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Research Article

Analysis of Fractures and Discontinuities in Jurassic-Cretaceous Limestones of Mugla Seydikemer Utilizing Ground Penetrating Radar

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ABSTRACT

This research examines the structural discontinuities and fracture-crack systems of Jurassic-Cretaceous limestones in the Seydikemer Boğalar area of the Muğla province using Ground Penetrating Radar (GPR). The region's geology has intricate fracture networks resulting from tectonic activity, which provide significant information for hydrogeological dynamics and engineering endeavors. The limestones have a grey hue and strong strength on new fracture surfaces, but they transition to brown and display reduced strength in changed zones. The GPR technique allowed comprehensive mapping of subsurface discontinuities with data gathered from 12 distinct profiles. Besides near-surface cracks, fracture systems reaching deep were also detected with radargrams. The data was combined with field observations to thoroughly evaluate the depth and scope of subsurface discontinuities. This technique identified vulnerable locations of possible danger for mining and building projects. The study's results indicate that GPR effectively maps discontinuities in carbonate rocks, such as limestone, by delivering high-resolution data. This research carried out in the Seydikemer Boğalar area of Turkey, illustrates the efficacy of Ground Penetrating Radar (GPR) in geotechnical and mining endeavors, offering a significant addition to analogous worldwide studies in the literature. The forthcoming amalgamation of GPR with other geophysical techniques will facilitate the creation of more intricate models of subsurface formations.

1. Introduction

Precise evaluation of subsurface formations is crucial for engineering endeavours and environmental risk evaluations. Specifically, comprehensive mapping of fractures and fracture networks in carbonate rocks, such as limestone, is crucial for groundwater flow, mining safety, and construction stability [1-2]. Recognizing structural discontinuities in limestone rocks enhances project safety while reducing environmental consequences and possible dangers [3-4].

Ground-penetrating radar (GPR) is a proficient technique that yields high-resolution data, allowing intricate imaging of subsurface discontinuities [5]. Ground Penetrating Radar (GPR) can examine subsurface structures using high-frequency electromagnetic waves and is especially significant for detecting fracture-crack systems in hard rocks like limestone [6-7]. A comprehensive analysis of subsurface structures' depth, strike, dip, and inclination provides essential information for geotechnical and engineering purposes [8].

The Jurassic-Cretaceous limestones in the Seydikemer Bogalar region provide a significant geological context for examining structural discontinuities. This research evaluated the limestones' fractures and fracture systems using Ground-Penetrating Radar (GPR). The acquired data were amalgamated with field observations and stratigraphic information to elucidate the distribution and depth of subsurface discontinuities [9-10]. The structures identified by GPR radargrams provide significant insights for mineral exploration and construction endeavours, facilitating more dependable risk assessment in field investigations [11].

Integrated methodologies are often used to examine carbonate rocks globally. Research in the UK indicates that Ground Penetrating Radar (GPR) yields high-resolution data for identifying karstic voids and cracks inside limestone formations [7]. Research in Japan using Ground Penetrating Radar (GPR) to detect water flow and discontinuities in karst landscapes validates the efficacy of this technique [4]. This research, carried out in the Seydikemer Boğalar region of Turkey, significantly enhances the literature on geotechnical analysis techniques by illustrating the efficacy of Ground Penetrating Radar (GPR) in areas with analogous geological formations.

Limestones are crucial for assessing soil characteristics, particularly in engineering and mining. Identifying the structural discontinuities of these rocks facilitates risk assessment in various domains, including groundwater flow, foundation stability, and mine safety [1]. The Ground Penetrating Radar (GPR) technique employed for examining subsurface structures is crucial for delineating subsurface discontinuities by delivering high-resolution data [8]. With the GPR method, this study studied cracks and discontinuities in Jurassic-Cretaceous limestones in the Seydikemer Boğalar region.

