Research Plan

Disturbance of microfauna by marine intrusion of lava from the 2021 Cumbre Vieja volcanic eruption on La Palma, Canary Islands

Robert W. Schmieder
Cordell Expeditions

Rui Quartau
Instituto Hydrographico

Emilia Salgueiro
Instituto Portrugues

Sergio Avila
University dos Açores

ABSTRACT

This document describes a plan to investigate populations of benthic microfauna (foraminifera, mollusks) on La Palma Island, Canary Islands, in and around marine areas that experienced flowing molten lava during the 2021 volcanic eruption of the Cumbre Vieja volcano. The project goal is to obtain insights into the extent of sudden destruction of the community by the lava flow, and the eventual repopulation of the destroyed areas. In 2022, collections of sediment were made by the Consorcio Plataforma Oceánica de Canarias (PLOCAN) and University of Las Palmas de Gran Canaria (ULPGC) in areas of lava flow into the near offshore due to the 2021 eruption of the Cumbre Vieja volcano. We plan to obtain small samples of these collections and analyze them for the microfauna (sizes ca. 0.1-3 mm). In addition to taxonomic identifications, we will generate various statistical measures to show various properties of the microfauna populations.

This version:
19 Dec 2023

Cordell Expeditions • 4295 Walnut Blvd • Walnut Creek, CA 94596
(925) 934-3735 • info@cordell.org • www.cordell.org

CONTENTS

INTRODUCTION

On 19 Sep 2021, a volcano on La Palma Island, one of the Canary Islands, suddenly erupted, generating large amounts of molten lava that flowed directly through densely populated areas and to the coast. While there were no human fatalities, the lava buried more than 10 km^2 of land, destroying 2000+ homes.

The consequences to the environment in the path of the lava were, of course, catastrophic. Everything that was covered by the molten lava simply disappeared, including all living organisms. But the devastation was more widespread than the lava itself: the heat from the melted rocks caused large amounts of seawater to explosively boil, locally killing entire communities. Further away, the effects of the hot water were less, perhaps selectively killing some parts of the communities while other parts survived. We will refer to this process as “depopulation”.

Once the eruption had ceased (Dec. 2021), the lava cooled, solidified, and the nearby communities began to move into areas of solidified lava, a process termed “repopulation” (on land it is referred to as “ecological succession”). This process can take many years, and it will be inhomogeneous: the return of some species will be faster than others. It might take 10-50 years to return to the pre-eruption communities, and some populations may never recover.

In spite of the devastation, the 2021 eruption on La Palma provides a rare opportunity to learn more about the process of community devastation and repopulation. This document outlines a PLAN to investigate the initial stages of this process (the first few years of the recovery) by characterizing microfauna in the vicinity of the new land created during the eruption.

FIG. 1 – The eruption on La Palma Island, Canary Islands, Sept. 2021.

LA PALMA ISLAND

The Canary Islands

The Canaries is a group of seven islands belonging to Spain. They lie 100 - 450 km west of the Morocco/Western Sahara coastline. The group trends east-west. (**FIG. 2**). The islands are the southernmost region of Spain, and the largest and most populous archipelago of Macaronesia. Because of their locations, the Canary Islands have historically been considered a link between the four continents of Africa, Europe, North America, and South America. In 2019, the Canary Islands had a population of 2,153,389.

The Islands originated as separate submarine seamount volcanoes on the floor of the Atlantic Ocean. Each seamount, built up by the eruption of many lava flows, eventually became an island. Subaerial volcanic eruptions continued on each island. The largest island of the group, Tenerife, rises about 3,780 m above the ocean floor and 3,715 m above sea level. It supports nearly 1 million inhabitants. It has 15 telescopes on its highest peaks (2423 m ASL).

FIG. 2 shows the location of the Canary Islands.

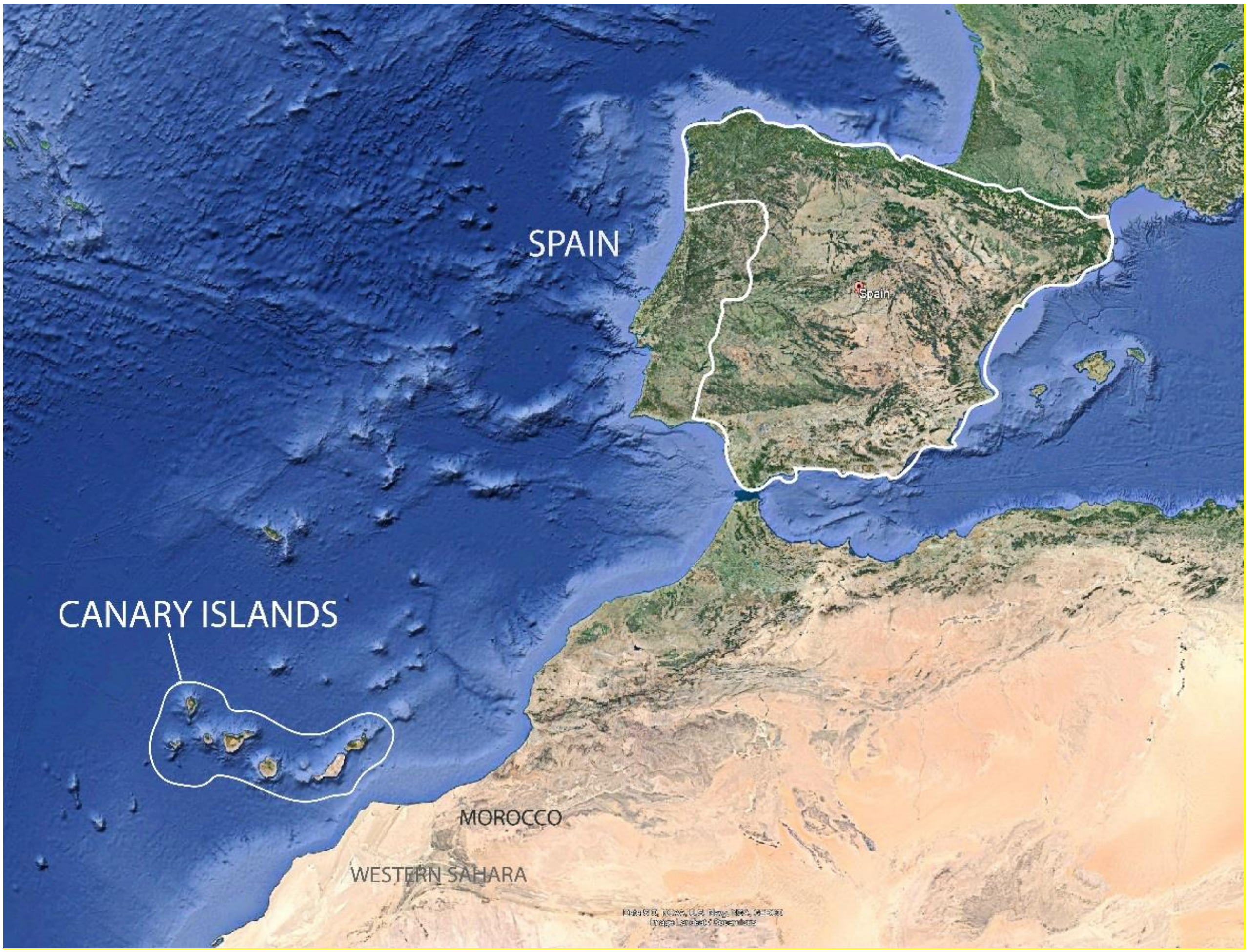


FIG. 2 - The Canary Islands, part of Spain.

La Palma Island

The present PLAN concerns La Palma Island, the northwesternmost of the Canary group, at 28°37’ N 17°56’ W. The island is 42 km long, and 24 km wide. It has an area of 708 km^2. Its highest elevation is 2426 m. Its population is nearly 90,000 (as of 2021). The island has 15 beaches and coves, which are well-known for the sunshine.

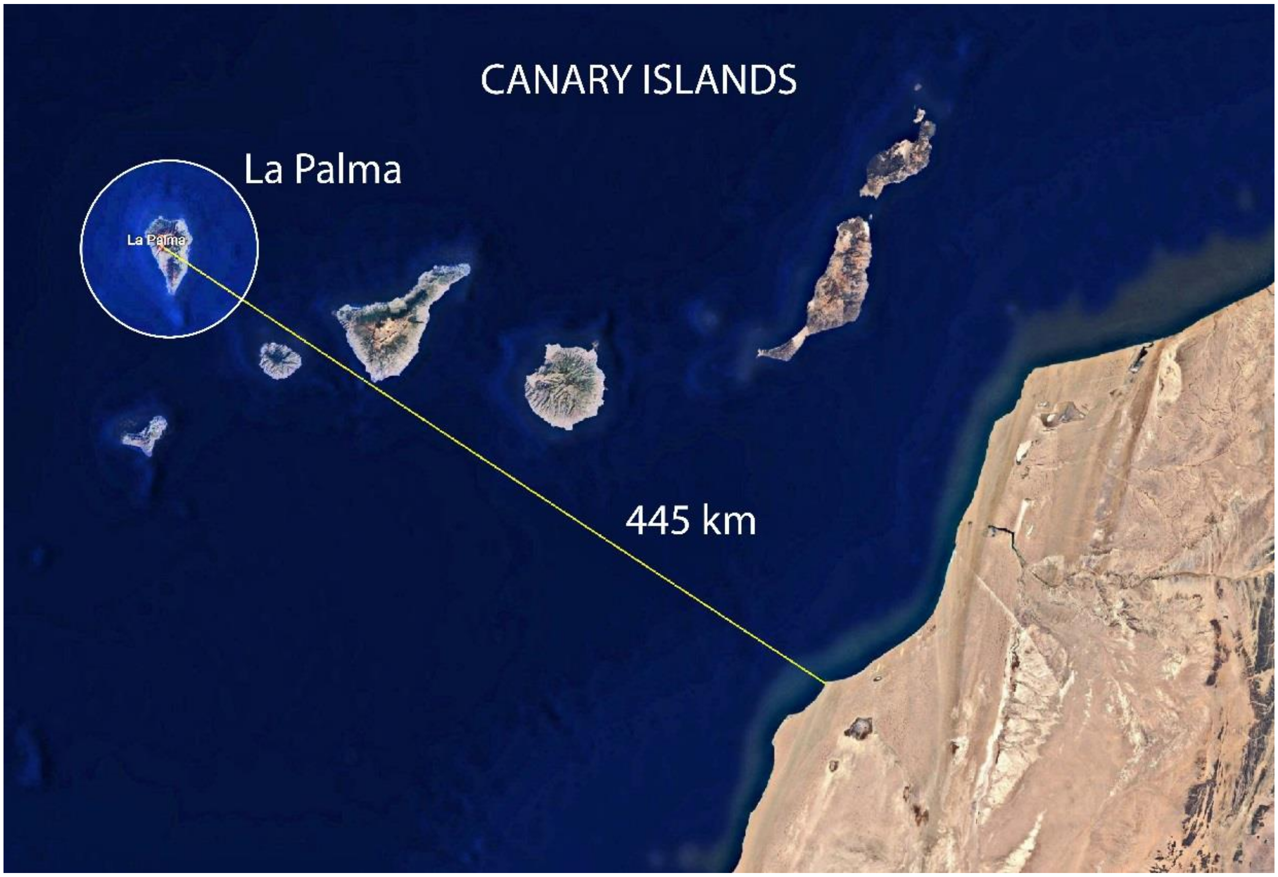


Fig. 3 – La Palma lies 445 km from the western African coast.

