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Geodiversity and Its Implication to Geoconservation of the Youngest Eruptive Sites of Western Samoa†

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Abstract: Western Samoa experienced its latest volcanic eruption between 1905 and 1911 that produced a complex scoria and lava spatter cone and an extensive lava field that destroyed Sale'aula village near the Pacific coast. This eruption referred to as the Matavanu eruption and it provided pāhoehoe type lava flows with superbly preserved surface textures, tumuli, and some littoral explosion craters in its distal lava field. The unique nature of the location made it to be selected as one of the "The First 100 IUGS Geological Heritage Sites" in October 2022. The region has been under investigation to document the geoheritage elements of the location, estimate its geodiversity and explore the potential to develop a geopark together with local communities. All this work intends to provide a firm knowledge base to identify effective geoconservation strategies. While the youngest eruptive products after over 100 years of revegetation are restricted in a coastal zone, previous research demonstrated that other young volcanic eruptions also took place in northern Savai'i in 1760 and 1902. Here we provide further data based on systematic evaluation of SENTINEL satellite imagery in combination with ALOS-PALSAR and SRTM 30-m resolution digital terrain model-based calculation of morphometric elements to demonstrate the young volcanic landscape in northern Savai'i has great volcanic geodiversity and the entire region should be considered under specific geoconservation strategies. The young volcanic landforms of scoria cones in the high-altitude regions of the island alongside with extensive and commonly tube-fed lava flows invaded the northern region of Savai'i also pose volcanic hazard to the region hence volcanic geoheritage can be the core element to enforce strong community volcanic hazard resilience. The newly proposed Samoa Geopark Project is the perfect avenue to achieve this.

Keywords: scoria cone, geodiversity, geoconservation, volcanic hazard, resilience, geopark

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1. Introduction

Western Samoa is in the SW Pacific and contain two large volcanic islands along some small offshore islets, each volcanic in origin [1–3]. The two main islands, Upolu and Savai'i are typical ocean islands with extensive volcanic lava shields topped by hundreds of small-volume post-shield volcanic cones, mostly as Strombolian style scoria (cinder) cones and associated lava spatter mounds and lava flows [3]. Both islands, beside the recent Quaternary fluvial and beach sediments are volcanic in origin [3]. The oldest volcanic rocks crop out in Upolu, while the general understanding of the volcanic eruption argued that the youngest volcanism exclusively occurred in Savai'i interpreted as a westward migration of volcanism in the last millions of years [3–7]. While this trend is in generally feasible there are evidence for young, Pleistocene volcanism along the dorsal ridge of Upolu without apparent spatial trends [1,8].

Young, extensive lava field-producing volcanic eruptions took place in the Holocene in the northern sector of Savai'i from scoria cone vents located in the main ridges at least ~700 m above sea level. The youngest eruption took place in the NE edge of Savai'i, commonly referred to as the Matavanu eruption that lasted about 6 years between 1905 and 1911 [9]. The eruption emitted large volume of mostly pāhoehoe type ocean island basalts and inundated the region producing an unconfined lava field in the coastal areas, enlarging the island itself. Partial erosion of the lava fields over the last about 100 years provided volcaniclastic sediments that built a basaltic sand spit and formed a lagune just adjacent to the terminus to the lava flows. This region currently been under investigation to determine the geoheritage values and geodiversity of the sites to identify various geosites as part of the Samoa Geopark Project currently part of a government-level initiative [10,11]. As a result of this increased activity on geoheritage studies culminated to list the Matavanu Eruption Site among The First 100 IUGS Geological Heritage Sites [https://iugs-geoheritage.org/videos-pdfs/iugs_first_100_book_v2.pdf—accessed on 24 November 2022]. Here we provide further evidence to justify this location as a globally significant geological heritage site using various morphological, satellite and direct observation data. In addition, first time a lava flow inundation modelling presented here, to highlight the volcanic hazard aspect of the region and its potential role in geoeducation for developing resilient society against natural hazards.

2. Materials and Methods

2.1. Study Area

The study area is part of the NE sector of Savai'i Island (Figure 1). Savai'i is a volcanic island reaching 1858 m above sea level (Mount Silisili) within 20-km from its coastlines. The island has a low slope in every direction with an exception toward the north where a large, scalloped shape escarpment clearly visible (Figure 1).

