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Landslide Processes on Volcanic Edifices in the Northeastern Part of the Atlantic Ocean

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Abstract—In the northeastern Atlantic (from south to north) the archipelagoes of the volcanic islands of Cape Verde, Canary, Selvagens, Madeira, and Azores occur. These were formed on the oceanic crust in the Miocene-Quaternary times. The analysis of the geological structure of the thirty islands leads to the conclusion that half of them were destroyed at different times in the course of their evolution by catastrophic landslide processes. Some of these islands were affected by such events repeatedly. These events caused tsunamis and formed large landslide masses in the adjacent parts of the ocean. Based on the data, volcanic edifices that might have been destroyed by landslide processes are proposed. A prerequisite for landslides to appear on a volcanic edifice could be a shift of its center of gravity.

Keywords: Cape Verde Islands, Canary Islands, Azores, volcanic edifice, landslide

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INTRODUCTION

The northeastern part of the Atlantic Ocean can be considered as one of the relatively "safe" regions of the Earth. It does not have active margins with seismic focal zones and island arcs. Nevertheless, from time to time, this region underwent natural catastrophes of various magnitudes caused by the geological processes. It is sufficient to mention the earthquake (M, 8.5–9.0) southwest of the coast of Portugal and the Lisbon tsunami of 1755 (Zitellini et al., 2001).

The aim of this work was to review the past large-scale landslide processes on volcanic edifices in the northeastern part of the Atlantic Ocean and to identify the objects where natural catastrophes may occur. Our task does not involve a comprehensive examination of the geology of the islands (the accompanying references will allow readers to obtain more detailed information if needed). We will not discuss hazardous natural phenomena related to rainfall, wave activity, floods, and erosion processes, and avalanches.

TERMS IN THE WORK

Active volcano means a volcano with eruptions known to have occurred during historical times.

Erupting volcano: A volcano that has been erupting in the last 5–10 ka.

Rift zone: A linear extensional structure of a volcanic edifice of the island composed of lava flows, cinder cones, and swarms of steeply dipping dikes.

A BRIEF OVERVIEW OF THE GEOLOGY OF THE VOLCANIC ISLANDS AND LANDSLIDE PROCESSES IN THE NORTHEASTERN PART OF THE ATLANTIC OCEAN

The archipelagos of volcanic islands in the northeastern Atlantic occur from south to north: Cape Verde, the Canary Islands, Selvagens, Madeira, and the Azores, which sometimes have the common geographic name Macaronesia (Fig. 1) (Mitchell-Thome, 1976).

The Cape Verde Islands archipelago (Fig. 1) is located 550–800 km west of the coast of Senegal. It consists of ten large and eight small islands forming two chains: the northern Windward (Barlavento) and the southern Leeward (Sotavento) islands.

The island of Santo Antão (*Tectonic*..., 1990; Masson et al., 2008) is situated in the western part of the Barlavento chain. It was formed as a result of the activity of three Pliocene–Late Pleistocene volcanic edifices composed of phonolitic, basaltic, and nephelinite lavas, as well as pyroclastic formations and tuffs aged 0.17–0.09 Ma. A hilly relief originated due to the formation of two large landslides and avalanches with ages more than 500 and 200–400 ka was discovered on the southeastern slope and the foothill of the island (Masson et al., 2008). Later, a volcanic cone named Topo de Coroa with a height of 1979 m (Fig. 2) was formed in the landslide cirque in the west of the island. The ancient parts of the island's northern slope, with

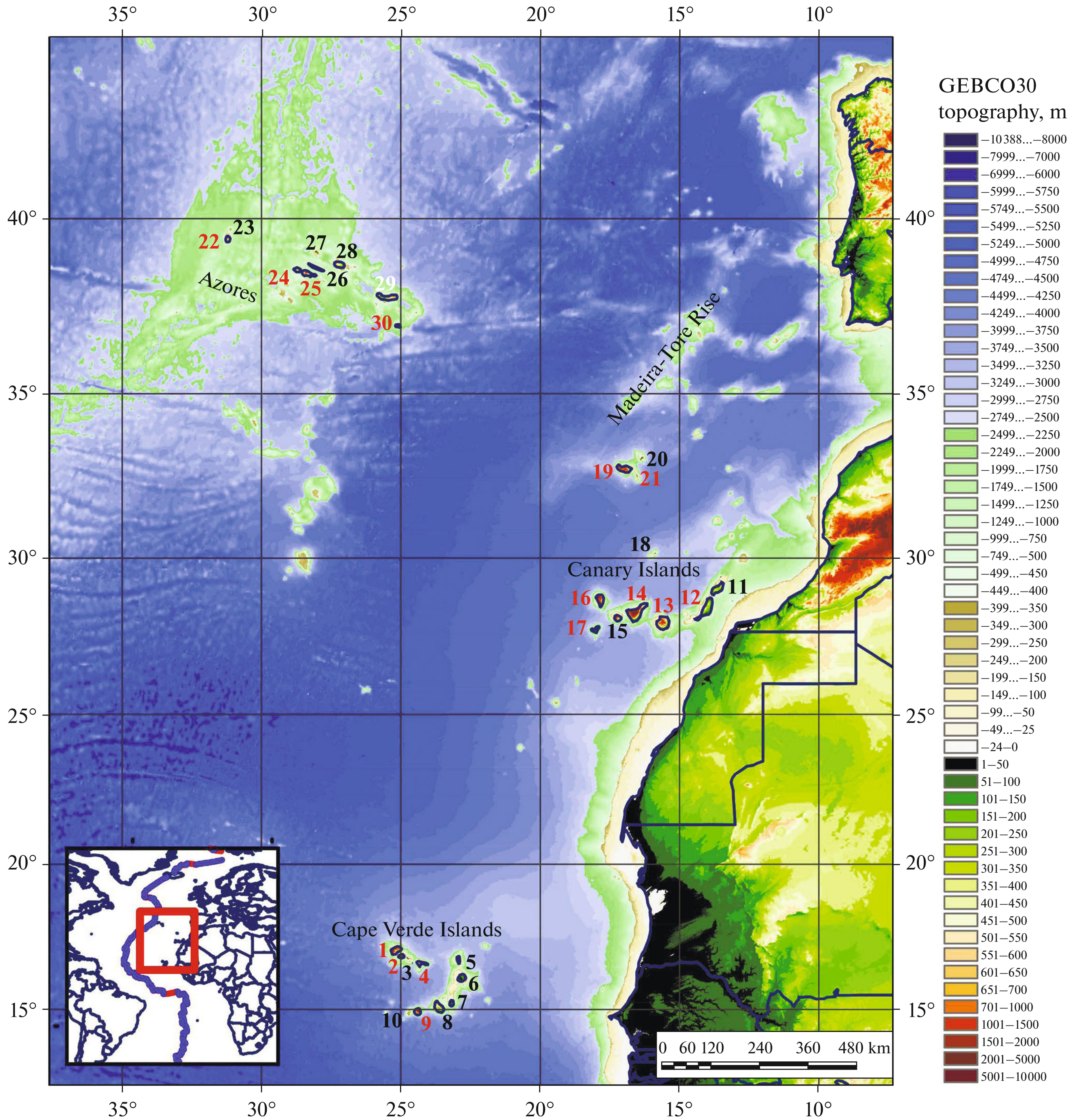

Fig. 1. The names of geographic objects in the northeastern Atlantic mentioned in this work. Islands are designated by numbers (red, with large landslides): (1), Santo Antão; (2), São Vicente; (3), Santa Luzia, Branco, Razu; (4), Sào Nicolau; (5), Sal; (6), Boavista; (7), Maio; (8 Santiago; (9), Fogo; (10), Brava; (11), Lanzarote; (12), Fuerteventura; (13), Gran Canaria; (14), Tenerife; (15), Gomera; (16), La Palma; (17), El Hierro; (18), Selvagens; (19), Madeira; (20), Porto Santo; (21), Desertas; (22), Flores; (23), Corvo; (24), Faial; (25), Pico; (26), São Jorge; (27), Graciosa; (28), Terceira; (29), São Miguel; (26), Santa Maria.

slopes up to 22 degrees, also developed landslide-avalanche deposits with ages from 0.7 to 1.4 Ma.

