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Geomorphological heritage inventory of Irazú Volcano, Costa Rica

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ABSTRACT

Volcanoes are part of the natural environment, and the interactions with humans are inescapable. The geoheritage studies in tropical regions, specifically tropical volcanoes, are scarce despite the uniqueness, scientific value, and beauty of these features. We performed an integrated approach for the inventory and management of the geomorphological heritage of the Irazú Volcano National Park, one of the most visited parks in Costa Rica. We identified eleven geomorphosites including volcanic craters, hills, domes, lagoons, and caves. The average in the assessment of scientific values of all the identified geomorphosites was 0.67. The site that rated the highest average between all the geomorphosites (0.94) was the Principal Crater. Other geomorphosites with high average and similar conditions were Diego de la Haya Crater, Playa Hermosa Crater and Sapper Hill, which show outstanding characteristics. Irazú volcano has an exuberant geodiversity and this assessment shows its geological and cultural richness. This demonstrates the importance and value that the volcano poses for the geoheritage of Costa Rica, Central America and tropical regions.

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1. Introduction

Geoheritage studies in tropical regions have been increasing during the recent years (Gordon, Crofts, Díaz-Martínez, & Sik, 2017). Many initiatives focused on sustainable development have been developed with the aim of establishing geoparks whose basis is the protection of geoparks (Rosado-González, Palacio-Prieto, & Abreu, 2019). In addition, the work of Mucivuna, Reynard, and Motta (2019) who compiled different works about geoheritage obtaining statistics focused on the objective of these works, design of methodologies and its applications, among others.

A geomorphosite is defined as a part of the Earth's surface whose importance lies in the fact that it serves to help understand Earth's history (Panizza, 2001). Furthermore, Reynard, Fontana, Kozlik, and Scapozza (2007) defined a geomorphosite as a landform with added values from a historical, cultural, aesthetic and socio-economic point of view. Palacio (2013) refers to geomorphosites as having great geographic value, not just geological and geomorphological value. Bouzekraoui et al. (2018) emphasizes that a geomorphosite can be the best tool to contribute to the economic and sustainable development of communities.

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Ilies and Josan (2008) explain that there will be similar geomorphosites, but there is none similar in morphology as in cultural values given by the population.

Geomorphosites represent a scientific and natural heritage value where geodiversity conservation strategies are promoted, which are part of the landscape, and demonstrate the integrity of the territory and the sustainability of the natural environment (López, 2017). The scientific value of geomorphosites provides a context of human and natural history, as well as an understanding of the territory, landscape, and geoheritage (González, Serrano, & González, 2014).

Geoheritage studies in tropical regions have been increasing during the recent years. In particular, the recognition of volcanic geoheritage has gained attention in recent years, where many studies on geoheritage, geoconservation and geotourism have emerged (Németh, Casadevall, Moufti, & Marti, 2017). In Costa Rica, the studies of potential geoparks and geomorphosites have been developed by Pérez-Umaña and Quesada-Román (2018b). Previously, the only volcanic geoheritage studies have been conducted on Poás volcano (Pérez-Umaña, 2017; Pérez-Umaña & Quesada-Román, 2018a). According to the Central Bank of Costa Rica, tourism represents the 6.3% of the Gross Domestic Product (GDP) of the country. In addition, Costa Rica receives ~3 million tourists annually. For this reason, geoheritage studies bring an important opportunity to enhance the knowledge of the geomorphosites of several heavily visited national parks in Costa Rica. Here, we evaluate the geomorphosite inventory of the Irazú Volcano using an integrated approach for the inventory and management of geomorphological heritage for the promotion of geoheritage in different environments in Costa Rica.

2. Geophysical characterization of Irazú Volcano

2.1. Geology of Irazú Volcano

Irazú volcano ($9^{\circ}98'$ north latitude, $83^{\circ}85'$ west longitude) is located southeast of the Central Volcanic Range of Costa Rica and north of the city of Cartago (Fig. 1). The massif is a product of the subduction process between Cocos and Caribe plates (Galindo et al., 2004). It is a complex volcanic shield with an irregular form and a basal area of between 500 and 778 km² (Alvarado, 2011). Its base is shared with the Turrialba volcano and it is the highest volcano in Costa Rica with a submit height of 3432 m (Bergoeing, 2009).

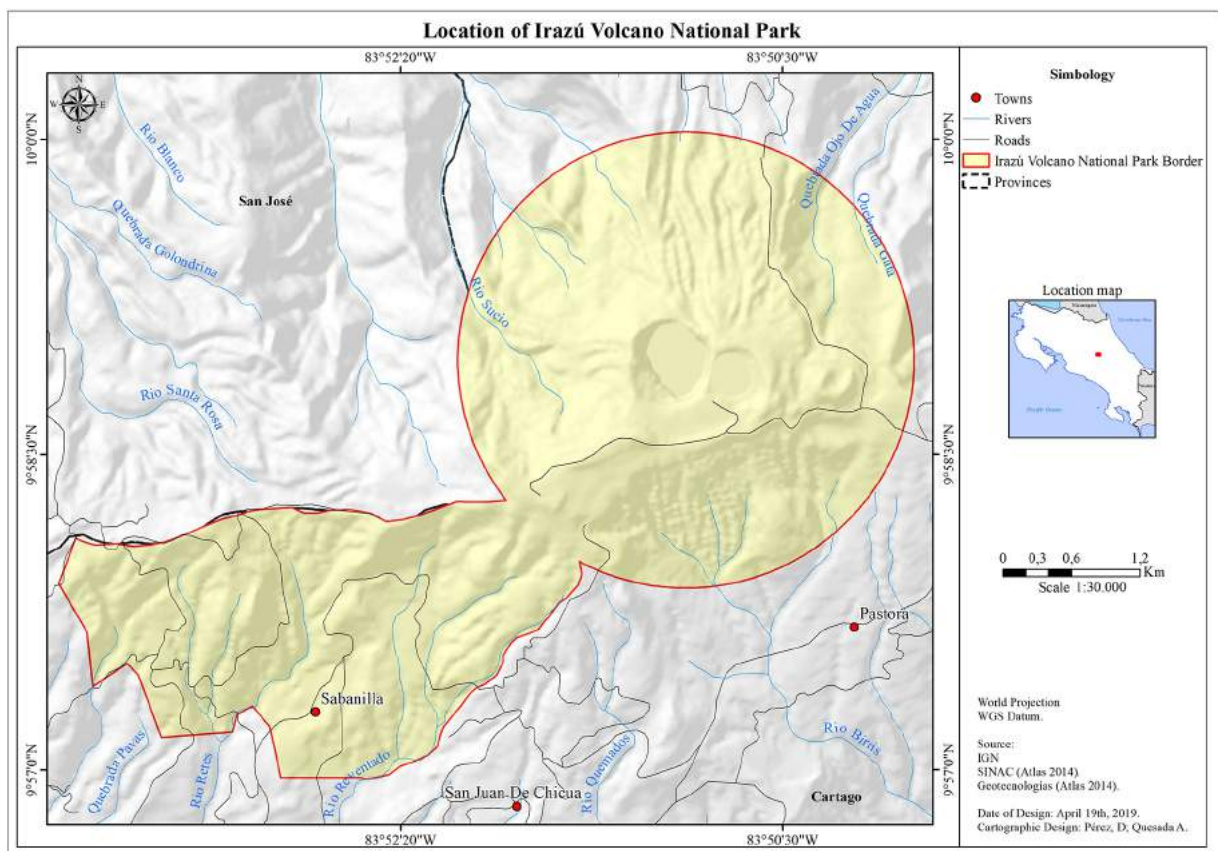


Fig. 1. Location of Irazú Volcano National Park.

