



Article

# Dominican Larimar Mining—Current State and Future Prospects

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**Abstract:** This paper presents basic mineralogical and petrological data of the rocks hosting larimar deposit from the Sierra de Bahoruco, in the SW part of the Dominican Republic. Larimar is a unique ornamental stone with a wealth of decorative qualities. The Las Filipinas Larimar Mine in Barahona Province is the only place of this type in the world. Its production and distribution require radical action; hence, the paper also provides current information on the extraction of this raw material and prospects for the future. The paper indicates the possibility of using a new adit support system based on a mixed support (arch support and shotcrete). Numerical analysis shows the need to create a shotcrete coating around the entire circumference, about 15 cm thick. The variable geotechnical situation around the excavation, caused by the planned operation, prompts the use of slightly different solutions in the field of support. The article presents an outline of the technology using Polish experience. It is a support-bolt casing system with the latest achievements in this field.

**Keywords:** larimar; Dominican Republic; mineralogy; petrology; mining



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## 1. Introduction

Larimar (lorimar) is a unique gemstone of the world, also called Dolphin Stone, Atlantis Stone and Stefilian's Stone. It was accidentally encountered on 22 November 1916 by Father Miguel Fuertes Domingo Lorén near the city of Barahona (Barahona Province) in the SW part of the Dominican Republic [1]. After nearly 60 years, it was rediscovered by Miguel Méndez in the Sierra de Bahoruco region and named after his daughter Larisa—*lari*—and the Spanish word for sea—*mar* [1–6]. Currently, the importance of larimar for the Dominican Republic is evidenced by the fact that the nature reserve El Monumento Natural Miguel Domingo Fuertes was named after its first discoverer. Additionally, in March 2018 the Dominican National Congress was established on 22 November as the “National Day of Larimar” (Día Nacional del Larimar).

The Las Filipinas Larimar Mine, the world's only mine of its type, is located in the aforementioned Sierra de Bahoruco. The larimar is found within the effusive and piroclastic rocks of the Dumisseau Formation (DFm) of the Caribbean Volcanic Province [7–10]. The uniqueness of this stone is the result of structural heterogeneity, mineral composition, color, physical properties and high ornamental qualities. Also unique is the larimarized fossil charcoal found in the larimar deposit [11,12].

Larimar is an example of complex mineralization in which the main component is blue pectolite with other accompanying phases, e.g., calcite, natrolite, prehnite, clay and SiO<sub>2</sub> group minerals and phosphates (apatite). It is referred to by some researchers as a

pectolite rock [5,6,13] due to its complex mineral characteristics. However, it seems that it would be more correct to call larimar a polymineral because its genesis deviates from the accepted genetic criterion of a typical rock.

Chemically, pectolite is a hydrated Na and Ca silicate  $\text{Ca}_2\text{Na}[\text{Si}_3\text{O}_8\text{OH}]$ ; structurally, it is a member of the pectolite–schizolite–serandite series [14–18]. Usually, its individuals are colorless, white, grayish or slightly colored. Most often, the color of a pectolite is due to the presence of structural substitutions and mineral admixtures, such as  $\text{Cu}^{2+}$ ,  $\text{Fe}^{2+}$  and probably  $\text{V}^{3+}$  ions [19]. The quantity of these ions and mineral phases also affects the color of most larimar nodules as well as some physical properties and their thermoluminescence [20–24]. Recent results of the study (microscopic, SEM-EDS, CL, EPMA, FT-IR, FT-Raman, UV-VIS-NIR, TGA, PXRD) of the concept of larimar classification are presented by J. Kowalczyk-Szpyt [20]. Further tests are still in progress.

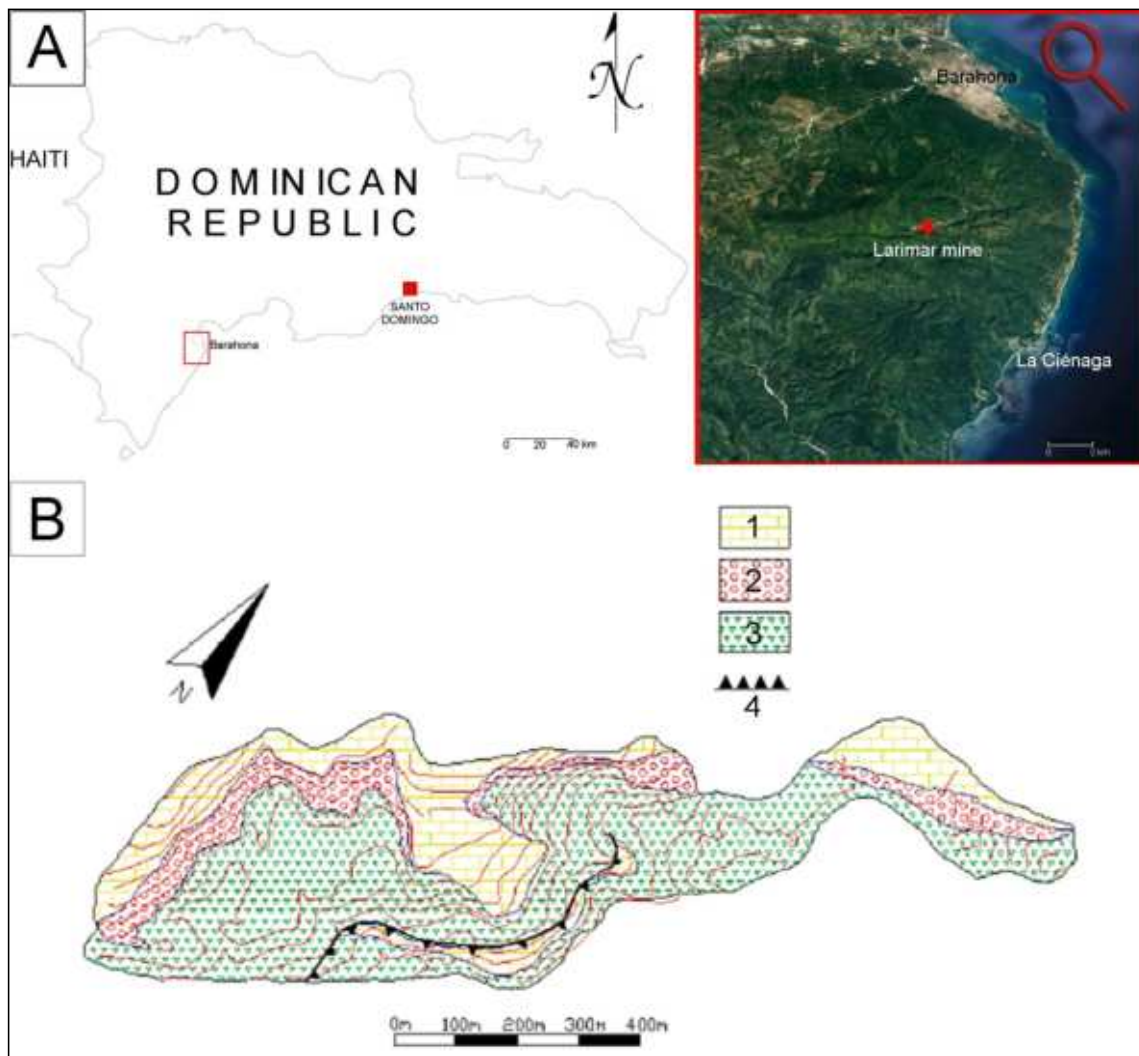
In world literature, few works are devoted to larimar and the geological situation of its deposit [1,5,6,9,12,13,19,20,25–31]; much of the work relates to the regional geology of Hispaniola Island [32–36] and others. In this paper, the authors present the latest mineralogical and petrological data of rocks hosting blue pectolite mineralization, as well as the current status of the Las Filipinas Larimar Mine in Bahoruco mountain range (Barahona Province) and the potential future mining operations.