The island of São Vicente (*Tectonic*..., 1990; Ancochea et al., 2010; Masson et al., 2008) was formed as a result of the Pliocene–Pleistocene volcanic processes. The oldest alkaline pillow lavas, with an age of 9 Ma, constitute the foundation of the island together with pyroxenites, gabbro-syenites, nephelinite syenites, and a complex of dike swarms. The northeastern part of São Vicente paleovolcano, which formed 6.5–

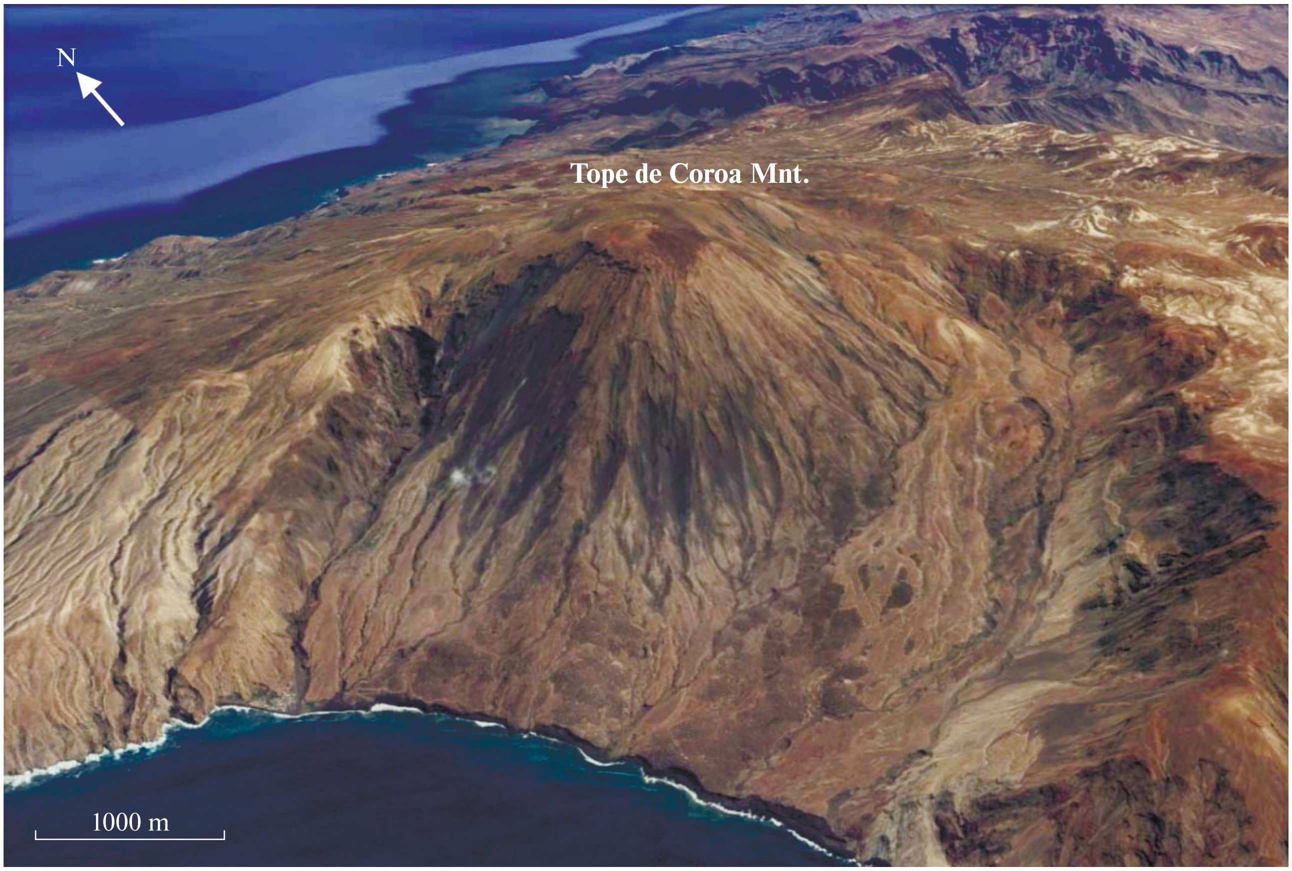

Fig. 2. The landslide cirque with newly formed volcanic cone of Tope de Coroa on Santo Antão Island. View from the southeast (https://earth.google.com).

4.5 Ma ago, was destroyed by a giant landslide circa 4.5–3.1 Ma ago, after which the volcanic edifice of Monte Verde (Fig. 3) began to form.

The island of São Nicolau (*Tectonic*…, 1990; Masson et al., 2008) appeared as a result of four stages of volcanic activity with ages ranging from more than 6.2–5.7 Ma to less than 100 ka. An effusive-pyroclastic complex of alkaline picrites and melanephelinites was formed at the earlier stages. Higher in the succession, pyroclastic and effusive complexes composed of nephelinites and basanites were developed; these were intruded by phonolite dykes. The most recent volcanic complex was formed at the last stage. Extensive landslide bodies were discovered on the northern and southern slopes of the island (Masson et al., 2008).

The island of Brava (Madeira et al., 2009) is located in the western part of the Sotavento ridge and is composed of three volcanic complexes. The lower complex is represented by ankaratrite and nephelinite pillow lavas, breccias, and hyaloclastites formed on a submarine rise. They are intruded by sienites, pyroxenites, and carbonatites. The upper Pleistocene–Holocene complex is primarily composed of phonolites, formed during phreatic and Plinian eruptions.

The island of Fogo (Hildner, 2011; LeBas et al., 2007; Richter et al., 2016) is the summit of an active volcanic edifice, with a total height above the bottom of the adjacent deep-sea basin reaching nearly 6000 m (Fig. 4). Since the time of the first Portuguese settlements (~1.5 ka), at least 27 eruptions have been docu-

Fig. 3. The Monte Verde volcanic edifice on São Vicente island. View from the southeast. Photo by the author.

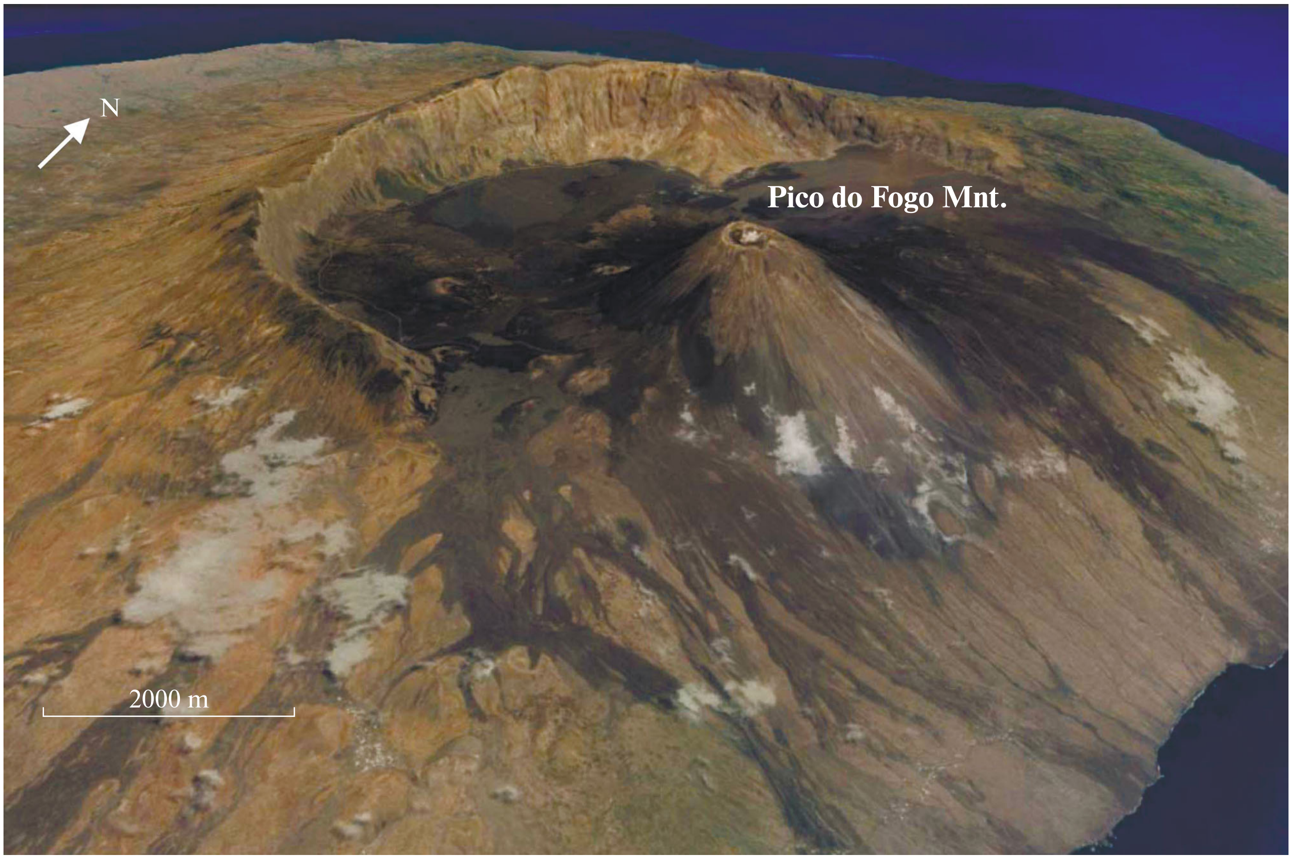

Fig. 4. The landslide cirque with newly formed volcanic cone of Pico on Fogo Island. View from the southeast (https://earth.google.com).