Three craters are located at the summit of the volcano: Playa Hermosa crater, the Principal Crater and Diego de la Haya crater. Northwest of the Principal Crater is an unstable area known as “Las Fumarolas” (Ulloa, Campos-Fernández, & Rojas, 2013). This area is recognized by the gas emanations inside of the crater. Las Fumarolas is an area of strong hydrothermal disturbance, with a system of caves where 20 varieties of sulfates can be found, among which can be found melanterite, alunogen, hexahydrite, gypsum and accumulations of sulfur (Ulloa et al., 2013).

In 1994 the volcano restarted its activity (Alvarado, Mora, & Ulloa, 2013). During the 1994 event phreatic explosions reaching 800 m in height were reported over the crater, and the ash covered the Central Valley of Costa Rica without affecting the population (Alvarado et al., 2013). South of the summit of Irazú Volcano three volcanic cones are located: Noche Buena hill, Guardián hill, and the Pasquí hill. One of the biggest lava flows in Costa Rica, the Cervantes flow (Alvarado & Vega, 2013; Vargas, 2014) emerged from the latter one.

2.2. Geomorphology of Irazú Volcano

Three quarters of the slopes of the Irazú volcano are located on the Caribbean side, where annual rainfall exceeds 4000 mm. Consequently weathering and erosion processes favor the occurrence of landslides (Fallas et al., 2018). The main crater, which was active between 1963 and 1965 (Murata, Dondoli, & Sáenz, 1966), has a circular shape of about 1000 m in diameter and a depth of 250 m. Its internal walls are composed of lava flows with vertical slopes (Fig. 2).

The small and ephemeral lake at the bottom of the crater has presented noticeable changes in its color, temperature pH, and depth from 1965 to the present (Ramírez, Cordero & Alvarado, 2013). During 1977, 1979, 1982–1983, 1987, 1990, and recently between 2010 and 2017 the lake has been empty due to fractures forming beneath the crater that drains the lake. Inside the crater, and along its rim and slopes several landslides are visible. The result of the constant seismic activity area large deposits of volcanic debris.

In this same sector of the crater, in the outer wall of this same sector, lies the landslide that took place in 1994 and exposed the famous Minerals Cave (Ulloa et al., 2013). This sector currently has slopes $>55^\circ$, although there is a flat area to the northwest. The drainages ways in this area are deep and change abruptly due to blocks or obstacles that remained after the 1994 event (Fallas et al., 2018).

To the east of the main crater, is another depression known as the Diego de la Haya crater. It has an oblong morphology, with a depth less than the main crater (80 m) due to the accumulation of ash from the last eruptive period. At its edges some fans and colluvial deposits can be observed. On occasion a small ephemeral lake can form in its central part, but this occurs mainly in the rainy season and persists only for a few weeks (Fallas et al., 2018).

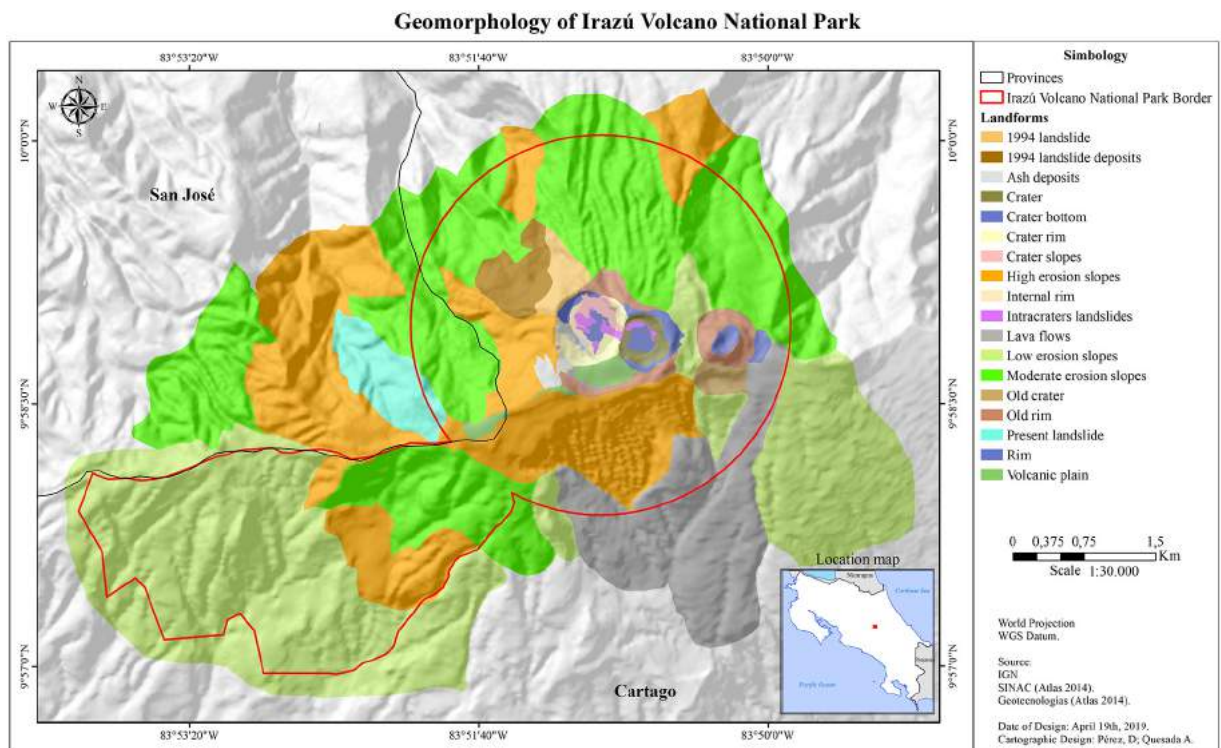


Fig. 2. Geomorphology of Irazú Volcano National Park. (Modified from Fallas et al., 2018).

To the south of the Principal Crater and Diego de la Haya is Playa Hermosa “Volcanic plain”. This is considered to be volcanic terrace where deposits of low-density pyroclastic flows have accumulated at the edges of a larger depression that has been interpreted as a boundary of a larger crater (Fallas et al., 2018). In this extensive flat sector (Fig. 2), an ephemeral lake is frequently formed during the rainy season. To the east of the craters is a pyroclastic cone, known as La Laguna.

Another destroyed small, degraded pyroclastic cone is located east of this structure. While to the south another, somewhat eroded cone is located. About two kilometers to the southwest of the main crater is a large landslide that represents a hazard to the sector where the radio and television towers of many stations and channels of the country are located (Fig. 2). Because of the location of these towers it is known as Towers Landslide which has estimated volume of 7 million cubic meters (Mora & Pirulli, 2017). In this sector the slopes are $>55^\circ$ and the materials present correspond with pyroclastic and lava affected by hydrothermal alteration.

