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Post-caldera volcanism of Deception Island (Antarctica): new insights from Tephra studies and Port Foster Bay volcanic deposits

Joaquín Hopfenblatt Hours



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TEPHRA STUDIES AND PORT FOSTER BAY VOLCANIC DEPOSITS

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Ph.D Thesis

Joaquín Hopfenblatt Hours

January 2024

Supervised by Dr. Adelina Geyer Traver and
Dr. Meritxell Aulinas Juncà

Tutored by Dr. Meritxell Aulinas Juncà

Doctoral Program in Earth Sciences HDK09

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To obtain the degree of doctor from the University of Barcelona

This thesis was conducted within the framework of the Doctoral Program in Earth Sciences

HDK09, supervised by **Dra. Adelina Geyer Traver** and **Dra. Meritxell Aulinas Juncà** and

tutored by **Dra. Meritxell Aulinas Juncà**.

Barcelona, 2024

Joaquín Hopfenblatt Hours

Adelina Geyer Traver

Meritxell Aulinas Juncà

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Abstract

Deception Island (South Shetland Islands) is one of the most active volcanoes in Antarctica and has experienced over 20 explosive eruptive events in recent centuries. Recent eruptions in 1967, 1969, and 1970, as well as volcanic unrest episodes in 1992, 1999, and 2014–2015, highlight the ongoing and potential future volcanic activity on the island. Despite this volcanic activity, the region has witnessed a substantial increase in scientific bases, tourist activities, and air and vessel traffic in the last decades. This surge in interest has raised concerns as the escalating infrastructure and population in the area are increasingly exposed to the risk of future eruptions. This enhanced exposure necessitates an urgent, and accurate, long-term assessment of the volcanic hazard posed by Deception Island. Previous attempts at such assessments have been limited by the incompleteness of the island's eruptive record. The complexities of Deception Island's magmatic and volcanic evolution demand continued significant research efforts to enhance our understanding and contribute to more effective hazard assessments.

This Doctoral Thesis combines diverse research lines, revealing crucial insights into the island's past, present, and potential future volcanic evolution as well as the associated impact of future eruptive events. The investigation encompasses two primary research lines: (1) the study of Port Foster's most relevant eruptive episode, focusing on the formation of the Stanley Patch volcanic edifice, and (2) the identification, compositional, and textural characterization of tephra layers sourced from Deception Island. These research lines are integral to enhance our understanding of the island's geological evolution since the caldera collapse.

Significant efforts have been made to understand the complex magmatic and volcanic evolution of Deception Island, with special interest in its subaerial parts. However, studies on submerged volcanic cones within Port Foster, the sea-flooded part of Deception Island's caldera depression, are comparatively scarce. The study of the Stanley Patch volcanic edifice

utilizes new geophysical data, including bathymetric data and ultra-high-resolution parametric seismic profiles, obtained during the 2017–2018 Spanish Antarctic Campaign. Juvenile rock samples collected from Stanley Patch by SCUBA diving provide valuable insights into the subaerial monogenetic explosive eruption responsible for the formation of this scoria cone. These findings suggest that the caldera could have opened to the sea, leading to complete flooding only after the construction of the Stanley Patch volcano, approximately less than 2000 years ago. The potential triggers for the caldera wall breach include sector collapse, explosive eruption, and/or overtopping of the sea with gradual erosion of the spillway. This transformative event not only altered the sedimentary dynamics within the caldera depression but also marked a shift in the eruptive style of post-caldera volcanic activity, increasing the potential for phreatomagmatic eruptions.

Volcanic ash layers found in marine and lacustrine sediment cores and glaciers outside Deception Island are fundamental sources of information for reconstructing the explosive eruptive record of the volcano. The spatial distribution of the tephra layers, as well as their physicochemical analysis, are invaluable for determining the size and explosiveness of past eruptive events as well as for assessing the extent and impact of their related hazards (e.g., ash fall-out). The DecTephra database is a comprehensive compilation of 362 tephra layers found in marine and lacustrine sediment cores and glaciers sourced from Deception Island. This database serves as a valuable tool for studies on volcanology, petrology, geochemistry, tephrochronology, and regional ash transport. In addition, it can function as a valuable resource for paleoenvironmental and paleoclimatic studies requiring tephrostratigraphic and tephrochronological control at local and regional scales. DecTephra also has the potential to help assess the contribution of volcanic forcing to Holocene climate variability in the Southern Hemisphere.

Furthermore, characterization of tephra fragments from the 1970 eruption provides detailed insights into the eruptive styles and geochemical features of juvenile fragments. Tephra plotted on the compositional field of the second magma series, being the first

occurrence of such features in samples (rocks, tephra, or cryptotephra) not directly linked to the colossal caldera collapse event and their deposits. The identification of a second magma series challenges previous assumptions and suggests a potential magmatic system maturity, possibly heralding a new caldera cycle after the collapse event. Finally, the preliminary results of tephra found at the Bransfield Strait are similar to those of the 1970 Deception Island event, indicating a common phreatomagmatic eruptive style. However, distinct alkali content trends in Bransfield Strait tephra pose intriguing questions regarding their origin, emphasizing the need for further examination to disentangle potential analytical biases.

In conclusion, the combination of research lines pertaining to Port Foster and tephra studies provides significant advancements in our understanding of the post-caldera volcanic activity of Deception Island. The insights gained not only contribute to our comprehension of the island's geological evolution but also serve as a basis for accurate hazard assessments, comprehension of Deception Island's post-caldera volcanic activity, its past and future evolution, and the potential impact of future eruptive events.



PART I

1 CHAPTER 1:

Introduction

1.1 Worldwide volcanic activity and related hazards: General overview

Volcanism, a natural phenomenon characterized by the eruption of molten rock, gases, and other materials from Earth's interior, has fascinated and intrigued humanity for centuries (Sigurdsson et al., 2015). Currently, there are over 500 active volcanoes worldwide, with approximately 50 eruptions in an average year (Smith, 2013). These eruptive events, which can occur in subglacial, subaerial, or submarine environments, may pose a threat to society, infrastructure, environment and climate at local, regional and, in some cases, also global scale.

Over the last 500 years, volcanic eruptions have been responsible for more than 270,000 fatalities (Brown et al., 2017). Indeed, volcanoes can produce a number of potentially lethal hazards (Baxter, 1990), which are commonly divided into direct (e.g., tephra fall, pyroclastic density currents (PDCs), lava flows, ash clouds, columns, lahars) and indirect (e.g., famine, fires, tsunamis) (Tilling, 2005). Historically, most volcano-related fatalities have been due to indirect causes, such as famine arising from crop failure caused by falling volcanic ash, gas emissions, tsunamis or PDCs (e.g., 1883 Krakatoa eruption) (Latter, 1981; Brown et al., 2017). One of the biggest explosive eruptions that caused worldwide deleterious effects occurred in 1815 at Tambora volcano (Indonesia), where PDCs instantly killed all people along with fauna and flora up to 20 km distance around the eruptive vent (Self et al., 2004; Sheets, 2015).

In the 20th century, volcanic eruptions have left tens of thousands of fatalities, the most destructive episodes being the 1902 Mount Pelée eruption in the Caribbean Martinique Island (c. 30,000 fatalities) or the 1985 Nevado del Ruiz eruptive event in Colombia (c. 23,000 fatalities) (e.g., Brown et al., 2017). Examples of highly destructive volcanic eruptions

occurred during the 21st century include, among others, the 2002 and 2021 eruptions of Nyiragongo volcano (Democratic Republic of Congo), the 2010 Merapi eruption (Indonesia), Mount Ontake's (Japan) phreatic explosion in 2014, the Anak Krakatoa (Indonesia) eruption 2018, or the 2019 Whakaari (White Island, New Zealand) phreatomagmatic event (e.g., Rahman et al., 2016; Yamaoka et al., 2016; Omira & Ramalho, 2020; Harvey, 2021; Baker et al., 2022; Sadiki et al., 2023).

Beyond human fatalities, the mid- to long-term disruptions in our daily life caused by volcanic eruptions are numerous and most commonly related to volcanic tephra fall out and dispersal (e.g., water supplies and soil contamination, air pollution), lava flows (e.g., destruction of infrastructure), and gas emission (e.g., climatic effects). For instance, tephra fragments can be highly abrasive because of their hardness and angular morphology (Wilson et al., 2014), and its accumulation due to falling can increase the loading of roofs or structures, damaging buildings and infrastructure (Spence et al., 1996). Additionally, the presence of tephra in the atmosphere may cause severe aviation problems. Tephra particles can become “sticky” as they pass through their glass transition temperatures when they enter the hot parts of the airplane's engines or turbines, causing minerals to melt. This glassy material can clog the air bleed holes and may adhere to metallic surfaces, leading to catastrophic consequences for jet aircraft, with loss of engine power and potentially loss of aircraft (e.g., Connor et al., 2001; Prata & Rose, 2015). As a result, air traffic must be either suspended or reorganized when specific hazardous levels of volcanic tephra are detected in the atmosphere. Indeed, during the 2010 Eyjafjallajökull eruption (Iceland) c. 100,000 flights were canceled all across Europe during a six to eight-day airspace ban, causing a global economic impact of approximately US\$ 5 billion (Prata & Rose, 2015), and affecting 10,000,000 passengers (e.g., Lund & Benediktsson, 2011). At the same time, the condensation of volcanic gasses (e.g., SO₂, CO₂) in the troposphere can lead to the formation of clouds, alongside the stratospheric sulfuric acid aerosols created by SO₂. This increased absorption of solar radiation can result in an increase in tropospheric albedo, resulting in a local surface cooling (Sigurdsson, 1990). For example, after the 1815 Tambora eruption, the aerosol cloud was distributed globally and a global cooling of 1 - 1.5°C (Self et al., 2004), causing a “year without a summer” with devastating distal effects on agriculturally based societies (Sheets, 2015).

In light of the fact that approximately 500 million people currently reside in volcanic regions, and the ongoing trend of settling in vulnerable areas is expected to continue, the likelihood of more individuals being affected by volcanic eruptions in the future is on the rise (Simkin et al., 2001). To illustrate, in places like Mount Etna in Italy (Duncan et al., 1981) and Mount Mayon in the Philippines (Heijmans, 2001), people have compelling reasons for residing in proximity to these volcanoes. These reasons range from the allure of fertile farmland and dependable water sources to opportunities in tourism, geothermal energy, and mineral resources (e.g., Kelman & Mather, 2008; Uehara, 2005). Moreover, some individuals find themselves in these regions out of necessity, often due to financial constraints or other circumstances. This is particularly worrisome given the potential for heightened human exposure to volcanic hazards, especially in urban areas (Chester et al., 2000).

One way to mitigate the potential destructive effects of volcanic eruptions is to carry out a proper volcanic hazard assessment (long- and short-term) and the elaboration of hazard maps (e.g., Tilling, 2005). Long-term volcanic hazard assessment involves analyzing geological records to understand past volcanic activity (typology and recurrence of volcanic events), to fully comprehend the evolution (past and future) of a volcanic system and characterize the potential future eruptions and their related hazards (Tilling, 2005). This can be achieved through temporal and spatial analyses of various geological data, such as stratigraphic records or geochronological data, to estimate the probability of an eruption occurring within a specific time interval (Martí & Folch, 2005). Additionally, spatial analysis helps to identify areas with the highest likelihood of hosting new events. It is critical to know the location of previous events, such as ash-fall, lava flows, PDCs, and lahars, in order to have a comprehensive understanding and observe them in context (e.g., Bartolini et al., 2014). The short-term volcanic hazard assessment includes not only geological data but also monitoring signals such as Global Positioning System (GPS) data to measure potential ground deformation processes, seismicity, and geochemical data, among others (e.g., Chouet et al., 1994; Massonnet et al., 1995; Martí & Folch, 2005; Tilling, 2005).

1.2 Volcanism in Antarctica

The preservation of evidence for the earliest volcanism in Antarctica is poor and scattered, with small outcrops primarily found in the Transantarctic and Ellsworth Mountains (Fig. 1.1) (e.g., Goodge, 2020) due to prolonged tectonic activity from the Late Neoproterozoic to mid-Paleozoic era when it was part of the Gondwana supercontinent. In contrast, evidence of volcanism since the Jurassic period is widespread and generally well exposed (e.g., Smellie, 2020).

There are over 100 volcanoes on the Antarctic continent, with 13 volcanoes (Paulet Island, James Ross Island, Seal Nunataks Group, Hudson Mountains, Mount Takahe, Toney Mountain, Mount Waesche, Mount Siple, Mount Berlin, Royal Society Range, Mount Melbourne, Mount Rittmann, and The Pleiades) with at least one confirmed or suspected eruption during the Holocene (Fig. 1.1) (Global Volcanism Program, <http://www.volcano.si.edu>). In addition, Deception Island, Penguin Islands, Melville Peak, Mount Erebus, Young Island, and Buckle Island (Fig. 1.1) have reported historic activity (since 1820 CE) (Global Volcanism Program, <http://www.volcano.si.edu>). Mount Erebus and Deception Island, considered the most active volcanoes in Antarctica, are the only ones that have been clearly observed during an eruption (e.g., Geyer, 2021; Sims et al., 2021).

Despite their remote location, active Antarctic volcanoes are a matter of concern since thousands of people live and work in Antarctica at any given time. For example, during the Antarctic summer, McMurdo Station (United States of America) can support more than 1,200 people (<https://www.nsf.gov>). Indeed, the number of tourists visiting Antarctica has increased since the first commercial cruise in 1966 (Bender et al., 2016) (Fig. 1.2), particularly near the South Shetland Islands and the Antarctic Peninsula region (Fig. 1.1). Antarctic visitors increased from 30,000 to 103,988 between 2012 and 2023, with a notorious decrease during the COVID-19 pandemic (IAATO, International Association of Antarctica Tour Operators) (Fig. 1.2). In addition to the presence of tourists, Antarctica hosts numerous scientific activities carried out by research vessels and in Antarctic bases. The Antarctic Peninsula region alone, together with the South Shetland Islands, hosts 25 research stations (both temporary and year-round) and three summer field camps located inside (e.g., Gabriel de Castilla Base, Spain;

Deception Island) or within a 150 km radius of Deception Island (e.g., Geyer, 2021; Geyer et al., 2021). For instance, in this same island, British and Chilean scientific stations were destroyed and covered by volcanic ash during the 1967, 1969, and 1970 eruptions (e.g., Roobol et al., 1975; Smellie, 2002a; Pedrazzi et al., 2014).

Considering all the above, it is evident that the exposure of the population and infrastructure to potential future volcanic hazards has remarkably increased in Antarctica, particularly in the South Shetland Islands (e.g., Geyer et al., 2017; Geyer, 2021). This urges the need to improve the knowledge on past volcanic activity, to understand and assess the size and typology of potential future eruptions, improving monitoring networks and data interpretation, conducting vulnerability assessments, implementing mitigation strategies, and establishing early-warning systems and communication protocols (Geyer, 2021).

Currently, a detailed long-term volcanic hazard assessment is only available for Deception Island (Bartolini et al., 2014). It includes a volcanic susceptibility map, the estimation of the eruptive recurrence, and the definition of the most likely future eruptive scenarios. Preliminary volcanic hazard assessment maps have also been carried out for Mount Erebus (Poirot, 2002; Ahser, 2004) and are currently in development, but these are lacking for the rest of Antarctic volcanoes. This highlights the lack of volcanic hazard assessments in the several active Antarctic volcanic systems.

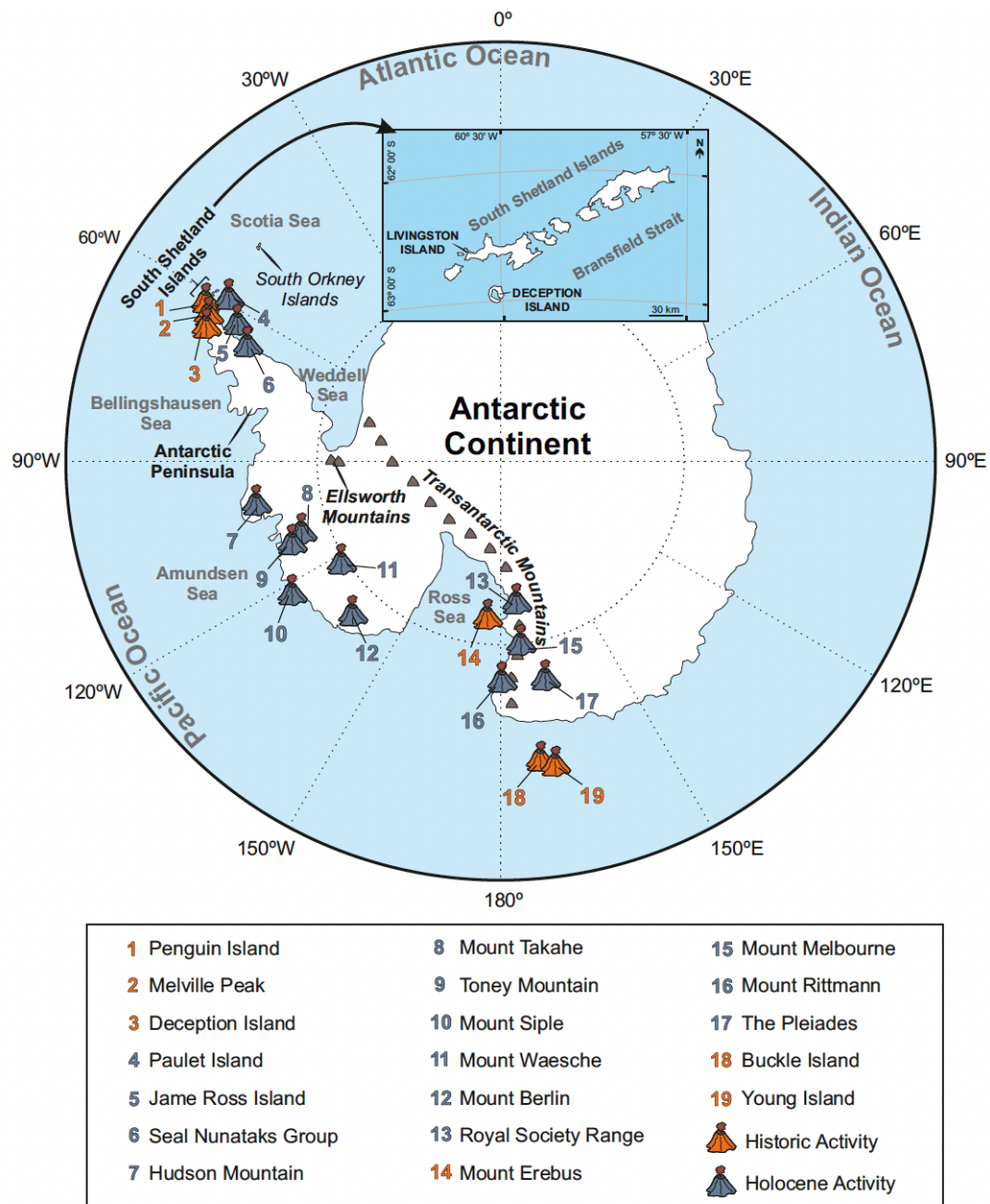


Figure 1.1. Simplified map of Antarctica indicating the location of those volcanoes with recorded activity during the Holocene and, if it is the case, with historic activity (i.e., since 1820 CE) (Global Volcanism Program, <http://www.volcano.si.edu>).