mented on Fogo, including the most large-scale ones that occurred in 1785, 1799, 1847, 1852, 1857, and 1951. The last eruptions occurred in 1995, and 2014–2015, leading to human evacuation and damage by lava flows. The edifice was formed during four stages. Carbonatites and alkali basalt complexes were formed on a seamount at the first stage, circa 4.5 Ma ago. These were overlaid by subaerial alkali basalt lavas, which were subsequently intruded by high-alkali basalts and intermediate lavas. The catastrophic collapse of the eastern flank of the edifice occurred ~70 ka, resulting in the formation of a landslide cirque with a diameter of about 8 km. On the eastern edge of this cirque is the volcanic cone of Pico de Fogo, with a summit height of 2829 m above the sea level. It began forming circa 62 ka by ongoing flows of alkali basaltic lavas into the cirque. The collapse of the volcano led to the formation of large landslide masses and tsunamigenic deposits on the islands of Santiago and Maio (at distances of 50 and 120 km, respectively) from tsunamis with heights of approximately 170 m (Masson et al., 2008).

The Canary Islands archipelago (Carracedo et al., 2015; Coca et al., 2014; Hunt et al., 2013; Perez-Torrado et al., 2006; Schmincke and Graf, 2000) is part of the eponymous volcanic province located west of the coast of Morocco. It comprises seven large islands and several smaller ones, as well as seamounts (Fig. 1). In the past 2 Ma, 11 large landslides occurred on the Canary Islands, 8 of which led to the formation of thick turbidite deposits in the Madeira Basin.

The eastern islands of the Lanzarote and Fuerteventura archipelago are located on the East Canary Ridge (Vázquez et al., 2015a) trending northeast-southwest with depths ranging from 50 to 200 meters. It is 8–20 km wide and has an absolute height of 1200 m. The slope gradient is 8° on average reaching 40° on the eastern slope and 20° on the western slope.

The island of Fuerteventura (Acosta et al., 2004; Krastel et al., 2001; Steiner et al., 1998; Stillman, 1999) is primarily composed of Miocene–Quaternary volcanic rocks, underlaid by Jurassic–Cretaceous tholeiitic pillow lavas and terrigenous–carbonate complexes of oceanic basement rocks. These rocks were intruded by a polyphased Late Oligocene–Early Miocene complex, consisting of ultramafic rocks, gabbro, and syenites, with Early Miocene (24–17 Ma) dikes intruding with intensity of up to 95%. In the Miocene, after a regional hiatus, three large volcanic edifices began to form under subaerial conditions: the

Northern (>22–12.8 Ma), Central (>22.5–12.8 Ma), and Southern (20.7–19.3 Ma). Their heights might have reached 3000 meters. The last two were destroyed by large landslides, with the most recent 15 Ma ago. Their remnants are located on the western slope of the East Canary Ridge in the form of a large landslide mass (25 × 15 km) with large (up to 11x6 km) blocks and debris flows (65 × 70 km) at depths of 2800–3300 m. A debris flow called Djanalia 2 Ma was identified to the south (Krastel et al., 2001).

The island of Lanzarote (Acosta et al., 2004; Marinoni and Pasquare, 1994; Carracedo et al., 1992) is located north of Fuerteventura. It consists of two volcanic complexes: a pre-erosion Miocene complex (15.6–5.7 Ma) and a post-erosion Pliocene complex (<1.2 Ma). Most of the island is composed of Pleistocene lavas. In historical times, volcanic activity on the island intensified. In 1730–1736, fissure eruptions in the northeastern of the island covered about one-quarter of its territory with lava flows and pyroclastic formations.

The island of Gran Canaria (Acosta et al., 2004; Funck and Schmincke, 1998; Krastel and Schmincke, 2002; Pérez-Torrado et al., 2006; Schmincke and Graf, 2000) is located in the central part of the Canary archipelago. It has a shelf up to 10 kilometers wide, with an edge at a depth of ~125 m. The maximum elevation of the island is 1949 m. Volcanic processes on Gran Canaria began about 14–15 Ma ago and occurred during three main phases. In the Miocene, a volcanic edifice up to 2000-m high was formed; it consisted of trachytic and rhyolitic ignimbrites. Trachyte—basanite—phonolite volcanic complexes of the Roque Nublo stratovolcano up to 3000-m high began to form in the Pliocene. Late Pliocene–Quaternary basanite and nephelinite lavas erupted mostly in the north of the island. Two eruptions occurred 3 ka. Large landslide events occurred on Gran Canaria during two stages. In the Miocene, the volcanic edifice was destroyed by landslides and avalanches, leading to the formation of a hilly seabed relief, particularly in the strait between the islands of Tenerife and Gran Canaria, in the hiatus 9–5 Ma ago. At the end of the Pliocene volcanic phase, the Roque Nublo stratovolcano was destroyed by a large landslide on the northern slope of Gran Canaria. A landslide body with large (>100-m in diameter) blocks, many of which are highly brecciated, is located in the water area. One of these blocks is 1200-m long, 800-m wide, and ~300-m thick.

The island of Tenerife (Criado and Paris, 2005; Hunt et al., 2013), the largest island in the Canary archipelago, is a complex volcanic edifice with dissected mountain relief. It was created during two main volcanic stages. At the first late Miocene-Pliocene stage (16.1–3.2 Ma), volcanoes were formed in the north (Anaga) and northwest (Teno) of the modern island. These were destroyed by landslide processes 4.7–4.1 and 6.3–6 Ma ago, respectively, and were composed of series of basaltic lavas and pyroclastic flows, as well as trachytic, trachybasaltic, and phonolitic intrusions. After the erosional hiatus in the Pliocene and Pleistocene, volcanic edifices began to form in three rift zones (northeastern, southern, and northwestern). Large landslide masses formed at this stage. A new central-type Caldera del Rey edifice was formed on the southern branch and was destroyed 200 thousand years ago by the Icod de los Vinos landslides (<0.15 Ma), which moved northward, forming the landslide cirque of Cañadas. At the most recent stage, the Teide and Pico Viejo volcanoes, with heights of 3715 m and 3125 m, respectively, were formed on the northern edge of the island. They consist of basanite and phonolitic lavas and pyroclastic flows (Fig. 5). Two large landslides aged 2.4 Ma (Tigaiga) and 0.6–1.4 Ma were also discovered in the north of Tenerife Island (Hunt et al., 2013).

The island of La Gomera (Casillas et al., 2010; Hunt et al., 2014; Llanes et al., 2009) represents a polyphased volcanic central-type Alto-de-Garajonay edifice 1487-m high, composed of three complexes: the basement, ancient edifice, and young edifice. The basement is represented by Middle Miocene intrusions of gabbro, pyroxenites, and syenites, pillow lavas, and breccias formed in submarine conditions, which were intruded by dike swarms. The ancient complex was formed by two volcanic edifices with a total age of 10.5–6.4 Ma, which could have reached heights of 1900 and 2600 m, respectively. They are composed of basaltic and trachyte-phonolite series. The youngest volcanic edifice on La Gomera is composed of basaltic, trachybasaltic, and trachyandesite lavas with an age of 5.7–4 Ma. A large landslide, Tazo, occurred in the north of La Gomera 9.4 Ma ago. Its amphitheater is currently filled with avalanche debris, agglomerates, and lava flows from the younger volcano. At the boundary of 4 Ma, nine large debris flows were formed on all slopes of the new edifice, some of which were stopped by basaltic flows with an age of 2.8-2 Ma.

