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Post-caldera evolution of Deception Island (Bransfield Strait, Antarctica) over Holocene timescales

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A B S T R A C T

The study of palaeoclimatic changes in fast warming regions can contribute to the understanding of the forcing mechanisms responsible for the global changes that are presently happening. Deception is an active volcanic island in the Bransfield basin that has a complex history strongly influenced by both magmatic and tectonic processes. However, without accurate information on the distribution of melt, depth of sediments and Holocene timescales of its volcanic eruptions, the models for the post-caldera evolution of Deception Island are poorly constrained. Although this region has undergone severe environmental changes due to recent eruptions, hindering the location of potential study areas of paleo-volcanic eruptions, it is still possible to reconstruct post-caldera evolution at a local scale. Employing analyses such as radiocarbon dating, stable carbon and nitrogen isotopic compositions and particle-size distributions in subsoil horizons, we have studied the coastal areas of Whalers Bay and between Wensleydale Beacon and Cross Hill to identify the major periods of alluvial sedimentation on Deception Island. Whalers Bay was influenced by a large amount of moving water generated by ice melting. The coastal location of both sampling sites contributes to preserve the sedimentation history in their soil profiles, despite the severe environmental changes due to recent eruptions. Our findings indicate that from approximately 13 to 5 cal kyr BP, the accumulation of organic matter was stable and the landforms were not altered. After that time, post-caldera eruptions occurred, melting the glacier and, consequently, flooding surficial soil layers with mud. These changes are consistent with old ^{14}C ages for subsoil organic matter and, therefore, with the occurrence of intense cryogenic disturbance processes.

1. Introduction

The study of palaeoclimatic changes contributes to the understanding of the forcing mechanisms responsible for the global climate changes that have been happening in recent decades (Bentley et al., 2009). In this context, Deception, a Quaternary volcanic island formed on the spreading axis of the Bransfield Strait in the northern Antarctic Peninsula (Vaughan et al., 2003), is considered an outdoor laboratory for volcano geophysics and phenomena such as debris-flow processes, being the site of several multidisciplinary studies on the origin and morphology of the South Shetland Islands archipelago (e.g., Smellie, 2002; Lee et al., 2007; Torrecillas et al., 2012 and 2013; Toro et al., 2013; Liu et al., 2016; Prudencio et al., 2015). Deception Island has traditionally been treated as a < 0.75 Ma collapsed caldera formed by the subsidence of overlapping volcanoes into a magma chamber along arcuate and radial faults (Martí et al., 1996; Smellie, 2001 and 2002; Russell et al., 2014). According to the model proposed by Martí et al. (2013), the caldera was formed during or after a single eruptive event and numerous tectonic faults favored the downward movement of the caldera blocks, destroying the associated magma chamber. Volcanism then re-ascended, fed by deeper magmas and using the same fractures and faults that controlled the caldera collapse as pathways, as a very active geothermal system.

Unfortunately, the very few published data on the subject prevent a satisfactory understanding of the post-caldera geological evolution in this region. Therefore, our knowledge about the volcanic history of Deception Island is incipient and usually related to the approximately 20 eruptions that have occurred in the last two centuries (Roobol, 1982; Torrecillas et al., 2012 and 2013). The latest eruptions happened in the late 1960s and 1970s, damaging or even destroying scientific bases on

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the island (Baker et al., 1975; Roobol, 1982; Pallas et al., 2001; Smellie, 2002). In terms of scientific research, these recent eruptions tend to hinder the location of study areas suitable for further study of the landscape evolution and the soil development of Deception Island, mainly during the Holocene (Liu et al., 2016). The few existing geochronological data are based on isochronous tephra deposits and, therefore, there is only a relative chronological control for environmental changes occurred in the region (Lee et al., 2007; Liu et al., 2016). Several Holocene tephra layers in ice, lake and marine sediment cores found in the northern Antarctic Peninsula are thought to have originated from Deception Island's eruptions (Smellie, 2002; Kraus et al., 2013; Liu et al., 2016). Radiocarbon dates from tephra horizons indicate that several eruptions occurred during the last 5.0 cal kyr BP in the area (Lee et al., 2007; Liu et al., 2016). However, geochronological information is still needed to sustain hypotheses about post-caldera volcanic history and paleo-environmental reconstructions.

Geochemical and geochronological analyses such as the determination of stable isotope ratios and radiocarbon dating of the organic matter present in sedimentary deposits can provide meaningful information on the complex history of Deception Island during Late Pleistocene-Holocene times (Lee et al., 2007; Toro et al., 2013; Liu et al., 2016). The objective of this work is to assess the data from coastal soils in ice-free subpolar areas of Whalers Bay and between Wensleydale Beacon and Cross Hill. These areas were deeply affected by recent eruptions that could have promoted changes in the sequences of their sedimentary deposits (Smellie, 2002).

