**Taming Fogo Island: Late Holocene volcanism, natural fires and land use as recorded in a scoria-cone sediment sequence in Cabo Verde**

Alvaro Castilla-Beltrán\*1,2,3, Alistair Monteath4,5, Britta J.L. Jensen4,Lea de Nascimento3, José María Fernández-Palacios3, Nichola Strandberg5, Mary Edwards5, Sandra Nogué5,6,7

**Affiliations**

1. Departamento de Geografía e Historia, Universidad de La Laguna, Spain;
2. Archaeological Micromorphology and Biomarker Research Lab, Instituto Universitario de Bio-Orgánica Antonio González, Universidad de La Laguna, Spain;
3. Island Ecology and Biogeography Group, Instituto Universitario de Enfermedades Tropicales y Salud Pública de Canarias (IUETSPC), Universidad de La Laguna (ULL), 38200 La Laguna, Canary Islands, Spain;
4. Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Canada;
5. School of Geography and Envronmental Science, University of Southampton;
6. CREAF, centre de Recerca Ecològica i Aplicacions Forestals, Bellaterra (Cerdanyola del Vallès), Catalonia, Spain;
7. Universitat Autònoma de Barcelona, Bellaterra (Cerdanyola del Vallès), Catalonia, Spain;

**Keywords**: Culture-environment interactions, Fire, Holocene, Island palaeoecology, Volcanism

\*Corresponding author email: acastilb@ull.edu.es

**Abstract**

Cabo Verde remained uninhabited until 1460 CE, when European sailors founded a settlement in Santiago, and soon after in Fogo island. The degree to which different island ecosystems in Cabo Verde have been transformed by humans remains uncertain because of a scarcity of historical information and archaeological evidence. Disentangling these processes from natural ones is complicated in islands with a history of volcanic impacts and other natural hazards. In this paper, we apply microfossil (pollen, non-pollen palynomorphs, and phytoliths), and sedimentological analyses (granulometry, X-Ray diffraction, loss on ignition, and tephrostratigraphy) to a 2-m sediment sequence deposited in a scoria cone from 4100 cal yr BP (calibrated years before 1950 CE) to the present. The organic-rich basal sediments indicate that between 4100 and 2600 cal yr BP the pre-settlement landscape of Fogo was an open grassland, where fire was infrequent and/or small-scale. An increase in volcanic glass deposition after 2600 cal yr BP, peaking ca. 1200 cal yr BP, suggests that there was a progressive activation of Fogo´s volcanic activity, contemporaneous with increased fire frequency and erosion pulses, but with little impact on local grassland vegetation. While dating uncertainty is high, the first evidence of intensive local land use by early settlers was in the form of cultivation of *Zea mays,* abundant spores of coprophilous fungi (*i.e. Sporormiella*), and peaks in charcoal concentrations between 800 and 400 cal yr BP. This was followed by large increases in pollen from pigeon pea (*Cajanus*), a diverse array of exotic trees (*Cupressus*, *Grevillea*) and invasive shrubs (*Lantana*). The introduction of these taxa is part of recent human effort to ‘tame’ this steep, dry and hazardous island by reducing erosion and providing firewood. An important outcome of these efforts, however, is a loss of fragile native biodiversity.

1. **Introduction**

As some of the last places on Earth to be settled by people, oceanic islands are ideal settings to analyse culture-environment dynamics and their effects on previously uninhabited ecosystems (Nogué et al., 2021). The case of Fogo Island (in Portuguese meaning fire, a clear allusion to its active volcanism) is of special interest as it represents the first tropical archipelago permanently settled by Europeans. In the past, effusive volcanism in Fogo has led to periods of almost total evacuation of the island (Ribeiro, 1960), a response that has happened recently in other small oceanic islands, such as Tristan da Cunha 1960-1963 CE (Roberts, 1971) and the Caribbean island of Montserrat in 1995 CE (la Sufrière volcanic eruption; Kokellar, 2002). Due to the scarcity of archaeological and historical evidence, understanding past ecological change and human transformation of Fogo´s landscapes remains challenging. Palaeoecological data can provide a historical perspective on the current socio-ecological challenges faced by Fogo’s communities (e.g. landscape degradation), revealing the long-term ecological impacts of natural hazards (e.g. volcanic eruptions) and land-use changes, including those derived from the early settlement of the archipelago by the Portuguese (1460 CE).

Historical sources indicate that natural hazards have shaped Cabo Verde’s environment and are often associated with periods of socio-ecological stress (Heckman 1985, Patterson 1988, Garfield 2015). These include volcanic eruptions (the most recent in 2014-2015), severe droughts (the most recent in the 1940s), and tropical storms (the last recorded being category-one Hurricane Fred in 2013). Such shocks triggered migrations between islands (e.g., the 1680 CE migration from Fogo to the neighbouring island of Brava after a volcanic eruption), and emigration to mainland Europe and America that has contributed to Cabo Verde’s history as a country of out-migration (Lam, 2021). It is also increasingly clear that Cabo Verde’s flora and fauna have been impacted by anthropogenic disturbances since the Portuguese settlement (Duarte et al., 2008, Castilla-Beltrán 2021a). For instance, previous palaeoecological studies from three islands of the Cabo Verde archipelago (Santo Antão, São Nicolau, and Brava) have revealed how early settlers impacted vegetation in the islands´ highlands (>800m a.s.l.) through fire use and livestock introduction, causing soil erosion (Castilla-Beltrán et al., 2019, 2020, 2021a).

As a result of this complex disturbance history, it is unclear how humans have culturally transformed local landscapes by introducing species from other regions, and how they have responded to unpredictable natural disturbances through time. In this paper, we set out to answer the following: 1) What was the pre-human landscape like, and did it change in response to Holocene volcanism? 2) How did people transform and adapt to a small, steep, volcanically active island? We aim to understand the interplay between cultural practices and natural hazards on an active volcanic island, revealing their socio-ecological consequences and their role in shaping Fogo´s present landscape.

* 1. **Fogo Island**

Fogo was the second Cabo Verdean Island (after Santiago) settled by Europeans ca. 1470 CE. It is the highest and steepest island in the archipelago (2829 m a.s.l.). It is mostly formed by the Monte Amarelo shield volcano that contains a prominent caldera-like depression considered product of a major flank collapse (Day et al., 1999) or by the intersection of two calderas followed by the collapse of the East flank (Martínez-Moreno et al., 2018). This depression (known as Chã) was subsequently the location of largely basaltic volcanism that led to the construction of the stratocone known as Pico do Fogo (e.g. Carracedo et al., 2015; Worsley, 2015). Pico Pequeno, a smaller cone built on the flank of Pico do Fogo, has been historically active and last erupted in 2014-2015, destroying crops, houses and infrastructure in the towns of Portela, Bangaeira and Ilhéu de Losna, located in Chã das Caldeiras (Capello et al., 2016). Since Portuguese colonization, more than 20 eruptions or periods of volcanic activity have been recorded, some with catastrophic consequences (Table 1). For instance, major volcanic activity took place between 1505 and 1760 CE, which caused an almost total abandonment of the island (e.g. 1660 CE) (Mitchell-Thomè, 1981) (Fig. 1).