Surrounding the main volcanic and recently active landforms, different erosional slopes were classified depending upon the degree that they have affected these surfaces. High and moderate erosion hillslopes are located mainly in the Caribbean side of the volcano due to the rainfall intensity (≥ 4000 mm annually). On the other hand, low erosional slopes and clear lava flows can be found on the Pacific side of Irazú volcano although there is lesser rain during the year, ~ 2000 mm.

3. Cultural characterization of Irazú Volcano

The Irazú volcano, like the Poás volcano, has historical, cultural, and economic importance to the population of Costa Rica (Pérez-Umaña et al., 2018). The history of this volcano goes back to the 18th Century (Bergoeing, 2009). González (1994) describes that the first historically reported eruption of Irazú Volcano was in 1723 and was reported by the Spanish governor Diego de la Haya. The governor wrote that in those years the people carried out different religious activities, in hopes that their Faith and prayers would be effective in calming the fury of the volcano. In this context, people had a great hope in their religion to control the volcano. One of the craters of the volcano is named after governor de la Haya in his honor for reporting the activity of the volcano in 1723.

Some sources say that the name Irazú is a variation of the name Istarú, which comes from an indigenous legend. The story is that a princess named Istarú was sacrificed by her father to ask for help to protect the town where they lived from the threat of a war by another tribe (Ceruti, 2010). Other sources report that the meaning of the name Irazú comes from an indigenous word, means “Hill of Tremor and Thunder”. The Spanish colonizers called it “Cartago's Volcano, Cob Volcano, Water Volcano and Santabárbara Mortal de la Naturaleza”, but, nowadays Irazú volcano is known as The Sentinel of the Central Valley (Alvarado, 2011). The Playa Hermosa Crater receives its name because the layers of thick ash resemble the black sands of a beach on the Pacific or Caribbean coast (Ross & Capelli, 2014). The name of Sapper Hill is in honor of Karl Sapper, a German naturalist who made different studies of this volcano (Alvarado, 2011). Irazú volcano has appeared in many different artistic representations. Alvarado et al. (2013) points out that Irazú Volcano has appeared on stamps, in novels and songs. In addition, the author notes the educational interest of the volcano because rocks and minerals of the volcanoes of Costa Rica can be found in different museums.

Alvarado (2011) and Vega (2017) said Retes Hill was an important place that was greatly respected by indigenous ancestors, this being a ceremonial site for them. The Orígenes database of National Museum of Costa Rica describe this place as an Archaeological Monument registered in 1953 which has ruins and remains of human settlements (Museo Nacional de Costa Rica, 2019).

At the scientific level, Irazú volcano is a very well-studied volcano both nationally and internationally. Historically, it was visited by Alexander Von Frantz, Karl Sapper, Karl Hoffmann, and many other scientists who studied its geology, ecology, geography and many other topics. Many were impressed by the scenic beauty of the volcano, as was the case of Karl Hoffmann, who in his ascent up to the massif was impressed by what he saw and described it in a letter to a colleague in Germany (Hilje, 2006).

4. Material and methods

The geomorphosites analyses were assessed using an integrated approach for the inventory and management of geomorphological heritage (Reynard, Perret, Bussard, Grangier, & Martin, 2016). The method involves two stages: 1) an inventory of the landforms with geomorphological interest in the study area, and, 2) an assessment of the selected geomorphosites in the study area.

The selection of the geomorphosites was based in the geomorphological map of the Irazú Volcano National Park (Fig. 2). Once the geomorphosites were selected, a bibliographic review was conducted to collect information about the landforms and identify possible geomorphosites that do not appear in the geomorphological map and were then included in the study.

Reynard et al. (2016) explains that the assessment has four steps. First, the description of the site (Table 1), where there is a general data characterization with a description for each geomorphosite noted.

Secondly, the assessment of the intrinsic values that are divided in scientific values and additional values was conducted. The intrinsic values refer to the value that is inherent to each site and is comprised of the scientific and additional values that are specific to each geomorphosite. The assessment of the scientific values uses the criteria shown in Table 2 and is done quantitatively as a description of the attributes of the geomorphosite in a scale of 0 (null) to 1 (very high).

The assessment of additional values includes three qualitative characteristics (Table 3). In this assessment any artistic and visual manifestation where the geomorphosite appears is considered. In addition, this manifestation is used to explain and possibly to propose the inclusion of the geomorphosite.

Table 1

General and descriptive data. Adapted from Reynard et al. (2016).

General data of the geomorphosite	
Data	Description
Identification code	This number is important in the location of the site in the synthesis map. Each code has three characters: capital letters for the region, letters for the process, and numerical code for the site.
Name	Name of the landform or very simplified description of the geomorphosite.
Toponymy	Area where the geomorphosite is situated.
Coordinates, minimum altitude, maximum altitude.	
Type	PCT: Punctiform (e.g. erratic boulder). Lin: Linear (e.g. valley, dike). AER: Areal (Crater, caldera, dome, cone, plug...).
Size	Punctiform: no indication or width [m] (e.g. sinkhole) or volume [m ³] (e.g. erratic boulder). Linear: length [m]. Areal: surface [m ²].
Property	PRI: Private. ASSO: Association. PUB: Public. COM: Common.
Protection status	Description of the protection status of the geomorphosite (inventories, natural reserves, zone of protection of the nature, etc.). If existing, the precise name and number of elements of an inventory or the protection regulation.
Location map	Location of the site relatively to the study area.
Photographs	Good quality, 300 dpi.
Descriptive data of the geomorphosite	
Description	Geomorphological features, archaeological findings, human infrastructures, biotopes related to the site.
Morphogenesis	Processes responsible for the landform genesis and development and can include temporal information (dating) and landform activity. Moreover, human transformations if existing are also analyzed.

Moreover, Serrano and González (2005) explain that additional values are intangibles and subjective factors, such as customs, narratives, artistic representations, and religious beliefs. Therefore, for this evaluation to be objective, there are estimated values of these characteristics based on bibliographic data and simple criteria (Reynard et al., 2007).

Table 2

Criteria used for the assessment of the scientific value. Adapted from Reynard et al. (2007) and Reynard et al. (2016).

Criteria	Qualitative assessment	Value
Integrity	State of conservation of the site. Bad conservation may be due to natural factors (e.g. erosion) or human factors.	0 = destroyed 0.25 = practically destroyed 0.5 = partially destroyed 0.75 = slightly damaged 1 = intact
Representativeness	Concerns the site's intrinsic value. Used with respect to a reference space (e.g. region, commune, country). All selected sites should cover the main processes, active or relict, in the study area.	0 = null 0.25 = weak 0.5 = moderate 0.75 = high 1 = very high
Rareness	Concerns the rarity of the site with respect to a reference space (e.g. region, commune, country). The criterion serves to identify exceptional landforms in an area.	0 = >7 0.25 = between 5 and 7 0.5 = between 3 and 4 0.75 = between 1 and 2 1 = unique
Paleogeographical interest	Importance of the site for Earth or climate history (e.g. evolution of volcanic landscape).	0 = null 0.25 = weak 0.5 = moderate 0.75 = high 1 = very high
Synthesis of scientific value	A sentence to summarize the scientific importance of the site.	Average

Table 3

Criteria used for the assessment of the additional values. Adapted from Reynard et al. (2016).

