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Analysis geoelectrical resistivity and XRF geochemistry to characterize limestone distribution and quality in a carbonate–volcanic terrain of Cimanggu, Pandeglang, Banten, Indonesia

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Abstract

Limestone quality in carbonate and volcanic settings is strongly influenced by lithological variability, non carbonate sediment input, diagenetic modification, and proximity to igneous bodies. This study aims to evaluate subsurface limestone occurrence, lithological characteristics, and geochemical quality in the Cimanggu area, Pandeglang, Banten, Indonesia, through combined application of geoelectrical resistivity data and X-ray fluorescence (XRF) analysis.

Geoelectrical investigation was conducted using 15 measurement datasets, consisting of 11 vertical electrical sounding points with Schlumberger configuration and four lateral profiles with Wenner configuration. Resistivity data were processed using IP2Win and Progress software to generate one dimensional models and correlated two dimensional subsurface sections. XRF analysis was performed on ten representative rock samples to determine major oxide compositions, particularly CaO, SiO_2, MgO, Al_2O_3, and Fe_2O_3, as indicators of limestone purity and impurity contribution.

Results identify five principal subsurface units: soil cover, claystone, low grade limestone, high grade limestone, and andesitic to basaltic igneous rocks. High grade limestone is mainly concentrated in the central part of the study area, particularly around GL 2, GL 3, GL 5, and GL 9, where carbonate intervals reach approximately 40–50 m in thickness. This limestone is chemically characterized by CaO >52%, SiO_2 <2.5%, MgO <0.5%, Al_2O_3 <1.1%, and Fe_2O_3 <1%. In contrast, low grade limestone occurs mainly in the western sector and near intrusive zones, showing CaO <52% with elevated impurity oxides.

Keywords: Geoelectrical resistivity; XRF Geochemistry; Limestone Quality; Carbonate-Volcanic terrain

1. Introduction

Limestone is a strategic carbonate resource that underpins a wide range of industrial sectors, including cement and lime production, construction aggregates, glass manufacturing, agriculture, ceramics, and environmental applications. Beyond its volumetric abundance, the economic value of a limestone deposit is governed by the spatial continuity of the carbonate body, the degree of lithological heterogeneity, and the concentration of major oxides such as CaO, MgO, SiO_2, Al_2O_3, and Fe_2O_3. These parameters are particularly important because limestone quality may vary significantly within a single deposit as a result of depositional facies changes, diagenetic modification, siliciclastic input, weathering, and interaction with non carbonate lithologies. Recent studies on carbonate raw materials have shown that mineralogical and geochemical characterization is essential for determining limestone purity, provenance, and suitability for

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industrial use, especially when the deposit is intended for high value applications such as cement, lime, or chemical grade carbonate products [1].

Surface geological observations in limestone exploration are commonly insufficient to define the three dimensional geometry and quality variation of carbonate bodies. This limitation is especially critical in tropical regions, where intense weathering, vegetation cover, soil development, and partial exposure may obscure the true distribution of limestone beneath the surface. Electrical resistivity methods provide an effective approach for imaging subsurface lithological variation because carbonate rocks, high clay, weathered zones, and igneous bodies commonly produce contrasting resistivity responses. Recent application of vertical electrical sounding using the Schlumberger configuration has demonstrated that resistivity data, when integrated with geological observations, can be used to construct lithostratigraphic logs, develop three dimensional limestone models, and support preliminary volume estimation [2]. However, resistivity interpretation must be treated carefully because resistivity values are not controlled by lithology alone. Porosity, fracture intensity, water saturation, clay content, weathering degree, and mineralogical impurities may all modify the electrical response of limestone[4]. Therefore, geophysical interpretation requires independent validation from field geology and geochemical analysis. X-ray fluorescence analysis is particularly valuable in limestone evaluation because it provides quantitative measurements of major oxide composition, allowing high calcium limestone to be distinguished from lower grade limestone affected by Mg enrichment, siliciclastic contamination, clay impurities, or iron phases. Studies of limestone and quicklime quality have also shown that impurities can reduce CaO content and influence the performance of limestone derived industrial products, reinforcing the need for chemical characterization in resource assessment.

The limestone deposit of PT Batara Chaka Lestari, located in Tangkilsari Village, Cimanggu District, Pandeglang Regency, Banten Province, Indonesia, represents a carbonate resource developed within a geologically complex setting where limestone is associated with claystone and andesitic volcanic or intrusive rocks. The exploration report indicates that the study area was investigated using geological observation, geoelectrical surveys, XRF analysis, and three dimensional block modelling. A total of 15 geoelectrical survey points and 10 XRF samples were used to interpret subsurface lithology and limestone quality. Based on the report, the lithological units consist of soil, low grade limestone, high grade limestone, claystone, and andesite. High grade limestone is characterized by CaO contents greater than 52%, whereas limestone with CaO contents below 52% is classified as low grade. The report further estimates an indicated limestone resource of 47.82 million tons and a measured limestone resource of 3.59 million tons.