Cabo Verde´s highly seasonal semi-arid climate makes drought one of the main natural hazards affecting livelihoods in the archipelago (Costa, 2020). The concentration of heavy monsoon rains in the wet season (July-September) can produce flash floods that transport great quantities of sediment downslope, a major limitation to soil formation and stability in Fogo (Ribeiro, 1960). Due to its young geology and sparse vegetation, it is believed that suitable soil development for agriculture was always very limited in Fogo, and this constrained socio-economic development and the island’s sustainability during the colonial era (Ribeiro, 1960). However, soil loss is also considered a legacy of colonial mismanagement of the island and remains a problem today (Lindskog and Delaite, 1996).

Currently, the most important remnants of native plants on Fogo (e.g., *Euphorbia tuckeyana*) are situated above the heavily transformed mid-elevation zones, but it is thought that they occupied most of the island before human arrival (Ribeiro, 1960). The most vegetated areas are found between 700 and 1500 m a.s.l. on the north-facing slopes of the island, where trade winds bring moisture through cloud condensation. Among the most common native taxa are *Artemisia gorgonum*, *Echium vulcanorum*, *Euphorbia tuckeyana*, *Lavandula rotundifolia*, *Lotus jacobaeus,* which constitute the main scrubland vegetation. *Faidherbia albida* (*Acacia caboverdeana*), *Dracaena draco* ssp. *caboverdeana*, *Sideroxylon marginata,* and *Ficus sur* are the main native tree taxa and are mostly found in gorges (Varela et al., 2022). The most common cultivars in Fogo include pinhão manso (*Jatropha curcas*), ricino (*Ricinnus communis*) and carrapato (*Furcraea foetida*), used for fencing and ephemeral constructions, and the most widespread cultivars are maize (*Zea mays*), sweet potato (*Ipomoea batatas*), manihot (*Manihot sculenta*) and leguminous crops. Many exogenous herbs and ruderals have been introduced to the island, of which *Lantana camara* is the most widespread invasive species, followed by *Tagetes minuta*, *Emex spinosus*, and *Alternanthera repens*, which are expanding throughout the island even in the most isolated areas, as noted in the early 20th century (Chevalier, 1935). Animal husbandry is of great importance, cows and goats being most common stock, while horses are recognized as the most valuable animals in the archipelago. It is thought that early livestock agriculture relied on native species such as *Sideroxylon marginata* and *Periploca chevalieri*. Animal populations saw huge changes during periods of socio-ecological stress (where human mortality also skyrocketed), when animals died of hunger or were slaughtered (Patterson, 1988). Since 1949 CE, the government has carried out successful afforestation programs in the highlands using exotic trees such as *Cedrus*, *Cupressus*, *Eucalyptus*, *Grevillea,* and *Mimosa* (Batista et al., 2015).

Fig. 1: Location of study site within the island of Fogo, and satellite map of the island indicating the approximate location of secondary scoria cones. Eastern view digitized from Ribeiro (1960), location of secondary cones from Brum da Silveira and Madeira (2006). Panel B shows population estimates based on Patterson (1988), and chronology of volcanic eruptions based on Instituto Nacional de Estatística (2018).

Table 1: Recorded socio-ecological consequences of volcanic eruption in Fogo (after Estatísticas do Ambiente 2016).

1. **Material and methods**

**2.1 Sample collection**

Volcanic craters and other basins have been shown to preserve sedimentary sequences with records of long-term landscape change (e.g. Castillla-Beltrán et al., 2019; Fritz et al., 2011; Zolitschka et al., 2006). These palaeoenvironmental records are important for understanding how humans have transformed local landscapes by fire, deforestation and introducing species from other regions, and how they have adapted to unpredictable natural disturbances through time. In May 2019, we visited the island of Fogo and explored the western slopes for suitable basins. We selected the Ka Nazario cone, the uppermost structure of a crater row situated on the north-western slopes at 1010 m a.s.l. in Vera Cruz, Mira-Mira area (14°58’26.2”N, 24°26’13.7”W) that extends ca. 450 m along the slope, with a crater diameter of 70 m and a flat bottom surface of sediment infill of ca. 40 m diameter. The sediment infill of the crater is derived from the erosion of its walls and in-blown material mostly originating from Fogo´s highland slopes. Currently, Ka Nazario cone is used for small-scale agriculture, including peas (*Cajanus cajan*) and sweet potato (*Ipomoea batatas*). At the time of the fieldwork, no livestock were present, but we cannot exclude grazing activities occurring during other parts of the year. We excavated a 2x2-m test pit 200 cm deep, revealing a sediment profile with horizontally stratified deposits with no complex stratigraphic features. The bottom of the crater was not reached. We sampled 50 g of sediment every 5 cm and placed the samples in individual sealed plastic bags. Each sediment sample represented an aggregate of 2-3 cm, with an unsampled 1-2 cm between (Fig. 1). The samples were transported to the University of Southampton (UK) and stored in a cold room at 4oC at the School of Geography and Environmental Science (SOGES), and later transported to the Ecology Laboratory at the University of La Laguna.

**2.2 Radiocarbon dating and Age-depth modelling**

We used accelerator mass spectrometry (AMS) radiocarbon dating to date four bulk sediment samples to generate a chronological framework for the Ka Nazario scoria-cone sediment sequence, assuming the surface represents the present day (-69 cal. yr BP) (Table 2, Fig. S1). We then used the R package Bacon (Blaaw & Christen 2013) with standard settings, and the Intcal20 northern hemisphere calibration curve (Reimer et al., 2020) to generate a Bayesian age-depth model. Modelled age ranges are reported at two sigma (95%) uncertainty throughout the manuscript.

Table 2: Radiocarbon results and their calibration using IntCal20 (Reimer et al., 2020) for bulk sediment 14C dating of Ka Nazario cone.

**2.3 Sedimentological analyses: elemental composition, gran size distribution, and loss on ignition (LOI)**

We analysed the elemental composition of sediments by X-Ray diffraction using a mounted Niton XL3T GOLDD. We used a set of 40 homogenised dried sediment samples of 5-cm3 and carried out 160-second measurements per sample. The results are semi-quantitative and expressed as a percentage of detected elements, best represented as ratios. In this study, we focus on the most abundant elements detected, including Si, Al, Fe, Ti, and Ca. As this analysis is non-destructive, we used the remaining material for grain size distribution analysis.