Criteria	Qualitative assessment
Ecological value	
Ecological influence	Importance of the geomorphosite for the development of a particular ecosystem or the presence of a particular fauna and vegetation.
Protected site	Consideration is taken of sites that are already protected in a national inventory, or at regional or local level for ecological reasons.
Ecological value	A sentence to summarize the ecological value.
Aesthetic value	
View points	Possibilities of the site to be observed. A site covered by a forest or very difficult to access would, in this case, have a lower score than a site visible from several viewpoints.
Contrasts, vertical development and space structuration	Contrasting landscapes (distinction of colors); landscapes with a vertical development (mountain) or landscapes with individual elements (isolated hill) that give that space structure are generally considered the nicest. In the contrary less contrasting landscape, flat and monotone reliefs (e.g. alluvial plain, large plateau) are considered as not nice.
Aesthetic value	A sentence to summarize the aesthetic value.
Cultural value	
Religious and symbolic importance	Spiritual and religious influence of the site.
Historical importance	Role of the site in the past. Presence of vestiges.
Artistic and literature importance	Presence of the site in artistic realizations (e.g. paintings, sculptures) and in books or poems.
Geohistorical importance	Role of the site in the development of geosciences.
Cultural value	A sentence to summarize the cultural value.

The third step is the documentation of use and management characteristics of the site, the state of protection of the geomorphosites against natural or human attacks to the site, presence of equipment like signage, and other characteristics linked to increase the educational interest of the site. In Table 4 the criteria used in the assessment are shown. To describe the protection status of and damage threats to geomorphosites, we will consider the management plan of the Irazú Volcano National Park (SINAC, 2008).

The last step is the valuation of the site. This divided into two sub-criteria, visitation conditions and educational interest. In the case of visitation conditions, the following indicators are used in the analysis:

- a) **Accessibility:** Three characteristics must be considered to be documented: 1) Location of the closest public transportation stop (railway station, bus stop) or the closest parking area, 2) Walking time from the closest public stop or parking lot, 3) Walking difficulty (steep slopes, slippery trail, no tracks, trail accessibility in winter or on rainy days or special infrastructure for hand-cap visitors).
- b) **Security:** Document if the risk of accidents in the exist. Only the natural hazards related to the trail conditions or geosite context (potential rockfalls, high cliffs, holes difficult to access) are documented. In this context, risk related with inappropriate behavior of the visitors is not documented.
- c) **Site context:** Positive and negative aspects related with the geomorphosite and its environment must to be documented.
- d) **Tourism infrastructures:** Every infrastructure close to the site are documented: transportation, facilities, accommodation facilities (toilets, drinking water and rest areas and others), restaurants, tourist offices, and others.

While in relation to Educational interest the following sub-criteria are considered:

- a) **Interpretative facilities:** All existing interpretative facilities must be documented. In this context, facilities like panels (facilities in situ) and booklets and website (facilities ex situ) are considered good guides to the visitors.
- b) **Education interest:** This takes into account the type of visitors and the ability to understand the site.

Table 4

Criteria used for the documentation of the protection of the site. Adapted from Reynard et al. (2016).

Subcriteria	Contains
Protection status	Summarize in one sentence the level of protection of the site relative to its link with different inventories, classifications or natural reserves
Damages and threats	Specify the level of damage of the site by human activities or natural processes. For the active sites (alluvial area), the change of processes allowing their formation or regeneration can be considered as attack even if is not localized in the site perimeter. As for threats, one must report if they are based on a real and feasible projection in short/medium term



Fig. 3. Principal Crater (courtesy of Stephanie Vázquez).

5. Results and discussion

5.1. Description and documentation of the geomorphosites selected

In this study 11 geomorphosites were selected, each one is located inside of Irazú Volcano National Park, specifically in touristic areas where people will have access or can view the volcano landforms. Among the main landforms chosen are craters, hills, domes, lagoons and caves (Fig. 3). The documentation of each geomorphosite is shown in Table 5.

The Principal Crater (Fig. 3) is the active crater of Irazú Volcano. It has a circular shape with a diameter of 1050 m and a depth of 300 m (Zúñiga, 2008). The crater was the site of the recent eruptions during 1963 to 1965, it exhibits deposits of the different materials from 1723 events. The activity described by Diego de la Haya came from the Principal Crater (Alvarado, 2011). Within the crater, a lagoon of sulphurous waters that has a yellow color is presented (Zúñiga, 2008). The Principal Crater is the most

Table 5
Documentation of selected geomorphosites in Irazú Volcano.

Geomorphosite		Data					
Code	Name	Altitude (m)	Surface (m ²)	Coordinates	Main geomorphological process	Characteristics	Type of geometry
IRAvol001	Principal Crater	3174	468,234	09°58'57" N - 83°50'59" W	Volcanic	Natural	SUR
IRAvol002	Diego de la Haya Crater	3275	218,514	09°58'53" N - 83°50'45" W	Volcanic	Natural	SUR
IRAvol003	Playa Hermosa Crater	3312	156,233	09°58'40" N - 83°50'57" W	Volcanic	Natural	SUR
IRAvol004	Dome	3384	180,163	09°58'46" N - 83°50'34" W	Volcanic	Natural	SUR
IRAvol005	Los Minerales Cave	2905	4909	09°59'12" N - 83°51'15" W	Volcanic	Natural	SUR
IRAvol006	Los Mucolitos Cave	2890	3627	09°59'14" N - 83°51'16" W	Volcanic	Natural	SUR
IRAvol007	Retes Hill	3180	20,237	09°58'18" N - 83°52'18" W	Volcanic	Natural	SUR
IRAvol008	Cabeza de Vaca Hill	3059	102,350	09°58'10" N - 83°53'14" W	Volcanic	Natural	SUR
IRAvol009	Reventado Lagoon	2982	3744	09°58'04" N - 83°52'10" W	Volcanic	Natural	SUR
IRAvol010	Moon's Valley Crater	3279	102,350	09°58'52" N - 83°50'14" W	Volcanic	Natural	SUR
IRAvol011	Sapper Hill	3432	939,700	09°58'36" N - 83°51'12" W	Volcanic	Natural	SUR



Fig. 4. Diego de la Haya Crater.

important landform of the volcano, because historically it is remembered as being responsible for the ashes that affected the Central Valley between 1963 and 1965 (Vargas, 2014).

Diego de la Haya Crater (Fig. 4) has a circular and oblong shape with a diameter of 690 m and a depth of 80 m (Zúñiga, 2008). This crater is named in honor of the Spanish governor Diego de la Haya Fernandez. The walls of this crater have an alternation of materials like slags, volcanic bombs and lapilli and prehistoric lava flows (Alvarado, 2011). During rainy season in this crater a small lagoon is formed that disappears during dry season (Zúñiga, 2008).

Playa Hermosa Crater (Fig. 5) has a diameter of 1200 m and is the remnant of an ancient caldera of what was originally the Irazú Volcano in its beginnings (Alvarado, 2011). Salguero (2013) indicated that there must have been a strong explosion that destroyed much of the top of the volcano. When the crater's soil is saturated, the ashes become impermeable and form a lagoon approximately 1.20 m depth (Mora, 2016).



Fig. 5. Playa Hermosa Crater.



Fig. 6. Dome.

Inside of the ancient caldera, at the east of Diego de la Haya Crater is located a Dome (Fig. 6) with an altitude of 3364 m and is formed by pyroclasts and lava flows with a crater at the north of the dome, in fact, the existence of this dome makes evident the migration of the eruptive focus in the volcano (Alvarado, 2011).