## 2. Geological Setting

Geologically, Hispaniola Island represents one of the numerous uplifts of the oceanic lithosphere in this region above the water level of the Atlantic Ocean and the Caribbean Sea, which are covered by marine carbonate sediments. The crystalline substrate of the island is mainly basalt cover and numerous rocks of the deeper zones (also from the upper mantle of the Earth), which can be seen in the form of outcrops of metamorphic rocks, including amphibolites. This region is seismically and volcanically active due to the continuous movement of tectonic plates [37–42].

The Sierra de Bahoruco consists of large anticlinal structures coexisting with smaller anticlines, forming anticlines extending for 5 and 10 km. The Las Filipinas larimar deposit (approximately 32 hectares) is located on one of the hills of the mountain range, at about 750 m above sea level, in Los Chupaderos town, about 7 km from the Barahona and about 10 km from La Ciénaga (Figure 1). This area is a part of the larger extensive Hôte-Selle-Bahoruco tectonostratigraphic unit (NW-SE), having a strong magnetic anomaly associated with overlying basaltic rocks (DFm). They are associated with the deep-sea volcanism, radiometrically dated at 88–92 Ma (Cenomanian–Turonian) [12,27,43,44]. The DFm unit is one of the emerged fragments of the Caribbean Large Igneous Province (CLIP), uplifted and accreted on the northern margin of the Caribbean Plate [7].

In the study area, the Dumisseau Formation rocks developed in the EW direction of the regional fault zone [5,19,25,27]. These are mainly basaltic rocks occurring in the form of several land eruption cycles accompanied by pyroclastic rocks [21,45–50]. Altogether they form a complex more than 1.5 km thick, intersected by dolerite dikes [51]. According to  $\text{Ar}^{40}/\text{Ar}^{39}$  analyses, the age of the volcanics is ca. 74 Ma (Miocene or Late Cretaceous), while that of the dolerite dykes was estimated at 52 Ma [10].



**Figure 1.** (A) Location of the Dominican Republic and the Las Filipinas Larimar Mine in the Barahona Province (based on aerial photo); (B) geological map of the Las Filipinas mine area [52]: 1—basaltic rocks; 2—pyroclastic rocks; 3—carbonate sediments; 4—tectonic deformations.

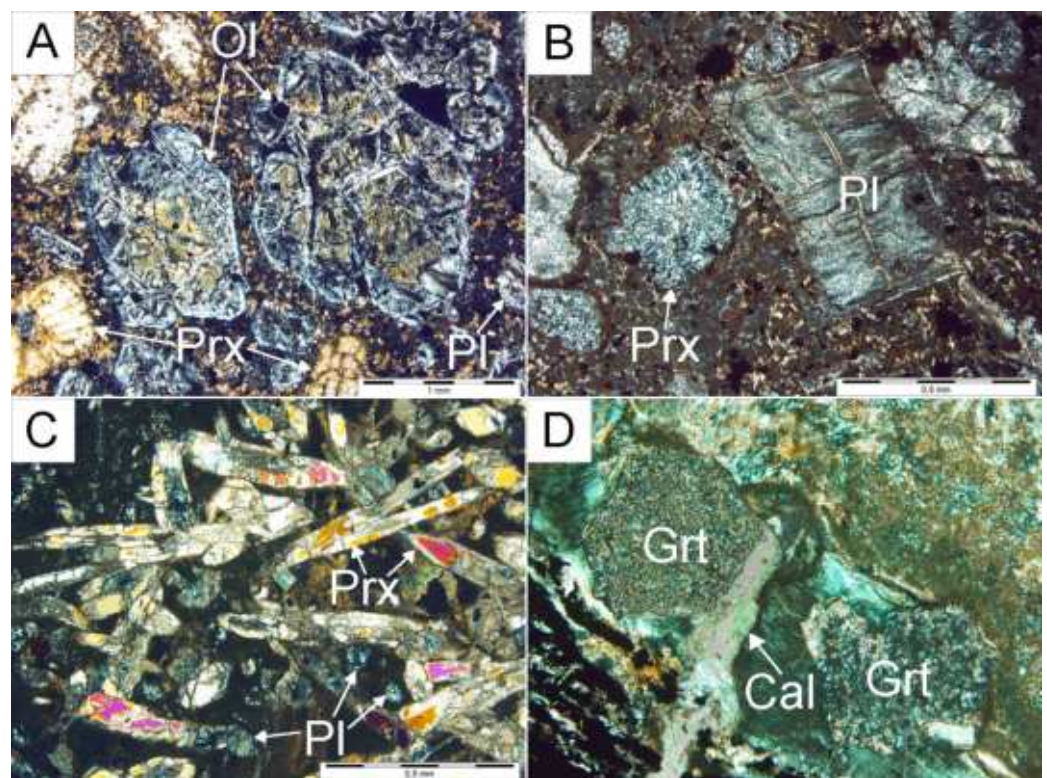
The volcanics are overlain by thick marine pelagic carbonate sequences of the Neiba Formation (NFm), aging from Paleocene to Middle Miocene, formed by cyclic marine transgressions [53]. In the contact zone between the volcanic and pyroclastic rocks, irregularly spread tree fragments (trunks and branches) as well as fine plant detritus with various degrees of fossilization were found [11,12,24]. As a result of post-magmatic hydrothermal activity, the tree fragments underwent complex mineralization, mainly with pectolite, calcite and prehnite, creating the globally unique larimar deposit.

### 3. Current Mineralogical and Petrological Data of the Rocks Hosting Larimar Deposit

In the lower part of the Demisseau Formation (DFm) complex, exposed in the area concerned, basalts with vesicular structure, volcanic breccias, granulometrically differentiated volcanic flow material and basaltic lava pillows were found. The upper series (with a thickness of 15–30 m) is formed by polygenic sediments of pyroclastic origin, lying unconformably on extrusive rocks. Both effusive and pyroclastic rocks were strongly transformed [21,31]. Between them there is a level of the paleosol, composed mainly of clay minerals, and a layer of sands, indicative of the gradual immersion of the area [10,12,31,54].

Macroscopically, basaltic rocks appear massive [20]. They are black in color, sometimes dark green. Under the optical microscope they show a typical porphyritic texture, some-

times poorly ordered (Figure 2). The mineral composition is dominated by phenocrysts within an almost completely recrystallized (devitrified) groundmass. Locally, traces of volcanic glass are visible, often replaced by a mixture of chlorite and calcite. The majority of phenocrysts include prismatic pyroxenes (diplaxite) and olivines, both strongly serpentinized, and also fairly numerous basic plagioclases (~n65) with poikilitic (xenokitic) structures and intensive signs of alteration (garnetization). In the marginal zones of those individuals, chlorites and small admixtures of saponite and celadonite also appear (SEM-EDS). Some of the plagioclase plates have been replaced by a mixture of zeolites (natrolite) and clay minerals (e.g., illite). Quite often carbonate assemblages (calcite) occur, sometimes forming veins, as well as prehnite and pectolite (SEM). Fine rims and veins of hematite occur in most pseudomorphs after pyroxenes. Among the opaque minerals, ilmenite dominates, although the presence of other Fe (e.g., magnetite, hematite) and Ti (e.g., rutile, titanite) oxides cannot be excluded.



**Figure 2.** Microscopic images in transmitted light of basalt samples. (A) General view; devitrified groundmass with strongly altered olivine (Ol), pyroxene (Prx) and plagioclase (Pl) phenocrysts (NX). (B) Inside strongly serpentinized pyroxene (Prx) and large plagioclase plate (Pl) altered into clay minerals (possibly illite); numerous opaque grains within the rock groundmass (NX). (C) Poikilitic structure of rock with plagioclase plates (Pl) and prismatic pyroxene (Prx) individuals (NX). (D) Pseudomorphs after plagioclases filled with spherulitic garnet (Grt) crystals crossing calcite (Cal) veins (NX). Photographs were taken by J. Kowalczyk-Szpyt.