Prior research has established the efficacy of GPR in delineating discontinuities in volcanic and carbonate formations [5]. Research utilizing GPR in Japan's karst regions has successfully identified subterranean cavities and discontinuities [4]. In Turkey, the use of GPR in carbonate rocks is still limited, and this study is an essential contribution to the literature in this field. An in-depth examination of the fracture and discontinuity systems in the Seydikemer Boğalar region enhances comprehension of regional geology and its engineering implications.

This work elucidates the comprehensive mapping of structural discontinuities in Jurassic-Cretaceous limestones using the GPR approach and underscores their significance for engineering endeavors. The research results may serve as a dependable approach in geotechnical endeavors, particularly for mineral exploration and building initiatives.

1.1. Geology of the Study Area

The Seydikemer Bogalar area is situated in the southern section of the Western Taurus Mountains and has significant geological variety. The fundamental units in the area include limestones from the Jurassic-Cretaceous period These limestones exhibit fractures and fracture systems formed due to tectonic events in the area. The region's stratigraphy starts with substantial limestone layers at the base, followed by more recent alluvial deposits. Limestone formations are characterized by their plentiful fossils and robust structures, whereas fractures and fracture systems significantly influence the contribution of these rocks to groundwater flow [3].

The research region has been subjected to active tectonism, forming fractures and fault lines in the limestones in various orientations. These structures are significant for both hydrogeological and engineering geology. Despite the great mechanical strength of the region's limestones, vulnerable zones have developed owing to fracture and crack systems. This is essential for using limestone in mining and building endeavours [7].

1.2. Ground Penetrating Radar (GPR) Method

This research intends to use the GPR approach to delineate fracture-crack networks and subsurface discontinuities. Ground-penetrating radar (GPR) employs high-frequency electromagnetic waves to investigate subterranean structures, using the reflection times of these waves to delineate such structures [5]. This investigation used a Python GPR device with a 100 MHz antenna frequency for data collection (Figure 1). This frequency delivers high-resolution data to a depth of around 10-15 meters on solid substrates like limestones.

Data gathering was conducted across 12 distinct GPR patterns. Profiles were acquired at 50-meter intervals in directions dictated by the topography, and the GPR data were analyzed with RadExplorer and GPRSoft Pro software. Noise filtration, gain modifications, and data rectification were performed throughout data processing. Profile data provide comprehensive information on subsurface discontinuities' location, depth, and orientation (Figure 2).

Figure 1. Python GPR.

2. Methods

This investigation included GPR data, field observations, and an analysis of the surface limestones' fracture-crack systems, alteration zones, and overall structural characteristics. Field observations provided critical data for assessing surface cracks' orientation, gradient, and magnitude. Observations revealed that the new fracture surfaces of the limestones were grey and exhibited great strength, but alteration processes resulted in the formation of brown, low strength zones on the surface (Figure 3). The modified areas reduce the mechanical strength of the limestones, which must be addressed in engineering and mining operations.

Figure 3a presents a comprehensive picture of the research area, illustrating the extensive distribution and topography of the surface limestones. The area is marked by noticeable rocky sections on the surface, indicating the natural exposure of the geological units. This image serves as a crucial reference for comprehending the geographic and morphological attributes of the limestone units.

Figure 3b is a panoramic photograph captured from the rocky region, illustrating the natural structures of the limestone formations. The rocky terrain depicted in the photograph illustrates the lithological variations at the surface and the geomorphological configuration of the area.

