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Application of Geomechanical Classification Systems in a Tourist Mine for Establishing Strategies within 3G's Model

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Abstract: Stability problems in rock masses are one of the main causes of subsidence events in underground mining areas. Zaruma, in the South of Ecuador, is characterised by mineral wealth, in which 65% of the population depends directly on artisanal mining activity. However, mineral extraction, without technical considerations and in many cases illegal, has negatively impacted the stability of tunnels generated under the city's urban area, reporting subsidence events in recent years. The aim of this study is to geomechanically characterise the main gallery of the tourist mine "El Sexmo" using two classic methods of geomechanical classification for the configuration of a model that complies with the 3G's (geotourism, geoconservation, and geoeducation) and supports the culture of sustainability in all areas of the sector. The methodology consists of (i) a field study design, (ii) a geological–geomechanical survey of the rock mass of a tourist mine using rock mass rating (RMR) and the Q-Barton index, and (iii) establishing a 3G's model for sustainable development. The results reveal that 100% of the rock mass of the tourist mine presents a rock quality classified as "Fair" (class III) by the RMR method, while, via the Q-Barton method, 92.9% of the rock mass obtains a "Poor" rating, except for station S05, rated "Very Poor". Furthermore, the study proposes additional support measures for three specific stations based on Q-Barton assessments, including fibre-reinforced sprayed concrete and bolting and reinforced ribs of sprayed concrete, considering that the mine is more than 500 years old and maintains geological features for geoeducation in geotechnical mining. Technical and social problems demand an innovative strategy, which, in this work, focuses on the 3G's model based on the quintuple innovation helix to develop sustainable underground geotourism.

Keywords: conservation; artisanal mining; illegal mining; ASM; mining geoheritage; geotourism; geoeducation; Zaruma

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1. Introduction

Cavities are underground open spaces of natural or artificial origin [1]. Detecting these structures is challenging and plays an important role in evaluating ground stability [2]. Mining activity generates one type of cavity that becomes a threat if not built with technical criteria [3].

Mine galleries, also known as underground mines, significantly affect the environment and local communities. These include land subsidence [4,5], water pollution [6–8], air pollution [9], habitat destruction [10], waste generation [11], and social and economic impacts [12]. In particular, the underground extraction of minerals generates surface subsidence and deformation, which must be considered in land use planning [13]. Information on natural hazard zones associated with the impacts of mining activities is essential and serves as a basis for the sustainable management of natural resources used by policymakers [14].

To mitigate negative impacts and ensure positive legacies for local communities, mining companies worldwide must achieve high-quality rehabilitation and return the site to a status that supports post-mining land use [15]. Abandoned mines can pose a significant risk to public safety, and associated caverns can occur because of various factors, such as geological processes, lack of maintenance, or human activity [16]. There are many cases of regional and local collapses related to abandoned mines. Examples include the chalk mine (France) [17], Castle Fields mine (UK) [18], room and pillar limestone mines (The Netherlands) [19], salt mines (Ukraine) [20], gypsum mine (United States) [21], mines of construction material, such as tuff and pozzolana (Italy) [22], and siderite mines (Spain) [23].

A significant step towards sustainable mining is the non-traditional use of underground mines and surrounding land [24], such as energy storage [25,26], domestic and industrial waste disposal [27], parking systems in vertical wells [28,29], scientific experimentation facilities [30], underground agriculture [31], underground ecological cities [32], and rehabilitation of underground mines for tourism and recreational purposes [33].

Several abandoned mines may have attractive features and educational, cultural, and technological benefits [34]. In addition, the conservation and regeneration of abandoned mining sites' natural, artificial, and social features can attract tourism development [33,35] and have positive implications for the local economy [36].

Historically, the first forms of geotourism can be traced to visits to caves and mines [37]. Geotourism, a form of tourism based on understanding and acquiring geological knowledge, was first proposed in 1995 [37–39]. A component of geotourism is underground geotourism [36], which explores the unique geological characteristics of underground spaces, including visits to natural caves, caverns, tunnels, mines, and other artificial underground structures [40–42]. Underground geotourism has become an opportunity for the sustainable development of mining sites [43] and provides an alternative for local communities after mining activities end [44]. However, geotourism of mining sites is a challenge because they are generally located in remote areas, present anthropogenic waste from mining activity, lack services (maintenance), host sources of contamination rock mass instability problems [18], and are habitats of wild species [45,46].

The long-term stability of abandoned mines typically involves time-dependent effects, including creep and gradual rock deterioration (weathering) [47,48]. There have been many investigations related to the failure and long-term stability of old underground engineering sites, including the work of [49], who developed an empirical index known as the abandoned mine instability index (AMII) to allow a rapid and preliminary assessment of geotechnical instability and subsidence hazards in post-mining areas. Gao et al. [50] applied rock mechanics theory to assess the stability of an ancient Longyou underground cavern and proposed a protection program. Additionally, a study on the old underground caverns of Heidong [51] evaluated the quality of the surrounding rock using the rock mass rating (RMR) and Q-Barton index, identifying the types and failure mechanisms of ancient engineering construction.

Geomechanical classifications are empirical methods that allow a preliminary evaluation of the behaviour of rock massifs, and their information generates an appropriate design for conceptual engineering projects of rock massifs [52]. The most widely used systems for estimating stability conditions and support measures for many underground constructions are rock mass rating (RMR) [53], Q [54], geological strength index (GSI) [55], mining rock mass rating (MRMR) [56], and rock mass index (RMi) [57]. Although there are several classifications of rock masses, using more than one classification is highly recommended to obtain a comprehensive understanding of the host rock and predict soil behaviour [58].

Geomechanical classification systems generate debate among geoscientists because they present limitations owing to subjective valuation uncertainties [59]. However, geomechanical classification is the only practical basis for the design of projects related to complex underground structures [58]. The quality of rock mass materials in underground excavations cannot be measured exclusively by strength tests but instead requires methodologies with holistic approaches that consider various geological parameters [57].

The need to reduce subjectivity has led to several studies comparing classification systems and proposing improved evaluation approaches. Some examples are the study by [60], which compares the 1998 and 2013 GSI versions and shows the conditions of the most conservative system. Furthermore, comparative research by [61] used the RMR, Q, RMi, and GSI systems to propose two new correlations for rock mass classification. Finally, applying the fuzzy set theory [59] to the rock mass excavability (RME) index to select an adequate tunnelling technique offers the possibility of using it in all index-based rock engineering classification systems.

Artisanal and small-scale mining (ASM) is a type of activity characterized by intensive labour and low technology, which, compared to technical large-scale mining (LSM), has a significant impact on the environment, generates geological hazards, and compromises the well-being of humanity [62,63]. ASM accounts for between 15 and 20% of the world's mineral production [64]. However, in this type of mining, social, environmental, and political problems are common (e.g., [65–67]), and their mitigation has been more intensively investigated in the last decade (e.g., [68–74]).

Zaruma is a mining city in the southwest of Ecuador with a unique geological mining heritage [75,76]. The gold potential of the sector [77–79] has allowed the development of intense mining activity of the ASM type through different types of exploitation. Thus, in the Zaruma environment, illegal mining has caused subsidence in various sectors related to the presence of cavities and abandoned pikes, particularly in urban areas [80]. Many of these cavities are not inventoried, are difficult to access, and constitute a geological risk.

In Zaruma, seven significant subsidence phenomena were observed from 2016 to 2022 (Figure 1). The first was the "La Inmaculada" school, with a 23 m cone of collapse (2016), followed by the Coliseo de Zaruma sinkhole (2016), Gonzalo Pizarro Street (2019, 2020, 2021), the Avenida Colón sinkhole (2021) [80,81], and the recent recurring event of 2016 at the "La Inmaculada" school in 2022. However, one of the collapses with the greatest impact on society was the collapse of the La Inmaculada School. This event triggered an increase in restrictions on mining activity in the urban area through the Mining Exclusion Zone (MEZ) decree (Ministerial Agreement No. 2017-002), issued by the competent body of the Ecuadorian state (Ministry of Mining). This decree, modified in 2017, prohibits mining in an area of approximately 1.77 km^2 around Zaruma.

The "El Sexmo" tourist mine is an icon of the mining history of southern Ecuador and has been a tourist complex since 2005. The gallery enabled for tourism is 405 m long, with heights that vary between 1.8 and 6.3m and a gallery width between 2 and 3 m. The mine offers an average of 9000 tourists a year services, such as an underground tour, an exhibition of the history of the mine, a gift shop, mineral exhibitions typical of the area, and green spaces with a viewpoint over the city [75]. However, its location within the ZEM raises the need to monitor the geotechnical properties of the rock mass to guarantee tourist safety. Additionally, within the services of the tourist complex, it is necessary to strengthen the geoeducation resources that exhibit mining geoheritage and geotechnics in a friendly form for non-technical audiences.