La Palma is currently the most volcanically active of the Canary Islands. The southern part of La Palma consists of the Cumbre Vieja, a volcanic ridge formed by numerous volcanic cones built of lava and scoria. Since the Spanish have kept records, there have been eight eruptions on the Cumbre Vieja:

1470–1492 Montaña Quemada
1585 Tajuya near El Paso
1646 Volcán Martín
1677 Volcán San Antonio
1712 El Charco
1949 Volcán San Juan: Duraznero, Hoyo Negro and Llano del Banco vents
1971 Volcán Teneguía
2021 Cumbre Vieja

It is the last of these, in September 2021, that motivates this project.

Fig. 4 – Satellite view of La Palma.

FIG. 5 – Civil view of La Palma.

La Palma Island before the 2021 eruption

FIGs. 6,7 show the area around Tazacorte, on the western side of La Palma, *before* the 2021 eruption of Cumbre Vieja volcano. The area is extensively occupied by houses and industry. Two small (and old) volcanic cones are prominent. The Cumbre Vieja ridge, from which the 2021 eruption emanated, appears rising in the distance.

FIG. 6 –Views of the area around Tazacorte on the west coast of La Palma before the eruption.

FIG. 7 – The western coastline of La Palma before the eruption. (**Upper**) A local village surrounded by banana orchards. (**Lower**) View of the beaches and the marina from the north, looking south.

The 2021 eruption

The volcano

At 14:13 UTC on 19 September 2021 a crack opened in the Cumbre Vieja ridge, throwing plumes of ash and lava into the air. Lava flowed down the mountain and through villages, engulfing everything in its path. By 28 September, the 6-km lava flow had reached the island's west coast. Clouds of white steam were reported where the red-hot lava hit the water in the Playa Nueva area.

FIG. 8 shows the eruption above the Tazacorte area.

FIG. 8 - The volcano erupts, 19 September 2021.

Flow of lava across the land

The lava flow, moving downhill, made a mildly meandering path toward the coastline, passing through major populated areas on the way. Its speed, at first 700 m/hr, eventually slowed to 30 m/hr. Officials made predictions for the speed and path of the flow and warned that toxic gases would be released when it reached the sea. The predictions were borne out a few days later.

FIG. 9 – Initially, the lava flowed down the most direct route, a distance of some 8 km. Eventually it hardened, forcing the flow to spread laterally by up to 3 km, covering an area of 12 km^2.

FIG. 10 – Location and extent of the lava flow near the end of the eruption.

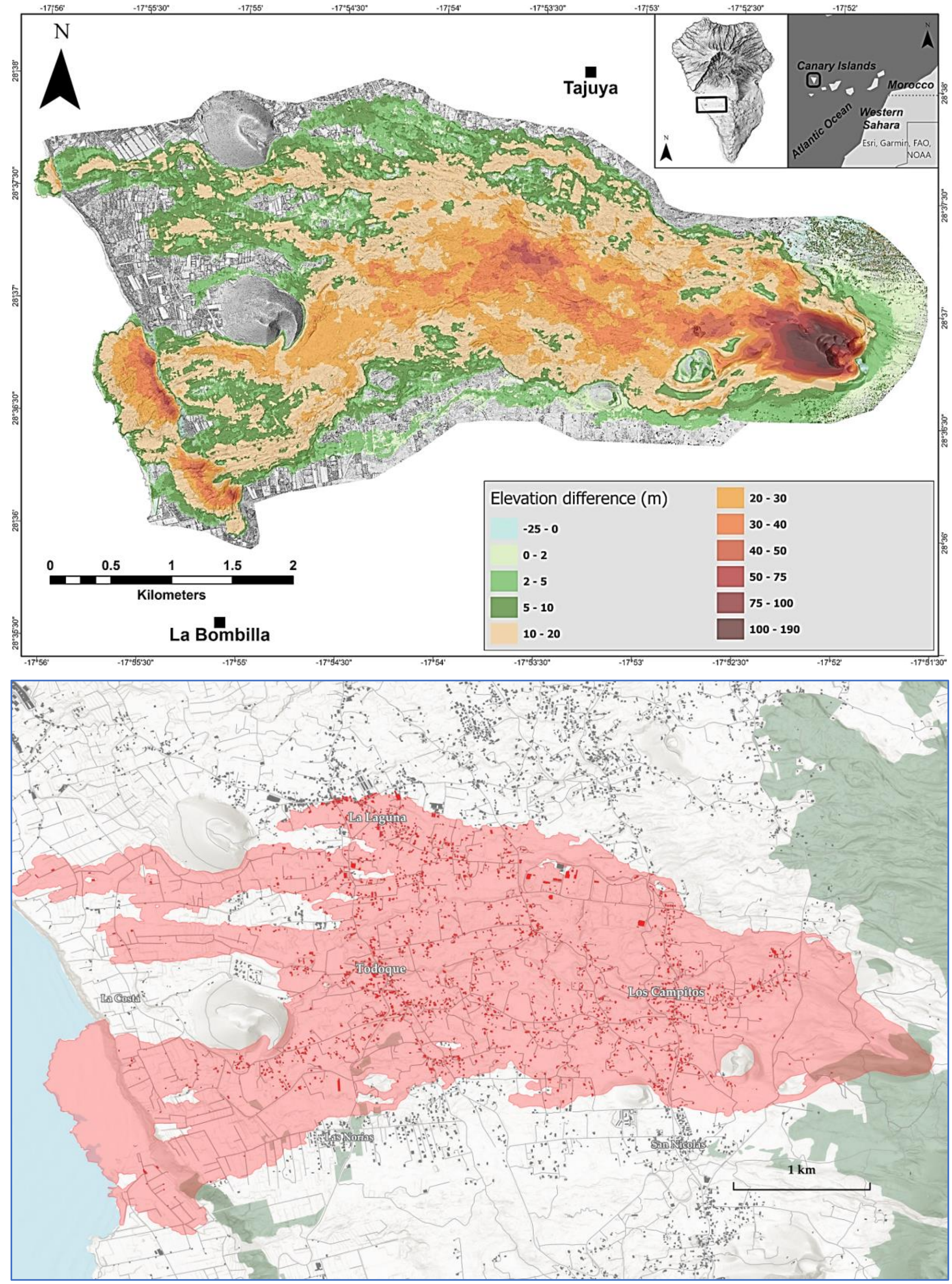


FIG. 11 – Detailed maps of the lava flow at the end of the eruption. (**Upper**) Topographic elevation change. (**Lower**) Area of near total destruction.

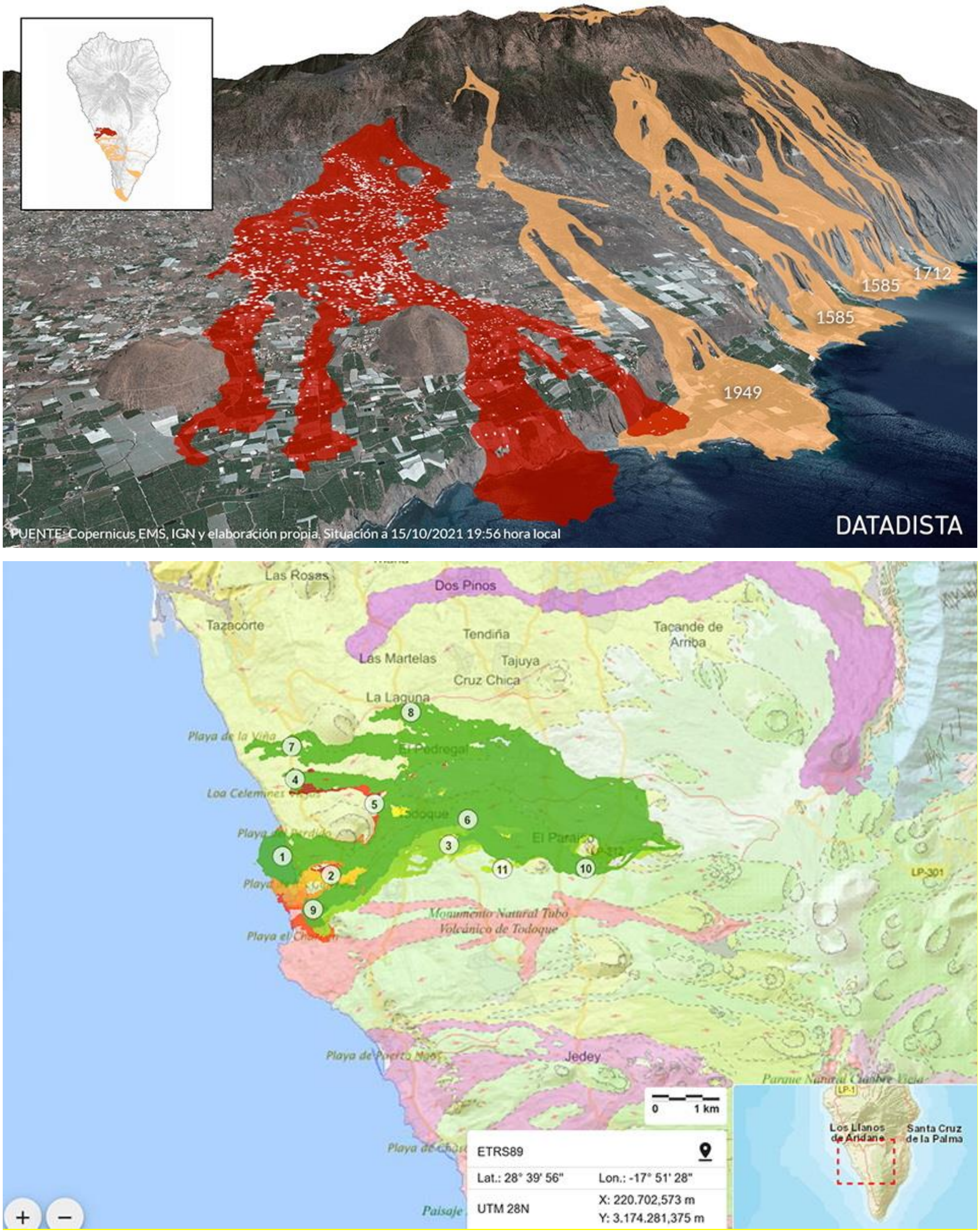


FIG. 12 – Historical eruptions and lava flows. (**Upper**) The 2021 eruption was similar to eruptions in 1712, 1585, and 1949 (right to left). (**Lower**) Overhead view of historical eruptions and lava flows. The green area is from 2021.

FIG. 13 – (**Upper**) Lava destroyed more than 2000 buildings. (**Lower**) This house was spared destruction but was left surrounded by high lava walls.

Flow of lava into the sea

On Sep. 28, 2021, at around 11:02 PM local time, the lava flow reached the sea at the Beach of Los Guirres, also called New Beach, in the municipality of Tazacorte. As the lava flowed into the sea it created a new delta, a roughly circular platform. As of Sep. 30, it measured 49 acres in area, and it continued to grow. By Oct. 2, it had grown to 68 acres. On 10 November, a second lava flow reached the sea. Not surprisingly, all the new land was claimed by the Spanish Government. **FIG. 14** shows the flow of the lava to the sea.