Grain-size distributions were analysed using a Malvern Mastersizer Hydro, using the soil analysis settings adjusted to non-spherical grains. We carried out an average of five measurements (20 seconds each) per sample, adjusting the obscuration parameter until a standard deviation below 5% was achieved in a minimum of five measurements. We present the results as averaged measurements of Dx10, Dx50, and Dx90 fractions, with a final set of grain-size and soil property data that includes percentages of clay, silt, and sand fractions.

Loss-on-ignition (LOI) was performed to determine the percentage of soil organic matter. We burnt 40 1-cm3 samples at 550oC in a furnace for 4 hours, weighing the sediment before and after the procedure (Heiri et al., 2001). We use the difference between the dried sample and the ashed sample weight as LOI. The ashed material was used to carry out phytolith and cryptotephra (non-visible volcanic ash) quantification analyses.

**2.4 Palynomorph and micro-charcoal analyses**

To process samples for pollen and non-pollen palynomorphs (NPP) analyses, we processed a set of 20 sediment samples of 2-cm3 (measured using volumetric displacement) and spiked them with a *Lycopodium* tablet (average 19,855 spores per tablet) for the calculation of palynomorph and micro-charcoal particle concentrations. We carried out standard pollen preparation in the Palaeoecological Laboratory at the University of Southampton. Briefly here, we deflocculated the sample with KOH, before sieving through a 10 µm mesh with water, after which we used hydrofluoric acid (HF) for 30 minutes, and acetolysis to eliminate organic particles. We stained the sample with safranin and mounted it on slides using glycerine jelly. In samples with low pollen concentration (section 200-70cm), a second preparation was carried out in the Ecology Laboratory of the University of La Laguna, using flotation with sodium polytungstate. We used a high-magnification microscope (x400, x1000) to identify and count palynomorphs. To identify pollen and spores, we consulted the Canary Islands and Cabo Verde pollen reference collection stored at La Laguna University and SOGES, University of Southampton, as well as tropical African pollen literature (e.g. Gosling et al., 2013) and non-pollen palynomorph literature (e.g. Gelorini et al. 2011). We quantified micro-charcoal concentrations using the same slides prepared for pollen analysis, by following the method outlined by Fisinger and Tinner (2011), counting opaque black fragments and *Lycopodium* in different fields of view until a total sum of 200 was reached.

We carried out stratigraphically constrained CONISS analysis of pollen percentage data using Tilia software to divide the record into pollen zones (Grimm, 1993). We first discarded samples that contained fewer than 50 pollen grains per 5000 *Lycopodium* spores. Secondly, we included all pollen grains in the pollen sums and calculated NPP and micro-charcoal concentrations per exotic *Lycopodium* spores counted. We used detrended correspondence analysis (DCA) using pollen percentages in the R package Vegan (Oksanen et al., 2013) to assess pollen assemblage variability as expressed in two main axes within a statistical space.

**2.5 Macro-charcoal quantification**

We used a set of 20 samples of 2 cm3 for macro-charcoal quantification, washing it with distilled water using a 180-μm sieve to retain the >180 μm sediment fraction. All charcoal fragments per sample were counted at low-power magnification in a Petri-dish.

**2.6 Phytolith analysis and tephra quantification**

To prepare samples for phytolith and microscopic tephra quantification we added a *Lycopodium* tablet to the 40 ashed samples previously used for LOI. We used a pipette to mount 1 ml of sediment in suspension on a microscope slide. We added Canada balsam and homogenised the particles in the microscope slide after the water evaporated. We proceeded to analyse the slides at x400 magnification, counting phytoliths and tephra shards in a sub-set of 20 samples (one every 10 cm), and only tephra shards in a further set of 40 samples (including the first set of 20, one every 5 cm), for a minimum of 10 transects per slide. We calculated tephra shard concentrations per *Lycopodium* spores counted, and plotted phytoliths as percentages using Tilia software (Grimm, 1993). We used the ratio D/P (spheroid decorated / Poaceae phytoliths), as a proxy for dominance of woody vs grassy vegetation (Alexandre et al., 1997).

**2.7 Tephra chemical characterisation**

We extracted glass shards using heavy liquid flotation (Turney, 1998) from sample KN65 (65 cm, the most glass-rich level according to the tephra quantification) and CG62, a glass-rich level from Cova Galinha site, a soil profile in neighbouring island Brava of similar age (see Castilla-Beltrán et al. 2021b for site and stratigraphic details) for electron probe microanalysis (EPMA). Sample CG62 was selected to assess potential correlations with Fogo and KN65 tephra chemistry. Samples were mounted in an epoxy resin stub and polished to expose internal glass surfaces before being carbon-coated for EPMA. We analysed the chemical composition of glass shards from sample KN65 (UA 3631) using wavelength dispersive spectrometry on a JEOL 8900 superprobe, at the University of Alberta (Canada), following established protocols (Jensen et al., 2008; 2021). Ten major-minor elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, Cl) were measured using a 5-μm beam, with 15-keV accelerating voltage, and 6-nA beam current. Time-dependent intensity corrections were applied using the probe for Windows software (Donovan et al., 2015) to correct for any Na loss incurred by the usage of a more focussed beam. Two secondary standards of known composition were run concurrently during EPMA to assess analytical accuracy and precision: i) ID3506, Lipari rhyolitic obsidian, and ii) Old Crow tephra (Kuehn et al., 2011). Subsequently, we analysed sample CG62 at the Tephra Analytical Unit, University of Edinburgh (UK), using a Cameca SX100 electron probe micro-analyser with a 5-μm beam, 10 KeV accelerating voltage and 5 nA current (Hayward, 2012). Ten major-minor elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, Cl) were measured alongside two secondary standards of known composition: i) Lipari rhyolitic obsidian and ii) BHVO-2g basalt. Results were normalized to 100 % and are presented as weight percent oxides (wt %) in all figures. The full dataset, including standard measurements, is reported in supplementary information (Table S1).

1. **Results**

Our analyses indicate that Ka Nazario cone (KN) holds a deposit of silty (average 42.2%) and sandy (average 57.2%) sediments that are likely a mixture of local materials and transported aeolian particles from Fogo and the Sahara desert. The resulting Bacon age-depth model (Fig.S1) provides 95% confidence ranges (mean 95% confidence range of 409 yr), suggesting a relatively steady sedimentation in the Ka Nazario cone since c. 4040 cal yr BP (see discussion). The basal sediments are relatively rich in organic matter (200-150 cm, avg LOI 10.5%), with a decreasing trend towards the upper levels of the record. The main elements that constitute KN sediments are Si (8.7%), Fe (8.0%), Al (3.7%), and Ca (2.5%). We distinguished two types of volcanic particles: Type 1, weathered lithic particles that are present in stable concentrations throughout the entirety of the record and represent re-worked volcanic material, and Type 2, volcanic-glass shards (pale-green colour and featuring vesicles), which were present between levels 140-0 cm in variable concentrations (Fig 2).