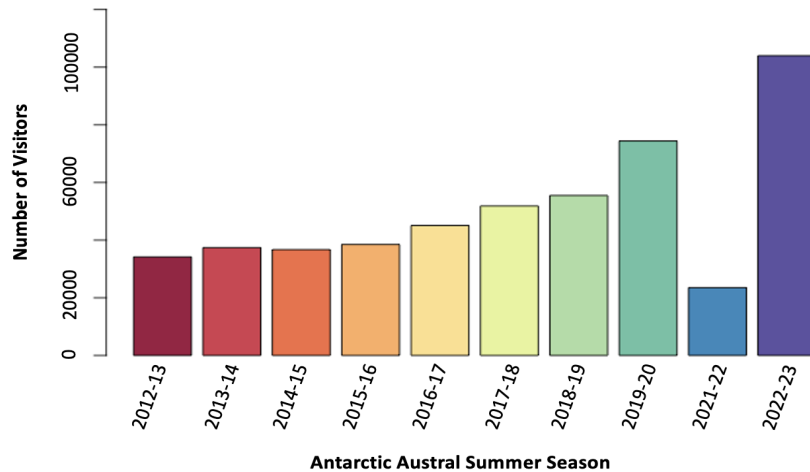


Figure 1.2. Number of Antarctic visitors during the last decade. Data from: IAATO, International Association of Antarctica Tour Operators, <https://iaato.org> (2023).

1.3 Deception Island (South Shetland Islands)

Deception Island (Fig. 1.3) is the most active volcano in the South Shetland Islands region with more than 20 explosive eruptions over the past few centuries (e.g., Roobol 1980; Pallàs et al., 2001; Smellie et al., 2002). The most recent eruptions occurring in 1967, 1969, and 1970 (e.g., Roobol et al., 1975; Smellie, 2002a; Pedrazzi et al., 2014), and volcanic unrest episodes (1992, 1999 and 2014-2015) (e.g., Ibáñez et al., 2003, Almendros et al., 2015) demonstrate that volcanic activity is likely to occur in the future.

The volcanic and magmatic evolution of Deception Island has been strongly marked by the development of a collapse caldera, which led the island to its particular horse-shoe shaped morphology (Fig. 1.3), dated at c. 8300 years, according to paleomagnetic data, (Oliva-Urcia et al., 2015) and 3980 ± 125 calibrated years Before Present (cal yr BP) based on tephrochronology, sedimentological studies and ^{14}C dating (Antoniades et al., 2018). After the caldera collapse, volcanic activity predominantly occurred along the structural borders of the caldera (e.g., Crater Lake eruption) and the interior of Port Foster (e.g., Stanley Patch volcanic cone) (Fig. 1.3). This has mainly consisted of hydromagmatic eruptions with variable intensity and explosivity degree mostly depending on the amount and provenance of water (i.e., aquifer, sea, and/or ice/snow melting) that interacted with the rising or erupting magma (e.g.,

Baker et al., 1975; Pedrazzi et al., 2014, 2018, 2020; Smellie, 2002b). Several submarine pyroclastic cones dot the Port Foster seafloor (López-Martínez and Serrano, 2002; Rey et al., 1995, 1997). These volcanic edifices show an arcuate NNW-SSE alignment and are characterized by relatively steep slopes and a dome-like or cone morphology, the largest one being Stanley Patch volcano (Fig. 1.3), first identified as a volcanic edifice in 1987 (British Antarctic Survey, 1987; López-Martínez & Serrano, 2002).

Deception Island, which hosts temporary military bases and scientific installations, is becoming one of the main tourist attractions in Antarctica (Pedrazzi et al., 2014), and some locations on the island may receive over 15,000 visitors every year (IAATO, International Association of Antarctica Tour Operators; Bartolini et al., 2014), who can be exposed to future volcanic activity. Therefore, it is very important to continue filling the gaps of geologic and volcanic knowledge in order to be able to make more accurate volcanic hazard assessments. The present research will enhance our knowledge of the geology and volcanic processes that occurred on Deception Island following the caldera-forming event, with a focus on understanding the eruptive style and history of the island more comprehensively.

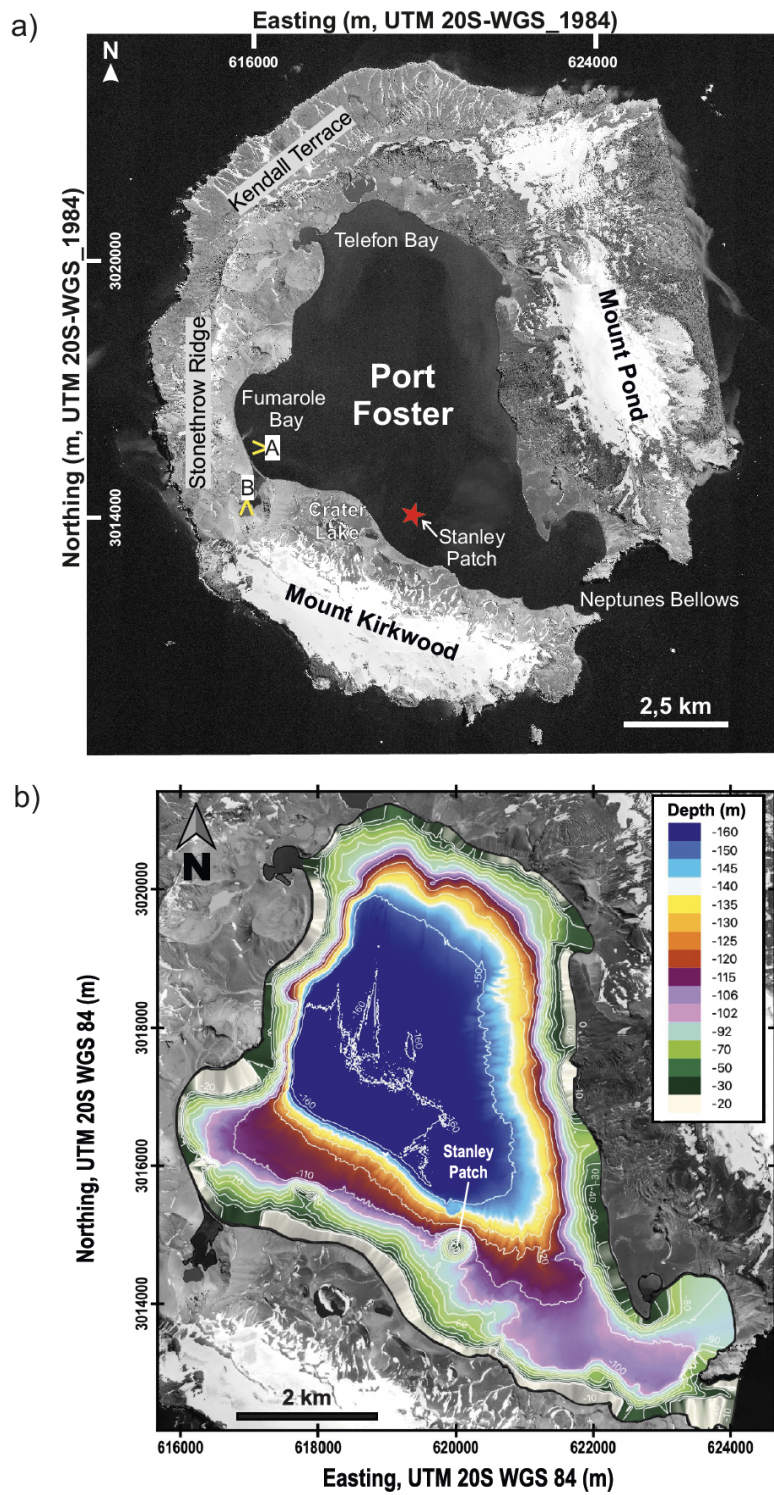


Figure 1.3. a) Orthophotomap of Deception Island (data obtained from Spatial Data Infrastructure for Deception Island-SIMAC; Torrecillas et al., 2006). A and B show the location of the images included in Figure 2.4. b) Digital Elevation Model of Port Foster obtained during the 2012 and 2017–2018 Spanish Antarctic Campaign by the Marine Hydrographic Institute. Location of Stanley Patch volcanic edifice is also indicated.

1.4 Current problematic and objectives

Despite the numerous studies related to Deception Island volcanic system published in the last decades (See Geyer et al., 2021 for comprehensive review and further detail), there is still a lack of knowledge regarding the island's post-caldera volcanic activity. Two of the most relevant pending issues are, an accurate assessment of the eruptive recurrence and deciphering those factors controlling the spatial and temporal evolution of the volcanic activity (i.e., location and typology of future events). Additionally, most of these studies have focused on the subaerial part of the island, leaving aside the submerged part (Port Foster Bay) (Fig. 1.3). In this sense, some questions arise, such as the type of eruption and dynamics of the submerged volcanoes and the potential magma-water interaction during the past eruptive events.

To effectively address these challenges and advance our understanding of Deception Island's post-caldera volcanic activity, as well as its potential future evolution, it is imperative to undertake a series of tasks. These tasks include determining the number, type, size, location, and impact of those eruptions occurred since the caldera's collapse (e.g., by investigating the distribution and extent of the tephra fall out deposits). Furthermore, it is essential to conduct complementary studies on the volcanic cones within Port Foster, such as Stanley Patch. This is necessary to have a more accurate picture of the evolution and dynamics of the island's post-caldera activity occurring within the caldera.

With this in mind, this Thesis has followed two distinct, but complementary, research lines: (1) the study of Port Foster most relevant eruptive episode (i.e., Stanley Patch volcanic edifice), and (2) the identification, as well as the compositional and textural characterization of tephra layers sourced from Deception Island. The final goal of this PhD Thesis is to enhance our overall comprehension of Deception Island's post-caldera volcanic activity, its past and future evolution, and the potential impact of future eruptive events.

For each research line, a brief summary of the specific objectives and performed tasks is provided below. Further detail can be found in the specific chapters and published papers (See Appendixes 1, 2 and 3).

Research line: Port Foster Bay most relevant eruptive episode

Objective: Full characterization of the Stanley Patch volcano (Fig. 1.3), the largest volcanic cone within Port Foster Bay, in order to establish the type and size of the eruption. Results obtained are also used to understand the timing of the caldera flooding by the sea.

Tasks: For the first time, rock samples were taken at various points within Stanley Patch crater. In addition, new bathymetric data and several parametric seismic profiles were obtained from Port Foster. These data were used to conduct a complete physical and chemical characterization of the volcanic cone, including petrographic descriptions, morphometric analysis studies, isotopic analyses, mineral chemistry analyses, and major and trace element geochemical analyses.

Research line: Tephra studies

Database on tephra and cryptotephra layers sourced at Deception Island

Objectives: Compilation of the published information on all tephra layers potentially sourced in Deception Island and construct a robust eruptive record for Deception Island. Based on the information included in the database, the aim is to evaluate the island's past explosive volcanic activity (e.g., magma composition, explosiveness, eruptive recurrence, etc.) and assess the extent and impact of the volcanic hazards. Preliminary results indicate that the database will also be of use for paleoenvironmental and paleoclimatic studies that require tephrochronological information at local and regional scales.

Tasks: During the last three decades, numerous tephra and cryptotephra layers sourced at Deception Island have been identified in ice cores, marine and lacustrine sediments, and glaciers located in the South Shetland Islands, Antarctic Peninsula, Antarctic Continent, South Orkney Islands, Bransfield Strait, and Scotia Sea (Fig. 1.1). A new database (DecTephra) has been created listing all identified layers, compiling information such as location and type of sampling, layer age, distance from Deception Island, and chemical analyses of major elements and trace elements. A review of all the content of

the research included in the database was conducted to determine where there was a lack of analysis or data to perform a complete tephra characterization.

Compositional and textural characterization of tephra layers sourced from Deception Island

Objectives: Full physicochemical characterization of the tephra layers found at Livingston Island's glaciers (Fig. 1.1) corresponding to the latest eruptive event on Deception Island (1970). The results obtained expand the information included in the DecTephra database and can be used as a starting point for future studies on Deception Island tephra layers found in glaciers and marine/lacustrine sediment cores outside the island. Preliminary physicochemical characterization of tephra layers retrieved from the marine sediments at the Bransfield Strait (< 40 km from Deception Island) (Fig. 1.1).

Tasks: (1) Physicochemical characterization of 19 tephra samples (Livingston Island) from the 1970 eruption, correlate the observations and main features of the 1970 tephras with the different eruptive phases described for the 1970 eruption and related volcanic deposits observed on the island. (2) Physicochemical characterization of 65 tephra layers found in the marine sediments of the Bransfield Strait. Results obtained in the first task are used to interpret the type of eruptive events responsible for the Bransfield Strait tephra deposits and, if possible, to correlate them with the volcanic vents identified on the island.

1.5 Thesis Overview

This PhD Thesis is organized as a summary of the results and discussions of three scientific articles that have been published in open access in two international peer-reviewed journals indexed in the Science Citation Reports (Journal of Volcanology and Geothermal Research and Continental Shelf Research). At the end, a general discussion has been included based on the observations and conclusions obtained in each of the sections.

All three articles are included in the Appendix of this manuscript and are briefly summarized in this section.

- **Hopfenblatt, J.**, Geyer, A., Aulinas, M., Álvarez-Valero, A. M., Gisbert, G., Kereszturi, G., Ercilla, G., Gómez-Ballesteros, M., Márquez, A., García-Castellanos, D., Pedrazzi, D., Sumino, H., Höskuldsson, A., Giralt, S., & Angulo-Preckler, C. (2021). Formation of Stanley Patch volcanic cone: New insights into the evolution of Deception Island caldera (Antarctica). *Journal of Volcanology and Geothermal Research*, 415, 107249. <https://doi.org/10.1016/j.jvolgeores.2021.107249>. Impact factor: 2.986. Position Q3(102/202).

This contribution includes the full characterization of the Stanley Patch volcanic cone. It consists of a multidisciplinary study that includes bathymetric data, several parametric seismic profiles of Port Foster Bay and Stanley Patch volcano, and a complete chemical characterization of the volcanic deposits. Important aspects were discussed, such as the geological environment, age of the eruption, and different stages of the geological evolution of the island. Additionally, this study provides new insights about the evolution of Deception Island caldera and the flooding of Port Foster Bay, complementing the studies related to volcanism within the bay. My contribution in this research is focused on the physicochemical characterization of the collected rock samples, the morphometrical analysis of the volcanic edifice and the interpretation of seismic profiles (Gómez-Ballesteros et al., 2018) and bathymetric data previously collected by the Spanish Marine Hydrographic Institute.

- Angulo-Preckler, C., Pernet, P., García-Hernández, C., Kereszturi, G., Álvarez-Valero, A. M., **Hopfenblatt, J.**, Gómez-Ballesteros, M., Otero, X. L., Caza, J., Ruiz-Fernández, J., Geyer, A., & Avila, C. (2021). Volcanism and rapid sedimentation affect the benthic communities of Deception Island, Antarctica. *Continental Shelf Research*, 220. <https://doi.org/10.1016/j.csr.2021.104404>. Impact factor: 2.629. Position Q2(29/66).

This study examined the relationship between benthic communities on the Stanley Patch volcanic cone in Port Foster Bay. This research includes interdisciplinary approaches for the integration of the characterization of Stanley Patch and benthic organisms living in their surroundings. The discussion centers on the evolution of Deception Island together with the development of benthic communities in a volcanic environment. Furthermore, it mentions the unique laboratory that the island provides for the comparison of rates of reestablishment of benthic communities on a volcanologically influenced shallow marine environment. My contribution as a co-author focuses on the geological part of the Stanley Patch volcano, by performing a complete physical and geochemical characterization of the volcano. This characterization is also included as results in Hopfenblatt et al. (2021).

- **Hopfenblatt, J.**, Geyer, A., Aulinas, M., Álvarez-Valero, A. M., Sánchez, A. P., Giralt, S., & Smellie, J. L. (2022). DecTephra: A new database of Deception Island's tephra record (Antarctica). *Journal of Volcanology and Geothermal Research*, 425. <https://doi.org/10.1016/j.jvolgeores.2022.107516>. Impact factor: 2.986. Position Q3(102/202).

In this study, we compiled information about tephra layers found in marine and lacustrine sediment cores and glaciers outside Deception Island (e.g., South Shetland Islands, Bransfield Strait, Antarctic Peninsula). We collected all tephra locations and the physical and geochemical features described by different authors published in scientific studies and created a new database of Deception Island tephra records (Hopfenblatt et al., 2022a). We mainly discuss geochemical analyses compared with Deception Island eruptive products, the eruptive recurrence of volcanic events, and the main problems related to the lack of information regarding tephra studies. Moreover, this study provides a full database of Deception Island's tephra record that can function as a resource for different

paleoenvironmental and paleoclimatic studies that require tephrochronological information at a local or regional scale.