2. Research Methodology

2.1. Geoelectrical Data Acquisition

Geoelectrical resistivity surveying was applied in this study to characterize subsurface lithological variation based on contrasts in electrical resistivity. This method is particularly useful for distinguishing carbonate rocks, clay, weathered materials, and igneous bodies, as each lithology generally exhibits a different electrical response depending on its mineral composition, porosity, water content, degree of weathering, and fracture intensity [5]. In the context of limestone exploration, resistivity data provide an important basis for interpreting the geometry, thickness, and continuity of carbonate units beneath the surface.

A total of 15 geoelectrical datasets were collected across the study area, consisting of 11 vertical sounding points and four Wenner survey lines. Field acquisition was carried out from 8 to 13 September 2025. The electrode spread length was approximately 100 m, although minor adjustments were made according to topographic conditions, land accessibility, vegetation cover, and field constraints. The survey layout was designed to cover the main limestone zone and adjacent areas where lithological variation, including claystone and andesitic to basaltic rocks, was expected to occur. The measured apparent resistivity data were processed using IP2Win and Progress software. Initial processing involved data checking, smoothing, and curve matching to reduce field measurement noise and improve the reliability of the resistivity model. The vertical sounding data were then inverted to obtain one dimensional subsurface resistivity models for each measurement point. These models were interpreted by considering resistivity values, local geological observations, surface lithology, and the known regional geological framework of the Bojongmanik and Honje formations.

2.2. XRF Geochemical Analysis

X-ray fluorescence (XRF) analysis was conducted on ten representative rock samples to determine their elemental composition and major oxide concentrations. This analysis was used as the principal geochemical approach for evaluating limestone quality, particularly by examining the relative abundance of CaO and SiO_2 [6]. In carbonate rocks, CaO is a key indicator of calcium carbonate purity and is commonly used to assess the suitability of limestone for industrial applications. Higher CaO content generally reflects a greater proportion of carbonate minerals, particularly calcite, and indicates a purer limestone composition [7].

SiO_2 was used to evaluate the presence of non carbonate materials, especially siliciclastic input, quartz, or possible influence from nearby igneous rocks. An increase in SiO_2 content may indicate dilution of the carbonate component by terrigenous sediment, volcanic derived material, or silica enrichment associated with alteration processes. Therefore, the CaO–SiO_2 relationship provides an important basis for distinguishing relatively pure limestone from limestone affected by siliciclastic contamination or igneous related influence.

Other major oxides, including MgO, Al_2O_3, and Fe_2O_3, were also considered to refine the interpretation of limestone quality and geological processes. MgO was used to assess possible dolomitization or magnesium enrichment during carbonate diagenesis. Elevated Al_2O_3 may indicate the presence of clay minerals or fine grained siliciclastic material, whereas higher Fe_2O_3 can suggest the contribution of iron minerals, mafic volcanic components, weathering products, or hydrothermal alteration. These oxide parameters are important because limestone grade is not controlled only by CaO content, but also by the proportion and origin of impurity components.