In this context, the present study aims to geomechanically characterize by applying two classical methodologies, RMR [53] and Q-Barton index [82], which allow (i) underground geomechanical framing, (ii) the definition of the most conservative method for the evaluation of rock quality in mining cavities, and (iii) establishing sustainability measures by configuring a model that complies with the 3G's (geotourism, geoconservation, and geoeducation) to reach the different spheres of society and contribute to the five innovation subsystems.

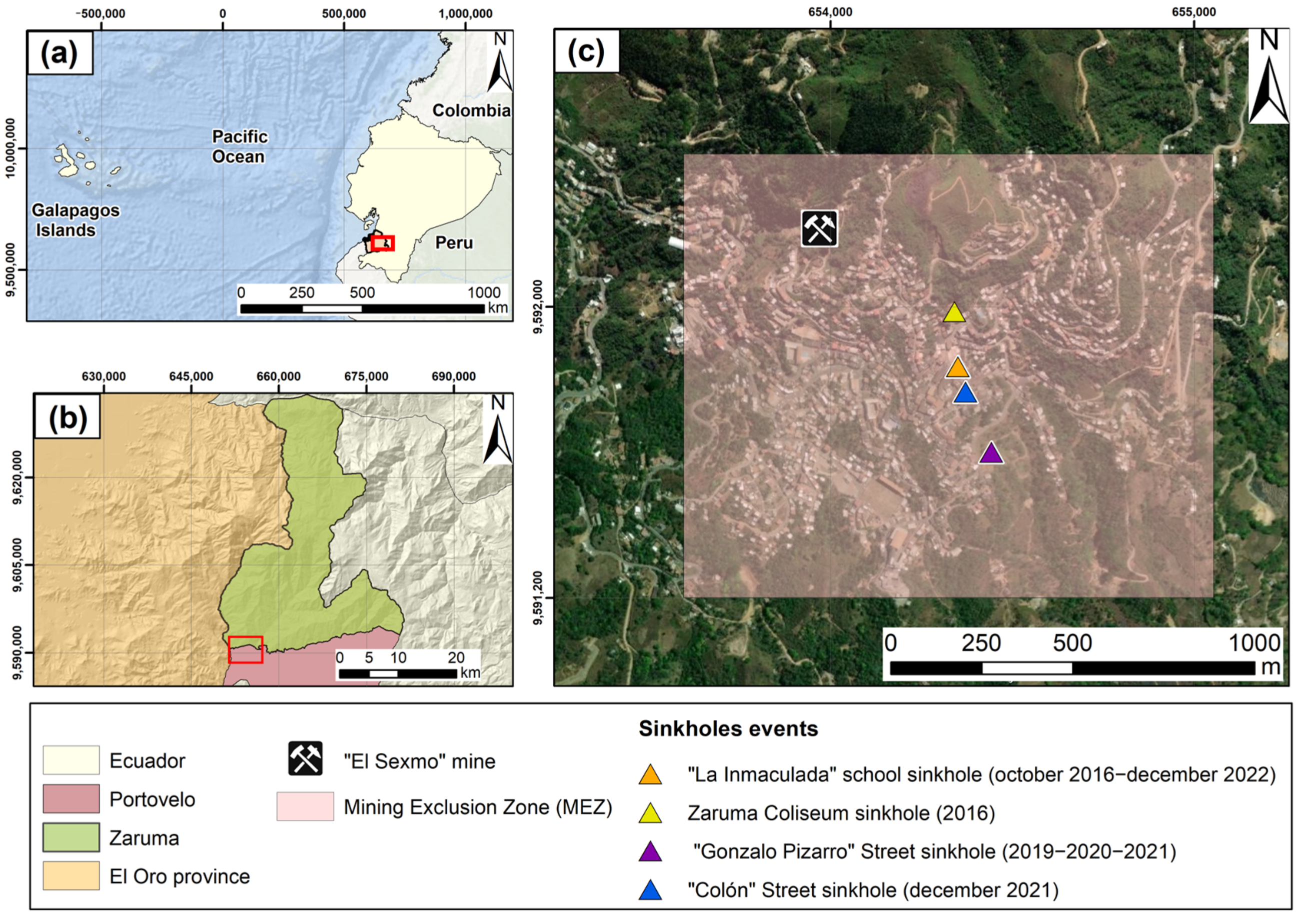

Figure 1. Study area location: (**a**) Ecuador in South America and Zaruma canton; (**b**) El Oro Province and Zaruma canton; (**c**) sinkhole events in Zaruma and location of "El Sexmo" mine.

2. Materials and Methods

The study methodology has a mixed approach that combines qualitative and semi-quantitative evaluations in a tourist mine based on geological–geomechanical parameters that allow for the proposal of geotourism, geoconservation, and geoeducation strategies in a sustainability framework. The study phases included: (i) field study design, (ii) geomechanical characterization of the rock mass in galleries using the rock mass rating (RMR) method [53] and Q-Barton index [82], and (iii) establishment of a 3G's model for sustainable development (Figure 2).

2.1. Phase I: Field Study Design

The study begins by evaluating existing problems based on a compilation and review of previous studies in the area, including scientific publications, technical reports from local organizations, and other literature related to the Zaruma–Portovelo mining district [83–86]. Specifically, in this phase, the geological–geotechnical data of research projects developed in the area, topography maps, and topographic surveys of galleries were analysed and relevant information on subsidence events recorded to date (e.g., affected area, depth of galleries, and stabilization measures used). Based on this information, subsequent phases that included fieldwork and data processing in specialized software were planned.

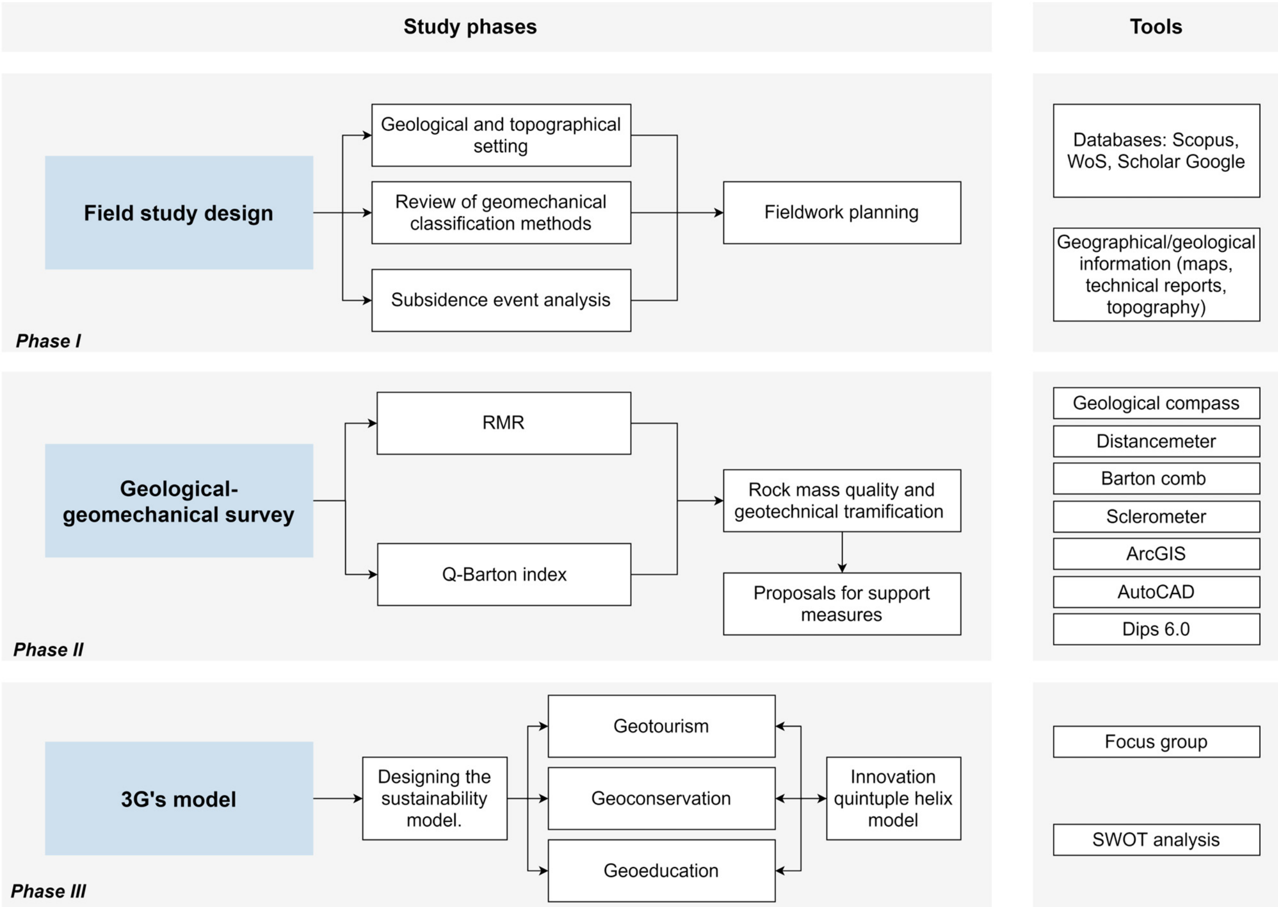

Figure 2. General methodological scheme of the study.