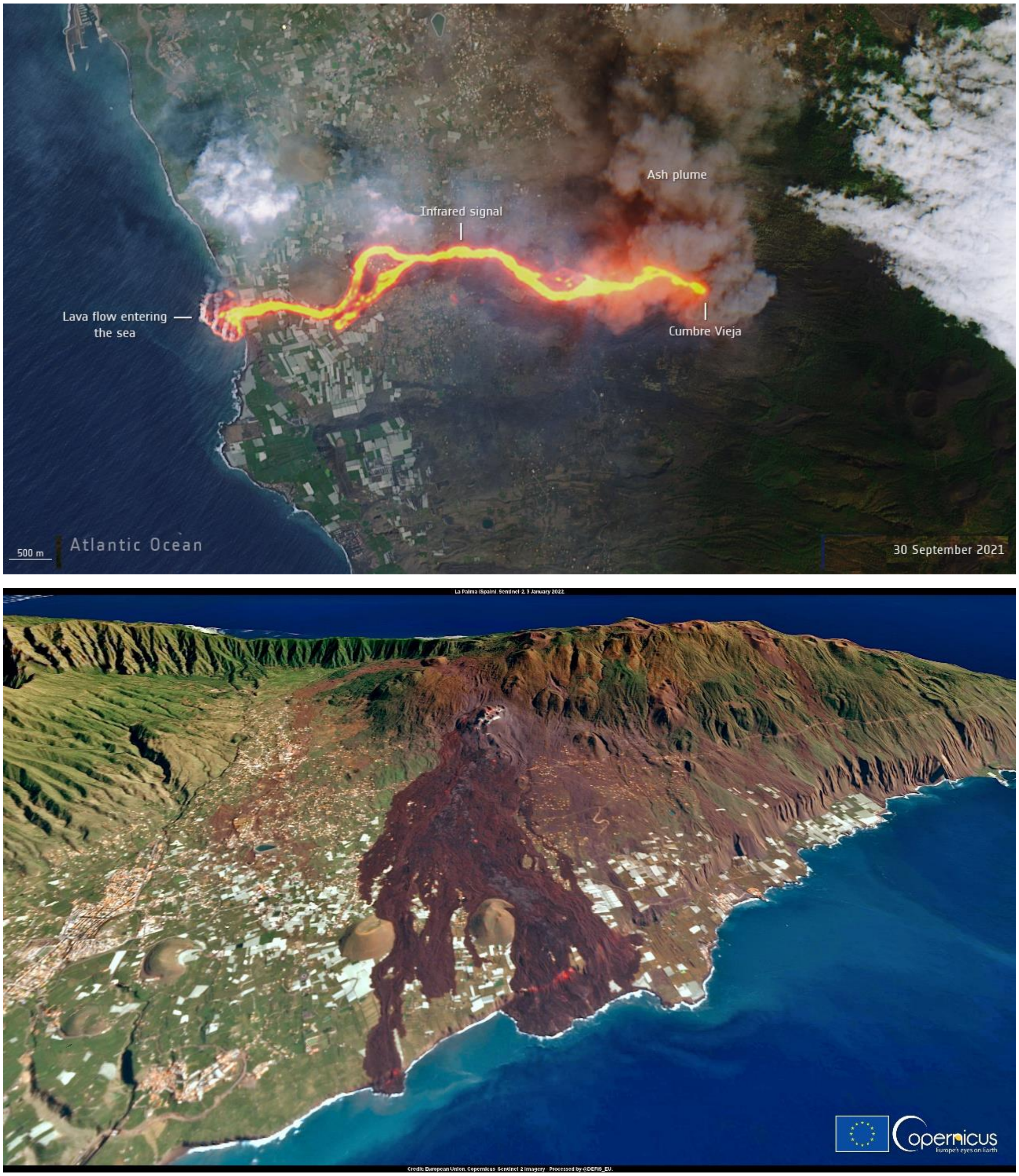


FIG. 14 – (**Upper**) The lava flows inexorably down the slope to the sea. (**Lower**) The lava cascades over the edge of the sea cliff and begins to build new land as it hardens.

FIG. 15–Only 10 days after the first eruption, the lava had passed through the town, skirted the small cone, and drained into the ocean, hardening into a new peninsula. During the next three months, the lava continued to ooze downslope, widening the area of devastation, and spilling into the ocean at several additional places.

Lava and seawater

As the molten lava approached the coastline, residents became aware of a different danger: generation of large amounts of toxic gases and vapors. The temperature of the lava is more than 1,000°C; when it hits cool sea water it creates a thermal shock that vaporizes the seawater and drives chemical reactions. Large quantities of clouds are released that contain sulfuric, hydrochloric, and hydrofluoric acid, which can cause skin irritation and breathing difficulties. If that weren't enough, the clouds can contain fine glass particles. The term used to refer to this material is "laze". **FIG. 16** show photographs of the plume on La Palma, and a similar plume in Hawaii in 2018.

FIG. 16 – As the molten lava enters the ocean, huge clouds of steam and toxic gases are released. (**Upper**) La Palma 2021. (**Lower**) Hawaii 2018.

New land from lava

As the lava entered the ocean, it cooled and solidified, spreading out into a roughly semicircular platform about 500 m across. As the flow continued over the next several weeks, the platform took on a more rectangular shape: about 0.5 km x 1.0 km.

FIGs. 17-19 show the new land being accumulated by the continued flow of lava.

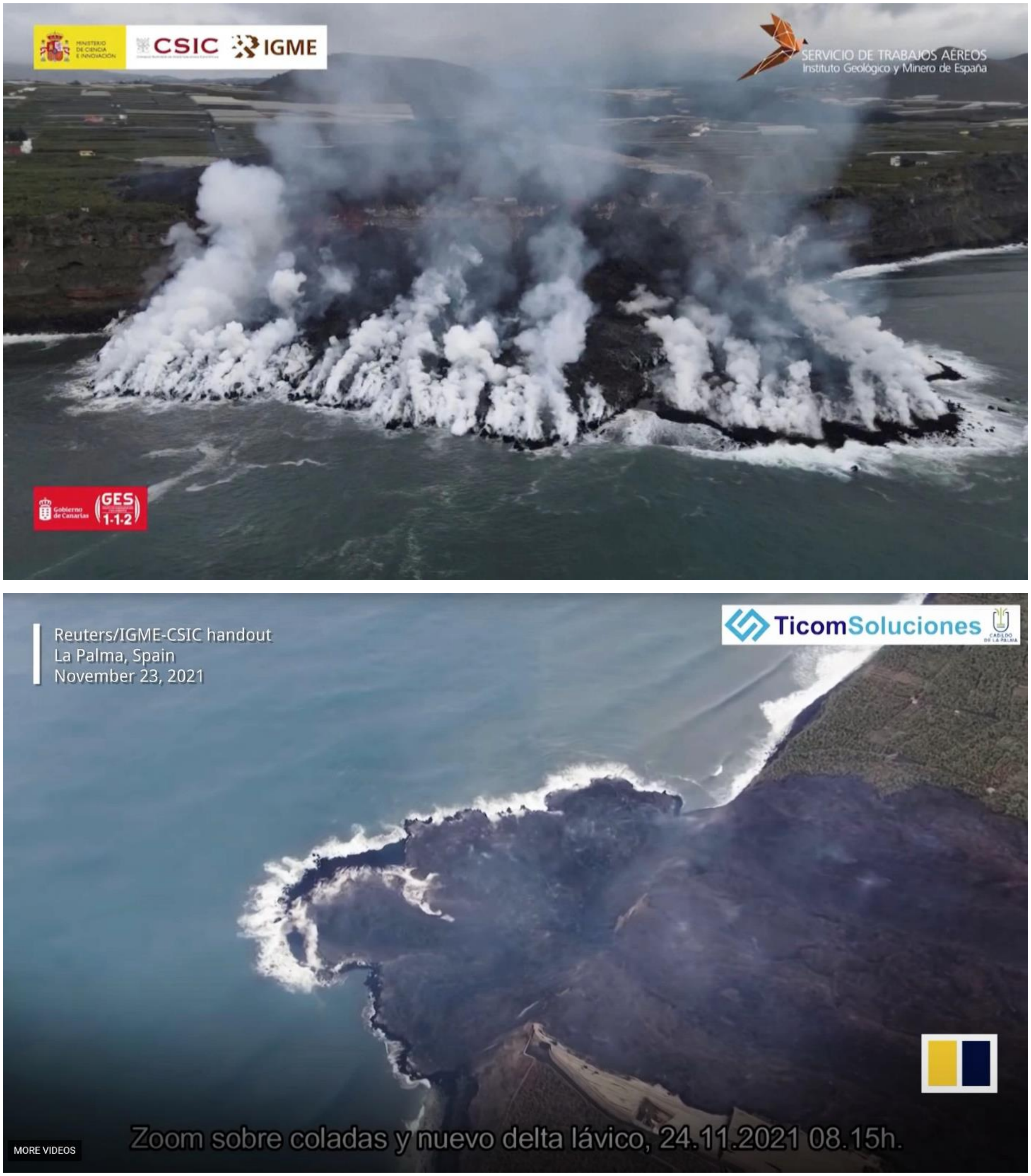


FIG. 17 –Lava enters the ocean and begins to harden, forming a solid peninsula.

FIG. 18 – Local hotspots continue to smoke, but eventually the deposit cools and hardens into rock. Our interest is in the marine microfauna in the vicinity of the new peninsula.

FIG. 19- (**Upper, looking east**) The flow on 13 Dec. 2021, near the end of the eruption. (**Lower, looking south**) The final deposits after the eruption ceased. Some new roadways cut across the lava are visible.

LITTORAL MICROFAUNA

This PLAN is based on sampling two classes of microscopic organisms: foraminifera and gastropods. Here we review briefly these two classes.

Foraminifera (“forams”) are a class of single-celled organisms characterized by streaming granular ectoplasm for catching food, movement, and other uses. Typically, they are microscopic (ca. 0.01-1.0 mm), and are almost exclusively marine, living in the water column (“planktonic”) or on the seafloor in fine sediment (“benthic”). Most foraminifera synthesize a shell (called a “test”) that can have multiple chambers with openings (“foramen”) between adjacent chambers. There are more than 60,000 named species of foraminifera; they are found worldwide, including in the waters around the Canary Islands.

Mollusks are also a class of invertebrates, but unlike foraminifera, they are multi-cellular. Many mollusks grow to fist-sized or larger, but a significant number of species are microscopic (0.3-3 mm). Most mollusks synthesize a calcium carbonate shell, and most of those are spiral and spired (tall, with low angle). Marine mollusks typically live in sediment, hence are benthic. Most mollusks are right-handed spirals (gastropods): they grow clockwise when viewed from above. Another group is the bivalves. Mollusks occur in all habitats worldwide, comprising more than 65,000 named species.

FIG. 20 shows microscope images of typical foraminifera and gastropods. These collections are from Terceira Island in the Azores. Most of the La Palma specimens will be species different from those shown here.

FIG. 20 – Typical microfauna found in the Eastern Atlantic. (**Left**) Foraminifera. (**Right**) Gastropods. These specimens were collected on Terceira Island, Azores, in 2022.

Volcanic intrusion

FIG. 21 shows a schematic of the process of intrusion of molten lava onto a marine shelf. Three successive flow events are shown, originating from higher elevation, and pouring over the edge of the previous flows. The curves plotted below the cross sections are the relative abundances of three species having three different distributions as a function of distance from the shoreline/last lava flow.