1.6 Thesis Structure

This Doctoral Thesis comprises seven chapters divided in four parts. Part one contains the first three chapters (1, 2 and 3). The first chapter is the main introduction of volcanism in Antarctica, focusing on Deception Island and their related volcanic hazard-associated problems to solve together with the hypothesis and the main objectives. The second one describes the geodynamic context and evolution of the Deception Island region, and the third chapter explains the methodology. Part two includes the fourth chapter, which describes the main results of Port Foster Bay's most relevant eruptive episode. Part three of this thesis includes the main results related to tephra studies in chapter five. Finally, part four comprises chapters six and seven that develop a global discussion with future work, followed by general conclusions.

2 CHAPTER 2

Deception Island: Geodynamic Setting and Geological Evolution

2.1 Geodynamic Context: Bransfield Strait and South Shetland Islands

The Bransfield Strait (Fig. 2.1) is an ~ 4 Ma old back-arc rift developed in the continental lithosphere of the Antarctic Peninsula, which was the site of subduction of the Phoenix Plate throughout the Mesozoic (Barker, 1982; McCarron & Larter, 1998) (Fig. 2.2). Its tectonic evolution has been explained as related to: (i) the passive subduction of the former Phoenix Plate and the slab rollback of the South Shetland Trench (Smellie et al., 1984; Maldonado et al., 1994; Lawver et al., 1995, 1996) (Fig. 2.2); (ii) a sinistral movement between the Antarctic and Scotia plates causing oblique extension along the Antarctic Peninsula continental margin (Rey et al., 1995; Lawver et al., 1995; Klepeis et al., 1996; Gonzalez-Casado et al., 2000); or (iii) mechanisms (i) and (ii) occurring simultaneously (Galindo-Zaldívar et al., 2004; Maestro et al., 2007).

Complex regional geodynamics have conditioned the timing and composition of the magmatism in the region (Košler et al., 2009; Haase et al., 2012; Kraus et al., 2013). On the one hand, the South Shetland Islands, separated from the Antarctic Peninsula by the Bransfield Strait (Fig. 2.1), is a magmatic arc, whose formation began during the Jurassic to early Cretaceous in the southwestern part of the archipelago. Marine sediments are succeeded by terrestrial volcanic sandstones and conglomerates, followed by basaltic to dacitic lavas interbedded with ignimbrites on Livingston Island (Smellie et al., 1984). K – Ar dating suggests an Early Cretaceous age for the extrusive sequence (Smellie et al., 1984). More recent quaternary magmatism, connected to rifting and back-arc basin formation, is mostly concentrated in Deception, Penguin, and Bridgeman Islands (Figs. 2.1b, 2.2) (e.g., Birkenmajer et al., 1990; Hole et al., 1994; Haase et al., 2012; Smellie, 2021).

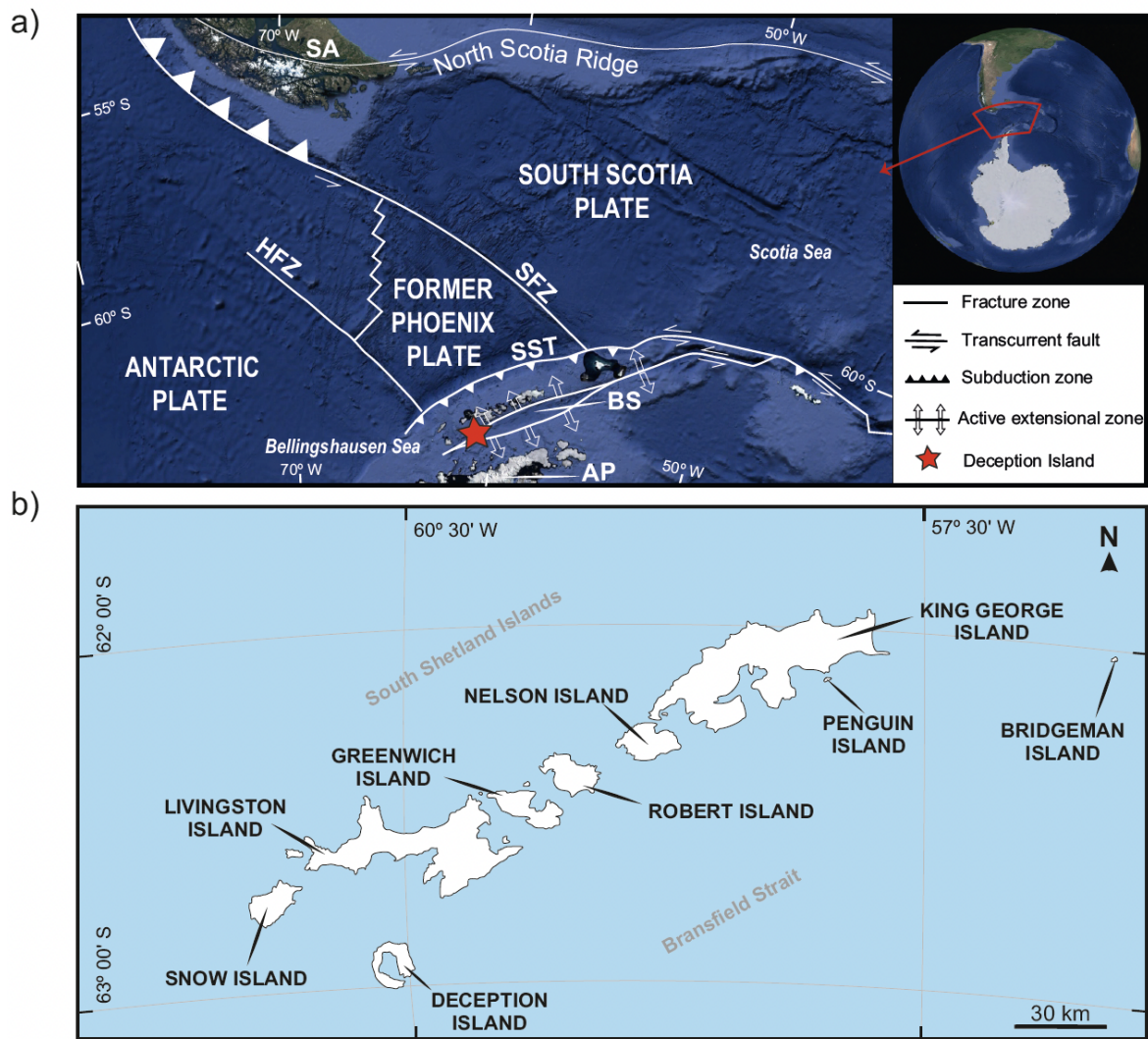


Figure 2.1. a) Simplified regional tectonic map (modified from Martos et al., 2014). AP: Antarctic Peninsula, BS: Bransfield Strait, HFZ: Hero Fracture Zone, SFZ: Shackleton Fracture Zone, SST: South Shetland Trench. Google Earth image source: Landsat/Copernicus – U.S. Geological Survey. b) South Shetland Islands map.

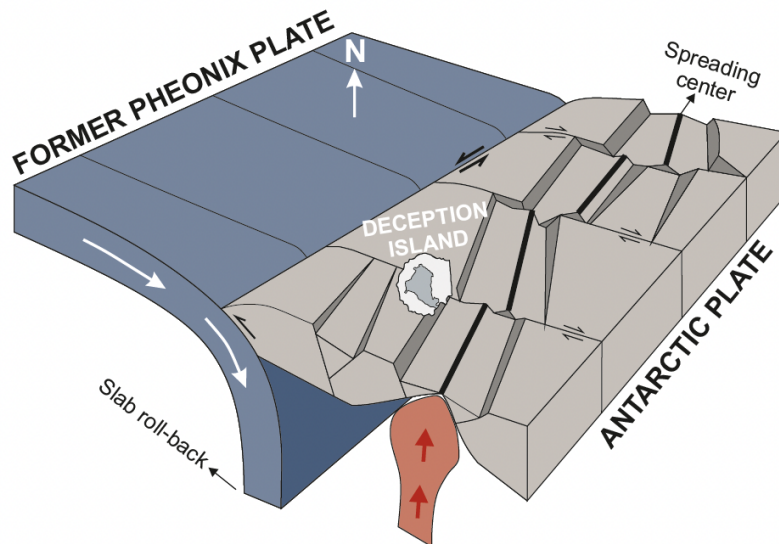


Figure 2.2. Simplified tectonic map of the Bransfield Strait and the South Shetland Islands and location of Deception Island (modified from Grad et al., 1992).

2.2 Deception Island geological evolution

Deception Island consists of a horseshoe-shaped composite volcanic complex located at the southwestern end of the Bransfield Strait (e.g., Grad et al., 1992; Catalán et al., 2013, 2014; Martí et al., 2013) (Figs. 2.1a, 2.2). According to K – Ar age estimations (Keller et al., 1992) and paleomagnetic studies, the island's exposed subaerial rocks are younger than 0.75 Ma (Valencio et al., 1979). Paleomagnetic data suggest ages of c. 8,300 years for the caldera collapse, which strongly marked the island's morphology and subsequent volcanic evolution (Oliva-Urcia et al., 2015). However, more recent findings indicate that the most likely age for the caldera-forming event is $3,980 \pm 125$ calibrated years Before Present (BP) based on tephrochronology, sedimentology studies, and ^{14}C dates (Antoniades et al., 2018). The caldera-forming event led Deception Island to its known roughly circular morphology. The island's highest peaks are Mount Pond on the east side of the island, with an altitude of (539 m.a.s.l.) and Mount Kirkwood on the west side of the island with an altitude of (452 m.a.s.l.) (Fig. 2.3) (Smellie, 2002b).

Building upon these earlier studies, Martí & Baraldo (1990) divided the stratigraphic sequences of the island into pre-caldera, which include Basaltic Shield and Yellow Tuff

Formations, and post-caldera deposits (Fig. 2.3). Later, Smellie (2001) conducted a meticulous reevaluation of Deception Island's stratigraphy by comparing and synthesizing previously published stratigraphic successions leading to uniting the Pre-caldera group of Martí & Baraldo (1990) as the Port Foster Group (divided into Fumarole Bay, Basaltic Shield, and Outer Coast Tuff Formation (OCTF)) and the post-caldera deposits into the Mount Pond Group (Fig. 2.3). More recently, Martí et al. (2013) proposed a simpler subdivision of the volcanic deposits, classifying them as pre-caldera (Basaltic Shield Formation), syn-caldera (OCTF), and post-caldera (Post-caldera Formation) (Fig. 2.3).

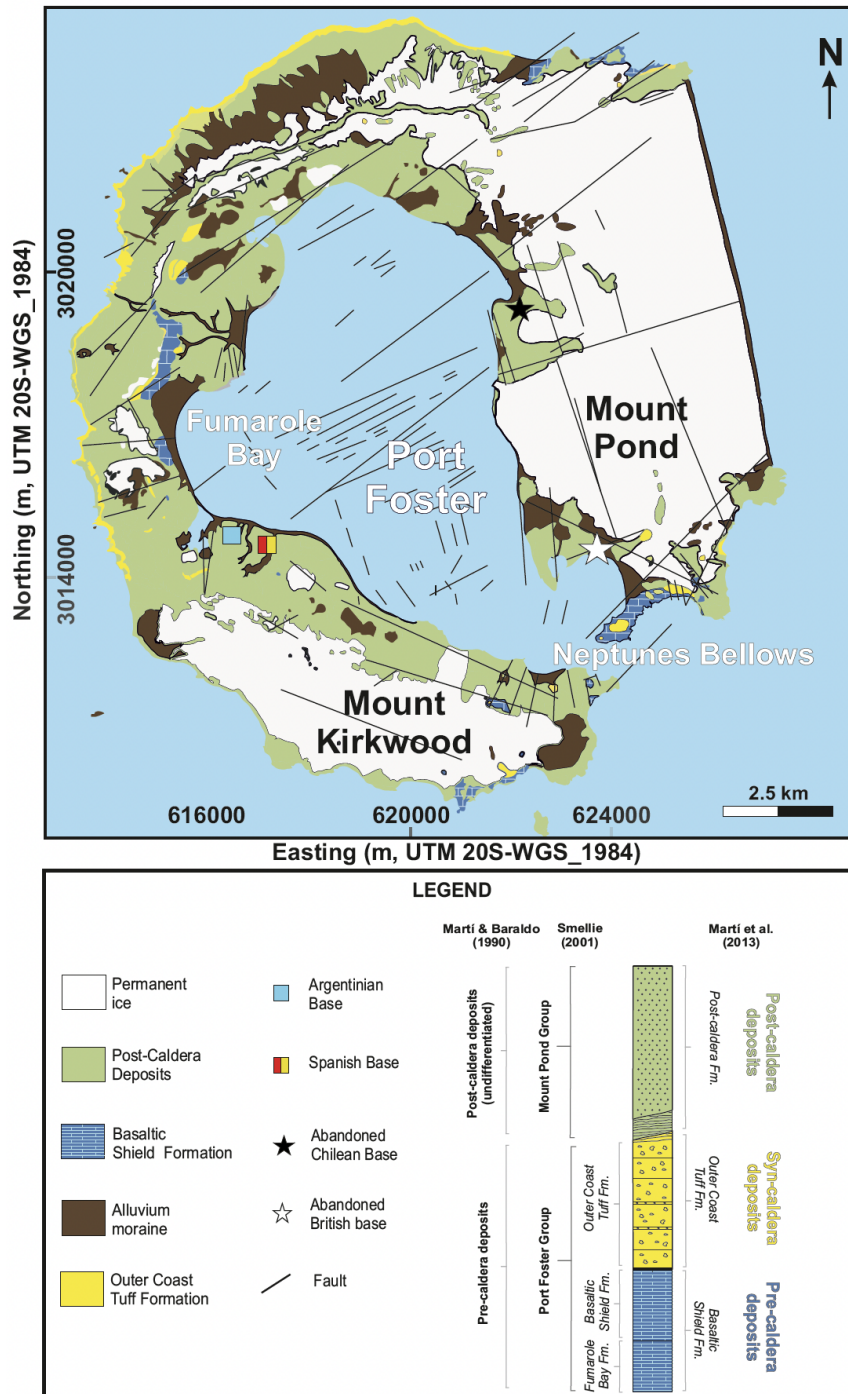


Figure 2.3. Simplified geological map of Deception Island (after Smellie & López-Martínez, 2002; modified from Martí et al., 2013) showing the distribution of the two main tectonic fault sets (NW-SE and NE-SW; De Rosa et al., 1995). Data obtained from Spatial Data Infrastructure for Deception Island SIMAC (Torrecillas et al., 2006). Synthetic stratigraphic section of Deception Island with the divisions proposed by Martí & Baraldo (1990), Smellie (2001) and Martí et al. (2013).

2.2.1 Pre-caldera stage

The pre-caldera stage is characterized by the formation of multiple shoaling seamounts and a main subaerial volcanic edifice and is represented by the Basaltic Shield Formation (Figs. 2.2, 2.4a, 2.5a), in which most of the units correspond to lava flows, Strombolian deposits, and palagonitized hyaloclastite breccias (e.g., Smellie, 2001, 2002b; Martí et al., 2013). The most primitive magmas ascended directly from pressures (P) > 6.5 kbar (i.e., depths ≥ 25 km, assuming an average crust density of 2650 kg/m^3), which suggests an upper mantle origin (Smellie, 2001; Barker et al., 2003) (Fig. 2.6). Further evolved pre-caldera magmas were temporarily stagnated at the crust-mantle boundary, between 15 and 20 km depth ($P \sim 4 - 5$ kbar) (Geyer et al., 2019) (Fig. 2.6).

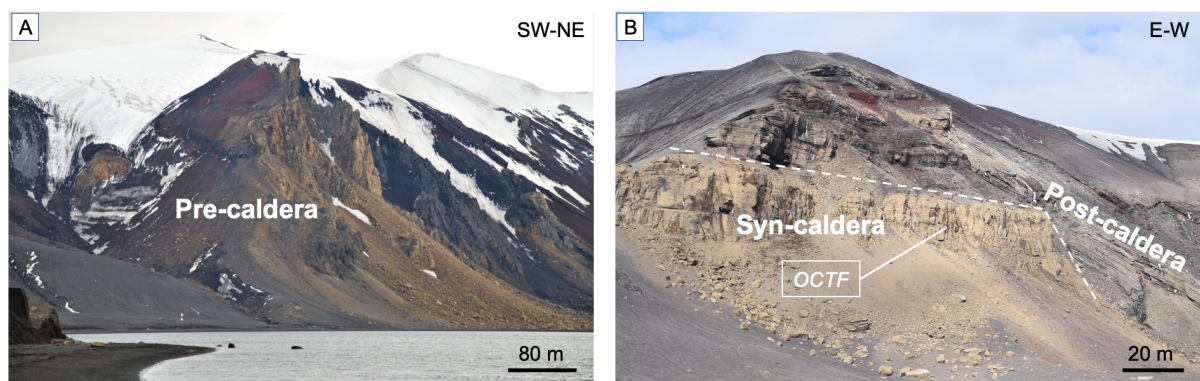


Figure 2.4. Pre, Syn and Post-caldera deposits. Location marked in Figure 1.3. OCTF: Outer Coast Tuff Formation. (Images: Antonio M. Álvarez Valero)

2.2.2 Syn-caldera stage

The principal syn-caldera depositional unit of the Outer Coast Tuff Formation (OCTF) mainly corresponds to basaltic-andesitic dense pyroclastic density current deposits (PDCs) lying unconformably over the pre-caldera material and forms an almost continuous outcrop that encircles most of the island (e.g., Smellie, 2001, 2002b, 2002c; Martí et al., 2013) (Figs. 2.3, 2.4b, 2.5b). Two different magmas erupted simultaneously during the caldera-forming

event (Smellie, 2002b; Geyer et al., 2019). The dominant one was stagnated in an intermediate-depth reservoir ($\sim 10 - 11$ km depth; $P \sim 3$ kbar) (Fig. 2.6), which has been suggested to be responsible for the caldera-forming event (Geyer et al., 2019). The second, and more mafic magma component, formed at a deeper source (> 15 km depth), and its arrival into the shallower reservoir may have triggered the explosive eruption culminating in the caldera formation (Geyer et al., 2019) (Fig. 2.6).

