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Article

Historical and Contemporary Use of Natural Stones in the French West Indies. Conservation Aspects and Practices

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Abstract: The French West Indies (F.W.I.), in the Eastern Caribbean, are part of a biodiversity hotspot and an archipelago of very rich geology. In this specific natural environment, the abundance or the lack of various natural resources has influenced society since the pre-Columbian era. The limited size of the islands and the growth of their economy demand a clear assessment of both the natural geoheritage and the historical heritage. This paper presents a brief review of the variety of the natural stone architectural heritage of the F.W.I. and of the available geomaterials. Some conservation issues and threats are evidenced, with particular emphasis on Guadeloupe. Some social practices are also evoked, with the long-term goal of studying the reciprocal influence of local geology and society on conservation aspects. Finally, this paper argues that unawareness is one of the main obstacles for the conservation of the geoheritage and the natural stone architectural heritage in the F.W.I.

Keywords: building stones; Guadeloupe; Martinique; French West Indies; eastern Caribbean; cultural heritage; geological heritage; historical and Archaeological sites

1. Introduction

In 2002, the law for a Democracy of Proximity [1] was voted by the French parliament. It stated that the State takes care of the conception, the animation, and the evaluation of the Natural Heritage. This heritage shall include all ecological, fauna, flora, geological, mineralogical, and paleontological items of interest. For the Geoheritage [2], in which human-related sites of interest are considered, Guadeloupe in the French West Indies (F.W.I.) was chosen as a test territory. Indeed, its geology is very rich and very peculiar [3,4], with a lot of variation. It includes, for example, a carbonate platform, coral reefs (both actives and fossils), mangrove-bearing mudflats, on-shore and submarine thermal springs, a great variety of volcanic deposits, tropical karsts, and an active volcano, La Soufrière. So, as recently as 2003, local stakeholders in Guadeloupe have been referencing several sites and created a collection of 33 outcrops' descriptions. In 2015, all these sites had been validated at the national level and entered into a national database (IGeotope) [5]. This inventory is meant to be permanent and a living collection. Since late 2018, the previous outcrops' descriptions are re-evaluated and new information (GIS mapping, petrological analysis) is being collected for later addition to sites descriptions. One of the goals of this second phase of inventory is also to add new sites, emphasizing on human-related sites. When finalized, a territorial geological and natural stone architectural heritage catalogue reveals itself a powerful tool for policy making and education. Despite the need to inventory the underground for resource purposes (water, building stones, mining) that has motivated geological research for centuries, such an inventory is meant to be used for protecting areas of natural interest, for teaching and for developing tourism.

The study presented in this article was conducted in order to further develop this inventory. One of the goals was to gather field observations and existing information with the long-term objective of evaluating the patrimonial value of the local geodiversity and the local natural stone structures. This paper presents the first results of this study. A second, long-term, objective will be to document whether the local geology of different islands in the French West Indies has influenced building styles and society. Finally, another objective is to make a first assessment of the preservation of natural stones structures and to evidence potential threats. Indeed, in isolated environments with limited mineral resources, such as the Lesser Antilles archipelago, people have had to develop a specific knowledge of the local geology, for all purposes. In Martinique, clays were traditionally used for making roof tiles [6], but, in Guadeloupe, this activity has remained artisanal because of a lack of knowledge of the resource and the poor quality of clays [7]. They are still used only for medicinal and recreational purposes [8]. Paradoxically, the recreational use of clays in Guadeloupe tends to have a greater impact on the resource than the industrial use of clay in Martinique because of the limited resource and concentration of activity on a small area.

In buildings, the traditional creole architecture mainly uses wood, but some 19th and 20th century city center buildings and churches were made with volcanic stones (mostly andesite). Local limestones were processed in artisanal to semi-industrial limekilns. Stone-made houses and other buildings, limekilns and their extraction sites have a cultural value and represent an economic interest for tourism, but they suffer from a lack of protection, restoration and a poor awareness within the population. Indeed, although it is very present, most people remain unaware of this link between the local culture and the local geology. Nowadays, uncontrolled limestone quarries endanger many remarkable outcrops. Most of these quarries are small and designed solely to create a suitable flat area for building a concrete made house. The extracted limestone is used as a rather poor-quality road foundation material. With the densification of the population of the F.W.I. during the twentieth century, the anthropization of landscapes became important and limestones were excavated in many places, sometimes strongly impacting the landscape. Nowadays the population is slowly decreasing but the habit persists.

Finally, this article deals with the architectural heritage of the French West Indies, with emphasis on the use of dimension stone and other geomaterials, and exposes some related conservation issues. Then, with a main focus on Guadeloupe, it argues that unawareness is an important hindrance to the conservation of the local stone-built heritage in the French West Indies.

2. Context of the Study

Geological Context of the French West Indies

Located in the eastern Caribbean, the French West Indies are part of the Lesser Antilles arc [9]. They range south to north along the Caribbean plate boundary (Figure 1), where the North and the South American plates are subducting beneath the Caribbean plate. The geology of these islands is characteristic of subduction arcs, with a variety of volcanic formations along with scarce plutonic rocks and sedimentary deposits that form large carbonate platforms. The arc has been quasi-continuously active since the Eocene [10], with an inward migration of volcanism in its northern half. This has resulted in a variety of islands with either steep or shallow-shelf topography and an interbedding of volcanites and sediments. The Cenozoic migration of magmatism has also led to the formation of two distinctive sets of islands, the most recently active forming an internal arc (from Martinique to the Virgin Islands) and the others being associated with an inactive, older arc (Eocene to Miocene). From Dominica and further south, the two arcs, active and Eocene, are superimposed since very little migration occurred. Martinique island is formed by the two arcs. In the south and the east, Oligocene volcanic formations outcrop, the volcanic rocks are Miocene in the central part of the island and Plio-Pleistocene further west and north (Figure 2). The age variation of the volcanism, from east to west, from Oligocene to the Montagne Pelée active volcano, underlines the cenozoic westward migration of the magmatic activity. In Guadeloupe, the volcanic activity is occurring in the western part (Basse-Terre) and the eastern part (Grande-Terre) is covered with a carbonate platform

(Figure 3). The typology of rocks that outcrop is then separated, with massive andesites, suitable for producing dimension stones, in the West and limestones, suitable for lime production, in the East.