The last panel (after three lava flows) suggests that the populations might be starting to return to their distributions before the flows, but possibly with changed horizontal scaling. That is, one species might be more aggressive in reestablishing its natural distribution, whereas another species might be slower. In the absence of other changes in the environment over times comparable to repopulation, it is an assumption that at very long times, e.g., 100 years, the populations will have distributions similar to those before the lava flows occurred but displaced further offshore. However, to the extent that the original seafloor was altered by the lava flow, it may never return to its previous composition.

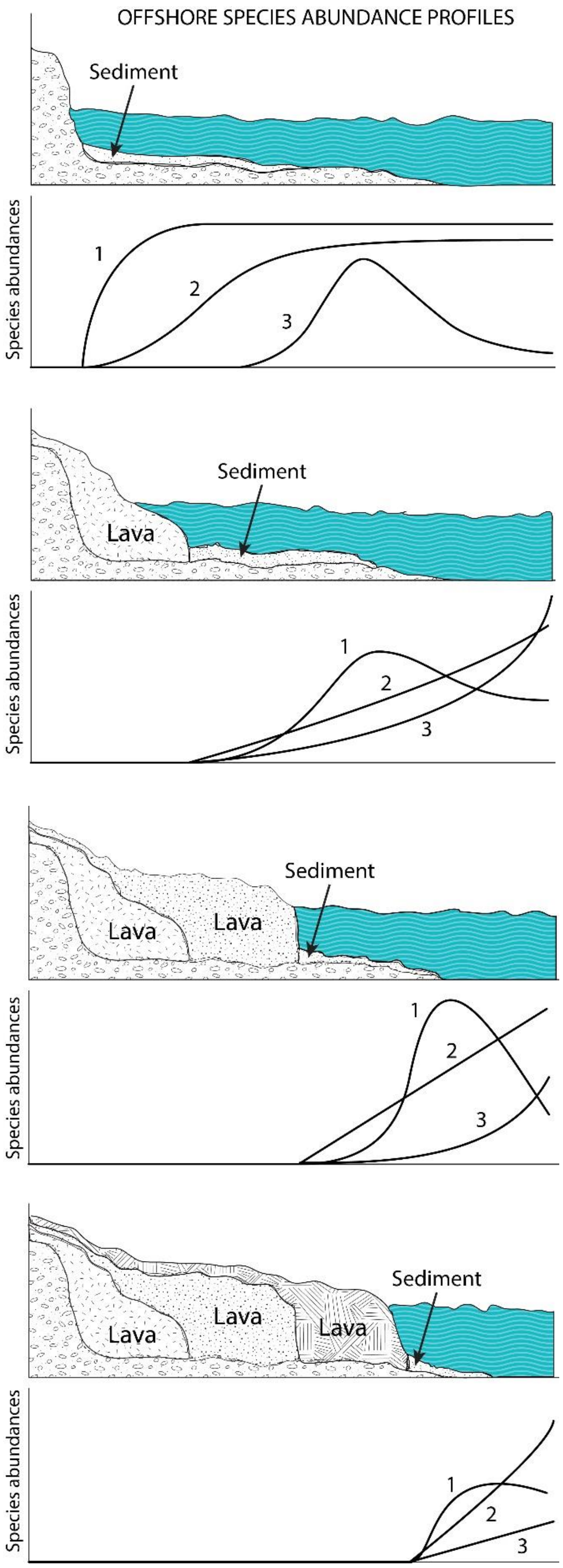


FIG. 21 – Intrusion of flowing lava into the marine environment, including relative populations of three species as a function of distance from the shoreline.

Repopulation

In the Azores, the most recent eruption was at Caplinhos on Faial Island in 1956, almost 70 years ago, so the area around that lava flow probably is now back to equilibrium, or nearly so. In contrast, the eruption on La Palma is (as of this writing) just over 2 years old.

FIG. 22 shows our strategy for observing the repopulation of the La Palma coastline. collections will be made at intervals of 1 or 2 years at first, and later at larger intervals, at the same locations, and the same analysis will be done, enabling comparison of changes. We hope to get photographic records of the bottom in the area being sampled, to enable incorporating environmental changes in the population measurements.

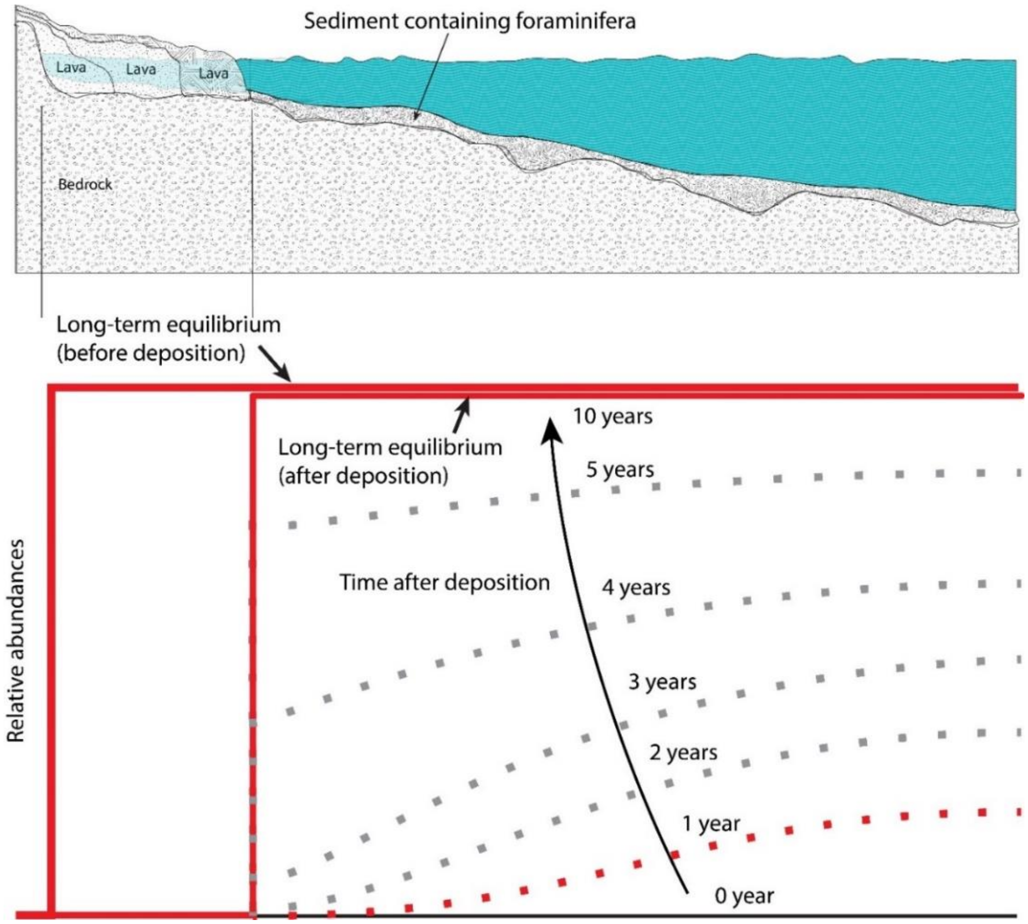


FIG. 22 –Repopulation in the vicinity of a lava flow.

THE 2023 FIELD WORK

Area of the fieldwork

FIG. 23 shows a nominal boundary for the highest priority fieldwork. The area within the red boundary includes areas adjacent to the new land (lava flow) and areas further away. The collections made by PLOCAN and the ULPGC covered this area, plus a large adjacent area.

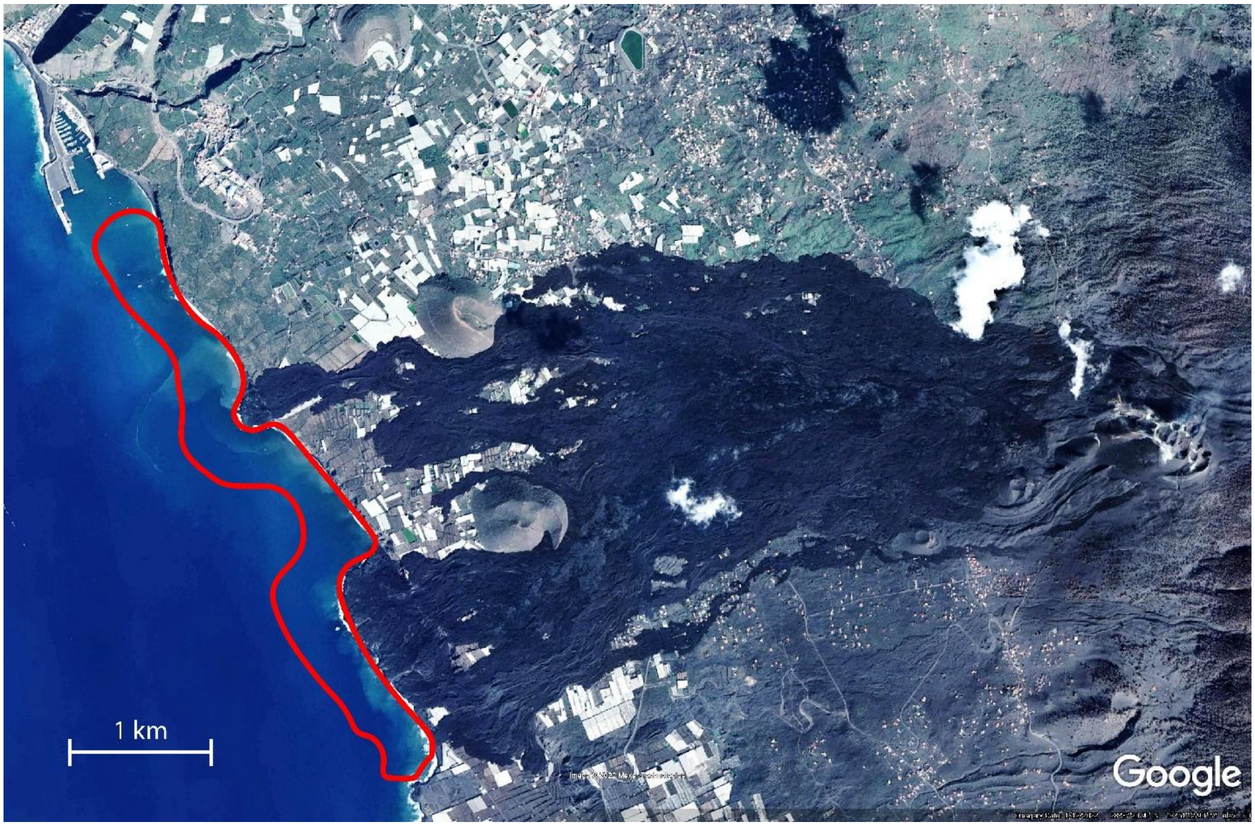
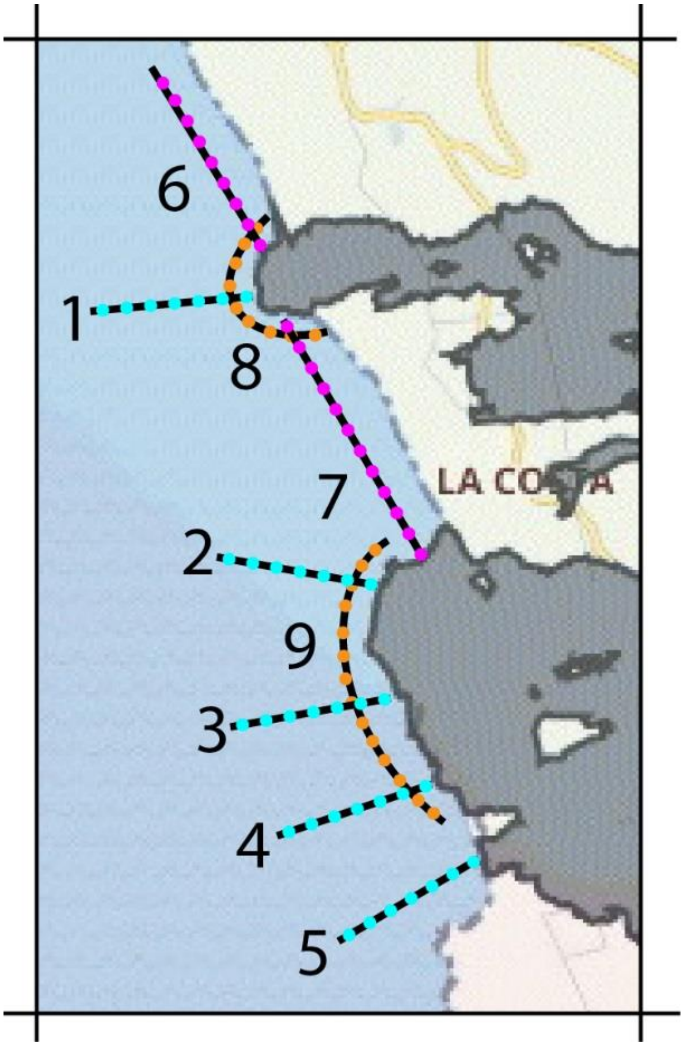


FIG. 23 –The area of interest for investigating microfauna in the vicinity of the lava intrusion into the marine environment.