3. Result

3.1. Geoelectrical Interpretation

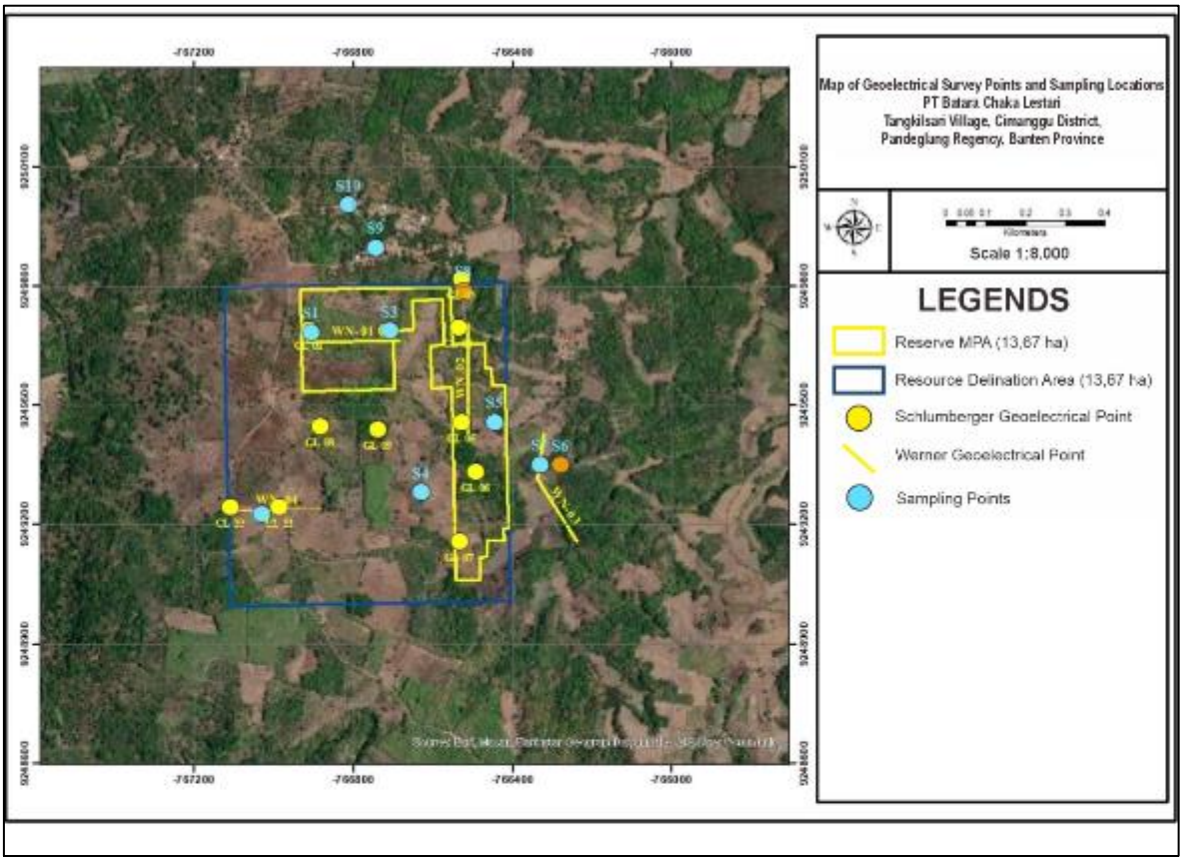

Figure 1 Geoelectrical points in the investigation area

Geoelectrical survey results indicate that the study area can be classified into five main subsurface units: overburden soil, claystone, low grade limestone, high grade limestone, and andesitic igneous rock. Based on the resistivity summary, the overburden soil is characterized by resistivity values of 2.0–20 ohm m at depths of 0–3.5 m, whereas claystone shows relatively low resistivity values of 0.1–6.0 ohm m at depths of 18–50 m. Low grade limestone is identified by resistivity values of 13–31 ohm m at depths of 1–25 m, while high grade limestone exhibits a wider resistivity range of 5–145 ohm m at depths of 3–60 m. In contrast, andesite is marked by very high resistivity values, ranging from 1000 to 3200 ohm m.

High grade limestone is predominantly distributed in the central part of the study area, particularly around geoelectrical points GL 2 and GL 9. At GL 2, high grade limestone occurs from approximately 7 m to 58 m depth, with a thickness of about 50 m. At GL 9, this unit extends from 1 m to 47 m depth and is underlain by claystone. These results suggest that the central part of the study area represents the main zone of better quality limestone development. At GL 3, high grade limestone is interpreted between depths of 3 m and 41 m, while andesitic igneous rock occurs at depths of 41–60 m. This condition indicates the presence of an underlying igneous body, which may be associated with the Honje Formation or andesitic–basaltic intrusion. Similar igneous units are also identified at GL 6 and GL 7, occurring at depths of approximately 28–40 m and 31–45 m, respectively, and are characterized by high resistivity values exceeding 1000 ohm m. These data imply that the igneous body is more extensively developed in the southern to southeastern part of the study area.

The Wenner survey lines further support this interpretation. Line WN 01 reveals the presence of high grade limestone, low grade limestone, and claystone, with high grade limestone becoming thicker eastward. Line WN 02 shows high grade limestone and claystone, with a similar eastward thickening trend of the high grade limestone unit. Line WN 03 is dominated by low grade limestone and andesite, where the andesitic body also tends to thicken toward the east. Meanwhile, WN 04 indicates the occurrence of low grade limestone, high grade limestone, and claystone, with a closure of high grade limestone and a thickening tendency toward both the eastern and western parts of the section.