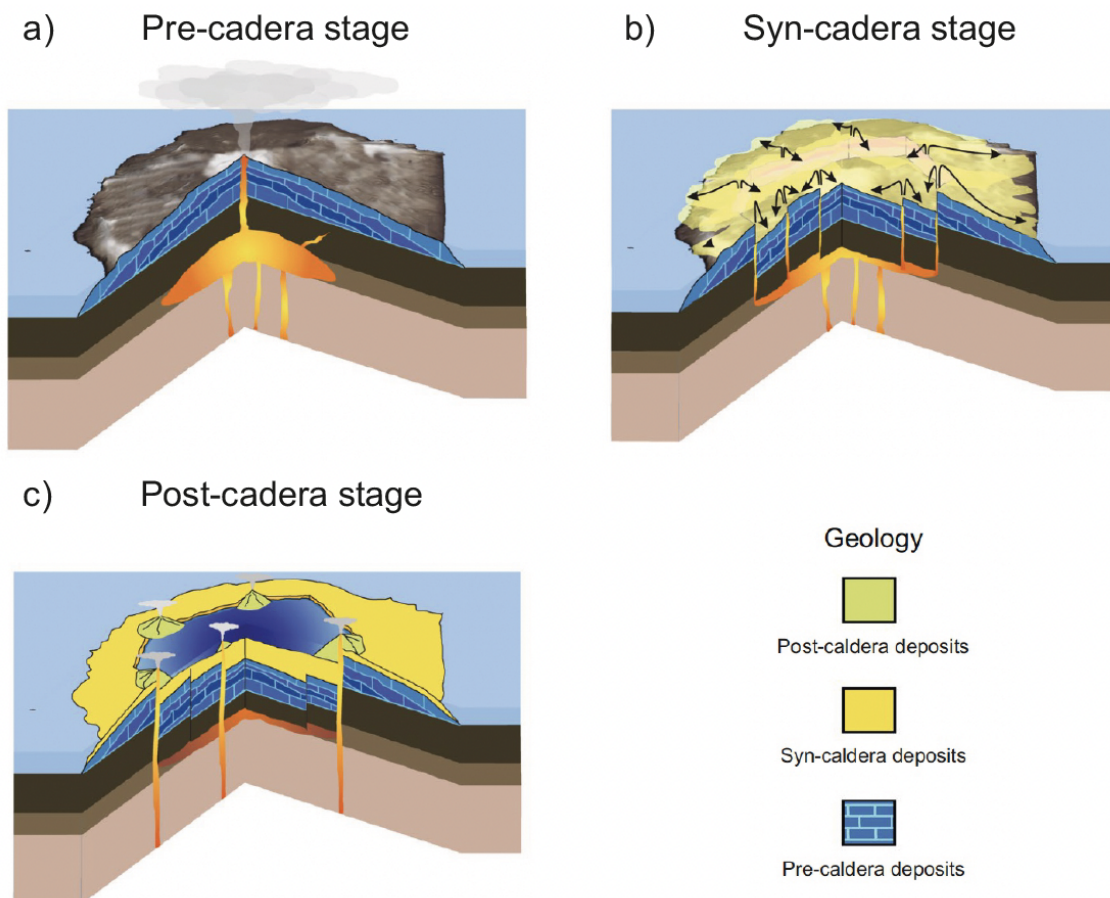


Figure 2.5. Simplified sketch illustrating the different stages of Deception Island's evolution (modified from Martí et al., 2013).

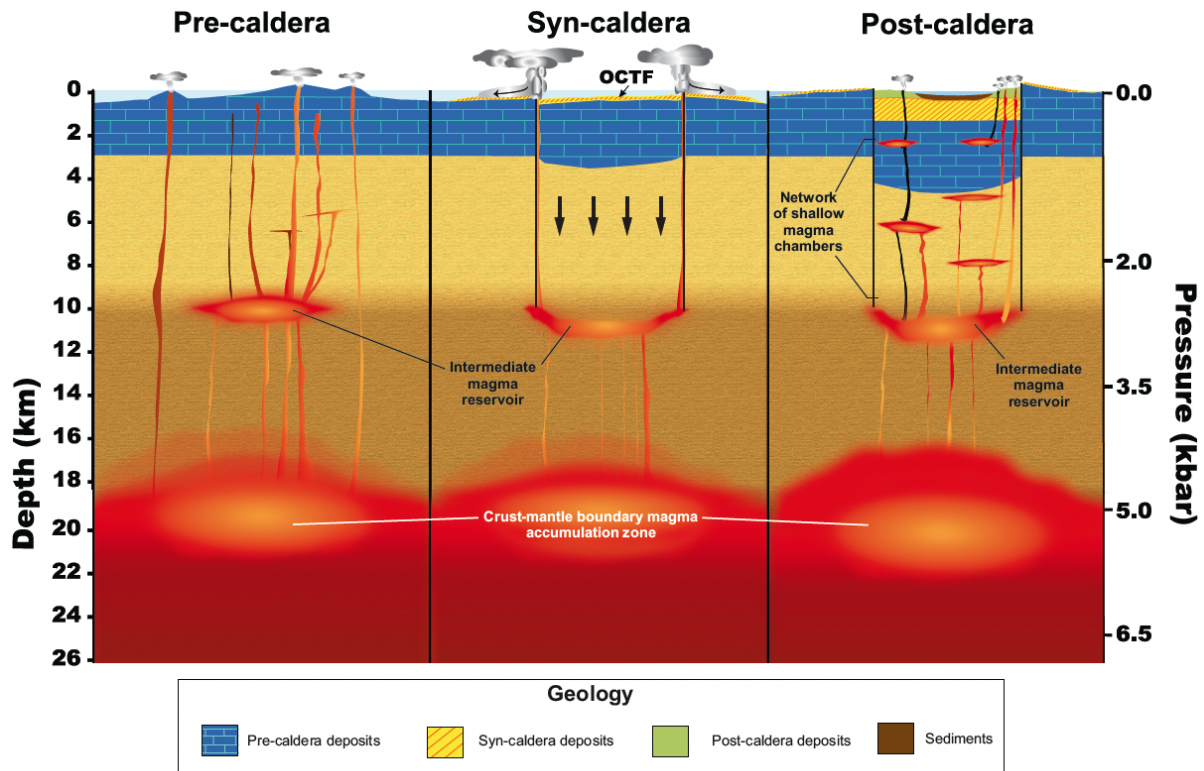


Figure 2.6. Conceptual model of the magmatic system of Deception Island modified from Geyer et al. (2019) based on *P-T* estimates. See Geyer et al. (2019) for further information.

2.2.3 Post-caldera stage

2.2.3.1 Port Foster Bay formation

Port Foster Bay is assumed to have formed soon after the caldera-forming event by marine inundation of the collapsed depression via gaps in the caldera rim created by local sector collapse and/or volcanic events (e.g., Aparicio et al., 1997; Smellie & López-Martínez, 2002). The bay is open to the sea by a narrow shallow entrance (< 500 m wide and < 25 m deep) at Neptunes Bellows (Fig. 2.3) and is composed of three sub-basins (Cooper et al., 1998; Smellie & López-Martínez, 2002; Rey et al., 2002) (Fig. 2.7a-c): (i) sub-basin 1 (165 m maximum water depth) that occupies the entire northern half of the bay; (ii) sub-basin 2 (< 110 m water depth), which extends from east of the Stanley Patch into Whalers Bay; and (iii) sub-basin 3 (100 – 120 m water depth), a smaller basin in Fumarole Bay. Whereas the limit between sub-

basins 2 and 3 is subdued, sub-basin 1 is delimited on its southern and southwestern sides by a striking ENE-dipping monoclinical structure related to a major NNW-SSE trending fault (Cooper et al., 1998; López-Martínez & Serrano, 2002) (Fig. 2.7a-c). This structure has been interpreted as essential for the development of caldera collapse (Rey et al., 1997, 2002).

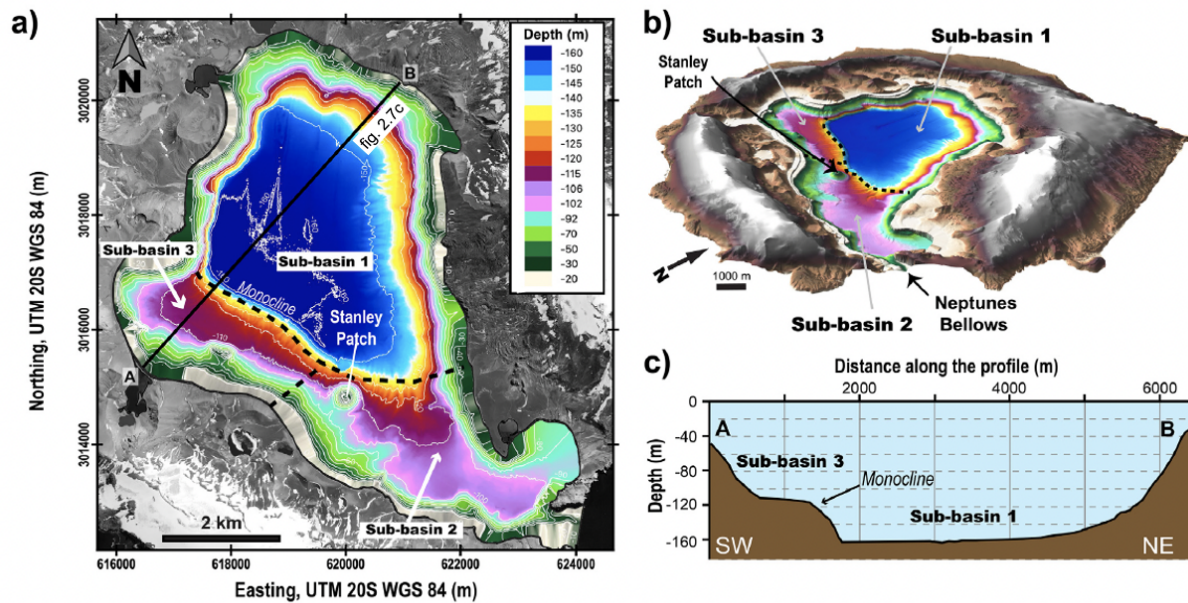


Figure 2.7. a) Deception Island orthophotomap (data obtained from Spatial Data Infrastructure for Deception Island SIMAC, Torrecillas et al., 2006) and Digital Elevation Model of Port Foster obtained during the 2012 and 2017–2018 Spanish Antarctic Campaign by the Marine Hydrographic Institute. The limits of the different sub-basins are also indicated according to Cooper et al. (1998), Paredes et al. (2006) and Rey et al. (2002). b) 3D shaded relief map of Port Foster and Deception Island. Vertical exaggeration is $\times 1.5$; c) bathymetric profile of Port Foster. The location is shown in a).

Seismic studies within Port Foster Bay's seafloor have imaged geological structures at the top 300 m below the seafloor in the central part of the caldera depression (e.g., Kowalewski et al., 1990; Rey et al., 1995, 2002; López-Martínez & Serrano, 2002; Somoza et al., 2004). Within sub-basin 1, they mapped a major fault zone that trends 60N across the bay associated with numerous graben-like structures and small-displacement normal faults, mainly oriented NE-SW and NW-SE (Fig. 2.3). This structural pattern reflects the regional tectonic influence of the Bransfield Strait marginal basin (Martí et al., 1996; López-Martínez

& Serrano, 2002). The basin infilling comprises three seismic units (A, B, and C, from older to younger, according to Rey et al., 1995, 1997) separated by unconformities that are understood to be individual deformation events that disturbed the geometry of the sedimentary materials (Fig. 2.8) (Rey et al., 1995, 1997; López-Martínez & Serrano, 2002). Unit A is interpreted as the intra-caldera facies of the OCTF deposited during the caldera-forming eruption (Rey et al., 2002; Martí et al., 2013). It gently dips to the southwest and is overlain by two major post-caldera sedimentary units, B and C, both divided into several sub-units (Fig. 2.8). Their distribution and strata patterns suggest either that basinal subsidence occurred along the monocline at greater rates than local sedimentation or that subsidence in the southwestern part of the basin was accompanied by uplift in the northeast (Fig. 2.8) (Rey et al., 2002). As a consequence, the sedimentary infilling sequence inside Port Foster Bay has been described as a giant 'slab,' which, after the initial collapse, rotated about a NW-SE orientated axis, subsiding in the south-west and rising in the north-east (Rey et al., 2002). Indeed, during the last decades, ground deformation monitoring (e.g., Fernandez-Ros et al., 2007; Almendros et al., 2015; Rosado et al., 2019) and the analysis of bathymetric variations (Cooper et al., 1998) have shown that, in the past, the basin floor has experienced notorious deformation episodes, including uplift/subsidence stages. It has been suggested that, at least for sub-basin 1, the caldera floor has experienced uplift at a rate of 0.3 – 0.5 m/yr over the past 50 years (Cooper et al., 1998). This process could be related to the following (Cooper et al., 1998): (i) local tectono-magmatic effects associated with shallow 207 magma chambers, (ii) volcano-tectonic effects of caldera development, and (iii) the rapid influx of reworked unconsolidated tephra during annual spring thaw periods and episodes of abrupt glacial melting by eruptions and glacial activity (Rey et al., 2002). The proximal sediments of Port Foster Bay (water depths < 50 – 70m) consist of volcanoclastic gravels and morainic deposits, whereas deeper-water regions are dominated by sand, silt, and mud (Rey et al. 1997, 2002).

Several submarine pyroclastic cones dot the Port Foster Bay seafloor (Rey et al., 1995, 1997; López-Martínez & Serrano, 2002). These volcanic edifices show an arcuate NNW-SSE alignment and are characterized by relatively steep slopes and a dome-like or cone morphology, the largest of which is the Stanley Patch volcano (Figs. 1.3, 2.8) (López-Martínez & Serrano, 2002).

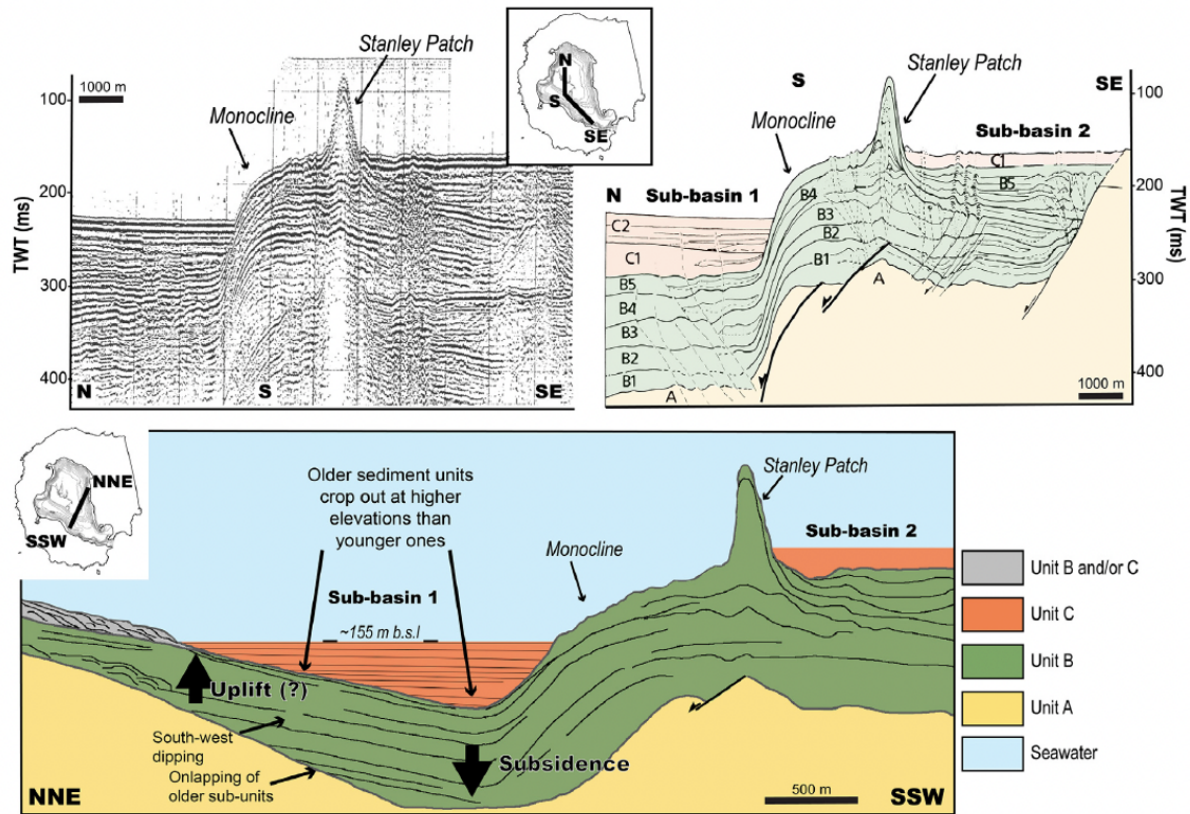


Figure 2.8. (Top) Composite seismic reflection profile (Sparker) (left) and its interpretation (right) obtained across Port Foster, showing the seismo-acoustic depositional units A, B and C described in the text (after Rey et al., 1995). (Bottom) simplified schematic composite section across Port Foster (modified from Kowalewski et al., 1990; Rey et al., 1995; Smellie, 2002b).

2.2.3.2 General overview of post-caldera volcanic activity

Early post-caldera volcanic activity was characterized by extensive eruptions on the outer island slopes, especially Kendall Terrace and Mount Kirkwood (Figs. 1.3, 2.4, 2.5), and along the caldera rim (Smellie, 2001, 2002b). In contrast, the most recent eruptive vents (except the one at the Stonethrow Ridge) are located along the structural borders of the caldera and the interior of Port Foster Bay (Figs. 2.2, 2.5c). These have mainly consisted of small volume eruptions ($< 0.1 \text{ km}^3$) with variable degrees of explosiveness depending on the amount and provenance of water (i.e., aquifer, sea, and/or ice/snow melting) that interacts with the rising or erupting magma (e.g., Baker et al., 1975; Smellie, 2002d; Pedrazzi et al., 2014, 2018).

