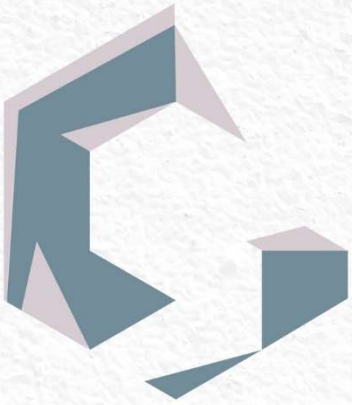


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NEW CHALLENGES ON DIMENSION STONES, FROM PORTUGAL TO THE WORLD

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THE IMPORTANCE OF STRUCTURAL AND SEDİMENTOLOGICAL STUDIES IN A MARBLE QUARRY; AN EXAMPLE FROM BILECIK MARBLE QUARRIES (TURKEY)

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Abstract

There are very rich natural stone resources in Turkey, and high quality products have been produced for the world market with modern production methods from these resources in recent years. Turkey's natural stone export revenue in 2022 has exceeded 2 billion dollars. This study was carried out to emphasize the effects of tectonic-controlled structures (faults, cracks, cracks, folds…) and sedimentological features on the quarry productivity in the marble quarries in Bilecik, and to determine the geological factors that affect the development of the patterns observed in the marble quarries, and to explain the effects of these patterns on the marble quarrying. Within this scope, stratigraphic, sedimentological, structural and engineering geology studies were conducted at different stratigraphic levels in the quarries producing marble in the region. The marble patterns observed in the quarries in this region were determined as Bilecik Beige (Bilecik Beige-oolithic, Bilecik Beige-reefal, Bilecik Beige-fossiliferous, Bilecik Beige-nonfossiliferous) and Rosalia (Rosalia breccia, Rosalian stylolitic). The geological parameters controlling the formation of these patterns and the quarry productivity are (1) the stratigraphic level at which the marble quarry is excavated, (2) the lithological and sedimentological characteristics of the rocks, (3) the characteristics of the faults (types, dip directions, dips) passing through or near the quarry, (4) fracture-crack density in the region, (5) secondary mineral developments and the abundance of these mineral veins.

Key words: Marble pattern, Faults, Sedimentological features, Bilecik, Turkey

1. Introduction

The mineral wealth of a country depends on the geological structure and geological evolution of that country. Because of its geological evolution, Turkey is located both in the Alpine-Himalayan mountain formation system and has been affected by immature tectonic activities. For this reason, it has rich resources in terms of marble, limestone, travertine, granite and basalt in various colours and patterns formed in a wide geological time. When the carbonate rocks in our country are evaluated in terms of quality, colour, pattern and reserve, they have the characteristics and potential to compete with the carbonate rocks around the world.

The block efficiency is low because larger blocks cannot be obtained while cutting blocks in limestone quarries operating in Turkey. The most important parameters affecting the quarry productivity are the facies change occurring during the formation process of the limestone and the deformation of the limestone quarries by tectonism due to the geological conditions of the country.

The study area is located in the province of Bilecik on the Sakarya Continent of the Western Pontides (Figure 1a). The Western Pontides region includes the Istranca Massif, the Thrace Basin, the Istanbul-Zonguldak Union, the Biga-Armutlu-Ovacık Zone, and the Sakarya Zone (Yılmaz et al., 1997; Okay and Tüysüz, 1999; Yiğitbaş et al., 1999; Elmas, 2012). The basement of the Sakarya Zone consists of metamorphic rock assemblages such as high-grade schists, gneisses, amphibolites and metaophiolites (Yılmaz et al., 1981). This metamorphic basement (Uludağ Group and Karakaya Complex) is unconformably overlain by a transgressive Jurassic-Cretaceous sequence (Figure 1a). The province of Bilecik, where the study area is located, is one of the leading marble production areas in the west of the Sakarya Zone. The marble quarries in the northern areas of Bilecik were excavated within The Middle-Upper Jurassic Bilecik Limestone, Cretaceous aged Vezirhan Formation and/or at the contacts of these two units (Figure 1b). Block stone of different colours and patterns are produced from 14 marble quarries (Quarries: K, V, N, T, E, G, S, W, H, O, U, F) in this region, controlled by some geological factors.