Pollen preservation varies throughout the record and, generally, pollen grains show more signs of degradation in the basal and middle sections of the profile (200-70 cm), which likely explains the diminished palynological diversity in this part of the sequence. Pollen concentrations were also low between 200 and 70 cm, where pollen sums are limited to an average of 95 pollen grains. In contrast, preservation of fungal and fern spores is good throughout the profile. The NPP assemblage is strongly dominated by *Brachydesmiella* spores (avg. 1290% over the pollen sum).

Figure 2: (A) Microscope photographs of volcanic particles found in Ka Nazario site, Fogo Island (Cabo Verde), including type 1 lithic particles largely eroded from local volcanic rocks, and type 2 volcanic glass shards from primary airfall and, most likely, some reworked tephra from the local catchment area. (B) Total Alkali Silica (TAS) diagram (Le Maitre et al., 1989) shows the alkaline nature of these intracontinental volcanics. (C,D) Glass geochemistry of KN65 and CG62 type-2 shards in comparison to the glass composition of tephra layers confidently attributed to Fogo, Brava and Cadamosto by Eisele et al. (2015).

CONISS analysis divided the pollen record into four main zones (KN 1-4) (Fig 3): Zone KN-1 (200-100 cm, 4100-1600 cal yr BP) is characterised by high levels of organic matter, (average 8.69%), and relatively stable median grain sizes (77.5 μm), with the notable exception of a peak in level 120 and 100 cm (115 and 142 μm respectively). The pollen assemblage in this zone is affected by degradation, and pollen counts are ~100 grains. The pollen assemblage, which is likely to be affected by poor preservation, is dominated by Asteraceae (avg. 25%), Poaceae(avg. 24%), and Urticaceae (avg. 23%), with minor presence of Caryophyllaceae(2.8%), Amaranthaceae(avg. 2.3%) and *Plantago* (avg. 1.2%) (Fig 3). The phytolith assemblage is almost completely dominated by Poaceae bulliform morphotypes, and the ratio D/P (spheroid decorated / Poaceae), supports the dominance of herbaceous taxa (Fig 3). This zone also shows the highest diversity of fern spores, including *Selaginella*-type (avg. 21%), Monolete psilate (avg. 13.5%), Pteridaceae(avg. 9.3%), and *Davallia* (avg. 7%). *Debarya*-type algal zygospores are also present. Macro- and micro-charcoal concentrations are lowest between 200-150 cm (avg. 0.5 and 1320 per cm3 respectively), but they show a peak in level 130 cm (5 and 15,447 per cm3 respectively (Fig 4). There is a decrease in organic matter and a peak in calcium input coincident with the charcoal increase. Weathered volcanic materials in the form of orange crystalline particles are widespread, probably originating from the erosion of the scoria-cone volcanic rocks. Green tephra shards are recorded between levels 140 and 100, following an increasing trend in concentration (6100-16,200 shards/g) (Fig 4).

Figure 3**:** Pollen percentage diagram of Ka Nazario (KN) site (Fogo, Cabo Verde) including CONISS analysis. Bars represent levels with low pollen sums and poor pollen preservation, and coloured fills levels with high pollen sums and good pollen preservation.

Zone KN-2 (100-50 cm, 1600-700 cal yr BP) is characterized by decreasing levels of organic matter, (average 8.69%), peaks in grainsize in levels 95-90 cm and increasing K content (average 0.39%) and K/Ti ratio scores (Fig 4). Volcanic glass (type 2) is abundant in this section, peaking at 65 cm (1,932,930 shards/g), after which shard concentrations decrease, but stay abundant. Improved pollen preservation reveals further diversity within the open landscape taxa, including the punctuated presence of *Euphorbia*, *Echium*, Caryophyllaceae, *Lavandula*, *Acacia*, *Campanula,* and *Lotus*. At the upper boundary of this zone (level 50 cm), we recorded the first evidence of human land-use in the form of pollen grains of *Zea mays*, Cerealia, and coprophilous fungal spores (i.e. *Sporormiella*). A higher phytolith D/P index supports the interpretation of a landscape with increased woody vegetation, as does the presence of fungal spore *Bactrodesmium*, which is known to infect the bark of shrubs and trees (Gelorini et al., 2011). Hexagonal phytoliths diagnostic of Cyperaceae are also present. Macro- and micro-charcoal concentrations are the highest on the record, peaking at level 50 cm (10 and 29,800 per cm3 respectively) (Fig. 4).

Zone KN-3 (50-15 cm, c. 700-200 cal yr BP) shows prominent peaks in sand deposition, the lowest levels of organic content in the record (avg LOI 4.01%) and increases in Ti and Fe percentages (2.2 and 9.5% respectively), as well as K/Ti ratio scores (Fig 4). The concentrations of volcanic glass (type 2) (avg. 181,000 shards/g) and charcoal particles are stable. There is widespread evidence of land use in the form of *Zea mays* pollen grains (up to 3 % in level 30 cm), coprophilous fungal spores (*Cercophora*, *Delitzchia*, *Sordaria*, *Sporormiella*, *Podospora*) and acicular phytoliths found in crops consistent with those produced by Fabaceae.

Finally, zone KN-4 (15-0 cm, c. 200 cal yr BP-present) is constituted by mostly unconsolidated agricultural topsoil, characterised by high percentage of fine sand, poor organic content and abundant Type 2 tephra shards and crop pollen grains, such as *Cajanus cajan* (up to 60% in level 10 cm) and *Lens* (up to 20%). The pollen assemblage is also characteristic due to the presence of pollen of introduced taxa, including *Cupressus*, *Grevillea*, *Mimosa*, and *Prosopis*, as well as introduced shrubs such as *Ricinus* and Verbenaceae (i.e. *Lantana*). Concentrations of *Brachydesmiella* spores decrease, while those of *Spegazzinia* sp. increase. Pollen of native woody species, such as *Dichrostachys* and *Faidherbia albida* (*Acacia caboverdeana*), is also present in this uppermost part of the sequence*.*

1. **Discussion**

Palaeoenvironmental research has the potential to provide a long-term view of past ecological change and human transformation in Fogo, an island where scarce historical and no archaeological research has taken place. The dry local environment and steep slopes with high rates of erosion prevent the existence of permanent lakes and bogs, which yield deposits more typically used in palaeoecology. In this context, scoria-cones such as the KN site, and other volcanic basins, provide novel alternatives that have potential for the reconstruction of culture-environment interactions. Dry climate and coarse sediments do, however, impose important limitations in our study. First of all, coarse sediments were challenging to sample, and fine resolution was not possible due to soil profile instability. It was not possible to excavate deeper than 200 cm with the equipment on hand, yet future expeditions could reach older deposits.