The island of La Palma (Fernández et al., 2021; Staudigel and Schmincke, 1984) is located in the northwest of the Canary archipelago. In the north of the island, there are remnants of a complex polyphased stratovolcano, characterized by a mountain relief with a maximum elevation of 2426-m above sea level (Roque de Los Muchachos). Southward lies the sub-meridional Cumbre Vieja ridge, corresponding to an island rift zone. The basement of La Palma is composed of pillow lavas, trachyte flows intruded by gabbro, and numerous dikes. It was formed underwater approximately 3-4 Ma ago. After a hiatus of about 1.5 Ma, basaltic lava flows and pyroclastic formations of the Garafia (1.7–1.2 Ma) and Taburiente I (1.08–0.83 Ma) volcanos began to form. Following the slope failure of the latter, eruptions of basaltic lavas and pyroclastic flows resumed, leading to the creation of

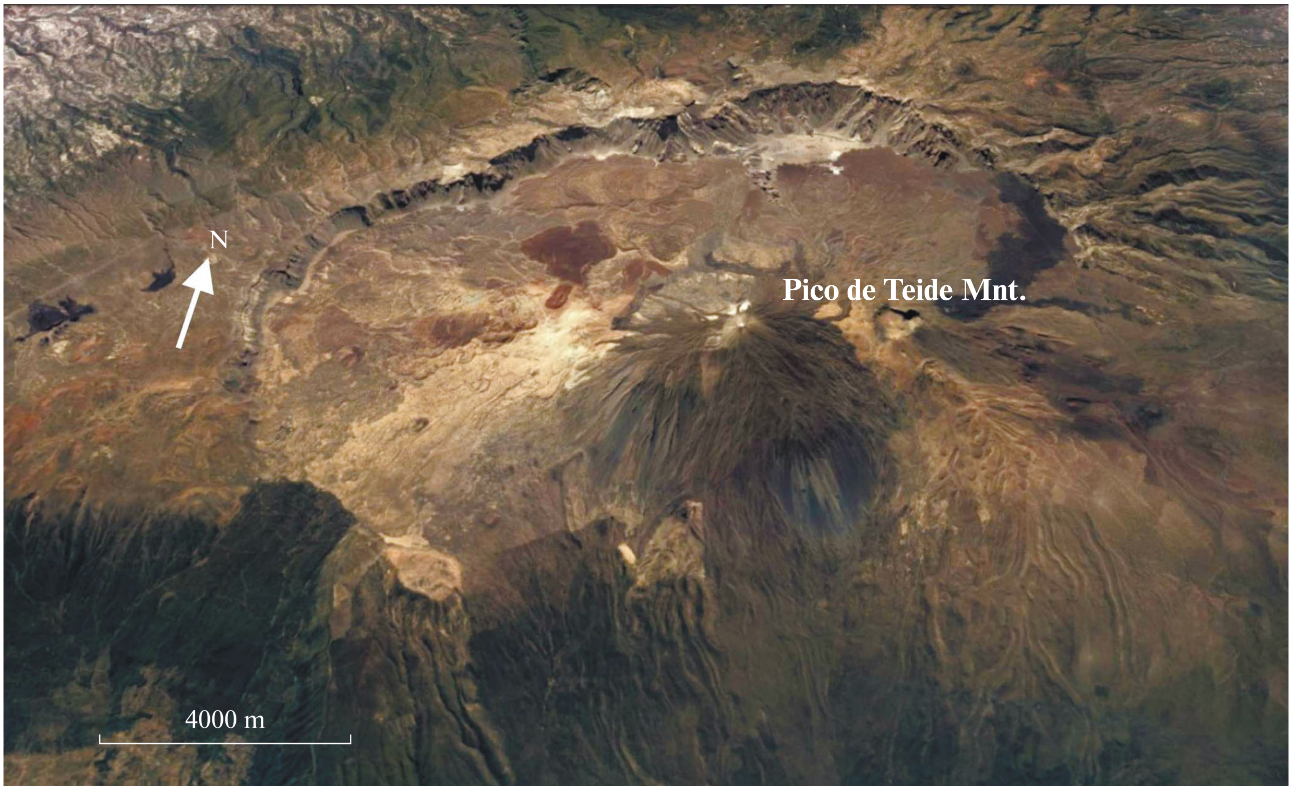

Fig. 5. The landslide cirque with newly formed volcanic cone of Tope de Teide on Tenerife Island. View from the northeast (https://earth.google.com).

two new edifices, Taburiente II and Cumbre Nueva. The recurrence of volcanic activity led to the formation of Bejenado volcanic edifice <0.59 Ma ago and the appearance of numerous small volcanic cones to the south caused by fissure eruptions in the Cumbre Vieja rift zone (<0.54 Ma ago).

The La Palma volcanic edifice (Fernández et al., 2021) was destroyed twice by the large-scale landslides. The western slope of the Taburiente edifice was destroyed by the gigantic Playa de la Veta landslide approximately 1 Ma ago and the volcanic edifice of Cumbre Nueva collapsed circa 0.6 Ma ago. All landslide masses shifted westward, forming extensive hilly areas at the bottom of the Atlantic Ocean.

The island of El Hierro (Gee et al., 2001; Münn et al., 2006; Tsiogalos, 2017) is located in the southwest of the Canary archipelago. It is an above-water portion the volcano with a maximum height of 1500 m (Malpaso mountain). The total height of the edifice above the ocean floor exceeds 5500 m. It was formed due to the development of its rift zones (Northeastern, Western, and Southern zones) during three main stages. At the first stage, 1.2–0.8 Ma, basanite lava flows of Tinñor stratovolcano were formed in the northeast of the modern island under subaerial conditions. Its eastern slope was destroyed by a massive landslide 882–545 ka. After these events, 545–176 ka, the Golfo stratovolcano started erupting lava flows of trachytes and basanites, its eastern slope was destroyed by two large landslides, Las Playas (176–134 ka) and San Andreas (545–176 ka). Its southern slope (El Julan) collapsed almost simultaneously (545–200 ka). All mentioned formations on the island were intruded by dike swarms. At the most recent stage (<145 ka), all rift zones became active, which resulted in the formation of 220 volcanic cones associated with lava flows and pyroclastic formations of alkali basalts. Approximately 13 ka , a large landslide El Golfo destroyed the northwestern slope of the island edifice.

The Selvagens Islands (Santos et al., 2019) are located 165 km north of Tenerife Island (Fig. 1) and include three small islands that crown a two-summit submarine volcanic edifice that was formed by the Late Oligocene (28.9–24.2 Ma), while the youngest volcanic rocks have an age of 3.4 Ma. On the northern slopes of the island shelf, at depths ranging from 400 to 2500 m, there are escarpments of landslides extending from 300 to 3100 m. Seven smaller escarpments of landslides are located along the southeastern flank.

The Madeira Archipelago (Fig. 1) (BrumDaSilveira et al., 2012; Fonseca et al., 2002; Klugel et al., 2005; Quartau et al., 2018; Ribeiro and Ramalho, 2010) is situated in the southern part of the Madeira-Tore Ridge and comprises volcanic islands (with ages of terrestrial edifices) such as Madeira (5.3 Ma to <10 ka), Desertas (5.1–1.9 Ma), Porto Santo (14.3–11.1 Ma), and rocks.

The island of Madeira is a volcanic edifice composed of three complexes: the lower (Miocene, >7 Ma), intermediate (Plio-Pleistocene, 5.57–1.8 Ma), and upper (Pleistocene-Holocene, circa 1.8–0.007 Ma). The lower complex was formed under marine conditions by alkaline basaltic lavas, hydrothermally altered hyaloclastites, intruded by dikes. The intermediate complex was formed by eruptions of Strombolian, volcanic, and Hawaiian types. The upper complex consists of lavas and tuffs formed by central-type edifices and fissure eruptions. The most recent eruption occurred 6 850 years ago. Currently, gas emissions and hot springs are known to have taken place on the island. Three large landslides and debris flows are identified on the northern slope of Madeira, and the arcuate escarpments of these landslides are well pronounced both at the shelf edge and along the coastline, ranging in length from 15 to 25 km. The landslide bodies shifted into the ocean at distances from 20 to 85 km. The northwest landslide created a chaotic landscape, dominated by the blocks ranging in diameter from hundreds of meters to 3 km, with heights reaching up to 600 m. Southeast of Madeira, a hilly relief extends for 4000 km^2, created by both submarine volcanic cones and landslide formations known as the "Funchal landslide," whose escarpment is well-defined along the coastline (Quartau et al., 2018).

Porto Santo Island (Mitchell-Thome, 1976; Schmidt and Schmincke, 2002) is located 45 km northeast of Madeira. It represents the remnants of an ancient, eroded volcanic edifice, primarily composed of trachytic lava flows, hyaloclastites formed under shallow-marine conditions, as well as intrusions and dikes. The ancient complex is unconformably overlaid by marine and subaerial pillow lavas, hyaloclastite breccias with layers of Middle Miocene calcarenites. Landslides and debris flows are developed on the slopes of the Porto Santo Island edifice in its northern and southern parts. The debris material moved into the ocean at the distances of 42 and 50 km, respectively. The escarpments of these landslides, with lengths of up to 10 km, are well-defined as amphitheaters at the edge of the island shelf.