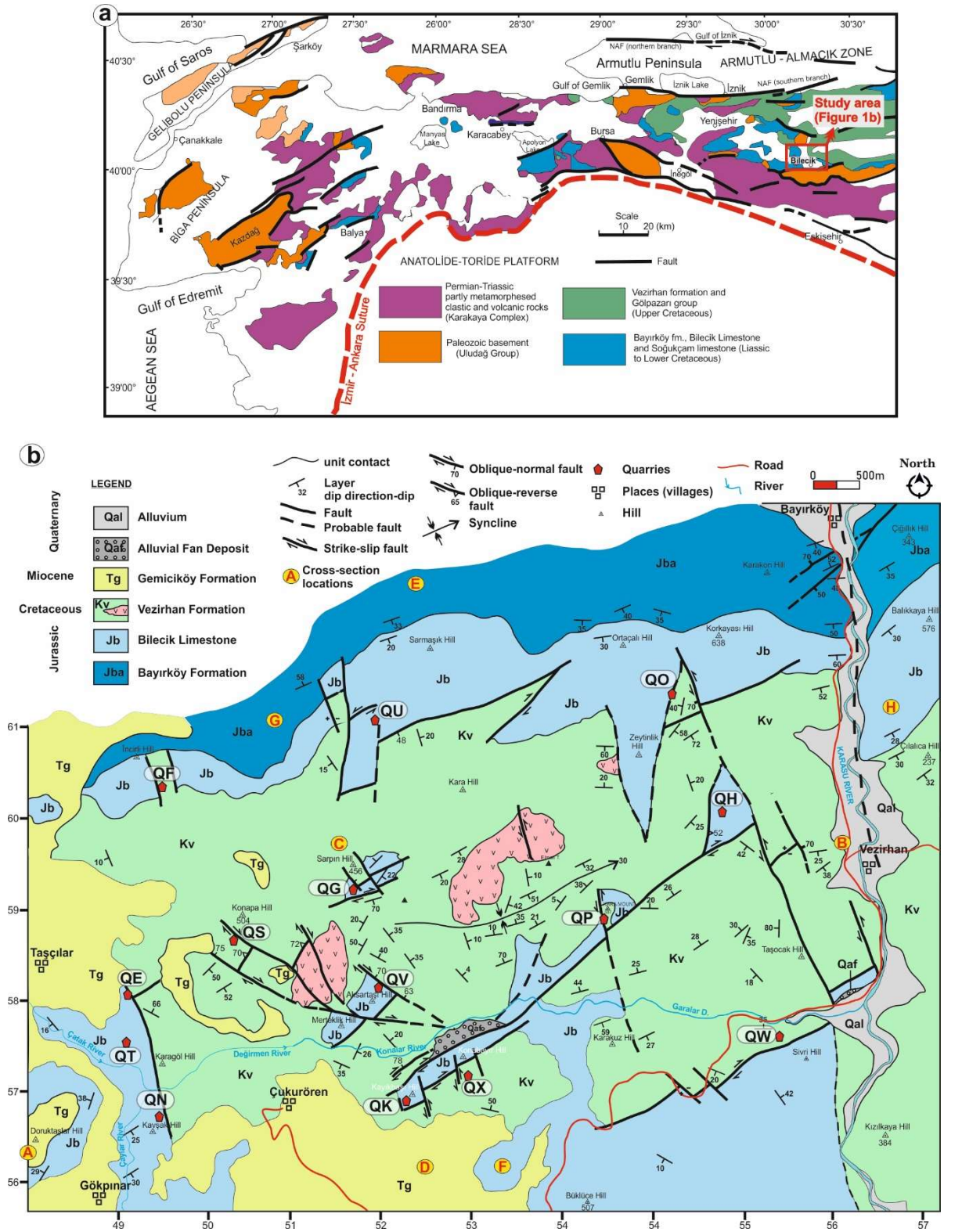


Figure 1. a. *Simplified geological map of Sakarya Continent and major tectonic units of western Turkey separated by the sutures (modified from Yılmaz et al., 1997).* ***b.*** *Geological map of the study area (northern Bilecik, Turkey).*

Studies on identifying the geological parameters controlling the marble patterns and block efficiency from quarries in Turkey are quite limited. It is crucial to determine the marble pattern and block efficiency that will be extracted from a quarry in advance for marble mining. This study aims to highlight the effects of structures that have developed under tectonic control (faults, fractures, folds, etc.) on the selection of marble quarry locations and quarry productivity, to identify the geological factors affecting the development of patterns observed in marble quarries, and to explain the effects of these patterns on marble quarrying.

2. Geology of the study area

In the vicinity of the study area, the basement of the Sakarya zone is formed by the Söğüt metamorphics, which are composed of high-grade schists, gneisses, amphibolites, and migmatites of the Lower Paleozoic age (Çoğulu et al. 1965; Delaloye & Bingöl 2000; Okay et al. 1996, 2002; 2006; Topuz et al. 2007). This metamorphic basement is unconformably overlain by a transgressive Jurassic-Cretaceous sequence, which is observed extensively within the study area. The Bayırköy Formation, which is composed of Lower Jurassic aged conglomerate, cross-bedded sandstone, and debris flow deposits, represents the base of this transgressive sequence. This unit stratigraphically includes carbonate lenses and limestone intercalations upward. The Middle-Upper Jurassic aged Bilecik Limestone conformably overlies the clastic sediments of the Bayırköy Formation. The stratigraphically lower portions of the Bilecik Limestone consist of oolitic limestone levels developed in environments where wave activity was effective in shallow marine settings. Stratigraphically, this limestone, which are rich in fossils and have a reefal character, are characterized by micritic limestone with low fossil content in the upper levels. The Vezirhan Formations, which have a deep-sea character, consisting of Cretaceous-aged chert limestone, red radiolarite, and pelagic limestone, conformably overlay these units. The Vezirhan Formation starts with semi-pelagic limestone that is white or cream-coloured, porcelain-like in appearance, nodular or banded with clay interlayers at the base. Above this level, pinkish-brown pelagic limestone, chert, and radiolarites are present. Greenish volcanic and volcanoclastic layers are also found as intercalations within this sequence. These units are unconformably overlain by the Miocene aged Gemiciköy Formation, consisting of coarse-grained clastics such as conglomerate and sandstone (Figure 1-2).