The width of the study area above is about 300 m. **Appendix 1** gives the calculation of this width as an estimate of the distance from the molten lava that the benthic communities would be totally destroyed.

Collection locations

FIG. 24 shows a conceptual plan for the collections. In fact, the PLOCAN and ULPGC collections, carried out before the authors were aware of them, extend over a much larger area.



RADIALS
  1 North
  2 Central north
  3 Central middle
  4 Central south
  5 South
PARALLELS
  6 North
  7 Central
PERIMETERS
  8 North
  9 Central

FIG. 24 – An initial plan for investigation of the area around the 2021 lava deposition.

FIG. 25 shows hypothetical profiles for the nine transects of **FIG. 24**. These profiles are meant to represent only one sampling time.

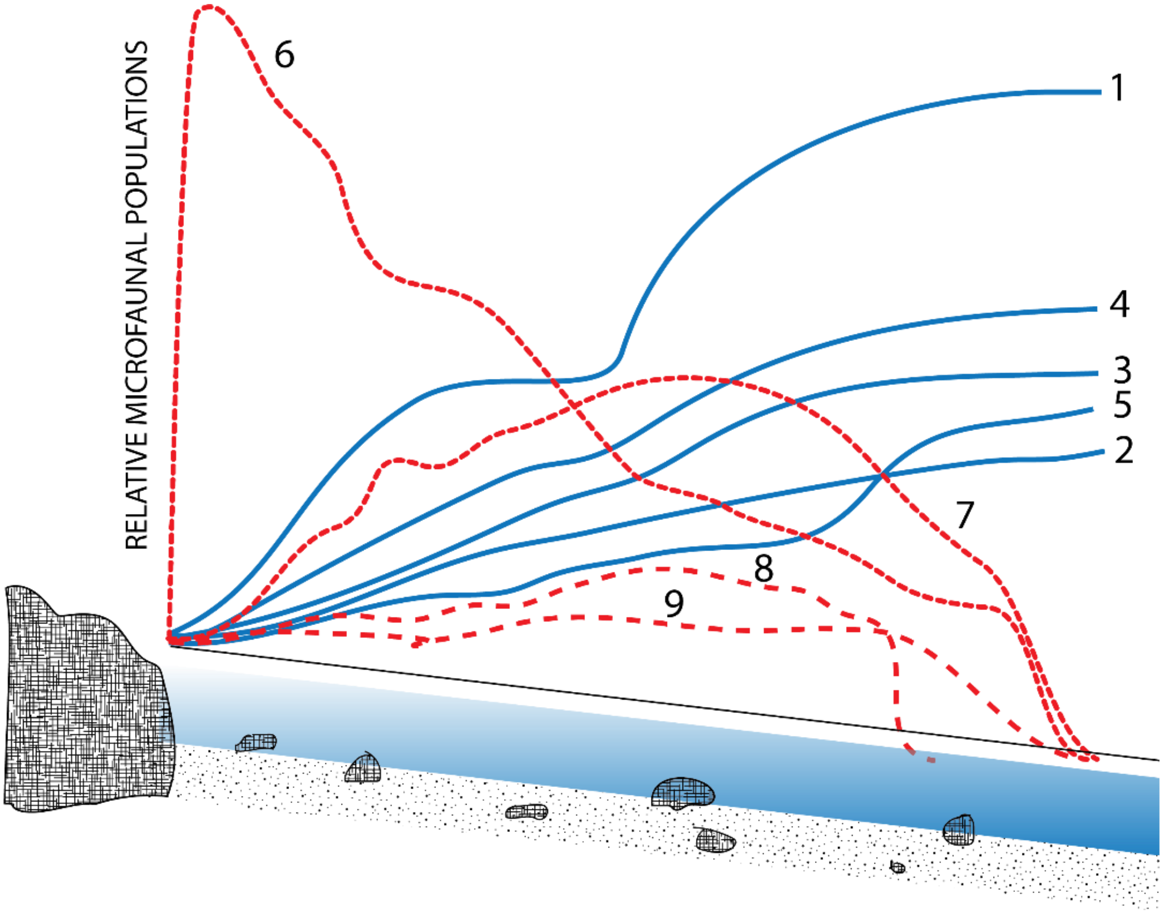


FIG. 25 – Hypothetical profiles of the transects shown in **FIG. 24**.

Collection procedure

Note: This page was part of he original PLAN for obtaining collections by diving. The existence of the PLOCAN/ULPGC collections, unknown to us at the time, makes the diving unnecessary; this page is included for general reference.

The samples will be obtained by divers using pre-labeled plastic specimen bottles. **FIG. 26** shows the concept for sampling in the vicinity of a lava flow (for simplicity the seabed is sown level). The location of each collection will be recorded with a GPS. The area around each collection will be photographed by the divers.

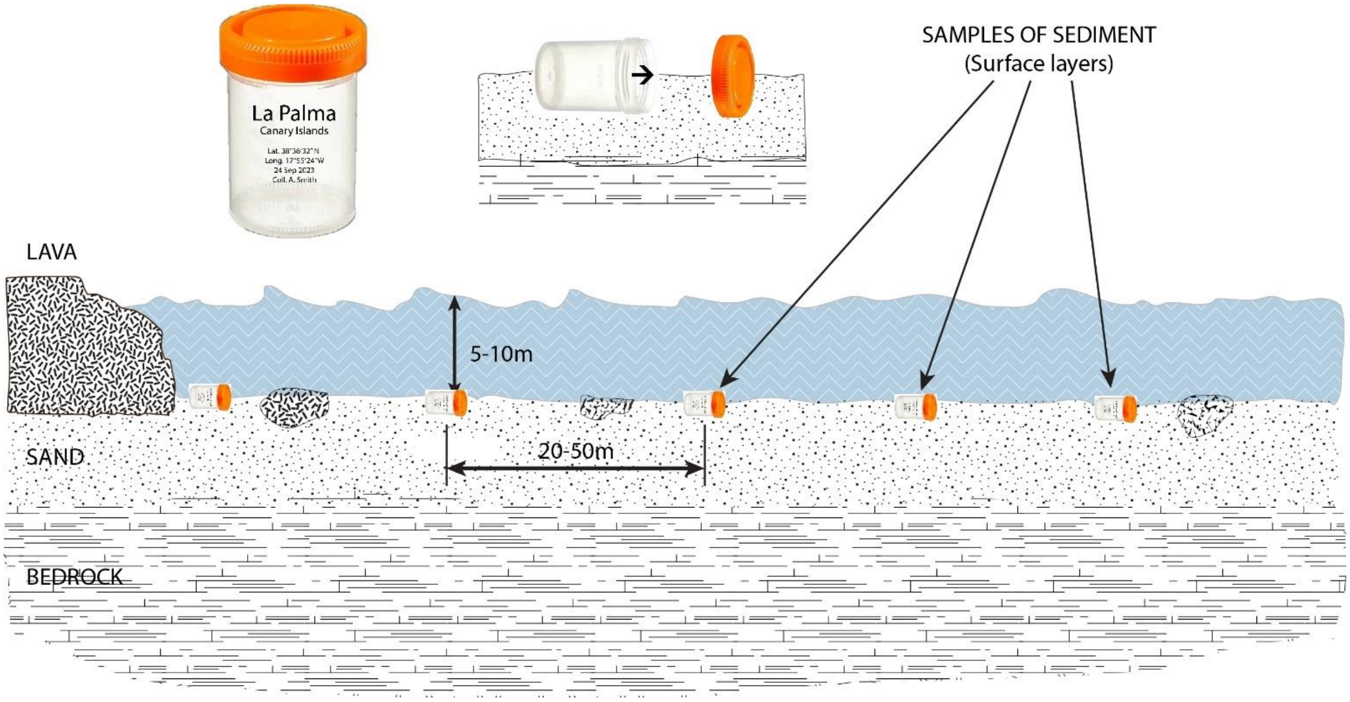


FIG. 26 –Proposed geometry of the collection sites.

The collections will be air dried and repackaged in sterile specimen bottles and transported personally by the PI to the lab in California.

The individual collections will be separated by sieving with the following meshes: #5 (4000µm), #10 (2000µm), #35 (500µm), #60 (250µm), #120 (125µm), #230 (63µm). A splitter will be used to obtain subcollections of about 1 cm^3. A preliminary microscopic examination will be made of each size fraction to determine the general nature of the sediment.