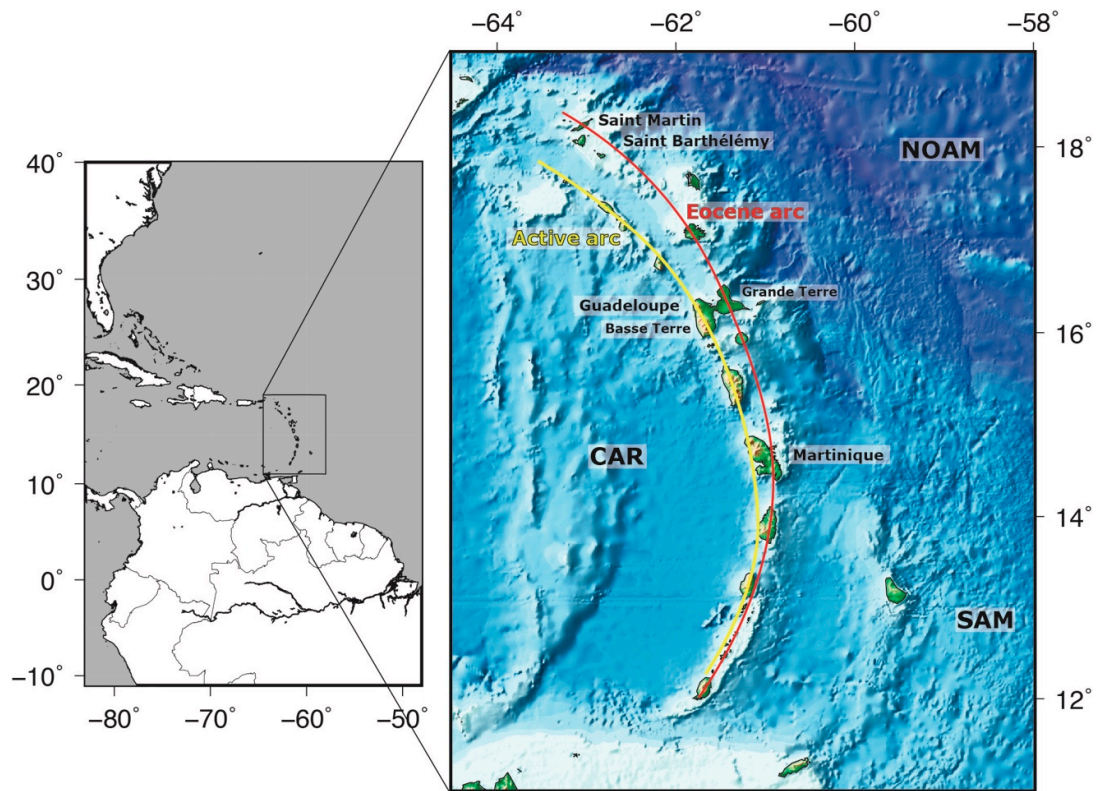


Figure 1. Map of the Eastern Caribbean. CAR: Caribbean plate, NOAM: North American plate, SAM: South American plate.

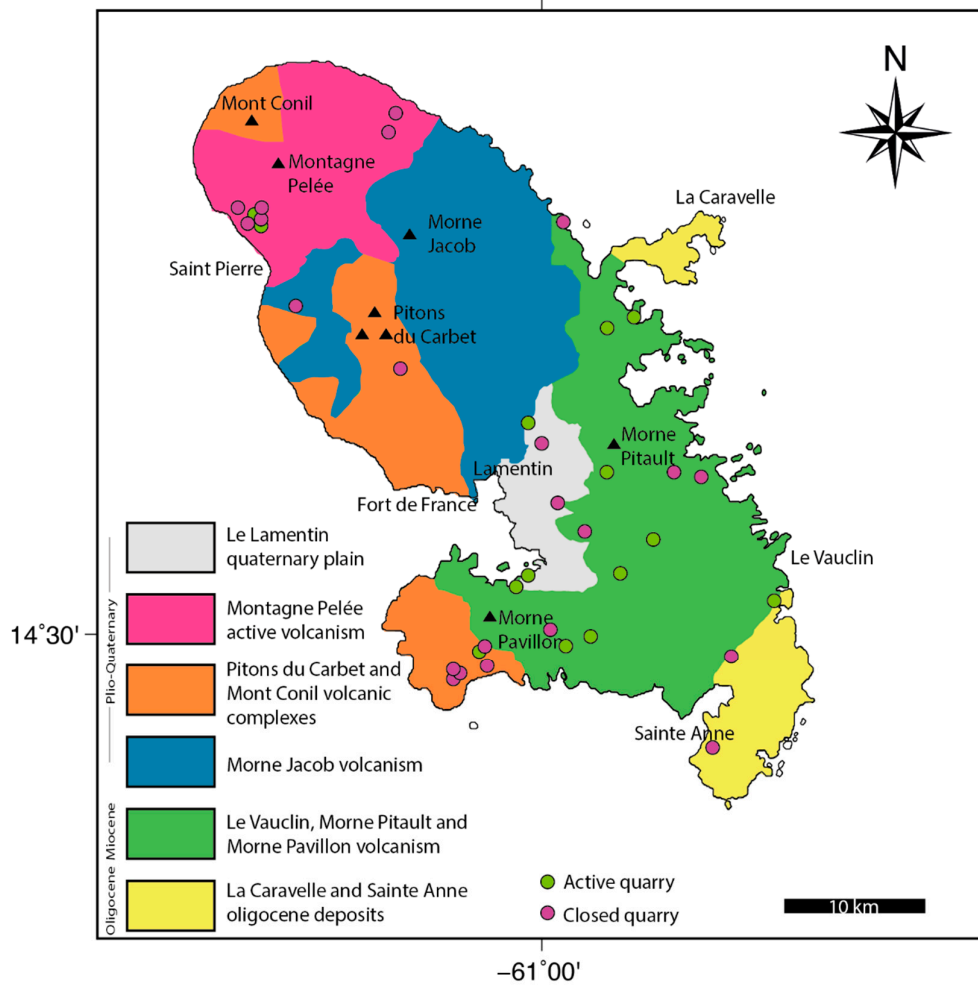


Figure 2. Simplified geological map of Martinique. Modified, after Westercamp et al., 1989 [11]. Active and closed quaries referenced in the national database InfoTerre [12].