The described basaltic rocks are intersected by dark green dolerite veins of varying thickness [20]. Under the optical microscope, the texture of the rocks is sub-ophitic, typical of the diabase type. In SEM images, fine-crystalline pyroxene grains are enclosed in large plagioclase plates. Some of the plagioclase pseudomorphs are fully filled with grains of calcium-ferruginous garnets. The grains of pyroxene are considerably smaller (less than 1 mm), strongly serpentinized and partly chloritized. Previously existing empty spaces between the plagioclase plates and pyroxene grains have been filled with clusters of secondary minerals: celadonite, chlorite, prehnite and calcite. Calcite together with prehnite and pectolite are also components of small veins intersecting the dolerites and

forming thin incrustations on the rock surface. The rocks contain also grains of ilmenite that considerably dominate over magnetite and very fine grains of copper sulfides. In comparison to basalts, the quantity of the opaque grains seems to be lower, but their sizes are clearly larger.

Pyroclastic rocks are dark green or brownish [20]. They are composed of rather strongly altered components, i.e., dominant litho- and crystalloclasts and minor vitroclasts.

- Lithoclasts are represented by fragments of volcanics (basalts). In the groundmass, only pyroxenes are preserved a state that allows their primary nature (mainly orthopyroxenes, bronsite–hypersthene) to be determined. Some pyroxene grains show a lamellar structure resulting from exsolution of diopsides. In many places, they are accompanied by accumulations of pectolite and garnets. Plagioclase plates are almost completely altered. Many are filled with isotropic, usually irregular garnet grains. Sometimes they are intergrown with pyroxene prisms, which clearly indicate the order of crystallization of the different mineral phases. They are accompanied by numerous iron and titanium oxide clusters (e.g., magnetite, ilmenite, rutile), well visible on SEM images. Titanite grains are also quite numerous. Secondary products include calcite, serpentine group minerals, pectolite, pumpellyite, prehnite and garnets.
- Crystalloclasts are represented by pyroxenes (and possibly olivines) and plagioclases, they are all heavily altered.
- Vitroclasts (palagonite glass) are yellow-brownish; some of them are altered (chloritized).

In conclusion, the volcanics described above are characterized by structural–textural peculiarities and mineral composition that indicate the formation of these rocks under specific conditions. In basalts, the quantity and type of secondary phase minerals are highly diversified, and these minerals include: natrolite, pectolite, prehnite, calcite, the serpentine group minerals, clay minerals (chlorite, chlorite/smectite), celadonite, magnetite, ilmenite, pumpellyite and garnets with an admixture of Ti. The majority of them were developed in hydrothermal processes (200–400 °C). On the other hand, pyroclastic material after deposition and cementation changed into tuff, genetically related to spilite-like assemblage formed in deep rift zones. This is indicated by the elevated sodium contents of these rocks and also the high quantities of glass (palagonite). The spilite-derived pyroclastics (spilite tuffs) were later affected by many physicochemical processes.

Based on the above considerations it appears that the original environment for the formation of pectolite mineralization was associated with the marine reservoir in which volcanic phenomena occurred [20]. Strongly heated basalt magma cooled down, outgassed and contracted, causing the formation of numerous internal fractures. This environment ensured the inflow of  $\text{Na}^+$  and  $\text{Ca}^{2+}$  ions, making it possible to form the silica aggregates but first of all specific hydrated silicates in which such ions as  $\text{K}^+$ ,  $\text{Fe}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{Al}^{3+}$  were built in the structures, and Cu, Fe and Ti were dispersed as extra-structural admixtures in forming future larimar specimens.

#### 4. Current State of Larimar Mining

The Las Filipinas Larimar Mine is located high in the mountains, surrounded by a subtropical forest. The Dominican government transferred the right to extract the stone to the local population [54]. Starting from the 1970s, the exploitation of larimar in the Sierra de Bahoruco area continued until the mine was closed in August 2021. From the beginning, larimar was exploited with very primitive mining techniques, using small dimension cross-section shafts hollowed from the surface, at the bottom of which extraction galleries or drifts were bored in the mountainside, and from these, smaller shafts were drilled. (Figure 3).



**Figure 3.** Mining of larimar in basaltic rocks at the Las Filipinas mine. (A,B) Shallow excavations in the slope of the hill with a primitive timber lining (as of 2013); (C,D) tunnel with steel and timber support and concrete rendering (as of 2016); (E,F) tunnel as of 2020; Photographs were taken by L. Natkaniec-Nowak and K. Broda.

Mining was mostly carried out with shovels and pickaxes, without the use of explosives. Currently, mining activities can still be called craftsmanship, despite the introduction of electric hammers and three-wheeled motorcycles for the transport of both output and gangue. The excavated material and waste rock (waste) were transported vertically through shafts by hand or by electric winches and along the pavements in buckets and wheelbarrows. Both the exploration and production works were carried out in a less systematic manner, without clear planning. The ventilation and drainage systems were very primitive. In the area of the Las Filipinas mine, which is of interest to us, including the main drift providing access to the deposit, mining was carried out for over 30 years [28]. Due to the low standards of work safety, which resulted in a large number of accidents, the Dominican authorities decided to intervene and build a new tunnel, 1000 m long, which was to facilitate access to the larimar deposit and improve safety conditions by improving drainage, ventilation and creating an escape route in the event of an emergency [28].

The construction of the adit started in June 2007 with the support of European programs supporting mining in the Caribbean. The project was completed after 426.7 m with a slope of 2% of an adit built to the west of the main entrance at an elevation of 749.65 m above sea level. At the end (764.92 m asl), a ventilation gallery rises to the surface for 25 m. The western end of the drift was connected to the surface by a 55 m long shaft, which was both the exit route and the natural ventilation shaft [55]. The bottom of the tunnel is inclined towards the main entrance. During construction, steel arches with a steel mesh were used, as well as anchoring the ceiling and sprayed concrete. Construction was completed in 2010, but the excavation was closed for several years. In 2012, during a storm, there was a flow of debris and soil, which flooded the western end of the tunnel, blocking access to the shaft inside the tunnel for about 20 m. The rubble was removed in 2013.

The exploitation of the larimar with the use of the adit started in October 2015. The exploitation was carried out using the old techniques, i.e., by boring sidewalks from the adit and then further shafts and pavements in the deposit area. From the very beginning of the operation, the first symptoms of adit tightening appeared, which intensified in 2016. There were deformations and buckling of the casing arches, sprayed concrete detachment and adit cross-section clamping. It was probably caused by an increase in the number of sidewalks and shafts in 2015–18 without prior reinforcement of the adit housing structure. There was a risk of the main entrance to the drift collapsing. To save this excavation, the Ministry of Energy and Mines (MEM) and the General Directorate of Mining (DGM) established cooperation with the Canadian Resource Institute International and Development (CIRDI) and BGC, which resulted in visits to the larimar mine in June 2017 and in June and July 2018.

In April 2019, LiDAR tests were carried out at the Las Filipinas mine. The results were presented to the MEM and DGM in the form of reports. In February 2020, following the invitation of the Director General of Mining of Santo Domingo (Dominican Republic), a group of scientists from the Faculty of Mining and Geoengineering of the AGH University of Science and Technology (Krakow, Poland) visited the mine.

## 5. Perspectives for Future

In view of the closure of Las Filipinas mine for safety reasons, it is necessary to develop a new operations strategy to return to the process of larimar mining. This strategy should take into account the objective possibilities derived from the quality and stability of the rock mass, as well as the knowledge accumulated after the use of the previous exploitation tunnel.