Post-caldera magmas outline a well-defined geochemical evolutionary trend, ranging from basalt to rhyolite (Aparicio et al., 1997; Smellie, 2002b; Geyer et al., 2019). Magma compositions and pressure-temperature (P-T) estimates indicate the presence of a complex network of individual, potentially interconnected, shallow (up to 10 km depth) magma chambers of variable volume and composition (Fig. 2.6). Magmas feeding this shallower part of Deception Island's plumbing system would ascend directly from the mantle or from the deep and intermediate magma accumulation zone (Aparicio et al., 1997; Smellie, 2001, 2002b; Martí et al., 2013; Galé et al., 2014) (Fig. 2.6).

2.2.3.2 Most recent eruptions (1967, 1969 and 1970)

Historic eruptions (1829 – 1970) include at least 70 dispersed eruptive vents (e.g., Baker et al., 1975; Smellie, 2002a; Smellie & López-Martínez, 2002; Martí et al., 2013; Pedrazzi et al., 2020), being the 1967, 1969 and 1970 eruptions, the latest events on the island.

According to Baker et al. (1975), earthquakes preceded the eruption which were experienced in November and these increased in frequency and intensity, culminating in the eruption, which began on December 4, 1967. A column of black ash and vapor was observed breaking through the partial ice cover of Telefon Bay, expanding rapidly to reach at first a height of 2.5 km high and then reaching a maximum height of 10 km (Pedrazzi et al., 2018). In addition, volcanic ash was noted on Livingston Island and probably on Greenwich Island (Roobol et al., 1975) (Figs. 2.9, 2.10).

The subglacial 1969 event occurred from a series of fissures that were situated beneath the Mount Pond glacier (Fig. 2.11) that later produced a *jökulhlaup* (Smellie, 2002b) that flowed Port Foster Bay, leading to the extension of the local coastline. These events severely damaged the British scientific station (Fig. 2.11), leading to its abandonment. The Chilean station (already affected by the 1967 eruption) was also destroyed (Baker et al. 1975; Smellie, 2002b) (Fig. 2.11).

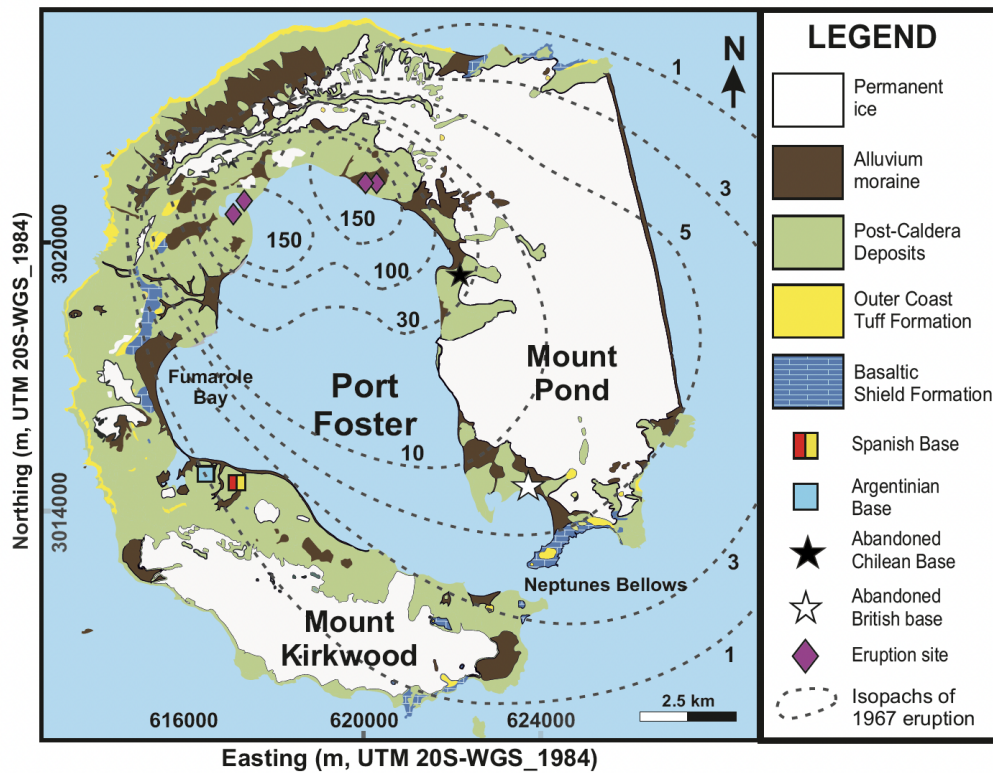


Figure 2.9. Simplified geological map of Deception Island (modified from Martí et al. 2013) showing the pyroclasts isopachs (in cm) for the 1967 eruption (Roobol et al., 1975).

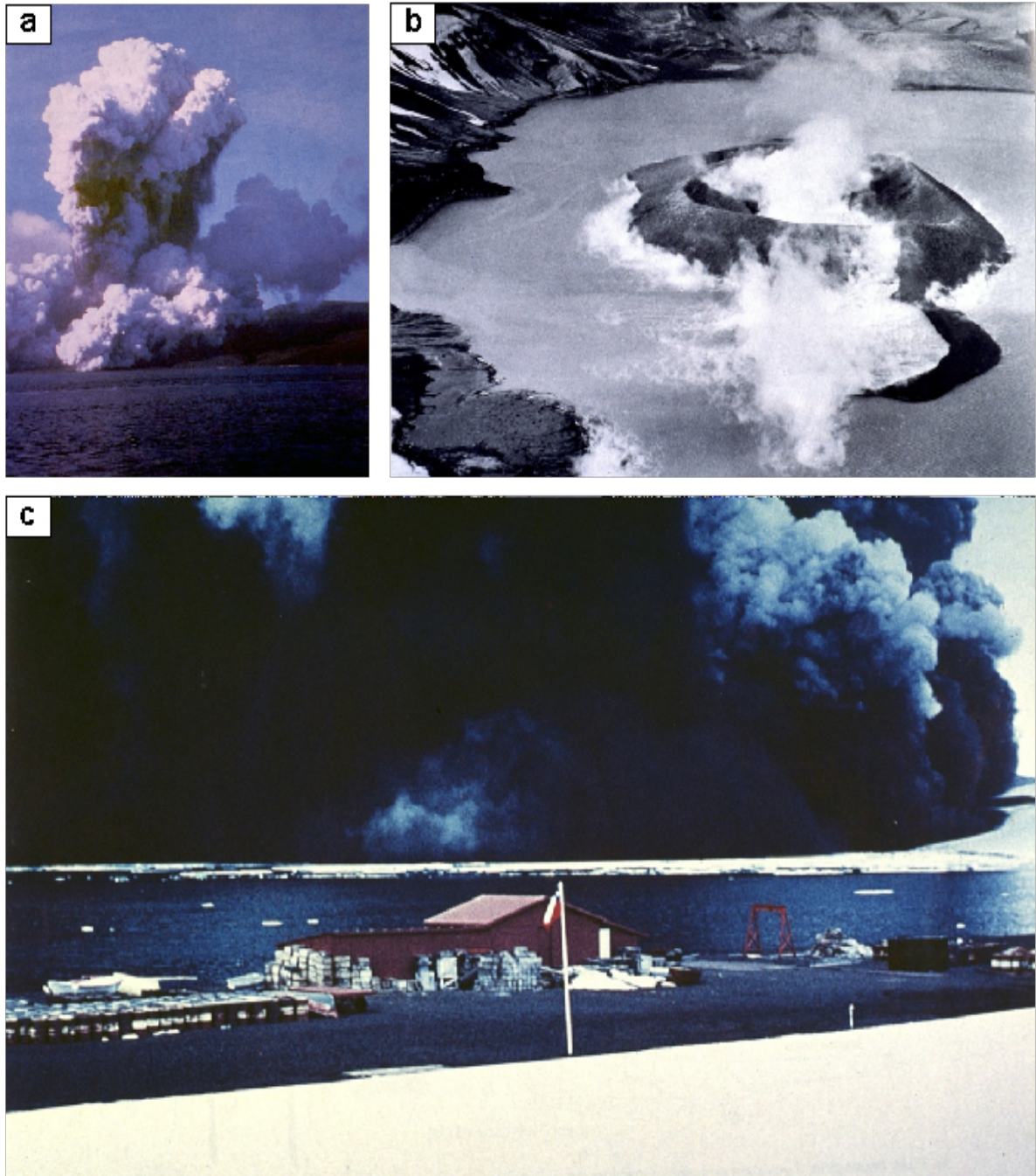


Figure 2.10. a) Image from the 1967 eruption (Image: British Antarctic Survey; González-Ferrán, 1995). b) Steam above a new island formed during the 1967 eruption in Telefon Bay (Image: Chilean Navy, 1967; González-Ferrán, 1995). c) Dark eruption plume originating from vents located about 2 km NW of the Chilean research station (Image: Bernardo Blass; González-Ferrán, 1995)

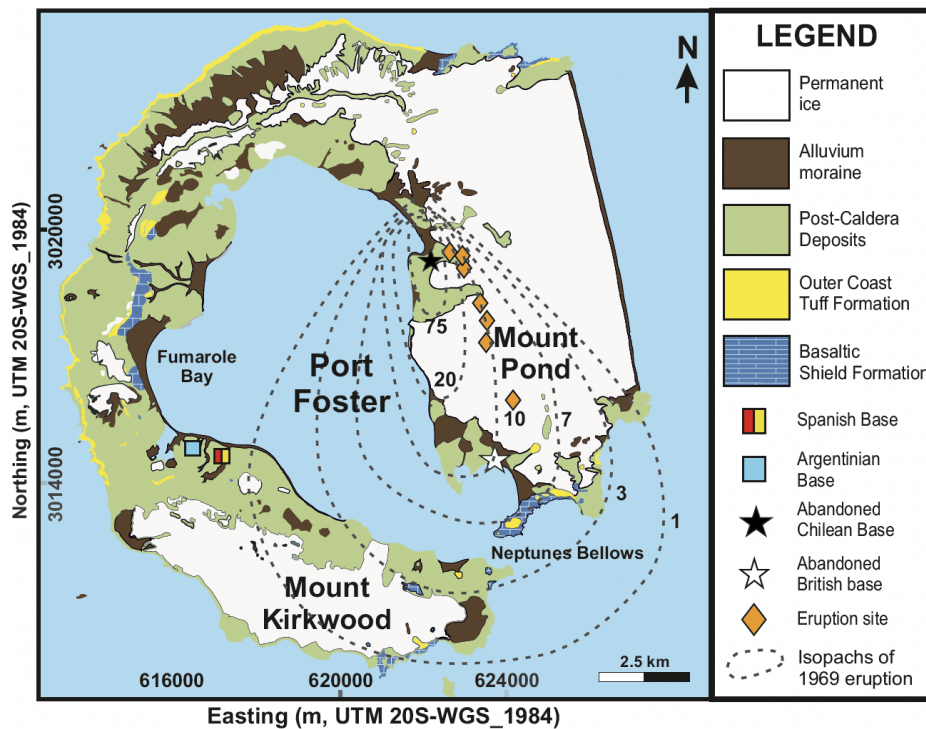


Figure 2.11. Simplified geological map of Deception Island (modified from Martí et al., 2013) showing the pyroclasts isopachs (in cm) for the 1969 eruption (Roobol et al., 1975).

The most recent eruption on Deception Island occurred during August 1970 and consisted of an eruptive event with magmatic and phreatomagmatic phases. About 13 vents opened in the northern part of the island in the same area as the 1967 eruption (Baker et al., 1975; Pedrazzi et al., 2014) (Fig. 2.12). The volcanic edifices developed during the eruption can be separated into two main groups: i) the eastern group, which consists of seven conical edifices, and ii) the western group, which consists of maar-like shaped edifices (Pedrazzi et al., 2014).

The 1970 eruption was one of the most violent eruptions during the last century of the volcanic activity on Deception Island, with a Volcanic Explosivity Index (VEI) of 3 and an estimated minimum bulk eruptive volume of 0.1 km^3 (Pedrazzi et al., 2014; 2018). Tephra fall-out from the 1970 eruption were reported in Arturo Prat station (4 mm) in Greenwich Island and further towards the NE on Bellingshausen station (1 mm) in King George Island (Fig. 2.12) (Baker & McReath, 1971; Baker et al., 1975; Pedrazzi et al., 2014).

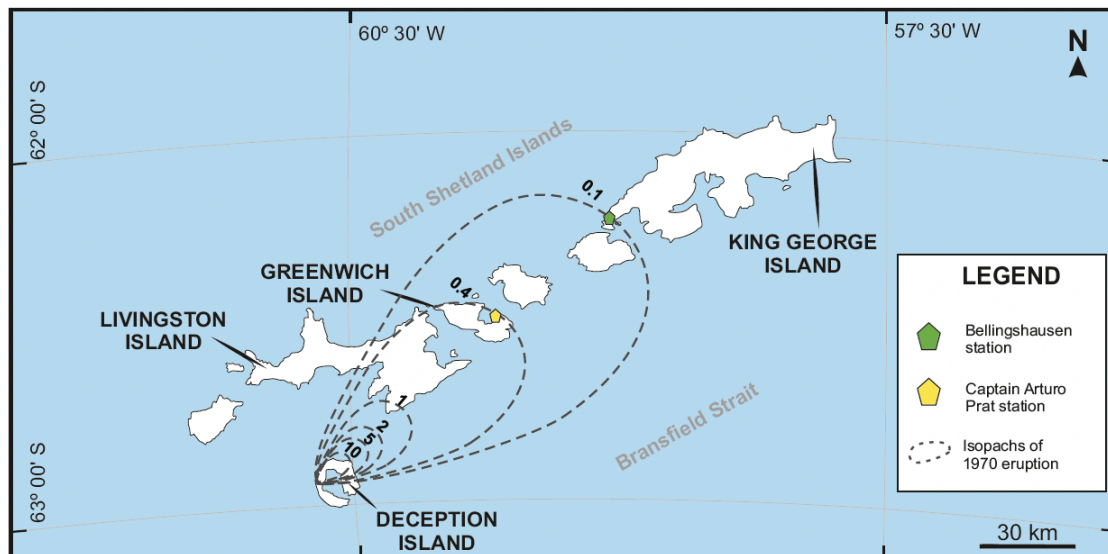
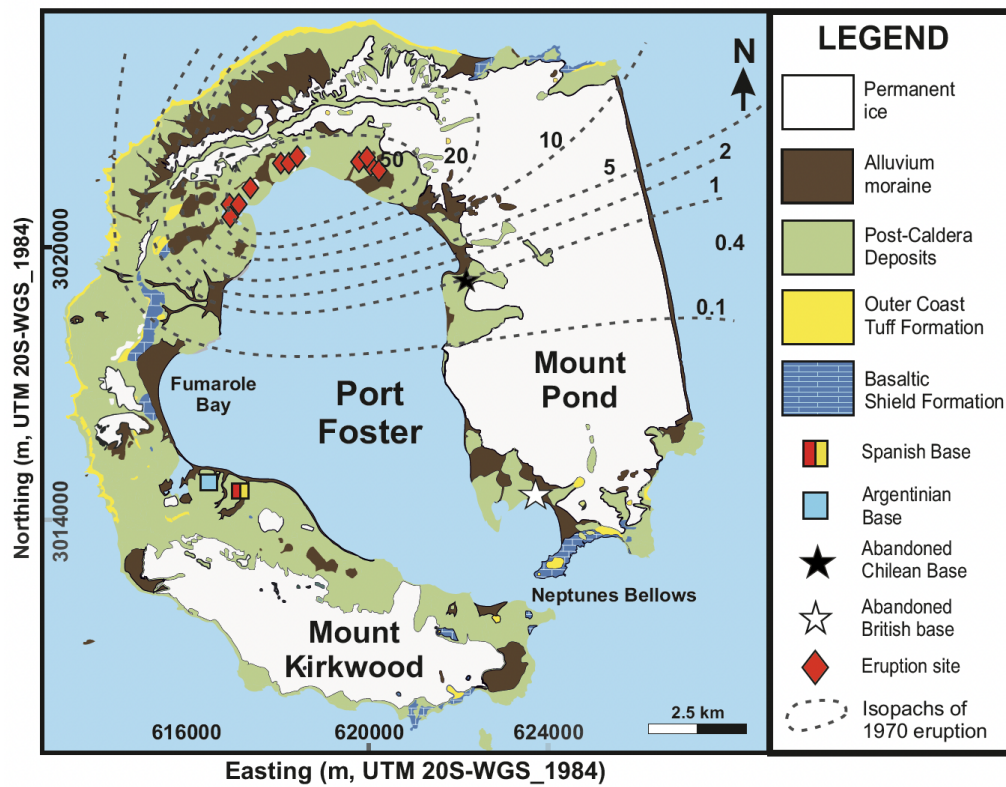


Figure 2.12. (Top) Simplified geological map of Deception Island (modified from Martí et al., 2013) showing the pyroclasts isopachs (in cm) for the 1970 eruption (Roobol et al., 1975; Pedrazzi et al., 2014). (Bottom) Isopachs (dashed lines; in cm) of the 1970 eruption in the South Shetland Islands (modified from Baker & McReath 1975).

3 CHAPTER 3

Methodology

A multidisciplinary approach incorporating various methodologies is necessary to achieve the goals of this PhD Thesis (Fig. 3.1). This chapter includes a brief summary of the different methods applied, and further details can be found in the published papers (See Appendixes 1, 2 and 3). For the sake of conciseness, those methods used in both research lines (**Characterization of Stanley Patch volcano** and **Tephra studies**) are described only once within the “Common Methodology” section. These common methods include fundamental techniques like sampling, petrographic studies, and geochemical analyses. Complementary, the section “specific methodology” describes those methods employed to pursuing one of the two research lines. These encompass a range of techniques, spanning from geophysical methods to morphometric analyses and the construction of a database.