While the age model based on four radiocarbon dates suggests a relatively stable history of sediment deposition during the last 4000 yr, it depends on the assumption of depositional continuity until the present. In previous studies, dating of upper soil profile records proved challenging, as increased erosion and land cultivation can introduce a mix of contemporaneous and old organic matter (see Castilla-Beltrán et al., 2019, 2020). The abundance of anthropic markers (pollen of crops cultivated in the present) that increase towards the surface provides validation that this section represents a period of human landscape transformation, but is not enough to be considered high resolution.

In addition, the preservation of palynomorphs is poor in basal sediments, but increases closer to the upper levels, a feature likely related to processes of oxidation and erosion. Our multi-proxy analytical approach was designed to overcome these shortcomings, as phytoliths and NPPs have a higher preservation potential than pollen grains, and the sedimentological analyses can offer control over the complex processes of sedimentation and percolation that are common in soils (Horrocks and D´Costa, 2003). The intersection of multiple proxies and comparison with similar sites in Cabo Verde allow for an interpretation of the scoria-cone record that yields new insights into volcanism, ecological dynamics and the human dimension landscape change.

**4.1 Timing and effects of Late Holocene volcanism on Fogo Island**

Although volcanic activity since the European settlement is relatively well documented (e.g., Ribero, 1960; Torres et al., 1997), constraints on pre-historic Holocene volcanism on Fogo Island are limited. Dating of surficial lava flows on the island and tephra deposits in nearby marine sediment cores are largely limited to the Pleistocene, with the youngest flows dated by the 3He exposure method to ~11,000 BP, and only three Holocene tephra deposits are tentatively linked with Fogo in the marine sediments (~6000, ~3000, ~1000 cal yr BP) (Foeken et al., 2009; Eisele et al., 2015). In this context, sediments accumulated in scoria-cones can hold information on past eruptions depending on their location relative to eruptive centres, dominant wind direction and other factors, including eruption type. The KN record is unlikely to preserve a complete history of Fogo´s volcanism because of discontinuous sampling and taphonomy. For example, minor eruptions could be obscured because of repeated re-working of tephra from the scoria-cone walls. Also, due to its westerly location and distance from diverse eruptive centres of Fogo, the KN record is biased towards eruptions from the western slopes of the islands. This limitation notwithstanding, our results add to the evidence that there was limited activity between 4100-1600 cal yr BP. This is further supported by the paucity of type-2 tephra shards in the KN record before 1600 cal yr BP, after which the KN record shows continuous and abundant deposits of primary glass shards. This indicates either a resurgence of Fogo´s volcanic activity that has been sustained until the present, or abundant deposition of volcanic glass on the landscape that continues to be re-worked into the accumulating sediment.

Figure 4: Composite diagram showing KN site including charcoal data, curves for LOI, selected elemental composition and grain size distribution data, tephra abundance, phytolith D/P ratio (grassy/woody), pollen DCA axis-1 and selected pollen and NPP percentages.

The prominent peak in glass shards ca. 1200 cal yr BP (KN65; UA 3631) analysed via EPMA indicates a tephra-phonolite and phono-tephrite composition, consistent with published glass data from confirmed Fogo deposits (Eisele et al., 2015; Fig 2). The sample (Fig 2; SI Table S1) is somewhat bimodal in composition, a common feature in Fogo´s eruptions, in which initial lava composition is more evolved than the latter emissions (Mata et al., 2017). We are unable to correlate these shard composition data to any previously described tephra in the region, as there are no tephra layers of this age reported and analysed elsewhere. Given the sedimentology of the site, it is not unlikely that some of these analyses are on reworked shards. However, the sharp, higher concentration peak with relatively consistent geochemistry suggests that the sample largely represents an eruption at this time. This peak could be product of undated eruptions within the western slopes of Fogo, which would explain its prominence in the record.

The compositional differences between Fogo (KN65) and nearby Brava’s (CG62) sample suggests different volcanic sources, with CG62 glass geochemistry much more consistent with Brava and the nearby seamount Cadamosto (Eisele et al., 2015). Eisele et al. (2015) did not find any Holocene-aged marine tephra in their study that were attributable to Brava or nearby seamounts. However, studies on phreatomagmatic craters and phonolitic lava domes scattered over Brava’s summit plateau have led several researchers to postulate that there has been Holocene activity prior to settlement (e.g., Machado et al., 1968; Madeira et al., 2010). The glass chemistry of the CG62 and its estimated age of 1495 cal yr BP (Castilla‐Beltrán et al., 2021b) indicates that these inferences are likely correct whether or not the glass shard peak represents primary airfall or local reworking. This is in contrast to historic times, when Fogo´s volcanic eruptions were likely responsible for the deposition of tephra on Brava (Castilla‐Beltrán et al., 2021b), which has had no reports of historic volcanic activity (e.g. Day et al., 1999).

The ecological impacts of Fogo´s volcanism can be direct (e.g., destruction of vegetation through fire or burial by ash) or indirect (e.g., nutrient enrichment of soils) (Ayyris and Delmelle, 2012; Payne and Egan, 2019). Due to the proximity (10.8 km) of the site to Pico do Fogo, it is likely that incandescent material in the form of lapilli fragments, volcanic bombs or lava flows directly ignited fires in the study area, as increases in charcoal concentration in zone KN-2 suggest. Further influence of volcanism could have come from tephra deposition and landslides caused by earthquakes affecting both local vegetation and soils. Palynomorph and phytolith assemblages preserved within the basal layers of the record permit an approximation of local ecological dynamics of the Late Holocene in Fogo´s highlands. The dominance of Poaceae, Asteraceae*,* and Urticaceae pollen indicates an open landscape; yet poor preservation conditions likely obscure the floral diversity and hamper the reconstruction of this landscape. The abundance of *Brachydesmiella* spores, a saprophytic fungus that has been documented to decompose woody vegetation (Gelorini et al., 2011), and the diversity of fern spores indicate that this open landscape could have held a diversity of woody plants and ferns. The presence of zygospores of *Debarya* (from 3700 until 2300 cal yr BP) could be associated with seasonal flooding and the formation of ephemeral ponds. Pollen of *Pinus* likely originating from North Africa and the Canaries, as well as other taxa native to Europe such as *Alnus* (found in preparations carried out in both laboratories, making laboratory contamination unlikely)is classified as derived from long-distance transport (Hooghiemstra et al., 2006). There are no evident vegetation changes after the onset of volcanic glass deposition after 2500 cal yr BP. However, indicators of erosion (fine sand percentages) and local/regional fire (micro- and macro-charcoal concentrations) increase in this period, likely direct consequences of volcanic activity in the form of earthquakes that mobilised sediment and produces collapses of volcanic structures, and direct ignition of fuel sources by lava flows or volcanic bombs. The peak in volcanic glass shard deposition ca. 1200 cal yr BP (sample KN-65) coincides with a more diverse assemblage of pollen produced by herbaceous and shrub species, including *Echium,* *Euphorbia Faidherbia*, *Lavandula,* and *Lotus*. While substantial vegetation changes towards woody vegetation have been recorded in the neighbouring island of Brava around this period (Castilla‐Beltrán et al., 2021b), in the KN record any changes are difficult to ascertain due to the limited preservation of palynomorphs. The phytolith D/P index indicates an increase in woody elements in the landscape between 2000 and 1400 cal yr BP, and it could reflect succession between shrubs and grasses in the local environment, potentially leading to increased fuel load that could explain an increase in local fires. Overall, the general picture is of the continuity of an open landscape subjected to fires and erosion pulses in an increasingly active volcanic setting.