Undoubtedly, it is necessary to excavate a new main adit, maintaining the shoring system that was used in the old main adit (arch supports and shotcrete). As a main support system, five elements of yieldable steel arch support were chosen. The proposed system allows for a few centimeters of displacement before the set locks. Steel sets will be placed in 1m intervals. Depending on the rock mass quality, the aforementioned standing support will be reinforced with a layer of shotcrete, and its thickness will change with rock quality and depth. Initial numerical simulations indicate that in deeper sections of the main adit, a steel set invert will have to be installed to ensure stability of the design. One of the proposed designs is presented in Figure 4.

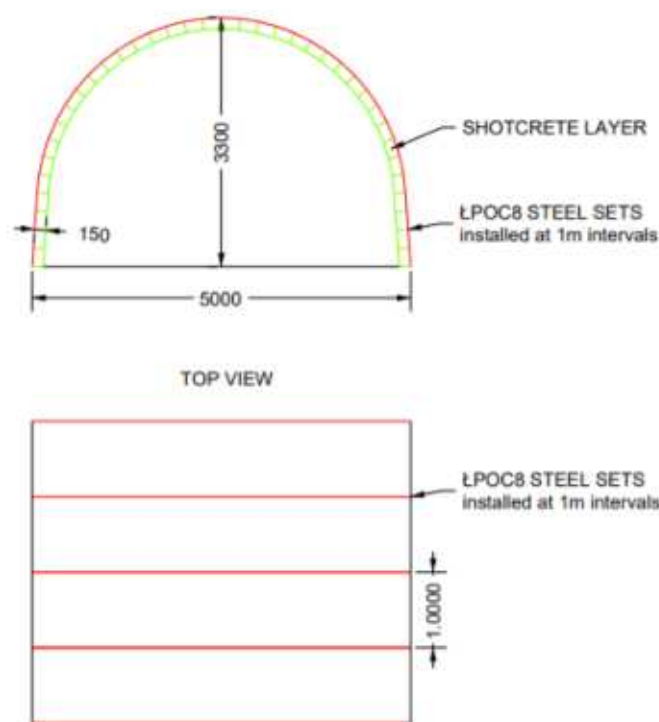


Figure 4. Preliminary support system.

Two different shotcrete thicknesses were tested with a simplified FLAC3D model. The first of them included 10 cm while the second was reinforced with 15 cm of shotcrete. The goal of the simulation was to find the maximum depth which satisfied two acceptance criteria:

- (1) Maximum main adit strain of 2% (ratio between opening width and observed displacement) [56];
- (2) Maximum bending moment observed in steel set <70 kNm.

Each model was 40 m wide, 40 m high and 16 m long. Additional stresses corresponding with analyzed depth were applied to the upper boundary of the model, and a hydrostatical stress state was assumed. The Mohr–Coulomb failure criterion was chosen, while cohesion and friction angle of the rock mass were recreated based on an RMR value equal to 19. Young’s modulus was derived from Equation (1) [57–59]:

$$E_m(\text{GPa}) = 0.0876 \cdot \text{RMR} \tag{1}$$

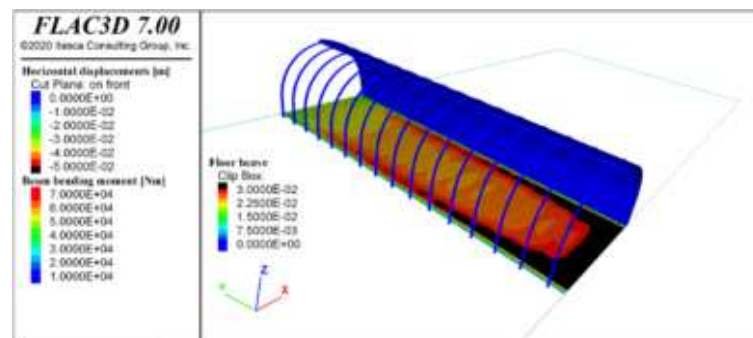
The rock mass properties are summarized in Table 1. Steel sets were represented with beam elements and their properties matched those of V32 (32 kg of steel per linear meter,  $W_x=121.4 \text{ cm}^3$ ) section type produced with S480W steel ( $R_e \geq 480 \text{ MPa}$ ,  $R_m \geq 650 \text{ MPa}$ ,  $A_5 \geq 17\%$ ). Sliding between different elements was not allowed.

Table 1. Rock mass properties.

Rock Mass Properties	
Rock Mass Rating (RMR)	19
Failure criterion	Mohr–Coulomb
Cohesion	100 kPa
Angle of friction	15°
Young’s modulus	1664.4 MPa
Density	2700 kg/m <sup>3</sup>
Depth	0–104

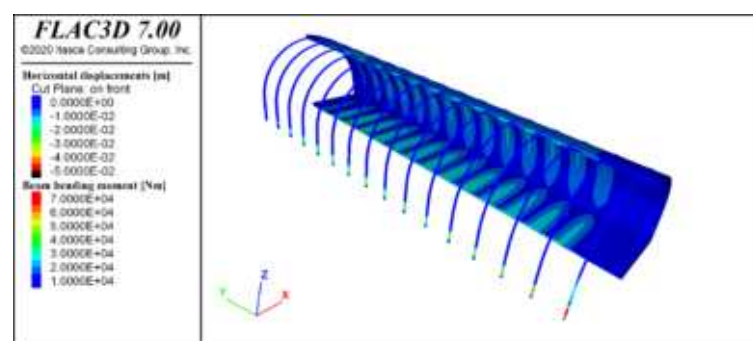


Simulation was divided into 16 steps, each recreating the advance of the main adit equal to 1 m. This included steel set installation and shotcrete spraying. The modeling procedure could be used to vary the Young's modulus of the shotcrete, thus recreating its curing process. Given the 5 m main adit width, the 2% main adit strain acceptance criteria translate into the maximum allowable loss of width of the main adit equal to 10 cm. The calculations commenced with the first design including the steel set at a 1 m interval reinforced with a 10 cm layer of shotcrete reaching a maximum allowable depth of 30 m for the design. Between 30 and 50 m below, the surface the structure was reinforced with another 5 cm of shotcrete. Figure 5 presents negligible horizontal displacement for the aforementioned design at 50 m below the surface. This depth is also a turning point for floor stability, as vertical displacements reached almost 4 cm.



**Figure 5.** Horizontal displacement of second design (15 cm of shotcrete) at 50 m below the surface.

At greater depths floor heave (floor lift) becomes an issue. It also leads to substantial horizontal displacement near the floor of the main adit. This can be mediated by placing an invert or with shotcrete application. An additional model was created, where a 15 cm layer of shotcrete was sprayed onto the floor of the main adit ensuring its stability up to a final depth of 104 m. Figure 6 presents a horizontal displacement plot for the aforementioned designed located 104 m below the surface. Those values reach almost 2 cm while the bending moment observed near the base of the steel set is near its maximum allowable value (67 kNm).



**Figure 6.** Horizontal displacement of third design (15 cm of shotcrete including the floor of the main adit) at 104 m below the surface.

Based on the preliminary numerical modeling results, the analyzed shoring system should be characterized by the parameters shown in Table 2. The aforementioned support scheme was calculated assuming hydrostatic stress state and no stress concentration induced by mining activity and was based on scarce data.