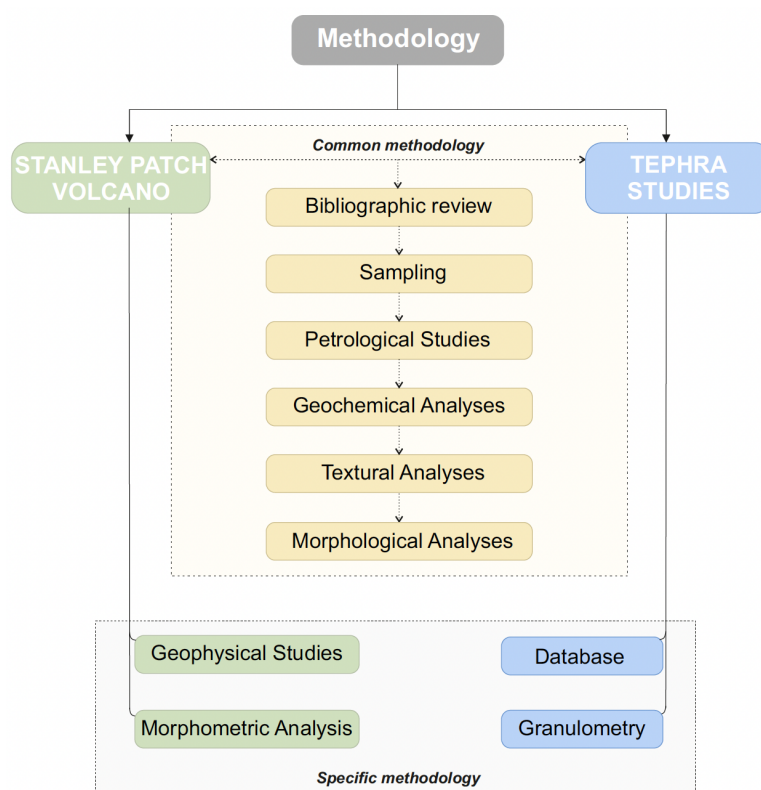


Figure 3.1. Flux diagram of the methodology, including common and specific methods used in this PhD Thesis.

3.1 Common Methodology

3.1.1 Sampling and collection method

A total of 105 samples (Supplementary Material 1) collected during several Spanish Antarctic campaigns were studied in this PhD Thesis. These correspond to 21 hand-specimen rock samples collected at Stanley Patch volcano (Supplementary Material 1) and 84 tephra samples retrieved from ice (Livingston Island) and marine sediment cores (Bransfield Strait) (Supplementary Material 1).

3.1.1.1 Stanley Patch volcano rock samples

Sampling was designed to find the shallowest spot at the southern side of the crater rim of Stanley Patch volcanic edifice. This location was selected for the collection of rock samples by SCUBA diving (Fig. 3.2). Fieldwork and sampling, was conducted during the 2017–2018 Spanish Antarctic Campaign and the Antarctic GALILEO-IHM cruise aboard the R/V Hespérides (2017/2018) (Gómez-Ballesteros et al., 2018; Angulo-Preckler et al., 2021). Of the 21 collected rock samples, we selected only those juvenile fragments of larger size (> 5 cm) and with a less weathered appearance (five in total, SUB_3 to SUB_5, SUB_7, and SUB_8) (Fig. 3.3, Table S2 of Hopfenblatt et al., 2021) for petrography and geochemistry studies, including major and trace elements analyses, as well as stable isotope ratios (δD and $\delta^{18}O$ isotopes).

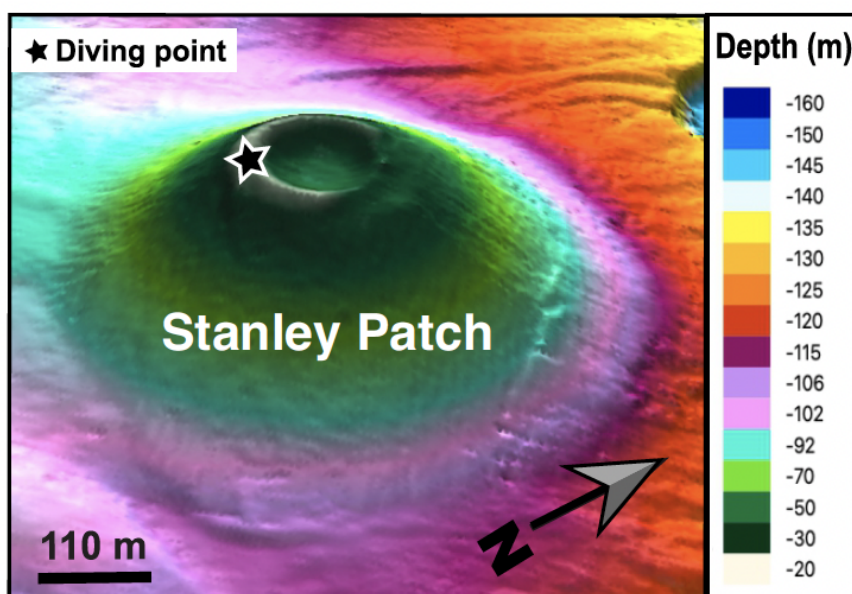


Figure 3.2. Digital elevation model of Stanley Patch volcanic cone. The location of diving point is also indicated.

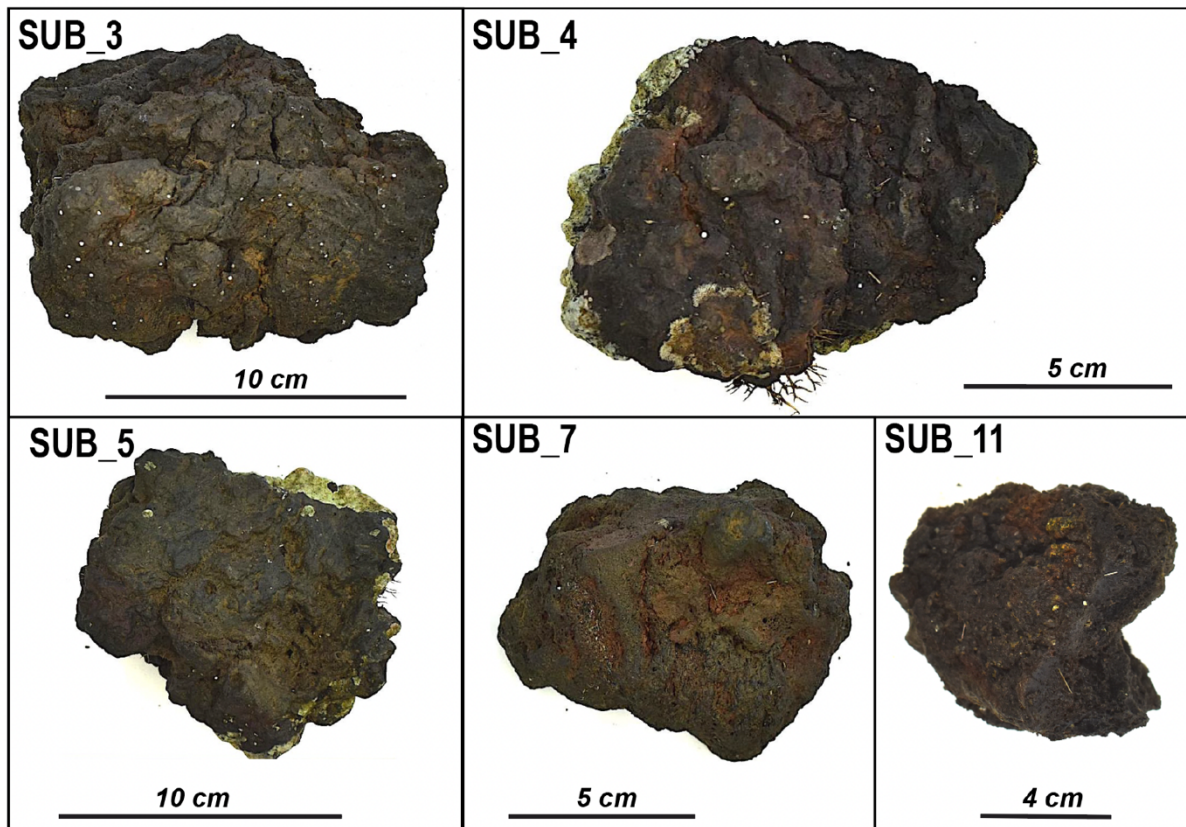


Figure 3.3. Images of the largest and less weathered rock samples collected by the divers at Stanley Patch volcano.

3.1.1.2 Tephra samples for physico-chemical characterization

1970 eruption tephra layers deposited on Livingston Island

In this research, we have characterized a total of 19 tephra samples belonging to the 1970 eruption tephra layer identified on Livingston Island. The samples were hand-picked or retrieved from ice cores at six different sampling sites located in Ereby Point, Burdick Peak, and Hurd Peninsula (Fig. 3.4).

The acquisition of the samples was funded by the Comisión Interministerial de Ciencia y Tecnología (project numbers ANT91-1270, ANT93-0852, and ANT96-0734) and Grup de Recerca de Processos Geodinàmics Superficials 3130-UB-06 (1999GR-00065). The samples

were collected during three different Spanish Antarctic campaigns conducted between 1994 and 2000 (Table 3.1).

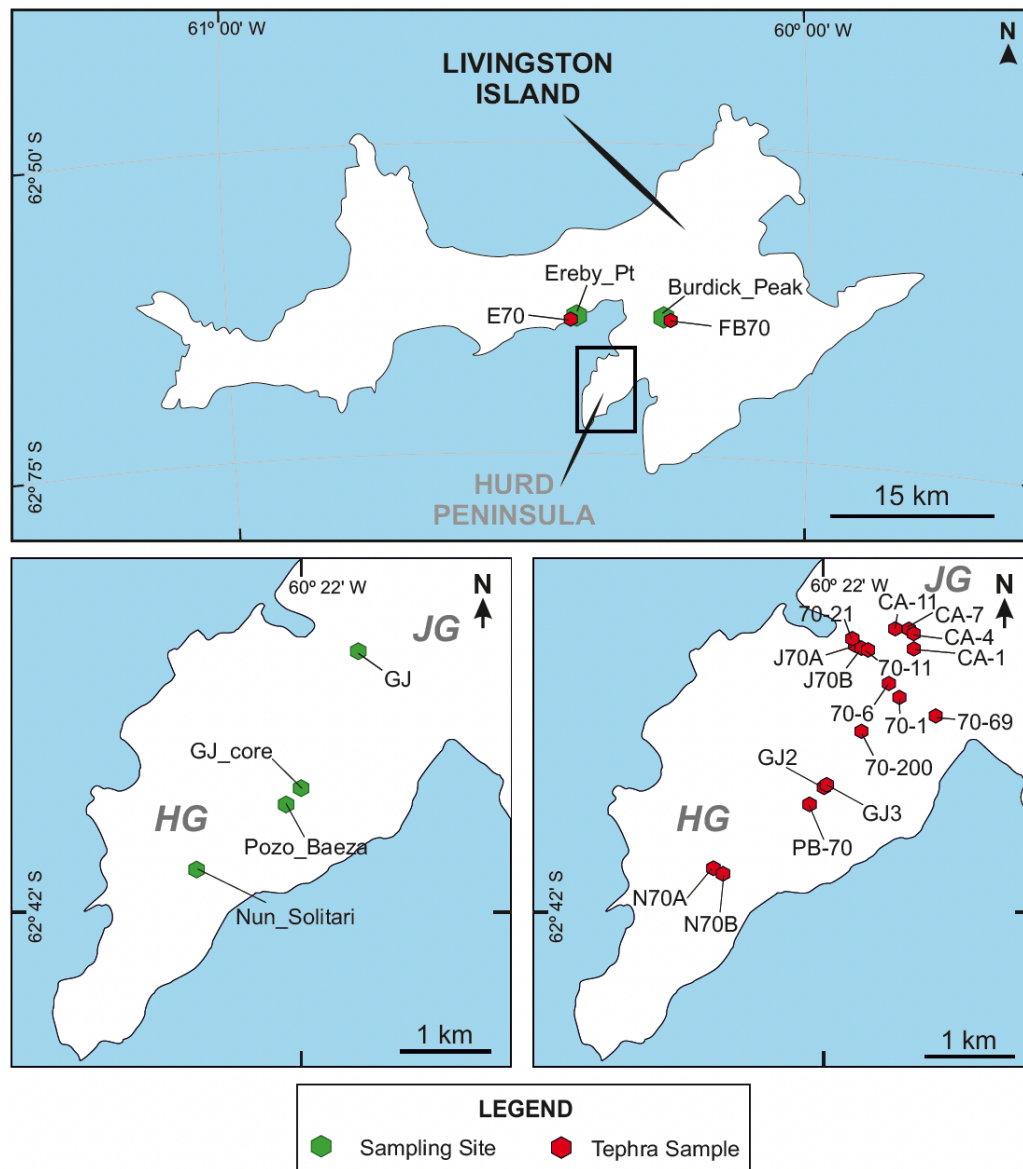


Figure 3.4. Location of the tephra sampling sites. HG: Hurd Glacier; JG: Johnsons Glacier. Two bottom maps correspond to black rectangle (top) of Hurd Peninsula.

Regarding sample collection methods, in those areas of easy access and where the ash layers were clearly and cleanly visible, samples were collected by hand picking, scraping the material from the englacial tephra layers. Instead, tephra layers located in glacial fronts were

sampled using a portable drilling machine specially designed for horizontal drilling and for operating under extreme conditions (Casas et al., 1998) (Fig. 3.5). When vertical drilling was required (e.g., Pozo Baeza sampling site), manual and electromechanical drilling machines were used. In the manual method, a maximum depth of 7 meters was achieved, while in the electromechanical drilling, the maximum depth was 16 meters (Fig. 3.5).

Scientific Campaign Year	Method	Samples
1994-1995	Horizontal ice drilling	N70A
		N70B
	Vertical ice drilling	E70
		PB-70
	Manual drilling	FB70
		J70A
1997-1998	Manual drilling	J70B
		CA-1
		CA-4
		CA-7
		CA-11
		70-6
		70-69
		70-11
		70-200
1999-2000	Vertical ice drilling	70-1
		70-21
		GJ2
		GJ3

Table 3.1. List of the Spanish Antarctic campaigns during which the 1970 tephra samples described in this PhD Thesis were collected. Scientific staff sampling each campaign: (i) 1994-1995: Glòria Furdada, Jordi Corbera, Jaume Calvet, Jorge Enrique, Vicenç Palà, Michel Pourchet, Joan Manuel Vilaplana and Josep Maria Casas (ii) 1997-1998: Josep Maria Casas, Laia Ximenis and Glòria Furdada; (iii) 1999-2000: Josep Maria Casas and Michel Pourchet.

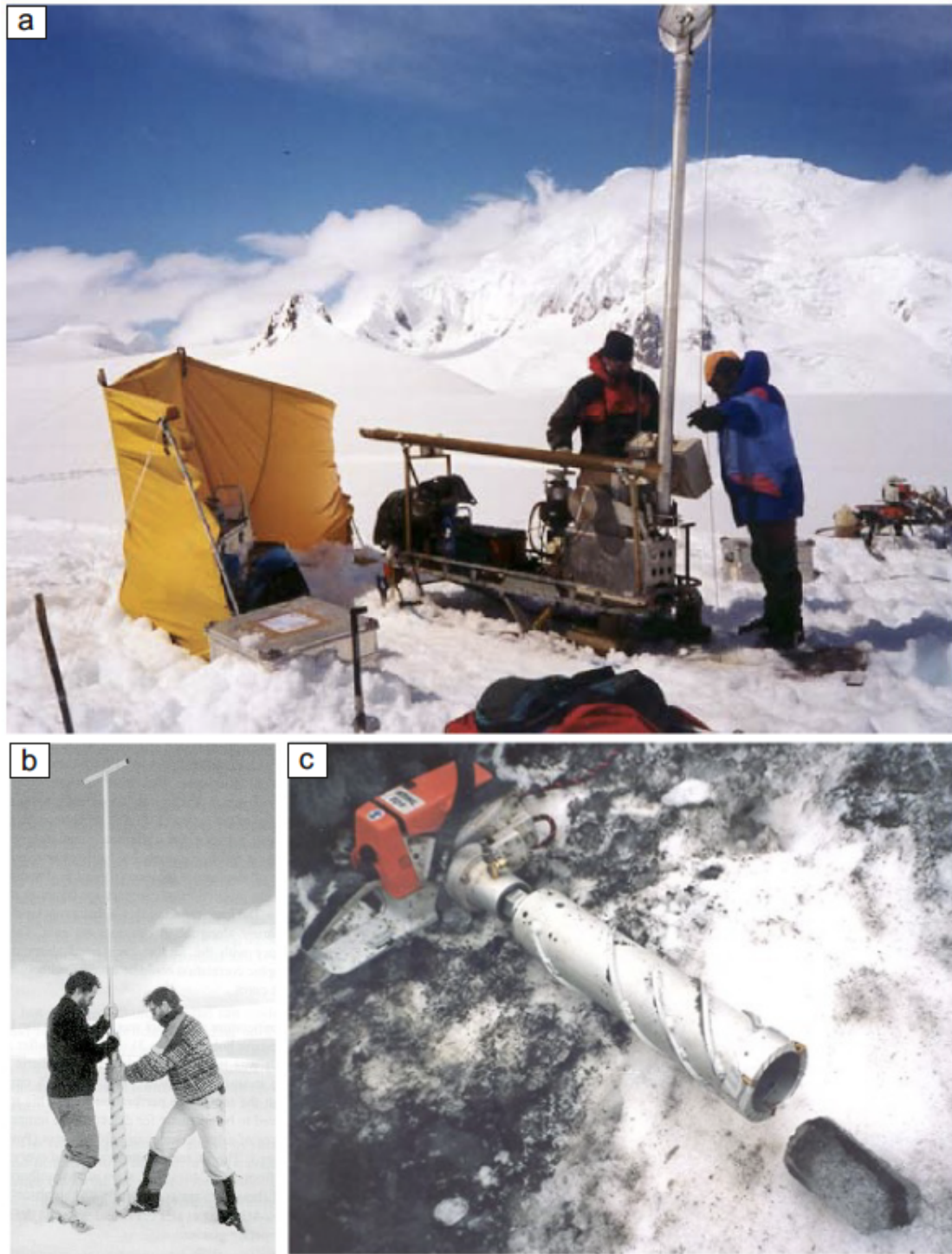


Figure 3.5. a) and b) Vertical manual ice core drilling (black and white) and an electromechanical drilling machine (Casas et al., 1998). c) The ice-drilling machine, together with a fragment of an ice core containing a thin tephra layer (Casas et al., 1998).