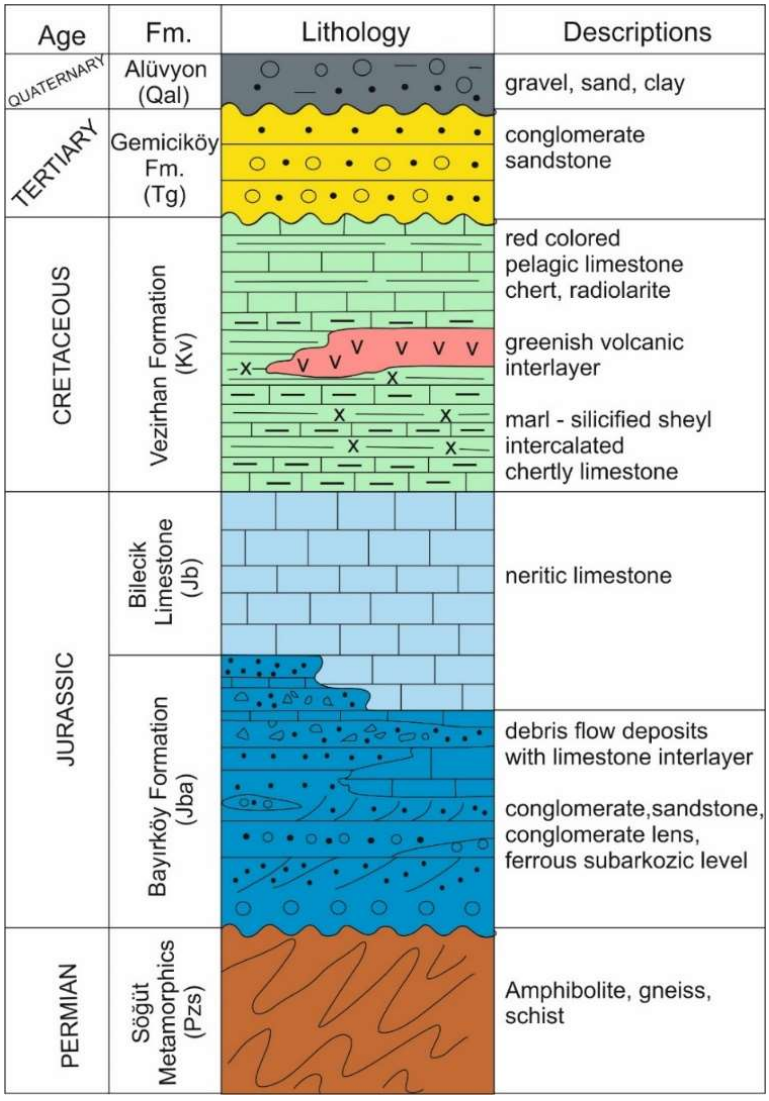


Figure 2. *Generalized stratigraphic section of the study area (Northern Bilecik, Turkey).*

3. Geological Parameters Affecting The Marble Texture

3.1. Lithological and sedimentological features

The QV, QT, and QU quarries are located in areas where the shallow marine character of Bilecik Limestone's lower levels are outcropped stratigraphically. Therefore, the Bilecik Beige-Fossil and Bilecik Beige-Oolitic patterns with a low abundance of fossils and/or an oolitic patterns are extracted from these quarries (Figure 3a-b). The QK, QG, and QH quarries are excavated in the Middle-Upper Jurassic-aged Bilecik Limestone's stratigraphically middle levels. These levels consist of limestone with abundant fossil reef-like characteristics. From these levels, the Bilecik Beige-Reef pattern is extracted (Figure 3c). In the quarries QP and QO, excavated at the contacts between Bilecik Limestone and Vezirhan Formations, the Bilecik Beige-Reef pattern belonging to the middle levels of Bilecik Limestone is observed.

Additionally, unlike the other quarries, blocks are extracted from lithologies belonging to the Vezirhan formation in the QP and QO quarries. In the QP and QO quarries, there is the Rosalia pattern extracted from the burgundy coloured pelagic limestone (Figure 3e). Furthermore, the greenish-beige coloured clay limestone with shale intercalations of the Vezirhan Formation also crop out at shallow depths in the QO quarry. These lithologies are less durable and more prone to plastic deformation compared to other rock types in the quarry. Therefore, zig-zag folds originating from tectonism have developed in the rocks at these levels of the Vezirhan Formation. The Zig-Zag Pattern, which arises from the relationship between rock type and tectonism, can be observed in the blocks extracted from these levels (Figure 3ı).