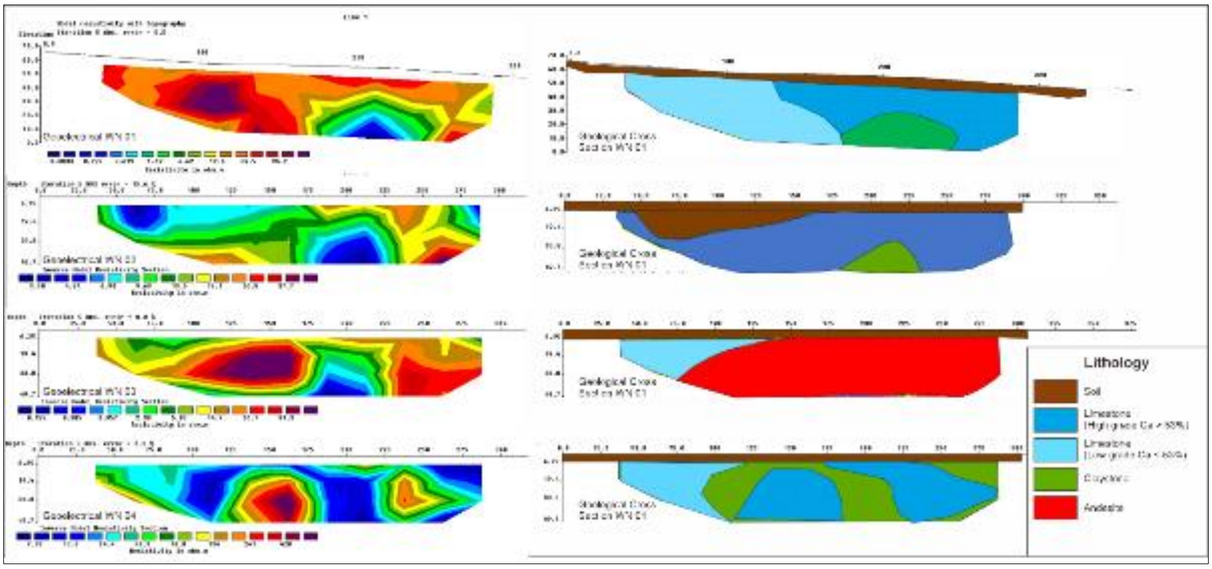

Figure 2 Results of geoelectrical Wenner measurements at points WN 01–04 and geological cross section of WN 01–04

3.2. X-ray fluorescence Interpretation

X-ray fluorescence (XRF) analysis demonstrates clear geochemical variability among the limestone and igneous rock samples in the Cimanggu area. This variability is primarily reflected by differences in CaO, SiO_2, Al_2O_3, Fe_2O_3, and MgO contents, which represent the main chemical parameters for evaluating limestone purity, impurity contribution, and possible alteration processes. In carbonate deposits, CaO is commonly used as the principal indicator of calcite high limestone, whereas SiO_2, Al_2O_3, and Fe_2O_3 generally reflect the presence of non carbonate components such as quartz, clay minerals, volcanic derived material, iron phases, or alteration products. MgO indicate dolomitic enrichment or magnesium substitution during carbonate diagenesis. High grade limestone is mainly represented by samples 3 and 4, which are located in the central part of the study area. These samples are characterized by CaO contents above 52%, MgO below 0.5%, SiO_2 below 2.5%, Al_2O_3 below 1.1%, and Fe_2O_3 below 1%. This geochemical composition indicates a carbonate high limestone dominated by calcium carbonate, with limited contribution from siliciclastic, high clay, and iron impurities.

Table 1 Recapitulation of XRF analysis results from the Integrated Laboratory of Diponegoro University and Geoservice in 2025

No	**Analite**	**Unit**	**Sample 1**	**Geoservice 1**	**Sample 2**	**Sample 3**	**Geoservice 3**	**Sample 4**	**Geoservice 4**
1	$CaCO_3$	Mass%	89.18	94.38	91.53	96.05	97.55	96.30	95.00
2	CaO	Mass%	49.94	52.85	51.26	53.79	54.63	53.90	53.20
3	Ca	Mass%	35.60	37.78	36.70	38.40	39.05	38.40	38.03
4	SiO2	Mass%	2.79	3.11	1.91	1.37	1.36	1.41	2.64
5	Al_2O_3	Mass%	0.87	1.50	0.61	0.13	0.91	0.05	0.95
6	Fe_2O_3	Mass%	0.96	0.70	0.74	0.66	0.42	0.48	0.59
7	MgO	Mass%	0.56	0.52	0.27	0.28	0.40	0.38	0.52
8	P_2O_5	Mass%	0.08	0.03	0.00	0.07	0.02	0.11	0.05
9	SO_3	Mass%	0.02	0.07	0.02	0.02	0.06	0.02	0.06
10	Cl	Mass%	0.01	0.00	0.00	0.01	0.00	0.00	0.00
11	K_2O	Mass%	0.36	0.13	0.22	0.12	0.03	0.13	0.05
12	MnO	Mass%	0.05	0.06	0.00	0.00	0.04	0.04	0.05
13	CuO	Mass%	0.01	0.00	0.00	0.00	0.00	0.00	0.00
14	SrO	Mass%	0.05	0.04	0.12	0.05	0.05	0.11	0.10
15	TiO_2	Mass%	0.00	0.04	0.00	0.00	0.03	0.00	0.04
16	LOI	Mass%	44.20	41.43	45.50	44.40	42.47	43.30	41.75
17	Sum	Mass%	99.89	100.56	100.64	100.89	100.55	99.93	100.03

Table 1 Continued Recapitulation of XRF analysis results from the Integrated Laboratory of Diponegoro University and Geoservice in 2025