Tephra layers retrieved from marine sediments along the Bransfield Strait

The studied tephras were sampled of 5 from the 19 marine sediment cores (those drilled closer to Deception Island) retrieved from Bransfield Strait (Fig. 3.6) during the 1998 - 2000 Spanish Antarctic campaign of the MAGIA (“Arquitectura, estratigrafía, y sedimentología de los márgenes y cuencas al Norte de la Península Antártica: procesos sedimentarios de origen glacial y marino, y reconstrucción paleoambiental durante el Cuaternario”) project (ANT-584/97) (Figs. 3.6, 3.7, Table 3.2). All of them were drilled using a gravity corer, employing a 3 meters long steel borer pinned to a load and connected to a reception system. The load hangs on a lever arm that counterbalances the core through a wire. First, the load is sent into the seafloor; then it is released and by gravity the core driller falls and drills the shallowest layer. Inside the bore hole, a PVC piece is located to recover the materials (García et al., 2008, 2011). A total of 65 tephra layers were previously identified and sampled by García (2008) along the five marine sediment cores (Table 3.2 and Fig 3.6). In this PhD Thesis we have performed a preliminary characterization of all 65 tephra samples collected by García (2008).

Core	Latitude	Longitude	Distance from Deception Island (km)	Depth Range (cm)	Nº Layers	Core Length (cm)
TG-40	-63.2323	-60.7461	30	20-110	11	122.5
TG-41	-63.2112	-60.5616	28	30-125	14	127
TG-43	-63.2348	-60.2163	37	18-110	10	110
TG-48	-62.8920	-60.3120	19	25-120	15	122
TG-50	-63.0070	-60.1841	23	15-57	14	83

Table 3.2: Drill location (in decimal degrees, WGS-84) and length of the studied marine sediment cores. The total number of tephra layers sampled in each core is also indicated (Nº of layers). Distance between the drilling site of each core and the center of Deception Island volcano (Coordinates: -62.957° / -60.643°, Hopfenblatt et al., 2022a) is provided (Distance from Deception Island). Depth Range (cm): Depths of the shallowest and the deepest tephra layer studied in each core.

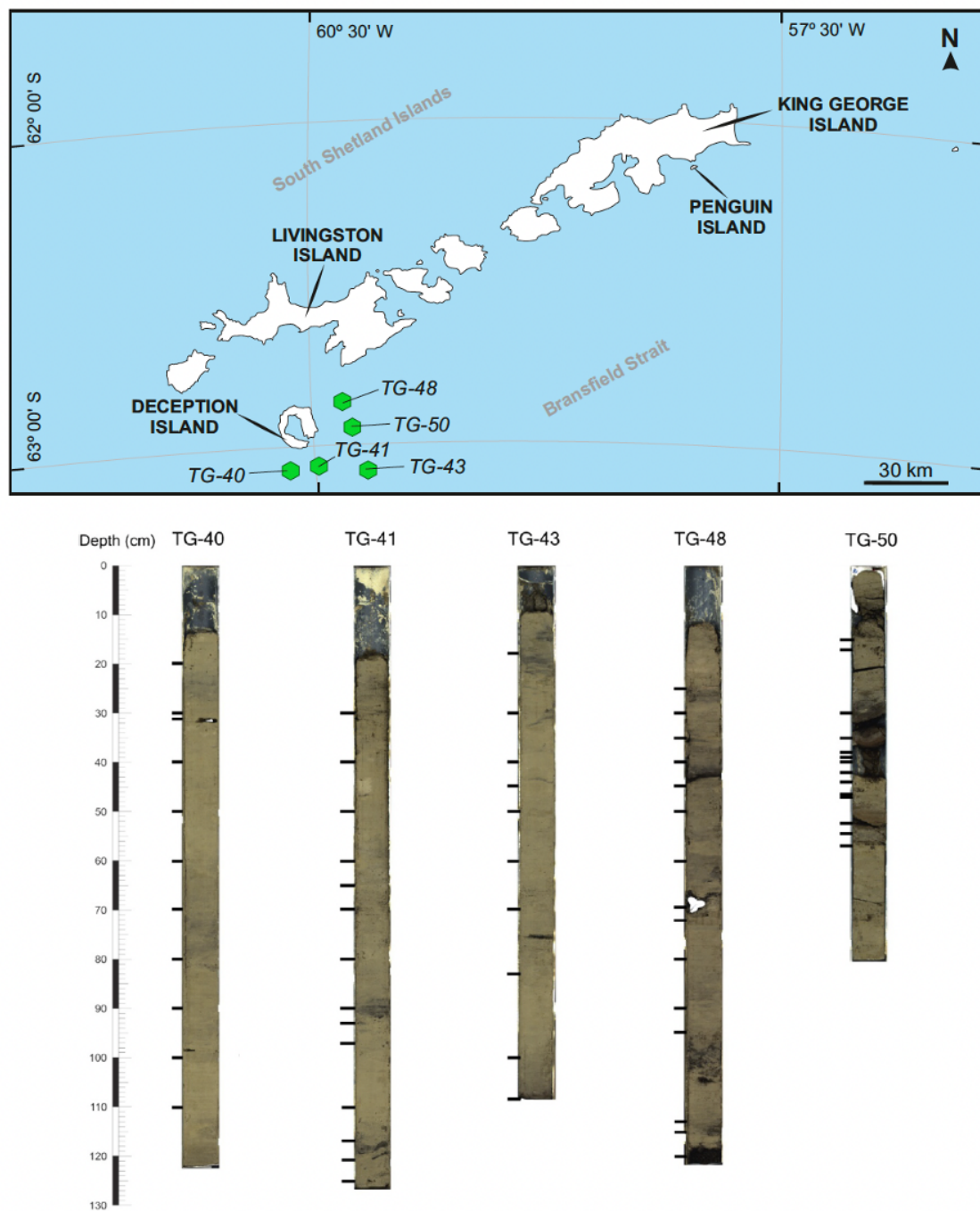


Figure 3.6: Location of the MAGIA project marine sediment marine cores studied in this PhD Thesis (top). Scanned cores with each tephra layer marked by a dark line (bottom). Core images made at XRF Core Scanner Laboratory at Universitat de Barcelona (UB) by Santiago Giralt (Geo3BCN-CSIC) and Guillem Gisbert (UB).

3.1.2 Petrological studies, textural and morphological analyses

Petrographic description and textural analysis of Stanley Patch rock samples and the studied tephras included observations from both hand specimens and thin sections. The latter were prepared with a thickness of 30 μm at the Servei de Làmina Prima of the (UB). Regarding the tephra samples from the 1970 eruption, counting of different types of juvenile and lithic fragments was made with the JmicroVision v1.3.4 Software.

Hand specimens of the rock samples and tephras were studied via a Leica M125 MC190 HD camera binocular microscope located at the Geosciences Barcelona (GEO3BCN-CSIC). Thin sections were also observed under the optical microscope (Zeiss Axiophot) at the Universitat de Barcelona (UB) and a Leica DM4500P optical microscope located at the GEO3BCN-CSIC. Additionally, more detailed observations of hand specimens and thin sections were obtained with a scanning electron microscope (SEM) model “Hitachi TM4000 Tabletop Microscope” at the GEO3BCN-CSIC, and the SEM model QUANTA FEI 200 FEG-ESEM (SEM-EDX) located at the Institute of Materials Science of Barcelona (ICMAB-CSIC). Further detailed studies of the microtextures and morphology of the tephras fragments were performed also with the SEM model QUANTA 200 FEI, XTE 325/D8395 at the Scientific and Technological Center of UB (CCiTUB). Samples analyzed at the SEM were beamed with a tungsten filament electron gun, and images were captured by detecting backscattered electron (BSE) and Secondary Electron (SE) signals using a high-sensitivity 4-segment detector.

3.1.3 Geochemical analyses

Whole rock major and trace element compositions of 5 samples from Stanley Patch volcano were analyzed by X-Ray Fluorescence (XRF) (Si, Al, Ti, Fe, Mn, Ca, Mg, K, Na, P, V, Ni, Cr, Y, Zr, Nb, Ga, Cu, and Zn) using a ThermoARL Advant'XP+ sequential X-ray spectrometer at the GeoAnalytical Lab at Washington State University (WSU). Trace elements and Rare Earth Elements (REE) (14 REEs & Ba, Th, Hf, Ta, U, Pb, Rb, Cs, Sr, Sc,) were also analyzed on the same samples by Inductively Coupled Plasma—Mass Spectrometry (ICP-MS) using an Agilent 7700 at WSU. Mineral and glass chemistry of selected 33 thin section samples (5 for Stanley Patch; 8 for 1970 eruption; 20 for Bransfield Strait) (Supplementary Material 1) were analyzed using a JEOL JXA-8230 Electron Probe Microanalysis (EPMA) at the CCiTUB. The instrument was calibrated for each session using primarily natural and synthetic standards from P and H Development Ltd. (<https://www.pandhdevelopments.com/>). Diopside or albite (Si), corundum (Al), orthoclase (K), rutile (Ti), wollastonite (Ca), periclase (Mg), albite (Na), Fe₂O₃ (Fe), rhodonite (Mn) and Cr₂O₃ (Cr), NiO (Ni) and celestine (Sr) were used as the primary standards. In the case of mineral phases, the detection limit of most elements at 2 sigma confidence level is below 0.03 wt. % except for Na (0.04 wt. %), Cr (0.08 wt. %), and Sr (0.14 wt. %). Glass detection limits are below 0.05 wt. % for Si, Al, Na, Mg, Mn, Fe, and Ni and 0.03 wt. % for Ca and K. Ti, Cr, and Sr show higher detection limits (0.08 wt. %, 0.14 wt. % and 0.3 wt. %, respectively). An up to 20-μm-diameter defocused beam was used for groundmass analyses to minimize Na migration.

All compositional binary and ternary variation diagrams shown in Chapters 4 and 5 were generated using R-Studio software (<https://www.rstudio.com/>) (R Core Team, 2014), specifically the *ggplot2* (Version 3.3.3) and *ggtern* packages (Version 3.3.0), respectively.

3.2 Specific Methodology

3.2.1 Stanley Patch Volcano

3.2.1.1 Bathymetry and seismic profiles of Port Foster Bay and Stanley Patch volcano

A swath bathymetry was acquired by a multibeam echosounder system (Kongsberg EM-1002), carried out by the Marine Hydrographic Institute (IHM) in 2012, 2017, and 2018. The multibeam operates 111 beams at 95 kHz frequency, with approximately 2° beam width. The different surveys were positioned to insonify 100% of the seafloor with a 33% overlap between them in order to fulfill International Hydrographic Organization (IHO) standards for multibeam surveying. The resulting data set was processed using Caris Hips & Sips V.7.1 software and interpolated to an 8 x 8 m sided regular grid in Port Foster and a 4 x 4 m sided regular grid for Stanley Patch volcano, providing virtually continuous coverage of the entire survey area with high spatial resolution. Then, Digital Elevation Models (DEM) surfaces were created with QGIS software version 3.10 “A Coruña” (<http://www.qgis.org/>) and GRASS GIS software version 7.6 (<http://grass.osgeo.org>) (Fig. 3.7a).

Parametric seismic profiles were obtained with a hull-mounted TOPAS PS 018 high-resolution parametric sounder designed for sub-bottom profiling with high spatial resolution at water depths of less than 20 m to full ocean depth. The +80% relative bandwidth, low-frequency signal is generated in the water column by non-linear interaction between two high-frequency signals (centered symmetrically around 18 kHz). The seismic profiles obtained were recorded working in high-penetration mode, by transmission of a Chirp wave (LFM), trying at all times not to interfere with the EM122 multibeam echosounder signal. Normal transmission frequencies vary from 2.0 kHz for the initial and 5 kHz for the final, with a pulse length of 10 ms, and transmitted at a 1500 ms internal mode trigger interval (Table 3.3). The record length was 400 ms at a sampling rate of 16.0 kHz. The deconvolution and initial 2 kHz filtering (HP filter) of the signal have always been applied in this Chirp mode. The TVG ramps

normally used during acquisition were 0.78 d/ms between the bottom and 5.4 ms depth, 0.77 d/ms between 5.4 and 25.9 ms, and 0.14 d/ms after 35.6 ms.

The seismic profiles were presented in two-way time and were analyzed with KingdomSuite (Version 8.4) software to identify, define the top and base, and interpret sedimentary units and acoustical facies. For conversion depth in double-time depth (TWT) to depths (in distance), seismic velocities between 1600 and 1900 m/s as typical for volcanic sediments (Hamilton, 1970; Johnston et al., 2015) have been considered. For specific seismic units, the depth points (in ms) of base and top extracted from the seismic profiles were imported into GRASS GIS and interpolated to 3D surfaces with the *v.surf.bspline* function, which performs bilinear/bicubic spline interpolation with Tykhonov regularization (e.g., Fathi & Maleki Shoja, 2018). Then, the *r.contour* function was applied to calculate the isobaths (Fig. S2 of Hopfenblatt et al., 2021).

ACQUISITION AND CONFIGURATION PARAMETERS						
ACQUISITION			PROCESSING			
T R A N S M I T T E R	Transmitter Mode	Normal	F I L T E R S	Filter	Active	
	Trigger Mode	Internal		Filter Type	Matched	
	Trig Interval	Manual		Corner Frequency	Auto	
	Ping Interval [ms]	1500		Replica Shaped	Active	
	Pulse Form	Chirp (LFM)	T V G			
	Start Frequency [kHz]	2		TVG	Active	
	Stop Frequency [kHz]	5.5		TVG Control	Tracking	
	Chirp Lenght [ms]	10		Offset [ms]	-50	
	Output Level [dB]	0				
	Output Level [%]	100				
	HRP Stabilization	Active				
	Beam Control	Auto				
	Transducer Sound Speed [m]	1510				
				Section A-B	5.4	0.78
			Section B-C	25.9	0.77	
			Section C-D	35.6	0.14	
R E C E I V E R 1	Delay Control	Manual/Auto	G A I N			
	Master Trig Delay [ms]	Variable With Depth				
	Delay Offset [ms]	30				
	Sample Rate [kHz]	16				
	Trace Rate [kHz]	400				
	Gain [dB]	22-34				
	HP-Filter [kHz]	2				
			Gain	Active		
			Auto Gain [dB]	7.5		
			Filter Coefficient	0		
			Mute	Active		
			Mute [ms]	10		

Table 3.3: Acquisition and configuration parameters applied during the Galileo IHM 2018 Cruise.

3.2.1.2 Morphometric analysis of Stanley Patch volcanic edifice

The morphometric analysis of Stanley Patch volcanic edifice was carried out with the 4 x 4 m grid size DEM. The estimated morphometric parameters are summarized in Table 3.4 and Fig. 3.7e. Shaded relief (Fig. 3.7b, d) and slope angle maps (Fig. 3.7c) were also created using QGIS from the DEM to manually delineate the cone base outline and crater rim, both identified by a break-in-slope (Fig. 3.7a). The pre-eruptive basal surface was obtained by interpolating the elevation data points around the volcanic cone (Fig. S3 of Hopfenblatt et al., 2021) using the *v.surf.bspline* function of GRASS GIS software version 7.6 (available at: <http://grass.osgeo.org>). The average slope of the basal plane (Sb_{mean}) was obtained by applying linear regression to the elevation points obtained along a profile aligned along the maximum dip direction of the basal surface. Complementarily, statistical analysis with R-Studio software (<https://www.rstudio.com/>) (R Core Team, 2014) was carried out to obtain data of mean, median, maximum, and minimum slopes, and standard deviation for both the crater and cone flanks.