The Mucolitos and Minerales caves (Fig. 7) are in the base of the landslide crown to the northwest of the Principal Crater of the volcano at 2890 m, in an area with hydrothermal altered pyroclasts. Mucolitos cave has a narrow opening with a height of 50 cm and a width of 1 m, and inside of the cave there are materials collapses produced by the alteration of the pyroclastic rocks (Ulloa et al., 2013). Minerales cave is located in an unstable area and is very wide reaching 50 m long and a height of 12 m. It has a very high relative humidity (maximum 92,4%). In it is found a great variety of minerals composed of the sulfates that predominate in the cave (Ulloa et al., 2013).

Retes Hill (Fig. 8), Cabeza de Vaca Hill (Fig. 9) and Sapper Hill (Fig. 10) are located to the west of Principal Crater. Alvarado (2011) quotes Bergoeing (2009) who explains that Cabeza de Vaca Hill is a volcanic relic. On the other hand, Retes and Sapper



Fig. 7. Los Minerales and Los Mucolitos Caves (Ulloa et al., 2013).



Fig. 8. Retes Hill (Vega, 2017).

Hills are probably ancient volcanic foci (Bergoeing, 1978; quote by Alvarado, 2011), so Alvarado (2011) recommends more studies on these hills to understand their origins. Retes Hill has an altitude of 3180 m, while the altitude of Sapper Hill, the highest part of the volcano is 3432 m.

Reventado Lagoon (Fig. 11) or Reventado crater is a possible ancient crater covered with vegetation where the Reventado river is born (Salguero (2013)). In 1922, this ancient crater opened, causing the water of the lagoon rush out and flood Cartago city (SINAC, 2008). Alvarado (2011) indicates that this crater is a horseshoe-depression, also called an amphitheater valley with steep and unstable walls.

Moon's Valley Crater (Fig. 12) is an ancient crater located outside of the ancient caldera of the volcano. This crater is little known because it is hidden from visitors. During rainy season a shallow stationary lagoon is formed (Vega, 2013).



Fig. 9. Cabeza de Vaca Hill.



Fig. 10. Sapper Hill.

5.2. Scientific value assessment

The results of the assessment of the scientific values of geomorphosites proposed in the Irazú Volcano are compiled in the [Table 6](#).

The results of the evaluation show that seven of the geomorphosites have an intact integrity. Only the Minerales and Mucolitos caves, Retes Hill and Sapper Hill have a low integrity because they are located in areas with landslides susceptibility. The Principal Crater has a very high representativeness, being one of the images to attract tourism in Costa Rica. Four of the geomorphosites have a high value (0.75) but not enough to equal the Principal Crater, also, five of them have a null or weak representativeness. Three of the geomorphosites are catalogued as Unique, these being Minerales and Mucolitos caves and Sapper Hill. The caves are unique due to their location and to the fact that they house a remnant of minerals. Sapper Hill is unique because it is the highest



Fig. 11. Reventado Lagoon (Vega, 2013).



Fig. 12. Moon's Valley Crater (Ticos Montañeando, 2017).

volcanic peak in Central America. The three craters did not get a very high valuation but are among the rarest sites within the massif. Six of the geomorphosites have a very high paleogeographic value for being representative of the geological history of Costa Rica. Four geomorphosites have a moderate (0.5) value and one has a weak value (0.25).

5.3. Additional values assessment

The geomorphosites of Irazú volcano are located in a National Park and they are protected from any threat that might harm them. Flora and fauna are not so exuberant or abundant as elsewhere because they have been altered by volcanic eruptions (Zúñiga, 2008). In the three craters are found Páramo vegetation receiving the gases emitted directly from the Principal Crater (Fig. 13A), while to the southwest in Prusia sector (Fig. 13B) a eucalyptus forest was planted due to the destruction of native forest by landslides and lahars in 1963 caused by the eruptions of the volcano (SINAC, 2008). Therefore, geomorphosites have not helped in the development of ecosystems. As long as there is latent activity, ecosystems will be affected by this activity.

Irazú Volcano is named The Sentinel of Central Valley because it is seen from every place in the Central Valley of Costa Rica, as well as from more distant places of the country. For that reason people can easily identify it. Geomorphosites like Cabeza de Vaca Hill and Sapper Hill are visible from Cartago, the city in the base of the volcano, but from long distances they are confused with the figure of the massif. Geomorphosites in the top of the volcano have an amazing scenic beauty without obstacles that impede their visibility. An example of scenic beauty is the Cloud's Bed observed from Sapper Hill (Fig. 14). In addition, Turrialba Volcano and the Talamanca Range landscapes can be seen from Irazú volcano. In case of Moon's Valley Crater when climatic conditions allow it, the Caribbean coast is visible from this crater. Geomorphosite locations bring benefits to these landscapes in order to be more attractive to tourists. The aesthetic value of geomorphosites is very high, because it is possible to see not only the geomorphosites of the volcano, but other landscapes that add value to the tourist visit this massif.

The cultural value of Irazú Volcano is very high. Indigenous groups have seen the volcano as a site of religious importance, from its name which is indigenous in origin to occupying Retes Hill as a ceremonial site. Historically, information on its activity

Table 6

Assessment of the scientific values of geomorphosites in the Irazú Volcano.

Geomorphosite		Criteria				Scientific values
Code	Name	Integrity	Representativeness	Rareness	Paleogeographic value	
IRAvol001	Principal Crater	1	1	0.75	1	0.94
IRAvol002	Diego de la Haya Crater	1	0.75	0.75	1	0.88
IRAvol003	Playa Hermosa Crater	1	0.75	0.75	1	0.88
IRAvol004	Dome	1	0	0	0.25	0.31
IRAvol005	Los Minerales Cave	0.75	0.25	1	1	0.75
IRAvol006	Los Mucolitos Cave	0.75	0.25	1	1	0.75
IRAvol007	Retes Hill	0.5	0.25	0.25	0.5	0.38
IRAvol008	Cabeza de Vaca Hill	1	0.75	0.25	0.5	0.63
IRAvol009	Reventado Lagoon	1	0.5	0.25	0.5	0.56
IRAvol010	Moon's Valley Crater	1	0.25	0.25	0.5	0.50
IRAvol011	Sapper Hill	0.5	0.75	1	1	0.81
Average		0.86	0.5	0.57	0.75	0.67

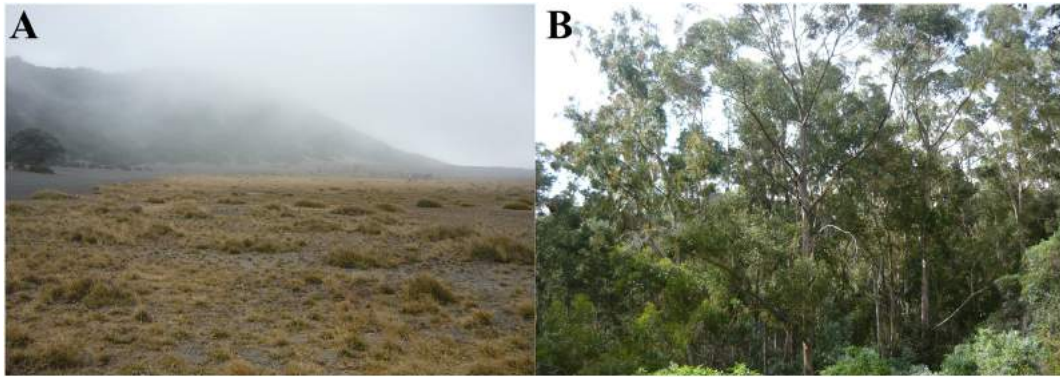


Fig. 13. Some vegetation presented in Irazú Volcano National Park. A) Páramo vegetation in Playa Hermosa Crater. B) Eucalyptus Forest at Prusia sector.

has been collected since 1723. It has been visited by a large number of researchers to study this massif making great contributions in different disciplines including the geography, geology, climatology and biology of Costa Rica. Irazú volcano has been the object of inspiration for artistic works and literature, such as novels, stories, legends and artistic representations such as stamps. At the cultural level, this volcano has a great presence in the culture of the Costa Rican population.