The Desertas Islands group (Ilhéu Chão, Ilhéu Deserta Grande, and Bugio) (Schwarz, 2004) consists of the remnants of the island volcanic rift zone composed of series of lava flows, cinder cones that are often superimposed on each other and are intruded by steeply dipping dike swarms. In the southwest and southeast of the Desertas Islands, the shelf edges and coastlines are arc-shaped in plan, approximately 10 km wide. Here, escarpments of landslide and debris flow deposits are shifted at 20 and 45 km, respectively.

The Azores archipelago (Fig. 1) (Azevedo et al., 2006; Carvalho et al., 2001; Hildenbrand et al., 2018; Madeira et al., 2016; Oliveira et al., 2004), consisting of nine volcanic islands and rocks, is located in the region of the triple junction of the North American, African, and Eurasian plates. On the first one, approximately 100 km away to the west of the Mid-Atlantic Ridge axis, there are volcanic islands of Flores and Corvo that crown a N-NE trending submarine rise with a height of ~60 km. It originated on the oceanic crust and is 9–10 Ma.

The island of Flores is a volcanic edifice with a maximum height of 914 m (Morro Alto Mountain); it started to form at the end of the Pliocene and rises from the ocean floor by 2500 m. The base complex (2.2–0.67 Ma) mainly consists of hyaloclastites and basaltic and hawaiite lava flows. The upper complex (0.6–0.003 Ma) is composed of trachytic, mugearite, and hawaiite lavas. Cinder cones and phreatomagmatic formations developed at the later stages of the edifice evolution (2-3 ka). The west of Flores volcanic edifice is found to contain three escarpments of landslides. The oldest of them was formed between 1.3 and 1.18 Ma, and the second one ~1.18 ± 0.05 Ma. The youngest landslide on Flores destabilized the lava flow that was 314 ± 30 ka. The landslide bodies shifted westward from the island at up to 50 km, creating a hilly seafloor relief. This region is aseismic; however, in 1847 and 1980, landslides and cliff collapses occurred on Flores, with the first event triggering a tsunami that resulted in ten casualties, both on the island itself and on Corvo Island, located 18 km to the north.

The island of Corvo (França et al., 2006; Márquez, 2014) is a volcanic edifice with a caldera, having a maximum diameter of 2.3 km and a depth of 300 m. The highest point on the southwestern rim of the caldera is 720 m. The basalts at the base, aged 1.5–1 Ma, are the oldest formations on Corvo. Later, a volcanic edifice with a caldera was formed by the flows of alkaline basalts, trachyandesites, and phonolites, aged 0.7–0.4 Ma. The most recent eruptions occurred 80–100 ka in the south of the island. The northern and western parts of the island are subjected to intense wave erosion, resulting in numerous landslides and avalanches.

East of the Mid-Atlantic Ridge lies the Azores Plateau, bounded by the 2000-m isobath. This region features a complex combination of W-NW trending ridges, basins, and seamounts, which together form a diffuse boundary between the African and Eurasian plates. Its northern edge borders the Terceira Rift. Southwestern of the rift lies the area with the most interesting two narrow subparallel ridges trending west-northwest. Stretching for about 100 km, the islands of Faial and Pico are located on the southernmost edge (Costa, 2014; Costa et al., 2015; França

Fig. 6. The Piquinho cone on the edge of the Pico volcanic caldera. Pico Island. View from the southeast (https://www.arrivalguides.com/en/Travelguide/Azores/doandsee/volcanic-landscape-of-pico-island-72653/).

et al., 2009; Quartau et al., 2015; Romer et al., 2018; Trippanera et al., 2014).

The island of Pico (Costa et al., 2015; Hildenbrand et al., 2008) stretches northwestward for 46 km. It consists of three volcanic edifices that developed during the Middle Pleistocene–Holocene. The oldest one, Topo Volcano, is located in the southeast of the island. The remaining portion of this volcano reaches a height of 1020 m and is composed of ankaramitic and basaltic lavas aged 186–115 ka. These lavas are overlaid unconformably by lavas and products of fissure eruptions (70 ka), which also formed numerous small cinder cones (Ashada Ridge). The western half of the island is formed by Pico stratovolcano, which has a caldera with a diameter of about 500 m and a depth of 30 m. The Pico Pequeno cone rises above its northern rim, with a height of 70 m. The stratovolcano began erupting 53 ka and has a maximum height of 2351 m. During historical times, four eruptions occurred on the island of Pico in 1562–1564, 1718, and 1720. Fumarolic activity on the Pico Pequeno cone is also being recorded today (https://www.destinazores.com/en/destination/pico/montanha-do-pico/).

The volcanic edifices on Pico Island were destroyed by three large landslides. The northern landslide has an escarpment extending for 55 km and is mainly located in the area of fissure eruptions, also affecting the northeastern part of Pico stratovolcano. Opposite this landslide, at the bottom of the Georges Strait with a maximum depth of 1270 m, there is a hilly-blocky relief covering an area of about 150 km^2. The largest blocks are 1700 m in length and up to 100-m high. The landslide cirque is partially filled with lava flows aged 70 ka, which indicates its formation during an older period of displacement of the northern part of the island (probably within an interval of 125–70 ka). We note that the zone of this landslide detachment is located in the fault areas of Faial Island. The second, smaller landslide is located on the southern slope of the Ashada Ridge and the remnants of Topo volcano. The displaced material is located under water at a distance of about 17 km from the southeastern edge of the island. Finally, the third landslide destroyed the structure of the southern slope of the Pico stratovolcano (Fig. 6).

Faial Island (Quartau et al., 2012) lies 6-km northwest of Pico Island. It consists of three volcanic complexes. The oldest terrestrial shield volcano, with an age of ~850 ka, is located in the northeast of the island. It is composed of hawaiite lava flows, which after the hiatus were overlaid by lavas from the edifice with an age of ~360 ka. Approximately at the same time (350–

120 ka), the graben of Faial, confined by normal faults with orientations of 110°–120° and dip angles of 60°–70°, began to form. The main part of the island is composed of lavas, pyroclastic formations, and basalt, benmoreite, and trachyte pumices from the Caldera volcano, which was formed between ~120 and ~40 ka. The highest point of the island, Cabeço Gordo Mountain (1043 m), is associated with it. In 1998, Faial Island was hit by a 5.8 magnitude earthquake (Marques et al., 2008), which resulted in damage, casualties, and landslides on the coastal cliffs and inner walls of the Central Volcano's caldera. Debris flows were formed in some valleys. The most recent (<16 ka) fissure eruptions of alkaline basalts and trachybasalts in the Capelo zone on Faial Island occurred in the west of the island. Historical eruptions are also known to have taken place in 1672–1673 and 1957–1958. In 1958, an eruption occurred in the Central Volcano's caldera.

The island of São Jorge (Hildenbrand et al., 2008; Marques et al., 2015; Viveiros and Zanon, 2018) is located 20-km northeast of the Faial-Pico Ridge. The maximum length of the island is 53 km, with a width of only 8 km. Its highest point is Pico Esperança in the central part of the island, with a height of 1053 m above sea level. The island consists of three volcanic complexes (basaltic lavas and pyroclastic formations) with ages ranging from 1.9 to <0.1 Ma. São Jorge Island underwent 12 or 13 eruptions in the past 5.6 ka. The most recent fissure eruptions of lavas are known to have occurred in 1580 and 1808, resulting in human casualties. In 1964, a submarine eruption was recorded at the western end of the island at a depth of about 1000 m. São Jorge Island is located within an active seismic zone and has experienced strong earthquakes multiple times (in 1580, 1757, 1808, and 1899), the most destructive one (magnitude of 7.4) occurred on July 9, 1757, leading to the death of 1034 people, extensive destruction, and changes in the landscape.

The volcanic edifices of the islands of Graciosa, Terceira, and São Miguel are located within the Terceira Rift.

Graciosa Island (Hipólito et al., 2013; Larrea et al., 2014; Sibrant et al., 2014) is a Middle Pleistocene–Holocene polygenic volcanic edifice with a maximum height of ~400 m. The oldest complex of Graciosa Island (1057.620 ± 120 ka) consists of hawaiite-type trachytic and basaltic lavas overlaid by pyroclastic formations. They are covered by volcaniclastic deposits (350–435 ka) and in turn, after the hiatus, by lavas and cinders aged ~110 ka and younger. Currently, there are no signs of significant volcanic or seismic activity on the island, but research shows that active fault movements occurred here 31 ka. Over the last 12 ka, at least ten volcanic eruptions were recorded on Graciosa Island, with the most recent eruption at 2000 ka. During historical times, eight earthquakes took place (in 1611, 1717, 1730, 1787, 1817, 1837, 1868, 1883), two of which had magnitudes >7, and some (in 1730) led to extensive destruction and human casualties.