**4.2 Taming Fogo Island: Land use and the anthropization of Fogo´s highlands**

Evidence of past landscape modification by people is useful to assess the specific transformations that have led to present environmental vulnerabilities, such as soil degradation and the expansion of invasive species (Nogué et al., 2017). In the case of Cabo Verde, human impacts have taken place throughout the last 550 years (since c. 1470 CE) (Castilla-Beltrán et al., 2021a). These impacts involved different culture-environment dynamics, from colonial-style experimentation towards intensive crop production to small-scale subsistence by local inhabitants. Since the early stages of colonization, animal husbandry and wood collection are thought to have affected native scrublands and open woodlands, even producing the extinction of at least two endemic plant species: *Stachytarpheta fallax* and *Habenaria petromedusa* (Romeiras et al., 2016). Fogo, as the second island to be settled, has gone through several stages of socioeconomic development; the first stage in the 15th century would have involved horse breeding and the early establishment of cotton plantations (Green, 2012), while New-World crops such as maize (*Zea mays*) made it to the archipelago as early as 1530 CE (Moran, 1982). The upper sediment layers from the Ka Nazario (Zones KN-3 and KN-4, covering the period from c. 800 cal yr BP to the present) show microfossil evidence of direct economic activities, volcanism, and fires likely of anthropic origin. Due to the sandy characteristics of the material in this section, particle percolation may have resulted in microfossil reworking between adjacent layers, meaning the biostratigraphy cannot be considered high-resolution. Therefore, single events cannot be inferred, but rather the record should be viewed as a succession of different periods characterised by distinct ecological processes. For instance, the first pattern is a peak in *Sporormiella* fungal spores, in level 50 cm (95% age-depth model probability min. and max. estimates of 1100-600 cal yr BP), a sample also containing the first evidence of agriculture in the form of pollen grains of *Zea mays*. We interpret the early presence of *Zea mays* as a percolation through sandy sediments, or perhaps it was incorporated into the soil through soil preparation for agriculture or from herbivore trampling. The combination of maize cultivation and intensive herbivore presence in levels 50-40 cm (minimum 95% age-depth model intervals of 600-400 cal yr BP) is contemporaneous with the highest charcoal concentration levels of the record, suggesting a first land-use. These indicators of first land use have also been recorded in other Cabo Verde records, for instance, *Zea mays* pollen grains alongside coprophilous fungal spores were found in Santo Antão, São Nicolau, and Brava sediments, indicating that maize agriculture and herding were adopted throughout the archipelago, and constitute reliable markers of early land use (Castilla-Beltrán et al., 2019, 2020, 2021b). In Fogo, the pollen assemblage in these levels also shows the presence of native species such as *Echium* cf. *vulcanorum,* *Euphorbia tuckeyana*, *Ficus* sp., and *Lavandula* cf. *rotundifolia*, representing a diverse native ecosystem.

The history of the archipelago, and particularly of Fogo Island, between the 16th and 19th centuries was marked by hardship brought about by volcanic eruptions, famines and a turn in the commercial role of Cabo Verde towards economic isolation, as other colonies outcompeted it in terms of productivity and strategic placement (Green, 2012). A gradual decrease in native species (e.g. *Artemisia*, *Echium*, *Lavandula*) and the progressive introduction of crops and non-native plants, are recorded in the KN sediments in this period. These dynamics are common to other Cabo Verdean islands. For example, it was recorded the introduction of *Lantana camara* and *Furcraea foetida* on Santo Antão during the period 250 and 100 cal yr BP (Castilla-Beltrán et al., 2019). In addition, a substitution of native woody scrublands by open pastures was recorded in São Nicolau c. 200 cal yr BP (Castilla-Beltrán et al., 2020). Importantly, these findings suggested that the Cabo Verdean islands were displaying a trend towards the loss of biotic distinctiveness (Castilla-Beltrán et al., 2021a). Other consequence of the first use of Fogo´s highland soils was an increase in sand deposition after c. 300 cal yr BP (Fig 4), probably eroding material from the crater edges linked to loss of vegetation cover through fire and grazing. Particle percolation imposes a limitation in the reconstruction of the impacts of particular short-term socio-ecological crises in this record, such as the almost total abandonment of the island after the 1680 CE eruption (Ribeiro, 1960). However, some of the consequences of Fogo´s volcanism in this period can be tracked in its neighbouring island, Brava, as migration to flee the volcanic hazards led to intensifying land use within the highlands, with evidence of increased fires and herbivore presence (Castilla-Beltrán et al., 2021b). Considering the evidence of pre-human fires and erosion pulses linked to volcanism, and the open grassland vegetation, our results support the idea of Fogo´s natural conditions (i.e. active volcanism, steepness, soil instability) as strong limiting factors that have historically constrained socio-economic development.

In the 20th century, a new period in socio-economic development started, based on the establishment of subsistence agriculture and afforestation initiatives using introduced trees (Baptista et al., 2015). This is evident in the top part of the record (level 30 cm-surface), where pollen of the crop Pigeon Pea (*Cajanus cajan*)becomes dominant, alongside evidence of other introduced taxa, such as *Cupressus, Grevillea*, *Mimosa*, and *Prosopis*. This shows the configuration of anthropogenic landscapes designed to provide wood resources and protect soils from the toll of previous centuries of land use, one were introduced trees have become widespread. The presence of pollen from *Dichrostachys* and *Faidherbia* in superficial levelsshows that at least some woody native taxa are integrated among tree plantations, likely remains of natural vegetation. Future studies could reflect on the socio-ecological benefits of promoting these taxa over introduced trees to improve livelihoods, soil stability and habitats for native fauna in different islands of Cabo Verde.