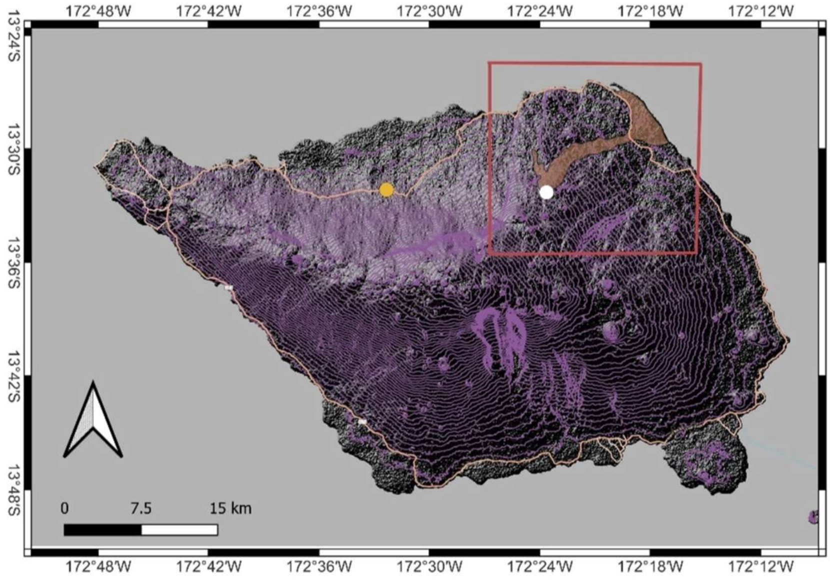

Figure 1. Location of the Savai'i Island represented by a hillshade model generated from SRTM 30-m resolution Digital Elevation Model (DEM) overlain by a 20-m interval contour lines. Main sealed road shown from ESRI Transportation layers while the outline of the lava flow field of the 1905-11 Matavanu Eruption is shown with a brown field with its source vent (white dot). One of the largest lava tubes of Samoa (Lauoleola) marked by a yellow dot that is in the middle lava flow field erupted in 1760 AD sourced from vents (Mauga Afi) in the dorsal ridge.

The origin of this feature is under debate, but a potential former volcano-collapse commonly argued as the main cause despite that there is no surface manifestation to any volcanic debris avalanches in the present-day island landmass, neither known from the sporadic sea floor data [12]. The 1905-11 lava flow field initiated from a vent located 650 m above sea level while a suspected second cone located about 900–1000 m above sea level (Figure 2). Geological mapping showed that the young lava flow followed a relatively narrow band prior entered to the coastal lowlands where expanded, leading to pond, inflate and deflate the low viscosity lava.