Terceira Island (Casalbore et al., 2015; Casas et al., 2018) is located within the eponymous rift and represents a volcanic edifice that began forming in the Middle Pleistocene (370–388 ka) and is active today. It is composed of basaltic and trachytic lavas and pyroclastic formations from four central-type volcanos with calderas. Two of them in the east of the island are considered to be extinct, in contrast to Pico Alto, which is associated with several ignimbrite flows and the youngest and actively growing Santa Barbara volcano (the highest point on the island is at 1023 m). The formation of the latter began 25 ka, with the last eruption recorded in 1761. On the slopes of Terceira Island, there are small but numerous landslides. The two largest landslides (with escarpment wall lengths up to 2 km) are located west of the island at depths of 100–600 m.

São Miguel Island (Carmo et al., 2015) is located in the southeastern part of the Terceira Rift and extends along its trend. It is composed of the products erupted from several stratovolcanoes and fissure systems that began developing since the Middle Pleistocene. The eastern part of the island consists of the oldest formations and inactive edifices. In the active central part of the island, there have been several eruptions of Hawaiian and Strombolian types, mainly with trachytic and basaltic lava flows.

Santa Maria Island (Ávila et al., 2018; Marques et al., 2020; Sibrant et al., 2015), the oldest island in the Azores archipelago, is located to the east. It has a relatively flat relief in its western half and a gently rolling relief in the eastern half, with the highest relief point at 590 m (Pico Alto). The volcanic edifices were formed on the island during three main stages. At the first stage, 5.7–5.3 Ma, an ancient shield volcano existed. At the second stage (4.3–2.8 Ma), it was young, composed of basaltic flows and dikes. At the third stage, several cinder cones aged 3.6–2.8 Ma were formed. On Santa Maria Island (Ávila et al., 2018; Marques et al., 2020; Sibrant et al., 2015), the collapse of the ancient volcanic edifice due to landslides occurred 5.3–4.3 and 3.6 Ma. Their escarpment walls manifest themselves as scarps, both in the island's topography and its underwater portion in the south, the east, and the west of the island.

DISCUSSION

Volcanic island edifices are hazardous not only because of lava flows, ash ejections and gas emissions but also because they are destroyed by large-scale landslide processes. It is established that landslides can occur very quickly and trigger catastrophic tsunamis. Two recent examples are:

Ritter Island (Ward and Day, 2003), which is located north of Australia within the island arc of the

New Guinea Sea. It was formed on March 13, 1888, as a result of the rapid collapse of a large conical edifice, ~750-m above sea level and ~2000-m above the bottom of the adjacent deep basin. The landslide generated a tsunami up to 20-m high, affecting areas up to 600 km away. The collapse of the edifice was not preceded by active volcanic or seismic events. Later, within a year, a new active volcanic cone was formed within the landslide cirque.

Anak Krakatau Volcano (Karstens et al., 2020; Ye et al., 2020) is located in the Sunda Strait. It began to form in 1929 inside the caldera of the Krakatau volcano, which had appeared in 1883. By 2018, its height had reached 300 m. On December 22, 2018, a catastrophic landslide occurred on its southwestern slope, which resulted in a tsunami that killed over 400 people.

The destruction of volcanic edifices due to landslides is known to have occurred at 400 Quaternary volcanoes and, since 1600, at least at 17 (Karstens et al., 2020). An indicative example is the collapse of the slope of Mount St. Helens Volcano (United States) in 1980, followed by an eruption (Glicken, 1996).

The archipelagos of volcanic islands in the northeast Atlantic were mainly formed on the oceanic crust during the Miocene–Quaternary period. They were formed during many phases of effusive activity (up to ten or more), intrusion of dikes and intrusions alternating with periods of dormancy.

Geometrically, an ideal stratovolcano is nearly a cone with a center of gravity at a distance of one-quarter of its height from its base. Its displacement upward along the axis or to the side will inevitably lead to instability of the entire figure. Volcanic edifices of ideal form occur rarely. They usually have a more complex structure than a simple geometric figure. Their instability can be affected by steepness of slopes, alternation of lava flows, tuffs, and pyroclastic flow deposits, uneven alteration of rocks by hydrothermal processes, seismic activity, and other factors that often act in combination. The height of the edifice is not a decisive factor. The intrusion of magma into the marginal portions of the volcanic edifice shifts its center of gravity and may lead to asymmetry and instability of the slopes. Similar consequences may also occur with landslides of volcano portions under the action of gravitational forces. Based on the above, identifying volcanic edifices with asymmetric structures or other deviations from ideal geometric shapes can indicate their potential hazard.

An analysis of the volcanic edifices in the archipelagos of the northeast Atlantic allows the conclusion that many of them were destroyed at various times by catastrophic landslide processes that triggered tsunamis. On some of these islands, new volcanic edifices were formed within landslide cirques. These phenomena were observed on the islands of Santa Antão, Fogo, Sãn Vicente, Pico, Gomera, and several others.

In the southwestern part of the Cape Verde archipelago, landslide events of different ages occurred on the islands of Santa Antão, Sãn Vicente, Sãn Nicolau, and Fogo. On the eastern rim of the landslide caldera of Fogo Island, the Pico de Fogo cone rises. It has an elevation of about 6000 m above the abyssal basin and steep slopes. The latter, as well as the island of Brava and Cadamosto seamount, lies in the area of increased seismic activity, which was recorded by the Cape Verde Geophysical Network (Faria and Fonseca, 2014). The above data enable us to consider this region as potentially hazardous, as large landslides can occur.

Currently, the Canary Archipelago has increased volcanic and seismic activity compared to the Cape Verde Islands. In the past 500 years, there have been 15 volcanic eruptions on the islands of Tenerife, El Hierro, La Palma, and Lanzarote. The main seismic activity of the archipelago and its water area is focused on the islands of Tenerife, La Palma, and El Hierro. A new submarine volcano was formed south of the latter in 2011–2012. Active hydrothermal activity was also detected to the west of the island. A "cloud" of numerous but low-magnitude seismic events is located between the islands of Tenerife and Gran Canaria, where a growing submarine volcano, Hijo de Tenerife, was identified.

Increased seismicity on the islands of La Palma and El Hierro has led some authors (Gee et al., 2001; Masson et al., 2008) to assume about the possible collapse of these edifices by large landslides that may generate massive tsunamis, reaching even the eastern coast of North America. This scenario is plausible since tsunamigenic deposits were found (Pérez-Torrado et al., 2006) on the islands of Gran Canaria, Tenerife, and Lanzarote. They are located at elevations of 40–190 m and up to 800 m from the coastline.

The Azores archipelago is at the stage of active formation, and in general, this classifies it as a region with increased volcanic and landslide hazards. We note that seismic activity across the entire archipelago has been increasing in recent years. In this context, the volcanic edifices located within the Terceira Rift, as well as Pico Island are the most hazardous. At present, Pico volcano is being actively destroyed by avalanches and landslides, which may indicate the potential catastrophic collapse of the entire volcanic edifice.

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CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

REFERENCES

J. Acosta, E. Uchupi, A. Munoz, et al., "Geologic evolution of the Canarian Islands of Lanzarote, Fuerteventura, Gran Canaria and La Gomera and comparison of Landslides at These Islands with Those at Tenerife, La Palma and El Hierro," Mar. Geophys. Res. **24** (1), 1–40 (2004). https://doi.org/10.1007/1-4020- 4352-X_1

E. Ancochea, M. J. Huertas, F. Hernan, et al., "Volcanic evolution of Sao Vicente, Cape Verde Islands: the Praia Grande landslide," J. Volcanol. Geotherm. Res. **198**, 143–157 (2010).

S. P. Avila, R. S. Ramalho, J. M. Habermann, et al., "The marine fossil record at Santa Maria Island (Azores)," Volcanoes of the Azores, Active Volcanoes of the World, Ed. by U. Kueppers and C. Beier (Springer-Verlag Gmb, 2018), pp. 155–196. 2018, https://doi.org/10.1007/978-3-642- 32226-6_9.