5.4. Use and management characteristics

Of the eleven geomorphosites proposed in this study ten are located inside of the Irazú Volcano National Park (Fig. 15), meaning that these geomorphosites have a high protection status. Only the geomorphosite Retes Hill is located outside of the national park but it is considered like another interest point of the volcano. Actually, the access to this geomorphosite is across the Irazú Volcano National Park.

The geomorphosites Principal Crater, Diego de la Haya Crater, Los Mucolitos Caves and Los Minerales caves are located inside of the Absolute protection area, classified as the area with the highest protection of the protected area, where the only permitted activities are related to research (SINAC, 2008). The caves (Mucolitos and Los Minerales) are located outside of the volcanic cone, therefore, tourists do not have access to these geomorphosites and they do not know about the existence of the caves. The caves are now only known to the people who visit the volcano. The only threat that the caves can suffer is the landslide hazard that could obstruct the entrance to the caves, losing the only access.

The Principal Crater and Diego de la Haya Crater are the most attractive landforms of the volcano, and even though they are located in the Absolute protection area tourist have access to them across the Extensive Public Use Area, where Playa Hermosa Crater is located. These three craters are visible at the same time from Sapper Hill, the other geomorphosite located in this area (Fig. 16). According with SINAC (2008), this area allows activities associated with recreation and tourism, and does not present any threat to the geomorphosites by visitors.

The other geomorphosites (Dome, Moon's Valley Crater, Cabeza de Vaca Hill and Reventado Lagoon) are located in the Restricted Use Area. This area does not have any significant impacts from people and the resources are still in their natural states (SINAC, 2008). Tourists do not have access to these geomorphosites but they can see them from different places inside of the national park. Although Retes Hill is outside of the National Park, it is another attraction of this area. The only access is across the forest of Prusia to the west of the national park, and the only place where the geomorphosite is visible is here. The geomorphosite has one known natural threat in front of a great landslide on the top of the hill (Fig. 17) where all the colluvial material goes to Sucio river (Vega, 2017). This landslide is the only risk to the geomorphosite because people do not have easy access to come to the site.



Fig. 14. Mosaic of photographs of the Cloud's Bed seen from Sapper Hill. To the right, border of Principal Crater.

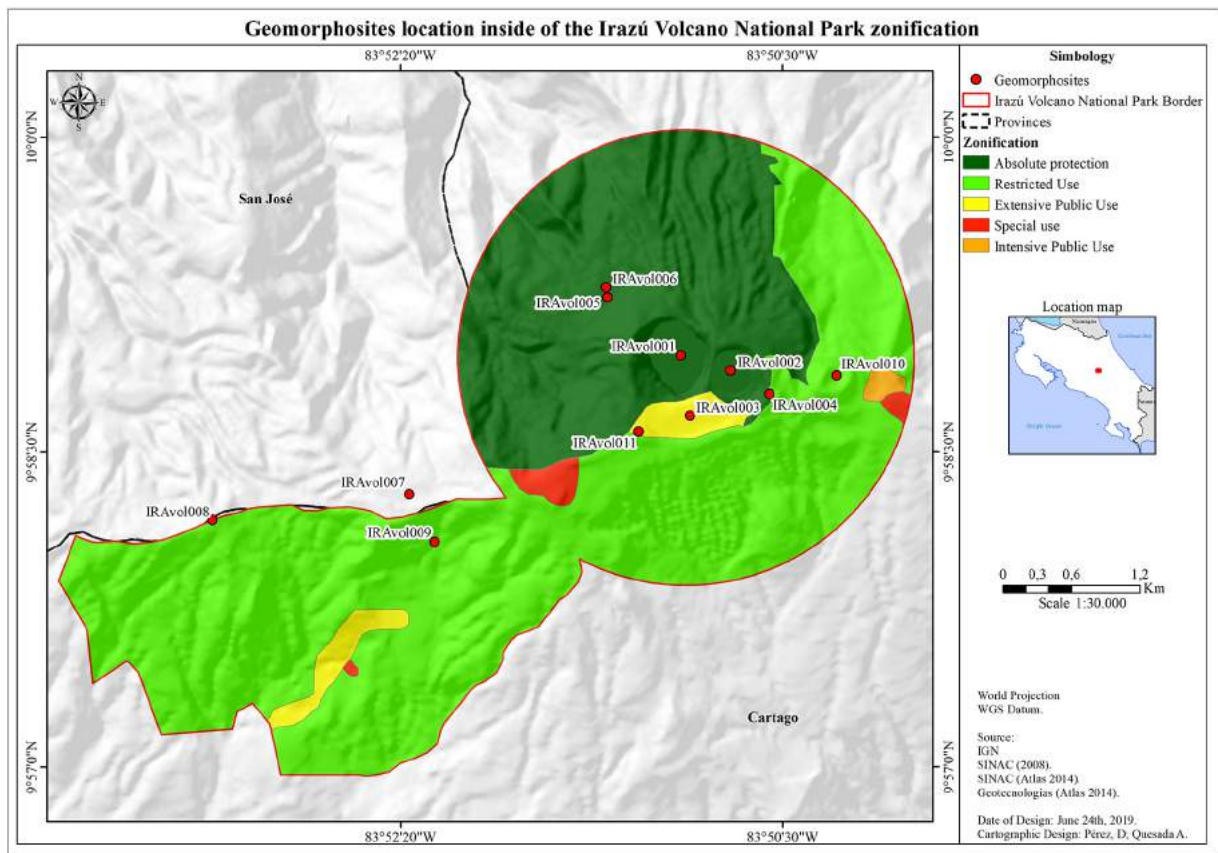


Fig. 15. Geomorphosites location inside of the zonification management plan.