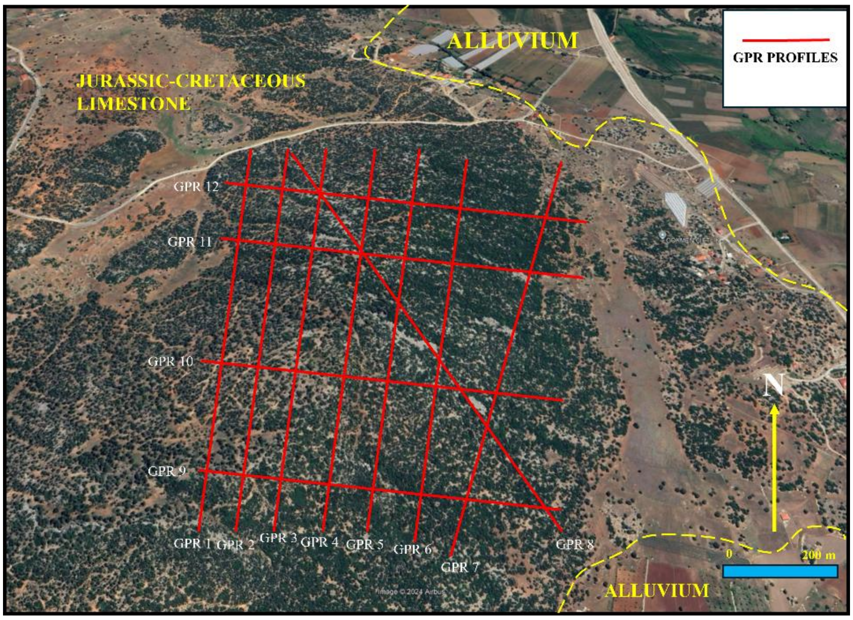

Figure 2. GPR Profiles of the study area.

Figure 3c shows the limestones' surface alteration features. The rocks exhibit brown and white hues in the alteration zones, signifying that the limestones have experienced physical and chemical weathering. These modified areas demonstrate that the limestones may have diminished in strength.

Figure 3d illustrates the newly formed fracture surface. The limestones in these regions are gray and demonstrate exceptional strength characteristics. The uniform color distribution and thick texture characteristics of the fresh surfaces suggest that the limestones possess a strong and resilient structure.

Figure 3e illustrates the detailed softened textures and the alterations in color to a white hue. The structural degradation resulting from modification renders the lithological and chemical variations of the surface limestones apparent.

Figure 3f illustrates the lithological variations of the limestones in detail. Different textural features and lithological changes are visible. The details elucidate the structural variability of the region's limestones.

These observations yielded essential data for comprehending the petrographic attributes of the limestones and underscored the significance of field observations in delineating underlying discontinuities.

Geological data, including the fracture-crack systems' direction, length, and spacing, were documented during field observations and used as a reference for interpreting the GPR radargrams. This enabled a more thorough evaluation of the subsurface continuity of structural discontinuities detected at the surface.

The GPR data obtained during the fieldwork enabled a comprehensive investigation of the underlying structures. The GPR data were acquired over 12 distinct profiles, each around 50 meters long, using a Python GPR instrument with a 100 MHz antenna frequency (Figure 1). This antenna frequency enables precise imaging from the surface to a depth of 10-15 meters and facilitates high-resolution identification of discontinuities, particularly in rigid substrates like limestone. GPR data processing was conducted with RadExplorer and GPRSoft Pro software. The data processing included noise filtration in the radargrams, gain modifications, and data rectification. The program was used to analyze the radargrams and get comprehensive information on the subsurface discontinuities' depth, extent, and orientation.

Figure 3. General view of limestones.

Radargram analysis demonstrated the subsurface continuity of the fracture and fracture networks on the surface. The discontinuity maps derived from GPR data were validated by comparison with field observations, and the collected data were assessed collectively. This method facilitated the identification of vulnerable areas that provide risks for mining and building endeavours. This approach has shown the efficacy of GPR in delineating subsurface discontinuities, yielding trustworthy findings via the integration and interpretation of data with structural elements in the field.

This paper thoroughly delineates the research's methodological framework, including the procedures for GPR data acquisition and analysis, its synthesis with geological observations, and the techniques used.