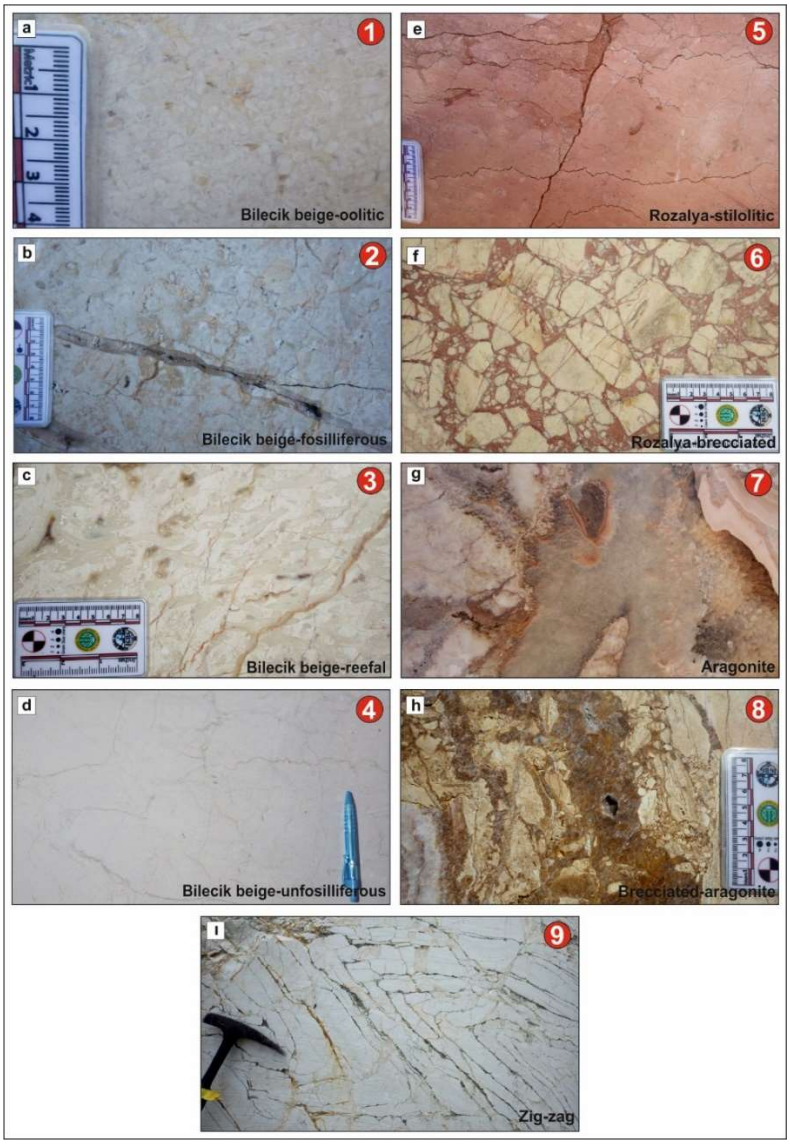


Figure 3. *Marble patterns from the quarries in the study area.*

3.2. Faults

The study area is located in a tectonically active region influenced by the North Anatolian Fault Zone (NAFZ) and the Eskişehir Fault Zone (EFZ) in terms of its geological location. The faults passing through the marble quarries in this region and their vicinity are given in the geological cross-sections in Figure 4. When the geological map of the study area (Figure 1b) and its cross-sections (Figure 4) are examined, it can be seen that the marble quarries in this region are generally aligned along these fault zones. The faults generally follow the contacts between the Middle-Upper Jurassic Bilecik Limestone and the Cretaceous-aged Vezirhan Formation. The blocks (footwall and hanging wall blocks) on both sides of the fault plane in the areas where the faults pass have undergone brittle deformation to form fault breccia. Brecciated patterns developed under tectonic control are observed in the blocks extracted from the marble quarry along these zones (Figure 3f). These brecciated patterns, observed in pinkish-red colours, are commercially called Rosalia breccia.

The quarries where the Rosalia breccia pattern is extracted are QK, QP, QO, and QU, and to a lesser extent, the QG and HDF quarries (Figure 1b). Apart from these brecciated zones, faults also cause the formation of various fracture systems in rocks, and the formation of these fracture systems leads to the formation of veins by various minerals settling in these fractures. In fact, the main factor controlling these triggering elements is faults. The strike, dip, and characters of the faults also play an important role in the marble patterns extracted from the quarries.

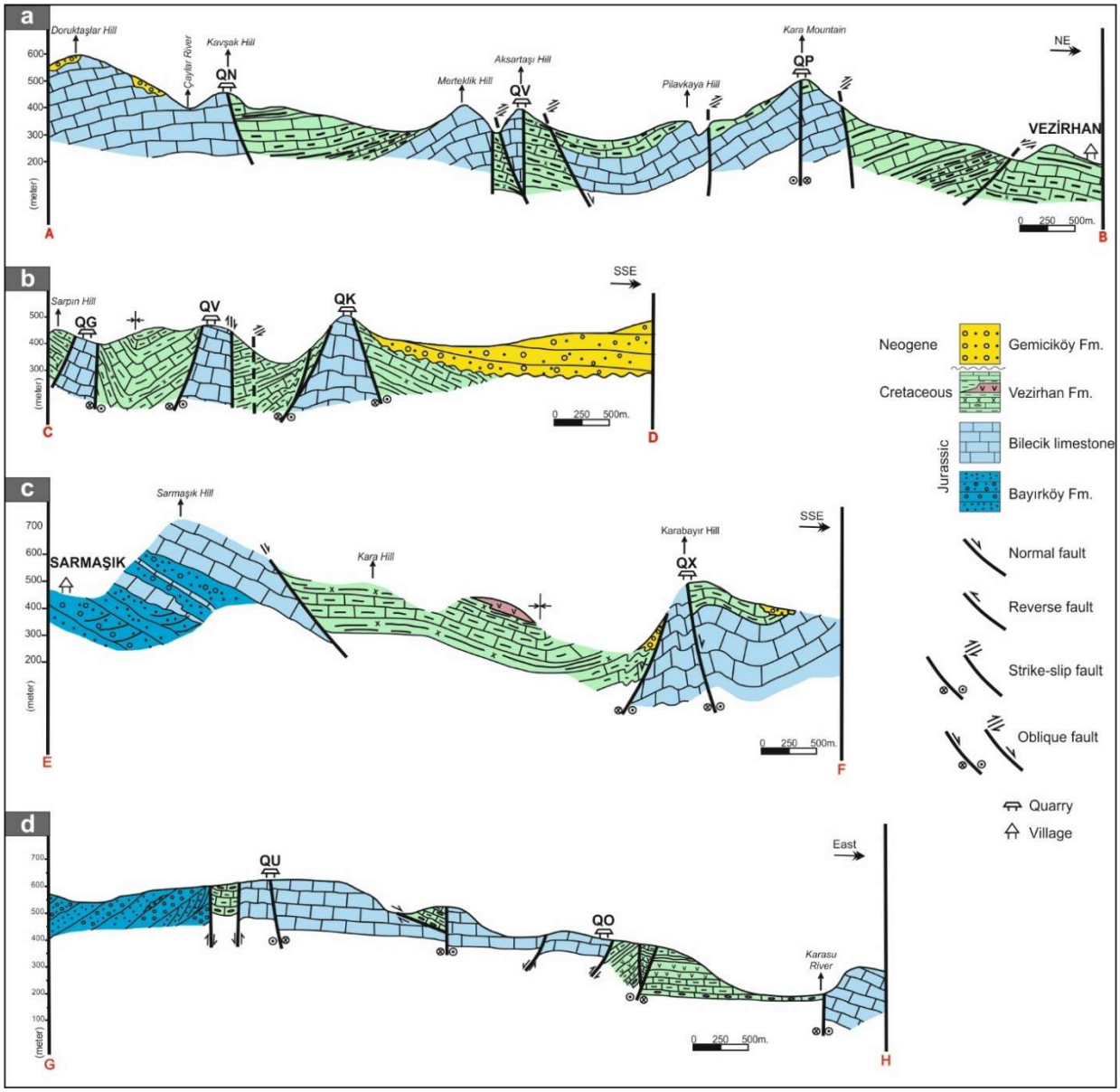


Figure 4. *Geological cross-sections along the quarry sites and routes passing through the vicinity of the study area (see Figure 1b for section routes).*

As part of this study, QK, QV, QN, and QH quarries were studied in detail. Within the scope of the detailed study, the detailed geological and structural geological characteristics of the four quarries were mapped, and pattern changes on a quarry basis were determined.

The QK quarry is surrounded by faults on all four sides (Figure 5). Along the right-lateral strike-slip fault zone passing north of the quarry, a wide alluvial fan deposit has developed on the northern slope of Konabayır Hill. In addition, the left-lateral strike-slip fault zones observed in the western and eastern parts of the quarry have caused the displacement and fragmentation of levels belonging to the Bilecik Limestone extracted from the quarry.

