Overall, Bali is considered geologically young, with the oldest exposed rocks dating back to the Miocene. Lithologically, Bali consists of several major formations, including the Ulakan Formation, Southern Formation, Pulaki volcanic formation, Prapatagung Formation, Asah Formation, and Quaternary volcanic formations. The Bangli area is predominantly composed of Quaternary volcanic deposits, particularly associated with the Buyan–Bratan and Batur volcanic systems. These deposits include tuff, volcanic breccia, lava, and laharic materials composed mainly of andesitic rocks and pumice. The relatively unconsolidated nature of these materials makes them susceptible to deformation and structural disruption, which is essential for interpreting subsurface fault structures [16, 26, 27].

3.3. *Integrated interpretation of fault structures*

This study investigated four survey lines located in Belantih, Lembean, Tembuku, and Sukawana within Bangli Regency using integrated GPR and electrical resistivity methods. At the Belantih site, GPR results revealed a shallow subsurface discontinuity at approximately 301 m along the profile, with depths ranging from 1 to 6 m. This anomaly was further validated by resistivity data, which identified a deeper structural discontinuity at approximately 51 m with a depth of up to 20.2 m. The resistivity contrast indicates a weak zone cutting through higher-resistivity layers, suggesting a fault structure. Based on the observed displacement pattern, this feature is interpreted as a normal fault, likely formed under extensional tectonic conditions.

At the Lembean site, GPR data indicated a similar shallow anomaly at approximately 290 m with depths between 1 and 5 m. The resistivity data confirmed this feature at approximately 144 m along the profile, extending to a depth of 11.8 m. The consistency between shallow and deeper anomalies supports the interpretation of a fault zone. Similar to Belantih, the structural characteristics suggest a normal fault system. In contrast, the Tembuku site did not show any significant indications of faulting. Both GPR and resistivity results revealed relatively continuous subsurface layers, with variations attributed to lithological differences rather than structural disruption. This suggests that deformation in this area is dominated by gentle subsidence or folding rather than faulting. At the Sukawana site, GPR data revealed a subsurface discontinuity at approximately 590 m with depths ranging from 0.5 to 8 m. However, the absence of resistivity data limits the ability to confirm this interpretation. Although the anomaly is indicative of a potential fault structure, further investigation using complementary geophysical methods is required to reduce uncertainty [28, 29].

3.4. *Implications for seismic hazard*

The identified fault structures in Bangli Regency are closely related to the regional tectonic setting of Bali, which is influenced by the subduction of the Indo-Australian Plate beneath the Eurasian Plate and the presence of a back-arc thrust system in northern Bali. These tectonic conditions contribute to active crustal deformation and frequent seismic activity. The presence of shallow fault structures, particularly in Belantih and Lembean, suggests that localized crustal deformation may play a significant role in generating shallow earthquakes in the region. Given that shallow earthquakes tend to produce stronger ground shaking, these structures represent important sources of seismic hazard.

4. Conclusion

This study demonstrates the effectiveness of integrating Ground Penetrating Radar (GPR) and electrical resistivity methods for identifying shallow subsurface fault structures in Bangli Regency, Bali, a region characterized by active tectonic processes. The results reveal consistent fault-related anomalies in Belantih and Lembean, where shallow discontinuities detected by GPR are supported by deeper resistivity contrasts, indicating the presence of structurally weak zones interpreted as normal faults formed under extensional stress conditions. In contrast, the Tembuku site exhibits relatively continuous subsurface layering with no clear structural disruptions, suggesting that lithological variation rather than faulting controls the observed geophysical responses. At the Sukawana site, GPR data indicate a potential shallow fault structure; however, the absence of complementary resistivity data introduces uncertainty, highlighting the importance of multi-method validation in geophysical investigations. The identified subsurface structures are consistent with the regional tectonic framework of Bali, which is influenced by the subduction of the Indo-Australian Plate beneath the Eurasian Plate and the presence of a back-arc thrust system, both of which contribute to active crustal deformation and frequent seismic activity. These findings underscore the significance of shallow fault systems as potential sources of localized seismic hazards, particularly in volcanic terrains dominated by heterogeneous and relatively unconsolidated materials. Overall, the integration of GPR and electrical resistivity methods provides a reliable and efficient approach for subsurface fault detection, reducing interpretational ambiguity and improving confidence in structural characterization. The results of this study not only enhance the geological understanding of Bangli Regency but also offer important implications for seismic hazard assessment and disaster risk mitigation, emphasizing the need for further high-resolution and multi-method geophysical investigations in tectonically active regions.

CRediT authorship contribution statement

Khrisma Nawangsih: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Korhan Cengiz:** Writing – review & editing, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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