3. Results

The GPR radargrams acquired throughout the investigation elucidated the regional limestones' structural discontinuities and fracture-crack systems in detail (Figure 4). Measurements over 12 profiles yielded data from the surface to a depth of roughly 10 to 15 meters.The radargrams provide comprehensive data on the strike, dip, and continuity of subsurface structures, proving especially useful in assessing the extent of subsurface fracture systems.

Discontinuities were detected between Profiles 1-4, spanning from the surface to around 5 meters. These discontinuities are observable as prominent reflections on radargrams.The surface discontinuities are aligned north-south and are regarded as permeable zones for groundwater movement (Figure 4).

The surface discontinuities oriented north-south are regarded as permeable zones for groundwater movement (Figure 4). The interplay of these discontinuities, particularly with groundwater, is crucial for the hydrogeologic systems in the area.

Significant discontinuities were detected between Profiles 5-8, extending to roughly 10 meters. The regions containing these profound discontinuities are identified as prominent reflection zones on radargrams. The detected discontinuities in the research region represent possible danger zones for geotechnical and engineering projects. In contrast to the surface cracks, the deep discontinuities' structural features indicate that their continuity in the subsurface persists substantially (Figure 4).

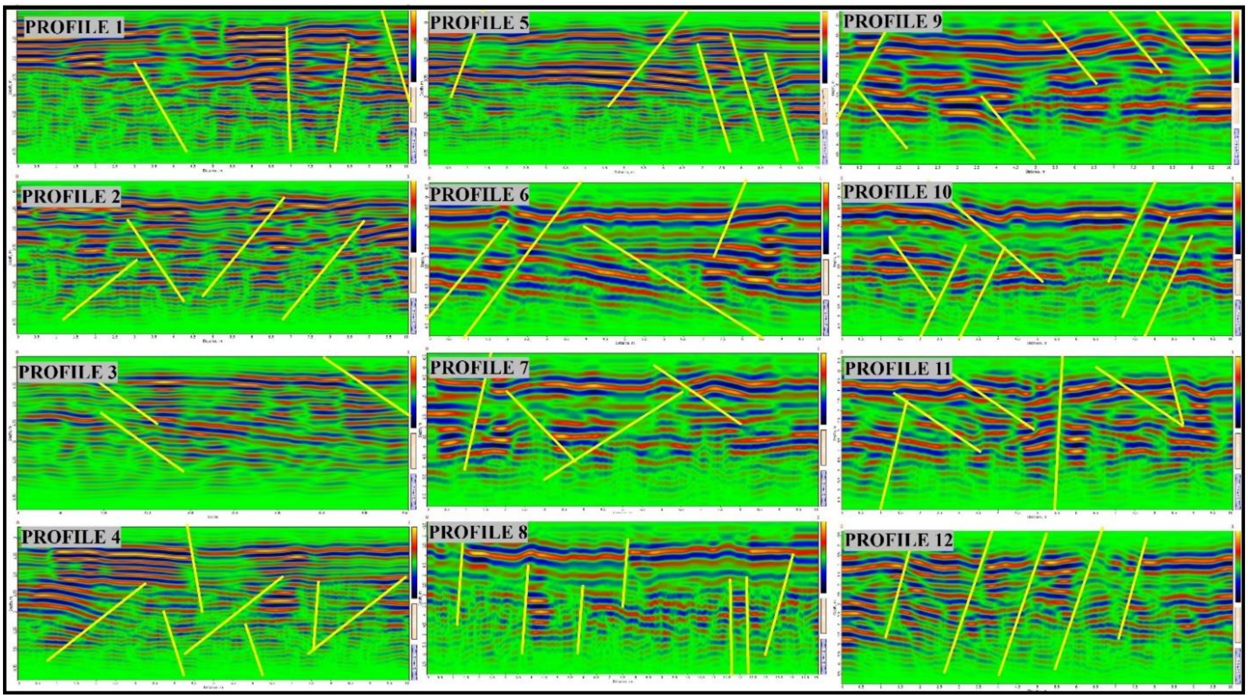

Figure 4. Radargram of the profiles.