A. Brum Da Silveira, S. Prada, R. Ramalho, et al., "Inventariacao do Património geológico da Ilha da Madeira," Secretaria Regional do Ambiente e Recursos Naturais-Relatorio Final (2012). https://geodiversidade. madeira.gov.pt

R. Carmo, J. Madeira, T. Ferreira, et al., Volcano-tectonic structures of São Miguel Island, Azores, In *Volcanic Geology of São Miguel Island (Azores Archipelago)*, Ed. by J. L. Gaspar, J. E. Guest, A. M. Duncan, F. J. A. S. Barriga, and D. K. Chester, *Geol. Soc. London*. Mem., **44**, 65–86 (2015). https://doi.org/10.1144/M44.6

J. C. Carracedo, E. R. Badiola, and V. Soler, "The 1730–1736 eruption of Lanzarote, Canary Islands: a long, high-magnitude basaltic fissure eruption," J. Volcanol. Geotherm. Res. **53** (1–4), 239–250 (1992).

J. C. Carracedo, V. R. Troll, and K. Zaczek, "The 2011–2012 submarine eruption off El Hierro, Canary Islands: new lessons in oceanic island growth and volcanic crisis management," Earth-Sci. Rev. **150**, 168–200 (2015).

A. Carvalho, M. L. Sousa, C. S. Oliveira, et al., "Seismic Hazard for the Central Group of the Azores Islands," Boll. Geofis.Teor. Appl. **42** (1–2), 89–105 (2001).

D. Casalbore, C. Romagnoli, A. Pimentel, et al., "Volcanic, tectonic and mass-wasting processes offshore Terceira Island (Azores) revealed by high-resolution seafloor mapping," Bull. Volcanol. **77** (3). 23–42 (2015). https://doi.org/10.1007/s00445-015-0905-3

D. Casas, A. Pimentel, J. Pacheco, et al., "Serreta 1998–2001 submarine volcanic eruption, offshore Terceira (Azores): characterization of the vent and inferences about the eruptive dynamics," J. Volcanol. Geotherm. Res. **356**, 127–140 (2018).

R. Casillas, C. Fernandez, J. R. Colmenero, et al., "Deformation structures associated with the Tazo landslide (La Gomera, Canary Islands)," Bull. Volcanol. **72** (8) 945–960 (2010). https://doi.org/10.1007/ s00445-010-0373-8

J. Coca, T. Ohde, A. Redondo, et al., "Deformation structures associated with the Tazo landslide (La Gomera, Canary Islands)," Bull. Volcanol. **72** (8), 945–960 (2010). https://doi.org/10.1080/01431161.2014.960613

A. C. G. Costa, *Mass-Wasting Episodes in the Geological Evolution of the Azores Islands: Timing, Recurrence, Mechanisms and Consequences*, These De Doctorat. Sciences De L'Univers (Universite Paris-Sud, 2014).

A. C. G. Costa, A. Hildenbrand, F. O. Marques, et al., "Catastrophic flank collapses and slumping in Pico Island during the last 130 Kyr (Pico-Faial Ridge, Azores Triple Junction)," J. Volcanol. Geotherm. Res. **302**, 33–46 (2015).

C. Criado and R. Paris, Volcanic Landscape and Geomorphological Evolution of Tenerife islands. Field Trip Guide-A2, 6th International Conference on Geomorphology: Geomorphology in Regions of Environmental Contrasts, Zaragoza, Spain, 2005 (Zaragoza, 2005).

B. Faria and J. F. B. D. Fonseca, "Investigating volcanic hazard in Cape Verde Islands through geophysical monitoring: network description and first results," Nat. Hazards Earth Syst. Sci. **14**, 485–499 (2014). https://doi.org/10.5194/nhess-14-485-2014

M. R. al Ferreira, "The volcanotectonic evolution of Flores Island, Azores (Portugal)," J. Volcanol. Geotherm. Res. **156** (Iss. 1–2), 90–102 (2006).

P. E. Fonseca, J. E. Madeira, S. N. Prada, et al., "Madeira Island preliminary geologicaldata andsatellite imagery analysis," In: EUROCK2002.Workshop on VolcanicRocks, Ed. by C. Dinis da Gama, L. Ribeiro e Sousa (Sociedade Portuguesa de Geotecnia, 2002), pp. 97–104.

Z. Franca, M. Lago, J. C. Nunes, et al., "Geochemistry of alkaline basalts of Corvo Island (Azores, Portugal): preliminary data," Geogaceta, No. **40**, 87–90 (2006).

Z. França, V. Forjaz, R. Tilling, et al., *Volcanic History of Pico and Faial islands, Azores. An overview* (Governo dos Açores, Secretaria Regional da Ciência, Tecnologia e Equipamentos, 2009).

T. Funck and H. -U. Schmincke, "Growth and destruction of Gran Canaria deduced from seismic reflection and bathymetric data," J. Geophys. Res. **103** (B7), 15393–15407 (1998).

M. J. R. Gee, A. B. Watts, D. G. Masson, et al., "Landslides and the evolution of El Hierro in the Canary Islands," Mar. Geol. **177**, 271–293 (2001).

H. Glicken, "Helens Volcano, Washington," U.S. Geol. Surv. Open File Report 96–677, (1996).

A. Hildenbrand, P. Madureira, F. O. Marques, et al., "Multi-stage evolution of a sub-aerial volcanic ridge over the last 1.3 Myr: S. Jorge Island, Azores Triple Junction," Earth Planet. Sci. Lett. **273**, 289–298 (2008).

A. Hildenbrand, F. O. Marques, and J. Catalao, Large–scale mass wasting on small volcanic islands revealed by the study of Flores Island (Azores), Sci. Repts. **8**, 13898

(2018).
https://doi.org/10.1038/s41598- 018-32253-0

E. Hildner, Magma Storage and Ascent of Historic and Prehistoric Eruptions of Fogo, Cape Verde Islands: A Barometric, Petrologic and Geochemical Approach, *Dissertation for the Doctorate Degree of the Department of Geosciences at the University of Bremen* (Bremen, 2011).

A. Hipólito, J. Madeira, R. Carmo, et al., "Neotectonics of Graciosa island (Azores): a contribution to seismic hazard assessment of a volcanic area in a complex geodynamic setting," Annal. Geophys. **56** (6), (2013).
https://doi.org/10.4401/ag-6222-S0677

J. E. Hunt, R. B. Wynn, D. G. Masson, et al., "Sedimentological and geochemical evidence for multistage failure of volcanic island landslides: A case study from Icod landslide on north Tenerife, Canary Islands," Geochem., Geophys., Geosyst. **12**, 1–36 (2011).
https://doi.org/10.1029/2011GC003740

J. E. Hunt, R. B. Wynn, P. J. Talling, et al., "Long-term (17 Ma) turbidite record of the timing and frequency of large flank collapses of the Canary Islands," Geochem., Geophysi., Geosyst. **15** (7), 2159–2181 (2014).
https://doi.org/10.1002/ggge.20138

J. E. Hunt, P. J. Talling, M. A. Clare, et al., "Multistage collapse of eight western Canary Island landslides in the last 1.5 Ma: Sedimentological and geochemical evidence from subunits in submarine flow deposits," Geochem., Geophys., Geosyst. **15** (8), 3322–3345 (2014).
https://doi.org/10.1002/2014GC005232

J. Karstens, K. Kelfoun, S. F. L. Watt, et al., "Combining 3D seismics, eyewitness accounts and numerical simulations to reconstruct the 1888 Ritter Island sector collapse and tsunami," Int. J. Earth Sci. **109**, 2659–2677 (2020).
https://doi.org/10.1007/s00531-020-01854-4

A. Klügel, T. R. Walter, S. Schwarz, et al., "Gravitational Spreading Causes En-Echelon Diking Along a Rift Zone of Madeira Archipelago: An Experimental Approach and Implications for Magma Transport," Bulletin of Volcanology **68** (1), 37–46 (2005).
https://doi.org/10.1007/s00445-005-0418-6

S. Krastel, H.-U. Schmincke, C. Jacobs, et al., "Submarine landslides around the Canary Islands," J. Geophys. Res. **106** (B3), 3977–3997 (2001).

S. Krastel and H. -U. Schmincke, "The channel between Gran Canaria and Tenerife: constructive processes and destructive events during the evolution of volcanic islands," Int. J. Earth Sci. (Geol. Rundsch.) **91** (4), 629–641 (2002).
https://doi.org/10.1007/s00531-002-0285-8

P. Larrea, C. Gale, T. Ubide, et al., "Magmatic Evolution of Graciosa (Azores, Portugal)," J. Petrol. **55** (11), 2125–2154 (2014).
https://doi.org/10.1093/ petrology/egu052

T. P. Le Bas, D. G. Masson, R. T. Holtom, et al.,
https://doi.org/10.1007/978- 1-4020-6512-5_35

P. Llanes, R. Herrera, M. Gomez, et al., "Geological evolution of the volcanic island La Gomera, Canary Islands, from analysis of its geomorphology," Mar. Geol. **264** (3–4), 123–139 (2009).
https://doi.org/10.1016/j.margeo.2009.05.001

J. Madeira, R. Ramalho, A. Hipolito, et al., "Urban risk from tsunami hazard at volcanic oceanic islands: examples from Macaronesia," Int. Conf. Urban Risks Lisbon, 1–8 (2016).