**Table 2.** Initial concept for new main adit support system (arch support and shotcrete).

Depth	Steel Set	Shotcrete	Floor Reinforcement
<30 m	1 m interval	10 cm	no
30 < d < 50 m	1 m interval	15 cm	no
50 < d < 104 m	1 m interval	15 cm	shotcrete 15 cm

A slightly different approach to the housing of the new main adit is presented below. It is a proposal based on the experience of Polish mines in difficult geological and mining conditions. The method is used especially in a situation where the excavation is subject to the influence of active or closed exploitation. The method is based on the use of a steel arch support and reinforcement of the rock mass with rebar anchors and cable bolts [60–62]. In this method, it is assumed that the rebar anchors cooperate only with the rock mass and the cable bolts with the rock mass and the support casing. During the drifting of the excavation, after the opening (with a heading machine or explosive materials), the exposed space around the entire perimeter is secured with a steel mesh. Then, rebar anchors are installed in a quantity determined by the design and local geological conditions. Anchors with a diameter of 22 mm and a length of 2.5 to 3.0 m are usually used. The load capacity of these anchors ranges from 250 to 300 kN, and the diameter of the holes in which they are installed is 27 mm. The anchors are glued with adhesive charges (polyester resin cartridge) along the entire length of the opening. Then, the steel arch set is installed on the face, spaced according to the design. Proper contact with the rock mass is an extremely important element that guarantees the correct operation of the support casing. This is achieved by performing mechanical lining in the bullflex system [63,64]. A system of fabric containers is placed behind the support casing door frames, which are filled with a mineral-cement binder. The binder fills the entire void between the rock mass and the casing. After hardening, it guarantees an even method of load distribution on the support casing arches and accelerates their cooperation with the rock mass. The next stage of strengthening the support and the rock mass is carried out several or several dozen meters behind the drift face. Cable bolts are installed here in the roof or in the roof and walls. In the main adit conditions, high load-bearing capacity anchors with pre-tensioning and injection gluing along the entire length should be used. It seems optimal to use one of the three types of anchors—Titan Bolt (by DSI Underground, Bennetts Green, Australia), Sumo Bolt (by Jennmar, Canonsburg, PA, USA) and IR7 (by Interram, Ogrodzieniec, Poland) with a length of 6 to 10 m, Figure 7.

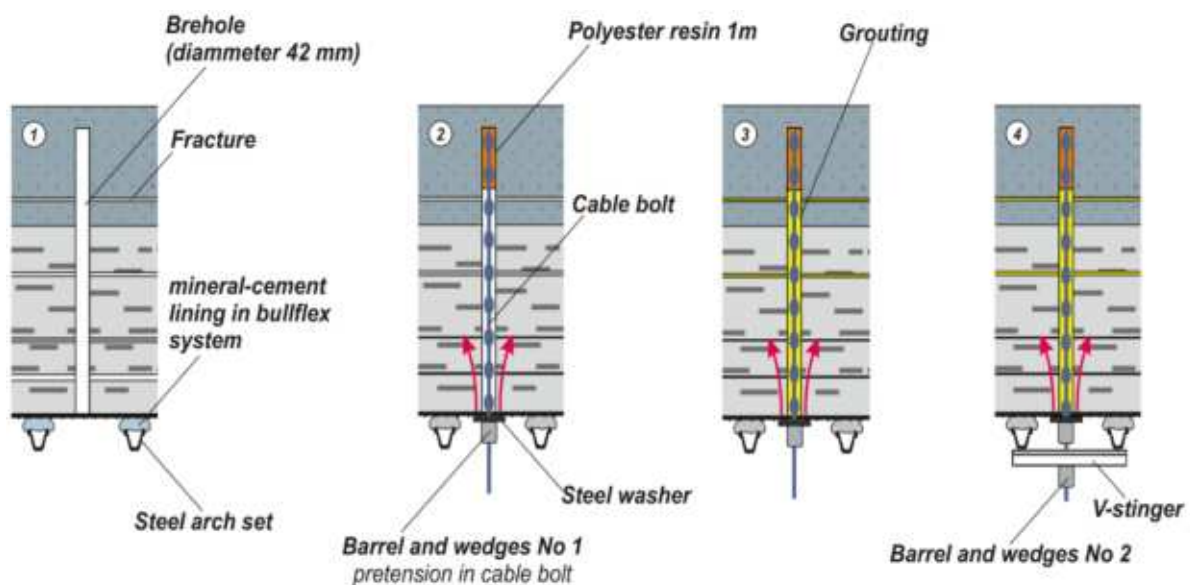
**Figure 7.** Titan Bolt (DSI).

All the above anchors are characterized by a similar structure, parameters and method of installation. The parameters of these bolts are summarized in Table 3.

**Table 3.** Properties of cable bolts.

Parameter	Titan	Sumo	IR-7/F
Capacity	550 kN	568 kN	>500 kN
Rod diameter	28 mm	28 mm	28 mm
Cage diameter	Ø36 mm	Ø35 mm	Ø34 mm
Anchor hole diameter	Ø42 mm	Ø42 mm	Ø42 mm

The bolt lock is a typical barrel and wedge clamp. The anchors are installed in two stages. In the first stage, after drilling a hole with a diameter of ~42 mm, the anchors are installed at the bottom of the hole on loads of resin with a total length of up to 1 m. Immediately after gluing, the washer and the barrel and wedges are attached, and with the use of a hydraulic cable tensioner, the initial tension is applied to the anchor (usually from 100 to 300 kN) [65]. The second stage of installation is usually immediately after the first or with a slight delay. At this stage, the mineral binder or a liquid two-component synthetic resin is fed under pressure. An adhesive connection of the rock mass with the prestressed anchor is thus obtained along the entire length, and additionally, the gaps that were not closed in stage I are filled, and thus the rocks are glued together. The section of the anchor protruding into the excavation is used to strengthen the support casing arches. This is done by building V-shaped stringers with holes and building another barrel and wedge clamp (Figure 8).

**Figure 8.** Diagram of cable anchor installation for reinforcing the support casing and the rock mass.

As a result, the rope anchor performs two important functions at the same time—it strengthens the rock mass and the arch support frame. An exemplary scheme of securing the new main adit according to the above technology is shown in two projections in Figure 9.

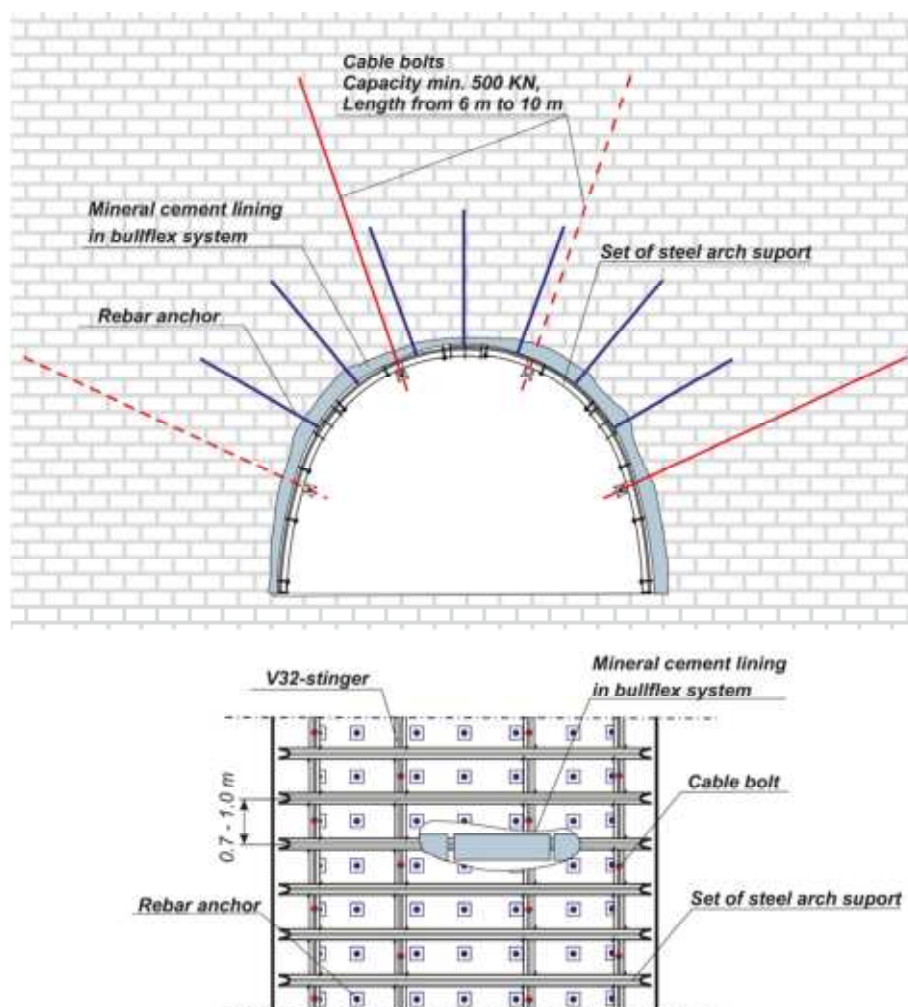


Figure 9. Proposal for a support system in the new main adit.