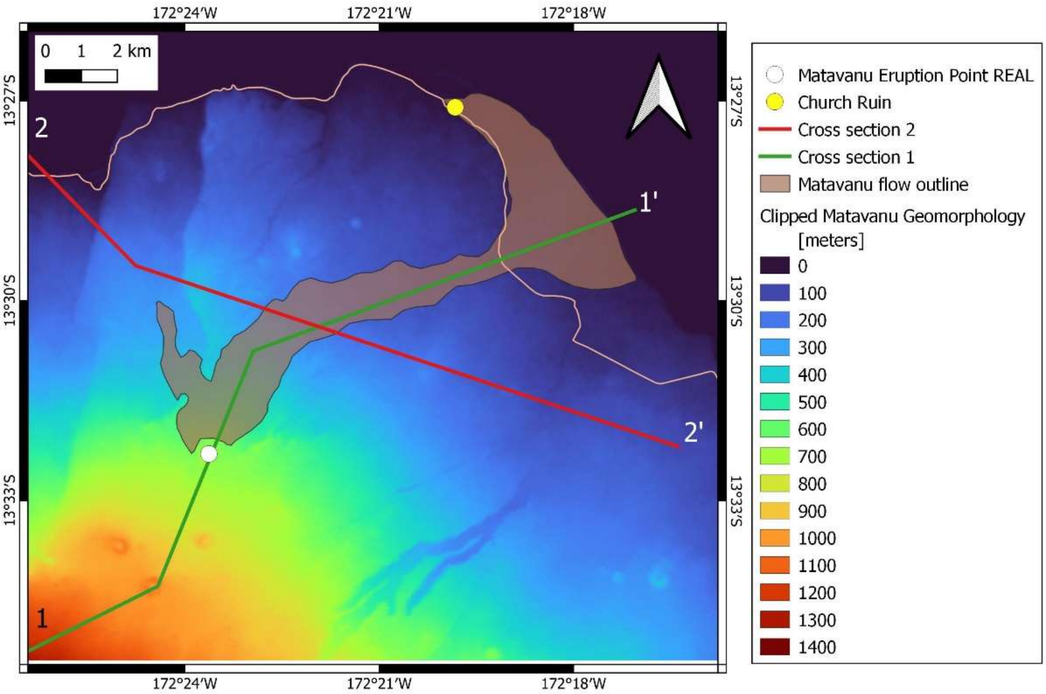

Figure 2. The location of the 1905-11 Matavanu Eruption Site on an SRTM 30-m resolution DEM. Cross section lines marked that are shown on Figure 3.

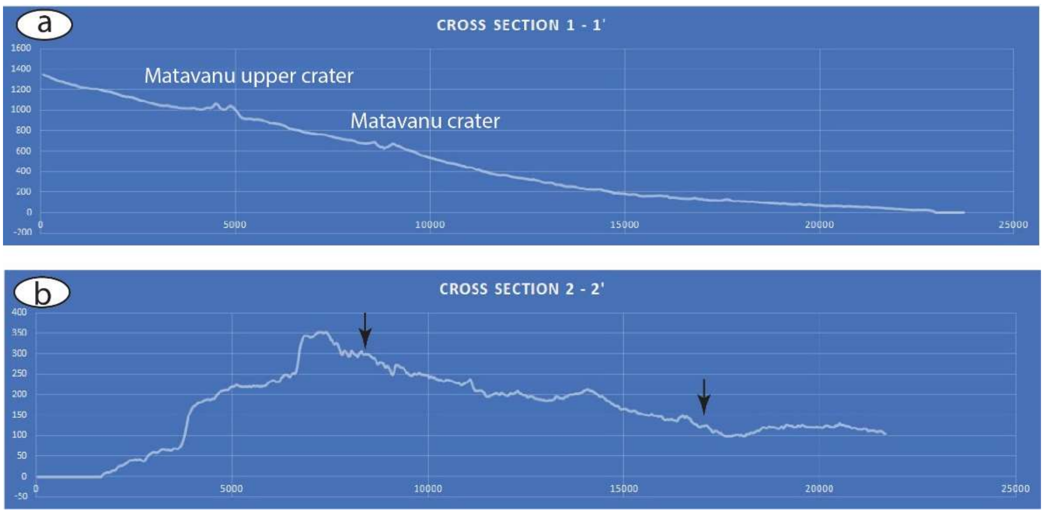

Figure 3. A longitudinal (**a**) and lava flow perpendicular (**b**) cross section across the lava flow field of the Matavanu Eruption Site. On "b" arrows mark the approximate position of the lava margins.

2.2. Satellite Imagery, Basic Terrain Analysis, Field Observations and Lava Flow Modelling

In this work we utilized freely available data sets such as Sentinel Hub (https://apps.sentinel-hub.com/eo-browser/), NASA Shuttle Radar Topography Mission

(SRTM) 30-m DEM (https://www.earthdata.nasa.gov) and ALOS-PALSAR 12.5-m DEM (https://search.asf.alaska.edu). For lava flow inundation modelling the Q-LavHA freeware was used (https://we.vub.ac.be/en/q-lavha).

We selected the True Colour Composite from the Sentinel-2 database, which was created true colour images based on the visible light bands of red, green, and blue. In this image the natural vegetation coverage over lava fields is well observable. In addition, the Geology 8, 11, 12 composite image was used to identify fresh basaltic rock surfaces based on the short-wave infrared (SWIR) bands 11 and 12. Near Infrared (NIR) band 8 in the same composite image highlights vegetation that is a useful information to see the status of vegetation coverage over young lava flows.

For basic terrain analysis within the Q-GIS software environment (https://qgis.org) SRTM and ALOS-PALSAR elevation data were used to generate slope angle map to see the morphological variety of the study area. To see the region morphological variation a geomorphon [13] map was created.