Analysis of Profiles 9-12 indicated discontinuities continuing from the surface to greater depths, oriented in a southeast-northwest orientation.

The discontinuities appear as crossing reflectors in the radargrams, revealing the intricate structure of the fracture-crack systems in the area.The discontinuities revealed in Profiles 10 and 11 provide significant insights on the subsurface continuity of the fractures exhibited at the surface.

These discontinuities are regarded as essential factors in assessing the integrity of subterranean structures and identifying possible danger zones (Figure 4).

Radargram analysis and field observations were integrated to provide a detailed model of the structural discontinuities within the limestones of the area. The underlying continuity of fractures and cracks seen on the surface was corroborated by GPR radargrams, and the subsurface distribution of these discontinuities was delineated (Figure 4).

These models provide dependable data, particularly for mining operations and building endeavours, facilitating the identification of possible vulnerabilities and danger zones. The newly observed fracture surfaces in the field were grey and had great strength, while the changed zones were brown and shown low strength. In accordance with these findings, the GPR data revealed modified low resistivity zones with decreased reflection values on the radargrams. This illustrates the sensitivity of GPR to surface geological variations and its efficacy in precisely delineating structural discontinuities.

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4. Discussion

This study's findings indicate that the GPR approach yields high-resolution data for identifying structural discontinuities in carbonate rocks, such as limestone, and showcases the technology's analytical capabilities. Besides near-surface discontinuities, GPR data are very helpful for identifying deep fracture networks. The radargrams acquired in the investigation enabled a detailed analysis of subsurface structural features, including direction, slope, and continuity [5-7]. The capability of GPR to display underlying features seamlessly offers a considerable benefit in mapping limestone formations [7].

GPR's success in analyzing carbonate rocks is due to the method's ability to provide detailed imaging using high-frequency electromagnetic waves. GPR is highly effective in detecting near-surface structures, and this capability has found wide application in studies such as detecting water-filled cavities in karst regions [4]. However, the effectiveness of GPR can vary depending on ground conditions and rock types. For example, the attenuation of electromagnetic waves in highly conductive soils can limit the penetration depth of GPR [3].

In this study, to improve the effectiveness of GPR, noise filtering, gain adjustments and signal boosting techniques were applied during the data processing phase using RadExplorer and GPRSoft Pro software. This approach improved the quality of the radargrams and contributed to a clearer mapping of discontinuities [10]. However, due to the limited depth capability of GPR in some areas, additional geophysical methods are required to identify deeper parts of subsurface structures [12].

This research reaffirms the benefits of Ground Penetrating Radar (GPR) in identifying structural discontinuities in limestones, in contrast to worldwide studies. Research conducted in Japan demonstrates that Ground Penetrating Radar (GPR) is proficient in identifying karstic voids and water-filled fissures in karst regions [5]. Such findings underscore the significance of GPR, particularly for delineating groundwater movement channels and conducting hydrogeological modeling. Research in Indonesia has shown that Ground Penetrating Radar (GPR) is an efficacious technique for identifying discontinuities in volcanic and carbonate formations [7, 9].

A research in the Yahyalı district of Kayseri, Turkey, used GPR to detect Pb-Zn mineralization in carbonate rocks, confirming GPR's efficacy as a geophysical exploration technique [13]. This research underscores the efficacy of GPR in mining and engineering operations, illustrating its significance in analogous geological formations in Turkey. This work in the Seydilemer Boğalar area, akin to the research in Yahyalı, validates the benefits of GPR in delineating fracture-crack systems and constitutes a significant addition to the literature about using this technology to carbonate rocks.

The high-resolution data obtained by GPR on limestone formations may be used with other geophysical techniques to address depth constraints. Research indicates that electrical resistivity tomography (ERT) approaches may enhance depth investigations of near-surface structures when combined with ground-penetrating radar (GPR) data [8, 14]. Integrated methodologies are very efficacious in examining intricate systems, including karst formations and groundwater aquifers [11].