## 6. Summary

This paper presents the casing protection concept for the larimar mining process. In the Las Filipinas larimar (blue pectolite) deposit area, mafic igneous rocks (basalts), typical of eruptive formations, accompanied by pyroclastic rocks are observed [1,21]. The structural and textural features of the volcanics and the specific stress marks, internal cracks and deformation present in them indicate that the formation of these rocks occurred rapidly, under special marine conditions. These structural and textural features, as well as the characteristic mineral composition and the great variety of secondary products in them, should be taken into account when designing new technological solutions for mining this raw material.

In the work, the authors present several solution options. They propose a return to the shoring system used in the old main adit (arch support and shotcrete) for the shoring of the new main construction. However, an analysis of the available geological and geotechnical data is required for this project to allow for:

- (a) The viability of implementing the design to be determined;
- (b) The design to be optimized in the future.

General conclusions about the situation at the Las Filipinas mine could be grouped into several topics. The main ones are: poor knowledge of the deposit geology, defects in the construction of the drift support and uncontrolled exploitation in shafts and galleries affecting the rock mass surrounding the drift.

The presented support system should be a sufficient protection for the new tunnel. In Polish mines of hard coal, it is successfully used in difficult geological conditions at a depth of more than 1000 m. Naturally, when necessary, the load-bearing value of the above-described casing system can be increased by a reduction in frame spacing, installation of additional cable bolts, closing the support casing by building a steel floor bar or imposing a layer of shotcrete around the perimeter of the tunnel. To summarize, it should be emphasized that the design of the support, taking into account the selection of the appropriate system, including the selection of the type and spacing of the support arches, anchoring screens and length of the bolts, requires proper recognition of the geological properties of the rock mass. Such research should be carried out in two ways: laboratory and in situ. Control tests should also be carried out at the stage of excavation. It will also be necessary to prepare an appropriate monitoring system for the support and the rock mass for early decision-making on strengthening the support for the excavation.

The new main adit will be excavated in a rock mass that requires preliminary geophysical surveys. The BGC report (2018) stated that the RMR76 value of the rock mass in the area of the old main adit ranged from 19 to 34. The main adit will reach a maximum depth of 104 m.

## 7. Conclusions

1. The paper contains general assumptions of one of the variants of securing the main adit in the Las Filipinas Larimar Mine. To some extent the presented solution draws on the previous experience in the field of maintenance of the main works of this mine.
2. The selection of the potentially most effective method of supporting the mining pits requires a series of geophysical and geotechnical surveys. The tests to be conducted will enable the preparation of design assumptions for the new deposit access structure and the planning of operating works. The option of increasing the role/share of vertical shafts in accessing the deposit is also being considered.
3. A test site covering the entire field will be designed together with the Dominican side.

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## References

1. Alvarado, G.E.; Verdeja, E.; Rodriguez, J.; Barrantes, M. Contribution on the larimar host rock (Dominican Republic) and some notes about its origin. *Bol. Geol. Min.* **2007**, *128*, 767–782.
2. Woodruff, R.E. Larimar beautiful, blue and baffling. *Lap. J.* **1986**, *39*, 26–32.
3. Woodruff, R.E. The new caribbean gem. *North South Net. Inc.* **1987**, *11*, 7–59.
4. Lizzadro, J. The Interesting Story of a New Blue Gemmaterial Called Larimar. Lizzadro Museum, Summer-Fall. January 1987; 13–14.
5. Fuertes Marcuello, J.; Garcia Guinea, J. Caracterización mineralógica e histórica del larimar de Barahona (República Dominicana). *Bol. Inst. Gemol. Español* **1990**, *32*, 6–12. (In Spanish)
6. Kowalczyk, J.; Natkaniec-Nowak, L.; Wachowiak, J. Larimar—A Unique Pectolite Rock from the Dominican Republic. *Geol. Geophys. Environ.* **2015**, *41*, 101–102. [[CrossRef](#)]