No	**Analite**	**Unit**	**Sample 5**	**Geoservice 5**	**Sample 6**	**Sample 7**	**Sample 8**	**Sample 9**	**Sample 10**	**1 BCL**	**3 BCL**
1	$CaCO_3$	Mass%	93.50	96.09	5.60	77.20	2.74	90.36	89.57	92.96	93.05
2	CaO	Mass%	52.36	53.81	3.14	43.23	0.96	50.60	50.16	52.06	52.11
3	Ca	Mass%	37.30	38.46	3.00	31.00	1.50	36.10	35.80	37.21	37.25
4	SiO_2	Mass%	1.13	2.09	40.80	3.30	29.80	1.27	2.01	4.34	4.21
5	Al_2O_3	Mass%	1.36	0.89	14.70	2.51	17.00	0.53	1.09	1.47	1.49
6	Fe^2O_3	Mass%	0.57	0.45	6.32	2.64	8.32	0.72	0.92	0.67	0.54
7	MgO	Mass%	0.35	0.51	0.56	0.49	1.15	0.54	0.64	0.67	0.51
8	P_2O_5	Mass%	0.08	0.03	0.12	0.13	0.06	0.09	0.10	0.02	0.02
9	SO_3	Mass%	0.02	0.06	0.00	0.04	0.04	0.04	0.04	0.07	0.1
10	Cl	Mass%	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00
11	K_2O	Mass%	0.14	0.04	2.15	0.34	0.26	0.15	0.27	0.19	0.25
12	MnO	Mass%	0.00	0.03	0.19	0.17	3.32	0.03	0.06	0.06	0.08

13	CuO	Mass%	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00
14	SrO	Mass%	0.13	0.10	0.03	0.07	0.01	0.19	0.06	0.04	0.03
15	TiO_2	Mass%	0.00	0.03	0.45	0.26	1.18	0.00	0.00	0.1	0.06
16	LOI	Mass%	44.50	42.09	30.60	47.70	37.90	46.40	45.20	40.84	40.98
17	Sum	Mass%	100.64	100.15	99.07	100.89	100.01	100.58	100.54	100.85	100.62

Occurrence of high grade limestone in the central part of the study area is also consistent with the geoelectrical interpretation, which shows thicker and more continuous limestone bodies around GL 2, GL 3, GL 5, and GL 9. This relationship suggests that the central zone may represent the main carbonate accumulation area, where carbonate sedimentation was less affected by volcanic, siliciclastic, or clay. From a depositional perspective, this condition may reflect a relatively open and stable shallow marine carbonate environment, carbonate producing organisms and carbonate mud were able to accumulate with limited dilution by non carbonate sediments. In contrast, low grade limestone represented by samples 5 and 7 shows lower CaO contents, generally below 52%, accompanied by higher SiO_2, Al_2O_3, and Fe_2O_3 values. These samples are located relatively close to the andesitic to basaltic intrusive zone, suggesting that limestone quality in this area may have been affected by volcanic or intrusion related processes. The increase in SiO_2 may reflect the addition of silica high material derived from volcanic rocks, siliciclastic input, or hydrothermal alteration near the intrusive contact. Elevated Al_2O_3 may indicate the presence of clay minerals or aluminosilicate components, whereas higher Fe_2O_3 may be related to iron minerals derived from mafic volcanic material, weathering products, or hydrothermal fluids.

Another low grade limestone group is represented by samples 1, 2, 9, and 10. These samples are characterized by CaO contents below 52%, MgO contents above 0.5%, SiO_2 above 3%, Al_2O_3 above 1.5%, and Fe_2O_3 generally below 1%. This geochemical pattern differs from the intrusion proximal low grade limestone because the relatively higher MgO content suggests possible local dolomitization or magnesium enrichment during diagenesis. The increase in MgO may reflect partial replacement of calcium by magnesium in carbonate minerals, resulting in a decrease in CaO concentration and a shift toward a less pure limestone composition. The relatively high SiO_2 and Al_2O_3 contents in this group also indicate a stronger contribution of siliciclastic or high clay. This may reflect deposition in a more restricted, turbid, or marginal carbonate environment where carbonate sedimentation was mixed with terrigenous input. In such settings, limestone quality can decrease because carbonate components are diluted by fine grained siliciclastic sediments, clay minerals, or reworked volcanic material. Therefore, samples 1, 2, 9, and 10 may record a mixed carbonate siliciclastic depositional setting, combined with local diagenetic modification.

The XRF results also show that igneous rock samples are chemically distinct from limestone. Igneous samples are expected to have significantly lower CaO and higher SiO_2, Al_2O_3, Fe_2O_3, and other oxide contents compared with carbonate samples. This contrast supports the interpretation that the andesitic to basaltic rocks represent a separate volcanic or intrusive component within the study area. Their presence is important because they may influence adjacent limestone quality through direct lithological mixing, thermal interaction, weathering, and hydrothermal alteration. This is particularly relevant in the southern to southeastern part of the study area, where geoelectrical data also indicates high resistivity bodies interpreted as andesite or basalt.

4. Discussion

4.1. Relationship between the Bojongmanik-Honje Formations and Lithological Distribution

The lithological distribution in the study area reflects a close spatial and genetic relationship between the carbonate dominated Bojongmanik Formation and the volcanic products of the Honje Formation. The Bojongmanik Formation is interpreted as the principal limestone unit, whereas the Honje Formation, together with andesitic–basaltic intrusive rocks, represents the volcanic component that locally modifies the physical, geochemical, and possibly diagenetic characteristics of the carbonate succession. This geological relationship is particularly important because the Bojongmanik and Honje formations are reported to have an interfingering contact in the regional geological framework of the study area. As a consequence, the limestone body does not form a laterally uniform carbonate package, but instead shows spatial variation in thickness, quality, and association with non carbonate lithologies.