In investigations using both GPR and ERT, GPR offered comprehensive insights into subsurface structures, whilst ERT served a supplementary function in identifying discontinuities at various depths [12]. The findings from the use of GPR only in the Seydilemer Boğalar region have validated GPR's capacity to detect subsurface discontinuities; nonetheless, it is recommended that future data integration with other methodologies to enhance depth analysis might be advantageous.

The GPR approach has gained prominence in Turkey to examine subterranean structures in recent years. In gold mineralization investigations in the Bayburt-Zarani area, fracture-crack systems were detected by GPR, demonstrating the significance of GPR in mineral exploration projects [15]. In geological and hydrogeological investigations throughout several regions of Turkey, the high-resolution capability of GPR is emphasized as an essential instrument for enhancing the safety of mining sites and construction zones [3]. Ground Penetrating Radar (GPR) is widely used to examine karst systems, volcanic formations, and carbonate strata. Research conducted in Europe, particularly in Britain and Italy, has shown that GPR is proficient at detecting karst formations and groundwater flow routes [10]. These studies provide significant insights into integrating GPR within geotechnical evaluations, groundwater management, and mining site investigations [7].

This research, carried out in the Seydikemer Boğalar area, has shown the significance of Ground-Penetrating Radar (GPR) in examining analogous geological formations in Turkey and indicated that this technique has extensive applicability in engineering initiatives and environmental risk assessment. The technique outlined in the paper offers direction for forthcoming geotechnical assessments and mining endeavours.

This study clearly illustrates the advantages of GPR in examining limestone buildings; nonetheless, it is advisable that further research use varying antenna frequencies and encompasses bigger regions to enhance the depth and breadth of this data. Moreover, integrating GPR data with 3D modeling approaches may provide a more comprehensive examination of discontinuities [4]. These methodologies will enhance the reliability and comprehensiveness of outcomes in both field research and data processing procedures.

Future research should use GPR, ERT, and other geophysical techniques to enhance the precision of assessing rocks' structural characteristics and hydrogeological parameters. Specifically, enhanced mapping of karst formations and groundwater flow trajectories will be essential in reducing hazards associated with engineering projects [5, 14].

Augmenting the quantity of integrated studies in Turkey and globally would facilitate the more effective use of geophysical methodologies and enhance the efficiency of field study planning [13].

5. Conclusion

This research sought to elucidate the structural discontinuities and fracture-crack systems of Jurassic-Cretaceous limestones in the Seydikemer Boğalar district of Muğla province using Ground Penetrating Radar (GPR). The study's results unequivocally illustrated the high-resolution data acquisition capability of GPR in examining the interior structure of carbonate rocks, including limestone. The acquired radargrams enabled us to ascertain the structural attributes of subsurface formations, including strike, dip, and depth, by meticulously mapping from shallow discontinuities to profound fracture systems. The study's findings indicate that the GPR technique is an excellent instrument for comprehensively characterizing subsurface discontinuities and fracture systems. It specifically furnished dependable data to pinpoint vulnerable areas of danger for mining operations and building endeavours. GPR radargrams validated the underlying continuity of fractures and surface-observed fractures, and the propagation of these discontinuities through depth was meticulously recorded. The findings were amalgamated with field observations to provide more complete and precise results.

The results reported in this research establish a crucial foundation for sustainable mining operations and secure engineering projects in the Seydikemer Boğalar area. Future analogous investigations may provide more thorough findings by merging GPR with other geophysical technologies, facilitating the development of more intricate models of subterranean structures. GPR's high-resolution capacity significantly contributes to geotechnical research both domestically and globally.

The work contributes to developing GPR applications in Turkey and is a reference for other possible applications of this technology in carbonate rocks. Future studies may expand the application of GPR across several geological units to provide a more thorough assessment of discontinuities.

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