2.2. Phase II: Geological–Geomechanical Survey

The underground survey contemplated the section enabled for tourism of the "El Sexmo" mine. Specifically, this stage focused on the geological and geomechanical analysis of the rock mass divided into 15 stations (S) located in the main lithological changes and conditions of discontinuities, faults, or veins, as well as stabilized zones (Figure 3). Among the parameters evaluated, the study used the N-type Schmidt hammer to perform an in situ unconfined compressive strength (UCS) test, recording rebounds in the field for both joints and matrix. In addition, the authors selected three random points for collecting rock samples (Figure 3) and subsequent laboratory tests of the specific gravity of the rock by applying the bulk density method with paraffin. Finally, each station was evaluated using two specific methodologies: (i) rock mass rating (RMR) [53] and (ii) Q-Barton index [82]. The objective of these methods in the area is to zone the rock quality at depth and identify zones that require stabilization measures.

The first method used in the study consisted of RMR [53], a percentage value obtained by adding valuations according to defined parameters that depend on the state of the rock and discontinuities. The parameters evaluated included uniaxial compressive strength, rock quality designation (RQD) [87,88], spacing, persistence, openness, roughness, strength, weathering, and water filtration. These parameters obtain different evaluations according to the characteristics observed in the field and the scores established in the method (Table S1). The final RMR value for the rock mass changes according to the orientation corrections of the main families of discontinuities analysed, obtaining rock mass quality classifications that vary from very poor to very good (Table S1).

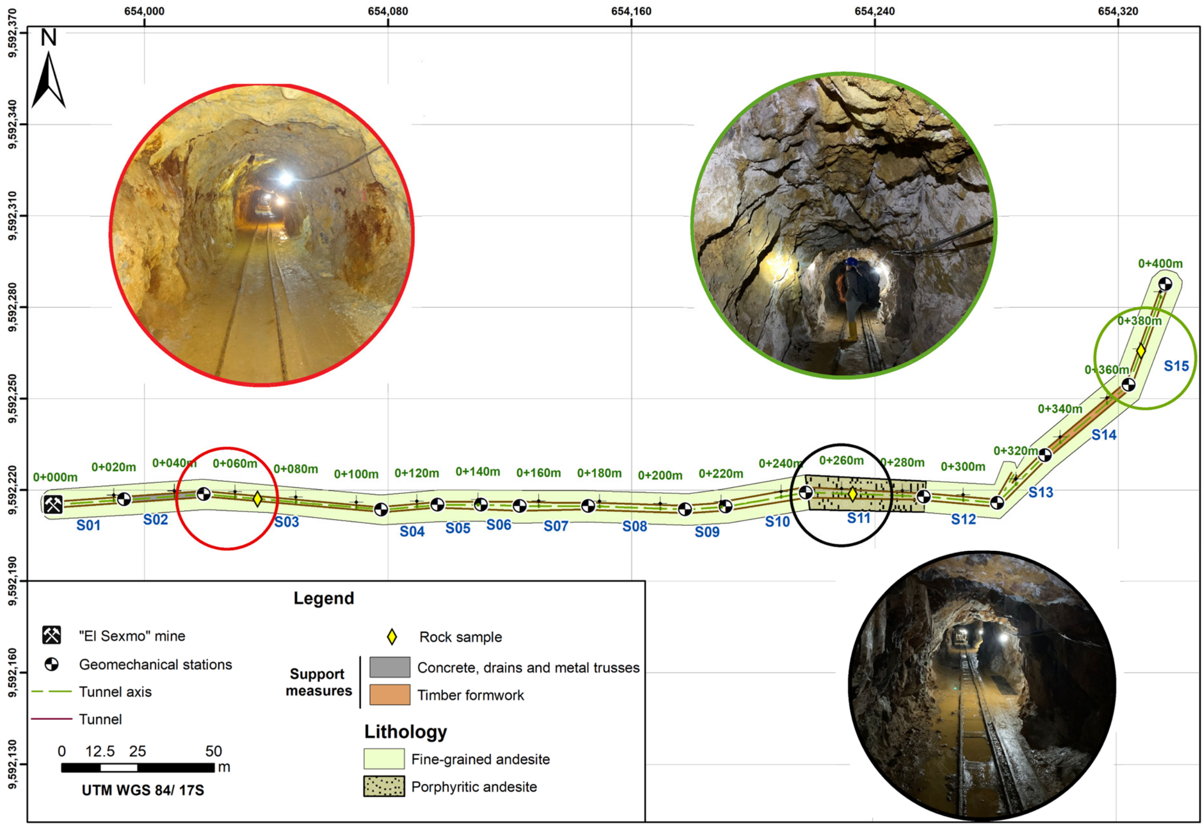

Figure 3. Stations and sampling points locations in the El Sexmo tourist mine.

Finally, the assessment of rock quality contemplates the use of the method proposed by Barton et al. [82], which evaluates the geomechanical behaviour of the rocks through (Equation (1)) and establishes a qualitative classification of their quality (Table S2) through the use of six parameters: RQD [87,88], the relationship between the continuity and roughness of the fracture planes (Jr), number of fracture systems (Jn), the relationship between the alteration and the type of filling of the discontinuity (Ja), moisture of the fracture planes (Jw), and stress reduction factor (SFR) (Table S3) [82]. The final value of Q can classify rock masses with quality ranging from exceptionally poor to exceptionally good.

$$Q = (RQD/Jn) \times (Jr/Ja) \times (Jw/SRF), \quad (1)$$

2.3. Phase III: 3G's Model

Based on the information obtained from the previous phases, this study planted the design of a 3G's model that allows for establishing management proposals in the three axes of geotourism, geoconservation, and geoeducation. The tool used for this analysis consisted of a focus group [89] made up of six experts in artisanal and small-scale mining, geotourism, hydrogeology, geotechnics, and the environment. The participation of experts in different areas allowed the development of a SWOT analysis [90,91] to determine the strong and weak pillars, as well as the potential opportunities and threats of the inclusion of underground geotourism development measures. Based on the qualitative method, this study generated specific strategies with sustainability criteria that allow the integration of geotechnics and geoconservation with the participation of the five systems of the quintuple helix innovation model of Carayannis and Campbell [92]. The quintuple helix model [92] promotes interactions between the educational system, the economic system, the public based on media and culture (civil society) [93], and the political system, and adds as a fifth helix the 'natural environment' to generate knowledge and promote sustainable development.

3. Results

3.1. Geological–Geomechanical Survey

3.1.1. Geological Context

The "El Sexmo" mine is formed by volcanic rocks from the Celica Formation of the late Cretaceous [94], represented by massive light-to-dark-greenish andesites and plagioclase phenocrysts. In the mine, it is possible to identify from small veinlets to veins filled with quartz and ore minerals, such as pyrite and chalcopyrite. Regionally, the mine is part of a system associated with Au ± Ag ± Cu intermediate sulfidation veins [77], whose origin is due to early Miocene continental arc magmatism [95] and has been related to alterations mainly of the argillic type. Specifically, at station 11, 240 m along the mine, there is a lithological change from fine-grained andesite with a grey–green hue with quartz veins to porphyritic andesite with a dark grey–green hue with plagioclase and amphibole minerals contained in a fine-grained to medium-grained matrix with veinlets with quartz fillers.

3.1.2. Discontinuity Study

The rock mass of the "El Sexmo" tourist mine was analysed based on the 15 defined stations considering geological, structural, and geotechnical variations. Each station section evaluated included structural measurements of the main joints (minimum three and maximum five joints per station according to the processing with Dips 6.0). The in situ evaluation process reflected a similar trend in the physical–mechanical properties of the rock and joints. However, there are specific stations where mineralized veins, faults, or water flowing in the rock mass represent stations with variable physical–mechanical properties for the RMR and Q-Barton geomechanical classification. Table 1 summarizes the average scores assigned by each station, considering the parameters established according to the geomechanical classification methods used.