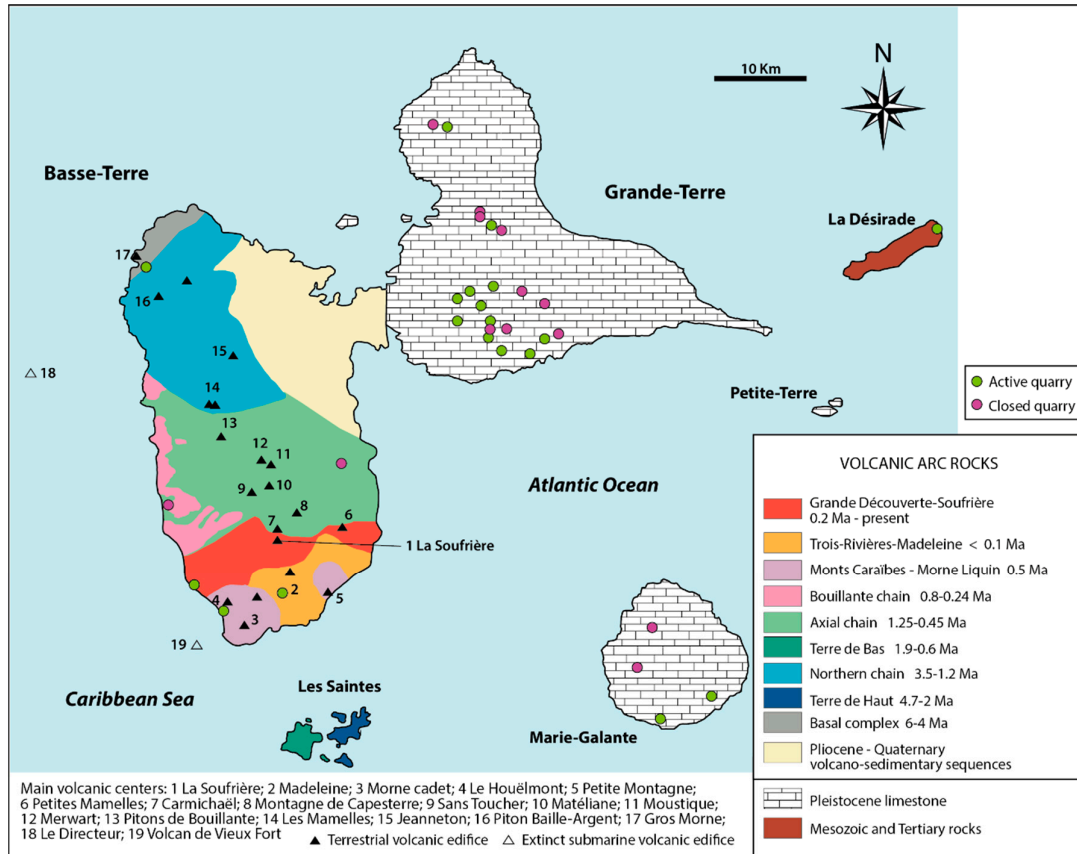


Figure 3. Simplified geological map of Guadeloupe, modified, after Komorowski et al., 2004 [13]. Active and closed quarries referenced in the national database InfoTerre [12] (for active quarries in 2019, see Figure 4).

3. Geoheritage Inventory

3.1. Geosites

In 2007, a National Geological Heritage Inventory [14] was launched in France. This state-funded program resulted in the description of several hundreds of geosites throughout the country, in both mainland and overseas territories. The majority of the referenced sites are natural (outcrops, landscapes, geological peculiarities, stratotypes, mineral deposits, various geological bodies), but some are also anthropogenic, especially sites located in quarries and mines, whether they are still in activity or not. Archeological sites are usually not included in this inventory, nor stone-built structures. The main purpose of this inventory is to gather information about the geological heritage and to provide it to the local authorities responsible for land-use policies. It is not an active protection measure, but it is designed to raise awareness about the geological heritage in order to avoid unintentional destruction of valuable outcrops. Each geosite is described in a technical note containing information such as a brief geological description, accessibility, any active protection measure, geological interest, educational interest, scarcity (local, regional, national, international), vulnerability and potential threats, relevant bibliographic references and the geographical perimeter of the site. All technical notes are included in public documents, but the information is not easily accessible to the general public. In Guadeloupe, Saint Martin and Saint Barthelemy the actual inventory has 33 sites, only one of which is located in Saint Martin and one in Saint Barthelemy.

One of the sites in Guadeloupe is inside the perimeter of an active quarry and one is a petroglyph archeological park, in Trois Rivières.

3.2. Present Day Geomaterials Extracted in the French West Indies

Today, a number of extraction sites are active in the French West Indies. Most of them are small limestone quarries and some extract andesite. None produces dimension stones on a regular basis. In the northern part of the arc, in Saint Martin, only one quarry is active (Hope Hill), it exploits andesite and volcanic tuffs [15]. In Martinique, 11 quarries exploit volcanic rocks, one limestone and two produce clay for the local roof-tile industry [16], a traditional specificity of this island in the Caribbean. In Guadeloupe, in 2019, 10 quarries produce stone from the limestone deposits, mostly in the Grand-Fonds area, one site exploits massive andesites (*Deshaies*) and two, in the south of Basse Terre, are extracting andesitic lapilli [15]. This section is mainly focused on Guadeloupe, where more information is available than in Martinique and Saint Martin. Figure 4 presents a map of the mineral resources of Guadeloupe, with the authorized quarries that are currently active.

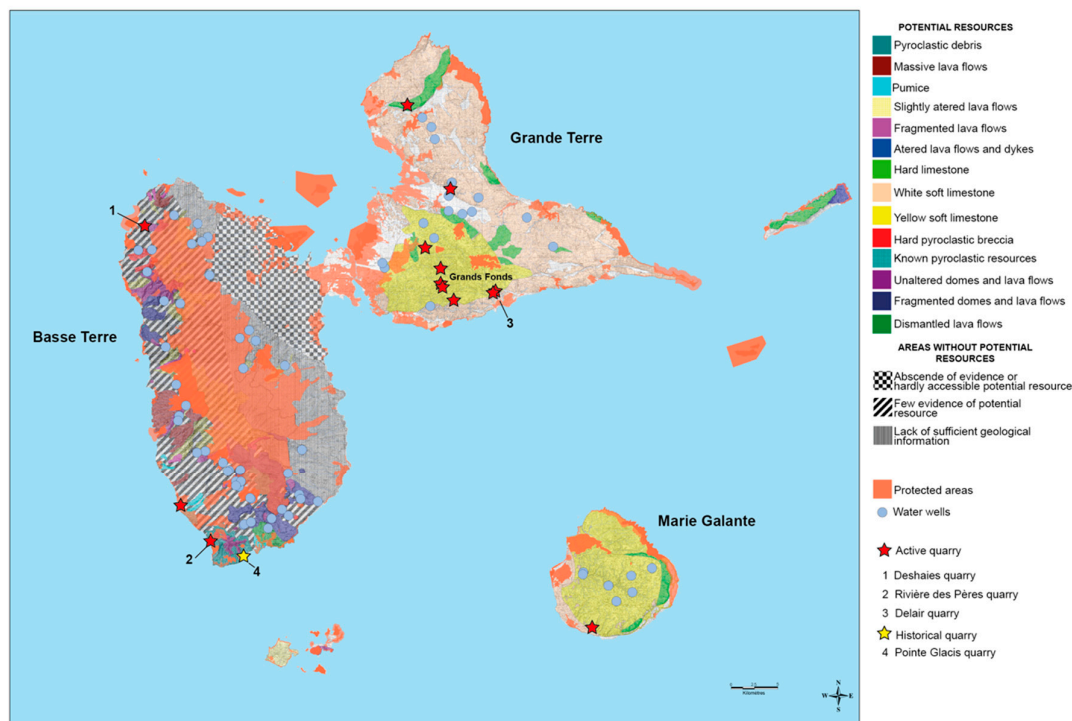


Figure 4. Map of the mineral resources of the Guadeloupe archipelago, modified after Bourdon and Chauvet, 2012 [15]. Red stars: quarries currently active in 2019.

The quarry in Deshaies is mining two different quality of rocks. Their average composition is given in Table 1. In the upper part of the pit, the volcanic rocks are more or less massive, with important weathering along the joints. Currently, this horizon is used for the manufacture of aggregates for hydraulic concretes. It is a massive basaltic andesite with a microlithic texture, plagioclases, pyroxenes and amphiboles phenocrysts and microcrystals of apatite and ilmenite (Figure 5a). There are abundant alteration zones that are rich in phyllosilicates (clay and chlorite). In the lower part of the exploitation the rocks are much less altered and fractured. They have a microlithic texture, with mostly pyroxenes and plagioclase unaltered phenocrysts (Figure 5b). This horizon is mined for producing road aggregates. Both types of aggregates produced from the Deshaies quarry require the use of explosives (the quarry uses 70 tons per year) and rock-crushing.