7. Sen, G.; Hickey-Vargas, D.G.; Waggnaer, E.; Maurrasse, F. Geochemistry of basalts from the Dumisseau Formation, Southern Haiti: Implications for the origin of the Caribbean Sea crust. *Earth Planet. Sc. Lett.* **1988**, *87*, 423–437.
8. Lewis, J.F.; Draper, G. *Geological and Tectonic Evolution of the Northern Caribbean Margin: Decade of North American Geology*; Geological Society of America: Boulder, CO, USA, 1990; Volume H, pp. 77–140.
9. Révillon, S.; Hallot, E.; Arndt, N.; Chauvel, C.; Duncan, R.A. A complex history for the Caribbean Plateau: Petrology, geochemistry, and geochronology of the Beata Rigde, South Hispaniola. *J. Geol.* **2000**, *108*, 641–661. [[CrossRef](#)]
10. Escuder-Viruet, J.; Joubert, M.; Abad, M.; Pérez-Valera, F.; Gabites, J. The basaltic volcanism of the Dumisseau Formation in the Sierra de Bahoruco, SW Dominican Republic: A record of the mantle plume-related magmatism of the Caribbean Large Igneous Province. *Lithos* **2016**, *254*, 67–83. [[CrossRef](#)]
11. Kowalczyk, J.; George, C.; Nataniemc-Nowak, L.; Wachowiak, J.; Wagner, M. Larimarized fossil charcoal from Sierra de Bahoruco (Barahona Province, Dominican Republic). In Proceedings of the 1<sup>er</sup> Congreso Internacional de Geología Aplicada, Santo Domingo, Republica Dominicana, 15–17 March 2017; p. 34, In Resumenes Ponencias.
12. Wagner, M.; Wachowiak, J.; Kowalczyk, J.; Natkaniec-Nowak, L.; Heflik, W.; Georges, C. Petrographic and mineralogical studies of fossil charcoal from Sierra de Bahoruco (Barahona Province, Dominican Republic). *Int. J. Coal Geol.* **2017**, *173*, 142–149. [[CrossRef](#)]
13. De Leon, R.O. El Larimar: Origen y composición. Suplemento Listin Diario del Museo de Historia Natural. *Rep. Dominic. Marzo 1986*, 6–8. (In Spanish)
14. Schaller, W.T. The pectolite-schizolite-serandite series. *Am. Miner.* **1955**, *40*, 1022–1031.
15. Semenov, E.I.; Maksimiyuk, L.E.; Arkangelskaya, V.N. Sobre los minerales del grupo serandita-pectolita. *Azp. Vses. Min. Obshch.* **1976**, *104*, 154–163. (In Russian)
16. Hammer, V.M.F.; Libowitzky, E.; Rossman, G. Single-crystal IR spectroscopy of very strong hydrogen bonds in pectolite,  $\text{NaCa}_2[\text{Si}_3\text{O}_8(\text{OH})]$ , and serandite,  $\text{NaMn}_2[\text{Si}_3\text{O}_8(\text{OH})]$ . *Am. Miner.* **1988**, *83*, 569–576. [[CrossRef](#)]
17. Arakcheeva, A.; Pattison, P.; Meisser, N.; Chapuis, G.; Pekov, I.; Thélin, P. New insight into the pectolite—Serandite series: A single crystal diffraction study of  $\text{Na}(\text{Ca}_{1.73}\text{Mn}_{0.27})[\text{HSi}_3\text{O}_9]$  at 293 and 100 K. *Z. Krist.* **2007**, *222*, 696–704. [[CrossRef](#)]
18. Frost, R.L.; López, A.; Theiss, F.L.; Romano, A.W.; Scholz, R. Vibrational spectroscopic study of the silicate mineral pectolite— $\text{NaCa}_2\text{Si}_3\text{O}_8(\text{OH})$ . *Spectrochim. Acta A Mol. Biomol. Spectrosc.* **2015**, *134*, 58–62. [[CrossRef](#)] [[PubMed](#)]
19. Woodruff, R.E.; Fritsch, E. Blue Pectolite from the Dominican Republic. *Gems Gemol.* **1989**, *25*, 216–225. [[CrossRef](#)]
20. Kowalczyk-Szpyt, J. *Mineralogical, Petrographical and Geochemical Study of the Larimar from the Sierra de Bahoruco Massif (Barahona Province, Dominican Republic)*; Faculty of Geology, Geophysics and Environmental Protection: Krakow, Poland, Unpublished; 155p. (In Polish)
21. Kowalczyk, J.; Heflik, W.; Natkaniec-Nowak, L.; Wachowiak, J. Extrusive Basic Rocks from Sierra de Bahoruco (S-W Dominican Republic) with its Accompanying Processes of Transformation. In Proceedings of the Mineralogicko-Petrologická Konferencia Petros, Bratislava, Slovakia, 25 March 2017; pp. 28–29.
22. Correcher, V.; Garcia Guinea, J.; Castillejo, M.; Oujja, M.; Rebollar, E.; Lopez-Arce, P. Laser-induced fluorescence and thermoluminescence response of a Na-Ca rich silicate. *Radiat. Meas.* **2006**, *41*, 971–975. [[CrossRef](#)]
23. Kowalczyk, J.; Natkaniec-Nowak, L.; Wachowiak, J.; George, C. Preliminary Mineralogical and Petrographical Studies of the Larimar from Dominican Republic (Sierra de Bahoruco, Barahona Province). In Proceedings of the Polish Geological Congress, Wroclaw, Poland, 22 November 2016; pp. 167–168.
24. Kraj, K. *Mineralogical and Dendrological Studies of Mineralized Tree Trunks from Barahona Province (Dominican Republic)*; Faculty of Geology, Geophysics and Environmental Protection: Krakow, Poland, 2017; Unpublished work. (In Polish)
25. Bente, K.; Thum, R.; Wannemacher, J. Colored Pectolites, so called “Larimar”, from Sierra de Bahoruco, Barahona Province, southern Dominican Republic. *Neues Jahrb. Mineral. Monatsh.* **1991**, *1*, 14–22.
26. Espí, R.J.A. Singularidad del yacimiento mineral de la sierra de Bahoruco (República Dominicana) y su carácter patrimonial. *De Re Met. Madr.* **2007**, *9*, 41–52. (In Spanish)
27. Espi, J.A.; Borrego, A.G. Petrographic Assessment of Organic Material Associated to Pectolite Deposits in Dominican Republic, Implications for its Genesis. In Proceedings of the International Conference for Coal and Organic Petrology, Oviedo, Spain, 21–27 September 2008; The Society for Organic Petrology: Oviedo, Spain, 2008.
28. Espi, J.A.; Pérez-Puig, C. *El Proyecto Sobre el Estudio Geológico y Realización de Infraestructuras de Apoyo a la Minería del Larimar en la República Dominicana*; Escuela de Minas de Madrid: Madrid, Spain, 2009.
29. Sullasi, H.L.; Houry, H.J.; Barros, V.; Libonati, R.; Guzzo, P.L.; Asfora, V.; De Araujo, R.E.; Capriles, M.; Reyes, J. Thermoluminescence response of the larimar rocks. *Radiat. Meas.* **2010**, *45*, 540–542. [[CrossRef](#)]
30. Kloprogge, J.T.; Wood, B.J. X-ray Photoelectron Spectroscopy study of so-called “Larimar”, blue pectolite from the Dominican Republic. *SDPR J. Earth Sc. Environ. Stud.* **2016**, *1*, 1–5.
31. Espi, J.A.; Pérez-Puig, C. Origin and model formation of the semi-precious Larimar stone in the Sierra de Bahoruco, Dominican Republic. *Bol. Geol. Miner.* **2017**, *128*, 803–828. [[CrossRef](#)]
32. Bowin, C. The Geology of Hispaniola. In *The Gulf of Mexico and the Caribbean*; Nairn, A.E.M., Stehli, F.G., Eds.; Springer: Boston, MA, USA, 1975.
33. Donnelly, T.W.; Beets, D.; Carr, M.J.; Jackson, T.; Klaver, G.; Lewis, J.; Maury, R.; Schellenckens, H.; Smith, A.; Wadge, G.; et al. History and tectonic setting of Caribbean magmatism. *Geol. Soc. Am.* **1990**, *13*, 339–374.