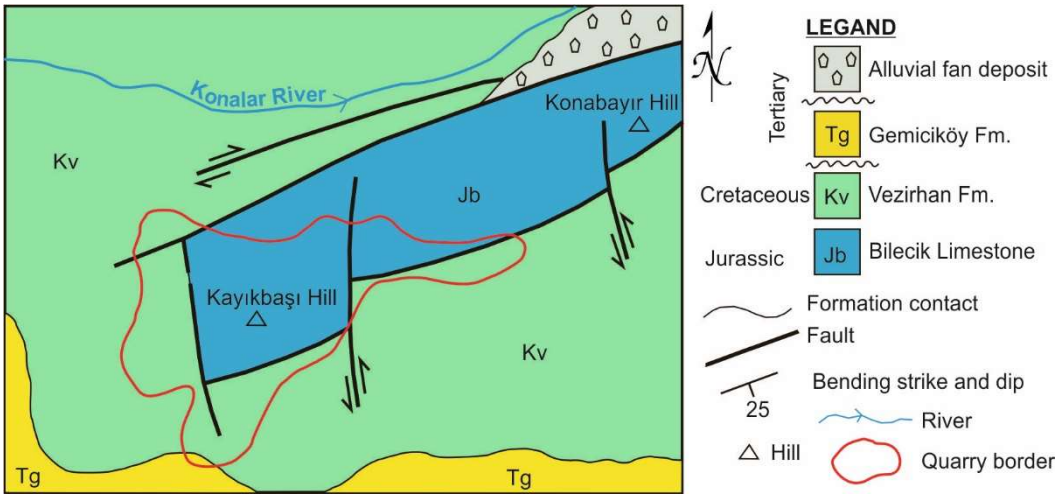


Figure 5. *Geological map of the QK Quarry and its vicinity.*

There is a vertical slip on the southern part of the QV Quarry and a right-oblique normal fault dipping east on the eastern part (Figure 6). As the fault, that borders the QV Quarry from the east dips outside of the quarry, rather than inside, when going deeper into the quarry, blocks with less effect from the fault, which are more clear-in pattern and have better strength, are reached (Figure 9a). The dip direction of faults is towards the outside the quarry ensures that the blocks extracted from the quarry are less affected by the fault. Therefore, no tectonic breccia pattern is observed in the Vezir Quarry, or it is observed locally.

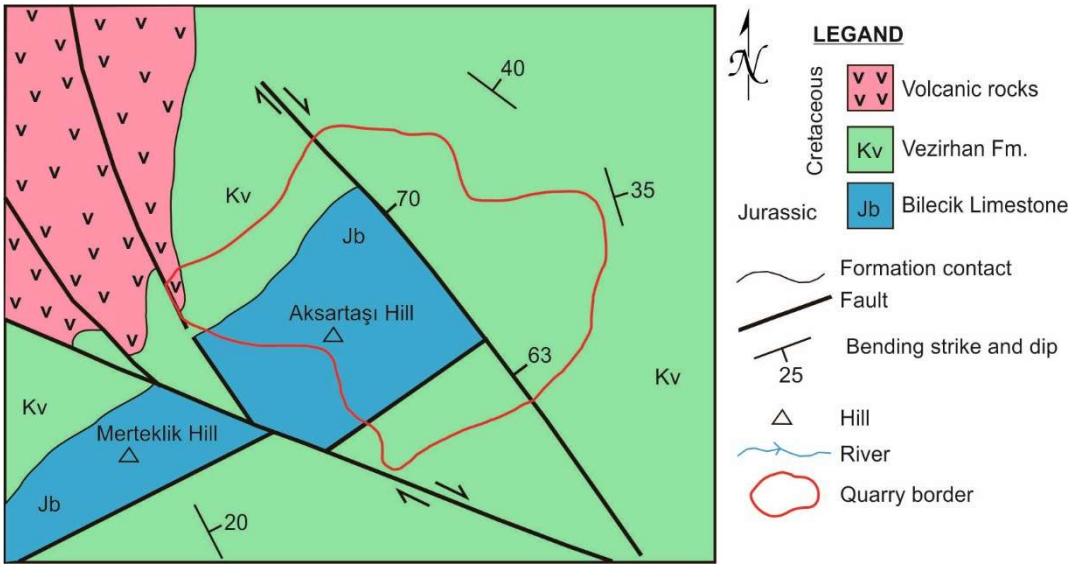


Figure 6. *Geological map of the QV Quarry and its vicinity.*

There is a fault that extends towards the QN quarry to the east of the QT quarry and is located at Kavşak Hill in the south (Figure 1b and Figure 7). Since this fault is located away from the quarry and dips to the east (away from the quarry), it does not significantly affect the patterns in the QT and QN quarries. Additionally, there is a secondary fault connected to this main fault located just north of the QT Marble quarry. This fault is also a normal fault dipping to the north (away from the quarry) and does not significantly affect the patterns in the QT quarry. There is also a fault that extends along the N20W strike in the east of the QN quarry and dips

towards NE (Figure 9c). This fault, similar to the fault in the QT quarry, dips both towards the edge of the quarry and outside the quarry, so it moves further away from the quarry as depth increases. This does not have a significant negative impact on the Bilecik Beige pattern and block efficiency in the quarry.