The interfingering relationship between carbonate and volcanic units provides a plausible explanation for the heterogeneous distribution of limestone observed from the geoelectrical and geochemical datasets. In such a mixed carbonate–volcanic setting, limestone deposition was likely influenced by changes in depositional energy, sediment supply, water depth, and proximity to volcanic or siliciclastic sources. Carbonate accumulation would have been more favorable in areas where marine conditions were relatively stable and where the input of volcaniclastics, clay, and terrigenous material was limited. Conversely, areas closer to volcanic sources or intrusive bodies would have received greater non carbonate input or experienced post depositional alteration, resulting in lower carbonate purity and a more complex geochemical signature.

The concentration of high grade limestone in the central part of the study area suggests that this zone may represent a relatively stable carbonate depositional domain within the Bojongmanik Formation. This interpretation is supported by the XRF results from samples S3 and S4, which are characterized by CaO contents greater than 52%, low MgO, low SiO_2, low Al_2O_3, and low Fe_2O_3. Such a geochemical composition indicates a limestone body dominated by calcium carbonate, with limited siliciclastic contamination and minor contribution from clay or iron materials. From a depositional perspective, this condition may reflect carbonate sedimentation in a relatively open and clearer shallow marine setting, where carbonate producing organisms and carbonate mud were able to accumulate without significant dilution by volcanic or terrigenous sediment.

In contrast, low grade limestone distributed in the western part of the study area and near the intrusive zone shows a different geochemical character. These limestone samples are marked by lower CaO values and relatively higher SiO_2, Al_2O_3, Fe_2O_3, or MgO contents. This pattern indicates that the limestone quality was affected by a greater proportion of non carbonate components. Elevated SiO_2 and Al_2O_3 may reflect siliciclastic input, volcanic ash contribution, or clay contamination during deposition. Higher Fe_2O_3 may indicate the influence of iron minerals derived from volcanic material or alteration products, whereas increased MgO may suggest local dolomitization or magnesium enrichment during carbonate diagenesis. Therefore, the low grade limestone is not merely a lower purity carbonate facies, but may record a more complex interaction between primary depositional conditions and secondary alteration processes.

The occurrence of andesite in the southern to southeastern part of the study area further strengthens the interpretation that volcanic influence played an important role in controlling limestone quality. Geoelectrical data show that andesitic rocks are characterized by very high resistivity values, distinguishing them from limestone and claystone units. The presence of these high resistivity bodies beneath or adjacent to carbonate units suggests that the limestone succession was locally affected by igneous activity or volcanic materials related to the Honje Formation. In areas closer to these volcanic bodies, the decrease in CaO and increase in silica components may be associated with magmatic hydrothermal fluids, contact related alteration, or the incorporation of volcanic derived material into the carbonate system.

This relationship also explains why limestone quality cannot be inferred solely from surface exposure. Although limestone may appear relatively similar in the field, its subsurface continuity and chemical grade can vary significantly due to the interfingering of carbonate and volcanic lithologies. The geoelectrical interpretation indicates that high grade limestone tends to form thicker and more continuous bodies in the central part of the area, whereas low grade limestone and volcanic rocks are more prominent toward the marginal or intrusive influenced zones. This spatial pattern suggests that the central zone represents the most prospective area for higher quality limestone, while the western and southern–southeastern zones require more careful evaluation because of lithological mixing and possible alteration.

Overall, the relationship between the Bojongmanik and Honje formations exerts a fundamental control on limestone distribution and quality in the study area. The Bojongmanik Formation provides the main carbonate framework, whereas the Honje Formation and associated andesitic–basaltic rocks introduce volcanic and siliciclastic influences that reduce carbonate purity in certain zones. The integration of lithological observations, geoelectrical interpretation, and XRF geochemistry therefore demonstrates that the limestone resource is controlled not only by the presence of carbonate rocks, but also by the spatial interaction between carbonate deposition, volcanic input, intrusive activity, and diagenetic modification. This integrated interpretation is essential for distinguishing high grade and low grade limestone domains and for improving the reliability of future resource estimation and mine planning.

4.2. Control of Andesitic/Basaltic Intrusion on Limestone Quality

The occurrence of andesitic to basaltic igneous rocks identified at GL 3, GL 6, GL 7, and along the WN 03 geoelectrical line indicates that the southern to southeastern part of the study area is influenced by volcanic or intrusive bodies. In the resistivity data, these igneous rocks are clearly distinguished by very high resistivity values, ranging from approximately 1000 to 3200 ohm m. This resistivity response contrasts sharply with the highly conductive claystone unit and the intermediate resistivity values generally associated with limestone. Such a contrast provides an important geophysical basis for delineating the spatial relationship between carbonate rocks and igneous bodies in the subsurface.