For the lava flow modelling the Q-LavHA software were employed. While this lava flow simulation technique was primarily developed to lava flows that are channel fed [14–16] instead of *sensu stricto* pāhoehoe tube-fed systems, we applied this simulation method as at least the upper flow regime of the 1905-11 lavas shows some surface propagation features. In addition, lava tubes are likely developed in the ponded sector of the flow fields where the steep slope of the (Figure 3) island quickly turn to be flat. The simulation followed the prescribed GIS techniques and run as a plug-in within the Q-GIS software environment.

3. Results

The lava flows of the 1905-11 eruption event classified as typical pāhoehoe flows especially in those areas where ponding in the flat coastal regions were evident. In this region, thin free flowing flows invaded the London Missionary Society (LMS) Church at Sale'aula (Figure 4a). Typical basaltic ropy surface textures are well-preserved (Figure 4b) in some places exposing thick crust along inflated-deflated lava flow regions (Figure 4c). The relatively thin flow lobes are clearly visible outside the invaded LMS Church (Figure 4d). In distal areas, near the present-day coast-line fresh lava flow field with smooth surfaced lava regions indicate long lasting inflation processes and substantial time to develop smooth thick crust over the ponding flows (Figure 4e).

The Sentinel satellite imagery shows a distinct vegetated upper flow region and a barren lower flow field (Figure 5a). This vegetation coverage certainly hinders the mapping of the true extent of the lava flow fields in the upper-middle flow fields (Figure 5a). While existing geological maps clearly show a relatively narrow band of the main flow field in the upper-middle flow facies, site visits revealed that young lavas are likely form more extensive coverage in this region and likely forming lava lobes that cover the northern sector of the study area. Along the upper flow region, just north of the source vent, current topography indicates that lava flow might have been flow down quickly on the steep slopes leaving behind just think flows. Such pattern is also recognized on the Sentinel-2 Geology 8, 11, 12 composite images where the fresh flow regions distinctly darker than the older, vegetated ones (Figure 5b).

For the basic terrain analysis, a slope angle map was created. The slopes of the study area shows well that the island has a steady slope that reaches about 1000-m above sea level within 15 km distance from the coastline (Figure 5c). The slopes showing a slight change about 200-m above sea level and that region correspond to the region where thick pāhoehoe lava flows are noted (Figure 5c). For the geomorphon analysis the region shows a uniform trend where the dominant portion of the area classified as "slopes – 6". This indicates that the dominant landform element "rules" a morphodiversity of the study area.

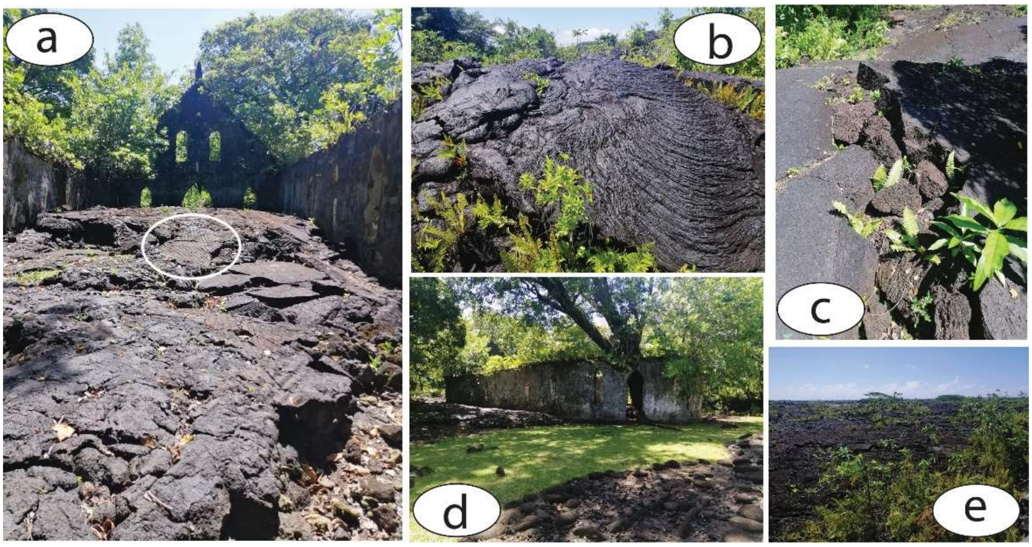

Figure 4. London Missionary Society (LMS) Church at Sale'aula invaded by the lava flows (**a**). Collapsed roof-plate marks clearly visible on the top of the lava (white circle). Typical pāhoehoe surface (**b**) and deflated lava pond with thick pāhoehoe crust (**c**) are common features in the distal flow field. Thin pāhoehoe lobes engulf the LMS Church while the flow field terminus preserves inflated lava fields (**e**).