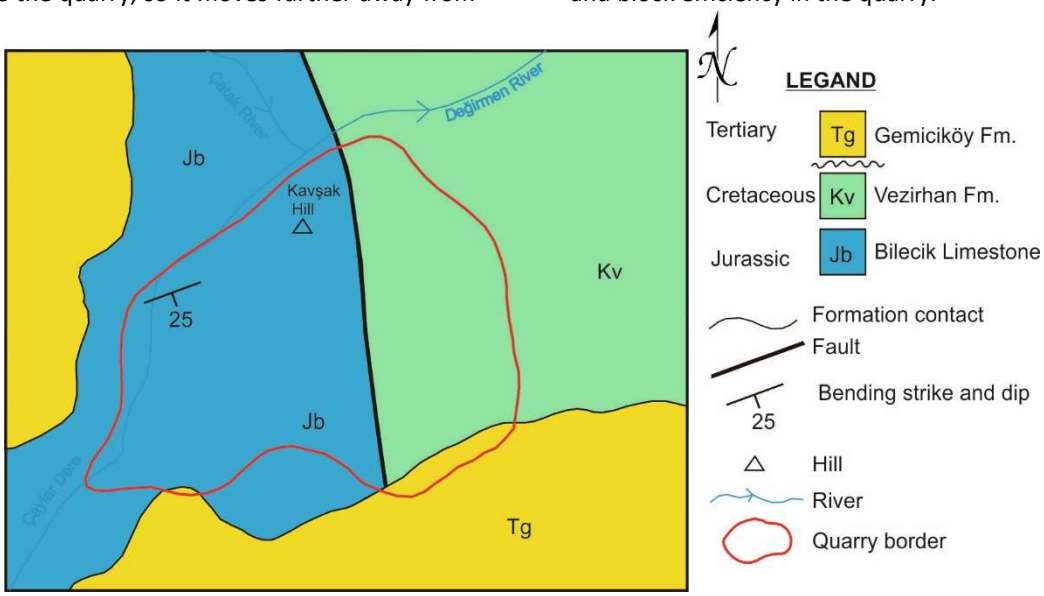


Figure 7. *Geological map of the QN quarry and its vicinity.*

The Bilecik Limestone, which is the rock type extracted from the QH quarry, is surrounded by faults on all sides at this location (Figure 8). The fault passing through the quarry and forms the boundary between the Bilecik Limestone and the Vezirhan Formation is a reverse fault with approximately N-S strike and a 52-degree dip to the south (Figure 9d). The Bilecik Limestone in the hanging wall block of the fault are pushed towards the red-brown pelagic limestone of the Vezirhan Formation. This reverse fault movement has caused significant deformation and fracturing in the rocks in both blocks. Additionally, since this fault dips into the quarry, the fault zone is approached as depth increases in the quarry (Figure 9d). This negatively affects the block efficiency in the QH quarry. The blocks extracted from the HDF quarry show a Rosalia (breccia) pattern due to the tectonic faults in the quarry (Figure 3f).