The Rivière des Pères quarry, at the extreme south of Basse-Terre, extracts hardened pyroclastic deposits, mostly lapilli, which require no explosive for the extraction. The aggregates are produced without rock-crushing and have a high vacuole content (Figure 5c,d).

Table 1. Chemical analysis of the Deshaies quarry rocks.

Content (%)	“Concrete” Rock	“Road Aggregate” Rock
SiO ₂	58.33	59.00
Al ₂ O ₃	17.76	17.91
Fe ₂ O ₃	7.29	7.26
CaO	7.08	6.81
MgO	2.76	2.79
CO ₂	1.41	0.77
Na ₂ O	3.22	3.35
K ₂ O	0.80	1.51

Data S.A.D.G. 2008 [17].

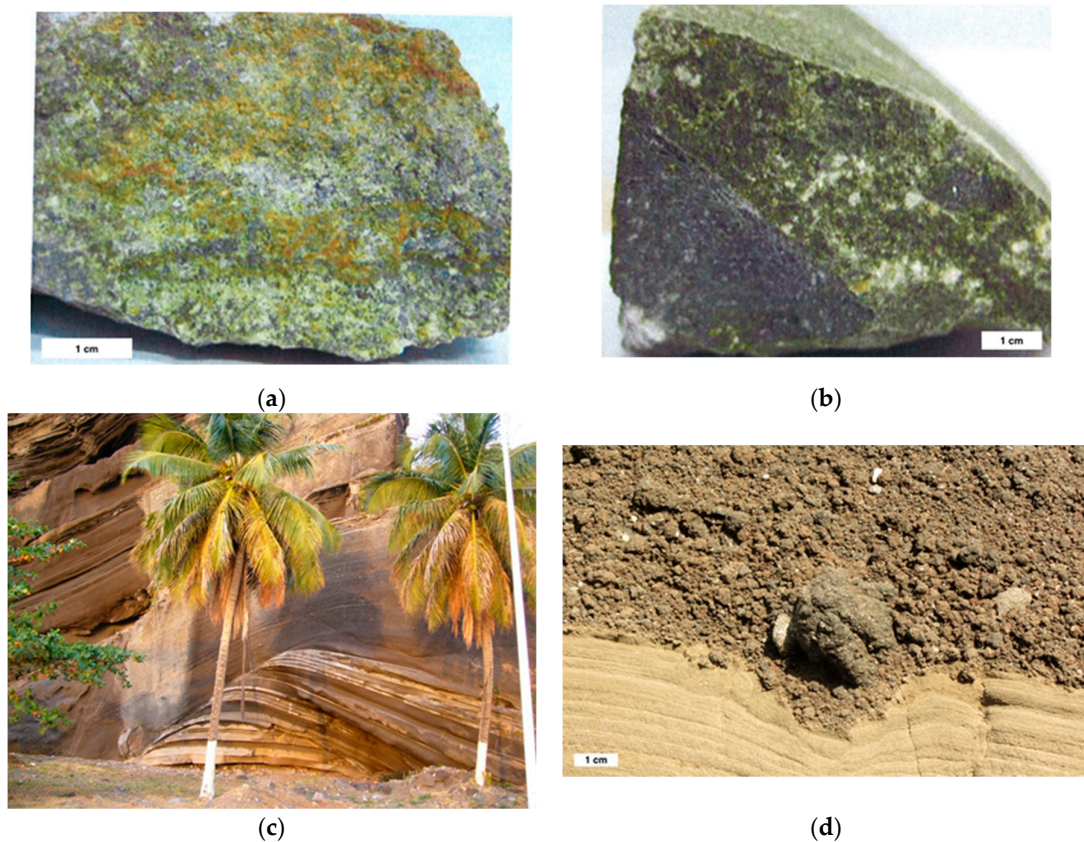


Figure 5. Basaltic andesite from Deshaies quarry, Guadeloupe (a) “Concrete” rock; (b) “Road aggregate” rock. Note the unaltered minerals on the fresh cut. Pictures a and b are from S.A.D.G. 2008 [17]. (c) and (d) volcanic deposits from Rivière des Pères, Monts Caraïbes, Guadeloupe. This outcrop is a geosite referenced in iGeotope; it is located one kilometer south of the Rivière des Pères quarry.

In the F.W.I., most quarries that are extracting limestones are in Guadeloupe (Marie Galante and Grande Terre), with only one in Martinique and none in Saint Martin and Saint Barthelemy. The carbonate platforms in Guadeloupe are well known and described [18–21]. They are constituted of an alternance of rodolitic algal limestones and reefal limestones, with intercalations of volcano-sedimentary detrital material. On Figure 6, the units 1 and 2 corresponds to the “Yellow” and “White soft limestones” of Figure 4, while units 3 and 4 are “hard limestones” (see also Figure 7).

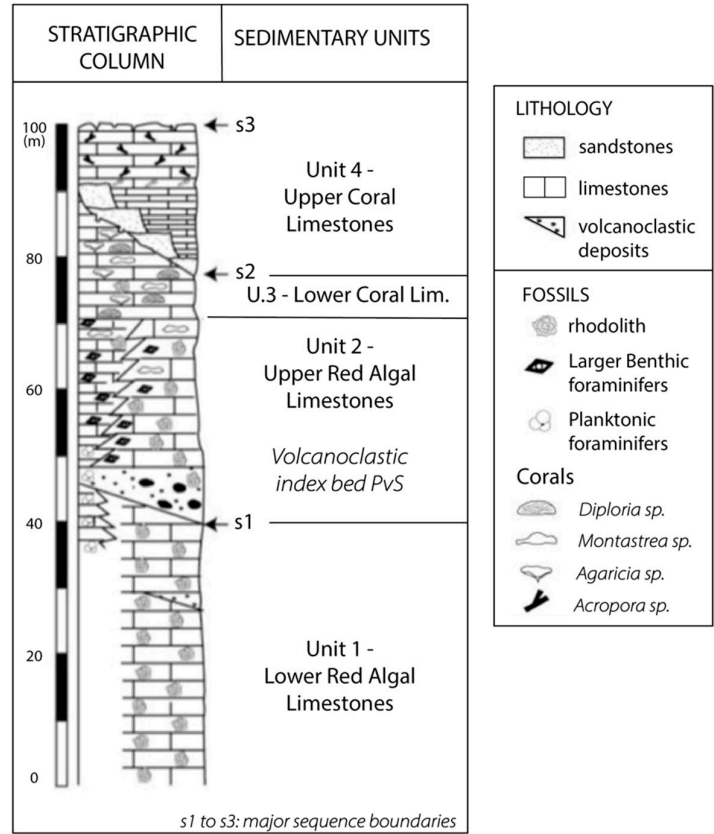


Figure 6. Synthetic stratigraphic log of the Grande-Terre and Marie Galante carbonate platform, Guadeloupe, from Conesa et al., 2012 [20].