Processing

The PLOCAN/UNLGC collections will be processed according to the following procedure:

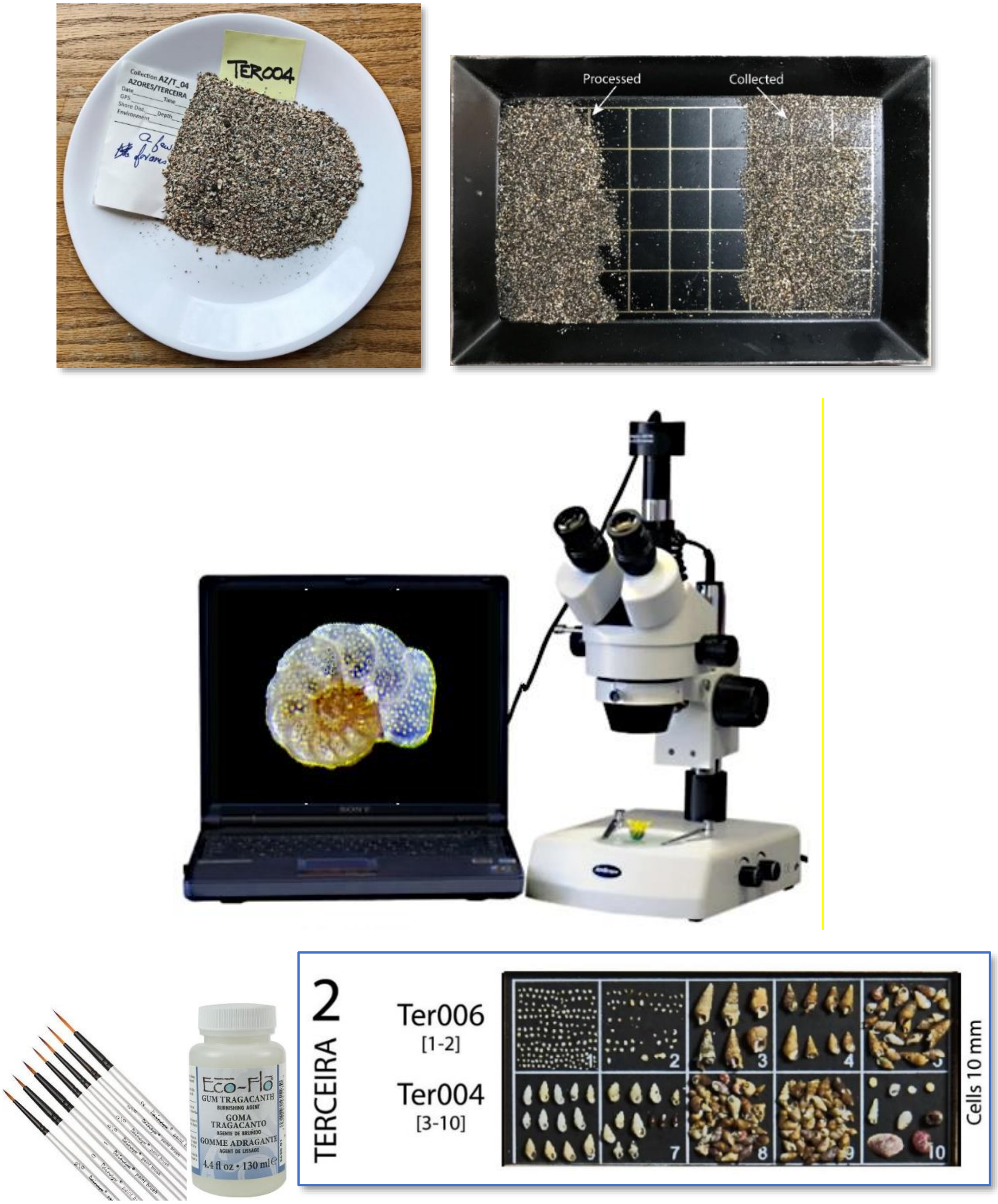


FIG. 27 –The tools for extracting individual microfauna from the sediment: microscope, picking tray, brushes, and the slide on which the picked specimens have been glued. On the slide pictured above there are both foraminifera (cells 1,2) and gastropods (cells 3-9). Cell 10 contains exceptional (and unidentified) specimens.

STATISTICAL ANALYSIS

We reiterate that this project will divide the collections into two classes: Foraminifera and molluscs (the latter mostly gastropods). The reasons for this are discussed in detail in Schmieder and Lima (2023). The central reason for this rather violent neglect of finer taxonomic boundaries (species, genera, etc.) is that the collections are going to be severely limited in number and in size. It was argued by Schmieder and Lima that in spite of this limitation, useful geographic and ecological information can be extracted from such "lumped-taxa" collections.

In this section we use examples from the paper by Schmieder and Lima to illustrate the kind of results expected from the present project.

Sand grain size

As an example, **FIG. 28** shows the observed dependence of the number of forams and gastropods in four of the six collections from Terceira, together with a model-dependent plot of the predicted functions. These dependencies are (apparently) due to size-dependent collisions with sand grains.

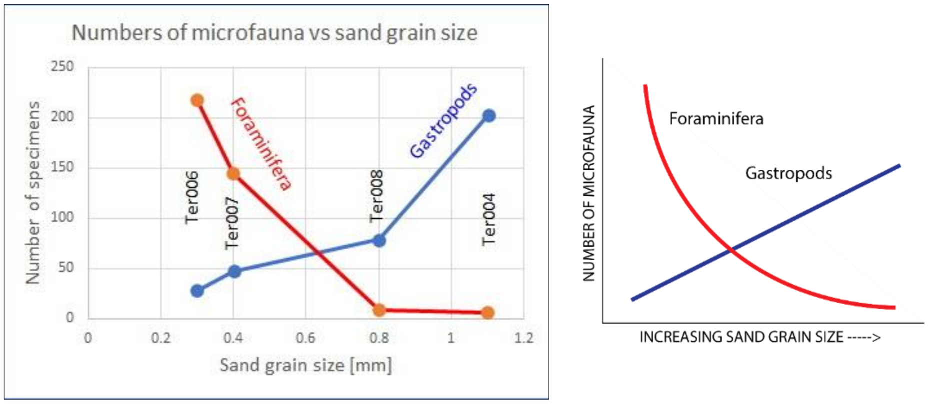


FIG. 28 – Relative numbers of microfauna from Terceira Island. (**Left**) Observed in four collections. (**Right**) Model-predicted dependence.

Magnetic fractions

Another example is the magnetic fraction of sand grains in the Terceira collections (**FIG. 29**). While we do not believe that the magnetic properties of the grains affect their mechanical properties, the image clearly shows the major differences in their size and structure. Thus, it is not unreasonable to believe that the two kinds of grains would have different collisional effects on the microfauna, and therefore would affect the distributions of forams and gastropods.

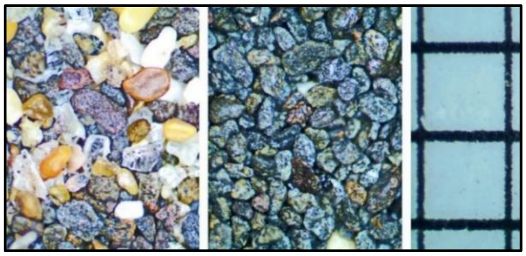


FIG. 29 –Images of the nonmagnetic (**left**) and magnetic (**right**) sand grains. Terceira collection **Ter006**. Grid 1 mm.

CURRENT STATUS (DECEMBER 2023)

Contacts were made with PLOCAN during early/mid 2023. In September 2023, the principal author (RWS) made a trip to La Palma to interact with the officials at PLOCAN/ULPGC, in particular Mariona Casamayor and colleagues. At that time, it was indicated that we might be able to acquire small samples of the sediment collections from 2022, but that we will need to interact with the University personnel to make the arrangements.

Currently, we are hoping to complete a meeting with the ULPGC personnel to make the arrangements for selection of the samples and their shipment to RWS. We are prepared to cover reasonable and appropriate expenses, if that is required, although we have no separate budget for this project.

During the execution of the project, we will keep PLOCAN/ULPGC personnel apprised of our progress, and especially of any discoveries made. We will produce a comprehensive Report documenting all aspects of the project.

APPENDICES

We include here a few excerpts and comments from published work on the effects of lava intruding into the marine environment, and the long-term recovery of the microfauna populations.

Appendix 1 - Determination of the study area

Boundary. Here we make an estimate of the area to be sampled. We do this by calculating how much seawater was boiled by the lava flowing off the cliff using the specific heats of lava and of water. Oddsson, et al., (2016) made a detailed study of lava-ice interactions, which has many similarities to lava-water interactions. In particular, they assumed that the lava has a heat capacity of 1.0 kJ kg^{-1} K^{-1}, while that for water is about 4 kJ kg^{-1} K^{-1} (about four times as large as lava). If we assume that the volume of the solidified platform is about 0.5x1.0x0.1 km^3 = 0.05 km^3, the heat contained in the platform was able to boil (1/4) 0.05 km^3 $\approx$ 0.01 km^3 = 10^7 m^3 of ocean water (neglecting radiation into the atmosphere and other loss mechanisms). If we assume that the water was 10 m deep, the heat from the lava could boil an area of 1 km^2. We assume that boiling water will kill all the microfauna. Since the platform has an area of 0.5 km^2, there is 0.5 km^3 of boiling water. If we distribute this area around the periphery of the 0.5 x 0.5 km^2 platform with width **w**, we find the relation $\mathbf{w}^2 + 0.5\,\mathbf{w} - 0.25=0$, for which the solution is **w**=0.3 km = 300 m. Thus, we estimate that we should sample some 300 m outward from the edge of the lava platform. A sensible strategy would be to make 10 collections 30 m apart along radial transect lines out to a distance of 300 m, and this is illustrated in **FIG. 24**.

Expansion. It may well happen that the area of volcanic disturbance was much greater. **FIG. 30** shows an expanded area for potential future study.

FIG. 30 -Expanded area of interest, to be determined by initial sampling of the smaller area.

Appendix 2 - Sampling over time

The essential goal of this work is to gain some insight into the recolonization of an area destroyed by volcanic eruption. Experience tells us that full recovery might take perhaps a decade, or more.

At the eruption, the entire population out to some distance (say 300 m) is driven to zero at the lava edge. Farther out the populations are less affected. In the absence of subsequent additional destruction, the populations along the transect will rise due to immigration from outlying areas and the re-establishment of viable local populations. At very long time, the populations will return to their pre-eruption values.

FIG. 31 shows the general plan for future sampling. Ideally collections would be made periodically. In the next section ("Recolonization") we quote from several sources on the process of recolonization.

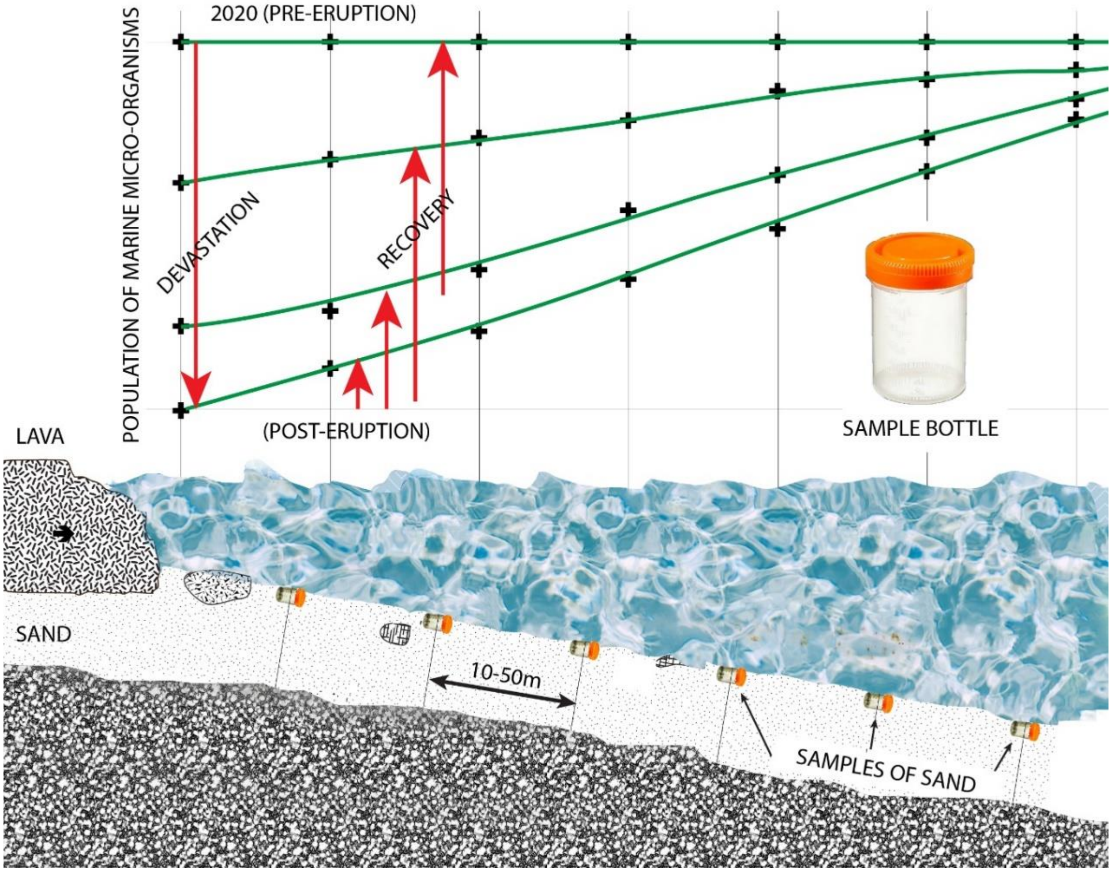


FIG. 31 – A proposed scheme for investigation of the time dependence of the benthic microfauna around the 2021 lava deposits.