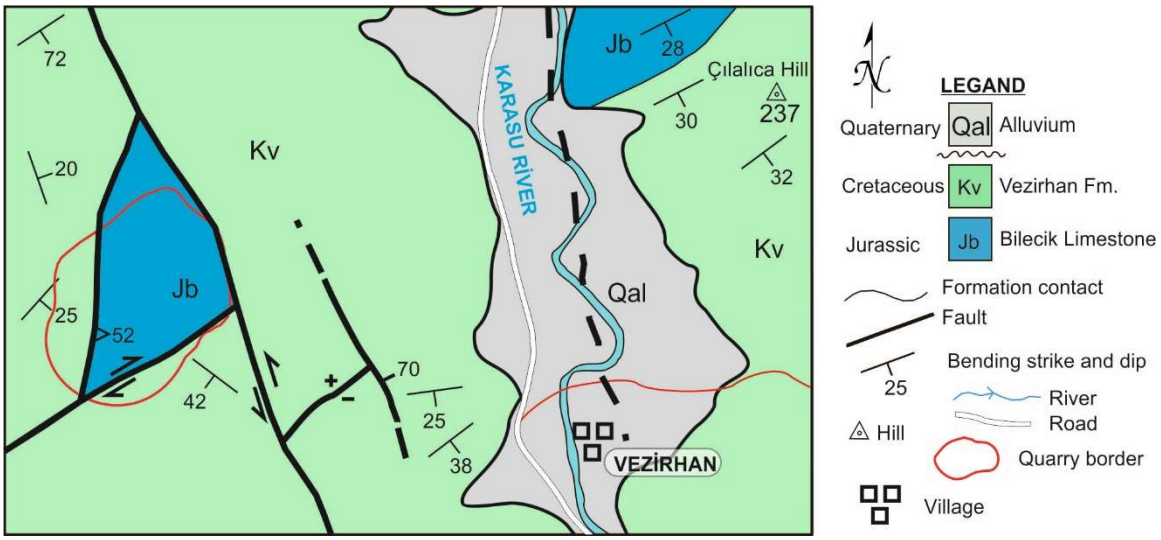


Figure 8. *Geological map of the QH quarry and its vicinity.*

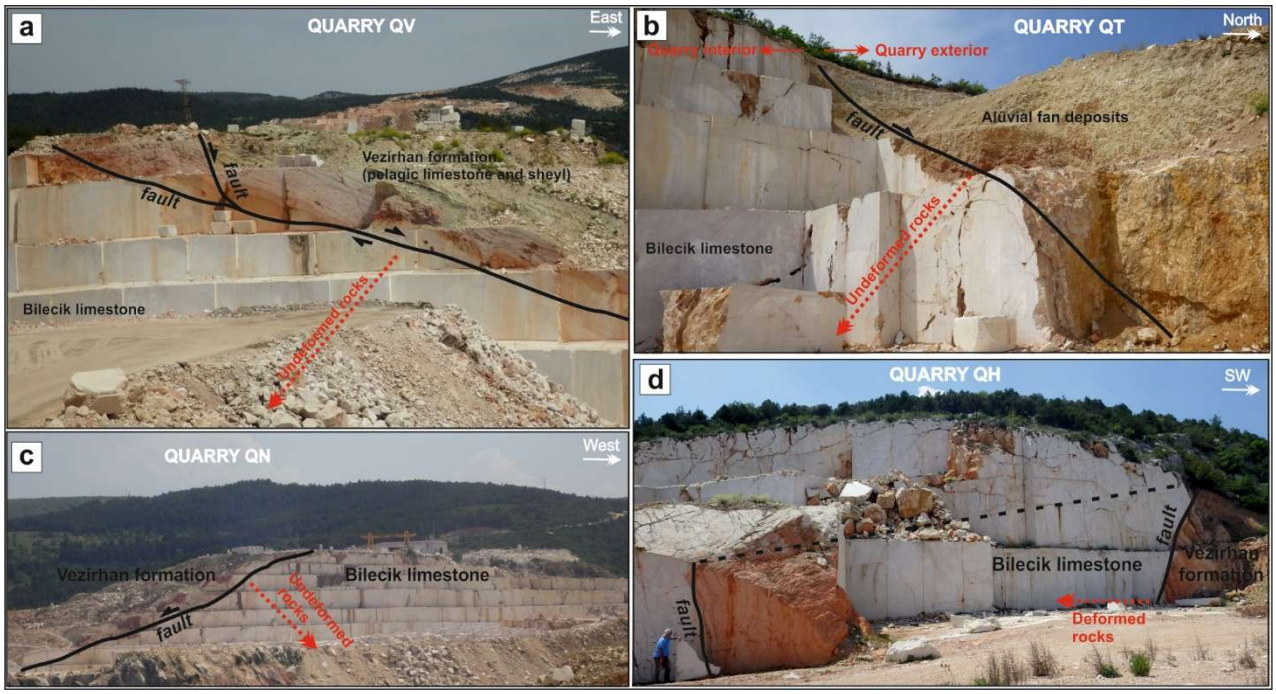


Figure 9. *The extents of the faults passing around the QV quarry (a), QT quarry (b), QN quarry (c), and QH quarry (d), and their effects on the rocks within the quarries.*

3.3. Discontunity

The fracture-crack systems observed in the marble quarries in the study area are all of tectonic origin. These include tension cracks (1) developed by tension, shear cracks (2) formed parallel to joint planes by shear movement, stylolite (3) developed in rocks parallel to the principal stress direction, and sigmoidal cracks (4) formed in brittle-ductile shear zones. Tension cracks and sigmoidal cracks are typically later filled with aragonite minerals, forming aragonite vein patterns. These tectonic fractures are present in each quarry in the region, but are more commonly observed in QP, QK, QE, QF, QU, and QO quarries, which are located on or near fault zones. Stylolitic fracture systems are typically observed in the pelagic limestone levels of the red-bordeaux coloured Vezirhan formation or in the breccia levels of the tectonic contacts between the Bilecik Limestone and Vezirhan Formation. This stylolitic fracture pattern is called the Rosalia-stylolitic pattern (Figure 3e) and is mostly extracted from QP, QO, and QK quarries.

The production of block stone in quarries is a long process that requires detailed engineering geology studies (such as fieldwork, discontinuity properties, lineament analysis, colour-pattern tracking, etc.) to estimate the potential production of block stone, determine the block sizes to be produced, manage the quarry according to the geological conditions and advance the production.

There are many parameters that affect the efficiency and production of block stone quarries. Among these parameters, those of geological origin directly affect efficiency and production. In this study, QK, QV, QN, and QT quarries were studied in detail. Within the scope of the detailed study, engineering properties of discontinuities were determined using the scanline method in accordance with the principles stated in ISRM (2007), and quarry discontinuity maps were prepared based on production benches for the relevant four quarries (Figure 10). The dominant orientation of the discontinuities in the quarry was determined using Dips 6.0 software (Rockscience, 2012) (Figure 11), and the spacing and aperture of the discontinuities were also determined. In addition, the block size index, volumetric joint count, and block quality designation that affect the block efficiency in the quarry were determined according to the discontinuities (Table 1).