(a)



(b)



(c)

Figure 7. (a) Reefal limestone in Delair quarry, Grande Terre. Note the large *Agaricia sp.* fossil colony above the hammer. Unit 3-Lower coral limestones; (b) *Acropora sp.* reefal limestone in Delair quarry. Unit 4-Upper coral limestones; (c) Rodolith from Unit 1-Lower red algal limestones, Grande Terre, Guadeloupe. Note the red algal carbonate concentric deposits around the volcanic debris.

3.3. Preservation Issues and Threats

Although the identification and the referencing in a national database of a heritage site does not automatically oblige the authorities to act for its conservation and protection, it is often seen as the first step towards active protection measures. In Guadeloupe, some geosites are protected, in fact, because they are located within regulated areas. Indeed, there are for example a National Park, a Natural Reserve and protected coastal areas. This is the case for the most spectacular sites, like the summit of the active volcano *La Soufrière*. On the contrary, some sites are neglected and some are endangered. The extraction activity appears to be often in tension with the conservation of the environment. In 2017, the quarry, south of Basse Terre (*Rivière des Pères*) was authorized to extend its activities in a natural area of high ecological value despite protests from the civil society [22]. In Grande Terre, almost all the quarries are extracting limestone in the Grand Fonds area. The Grand Fonds are a national heritage Geosite. It is a tropical karst that displays typical carbonate erosional features and remarkable sceneries. As the limestones have a low hardness, it is easy to open hill-side half-pits for the sole objective of providing a flat area for the construction of individual houses. This activity, sometimes illegally, strongly changes the landscape.

The first geosites in the F.W.I. were documented in Guadeloupe in 2003 [23] and in 2007 [24]. In early 2019, the author visited all sites from Guadeloupe (sites in Saint Martin and Saint Barthelemy were visited in 2017) in order to update their outcrop conditions and preservation status. Under tropical Caribbean conditions, the weathering can be very active, along with strong action of plant roots on rocks and soils. Indeed, 5 sites at least (over 33) were not easily visible anymore, due to vegetation growth or surface weathering. In particular, a site in southern Basse-Terre (*Pointe Glacis*—see Section 4.2.4). The sites that are the most vulnerable to weathering are small roadside outcrops, but even some landscapes associated with large geological formations are affected by anthropogenic activity. Two roadside sites have been covered with shotcrete for safety purposes. One of the sites, in Grand Fonds area, which is inside an active quarry (Delair), has been protected since its discovery. The quarry is not allowed to destroy the outcrop and has therefore concentrated its activity on other parts of the concession. The protection was then a success but, since then, the outcrop has been exposed to natural weathering and the sedimentary features that had motivated for its protection, although still present, are hard to read due to intense algae growth and carbonate surface dissolution (Figure 8a,b).

Apart from limestones, other georesources, that occur at locations that are not yet referenced within the geosites inventory, can also be faced with growing urbanization, or other activities, like for example, in Grande-Terre, the *Anse Babin* bay. In this area, local people come for mud bathing [8].

The mud is originally from the neighboring mangrove and is collected in shallow waters. This is done by the population only in Anse Babin, a small area with limited clay resource. As the bay is inside the lagoon, well protected from the ocean swell and any tidal current, clays accumulate on site, near the shore. However, the over-exploitation and collection for off-site personal use, possibly associated with the confusion between a natural resource and a renewable resource, has caused the rarefaction of the resource (Figure 8c,d).



(a)



(b)



(c)



(d)

Figure 8. (a) view from the south of the protected outcrop at Delair quarry, in Guadeloupe, in 2010. Several sedimentological facies were identifiable. The height of the escarpment is of 40 m; (b) view from the south-west of the same outcrop in 2019. Surface alteration has darkened the rocks, the structures are far less visible and a pile of materials from the quarry is blocking the access to the

escarpment; (c) the bay of Babin, in Guadeloupe; (d) mud collected at the sea bottom for mud bathing and let onshore after use.

4. Stone-Built Heritage

4.1. Pre-Columbian Heritage

The first known use of geomaterial in the F.W.I. are pre-Columbian artefacts [25,26]. Carved rocks are also documented in most of the Eastern Caribbean islands [27] and protected, since 1981, in Guadeloupe, by an archeological Park. Besides protection and awareness, the Park also generates tourist attractivity. The best known and preserved petroglyphs are located in Trois-Rivières, south of Basse-Terre island, Guadeloupe. The carved rocks are boulders of andesite, from the Monts Caraïbes massif. These rocks are silicic and resistant to weathering, at least far more than the Grande-Terre limestones. It is likely that the pre-Columbian inhabitants have used the limestones as well for carving, but that the erosion has erased the petroglyphs. This assumption is supported by the attested pre-Columbian human occupation of some cavities of the Grande-Terre and Marie Galante karsts [28] where some altered engravings are still preserved [29].

4.2. Colonial Heritage

Later, during the Colonial period (16th to 20th century), most of the buildings were constructed from wood; few used rubble stones and fewer still were constructed from dimension stone. Most of the stone-built structures are military buildings, churches, houses in civic centers and windmills. Although some are preserved, many are known only by their archeological remains [30]. There is very few information about both the stones that were used and the extraction sites. The location of the historical quarries is almost never known. It is likely that they were small, that they were in activity over short periods of time and that stone was produced as close as possible to the needs.

4.2.1. Military Buildings

During the 18th century, military and religious natural stone buildings were constructed in the French West Indies. In Guadeloupe, the plans of the military forts followed the typical European engineering of that time. They were made using both soldiers' workforce and slave labor and set in the best-suited places for the defense of the harbors and main cities, usually on the top of hills near the sea. The fact that their locations was chosen for defense purposes implied a necessary adaptation to the ground and different quarrying strategies. In Grande Terre, the *Fort Fleur d'Épée* (built between 1750 and 1763) is on a limestone spur. There, the builders extracted the limestones directly on site and constructed on the rocks, following the topography with only little earthworks (Figure 9a). The excavation of tunnels and underground rooms for gunpowder storage provided material for the outer fortifications and small size buildings within the perimeter of the fort. The quality of the material makes it strong enough for construction and easy to carve, but it is coarse grained. For ornamentation, andesite was then chosen and imported from Basse Terre (Figure 9b).

In Basse Terre, the *Fort Delgrès* surmounts unconsolidated debris flow deposits (Figure 9c). Consequently, all materials have had to be brought to the site. The fortifications and barracks were made with cemented volcanic rock pebbles. No reliable historical recording of the origin of the materials could be found during this study, but it is likely that the pebbles have been collected on Basse Terre western beaches and that the cement used lime from Grande Terre.