2. Study area

The South Shetland Islands, located in the northern Antarctic Peninsula region (Fig. 1A), between the Drake Passage and the Bransfield Sea (Fig. 1B), are part of a Mesozoic–Cenozoic magmatic arc that opened in a reaction to continental back-arc extension < 1.4 Ma (Fretzdorff and Smellie, 2002; Martí et al., 2013). According to Liu et al. (2016), many active or recently active volcanic centres in the South Shetland Islands (e.g., Deception Island, Penguin Island, Bridgeman Island), many submarine seamounts and several remnant volcanic centres on Livingston, Greenwich, and King George Islands (Fig. 1B) were developed due to arc magmatism and subsequent rifting. The most active volcano in this region is Deception Island (62°57′ S, 60°38′ W; Fig. 1C). It is a young (< 0.75 Ma) horseshoe-shaped stratovolcano (submerged basal diameter ≈ 25 km and emerged diameter ≈ 15 km; Martí et al., 1996), up to 540 m above sea level (a.s.l.) at Mount Pond and 460 m at Mount Kirkwood. Glaciers account for more than half of the island surficial area (Smellie, 2001; López-Martínez et al., 2012). The centre of the island is a depression, with ≈10 km in diameter and flooded by a relative sea level change, known as Port Foster, considered to be the caldera (Martí et al., 2013). On the southeast coast, Port Foster is connected to the sea via a shallow and narrow passage (Martí et al., 2013). According to Smellie (2002), although the eruption responsible for the caldera formation was a large event which may have expelled > 25–30 km^3 of magma, the magnitude of post-caldera eruptions seems to have been much smaller (typically < 0.05 km^3), forming tuff cones and maars with cinder cones and associated lavas.

The South Shetland Islands experiences a subantarctic maritime climate according to the Köppen climate classification. Deception Island has an ET (tundra climate) climate, South Hemispheric Polar Oceanic (Köppen, 1936; Michel et al., 2014). According to López-Martínez et al. (2012), common weather types connect with cold and dry periods predominant in winter, and the influence of the circumpolar trough of low pressure during summer, with strong westerly wind and wet and relatively warm air masses. The mean annual air temperature at sea level is ≈ −2.9 °C with extreme monthly temperatures ranging from −28 °C to +11 °C (Vieira et al., 2008). Snow cover melting and freeze-thaw cycles during summer are favored by such climate conditions (López-Martínez et al., 2012). The annual precipitation ranges from 500 to 800 mm (Bañón et al., 2013). Vegetation on Deception Island is characterized by being generally restricted to permanently moisturized areas of stable rock or soil (Downie et al., 2000; Bockheim, 2015). Most volcanic substrata, especially those evolved from the three 1967–70 eruption episodes (Fig. 1D), are characterized by being unstable, porous and arid, being devoid of broad plant communities. Deception Island's flora encompasses > 70 species of mosses, seven species of liverworts, and 70 species of lichens (Downie et al., 2000). Terrestrial springtails (Collembola: Hexapoda), mites (Acarina: Arachnida) and fresh-water nematodes (Nematoda) predominates in the invertebrate fauna (Downie et al., 2000; Angulo-Preckler et al., 2017).

Ice-cemented permafrost is missing on beaches and areas such as faults and fumaroles, but occurs widely from sea level to the highest peaks (Vieira et al., 2008). Around the shores of Port Foster, the occurrence of stream-deposited gravelly-sandy sediment is frequent, but Fumarole Bay, Whalers Bay and between Wensleydale Beacon and Cross Hill this kind of sediment is especially abundant (Smellie, 2001).

Whalers Bay, on the east side of Port Forster (62°58′42″ S, 60°33′30″ W, 9 m a.s.l), presents ice-free subpolar areas (Fig. 2). While, the 1967 volcanic eruption on Deception Island led to the deposition of a 1–5 cm layer of ash over Whalers Bay, the 1969 eruption resulted in a lahar and, consequently, to the partial burial of the site (Smellie, 2001). Lahars, also known as volcanic mudflows, are significant amounts of hot or cold melt water, often carrying debris (Jakob and Hungr, 2005; Bartolini et al., 2014). Due to their high bulk density and speed, lahars are very destructive. An example of their damaging power is the destruction of the British scientific station at Whalers Bay produced by the 1969 eruption (Baker et al., 1975; Smellie, 2002; Bartolini et al., 2014). Although they can potentially change the sequences of sedimentary deposits, Whalers Bay is still an ideal site for sampling soil/sediment depth profiles to obtain geochemical and geochronological data to assist in the reconstruction of the post-caldera deposit (alluvial sedimentation) evolution.

Even though the coastal area between Wensleydale Beacon and Cross Hill, on the west side of Port Foster (Fig. 3; 62°56′41″ S 060°41′27″ W, 26 m a.s.l), presents heated ground and, therefore, indirect volcanic hazards (Bartolini et al., 2014), it is considered an area that does not present extreme events of lahar, constituting an interesting site to study.

3. Material and methods

3.1. Sample collection

Soil sampling was carried out in two ice free areas of Deception Island: Whalers Bay and between Wensleydale Beacon and Cross Hill, during the austral summer 2013/2014. The sampling sites present the following lithological and physiographic features: sand and gravel as bedrock type and Holocene raised beaches at 5–6 m a.s.l. (Figs. 2 and 3). Soil profiles were collected from pits excavated down to a depth of 60 cm, with a stainless-steel tool to prevent organic contamination. Subsample sets were obtained after sectioning the soil samples at regular depth increments (5 cm), due to the lack of clear soil horizon differentiation. In a few situations, soil profiles displayed colour or grain size differences, used for sectioning the samples. In the field, soil temperature was measured at 45 cm depth using a digital thermometer. Sediment samples were kept at −20 °C to preserve the organic matter (OM) during transportation to the Fluminense Federal University in Brazil.

3.2. Sample preparation

Samples (200–300 g) from each layer of the soil profiles were dried overnight in an oven at 60 °C. Dried samples were then homogenized after the removal of large rock fragments and biological remains through a 2 mm mesh sieve. Old carbon contamination from bedrock-