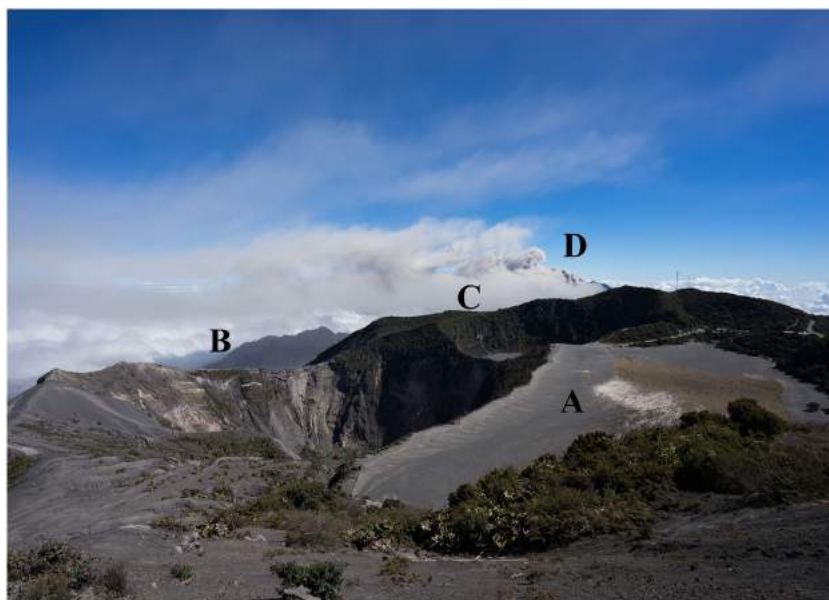


Fig. 16. Landscape from Sapper Hill. Here you can see Playa Hermosa Crater (A), Principal Crater (B), Diego de la Haya Crater (C) and Turrialba Volcano (D) at the same time. Source: Courtesy of Abimael Quijada.



Fig. 17. Landslide on the top of Retes Hill.
(Source: [Vega, 2017](#)).

5.5. Visitation conditions

Inside of the Volcanic Cone, a parking lot is located where tourists can park their vehicles and then walk to the geomorphosites. From the parking lot, the trail begins that leads to the craters after a 10-min walk. This trail goes through the Playa Hermosa Crater, so the tourist will walk inside of a volcanic crater, and view the craters Diego de la Haya and Principal crater. For tourist, it is a very easy trail to walk except during the rainy season when the trail gets wet and becomes slippery. Inside of the parking lot is located a cafeteria where people can visit at the end of the walk around the craters.

In addition, tourist can visit the top of Sapper Hill through a road located next to the parking lot. This road is only 1 km long but is in a bad state with slippery ground and loose rocks around the road. In this geomorphosite a viewpoint is located, but the



Fig. 18. Landscape from Sapper Hill. In the background, mountains of the Talamanca Range.

railings are in bad condition, so the visitors must be careful to avoid a fall. Sapper Hill is the highest point of the volcano and exhibits beautiful landscapes, being the principal attraction of this geomorphosite (Fig. 18).

The other geomorphosites are located in areas without an easy access. In case of the Retes Hill and Cabeza de Vaca Hill the only access is through a trail that is in poor condition, so only people who practice mountaineering have access to these geomorphosites. In addition, the Mucolitos and Minerales caves do not have visitors access because they are located in a dangerous site with a high risk of a landslide. For that reason, in this study they are considered as a landform with a high value even though people do not have ready access to them. To access to the Reventado Lagoon visitors must enter through the Prusia sector and climb the path that reaches with the geomorphosite. In humid conditions this trail is slippery, so people who to come to the site must be careful. Moon's Valley is located at the entrance of the national park. Visitors can arrive on foot or by car, but this road has rock falls and is slippery in the rainy season.

5.6. Educational interest

Irazú Volcano is an emblematic volcano for the population of Costa Rica. Taking into account that a geomorphosite has the importance of helping the population understand the history of the Earth (Panizza, 2001). Only the geomorphosites the Principal Crater and Diego de la Haya Crater have historic and educational importance relating to the actual eruptive history of the volcano. Unfortunately, the National Park does not have displays panels to identify different characteristics of the reliefs, only a sign with the name of the craters (Principal and Diego de la Haya) and their depth. Sapper Hill is similar, where only a sign with the highest altitude of the volcano is found. Some websites describe different geological characteristics of the Hills around the volcano massif, but much cultural information is difficult to found. For the collection of cultural information of each geomorphosite and it can be accessible to tourists could be created some online platform where tourists can access from their cellphones taking more advantage of the visit to each geomorphosite and learn more from each of them virtually.

Reventado Lagoon is one of the places, the existence of which people do not know and in the National Park the signage of this place is poor. In the case of the Mucolitos and Minerals caves a study of Ulloa et al. (2013) of this landform that was openly available to the population. With this study these caves are considered as an important place in the geoheritage of the volcano, and they need be shown to the public in order to present its scientific value.

6. Conclusions

Eleven geomorphosites were identified within the Irazú Volcano National Park. The diversity of geoforms is very high within the protected area, however, within the Restricted areas of the Management Plan there may be more geomorphosites, as well as other formations outside the national park that are important landforms within the geoheritage of the massif.

The average in the assessed of scientific values of all the identified geomorphosites was 0.67, with the Principal Crater being the one that obtained the highest average between of all the sites 0.94. This site is very important to the population and has a very high paleographic value, and a high rarity value. However, other geomorphosites with high averages and similar conditions include Diego de la Haya Crater, Playa Hermosa Crater and Sapper Hill, which show outstanding characteristics.

In the added values assessment, it is evident how the Irazú Volcano is important for the Costa Rican population, from the figure of national park, as a tourist attraction for its landscapes and natural attractions, and for being the inspiration of different artistic works, ceremonial center for indigenous people in the past and an open-air laboratory for different researchers.

The national park has the infrastructure to allow visitors to access it, but the roads must be improved so that the accessibility and experience of the visitors will be more convenient. The same applies to guardrails in areas where accidents may happen, such as on the edge of the craters. There should be better signage for visitors to learn about the natural attractions, not only with the name of the sites of interest or sketches of the trail route, there should be more information about the attractions that the visitor will observe in the national park. This will further increase the visitor's knowledge about this protected area and enhance its scientific value. Irazú volcano is a site with an exuberant geodiversity, geoheritage assessments show the geological and cultural richness of this massif, which demonstrates the importance and value that the volcano has for geoheritage of Costa Rica and Central America.

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References

- Alvarado, G. (2011). *Los volcanes de Costa Rica: geología, historia, riqueza natural y su gente*. San José. EUNED: Costa Rica.
- Alvarado, G., Mora, M., & Ulloa, A. (2013). La caída de "ceniza" proveniente del Volcán Irazú (Costa Rica) el 8 de diciembre de 1994: ¿Una explosión freática? *Revista Geológica de América Central*, 48, 159–168.
- Alvarado, G., & Vega, A. (2013). La geomorfología de la colada de Cervantes, volcán Irazú (Costa Rica): descripción de uno de los campos de lava más grandes de América Central. *Revista Geológica de América Central*, 48, 99–118.
- Bergoeing, J. (2009). *Costa Rica, paisajes volcánicos*. San José. Jadine: Costa Rica.