1. **Conclusion**

Dry regions on Earth are often the focus of ongoing biodiversity and sustainability challenges (Bonkoungou, 2001). Palaeoecological sites in these environments are difficult to find and study (Brunelle et al., 2018), limiting the knowledge of long-term ecological and land use change, which has been demonstrated to add valuable information on patterns and trends for management (Nogué et al. 2017). On Fogo Island, the study of a sediment sequence accumulated in a highland scoria-cone 1010 m a.s.l. offered an opportunity to examine landscape development in a historically highly active volcanic island. Despite poor pollen preservation in basal strata, the integration of multiple lines of evidence allowed us to analyse long-term interactions between vegetation, volcanism, fire, and soil dynamics. The main trend in the dataset is from an open grassland landscape subjected to minimum fire activity towards a phase of increasing native woody taxa, fire occurrence, and tephra deposition. Volcanic activity increases after 1200 cal yr BP, roughly contemporaneous with tephra deposition from local eruptions in Brava. The progressive activation of Fogo´s volcanic cones may have led to increases in fire occurrence and erosion pulses. Evidence of local land use outlines a change between an economy based on animal husbandry and cultivation of maize towards subsistence economies of leguminous crops. The introduction of a diverse array of exotic trees to provide wood and stabilize soils, and the establishment of invasive herbs has drastically transformed these slopes. This represents the latest chapter in a history of efforts to ‘tame’ this steep, dry and hazardous island.

1. **Acknowledgements**

We thank the Association of Environmental Archaeology for funding our expedition to Fogo Island through a Small Research Grant (2019) awarded to ACB. This research was carried out under two different research grants: +3 Geography PhD grant (2017-2020) and Juan de la Cierva Postdoctoral Research Grant (2022-2024), both awarded to Alvaro Castilla-Beltrán. Basal RC data was funded under NERC RC date award (2203.1019). We thank the vital help and guidance during fieldwork of Herculano Dinis, director of Projecto Vitó (CEPF-funded project), geographers José Luis Correira and Adilson Pina Golçalves (staff of Projecto Vitó), and student volunteer Tiogo Alves Gomes. We thank SUERC for funding the Radiocarbon dating of the basal sample (Grant number 2203.1019). Jordan Harvey and Chris Hayward kindly helped to prepare samples for EPMA at the University of Alberta and the University of Edinburgh.

1. **References**

Alexandre A, Meunier J-D, Lézine A-M, et al. (1997) Phytoliths: indicators of grassland dynamics during the late Holocene in intertropical Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology* 136: 213-229.

Ayris, PM, and Delmelle, P. (2012). The immediate environmental effects of tephra emission. *Bulletin of volcanology*, 74:1905-1936.

Baptista I, Ritsema C and Geissen V. (2015) Effect of integrated water-nutrient management strategies on soil erosion mediated nutrient loss and crop productivity in Cabo Verde drylands. *PloS one* 10: e0134244.

Blaauw M and Christen JA. (2013) Bacon Manual e v2. 3.5. 387-394.

Bonkoungou, E.G., (2001). Biodiversity in drylands: challenges and opportunities for conservation and sustainable use. Challenge Paper. The Global Drylands Initiative, UNDP Drylands Development Centre, Nairobi, Kenya.

Brum da Silveira A and Madeira J. (2006) Morphology and Structure of Fogo Island (Cape Verde): new data. Mirão, J. & Balbino, A. (eds.), Extended abstracts of the VII Congresso Nacional de Geologia, vol II: 679-682.

Brunelle A, Minckley TA, Shinker JJ, et al. (2018) Filling a geographical gap: New paleoecological reconstructions from the desert southwest, USA. *Frontiers in Earth Science* 6: 1-17.

Cappello A, Ganci G, Calvari S, et al. (2016) Lava flow hazard modeling during the 2014–2015 Fogo eruption, Cape Verde. *Journal of Geophysical Research: Solid Earth* 121: 2290-2303.

Carracedo, J.C., Perez‐Torrado, F.J., Rodriguez‐Gonzalez, A., Paris, R., Troll, V.R. and Barker, A.K., (2015). Volcanic and structural evolution of Pico do Fogo, Cape Verde. *Geology Today*, 31(4), pp.146-152.

Castilla-Beltrán A, de Nascimento L, Fernández-Palacios JM, et al. (2019) Late Holocene environmental change and the anthropization of the highlands of Santo Antão Island, Cabo Verde. *Palaeogeography, Palaeoclimatology, Palaeoecology* 524: 101-117.

Castilla-Beltrán A, De Nascimento L, Fernández-Palacios J-M, et al. (2021a) Anthropogenic transitions from forested to human-dominated landscapes in southern Macaronesia. *Proceedings of the National Academy of Sciences* 118.

Castilla‐Beltrán A, de Nascimento L, Fernández‐Palacios JM, et al. (2021b) Effects of Holocene climate change, volcanism and mass migration on the ecosystem of a small, dry island (Brava, Cabo Verde). *Journal of Biogeography* 48: 1392-1405.

Castilla-Beltrán A, Duarte I, de Nascimento L, et al. (2020) Using multiple palaeoecological indicators to guide biodiversity conservation in tropical dry islands: The case of São Nicolau, Cabo Verde. *Biological Conservation* 242: 108397.

Chevalier A. (1935) Les iles du Cap Vert. Géographie, biogéographie, agriculture. Flore de l'Archipel. *Journal d'agriculture traditionnelle et de botanique appliquée* 15: 733-1090.

Costa CGF. (2020) Revisiting disasters in Cabo Verde: a historical review of droughts and food insecurity events to enable future climate resilience. *Revista española de estudios agrosociales y pesqueros*: 47-76.

Day, S.J., Da Silva, S.H., Fonseca, J.F.B., (1999). A past giant lateral collapse and present-day flank instability of Fogo, Cape Verde Islands. *Journal of Volcanology and Geothermal Research*.

Donovan J, Kremser D, Fournelle J, et al. (2015) Probe for EPMA: Acquisition, automation and analysis, version 11: Eugene, Oregon, Probe Software. *Inc., http://www. probesoftware. com*.

Duarte MC, Rego F, Romeiras MM, et al. (2008) Plant species richness in the Cape Verde Islands: eco-geographical determinants. *Biodiversity and Conservation* 17: 453-466.

Eisele S, Reißig S, Freundt A, et al. (2015) Pleistocene to Holocene offshore tephrostratigraphy of highly explosive eruptions from the southwestern Cape Verde Archipelago. *Marine Geology* 369: 233-250.

Finsinger W and Tinner W. (2005) Minimum count sums for charcoal concentration estimates in pollen slides: accuracy and potential errors. *The Holocene* 15: 293-297.

Fritz, SC, Björck, S, Rigsby, CA, et al. (2011) Caribbean hydrological variability during the Holocene as reconstructed from crater lakes on the island of Grenada. *Journal of Quaternary Science* 26: 829-838.