Appendix 3 - Recolonization

Terceira Island, Azores

Dibella, et al., (2015) studied sediments collected during a Eurofleet marine geological survey offshore Terceira Island, Azores, in September 2011, about a decade after the offshore eruption. The authors were motivated to "obtain a seafloor characterization in a natural stressed environment like active volcanic areas of the Azores Islands." They found that "living specimens dominated the collections," and that "live and dead assemblages in most samples were similar", suggesting that "the first generation of foraminiferal colonizers was found." They concluded that "the recolonization process and the spatial distribution patterns are strongly influenced by the sea bottom high hydrodynamic regime which is responsible for volcanic deposit transport and depositional events." They also found that one species, *Angulogerina angulosa,* colonizes new sediments rapidly, an opportunistic behavior.

Recolonization of Mt. Pinatubo

Hess, et al. (1996, 2001) report on a multiyear study of the recolonization of the ash layer of Mt. Pinatubo by benthic foraminifera. The volcano, located in the Philippines, erupted on 15 June 1991. According to Wikipedia, "Surrounding areas were severely damaged by pyroclastic surges, pyroclastic falls, and subsequently, by the flooding lahars caused by rainwater re-mobilizing earlier volcanic deposits. … Benthic communities were blanketed by 8-9 cm of volcanic material…buried and decimated. … When first visited in 1994, some communities were found to be in the initial stages of recovery."

Hess, et al., write:

> Benthic foraminifera represent an ideal group for such studies because they are abundant in the deep sea and well-preserved in the geological record. However, only a few investigations are available on recent recolonization processes.

These authors monitored the re-establishment of the benthic foraminiferal community on Mt. Pinatubo over seven years. They reference several papers that indicate that the recovery time is "on the scale of years." The authors emphasize the complexity of the overall process, potentially involving:

1. Sediment gravity transport
2. Nutrient recycling and phytodetrital flux
3. Composition of the new habitat
4. Great distance for recolonizing species to reach the new habitat
5. Potential predation.

To this list we might add:

6. Irregular disturbance by violent weather events
7. Bioturbation by nonpredator fauna
8. Co- or counter- flow currents aiding or resisting dispersal of immigrates
9. Movement of trapped volcanic gases into the new habitat, generating mechanical movement, chemical modification, and direct effects on the biota.

First-generation foraminiferal colonizers

Di Bella, et al., (2015) studied sediments collected during a Eurofleet marine geological survey offshore Terceira Island, Azores, in September 2011. The authors were motivated to "obtain a seafloor characterization in a natural stressed environment like active volcanic areas of the Azores Islands." They found that "living specimens dominated the collections," and that "live and dead assemblages in most samples were similar", suggesting that "the first generation of foraminiferal colonizers was found." They concluded that "the recolonization process and the spatial distribution patterns are strongly influenced by the sea bottom high hydrodynamic regime which is responsible for volcanic deposit transport and depositional events." They found that one species, *Angulogerina angulosa*, colonizes new sediments rapidly, an opportunistic behavior.

Specimen density and Living/Dead ratio

A very simple but potentially valuable parameter was used by Hess and Kuhnt (1996) to organize colonizers in order of their succession. It was assumed that the fraction of living specimens in a sediment sample is a measure of the time of colonization: a high fraction of living specimens implies that the area was recolonized recently, whereas a low fraction implies it was colonized much earlier.

FIG. 32 shows the data of Hess, et al., for the living/dead ratio vs density of specimens. Clearly, there is an approximately linear anticorrelation relationship: R+cN =1, where R=ratio of live specimens to dead, N=number of specimens per 100 ccm, and c ≈ 1/500. This relation seems to confirm the ability to determine the sequence of recolonization by using the live/dead ratio and the density of specimens.

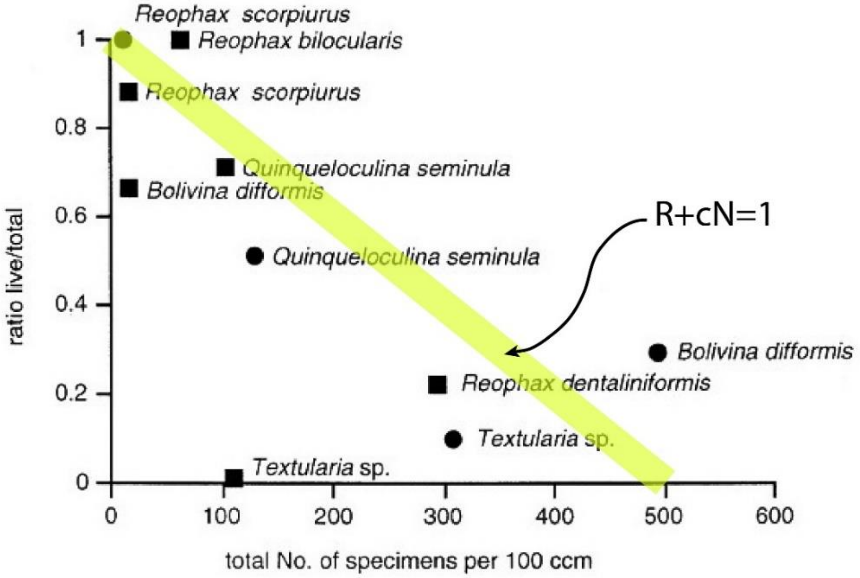


FIG. 32 – The ratio of living/dead foraminifera vs. population density.

Planktonic foraminifera tracking of oceanic current

Schiebel, et al., (2002) studied planktonic foraminifera to track the movement of the Azores Front Current System (AFCS). The Front lies some 250 km south of the central group of the Azores. It is known to move in response to seasonal and long-term environmental changes. The authors make use of the principle that the foraminiferal assemblages record the location of the AFCS, hence could be used to determine the varying position of the Late Quaternary Azores Current. … Foraminifera were collected in the water column (August 1997 and January 1999), and in surface sediments (October 1999) across the Azores Front. The faunal compositions of the foraminiferal assemblages, in both the water column and in the surface sediments, are different in the north and south of the islands. Analysis of the assemblages, including using oxygen isotope ratios d18O and d13O which can give the temperature of the water in which the forams lived, enabled various inferences about the Azores Current. The Schiebel study is a good example of the power of foraminifera assemblages to record the conditions at their creation, and also some aspects of their life.

Opportunism vs Resettlement

Di Bella, et al., (2014) provide an important comparison of recolonization after 20 years and after 110 years:

> The Azores area has been affected by volcanic activity that occurred in 2001..., while the last submarine eruption of Pantelleria Island [Mediterranean] dates from 1891. The different periods of eruption of the two areas allow to investigate on the way and time of the re-colonization process by foraminiferal assemblages. … the foraminiferal assemblages of the Azores area are dominated by opportunistic species (*Angulogerina angulosa*) and represent the first stage of re-colonisation after the eruption occurred in 2001, while the associations of Pantelleria Island (*Globocassidulina subglobosa*, *Lenticulina rotulata*, *Lobatula lobatula* and miliolids) must be considered as an advanced stage of resettlement with stable rich and well diversified assemblages. Moreover, in the Azores area many morphological abnormalities were recognized, confirming a more stressed environment than the Pantelleria bottom.

Recolonization of the intertidal and shallow subtidal community

Jewett and Drew (2014) describe the recolonization of the intertidal and nearshore benthic communities of Kasatochi Island (about midway on the Aleutian Islands, Alaska). One year following the eruption a reconnaissance survey found the intertidal zone devoid of life. The substrate was comprised almost entirely of medium and coarse sands with a depauperate benthic community. Four and five years following the eruption brief visits revealed dramatic intertidal and subtidal recolonization of the flora and fauna in some areas. Recolonization or lack thereof was tied to bathymetric changes from coastal and nearshore erosion over the study period.

Safe sites in establishment

del Moral and Grishin (1999) describe the importance of “safe sites”:

> Local biological effects modify colonization rates. The density of safe-sites (microsites favorable for seedling establishment) is crucial for establishment, but safe-sites are subject to competition.

Eruption on El Hierro Island 2011

El Hierro Island is the southernmost and westernmost of the Canaries. In October 2011, there was a shallow submarine eruption in the southern part of the island. It “caused severe effects in the seafloor morphology and substrate composition (e.g., lava extrusion and construction of the volcanic edifice), the water column (e.g., acidification, deoxygenation and fertilization) and the biological communities (e.g., changes in the composition and functioning of communities).” They remark:

> The volcanic eruption firstly buried most previously existing habitats and later on created a highly unstable and corrosive environment that affected some slow-growing organisms … Nevertheless, the eruption provided nutrients that are important for primary pelagic production that may have also promoted the establishment of dense populations of some sessile suspension feeders (e.g. N. cochlear, hydrozoans) in the newly formed hard substrates.

Statistics of survival

In Chapter 9 of his monograph *Volcanoes and the Environment*, J. S. Edwards (2009) writes:

> It is stating the obvious to allude to the lethal hazards of catastrophic vulcanicity, be they lava, mud or pyroclastic flows, or deep tephra, for living systems. The broader biological interest of vulcanicity is not so much in its lethality as in the statistics of survival and the modes of recolonization in devastated areas. Thus, my focus, in what follows, is on survival and revival of animal communities; survival as a facet of the perennial debate concerning the role of refugia, and revival as part of the little-understood process of primary colonization by animals.

Appendix 4 - Biodynamics

As a first step toward modelling the biodynamics, we have implemented a model of competing populations using ordinary differential equations. Numerical calculations of this model were done with Mathematica.

FIG. 33 shows a typical result of numerical calculations with this model. We assume there are three species of **foraminifera** (red, green, blue), and a population of organisms representing **food** (cyan), and a population representing **predators** (black). We omit the details of the calculations because these are only illustrative.