Table 1. Scores assigned by station according to the RMR and Q-Barton methods.

Station	$\frac{RQD}{UCS}$	$\frac{J_n}{RQD}$	$\frac{J_r}{Spacing}$	$\frac{J_a}{Condition}$	$\frac{J_w}{Water}$	$\frac{SRF}{Orientation}$	Unit Weight (Ton/m^3)	UCS (MPa)
1	84 2	30 17	3 17.5	8 10.5	1 7	1 4	2.86	23
3	86 4	17	12.5	15.9	1 7	1 7		30
4	83 4	17	11	17.8	1 7	1 2		36
5	90 4	17	13.8	12.4	1 7	1 2		27.5
6	92 4	20	10.2	16.4	1 7	1 2		47.5
7	80 4	17	12	19.3	1 7	1 5		48
8	91 4	20	15	12.7	1 4	1 4		34
9	97 2	20	15	15.6	1 4	0.5 7		21.5
10	91 4	20	13.3	14.6	1 7	0.5 10		25
11	78 2	17	10.8	17.2	1 7	0.5 4		24

Table 1. *Cont.*

Station	*RQD* / *UCS*	J_n / *RQD*	J_r / *Spacing*	J_a / *Condition*	J_w / *Water*	*SRF* / *Orientation*	Unit Weight (Ton/m^3)	UCS (MPa)
12	96 4	20	10	13.3	1 4	0.5 7		25
13	82 2	17	13.3	14.3	1 7	0.5 6		24
14	97 4	20	12.5	16.4	1 7	0.5 6		25
15	97 4	20	12	19.6	7	0.5 9		28

On the other hand, regarding the Dips processing of the main families of discontinuities considering the total length of the tourist gallery (404.8 m), according to the density concentrations, there are three main joints, two mineralized veins, and three geological faults with structural tendencies predominantly to favour mine management for each section analysed (Figure 4). The mine generally presents three different strikes, with structures with minimum dips of 43° and maximums of 81°. Rosette's diagram for joints in the tourist mine indicates a dominant NE–SW strike (Figure 5).

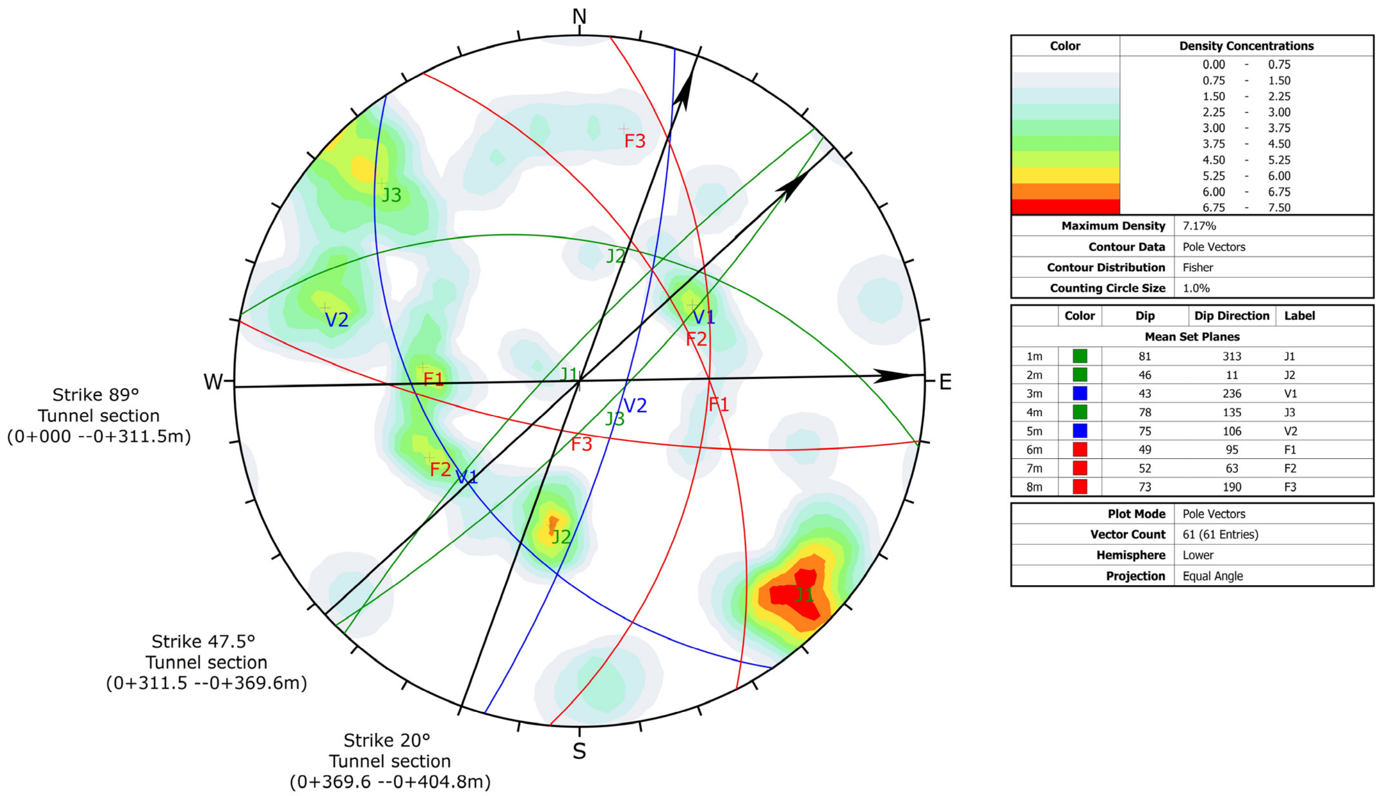

Figure 4. Fisher concentrations of joint sets.

3.1.3. Geotechnical Tracing of the "El Sexmo" Mine: RMR and Q-Barton Methods

The evaluation of the rock mass of the mine for the different stations did not consider station 2, which was already stabilized (Figure 6). Likewise, it is important to mention that, in the section of station 13, there is an intersection of galleries with a tunnel not enabled for tourism with a course of N30°. At station 14, the mine presents a stabilization measure that includes a wooden formwork for 36 m, taking measurements and assessments for the rock mass in the uncovered sections (Figure 6).