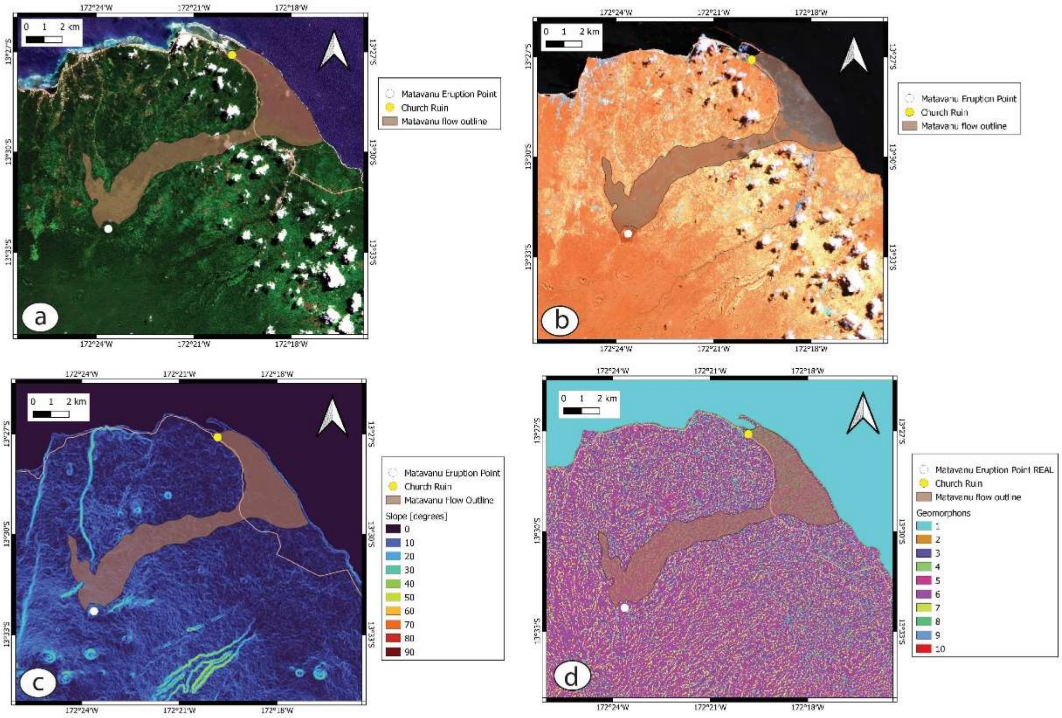

Figure 5. Visible light satellite image (**a**) and Sentinel-2 Geology 8 11 12 band image showing well the young lava flow surfaces. The slope map (**c**) demonstrates a monotonous sloping terrain within the scoria cones are marked as well as some deeply incised canyons along older lava flow margins. The geomorphon map (**d**) further demonstrates that the study area has monotonous landform classes within other landforms seemingly evenly distributed. Landform classes are (1) flat, (2) summit, (3) ridge, (4) shoulder, (5) spur, (6) slope, (7) hollow, (8) foot slope, (9) valley, (10) depression.

4. Discussion

The Matavanu Eruption Site represents the youngest and best-preserved volcanic sites in Western Samoa where the original volcanic geoforms are clearly recognizable. In this respect this location can play an exceptional role in geoeducation to disseminate knowledge on typical volcanic eruptions Western Samoa could experience. To check the lava flow inundation Q-LavHA software was employed. To generate a more realistic picture, the DEM region where lava flow was mapped (e.g., shown on available geological maps) was modified manually to run the simulation on a pre-lava flow surface. As the region slope reasonable high (Figure 5c), the simulation used actual flow length distances (13-km) (Figure 6a) and an order longer distances of 130-km (Figure 6b). The two models provided very similar lava flow inundation pattern that is slightly offset from the data currently available on the published geological maps [3] (Figure 6a and 6b). The most dramatic aspect of this simulation is that the 1905-11 lava flows, even if they are thin, might be filling the regions currently vegetated north of the mapped flow fields and while lava known from those regions their origin has not be considered entirely as the 1905-11 flow event. Similarly, while the geological maps show a northward trending lava flow, the current geological map clearly associate only the near-vent regions to be sourced from the 1905-11 event. The simulation however indicates that lava known from these regions might have leaped over the escarpment and potentially could have inundated the western side of the study area. These findings clearly suggest the need to conduct future geological mapping in the region in scale of 1 to 5000 or larger to be able to understand the flow inundation of the region. In both simulations however it needs to be considered that lava tubes likely formed where the lava flow entered to the gentle sloping coastal regions hence lava could have been transported successfully in regions where the Q-LavHA simulation (that operates best for channel-fed surface flows) could have not been able to provide satisfying results.