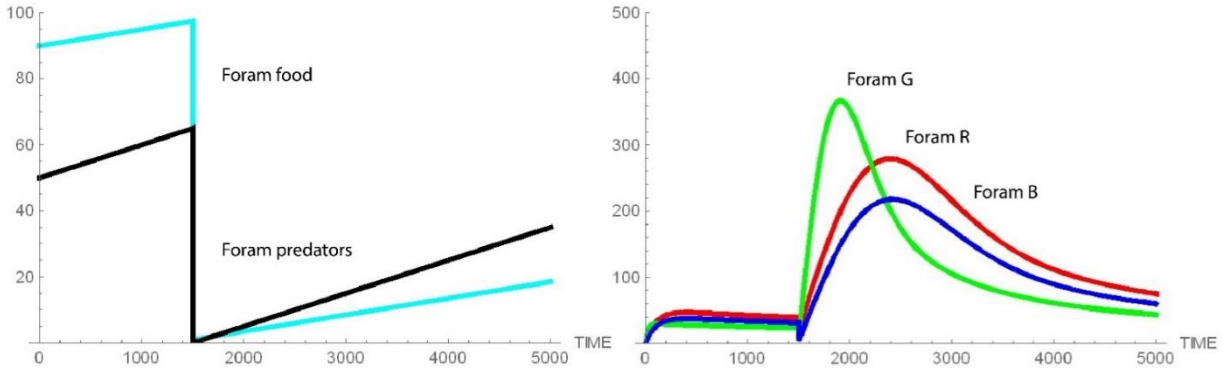


FIG. 33 - Hypothetical models of time development of populations after eruption

The dynamics can be described as follows: Initially, all five populations have reached some sort of near equilibrium. At time 1250 (no units), a catastrophe (i.e., the volcanic eruption) occurs, locally killing all five species. The foraminifera bounce back relatively rapidly, since they need very small resources, but the food and predator populations return more slowly. Eventually the foraminifera reach peaks (due to their mutual competition) and begin to return to their pre-eruption equilibrium levels. The recovery of the food and predators is much slower because there are insufficient resources for them to grow and multiply.

While these simulations cannot claim to be reality, they do give a qualitative idea of one dynamic that will be important to recolonization, namely species competition for food. This subject has been thoroughly elaborated (Murray, 1993).

The general goal of this project is to elucidate the *dynamics* of depopulation/repopulation of marine microfauna. To this end. attempts will be made to model the observed relative species abundances, including species-specific efficacy of transport, growth of newly established populations, mass movement of sediment by shallow slumping, entrainment in ocean flows, and other processes. The models would include water depth, flow directions and magnitudes, surf energy, nature and supply of nutrients, species mobility and ability to establish new colonies, processes such as rafting and airborne dispersal, and species fecundity and lifetimes. A specific goal is to assess the *extent* to which the shelf biota are reaching, or have reached, equilibrium.

REFERENCES

Volcanoes

Carracedo, Juan C.; Troll, Valentin R.; Day, James M. D.; Geiger, Harri; Aulinas, Meritxell; Soler, Vicente; Deegan, Frances M.; Perez-Torrado, Francisco J.; Gisbert, Guillem; Gazel, Esteban; Rodriguez-Gonzalez, Alejandro (May 2022). "The 2021 eruption of the Cumbre Vieja volcanic ridge on La Palma, Canary Islands". *Geology Today*. **38**(3): 94–107. doi:10.1111/gto.12388. ISSN 0266-6979

Cereceda, Rafael (30 September 2021). "La Palma volcano: How satellite imagery is helping us understand the eruption". *Euronews*.

"Canary Islands lava peninsula in the Atlantic doubles in size", *The Guardian*, 30 September 2021.

del Moral, R. and Grishin, Yu., 1999. *Volcanic Disturbances and Ecosystem Recovery*. Chapter 5. P. 137-160, in *Ecosystems of Disturbed Ground*, L. R. Walker, editor. Elsevier.

Edwards, J.S., 2009. *Volcanoes and the Environment*. Cambridge University Press. Chapter 9 - Animals and volcanoes: survival and revival.

Mitchell, N.C., 2003. Susceptibility of Mid-Ocean Ridge Volcanic Islands and Seamounts to Large-Scale Landsliding. *J. Geophys. Res*. (doi:10.1029/2002JB001997).

Mitchell, N.C., Schmitt, T., Isidro, E., Tempera, F. Cardigos, F., Nunes, J.C., Figueiredo, J., 2003. Multibeam sonar survey of the central Azores volcanic islands. *InterRidge News* **12**(2): 30-33.

Murray, J.D., 1993. *Mathematical Biology*. Springer-Verlag.

Oddsson, B., Gudmundsson, M., Sonder, I., Zimanowski, B., Schmid, A., (2016). “Experimental studies of heat transfer at the dynamic magma ice/water interface: Application to subglacially emplaced lava.” First published: 16 April 2016. https://doi.org/10.1002/2016JB012865

Pacheco, J., 2001. Processos Associados Ao Desenvolvimento De Erupçoes Vulcanicas Hidromagmaticas Explosivas Na Ilha Do Faial E Sua Interpretaçao Numa Perspectiva De Avaliaçao Do Hazard E Minimizaçao Do Risco. PhD thesis. Universidade dos Açores.

Quartau, R., Tempera, F., Mitchell, N.C., Pinheiro, L.M., Duarte, H., Brito, P.O., Bates, C.R., Monteiro, J.H., 2012. Morphology of the Faial Island shelf (Azores): The interplay between volcanic, erosional, depositional, tectonic and mass-wasting processes. *Geochemistry, Geophysics, Geosystems* **13**(4). https://doi.org/10.1029/2011GC003987.

Rueda, J.L., et al., 2014. Benthic and demersal communities after the submarine eruption of El Hierro: Spatial patterns of survival and colonization of fauna. IV Congress of Marine Sciences, Las Palmas de Gran Canaria, June 11th to 13th 2014, p.p. 378-379http://hdl.handle.net/10553/114755. ISBN 84-697-0471-0.

"The 'new land' created by the lava from the volcano now measures 27.7 hectares". *Canarian Weekly*. 2 October 2021. [La Palma, Canary Islands].

Wikipedia, 2021 “Cumbre Vieja volcanic eruption”.

[Wikipedia: “Geology of the Canary Islands”.

Microfauna

Abrantes, F., Meggers, H., Navea, S., Bollm, J. (2002). Fluxes of micro-organisms along a productivity gradient in the Canary Islands region (29°N): implications for paleoreconstructions. *Deep Sea Research* Part II: Topical Studies in Oceanography, **49**(17):3599-3629.

Catalogue of Portugese Foraminifera, https://foraminifera.eu/apf.html.

Chang, Y.-C., Mitchell, N.C., Quartau, R., Hübscher, C., Rusu, L., Tempera, F., 2022. Asymmetric abundances of submarine sediment waves around the Azores volcanic islands. *Marine Geology* **449**:106837.

Cole, P., Guest, J., Duncan, A., Pacheco, J.-M., 2001. Capelinhos 1957–1958, Faial, Azores: deposits formed by an emergent Surtseyan Eruption. *Bull. Volcanol*. **63**:204–220. https://doi.org/10.1007/s004450100136.

Di Bella, L., Frezza, V., Conte, A.M., Chiocci, F.L., (2015). Benthic foraminiferal assemblages in active volcanic area of the Azores Islands (North Atlantic Ocean). *Ital. J. Geosci*., **134**(1):50-59, (doi:10.3301/IJG.2014.22).

Di Bella, L., Frezza, V., Conte, A.M., Martolelli, E., Chiocci, F.L., Sposato, A., Chiocci, F.L., 2014. Foraminiferal assemblages in active volcanic areas: two study cases from Azores Archipelago (Atlantic Ocean) and Pantelleria Island (Mediterranean Sea). Conference: CONGRESSO SGI-SIMP 2014 "The Future of the Italian Geosciences - The Italian Geosciences of the Future" at: MilanVolume **31**. Sept. 2014.

Hess, S. and Kuhnt, W, 1996. Deep-sea benthic foraminiferal recolonization of the 1991 Mt. Pinatubo ash layer in the South China Sea. *Mar. Micropaleontol*. **28**:171-197.

Hess, S., Kuhnt, W., Hill, S., Kaminski, M.A., Holburn, A., de Leon, M., 2001. Monitoring the recolonization of the Mt. Pinatubo 1991 ash layer by benthic foraminifera. *Marine Micropaleontrology* **43**:119-142.

Jewett, S.C., Drew, G.S., 2014. Recolonization of the intertidal and shallow subtidal community following the 2008 eruption of Alaska's Kasatochi Volcano. *Biogeosciences Discussions* ID 70100067, USGS Publications Warehouse, Alaska Science Center Biology MFEB.

Romano, E., Bergamin, L., Di Bella, L., Frezza, V., Pierfranceschi, G., Marassich, A., Provenzani, C. 2021. Benthic foraminifera as environmental indicators in extreme environments: The marine cave of Bue Marino (Sardinia, Italy). *Ecological Indicators* **120**.

Sanchez-Perez, J., Usera, J., Alonso, I., Menendez, I., Cabrera, L., and Mangas, J., (2006). Study of sedimentary dynamics by means of foraminiferal analysis in Gran Canaria (Canary Islands-Spain). Anuario do Institute de Geosciencas – UFJ, ISSN 0101-9759, Vol. 29-1/2006, pp. 296-297

Schiebel, R., Schmukera, B., Alves, M., Hemleben, C., 2002. Tracking the Recent and late Pleistocene Azores front by the distribution of planktic foraminifers. *Journal of Marine Systems* **37**(1–3):213-227.

Schmieder, RW and Lima, J. (2023). "Littoral microfauna of Terceira Island, Azores." Cordell Expeditions Report 27 June 2023. 70 pp.

FIGURE CREDITS

2021 Cumbre Vieja volcanic eruption - Wikipedia

ESA - La Palma lava flows into the sea

https://www.esa.int/ESA_Multimedia/Images/2021/10/La_Palma_lava_flows_into_the_sea

https://www.euronews.com/2021/10/01/la-palma-volcano-satellite-image-shows-lava-flow-to-atlantic-ocean

https://www.puentedemando.com/el-volcan-de-la-palma-cumple-una-semana-de-destruccion/

Canarian Weekly (2021, December 16) Scientific data and logic suggest that the eruption is over. Accessed December 20, 2021.

El Pais (2021, December 15) La Palma volcano comes to stop: 'It is not emitting lava, nor sulfur dioxide, nor registering seismic activity'. Accessed December 20, 2021.

INVOLCAN (2021, December 17) La Palma. Accessed December 20, 2021.

Instituto Geografico Nacional (2021, September 19) Erupción en la isla de La Palma. Accessed December 20, 2021.

Klugel, A. *et al.* (1999) Chronology and volcanology of the 1949 multi-vent rift-zone eruption on La Palma (Canary Islands). *Journal of Volcanology and Geothermal Research*, 94 (1-4), 267-282.

NASA Earth Science Applied Sciences (2021) La Palma Eruption. Accessed December 20, 2021.

NASA Earth Observatory (2021) Eruption at La Palma. Accessed December 20, 2021.

Smithsonian Institution Global Volcanism Program (2021) La Palma. Accessed December 20, 2021.

Tenerife Weekly (2021, December 16) Cumbre Vieja lava devastates 1,237.3 hectares and destroys 2,988 buildings, according to Copernicus. Accessed December 20, 2021.

Volcano Discovery (2021, Dec. 17) La Palma volcano update: Volcano remains calm, but small quakes continue. Accessed December 20, 2021.

PERSONNEL

Principal Investigator:

Dr. Robert W. Schmieder [Biodynamics]
Cordell Expeditions
4295 Walnut Blvd.
Walnut Creek, CA 94596
Phone: (925) 934-3735 (incl. FAX)
Email: schmieder@cordell.org
Website: http://www.cordell.org

Co-investigators:

Robert W. Schmieder	Cordell Expeditions	schmieder@cordell.org	Biodynamics
Rui Quartau	Instituto Hidrográfico	rui.quartau@gmail.com	Geodynamics
Emilia Salgueiro	Instututo Português	Emilia.salgueiro@ipma.pt	Foraminifera
Sérgio Ávila	Univ. dos Açores	sergio.pa.marques@uac.pt	Mollusca