Influence of andesitic/basaltic intrusion on limestone quality is reflected by the geochemical variation of limestone samples located near the intrusive zone. Samples collected close to the andesitic body tend to show lower CaO contents and higher SiO_2 concentrations compared with high grade limestone from the central part of the study area. This pattern suggests that proximity to the intrusive body may have contributed to a reduction in carbonate purity. From a geochemical perspective, elevated SiO_2, Al_2O_3, and Fe_2O_3 values may indicate the contribution of volcanic derived material, hydrothermal alteration, or the incorporation of clay rich components into the carbonate system. These processes can dilute the calcium carbonate content and modify the original chemical composition of limestone.

The decrease in CaO near the intrusive body may be explained by several geological mechanisms. First, the incorporation of volcaniclastics or siliciclastic material during or after carbonate deposition could increase the proportion of non carbonate minerals within the limestone. Second, hydrothermal fluids associated with igneous activity may have promoted chemical alteration, calcium remobilization, and silica enrichment along the contact zone between limestone and intrusion. Third, thermal interaction between the carbonate host rock and the intrusive body may have enhanced recrystallization or localized diagenetic modification, resulting in changes in mineral composition and geochemical signature. These processes are consistent with the observed increase in impurity oxides and the classification of the affected limestone as low grade. The presence of higher Al_2O_3 and Fe_2O_3 in several low grade limestone samples further supports the interpretation of non carbonate contamination. Aluminium oxide is commonly associated with clay minerals or fine grained siliciclastic input, whereas iron oxide may reflect the presence of iron minerals derived from volcanic rocks, weathering products, or hydrothermal alteration. Therefore, the geochemical character of the low grade limestone near the intrusive zone is unlikely to be controlled by carbonate deposition alone. Instead, it reflects a more complex interaction between primary depositional processes, volcanic material supply, and post depositional alteration.

Geoelectrical data also suggest that the intrusive body is more extensively developed toward the southern–southeastern sector of the study area. This spatial distribution is significant because it corresponds to zones where limestone quality becomes more variable and where low grade limestone is more commonly interpreted. In contrast, the central part of the study area, which is relatively farther from the main intrusive influence, contains thicker and more continuous high grade limestone bodies. This spatial relationship indicates that distance from the andesitic/basaltic intrusion may be one of the key controls on limestone quality.

Overall, the quality of limestone in the study area is controlled not only by the original depositional environment, but also by post depositional processes, including diagenesis, possible dolomitization, hydrothermal alteration, and thermal interaction with volcanic intrusions. High grade limestone most likely represents carbonate accumulation that remained relatively isolated from volcanic and siliciclastic influence, whereas low grade limestone near the intrusive zone records chemical dilution and alteration caused by the addition of silica, alumina, and iron components. Therefore, the integration of resistivity data and XRF geochemistry is essential for identifying zones where intrusive rocks may have reduced limestone quality. This interpretation has important implications for future exploration, selective mining, and resource modelling, particularly in mixed carbonate–volcanic terrains where limestone grade may vary significantly over short lateral distances.

4.3. Correlation between Resistivity and Limestone Chemical Composition

Integration of geoelectrical and XRF datasets indicates that high grade limestone is generally associated with thicker and relatively continuous carbonate bodies in the central part of the study area. However, the relationship between resistivity response and limestone chemical quality is not always linear. Although resistivity data are highly useful for identifying subsurface lithological variation and estimating the geometry of limestone bodies, resistivity values are controlled by several factors other than chemical composition. These include porosity, water saturation, fracture intensity, clay content, weathering degree, and the presence of secondary minerals. Therefore, a limestone unit with favorable chemical composition may still show variable resistivity values depending on its physical condition and subsurface fluid content.

Complexity clearly reflected in the interpretation of the geoelectrical data. For instance, at GL 2, the high grade limestone unit shows relatively lower resistivity values compared with other measurement points, yet the subsurface interpretation still indicates a thick high grade limestone body, extending from approximately 7 m to 58 m depth. This lower resistivity response may be related to higher moisture content, enhanced pore connectivity, fractures, or localized weathering within the limestone. In carbonate rocks, such conditions can significantly reduce resistivity even when the rock remains chemically rich in CaO. Consequently, low or moderate resistivity values should not automatically be interpreted as low grade limestone without geochemical confirmation.

Conversely, high resistivity values do not always indicate high quality limestone. In the study area, very high resistivity values are also associated with andesitic igneous rocks, particularly in the southern to southeastern sector. This demonstrates that resistivity contrast alone may lead to ambiguous lithological interpretation if not supported by geological observation and chemical analysis. Andesite and massive limestone may both produce relatively high resistivity responses under certain conditions, but they have completely different geochemical compositions and industrial implications. Therefore, resistivity data are more reliable when used to define subsurface architecture, lithological boundaries, and possible continuity of limestone bodies, rather than as a standalone indicator of limestone grade.