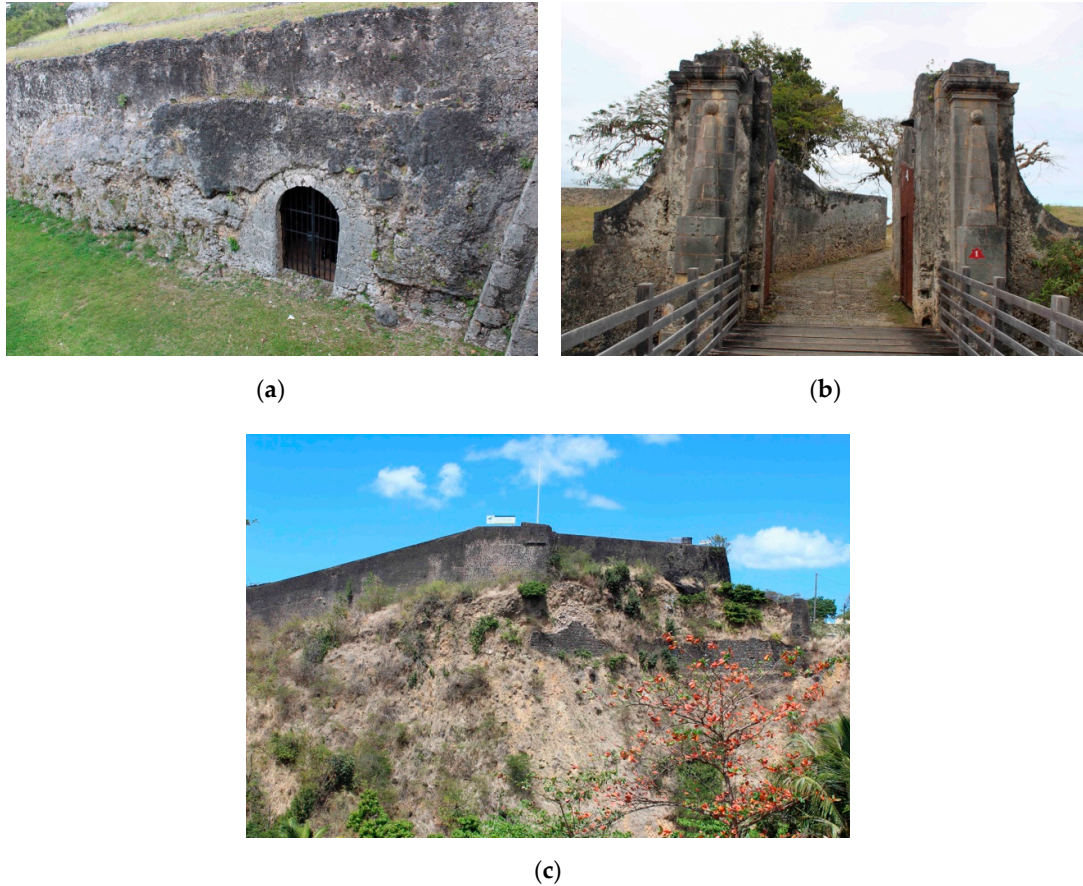


Figure 9. (a) Foundations of the Fort Fleur d’Epée, Guadeloupe. Entrance of a tunnel, excavated in the limestones, and inner wall of the fort, directly on the rocks; (b) main gate of Fort Fleur d’Epée with dimension stone ornamentations made with Basse Terre andesite; (c) northern fortifications of Fort Delgrès, Guadeloupe, above the gorge of Galion river. Note the unconsolidated debris flow materials, from La Soufrière volcano, forming the escarpment.

4.2.2. Religious Buildings

In Guadeloupe, natural stone religious buildings from the colonial period are found only in Basse-Terre, where volcanic rocks were quarried. They principally consist in the church of the village of *Vieux-Habitants* and the cathedral of Basse Terre city (Figure 10a–e), as well as several small chapels. *Vieux Habitants’* church was built in 1703, after the original wooden construction was burned in an act of war. Most of the edifice is recent (rebuilt in the 20th century) and now covered with an impermeability coating. Nevertheless, its original ornamental dimension stone main gate is preserved. It is made of greenish and reddish andesite. The facade was carved by workers from central France (Massif Central), where similar rocks are traditionally used [31]. The Basse Terre cathedral was built shortly after, in 1730, and displays a more important use of natural stone [32], especially for the facade, the vault, and the ornamentation.

The preservation state of the materials of the buildings in the center of Basse Terre city, and especially the Basse Terre cathedral, shows highly variable deteriorations of the dimension stones. Although the origin of the blocks is uncertain, their coloration, the important variability of textures and the abundance of vacuoles suggest a provenance from the slightly weathered top of Basse Terre lava flows (Figure 10e). The deterioration is particularly important where the porosity of the material is high. Alteration also strongly follows the fabric of the material, especially the magmatic fluidity. This implies that for the eventual restoration of the cathedral, it will be likely that the use of andesite blocks from local lava flows or debris flow deposits will be required. Indeed, the andesitic rocks

currently in exploitation at the quarry in northern Basse Terre are of different quality (color, fabric) and would presumably show a strong appearance difference with the stones used for the original construction of the building.



Figure 10. (a) facade of the Vieux Habitants church; (b) facade of the Basse Terre cathedral; (c) and (d) architectural elements of the Basse Terre cathedral; (e) rock alteration on the Basse Terre cathedral; (f) Basse Terre city center house, in front of the cathedral.

4.2.3. Houses

Natural stones houses in the French West Indies are mainly concentrated in the civic centers of Basse-Terre, in Guadeloupe (Figure 10f) and Saint Pierre, in Martinique (see Section 5.1 and Figure 13). There, some historical buildings are made with local dimension stones. Outside the main cities, only scarce natural stone houses are still preserved. They are usually made with boulders, but almost never with dimension stones. The house near the hamlet of Thomas, in Guadeloupe, is an example of local construction with pebbles collected directly on site, the house being only a few meters away from the beach (Figure 11). Unfortunately, this construction is not protected and in a very poor state

of preservation. The detail view of the walls shows that the rocks used are of various volcanic origin and size, with little cement. As only a small quantity of lime was needed for these types of constructions, usually the builders were collecting limestones from beach debris or even extracting coral-bearing rocks in shallow waters.