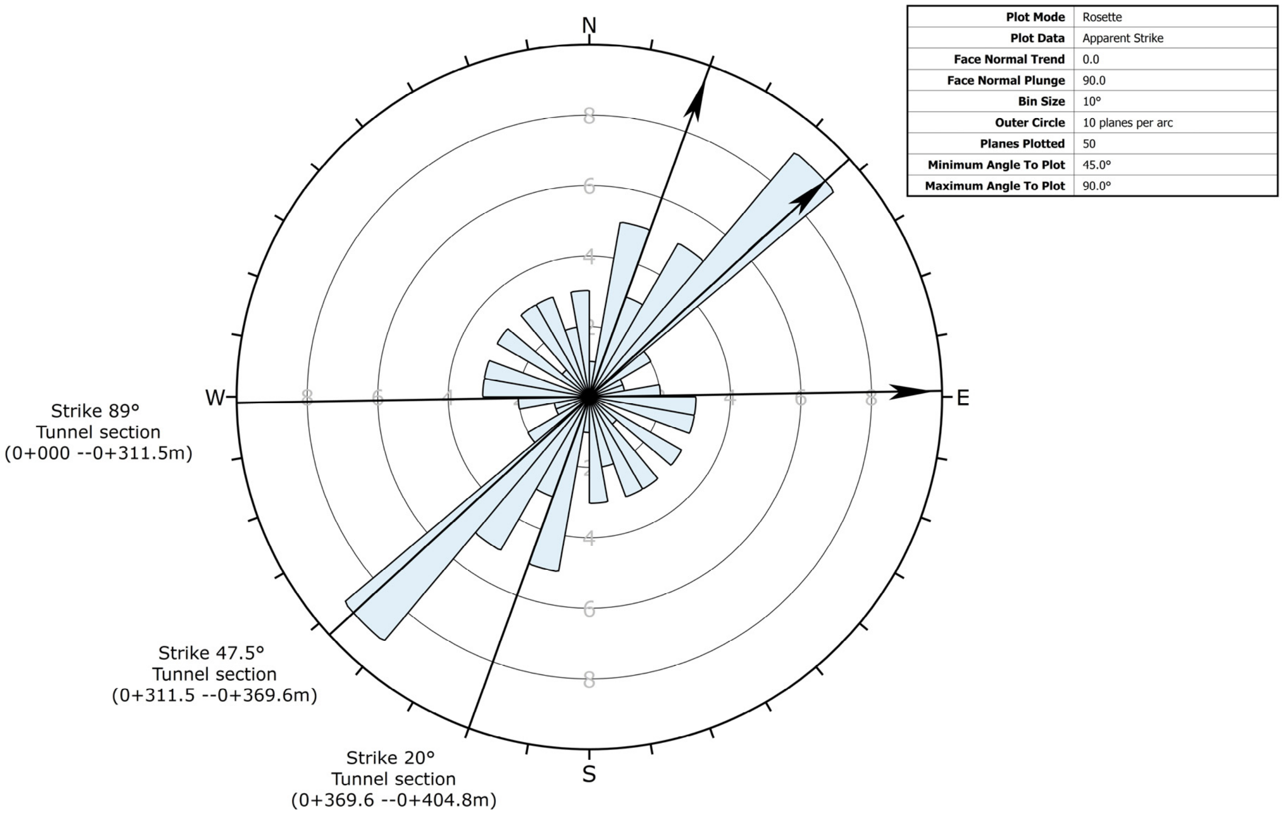

Figure 5. Rosette diagram for joints in the tourist mine.

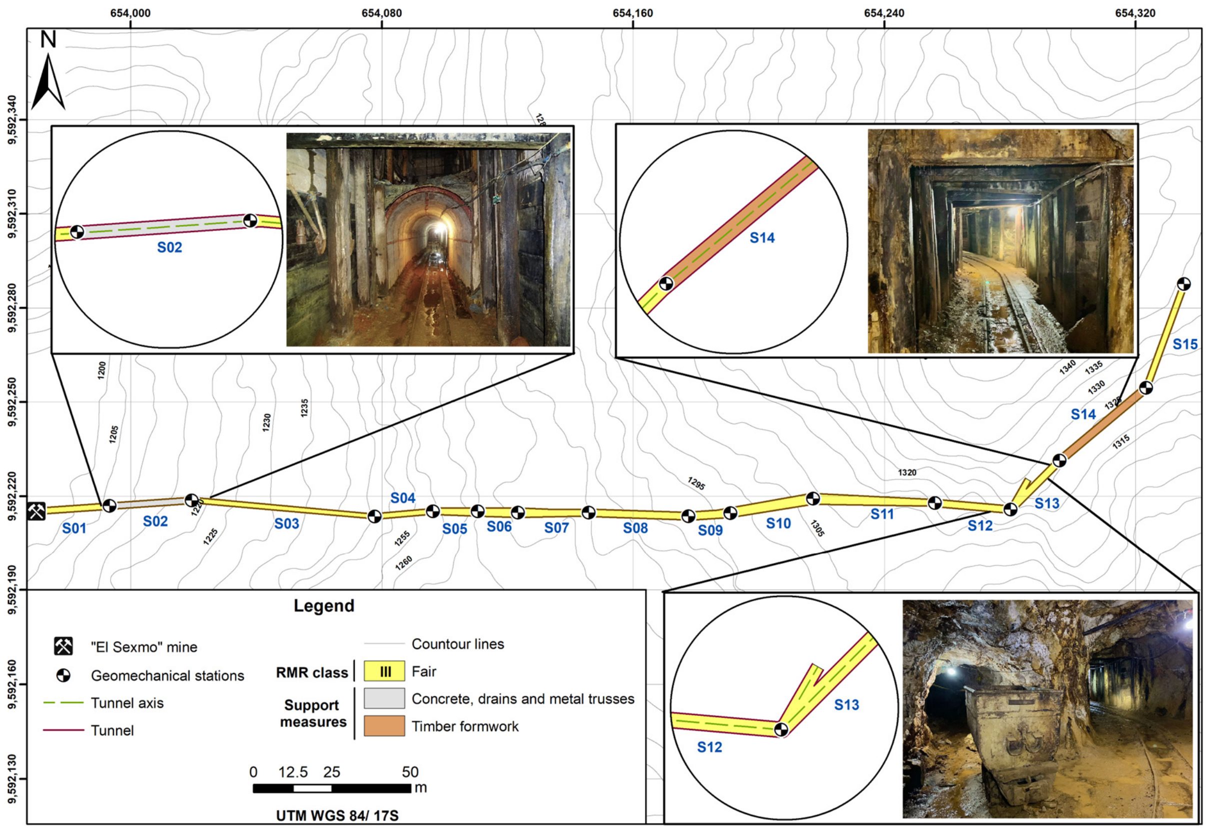

Figure 6. Underground geomechanical framing based on RMR method.

The results indicate that 100% of the section enabled for tourism presents a quality classified as fair by the RMR method (Table 2, Figure 6). In contrast, for the Q-Barton method, 92.9% of the rock mass is classified as poor (Table 2, Figure 7), except station 5 is classified as very poor, mainly due to the changes in the gallery's dimensions and the persistence and spacing of the present discontinuities.

Table 2. Final assessment for underground stations (RMR method and Q-Barton).

Station	RMR	Q-Barton Index	Qualitative Rating (RMR)	Qualitative Rating (Q-Barton)
1	50	1.05	Fair	Poor
3	48	1.08	Fair	Poor
4	58	1.04	Fair	Poor
5	49	0.56	Fair	Very Poor
6	58	1.15	Fair	Poor
7	57	1	Fair	Poor
8	51	1.14	Fair	Poor
9	48	2.75	Fair	Poor
10	46	2.28	Fair	Poor
11	54	1.95	Fair	Poor
12	45	2.40	Fair	Poor
13	48	2.05	Fair	Poor
14	54	2.58	Fair	Poor
15	54	2.43	Fair	Poor

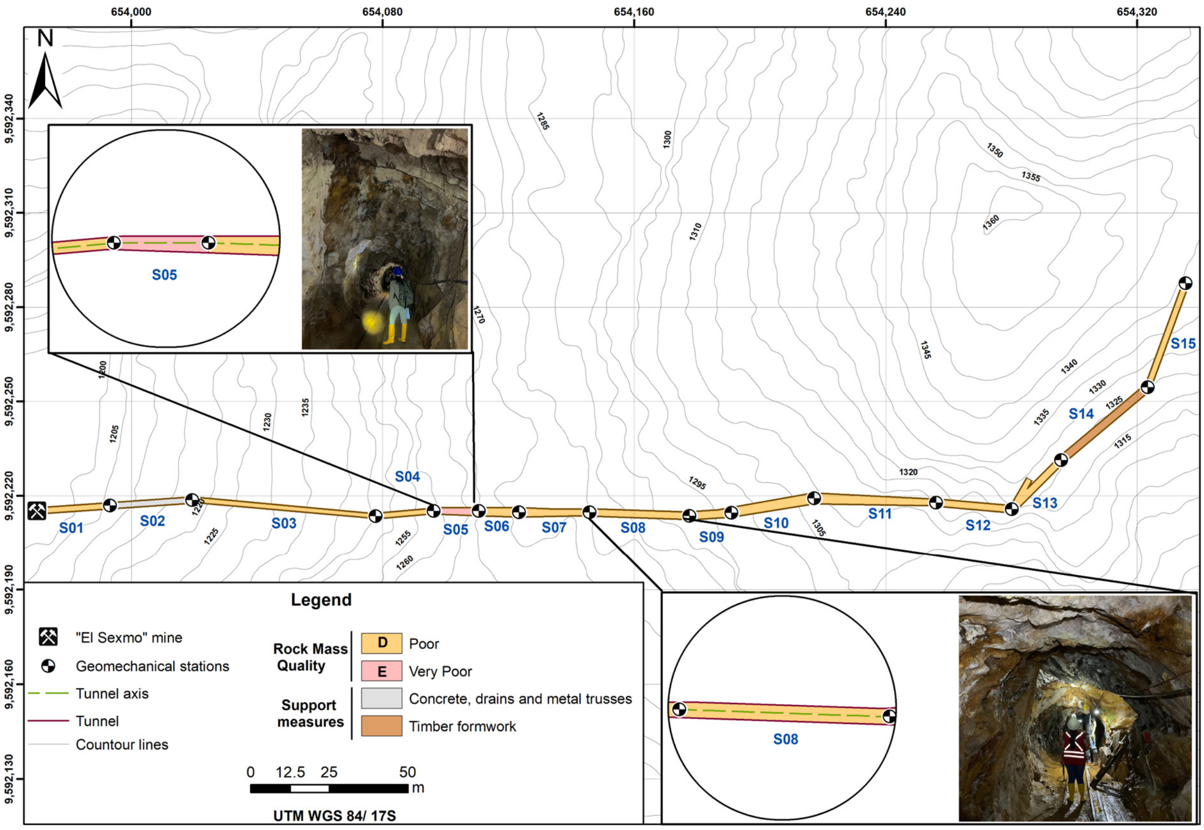

Figure 7. Underground geomechanical framing based on Q-Barton method.