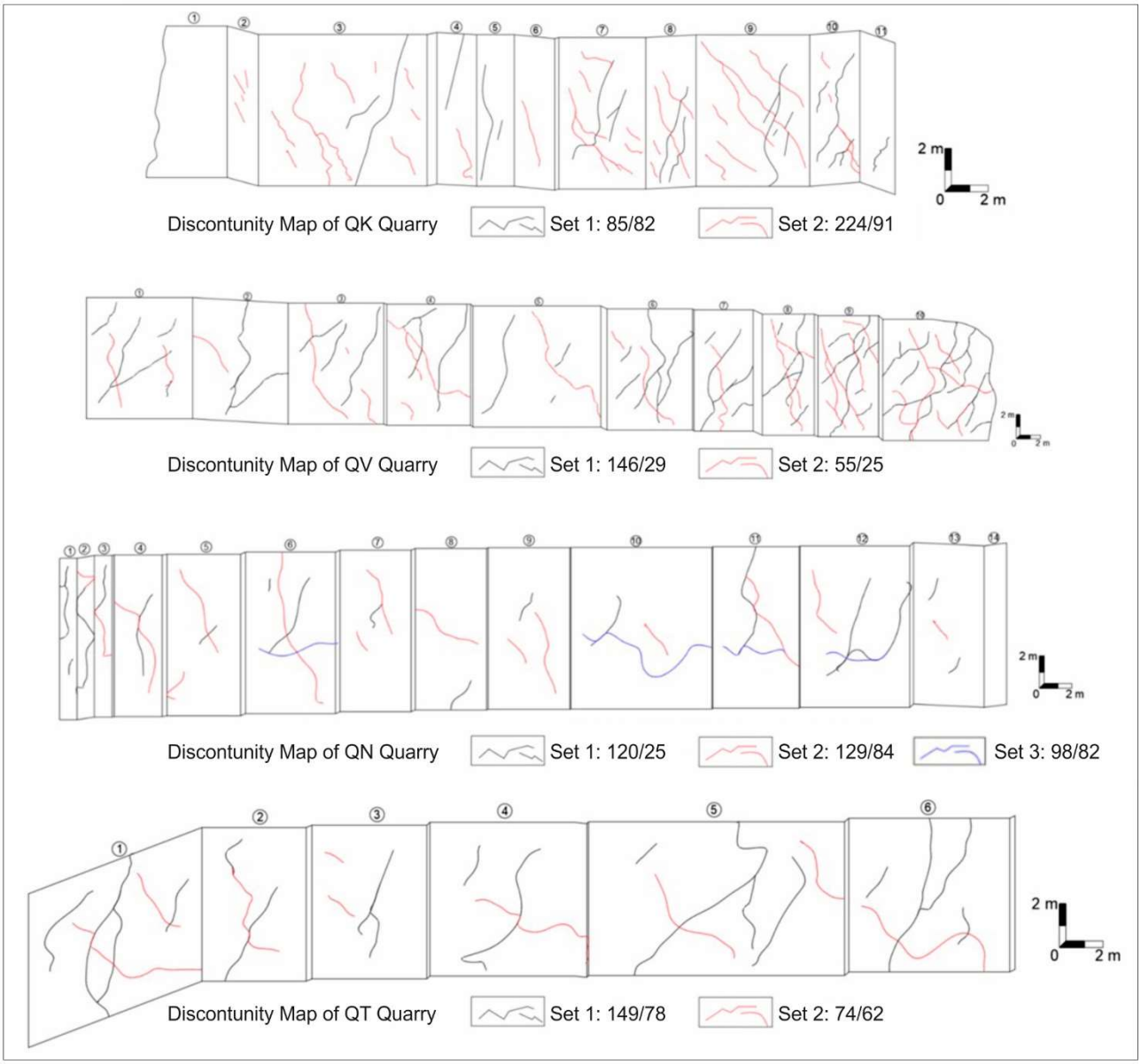


Figure 10. *Discontinuity maps prepared in the relevant quarries, (a) QK, (b) QV, (c) QN, (d) QT.*

Table 1. *Properties of discontinuities in QK, QV, QN and QT quarries.*

Quarry name	Number of discontinuity	Discontinuity orientation	Discontinuity spacing	Discontinuity aperture	Block size index (Ib)	Volumetric joint count (joint/m^3)	Block quality designation (BKG,%)
QK	95	Set1:85/82 Set2:224/91	2,90 m	17 mm	4.84	0,81	%80
QV	169	Set1:146/29 Set2:55/25	10 m	23 mm	2,50	0,91	%78
QN	96	Set1:120/25 Set1:129/84 Set2:148/85 Set3:98/82	14,9 m	29 mm	3,49	0,65	%83

QT	61	Set1:149/78 Set2:74/62	12,65 m	36 mm	3,73	0,53	%88

In light of these data, the block size that can be obtained from QK, QV, and QT quarries is controlled by 2 sets of discontinuities, while in QV quarry it is controlled by 3 sets of discontinuities. Discontinuities in QK quarry are defined as "very wide-spaced discontinuities", and those in QV, QN, and QT quarries are defined as "intensely wide-spaced discontinuities" (ISRM, 1981). Based on the data of volumetric joint count, all quarries examined are defined as sparsely jointed rock mass (Palmstorm, 1982 and 1996). The block size index is greater than 3 for all quarries except QV quarry, where it is 2.50. The Block Quality Index (Elçi and Türk, 2014) is greater than 50% for all quarries examined (Table 1).

3.4. Aragonite veins

As a result of tension and sigmoidal fractures in the quarries being worked on, aragonite minerals have filled in to form honey-coloured aragonite veins. The thicknesses of these veins range from a few millimeters to 15-20 centimeters, sometimes appearing as continuous bands while in other places they are discontinuous, fragmented by small faults. Especially the thin aragonite veins do not pose a problem in block production, but they do disrupt the homogeneity of the marble pattern. Aragonite veins can be observed within Bilecik Beige and Rosalia patterns (Figure 3b-c). However, in the QP quarry excavated on the strike-slip fault zones, the Aragonite pattern consisting of only aragonite or the brecciated-aragonite pattern with a very high aragonite ratio is extracted (Figure 3g-h). In fact, the thicknesses of aragonite veins can reach several meters, and the extracted blocks can be entirely composed of aragonite.

4. Conclusion

- Quarries for marble production in the northern areas of Bilecik were excavated within the Middle-Upper Jurassic Bilecik Limestone of the Jurassic-Cretaceous aged transgressive succession, Cretaceous Vezirhan Formation and/or at the contacts of these two units.
- The size of the blocks produced from these quarries is generally controlled by two, and rarely by a third set of discontinuities. The discontinuities in the quarries are "intensely wide- spaced" and "very wide-spaced". This indicates the low jointed nature of the limestone mass and allows for the production of economically valuable blocks from block quarries excavated within these limestone formations.
- The marble patterns in this region are identified as Bilecik Beige Pattern (Bilecik Beige-oolithic, Bilecik Beige-reefal, Bilecik Beige-fossiliferous), Rosalia Pattern (Rosalia-brecciated, Rosalia-stylolitic), Aragonite Pattern, Brecciated Aragonite Pattern, and Zig-Zag Pattern.
- The Bilecik Beige-oolithic pattern is stratigraphically extracted from the basal levels of the Bilecik Limestone, the Bilecik Beige-reefal pattern is extracted from the middle levels of the Bilecik Limestone with a shallow marine coral reef character, the Bilecik Beige-fossiliferous pattern is also extracted from the shallow marine middle levels, and the Bilecik Beige-nonfossiliferous pattern is extracted from the uppermost levels that represent a deeper marine environment.
- The Rosalia pattern is divided into two types: Rosalia-brecciated and Rosalia-stylolitic. The Rosalia-brecciated pattern is a brecciated pattern extracted from the fault zones where the Bilecik Limestone and Vezirhan Formation are in contact. The Rosalia-stylolitic pattern is extracted from the pelagic limestone of the Vezirhan Formation that represent a deep-sea environment with a reddish-brown colour.
- In addition to the Rosalia-brecciated pattern, Aragonite and Brecciated Aragonite patterns, which develop with the effect of secondary aragonite minerals emplaced in the fracture-cracks, are extracted from the fault zones.
- The geological parameters that affect marble production, block efficiency, and marble pattern in the study area (Bilecik North Quarries - Western Turkey) are (1) the lithological and sedimentological properties of the sequence, (2) faults (type, strike, dip, and density), (3) cracks-fractures, and (4) aragonite-filled veins.

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