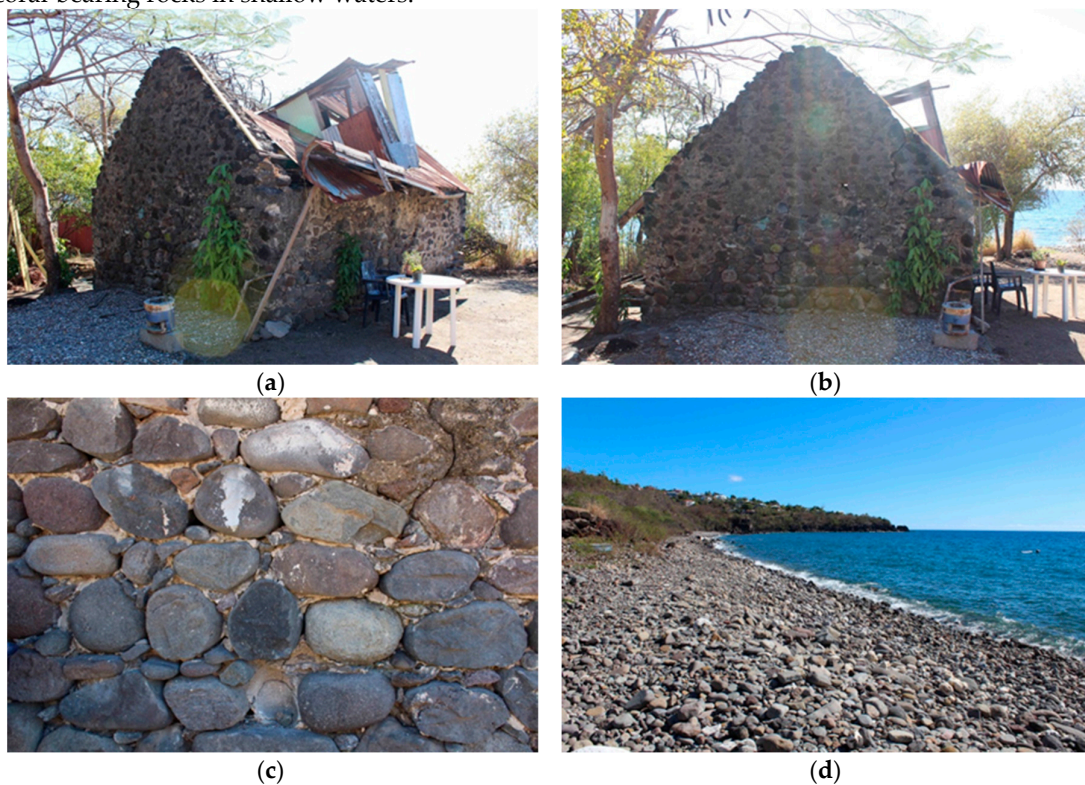


Figure 11. (a) and (b) house at Thomas hamlet; (c) same house, detail view of the walls (d) beach, on site, where the pebbles were most likely collected.

4.2.4. Industrial Buildings

The industrial history of the West Indies is tightly linked to the culture of sugar cane. Thus, the main stone made industrial buildings are windmills and sugar factories. They are particularly abundant in Grande-Terre (eastern Guadeloupe) and Marie-Galante, where they are an important element of the landscapes [33]. Windmills are probably the natural stone architectural heritage that is the most identified as such within the population in the French West Indies. They are consequently rather well preserved and some are integrated in architectural projects, such as hotels and resorts (Figure 12a,b). For the production of lime, limekilns have been built in different places of the islands, near the resources. Some were even built on small islets where no rock outcrops above sea level (Ilet Fajou). They were using only materials extracted directly from the sea floor at shallow depth. Surprisingly, the most important in Guadeloupe is located not on the carbonated Grande Terre, but on the volcanic island of Basse Terre. It exploited the only limestone outcrop of this part of the island, in Trois Rivières, which consists in a lens of reefal limestones, interbedded with volcanic deposits. It had the advantage of being close to both the resource and the demand for lime of Basse Terre city. The limekiln is protected, but poorly maintained (Figure 12c–f) [34]. The former quarry (*Pointe Glacis*) is in the geosites inventory, but benefits from no protection measure and is currently covered with vegetation and not accessible easily.



Figure 12. (a) typical landscape in Grande Terre, with a former sugar cane windmill, in Saint François; (b) example of a restored windmill and adjacent building, used as the main entrance of a hotel, in Le Gosier; (c) photograph of the Trois Rivières limekiln, taken in 2012 [35] and in 2019 (d); (e) detail of the walls of the limekiln; (f) Pointe Glacis former quarry.

4.2.5. Dry-Stone Walls

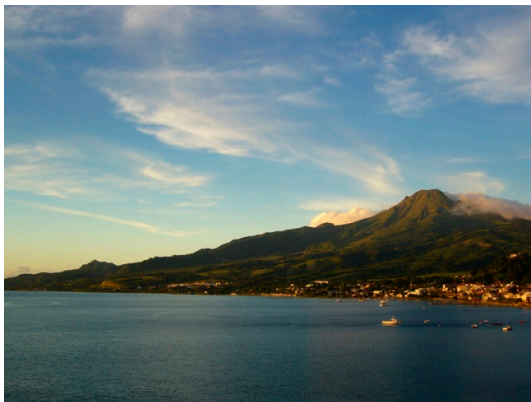
In November 2018, the Intergovernmental Committee for the Safeguarding of the Intangible Cultural Heritage has inscribed the Art of Dry-Stone Walling, Knowledge and Techniques on the Representative List of the Intangible Cultural Heritage of Humanity [36]. In the French West Indies, dry-stone walls have been traditionally used only in the northernmost islands of Saint Martin and Saint Barthélemy. In Saint Martin, few of these walls are still preserved. In Saint Barthélemy, they have been widely used for the separation of fields and they are an important part of the islands' agricultural landscapes.

5. Discussion

5.1. Historical Cities and Volcanic Crisis

In the French West Indies, from the 17th to the early 20th century, the city of Saint Pierre in Martinique and the city of Basse Terre in Guadeloupe were the main economic centers. Consequently, this is where natural stone buildings were concentrated. These cities have benefited from abundant water resources and prosperous soils for agriculture due the proximity of volcanoes, as well as favorable conditions for sailing ships trade. In the 20th century however, the transformation of the economy has been accompanied with a translation of the activity toward the central zones of the islands. Furthermore, both sites were impacted by volcanic eruptions. In Martinique, the Montagne Pelée volcano erupted in 1902 and 1929 [37–39]. The eruption of 1902 resulted in the dramatic destruction of the city of Saint Pierre and the death of more than 28,000 inhabitants [40–42]. The city was hit by nuée ardentes and pyroclastic flows and the ruins are still preserved (Figure 13). This eruption is a milestone for the development of both volcanology and risk studies. Indeed, it is the first volcanic eruption that has been monitored with the tools of modern science and it is the first time a risk, known by the scientists, has led to a warning to the authorities that has been ignored due to political reasons (the local authorities refused to order the evacuation of the population as suggested by the scientists because some elections were about to take place) [43,44]. Thus, the patrimonial value of Saint Pierre dimension stone buildings is related not only to their architectural specificity within the French West Indies, but also to the history of the city. In Guadeloupe, the city of Basse Terre was never struck by a catastrophic volcanic event, since the last magmatic eruption date from 1530, before the city was built [45]. However, several phreatomagmatic events have occurred on La Soufrière volcano since. The last one, in 1976, triggered intense debate among the scientists and the authorities. It resulted in the evacuation of the south of Basse-Terre for several months [46,47]. This accelerated the process of translation of the economic activity toward the geographical central part of Guadeloupe. However, unlike in Saint Pierre, the main territorial administrations are still located in Basse Terre city, allowing the preservation of its dynamism and its population density. Nowadays, although the historical dimension stone buildings are still in use, they suffer from the lack of sufficient preservation efforts.

In Martinique, the destruction of Saint Pierre resulted in a drastic change with regard to the use of natural stones as a construction material. Posterior constructions don't show a use of this type of material at such a scale, preferring wood and concrete materials. In Guadeloupe also, no city center has been built with intensive use natural stone after the 19th century.



(a)



(b)



Figure 13. (a) Montagne Pelée volcano overlooking Saint Pierre; (b), (c) and (d) ruins of Saint Pierre, after the eruption of 1902.

5.2. Geomaterials Exploitation and Landscape Preservation

With the transformation of the construction style, the need for dimension stones decreased in the 19th and 20th centuries, while the need for raw building materials increased. The quarrying activity changed consequently, which led to the abandon of small extraction sites, like the Pointe Glacis quarry, and the reduction of uncontrolled rock collection for building stones or lime fabrication. Although the construction of traditional buildings needs small amounts of rock, modern constructions and roads require a much higher supply. In the early 21st century, the quarries in the French West Indies had an overall production of more than 4.5 millions of tons per year (details in Table 2), and the production has been growing ever since.