Within the evaluation for both methodologies, stations 8 and 9 of the gallery correspond to sections for consideration of stabilization due to the presence of flowing water, faults (station 8), and grade III weathering (Figure 7).

3.1.4. Proposed Support Measures

The support measures correspond to the results obtained from the Q-Barton method [82]. The study considered three stations for the proposal of support measures (stations 5, 8, and 9). The choice of zones to stabilize consisted of three main aspects: (i) the presence of water, (ii) geological faults with decimetric thicknesses, and (iii) weathering and fracturing of the rock, evidenced in the field survey. According to the Q-Barton assessments and the type of gallery (ESR: G class), the support required for stations 8 and 9 includes fibre-reinforced sprayed concrete and bolting spaced between 9 and 12 cm. On the other hand, the support measure for station 5 consists of fibre-reinforced sprayed concrete and bolting spaced between 9 and 12 cm plus reinforced ribs of sprayed concrete (Figure 8).

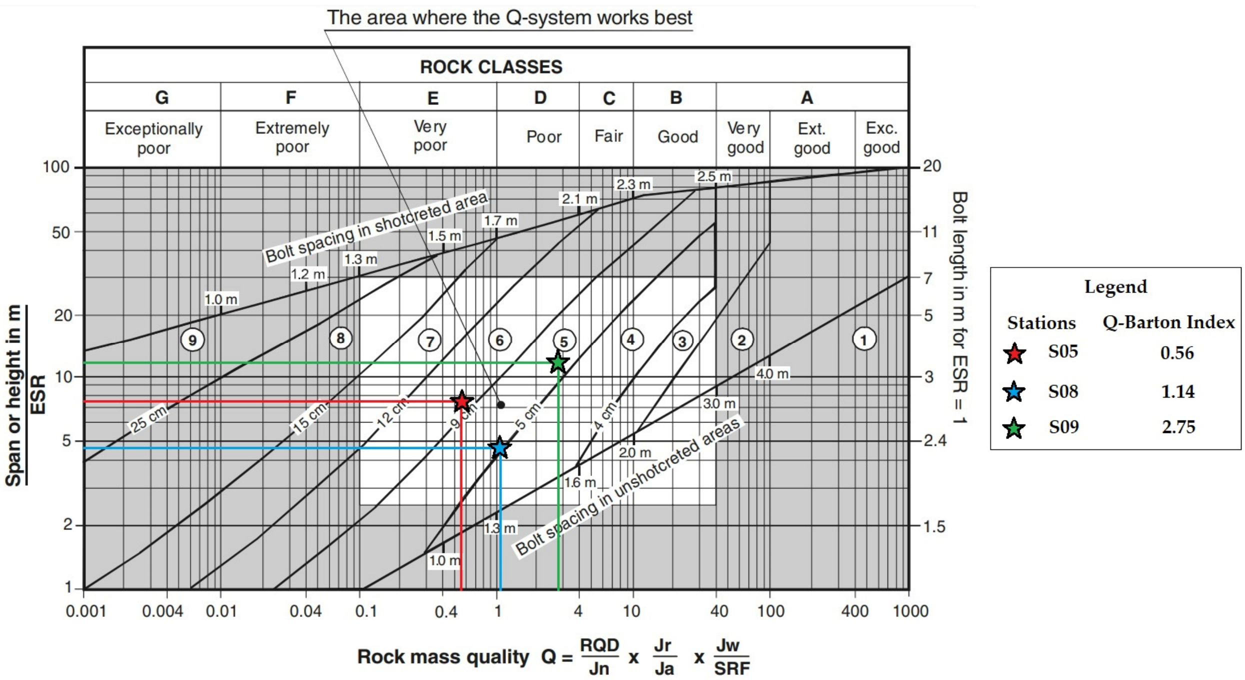

Figure 8. Q support chart in "El Sexmo" tourist mine [57].

Additionally, according to the current conditions of the mine, it is important to mention that the implementation of support measures includes those planes that are most susceptible to rockfall. Furthermore, in the case of the presence of water (stations 8 and 8), the support must include a drainage system, in addition to adequately conducting the flow and being visible to tourists. Finally, this study recommends monitoring the quality of the timber formwork for stations 2 and 14 of the mine.

3.2. The 3G's Model

Figure 9 shows the results of the SWOT analysis focused on developing underground geotourism (abandoned mines), integration of mining geotechnics (geoeducation), and geoconservation. The SWOT analysis allowed us to identify the key factors, weak points, opportunities, and threats that can influence the success of the 3G's model (geotourism, geoconservation, and geoeducation).

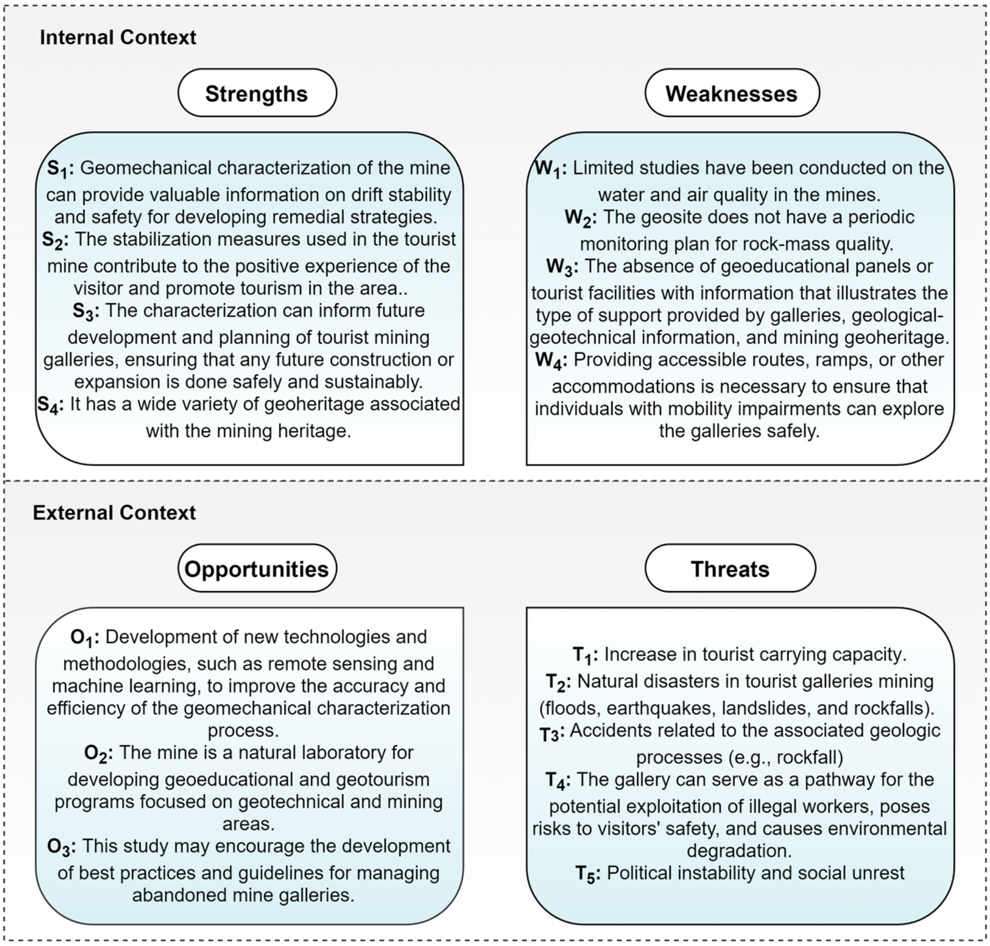

Figure 9. SWOT analysis.

In an internal context, developing geomechanical characterization studies to detect unstable areas within tourist mining galleries is a strength that can help prevent accidents and guarantee tourist safety. In addition, these studies may be the basis for future conditioning extensions of gallery tourist sections. However, some weaknesses were the absence of plans for monitoring and sustainable evaluation of the quality of the rock mass and its environment (water and air), as well as the limited development of didactic activities focused on mining geotechnics and geoheritage (e.g., geoeducational panels and design of geoeducation protocols).