Foeken JP, Day S and Stuart FM. (2009) Cosmogenic 3He exposure dating of the Quaternary basalts from Fogo, Cape Verdes: implications for rift zone and magmatic reorganisation. *quaternary geochronology* 4: 37-49.

Garfield R. (2015) Three islands of the Portuguese Atlantic: Their economic rise, fall and (sometimes) rerise. *Shima* 9: 47-59.

Gelorini V, Verbeken A, van Geel B, et al. (2011) Modern nonpollen palynomorphs from East African lake sediments. *Review of Palaeobotany and Palynology* 164: 143-173.

Gosling WD, Miller CS and Livingstone DA. (2013) Atlas of the tropical West African pollen flora. *Review of Palaeobotany and Palynology* 199: 1-135.

Green T. (2012) *The rise of the trans-Atlantic slave trade in Western Africa, 1300–1589,* Cambridge: Cambridge University Press.

Grimm E. (1993) *TILIA: a pollen program for analysis and display*.

Hayward, C. (2012). High spatial resolution electron probe microanalysis of tephras and melt inclusions without beam-induced chemical modification. *The Holocene* 22: 119–125.

Heckman J. (1985) Culture and the environment on the Cape Verde islands. *Environmental management* 9: 141-150.

Heiri O, Lotter AF and Lemcke G. (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25: 101-110.

Hooghiemstra H., Lézine AM, Leroy, SA, Dupont, L, & Marret, F. (2006) Late Quaternary palynology in marine sediments: a synthesis of the understanding of pollen distribution patterns in the NW African setting. *Quaternary International*, 148: 29-44.

Horrocks, M, D'Costa, DM, (2003) Stratigraphic palynology in porous soils in humid climates: An example from Pouerua, northern New Zealand. *Palynology*, 27: 27–37.

Instituto Nacional de Estatística (2018) Estatísticas do Ambiente 2016. In https://ine.cv/wp-content/uploads/2018/06/estatisticas-do-ambiente-2016.pdf

 Jensen B, Daviesa LJ, Nolan C, et al. (2021) A latest Pleistocene and Holocene composite tephrostratigraphic framework for northeastern North America. *Quaternary Science Reviews* 272: 107242.

Jensen BJ, Froese DG, Preece SJ, et al. (2008) An extensive middle to late Pleistocene tephrochronologic record from east-central Alaska. *Quaternary Science Reviews* 27: 411-427.

Kokelaar BP. (2002) Setting, chronology and consequences of the eruption of Soufrière Hills Volcano, Montserrat (1995-1999). *Geological Society, London, Memoirs* 21: 1-43.

Kuehn SC, Froese DG, Shane PA, et al. (2011) The INTAV intercomparison of electron-beam microanalysis of glass by tephrochronology laboratories: results and recommendations. *Quaternary International* 246: 19-47.

Lam K. (2021) Island-raised but foreign-made: Lived experiences, transnational relationships, and expressions of womanhood among Cape Verdean migrant women in Greater Lisbon. *Island Studies Journal,* 16(1), 2021, 101-114.

Le Maitre RW, Bateman P, Dudek, A, et al. (1989) *A classification of igneous rocks and glossary of terms. Recommendations of the IUGS Subcommission on the Systematics of Igneous rocks*. London: Blackwell Scientific Publications.

Lindskog P and Delaite B. (1996) Degrading land: an environmental history perspective of the Cape Verde Islands. *Environment and History* 2: 271-290.

Machado F, Azeredo Leme J, Monjardino J, Seita F. (1968) Carta geológica de Cabo Verde, notícia explicativa da ilha Brava e dos ilhéus Secos. *Garcia de Orta* 16:123-130.

Madeira J, Mata J, Mourão C, et al, (2010) Volcano-stratigraphic and structural evolution of Brava Island (Cape Verde) based on 40Ar/39Ar, U–Th and field constraints. *Journal of Volcanology and Geothermal Research* 196: 219-235.

Martínez-Moreno FJ, Santos FM, Madeira J, (2018) Investigating collapse structures in oceanic islands using magnetotelluric surveys: The case of Fogo Island in Cape Verde. Journal of Volcanology and Geothermal Research, 357: 152-162.

Mata J, Martins S, Mattielli N, et al. (2017) The 2014–15 eruption and the short-term geochemical evolution of the Fogo volcano (Cape Verde): Evidence for small-scale mantle heterogeneity. *Lithos*, 288: 91-107.

Mitchell-Thomè R. (1981) Vulcanicity of historic times in the Middle Atlantic Islands. *Bulletin Volcanologique* 44: 57-69.

Moran EF. (1982) The evolution of Cape Verde's agriculture. *African Economic History*: 63-86.

Nogué S, de Nascimento L, Froyd CA, et al. (2017) Island biodiversity conservation needs palaeoecology. *Nature Ecology and Evolution* 1: 1-9.

Nogué S, Santos AM, Birks HJB, et al. (2021) The human dimension of biodiversity changes on islands. *Science* 372: 488-491.

Oksanen J, Blanchet FG, Kindt R, et al. (2013) Package ‘vegan’. *Community ecology package, version* 2: 1-295.

Patterson KD. (1988) Epidemics, famines, and population in the Cape Verde Islands, 1580-1900. *The International Journal of African Historical Studies* 21: 291-313.

Payne RJ and Egan J. (2019) Using palaeoecological techniques to understand the impacts of past volcanic eruptions. *Quaternary International* 499: 278-289.

Reimer PJ, Austin WE, Bard E, et al. (2020) The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62: 725-757.

Ribeiro O. (1960) *A ilha do Fogo e as suas erupções*: Junta de investigaçôes do ultramar.

Roberts D. (1971) The demography of Tristan da Cunha. *Population Studies* 25: 465-479.

Romeiras MM, Catarino S, Gomes I, et al. (2016) IUCN Red List assessment of the Cape Verde endemic flora: towards a global strategy for plant conservation in Macaronesia. *Botanical journal of the Linnean Society* 180: 413-425.

Torres P, Madeira J, Silva L, et al. (1995) Carta geológica das erupções históricas da ilha do Fogo: revisão e actualização. *A erupcao vulcanica de1995 na ilha do Fogo, Cabo Verde”,* edited by Instituto *de* Investigação Científica Tropical, Lisboa, pp 119-132

Turney CS. (1998) Extraction of rhyolitic component of Vedde microtephra from minerogenic lake sediments. *Journal of Paleolimnology* 19: 199-206.

Worsley, P. (2015). Physical geology of the Fogo volcano (Cape Verde Islands) and its 2014-2015 eruption. *Geology Today* 31(4): 153-159.

Zolitschka B, Schäbitz F, Lücke A, et al. (2006). Crater lakes of the Pali Aike Volcanic Field as key sites for paleoclimatic and paleoecological reconstructions in southern Patagonia, Argentina. *Journal of South American Earth Sciences* 21(3): 294-309.