L. B. Marinoni and G. Pasquare, "Tectonic evolution of the emergent part of a volcanic ocean island: Lanzarote, Canary Islands," Tectonophysics **239** (1–4), 111–137 (1994).

R. Marques, P. Amaral, I. Araujo, et al., "Landslides on São Miguel Island (Azores): susceptibility analysis and validation of rupture zones using a bivariate GIS-based statistical approach," *Volcanic Geology of Sao Miguel Island (Azores Archipelago)*, Ed. by J. L. Gaspar, J. E. Guest, A. M. Duncan, F. J. A. S. Barriga, D. K. Chester, Geol. Soc. London. Mem. **44** (1), 167–184 (2015).
https://doi.org/10.1144/M44.13

F. Márques, A. Hildenbrand, A. Costa, et al., "The evolution of Santa Maria Island in the context of the Azores Triple Junction," Bull. Volcanol. **82** (6), 62 (2020).
https://doi.org/10.1007/s00445-020-01378-4.hal-030-04925

P. L. Márquez, The Magmatic Evolution of Graciosa and Corvo Oceanic Islands, Azores Archipelago, *PhD Thesis* (Universidad De Zaragoza. Departamento De Ciencias 2014).

D. G. Masson, T. P. Le Bas, I. Grevemeyer, et al., "Flank collapse and large-scale landsliding in the Cape Verde Islands, Off West Africa," Geochem., Geophys., Geosyst. **9** (7), 1–16 (2008).
https://doi.org/10.1029/2008GC001983

R. C. Mitchell-Thome, *Geology of the Middle Atlantic Islands* (Gebruder Borntrager, Berlin, Stuttgart, 1976).

S. Münn, T. R. Walter, and A. Klugel, "Gravitational spreading controls rift zones and flank instability on El Hierro, Canary Islands," Geol. Mag. **143** (3), 257–268 (2006).
https://doi.org/10.1017/ S0016756806002019

N. M. Perez, L. Somoza, P. A. Hernandez, et al., "Evidence from acoustic imaging for submarine volcanic activity in 2012 Off the west coast of El Hierro (Canary Islands, Spain)," Bull. Volcanol. **76** (12), 882–896 (2014).
https://doi.org/10.1007/s00445-014- 0882-y

F. J. Perez-Torrado, R. Paris, M. C. Cabrera, et al., "Tsunami Deposits Related To Flank Collapse in Oceanic Volcanoes: The Agaete Valley Evidence, Gran Canaria, Canary Islands," Mar. Geol. **227** (1–2), 135–149 (2006).

R. H. W. Romer, C. Beier, K. M. Haase, et al., "Correlated changes between volcanic structures and magma composition in the Faial Volcanic System, Azores," Front. Earth Sci. **6** (78), 23 (2018).
https://doi.org/10.3389/feart.2018.00078

R. Quartau, F. Tempera, N. C. Mitchell, et al., "Morphology of the Faial island shelf (Azores): the interplay between volcanic, erosional, depositional, tectonic and masswasting processes," Geochem., Geophys., Geosyst. **13** (4), 1–30 (2012).
https://doi.org/10.1029/2011GC003987

R. Quartau, J. Madeira, N. C. Mitchell, et al., "The insular shelves of the Faial-Pico Ridge (Azores Archipelago): a morphological record of its evolution," Geochem., Geophys., Geosyst. **16** (5), 1401–1420 (2015). https://doi.org/10.1002/2015GC005733

R. Quartau, R. S. Ramalho, J. Madeira, et al., "Gravitational, erosional and depositional processes on volcanic ocean islands: insights from the submarine morphology of Madeira Archipelago," Earth Planet. Sci. Lett. **482**, 288–299 (2018). https://doi.org/10.1016/j.epsl.2017.11.003

N. Richter, M. Favalli, E. Dalfsen, et al., "Lava flow hazard at Fogo Volcano, Cabo Verde, before and after the 2014-2015 eruption," Natural Hazards and Earth System Sciences **16** (8), 1925–1951 (2016). https://doi.org/10.5194/nhess-16-1925-2016

M. L. Ribeiro and M. M. Ramalho, A Geological Tour of the Archipelago of Madeira (Direccao Regional do Comercio, Industria e Energia, Laboratorio Nacional de Energia e Geologia, 2010).

R. Santos, R. Quartau, A. Brum Da Silveira, et al., "Gravitational, erosional, sedimentary and volcanic processes on the submarine environment of Selvagens Islands (Madeira Archipelago, Portugal)," Mar. Geol. **415**, 288–299 (2019).

A. L. R. Sibrant, F. O. Marques, and A. Hildenbrand, "Construction and destruction of a volcanic island developed inside an oceanic rift: Graciosa Island, Terceira Rift, Azores," J. Volcanol. Geotherm. Res. **284**, 32–45 (2014).

A. L. R. Sibrant, A. Hildenbrand, F. O. Marques, et al., "Volcano-Tectonic Evolution of the Santa Maria Island (Azores): Implications for Paleostress Evolution at the Western Eurasia-Nubia Plate Boundary," J. Volcanol. Geotherm. Res. **291**, 49–62 (2015).

R. Schmidt and H. -U. Schmincke, "From seamount to oceanic island, Porto Santo, Central East-Atlantic," Int. J. Earth Sci. (Geol. Rundsch.) **91**, 594–614 (2002). https://doi.org/10.1007/s00531-001-0243-x

H.-U. Schmincke and G. Graf, DECOS / OMEX II, Cruise No. 43, 25 November 1998–14 January 1999 (METEOR- Berichte, Universitat of Hamburg, 2000).

S. Schwarz, Magmatic and Volcanological Evolution of the Desertas Rift Zone (Madeira Archipelago, NE Atlantic), *Dissertation for the Doctorate Degree of the Department Geosciences at the Universaty of Bremen* (Bremen, 2004).

C. Steiner, A. Hobson, P. Favre, et al., "Mesozoic sequence of Fuerteventura (Canary Islands): witness of Early Jurassic sea-floor spreading in the Central Atlantic," GSA Bull. **110** (10), 1304–1317 (1998).

C. J. Stillman, "Giant Miocene landslides and the evolution of Fuerteventura, Canary Islands," J. Volcanol. Geotherm. Res. **94** (1–4), 89–104 (1999).

Tectonics and Magmatism of the Cape Verde Islands (Nauka, Moscow, 1990) [in Russian].

D. Trippanera, M. Porreca, J. Ruch, et al., "Relationships between tectonics and magmatism in a transtensive transform setting: an example from Faial Island (Azores, Portugal)," GSA Bull. **126** (1/2), 164–181 (2014).

S. M. Tsiogalos, Eruptive Dynamics and Petrological Evolution of Recent Volcanism on the El Hierro Island. Implications for Volcanic Hazard Sssessment, Thesis Dissertation for the Degree of Doctor of Philosophy (Universidad de Barcelona, Barcelona, 2017).

J. T. Vázquez, D. Palomino, O. Sanchez-Guillamon, et al., "Geomorphological characteristics of the passage of Lanzarote (east Canary Islands Region)," Resumenessobreel VIII Simposio, MIA15, Málaga, 2015 (Malaga, 2015), pp. 575–578. https://doi.org/10.13140/RG.2.1.1699.3766

F. Viveiros and V. Zanon, "Revisiting the subaerial AD 1580 and AD 1808 volcanic eruptions at Sao Jorge Island (Azores Archipelago, Portugal)," *20th EGU General Assembly, EGU2018, Proceedings from the Conference Held 4-13 April, 2018 In* (Vienna, Austria, 2018).

S. N. Ward and S. Day, "Ritter island volcano-lateral collapse and the tsunami of 1888," Geophys. J. Int. **154** (3), 891–902 (2003).

L. Ye, H. Kanamori, L. Rivera, et al., "The 22 December 2018 Tsunami from flank collapse of Anak Krakatau Volcano during eruption," Sci. Adv. **6** (3), 1–9 (2020).

N. Zitellini, L. A. Mendes, D. Cordoba, et al., "Source of 1755 Lisbon earthquake and tsunami investigated," Eos, Transactions, Am. Geophys. Union **82** (26), 290–291 (2001).

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