In the external context, three opportunities were identified:

1. The development of new geomechanical characterization technologies and methodologies that improve the precision and time of data collection (remote sensing and machine learning)
2. Abandoned mines can serve as natural laboratories for developing geoeducation and geotourism programs
3. The formulation of best practices for the management of abandoned mining galleries and the mining industry

On the other hand, the main threats were increased tourist carrying capacity, natural processes of abandoned mines (e.g., rockfall), possible access routes for illegal mining, and legal or regulatory challenges associated with managing abandoned mining galleries and mining in general.

The SWOT analysis allowed for establishing strategies that consider the axes of geotourism, geoconservation, and geoeducation (3G's) in the five systems of the fivefold helix innovation model by Carayannis and Campbell [92]. The proposed model is presented in

Figure 10, where each system interacts with the others and generates knowledge through sustainable and innovative solutions applied to abandoned mine geotourism while promoting stakeholder engagement. The strategies and contributions of each system are detailed below:

- Educational system: The academy can contribute to the development of a management model for underground geotourism (abandoned mines) by conducting research and scientific dissemination activities on mining geoheritage and sustainable tourism, identifying the potential impacts of geotourism (capacity load), designing geoconservation plans, and developing strategies to mitigate the effects detected. In addition, the system can promote the inclusion of new immersion technologies (virtual reality) and machine learning.
- Political system: The political system plays a key role in developing policies and regulations for the geotourism industry, in which it is necessary to carry out initiatives or programs that promote the conservation of mining geoheritage. In addition, this system must incentivise industry players to adopt sustainable practices for all its components. Finally, the political sector must ensure that geotourism is included in the academic curricula and strengthen the links between the other actors of the four subsystems (community–government–industry–academia).
- Economical system: actors in the economic sector, such as the tourism industry (hotels, tourism, and transport agencies), can implement sustainable practices in their activities, such as waste reduction, energy conservation, and promoting culture and local geological mining heritage. They can also work with local communities to develop sustainable tourism geoproducts and services that benefit tourists and the community. Additionally, within the management plan, the mining industry has to provide technical and financial support for monitoring and evaluating rock mass conditions, waste management, geoeducation programs, implementation of support measures, and inclusion of green technology.
- Natural system: The management model must include measures or practices to conserve natural resources (water, minerals, rocks, and energy), reduce waste, promote sustainable transport, and protect biodiversity and geoheritage. A good example is volunteer activities that allow tourists and the local community to develop an awareness of the conservation of biotic and abiotic components.
- Social system: Local communities are a fundamental part of underground geotourism, and the proposed 3G's model must prioritize their participation and commitment through tools such as workshops or forums. This model encourages community participation in the planning, evaluation, and development of geotourism. In addition, this type of management promotes cultural awareness and the preservation of geoheritage, guaranteeing local socioeconomic development.

The studied tourist mine is a clear example of abandoned mining sites for tourism purposes that comply with the interaction of the five subsystems of the Carayannis and Campbell model [92]. The "El Sexmo" tourist mine was born as an initiative by a private company (economic system) that conditioned it, intending for the community to inherit a vestige of the artisanal mining activity typical of the Zaruma–Portovelo mining district. This project includes craft stands made by the community (socioeconomic system) within its tourist facilities, which promote economic development and geoheritage education through geoproducts. In addition, within its operational plan, the local government (political–social–economic system) includes the mine as a site of geological interest for the "Ruta del Oro Geopark" project, which seeks to achieve sustainable development and mitigate illegal mining activity. The academic intervention (educational–natural system) complements this initiative through the projects the "Register of geological and mining heritage and its incidence in the defence and preservation of geodiversity in Ecuador" and "Proposal for the Ruta del Oro Geopark and its impact on territorial development", with a clear objective of identifying, evaluating, and disseminating the geotourism potential of the area [75,96,97], including geosite conditioning strategies considering the environmental impact [98]. Finally, the interaction between the five systems allows for the creation of knowledge of geoheritage and environmental awareness to achieve sustainable community development.

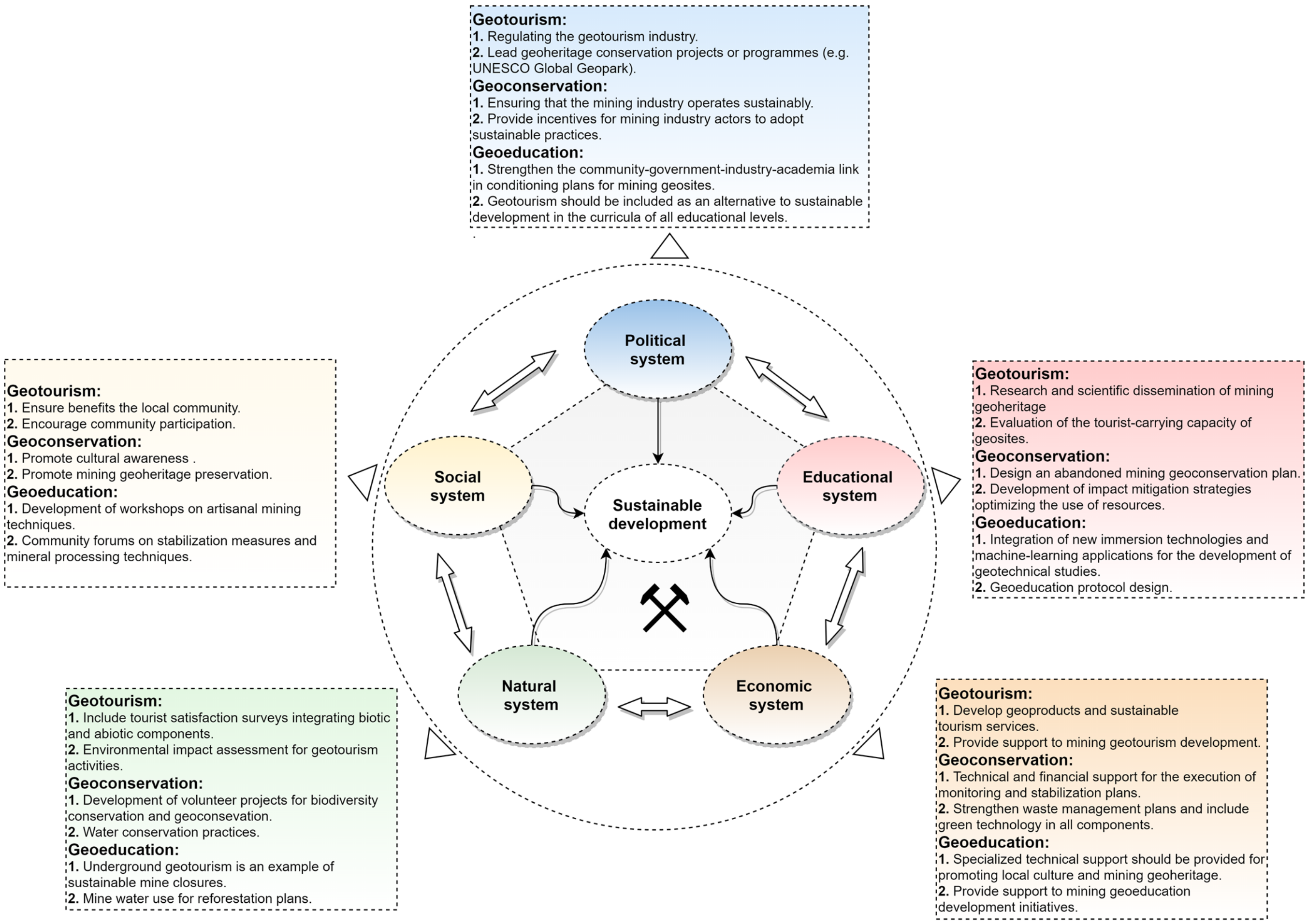

Figure 10. 3G's model for underground geotourism.

4. Discussion

This study proposes a methodology that integrates semi-quantitative and qualitative evaluations of abandoned underground mines as geotourism potential. From a semi-quantitative point of view, the quality of underground rock mass is studied as a tool for establishing stabilization measures that guarantee the safety of tourists. On the other hand, the qualitative analysis carried out by the focus group and SWOT analysis (Figure 9) raises the possibility of evaluating underground geotourism, in which the audience understands the importance of conserving the geological wealth of a mine and its direct relationship with geotechnics as a science that guarantees its safety and the operation of the underground geosite.