34. Draper, G.; Mann, P.; Lewis, J.F. Hispaniola. In *Caribbean Geology: An introduction*; Donovan, S.K., Jackson, T.A., Eds.; University of the West Indies: Kingston, Jamaica, 1994; pp. 129–150.
35. Sandoval Gutiérrez, M.I.; Baumgartner, P.; Escuder-Viruete, J.; Gabites, J.; de Lépinay, B. Late Cretaceous radiolarian biochronology of the Pedro Brand section, Tireo Group, eastern Central Cordillera, Dominican Republic: A contribution to the stratigraphy of the Caribbean Large Igneous Province. *Rev. Micropaleontol.* **2015**, *58*, 85–106. [[CrossRef](#)]
36. Diebold, J.B.; Driscoll, N.W.; Team, E.W. New Insights on the Formation of the Caribbean Basalt Province revealed by multichannel seismic images of volcanic structures in the Venezuelan Basin, Caribbean basins. In *Sedimentary Basins of the World*; Mann, P., Ed.; Elsevier: Amsterdam, The Netherlands, 1999; pp. 561–589.
37. Byrne, D.B.; Suarez, G.; Mccann, W.R. Muertos Trough subduction; microplate tectonics in the northern Caribbean? *Nature* **1985**, *317*, 420–421. [[CrossRef](#)]
38. Masson, D.G.; Scanlon, K.M. The neotectonic setting of Puerto Rico. *Geol. Soc. Am. Bull.* **1991**, *103*, 144–154. [[CrossRef](#)]
39. Mann, P.; McLaughlin, P.P.; Cooper, C. Geology of the Azua and Enriquillo basins, Dominican Republic; 2, Structure and Tectonics. In *Geologic and Tectonic Development of the North America-Caribbean Plate Boundary in Hispaniola*; Geological Society of America: Boulder, CO, USA, 1991; Volume 262, pp. 367–389.
40. Mann, P.; Prentice, C.S.; Burr, G.; Pea, L.R.; Taylor, F.W. Tectonic geomorphology and paleoseismology of the Septentrional fault system. *Bull. Seism. Soc. Am.* **1998**, *103*, 144–154.
41. Escuder-Viruete, J.; Hernaiz Huerta, P.P.; Draper, G.; Gutierrez, G.; Lewis, J.F.; Pérez-Estaún, A. Metamorfismo y estructura de la Formación Maimón y los Complejos Duarte y Río Verde, Cordillera Central Dominicana: Implicaciones en la estructura y la evolución del primitivo Arco Isla Caribeño—The metamorphism and structure of the Maimón Formation and Duarte and Rio Verde Complexes, Dominican Central Cordillera: Implications for the structure and evolution of the primitive Caribbean Island Arc. *Acta Geol. Hisp.* **2002**, *37*, 123–162. (In Spanish)
42. Goldfinger, C. Submarine paleoseismology based on turbidite records. *Ann. Rev. Mar. Sci.* **2011**, *3*, 35–66. [[CrossRef](#)]
43. Zoppis de Sena, R. *Atlas Geológico y Mineralógico de la República Dominicana Mapa Geológico de la República Dominicana Escala 1: 50000*; Servicio Geologico Nacional Republica Dominikana: Santo Domingo, Dominican Republic, 1988; p. 20.
44. Mauffret, A.; Leroy, S. Seismic stratigraphy and structure of the Caribbean igneous province. *Tectonophysics* **1997**, *283*, 61–104. [[CrossRef](#)]
45. Lapiere, H.; Bosch, D.; Dupuis, V.; Polvé, M.; Maury, R.; Hernandez, J.; Monié, P.; Yeghicheyan, D.; Jailland, E.; Tardy, M.; et al. Multiple plume events in the genesis of the peri-Caribbean Cretaceous oceanic plateau province. *J. Geophys. Res.* **2000**, *105*, 8403–8421. [[CrossRef](#)]
46. Escuder-Viruete, J.; Pérez-Estaún, A.; Contreras, F.; Joubert, M.; Weis, D.; Ulrich, T.D.; Spadea, P. Plume mantle source heterogeneity through time: Insights from the Duarte Complex, Central Hispaniola. *J. Geophys. Res.* **2007**, *112*, 1–19.
47. Escuder-Viruete, J.; Pérez-Estaún, A.; Joubert, M.; Weis, D. The Pelona-Pico Duarte basalts formation, Central Hispaniola. An on-land section of the Late Cretaceous volcanism related to the Caribbean large-igneous province. *Geol. Acta* **2011**, *9*, 1–22.
48. Hastie, A.R.; Kerr, A.C.; Mitchell, S.F.; Millar, I.I.; James, K.H.; Lorente, M.A.; Pindell, J.I. *Geochemistry and Tectonomagmatic Significance of Lower Cretaceous Island Arc Lavas from the Devils Racecourse Formation, Eastern Jamaica. The Origin and Evolution of the Caribbean Plate*; The Geological Society of London: London, UK, 2009; Volume 328, pp. 339–360.
49. Loeven, M.W.; Duncan, R.A.; Kent, A.J.R.; Krawl, K. Prolonged plume volcanism in the Caribbean Large Igneous Province: New insights from Curaçao and Haiti. *Geoch. Geoph. Geosyst.* **2013**, *14*, 4241–4259.
50. Whattam, S.A.; Stern, R.J. Late Cretaceous plume-induced subduction initiation along the southern margin of the Caribbean and NW South America: The first documented example with implications for the onset of plate tectonics. *Gondwana Res.* **2015**, *27*, 38–63. [[CrossRef](#)]
51. Escuder-Viruete, J.; Pérez-Estaún, A.; Weis, D. Geochemical constraints on the origin of the late Jurassic proto-Cretaceous oceanic crust in Hispaniola. *Int. J. Earth Sci.* **2010**, *98*, 407–425. [[CrossRef](#)]
52. IGME-BRGM-INYPSA. *Mapa geológico de la República Dominicana, escala 1: 50.000. La Ciénaga (5970-II)*; Informe inédito. Proyecto SYSMIN II-01-B; Servicio Geologico Nacional Republica Dominikana: Santo Domingo, Dominican Republic, 2010; p. 202.
53. Huerta, P.P.; Díaz de Neira, J.A.; García-Senz, J.; Deschamps, I.; Lopera, E.; Escuder Viruete, J.; Ardévol Oró, L.I.; Granados, L.; Calvo, J.P.; Pérez-Estaún, A. La estratigrafía de la Sierra de Neiba (República Dominicana). *Boletín Geológico Min.* **2007**, *118*, 313–336. (In Spanish)
54. Meznaric, M.; Hensold, G.; Karami, A. *Instituto Canadiense de Recursos Internacionales Y Desarrollo (CIRDI), Mina Larimar, Evaluación de peligros geotécnicos y opciones de Gestión—PROJECTO*; Servicio Geologico Nacional Republica Dominikana: Santo Domingo, Dominican Republic, 2018; Unpublished Report.
55. Geovértice. *Galería de Exploración, Mina Larimar—Levantamiento Topográfico: Planta y Longitudinal*; Geovértice: Santo Domingo, Dominican Republic, 2010.
56. Karakaplan, E.; Basarir, H.; Wesseloo, J. Theoretical Investigation of the Effect of Stress on the Performance of Support Systems Based on Rock Mass Rating (RMR) Support Recommendations. In *Proceedings of the Eighth International Symposium on Ground Support in Mining and Underground Construction*, Luleå, Sweden, 12–14 September 2016.
57. Bieniawski, Z.T. *Engineering Rock Mass Classification: A Complete Manual for Engineers and Geologists in Mining, Civil and Petroleum Engineering*; John Wiley & Sons: Hoboken, NJ, USA, 1989; 251p.

58. Birid, K. Comparative Study of Rock Mass Deformation Modulus Using Different Approaches. In Proceedings of the 8th Asian Rock Mechanics Symposium, Sapporo, Japan, 14–16 October 2014; pp. 553–563.
59. Galera, J.M.; Alvarez, Z.; Bieniawski, Z.T. Evaluation of the Deformation Modulus of Rock Masses: Comparison between Pressure Meter and Dilatometer Tests with RMR Predictions. In Proceedings of the ISP5-PRESSIO, Marne-la-vallée, France, 22–24 August 2005; Gambin, M., Mestat, P., Baguelin, F., Eds.; LCPC Publication: Paris, France, 2005.
60. Kaiser, P.K.; Ming, C. Principle of rockbolting design. *J. Rock Mech. Geotech. Eng.* **2012**, *4*, 215–227. [[CrossRef](#)]
61. Rak, Z.; Stasica, J.; Rawicki, Z. Selected problems in using roof bolting for the reinforcement of chock support in preparatory excavations. *Occup. Saf. Environ. Prot. Min.* **2016**, *2*, 3–13. (In Polish)
62. Rak, Z.; Ciešlik, J.; Stasica, J.; Dvorak, P. The importance of pre-tensioning cable bolts used to reinforce of arch yielding support. *E3S Web Conf.* **2018**, *66*, 03003. [[CrossRef](#)]
63. Małkowski, P.; Rak, Z.; Stasica, J. Elements of constructing mechanical lining in the light of previous experience. *Problemy Współczesnego Górnictwa* **2011**, *1/1*, 316–326. (In Polish)
64. Małkowski, P.; Rak, Z. Influence of mechanical lining on the state of stress around a gate drifted in weak carboniferous rocks. *Problemy Współczesnego Górnictwa* **2011**, *1/1*, 251–262. (In Polish)
65. Stankus, J.; Li, X.; Giza, D.; Rutyna, M. Rock Anchoring and Grouting: Use of SUMO Cable Bolts in Western U.S. Longwall Recovery. In Proceedings of the XXI International Scientific and Technical Conference in the Mining Natural Hazards, Targanice, Poland, 4–7 November 2014; Series Natural Hazards Versus Safe and Effective Mines. pp. 35–37. (In Polish).