Table 2. Volumes of production in the French West Indies.

Unit: (10 ³ .T/y)	Volcanic Rocks	Carbonated Rocks	Clay
Guadeloupe ¹	1500	300	-
Saint Martin ¹	250	-	-
Martinique ²	2450	45	40

¹ Data from 2007 [15], ² data from 2004 [16].

In order to follow the increasing demand, the production needs to rise and the impacted surface widens. On small territories, and the West Indies being a hotspot for biodiversity, this is a source of debate and conflicting interests within the society [48]. Recently, some quarries have been authorized to mine adjacent areas, providing they take biodiversity loss compensation measures [14]. Although the extraction of andesites, which requires mining techniques, is restricted to only a few sites, the softness of the carbonate platform limestones in Guadeloupe allows an easy mechanical extraction. In the Grands Fonds area, south of Grande Terre, Guadeloupe, seven authorized quarries are active and three others are located around the Grand Fonds and in Marie-Galante. However, in many places, the limestones are extracted without mining authorization, for earthwork purposes. The landscape appears to be strongly impacted (Figure 14).



Figure 14. (a) Delair active quarry, in Les Grands Fonds area, Guadeloupe; (b) example of landscape transformation for individual houses building in Les Grands Fonds.

5.3. Transmission of Knowledge and Natural Stone Heritage Preservation

The transformation of the society in small island territories and the intense weathering of geomaterials under tropical climate are putting the preservation of the natural stone architectural heritage, as well as the geological natural heritage, under growing tension. In Martinique, the ruins of Saint Pierre are remarkable because of both the history of the destruction of the city and their rare dimension stone architecture. The volcanic crisis of 1902 and 1929, accelerated to the abandon of the architectural style of the 19th century and, with the use of modern materials, the know-how has not been transmitted. In Guadeloupe as well, the natural stone architectural heritage is poorly preserved and not all historical buildings benefit from a protection. However, many constructions demonstrating the preservation of the traditional know-how can be seen in the French West Indies. For example, some natural stones walls are still made with the same techniques as in the 17th to 19th century (Figure 15a). In Saint Barthélemy, preservation efforts are being made and stone walls are still being built and keep structuring the landscapes of the island. However, they are no longer used for field separation but rather along the roads. According to modern standards, these walls use natural stone, but not dry stone (Figure 15c,d). This solution, that doesn't follow the traditional building modes, has been favored for esthetical considerations as well as for preventing earth, dirt, or any objects to be wind-pushed on the road. Traditionally, dry stones walls were preferred in Saint Barthelemy, which allowed the rain water to flow downhill during the rainy season. Today, during the heavy rain events in Saint Barthelemy, the water occasionally accumulates along the road-side stone walls, sometimes damaging the soils and infrastructures. In Europe, in areas submitted to strong wind episodes, dry stones were also favored for their resistance, as the space between the stones allows the wind to go through. In the Burren, Ireland, the stones are oriented in a manner that minimizes the resistance to the wind and that leave significant empty spaces in the wall, in order to let the airflow easily (Figure 15b).



(a)



(b)

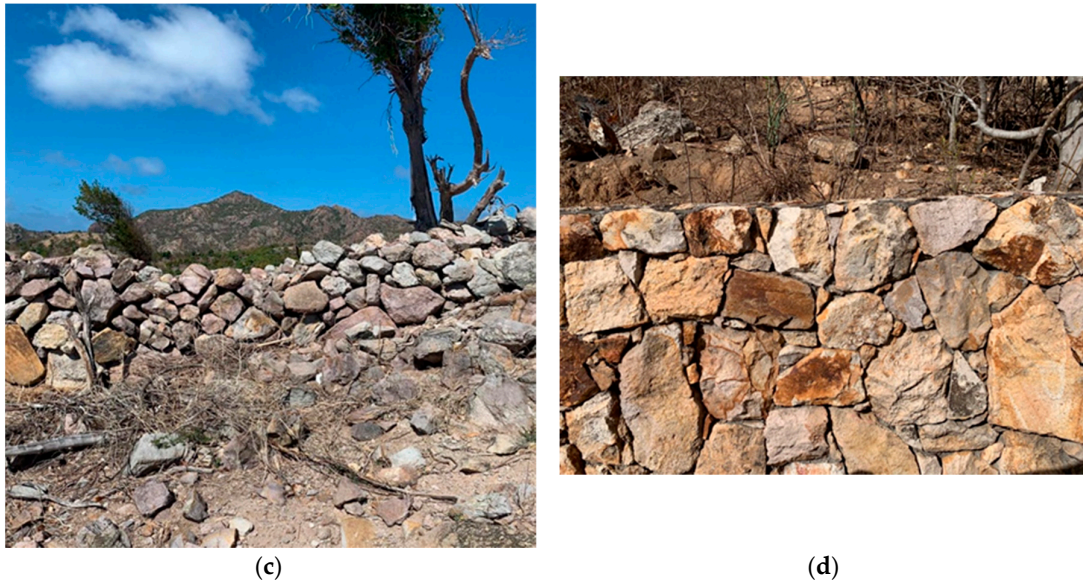


Figure 15. (a) 1970's natural stones wall in the University campus, Guadeloupe. To be compared with Figure 11c; (b) dry stone wall in the Burren, County Clare, Ireland. The stones are oriented in a manner that minimizes the resistance to the wind; (c) dry stone wall at the bottom of a hill in Saint Barthelemy; (d) modern road-side stone wall, Saint Barthelemy.

6. Conclusions

In the French West Indies, the natural stones architectural heritage and the natural geological heritage are notions that are still in development in the society. For example, in Guadeloupe, some traditional buildings and walls are made with boulders. Surprisingly this specific local know-how appears to be preserved and still used despite the fact that it is not an identified cultural heritage and that very few modern constructions use natural stones. In other places, like Saint Barthélemy, efforts are being made for the preservation of the natural stone architectural heritage. Paradoxically, some efforts forget to consider the environmental reasons at the origin of the traditional dry stones walling techniques. The limited abundance of natural resources in small island territories is also an important factor to consider. Indeed, unlike other natural resources, like wind, solar or geothermal energies or wood and halieutic resources, geological resources are not renewable at a rapid rate. Georesources, which are local and natural resources, are sometimes confused with renewable resources [49]. This can lead to unsustainable exploitation of georesources, associated with significant landscape changes and permanent loss of geodiversity. The brief assessment of the natural stone architectural heritage in the French West Indies presented in this paper also evidenced a lack of sufficient data for its conservation. Most historical extraction sites remain unknown. In order to better preserve this heritage for future generations, efforts are required for both raising geological awareness and science education within the population and better characterizing the geological heritage. In that sense, further studies are needed in the French West Indies. In particular, the geoheritage inventory should be extended to new geosites and its links with the architectural heritage emphasized. Petrological and geochemical analysis of the stones used to build the most significant architectural heritage buildings should be the subject of a specific study in order to identify historical quarries that could be re-used for their future restoration.

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