The results obtained for the geomechanical classification using the two classical methodologies validate the Q-Barton index as a conservative classification methodology that can be considered in a rock quality monitoring plan that includes support measures in areas susceptible to landslides [99–101]. Through the Q-Barton index, 13 of 14 evaluated stations present a poor rock classification with minimum values of one (Table 2). These results differ in the category from RMR, a method that classifies 100% of the mine as a rock mass of medium quality (Table 2, Figure 6). The main differences between the results obtained by RMR and Q-Barton are the stress field in situ and the spacing between the joints [102]. The stress system was only considered in the SRF for the calculation of the Q index, whereas the RMR only considered the resistance of the intact rock. However, the evaluation of discontinuities changes significantly in both methods: RMR considers the spacing (the greater the spacing, the greater the RMR), while the Q index evaluates the number of families (the greater the number of families, the lower the Q index, regardless of their spacing). According to Somodi et al. [58], using more than one geomechanical evaluation methodology favours understanding the behaviour of rock masses.

In this study, the use of RMR and Q-Barton made it possible to evaluate the parameters of the discontinuities for subsequent analysis of the areas recommended to be stabilized in the gallery. In general, the behaviour of rock mass quality using both methodologies varies between medium and poor. However, the in situ fieldwork made it possible to define three zones (S05, S08, and S09) that, although no evidence of landslides is observed in the field, it is advisable to stabilize to avoid collapses due to triggering events. such as intense rainfall or occurrence of seismic events. Another aspect of in situ validation is using numerical, analytical, and observational modelling methodologies to overcome the limitations of classification systems, as emphasized by other researchers, such as Palmström and Stille [103] and Genis et al. [104].

Support measures have been proposed based on the results of the Q-Barton index [57], a method widely used in underground construction [54,82,105]. The stabilization considered recommends three types of measures: (i) shotcrete with fibres and bolting (S05, S08, and S09), and, in some cases, reinforced ribs of sprayed concrete (S05) (Figure 8); (ii) monitoring of the state of the wooden formwork used in two stations to carry out future changes to wood; and (iii) implementation of drainage systems that prevent advanced deterioration of the rock mass. These measures can be implemented in the short or medium term to mitigate susceptibility to rockfall, with a secondary benefit and impact of geoeducation linked to geotechnics.

This research presents geotechnical study and stabilization measures as potential educational tools for technical and non-technical audiences. Indeed, this study provides a means to co-create knowledge and experience, effectively communicating the long-term planetary concerns facing society related to abandoned mines [106]. In addition, understanding geotechnical risk mitigation at geosites is essential for the geoconservation of mining sites for tourism purposes. These findings were validated by expert analysis using the SWOT method, in which the interpretation of geotourism linked to geotechnics reflected three fundamental aspects related to the operation of a 3G's model in the five systems of the five-fold helix model of innovation by Carayannis and Campbell [92].

The first highlights that the operation of a mining site for geotourism is conditioned by the geological wealth present, tourism facilities, and the strengthening of the community's sustainable development. The second aspect emphasizes that the use of mines as geosites for educational purposes requires monitoring plans for rock quality, water quality, and gas control to integrate new technologies, such as remote sensors or machine learning, to establish strategies that provide solutions to future scenarios that affect the safety of tourists, the conservation of geological features, or the construction and conditioning of new galleries in mines. Finally, the third aspect considers that the threats in a gallery, whether due to extreme natural events or anthropogenic activities (e.g., illegal mining activity, increase in tourist carrying capacity), can only be mitigated if there is integral participation of the political, economic, academic, social, and cultural systems, in which geoconservation and tourist security are priorities. Several studies have analysed the possibility of balancing geoconservation with tourism promotion (e.g., [107–110]).

The participation of different experts in designing a 3G's model made it possible to establish geoconservation, geotourism, and geoeducation strategies for tourist mines that promote the interaction of each subsystem of the quintuple helix innovation model, in which the local community represents a direct beneficiary. Emphasizing the participation of inhabitants in underground tourism represents a decisive axis to achieve sustainability [111,112]. Specifically, these proposals are summarized in three macro-strategies:

- From a geotourism point of view, it is necessary to strengthen the development of research studies that disseminate the geological wealth of the geosite at a national and

international level, as well as the participation of conservation projects and sustainable tourism promotion that involve appointments such as the UNESCO Global Geopark.
- The geoconservation of a mine requires the integral participation of the community–academy–company to develop plans for conditioning, stabilization, and tourist use in the short, medium, and long term, which avoids the deterioration of the scientific, academic, and tourist value of the main geological features.
- Within geoeducation, the model raises the possibility of exploiting the potential that geotechnics represents in the conservation of geological wealth and tourist safety through the design and installation of illustrative panels that facilitate the tourist guide to educate people of different academic levels.
- Within the community aspect, in artisanal mining areas, the community can lead events where tourists can learn about mineral exploitation and processing techniques used in ancient times. Additionally, to guarantee community participation in the sustainable use of abandoned mines for tourism purposes, the development of geoproducts, such as handicrafts, food, and companies that offer tourist packages, represents an alternative for economic development through products that exhibit and protect geoheritage, benefiting the local population [113–115].

This study contributes to research on underground geotourism to achieve sustainable tourism development in underground building heritage (UBH) sites [116,117]. Within this type of heritage, mines or caves are widely used for mining tourism, in which the scientific, cultural, educational, and recreational value stands out [109,118,119]. Several studies have promoted the sustainable use of abandoned mines in the tourism sector, taking advantage of geological wealth, promoting the conservation of geodiversity, and learning earth sciences [120–124]. However, the lack of management of the sites, little community participation, or lack of tourism promotion policies that consider carrying capacity can limit the sustainable development of a UBH [41].

Considering the importance of underground geotourism in the abandoned mines analysed in this study, it is necessary to recommend future tourism promotion studies using virtual reality and machine learning, in which tourists worldwide can access virtual tours to understand the geological and historical environment of the mines. This action aims to reduce susceptibility to risk due to degradation of the geosite in situ and achieve higher levels of promotion on an international scale.

5. Conclusions

The present investigation combines qualitative and semi-quantitative analysis for the geotechnical characterization of the tourist mine "El Sexmo", which is over 500 years old, and the generation of a 3G's sustainable management model. The geomechanical study indicates that 100% of the section enabled for tourism in the mine presents a rock quality classified as "Fair" (class III) by the RMR method, while, via the Q-Barton method, 92.9% of the rock mass obtains a classification of "Poor" (D class), except station 5, classified as "Very Poor" (E class). The study proposes support measures for three specific stations (stations 5, 8, and 9) based on Q-Barton evaluations, which include fibre-reinforced sprayed concrete and bolting. Regular monitoring and maintenance of the rock mass and stabilization measures implemented (Figure 3) are recommended, regardless of its Q-Barton index ranking, to detect any potential changes in behaviour and address any issues before becoming critical. While the methods used have advantages and limitations, they are widely applicable and provide a good starting point for further study and assessment of underground geotourism sites for decision making.

A multi-system approach is needed to sustain underground geotourism, particularly in abandoned mines. The educational, political, economic, natural, and social systems play important roles in developing policies, regulations, and practices that promote the conservation of mining geoheritage, sustainable tourism, and the mitigation of the potential impacts of mining underground geotourism. New technologies, such as virtual reality, remote sensing, and machine learning, can also contribute to developing this model.

In addition, the proposed 3G's model prioritizes community participation and cultural awareness to ensure local socioeconomic development while preserving mining geoheritage. Generally, a holistic approach involving all subsystems is crucial to ensure the sustainable development of underground geotourism.

However, it is important to note that the study has some limitations in geomechanical evaluations, such as the number of rock samples for laboratory tests, the estimation of the UCS using the Schmidt hammer, and the use of empirical methods for the characterization of rock masses. Therefore, it is recommended in future studies to perform additional geomechanical tests, such as the triaxial compression test or the indirect tensile strength test, to complement the UCS data of the Schmidt hammer, in addition to incorporating numerical modelling techniques, such as finite element analysis, to evaluate the behaviour of the rock mass under different load conditions.

The advantages of using the RMR and Q-Barton system for geomechanical characterization include its simplicity, broad applicability, and ability to assess rock mass quality rapidly. In addition, research shows the benefits of using the N-type Schmidt hammer for UCS in situ testing as it allows for fast, cost-effective data collection and is a non-destructive method. Overall, the 3G's model offers a valuable tool for conducting underground geotourism studies and provides a framework for sustainable tourism development in underground environments. However, it is important to note that implementing the model requires careful planning, thorough research, and regular monitoring to ensure its effectiveness and the safety of visitors.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/heritage6060245/s1, Table S1: RMR geomechanical classification [53]; Table S2: Rock quality according to the Q index [82]; Table S3: Descriptions and ratings for the Jr, Jn, Ja y Jw parameters [82].

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