XRF analysis provides a stronger geochemical basis for distinguishing high grade and low grade limestone. Samples S3 and S4, which are located in the central part of the study area, contain CaO values greater than 52%, indicating relatively high carbonate purity. These samples are also characterized by low concentrations of SiO_2, Al_2O_3, Fe_2O_3, and MgO, suggesting limited siliciclastic contamination, minor clay input, and weak dolomitization. This chemical signature supports the interpretation that the central zone represents the most prospective area for high grade limestone development.In contrast, limestone samples with CaO contents below 52% and elevated SiO_2, Al_2O_3, Fe_2O_3, or MgO are classified as low grade. The increase in SiO_2 and Al_2O_3 may reflect the presence of siliciclastic or clay rich components, whereas higher Fe_2O_3 may indicate volcanic influence, iron minerals, or alteration products. Elevated MgO may suggest local dolomitization or magnesium enrichment during carbonate diagenesis. These chemical variations show that limestone quality is controlled not only by the abundance of carbonate minerals, but also by depositional impurities and post depositional processes.

The combined interpretation of geoelectrical and XRF data therefore provides a more comprehensive understanding of limestone distribution and quality. Geoelectrical data contribute to defining the subsurface geometry, thickness, and lateral continuity of limestone units, while XRF data validate the chemical grade and industrial suitability of the carbonate material. Through this integration, high grade limestone can be more confidently delineated in zones where thick carbonate bodies coincide with high CaO and low impurity oxide contents. Meanwhile, areas with lower CaO and higher impurity oxides can be identified as lower quality zones, even if they locally show resistivity values similar to limestone.

Overall, the correlation between resistivity and limestone chemistry in the study area should be interpreted as complementary rather than directly proportional. Resistivity provides a physical image of the subsurface, whereas XRF provides chemical evidence of limestone quality. The most reliable classification of limestone resources is therefore achieved by integrating both datasets with field geological observations. This approach reduces uncertainty in lithological interpretation, improves the distinction between high grade and low grade limestone, and provides a stronger basis for three dimensional resource modelling, selective mining, and future drilling validation.

5. Conclusion

The Cimanggu area in Pandeglang Regency represents a carbonate–volcanic geological system in which limestone of the Bojongmanik Formation occurs in close association with volcanic rocks of the Honje Formation. The interfingering relationship between these formations has produced lateral lithological variation and strongly influenced the distribution and quality of limestone within the study area. Based on the combined interpretation of geoelectrical measurements and XRF geochemical data, the subsurface geology can be grouped into five main units: surficial soil, claystone, low grade limestone, high grade limestone, and andesitic and basaltic igneous rocks.

High grade limestone is mainly concentrated in the central part of the study area, particularly around GL 2, GL 3, GL 5, and GL 9. This zone is considered the most favorable area for limestone development because it contains relatively thick carbonate intervals, locally reaching approximately 40–50 m. The geochemical characteristics of this limestone are marked by CaO values above 52%, SiO_2 below 2.5%, MgO below 0.5%, Al_2O_3 below 1.1%, and Fe_2O_3 below 1%. These compositions, especially observed in samples S3 and S4, indicate a calcium carbonate rich limestone with limited contribution from siliciclastic, clay, and iron impurities. This suggests that the central area was likely deposited under relatively stable carbonate forming conditions with minimal influence from volcanic or terrigenous materials.

Low grade limestone, in contrast, is more widely developed toward the western part of the study area and near the intrusive zone. This limestone group is characterized by CaO contents below 52%, together with increased SiO_2, Al_2O_3, Fe_2O_3, and/or MgO. The reduction in CaO and enrichment of impurity oxides suggest that limestone quality was modified by several geological processes, including siliciclastic input, clay contamination, localized dolomitization, and interaction with andesitic–basaltic intrusive rocks. The occurrence of igneous rocks in the southern to southeastern sector further indicates that volcanic influence contributed to the spatial variation in limestone quality.

The geoelectrical method proved useful for identifying the geometry, continuity, and thickness variation of limestone beneath the surface. Nevertheless, resistivity data alone are insufficient to define limestone grade because resistivity may also be affected by porosity, groundwater content, clay proportion, fractures, weathering intensity, and the presence of igneous bodies. For this reason, XRF analysis provides an essential geochemical constraint for distinguishing high grade from low grade limestone based on major oxide composition. The integration of both datasets therefore produces a more robust interpretation than relying on either geophysical or geochemical data independently.

Overall, the central part of the Cimanggu area can be regarded as the principal prospective zone for high quality limestone, where thick carbonate bodies coincide with high CaO concentrations and low impurity contents. Conversely, zones adjacent to volcanic intrusions should be considered more vulnerable to quality degradation because of the higher likelihood of silica, alumina, iron oxide, or magnesium enrichment. These results emphasize the importance of integrating geophysical imaging with geochemical validation in limestone resource assessment, especially in geologically complex carbonate–volcanic settings. Such an approach can improve subsurface interpretation, reduce uncertainty in resource modelling, and support more selective exploration, drilling validation, and future mine planning.

Compliance with ethical standards

Disclosure of conflict of interest

We declare that we have no known competing financial or personal interests that could have influenced the work reported in this paper.

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