- Bouzekraoui, H., Barakat, A., El Youssi, M., Touhami, F., Mouaddine, A., Hafid, A., & Zwolinski, Z. (2018). Mapping geosites as gateways to the geotourism management in central high-atlas (Morocco). *Quaestiones Geographicae*, 1, 87–102.
- Ceruti, M. (2010). Los volcanes sagrados en el folclore y la arqueología de Costa Rica. *Mitológicas*, 25, 39–50.
- Fallas, M., Prado, A., Mora, M., Ruiz, P., Alfaro, E. J., & Soto, G. J. (2018). El deslizamiento del 8 de diciembre de 1994 en el volcán Irazú (Costa Rica): aspectos históricos y geomorfología con base en fotografías aéreas históricas y recientes. *Revista Geológica de América Central*, 58, 55–84.
- Galindo, I., Melián, G., Salazar, J., Hernández, P., Pérez, N., Ramírez, C., ... Notsu, K. (2004). Emisión difusa de Dióxido de Carbono en el Volcán Irazú, Costa Rica. *Revista Geológica de América Central*, 30, 157–165.
- González, C. (1994). Temblores, terremotos, inundaciones y erupciones volcánicas en Costa Rica 1608 – 1910. Cartago, Costa Rica: Editorial Tecnológica de Costa Rica.
- González, M., Serrano, E., & González, M. (2014). Lugares de interés geomorfológico, geopatrimonio y gestión de espacios naturales protegidos: el Parque Natural de Valderejo (Álava, España). *Revista de Geografía Norte Grande*, 54, 45–64.
- Gordon, E., Crofts, R., Díaz-Martínez, E., & Sik, K. (2017). Enhancing the role of geoconservation in protected area management and nature conservation. *Geoheritage*, 10 (2), 191–203. <https://doi.org/10.1007/s12371-017-0240-5>.
- Hilje, L. (2006). Karl Hoffmann: naturalista, médico y héroe nacional. *Santo Domingo de Heredia*. Editorial INBio: Costa Rica.
- Ilies, D., & Josan, N. (2008). Some theoretical aspects regarding the genesis of geosites. *Geojournal of tourism and Geosites*, 1, 7–12.
- López, R. (2017). Valoración de geomorfositos en la caldera de Huichapan, Hidalgo, como alternativa de fomento a la geoconservación del paisaje desde la perspectiva de geoparque. (Tesis de licenciatura). *Universidad Autónoma del Estado de México*, 148.
- Mora, D. (2016). 3 lagunas y hasta una pequeña cascada aparecen en el Irazú. Accessed from: <https://www.crhoy.com/nacionales/3-lagunas-y-hasta-una-pequena-ca-scada-aparecen-en-el-irazu/>.
- Mora, R., & Pirulli, M. (2017). Deslizamiento Las Torres, volcán Irazú, Costa Rica: definición de su volumen y su dirección preferencial de movimiento. *Revista Geológica de América Central*, 56, 51–67.
- Mucivuna, V., Reynard, E., & Motta, M. (2019). *Geomorphosites assessment*. Methods: Comparative Analysis and Typology. *Geoheritage*. <https://doi.org/10.1007/s12371-019-00394-x>.
- Murata, K. J., Dondoli, C., & Sáenz, R. (1966). The 1963–65 eruption of Irazú volcano, Costa Rica (the period of March 1963 to October 1964). *Bulletin Volcanologique*, 1, 765–793.
- Museo Nacional de Costa Rica (2019). Sitio Arqueológico Retes. *Obtenido desde*. http://origenes.museocostarica.go.cr/detalleBusqueda.aspx?id_sitio=8064.
- Németh, K., Casadevall, T., Moufti, M., & Marti, J. (2017). Volcanic Geoheritage. *Geoheritage*, 9, 251–254.
- Palacio, J. (2013). Geositos, geomorfositos y geoparques: importancia, situación actual y perspectivas en México. *Investigaciones geográficas, Boletín del Instituto de Geografía, UNAM*, 82, 24–37.
- Panizza, M. (2001). Geomorphosites: Concepts, methods and examples of geomorphological survey. *Chinese Science Bulletin*, 46, 4–6.
- Pérez-Umaña, D. (2017). *Evaluación del potencial turístico de geomorfositos del Parque Nacional Volcán Poás*. Tesis para optar por el grado de Licenciatura en Ciencias Geográficas con énfasis en Ordenamiento del Territorio: Universidad Nacional de Costa Rica.
- Pérez-Umaña, D., & Quesada-Román, A. (2018a). Metodología para la valoración y evaluación de geomorfositos en Costa Rica. *Revista Geográfica de América Central*, 60, 117–135. <https://doi.org/10.15359/rgac.60-1.4>.
- Pérez-Umaña, D., & Quesada-Román, A. (2018b). Una propuesta para la valoración de Geoparques en Costa Rica. *Anuário do Instituto de Geociências-UFRJ*, 3, 382–394. doi:10.11137/2018_3_382_394.
- Pérez-Umaña, D., Quesada-Román, A., De Jesús, J., Zamorano-Orozco, J., Dóniz-Páez, J., & Becerra-Ramírez, R. (2018). Comparative analysis of geomorphosites in volcanoes of Costa Rica, Mexico, and Spain. *Geoheritage*, 2, 545–559. <https://doi.org/10.1007/s12371-018-0313-0>.
- Ramírez, R., Cordero, C., & Alvarado, G. E. (2013). Variaciones y características en los cambios de nivel de la laguna cratérica del volcán Irazú (1965–2012), Costa Rica. *Revista Geológica de América Central*, 48, 141–157.
- Reynard, E., Fontana, G., Kozlik, L., & Scapozza, C. (2007). A method for assessing «scientific» and «additional values» of geomorphosites. *Geographica Helvetica*, 62, 148–158.
- Reynard, E., Perret, A., Bussard, J., Grangier, L., & Martin, S. (2016). Integrated approach for the inventory and management of geomorphological heritage at the regional scale. *Geoheritage*, 1, 43–60.
- Rosado-González, E., Palacio-Prieto, J., & Abreu, A. (2019). Geotourism in Latin America and Caribbean UNESCO global Geoparks: Contributions for sustainable development goals. In V. Ratten (Ed.), *Technological progress, inequality and entrepreneurship. From costumer division to human centricity* (pp. 107–122). Switzerland: Cham.
- Ross, Y., & Capelli, L. (2014). Costa Rica Parques Nacionales. Fronteras naturales. San José. Costa Rica: Producciones del Río Nevado.
- Salguero, M. (2013). Volcanes de Costa Rica. San José. Editorial Costa Rica: Costa Rica.
- Serrano, E., & González, J. (2005). Assessment of geomorphosites in natural protected areas: The Picos de Europa National Park (Spain). *Géomorphologie: relief, processus, environnement*, 3, 197–208.
- SINAC (2008) Plan General de Manejo Parque Nacional Volcán Irazú. Accessed from: <http://www.sinac.go.cr/ES/planmanejo/Plan%20Manejo%20ACC/Parque%20Nacional%20Volc%C3%A1n%20Iraz%C3%BA.pdf>.
- Ticos Montañeando. (2017). Cráter Valle de la Luna. Accessed from: <https://www.facebook.com/364984360309077/posts/960513557422818/> Accesado 9 de Julio 2019.
- Ulloa, A., Campos-Fernández, C., & Rojas, L. (2013). *Cueva Los Minerales, Volcán Irazú, Costa Rica: Descripción, Mineralogía, y Origen*. *Revista Geológica de América Central*, 48, 169–187.
- Vargas, G. (2014). Geografía de Costa Rica. San José. EUNED: Costa Rica.
- Vega, Y. (2013). Los Cerros Volcánicos del Irazú. Accessed from: <http://losrinconesdemipaicr.blogspot.com/2013/05/los-cerros-volcanicos-del-irazu.html/> Accesado 20 de junio de 2019.
- Vega, Y. (2017). Retes, Un sitio espiritual. *Cartago Mío*, 12, 24–25.
- Zúñiga, R. (2008). *Guía de los parques nacionales de Costa Rica*. Madrid: Jomagar.