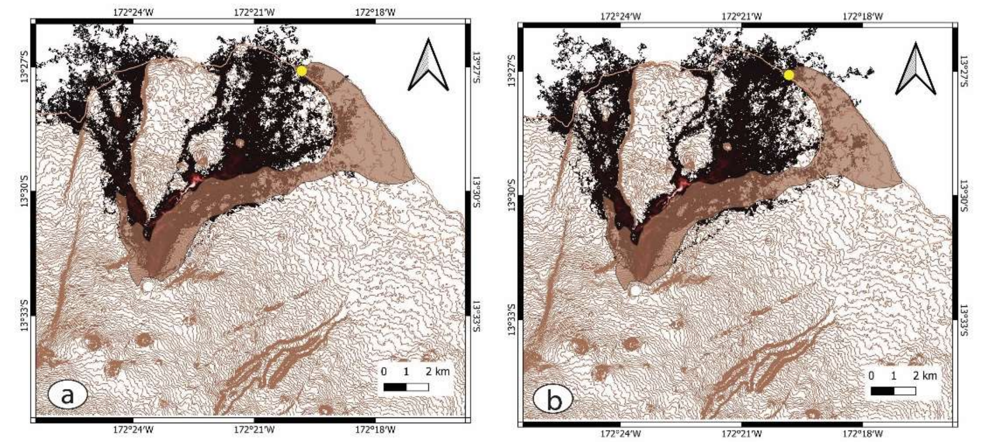

Figure 6. Results of Q-LavHA lava flow simulations of the 1905-11 Matavanu Eruption. Simulation distances were set to 13-km (**a**) to represent the maximum preserved flow distance and for 130-km following Euclidean simulation. Simulation yielded similar lava flow inundation that is slightly offset from the currently known mapped flow distribution patter. Contour lines are in 10-m intervals while the known lava flow distribution is marked by light brown field. Yellow dot marks the location of the LMS Church ruin while white dot represents the Matavanu eruption point.

In this research, the study area that successfully been listed to be one of The First 100 IUGS Geological Heritage Sites geodiversity estimation needs to be taken carefully. In previous research, when a 2.5 km-sized grid-based geodiversity estimate was performed, the study area scored relatively low values probably as a reflection of the overall monotonous slope (and other derived terrain parameters) as well as the simple geology (basaltic rocks only for instance) of the region [17]. This problem was addressed further in another research where the "grid" approach was changed to "real" distribution of mapped geological features as well as a refinement of the geological model of the region specifically designed to capture volcanic geoheritage elements [18]. Here in this work, a new angle of the scale problem of geodiversity estimates is presented. To identify the geoheritage value of a specific location and its geodiversity needs internally defined parameters that are scaled to the location. This is particularly a valid problem in areas like the 1905-11 Matavanu Eruption site where the young volcanism itself self-determine the geoheritage value of the location itself.

5. Conclusion

In this work we explored the geoheritage and geodiversity element of an iconic site representing the youngest volcanic eruption site in Western Samoa. The combined satellite and geomorphological data investigation revealed that the extent of the young lava flows is likely greater than currently expected. The Q-LavHA lava inundation simulation indicated further that the young lava flow field likely to be more extensive than the current geological maps indicate. While the terrain analysis indicates that the region has a monotonous topographical features "pushing" morphodiversity to a relatively low value, the geological diversity estimates need further revision such as assigning higher values for those regions where original volcanic geoforms in various scales (from micro, hand-specimen to outcrop and landscape element scales) are preserved.

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