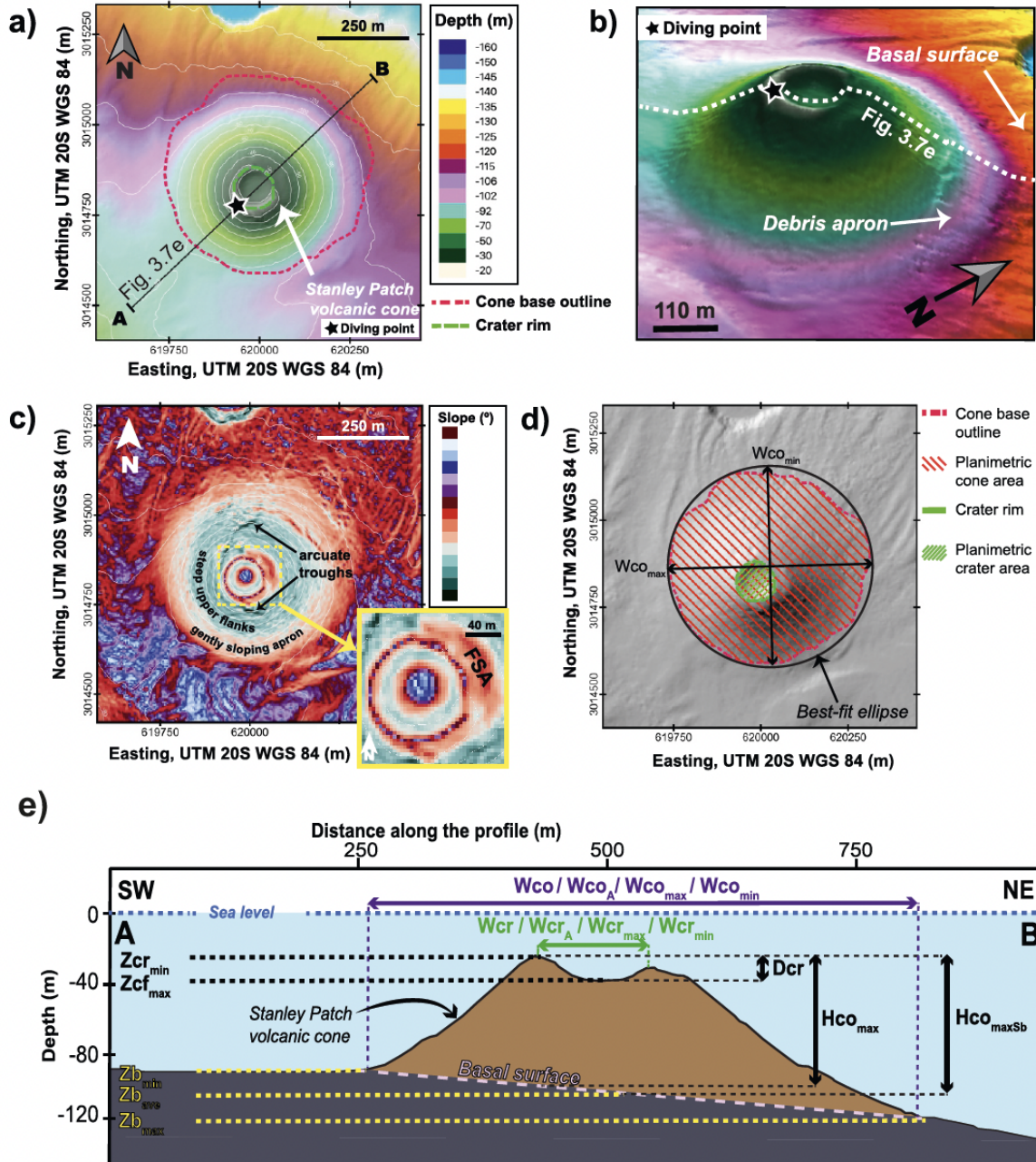


Figure 3.7. a) Bathymetric map of Stanley Patch volcano, showing the location of the profiles displayed at e) as well as the cone base outline and crater rim. b) 3D shaded relief map of Stanley Patch volcano: the debris apron around the NE side of the cone are clearly observed. c) Slope map of Stanley Patch volcano, showing the location of the flat summit area (FSA), the arcuate flank troughs and the surrounding debris apron. d) DEM-derived upper view of Stanley Patch volcano. Cone and crater planimetric area, cone base outline and crater rim are also indicated. e) Bathymetric profile across SW-NE direction (See a) and b) for location). The morphological parameters measured at the cone are also indicated (See Table 3.4 for further explanation) (modified from Angulo-Preckler et al., 2021).

Parameter	Unit	Description	Value
Aco	m ²	Planimetric area of the cone including crater and outer flanks (see Fig. 3.7d)	$2.4 \cdot 10^5$
Acr	m ²	Planimetric area of the cone including crater floor and inner flanks (see Fig. 3.7d)	$1 \cdot 10^4$
Dcr	m	Crater depth calculated as (Hooper & Sheridan, 1998; Wood, 1980a) $Dcr = Zc_{f_{max}} - Zc_{f_{min}}$	13
Hco _{max}	m	Maximum cone height calculated as the maximum elevation of the crater rim above the 3D basal surface (see Fig. 3.7e) (Favalli et al., 2009)	77
Hco _{maxStb}	m	Maximum cone height calculated as Settle (1979): $Hco_{maxStb} = Zb_{ave} - Zc_{r_{min}}$	80
Sb _{mean}	degree	Slope of the basal plane obtained by applying a linear regression to the points obtained along a profile aligned along the maximum dip direction of the basal surface (Figs. S3c, g of Hopfenblatt et al., 2021)	3
Vco	km ³	Cone volume enclosed between the DEM surface and the 3D base surface determined from the surrounding topography and the bilinear/bicubic spline interpolation with Tykhonov regularization (see Fig. S3e of Hopfenblatt et al., 2021)	0.06
Wcr _{max}	m	Maximum crater diameter measured along four profiles spaced 45° azimuthally, with one of them aligned along the maximum dip direction of the basal surface (Wood, 1980b)	123
Wcr _{min}	m	Minimum crater diameter measured along four profiles spaced 45° azimuthally, with one of them aligned along the maximum dip direction of the basal surface (Wood, 1980b)	117
Wcr _A	m	Average crater diameter calculated as (Wood, 1980b): $Wcr = (Wcr_{max} + Wcr_{min})/2$	120
Wco _{max}	m	Average crater diameter calculated as (Favalli et al., 2009): $Wcr_A = (4 \cdot Acr/\pi) 0.5$	113
Wco _{min}	m	Maximum cone basal diameter obtained from a manually drawn best-fitting ellipse, where the major axis corresponds to the cone's maximum diameter (Wood, 1980b) (see Fig. 3.7d)	589
Wco _A	m	Maximum cone basal diameter obtained from a manually drawn best-fitting ellipse, where the major axis corresponds to the cone's maximum diameter (Wood, 1980b) (see Fig. 3.7d)	578
Zb _{max}	m	Average cone basal diameter calculated as (Wood, 1980b): $Wco = (Wco_{max} + Wco_{min})/2$	584
Zb _{min}	m	Average cone basal diameter calculated as (Favalli et al., 2009): $Wco_A = (4 \cdot Aco/\pi) 0.5$	553
Zb _{ave}	m	Maximum basal depth b.s.l. (in absolute value)	120
Zcf _{max}	m	Minimum basal depth b.s.l. (in absolute value)	90
Zcf _{min}	m	Average basal depth b.s.l. (in absolute value) calculated as: $Zb_{ave} = (Zb_{max} - Zb_{min})/2$	105
Zcr _{min}	m	Maximum depth b.s.l. (in absolute value) of the cone crater floor	38
	m	Minimum depth b.s.l. (in absolute value) of the cone crater rim	25

Table 3.4. Morphometric parameters measured for Stanley Patch volcano. b.s.l. Below sea level.

3.2.1.3 Stable isotopes analyses of Stanley Patch rock samples

For isotope analyses, three of the studied rock samples (SUB_3, SUB_4, and SUB_7) were prepared by removing several centimeters of material from the surface to avoid late isotopic modification by weathering, together with an exhaustive petrographic analysis that confirmed the absence of secondary minerals, such as zeolite group minerals. Hydrogen and oxygen isotopic analyses were carried out at the Servicio General de Análisis de Isótopos Estables (NUCLEUS - Universidad de Salamanca. Detailed extraction procedures, standards, and equipment used, as well as reproducibility determination, described in Álvarez-Valero et al. (2020).

Argon isotopic ratios were measured using a noble-gas mass spectrometer MS-IV (a modified VG-5400) at the Department of General Systems Studies, Graduate School of Arts and Sciences, The University of Tokyo. K% is obtained by the K₂O wt% XRF analysis previously described. The analytical procedure in detail and calculation method are described by Miyoshi et al. (2012), Mori & Mashima (2005), Nagao et al. (1984, 1996), and Orihashi et al. (2004).

3.2.2 Tephra Studies

3.2.2.1 Database design and architecture

The DecTephra (Deception Island Tephra Record) database has been constructed based on an extensive review of 30 peer-reviewed scientific articles and 2 PhD theses (Moreton, 1999; Molina Castiella, 2014) published between 1988 and 2020. For a tephra layer to be included in the DecTephra database, its Deception Island origin needs to be confirmed (or highly suspected) based on the geochemical similarity between the tephra layer and Deception Island's erupted materials (e.g., Pallàs et al., 2001).

The current version of the DecTephra database comprises records of 362 tephra layers, including: (i) 12 layers described by Hodgson et al. (1998) and listed in the Antarctic

Tephra Database (<http://www.tephrochronology.org/AntT>); (ii) 60 studied by Moreton & Smellie (1998) and Moreton (1999), uploaded in the PANGAEA Repository (<https://www.pangaea.de>); (iii) 254 tephra layers found in marine/lacustrine sediments and ice cores; and (iv) 36 sampled englacial tephras. In this way, the database substantially updates the compilation by Smellie (1999) that listed c. 65 Upper Cenozoic tephra layers in the south polar region sourced at Deception Island. For each tephra layer included in the database, we compiled information regarding: (i) location (e.g., latitude, longitude, region) and sample details such as position within a sediment or ice core), and (ii) tephra layer characteristics (e.g., age, chemistry, granulometry). The latest version of the database is included is available for download on the DecTephra web page (<http://voldec.es/dectephra/>) and the Zenodo open-access repository (Hopfenblatt et al., 2022b; <https://doi.org/10.5281/zenodo.6077062>). For more information regarding database architecture and principal data tables included (Fig. 3.9) (See Appendix 3).

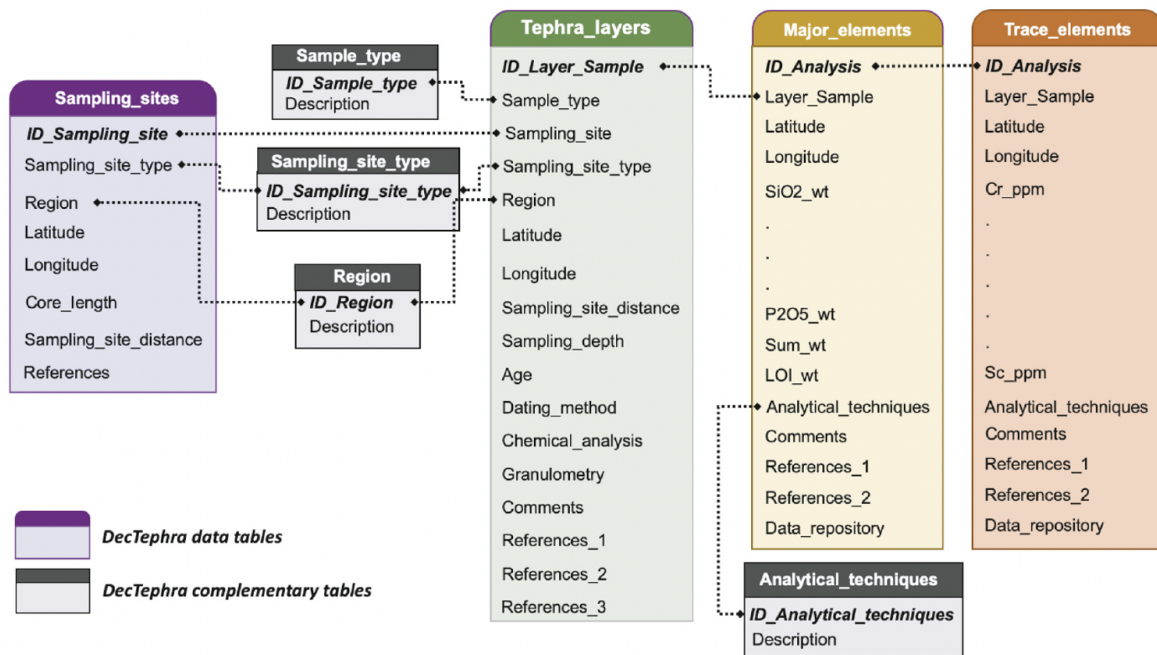


Figure 3.9. Structure of the DecTephra database, comprising principal data tables (Sampling_sites, Tephra_layers, Major_elements and Trace_elements) and complementary tables (Sample_type, Sampling_site_type, Region, and Analytical_techniques) (See Hopfenblatt et al., 2022b for further details) The References table is not included for clarity. Black dashed lines indicate connections between tables.

3.2.2.2 Granulometric analyses of the studied tephra samples

Granulometry analyses of the studied tephra samples were performed with a laser diffraction particle analyzer (Coulter LS230) at the Departament de Dinàmica de la Terra i de l'Oceà at the UB. This analyzer measures the percentage of volume of particles between 0.04 and 2000 μm by light diffraction (data available at Polo Sánchez et al., 2024). Coarser grains were separated and classified by dry sieving using a sieve shaker machine at Departament de Dinàmica de la Terra i de l'Oceà at the UB (Fig. 3.8).

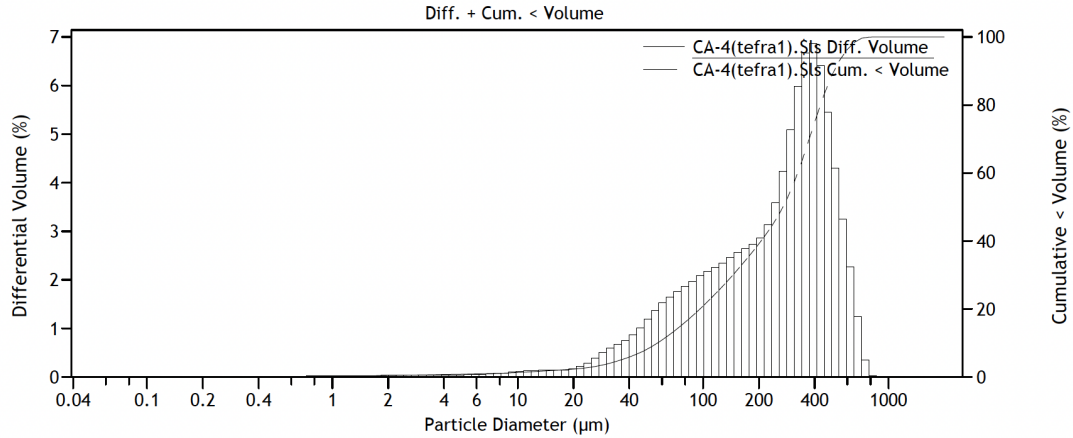


Figure 3.8. Example of Coulter results of sample CA-4 of the 1970 eruption of Deception Island.

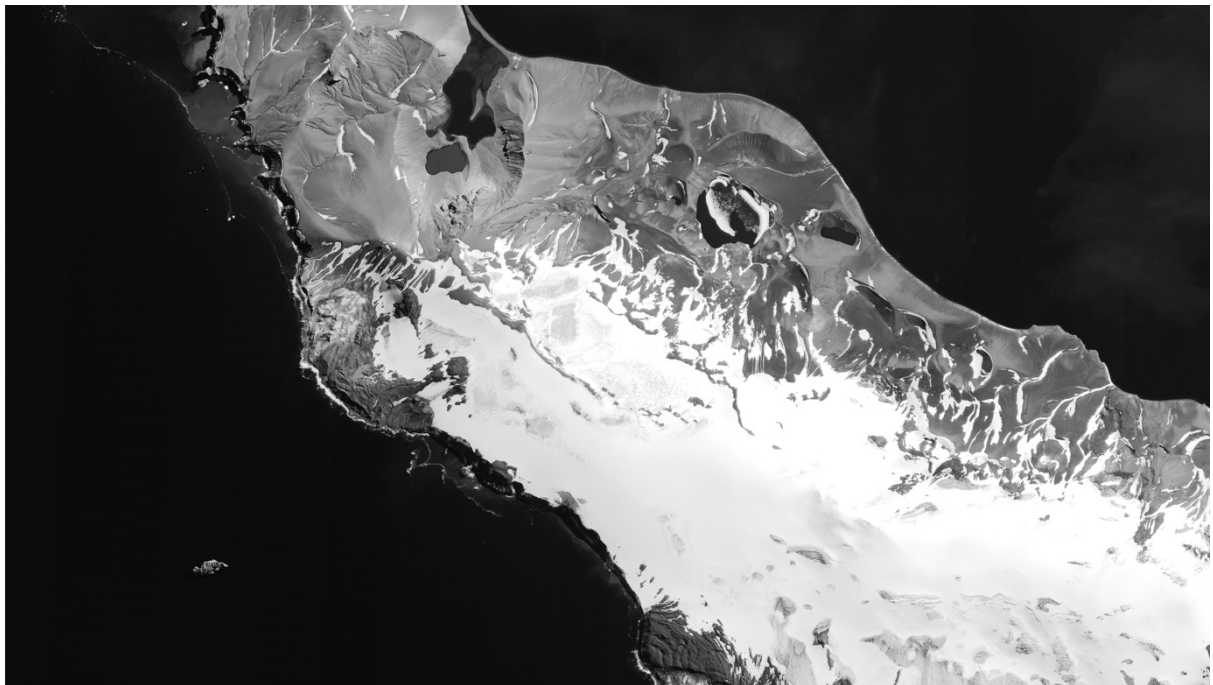
The grain sizes are expressed in phi (Φ) units calculated as Udden-Wentworth grain size scale (Udden, 1914; Wentworth, 1922, 1935):

- $Grain\ Size\ (\Phi) = -\log_2(Grain\ Size\ in\ mm)$

Based on the obtained results, median Me and sorting coefficient have been estimated as follows (Heiken and Wohletz, 1992; Cashman & Rust, 2016):

- $Median\ (Me) = \Phi_{50}$
- $Sorting\ coefficient\ (\sigma) = \frac{\Phi_{84} - \Phi_{16}}{2}$

Finally, results are displayed in the form of granulometric curves (e.g., Cashman & Rust, 2016), barplots and median-sorting coefficient diagrams (e.g., Dellino et al., 2001; Walker, 1971). Granulometric data has been also processed using the R programming language for statistical computing and graphics using the R-Studio software (<https://www.rstudio.com/>) (R Core Team, 2014), specifically the *ggplot2* package (Version 3.3.3).



PART II

4 CHAPTER 4

Stanley Patch volcano: Port Foster's Bay most relevant eruptive event

In this chapter, we present a summary of the full characterization carried out at Stanley Patch volcano and related erupted deposits. Results obtained have allowed establishing the type and size of the eruption, as well as to constrain the evolution of Port Foster Bay after the caldera collapse. Further details can be found on Hopfenblatt et al. 2021 (See Appendix 1 and 2).

4.1 Morphometry analysis

Stanley Patch rises sharply from the north-east, trending and gently dipping ($\sim 3^\circ$) seafloor (Fig. 4.1a). The overall shape of both crater and base is very circular, with a planimetric basal (A_{co}) and crater area (A_{cr}) of $\sim 2.4 \times 10^5 \text{ m}^2$ and $\sim 0.1 \times 10^5 \text{ m}^2$, respectively. The volcanic cone has a maximum basal diameter ($W_{co_{max}}$) of $\sim 589 \text{ m}$ and a minimum diameter ($W_{co_{min}}$) of $\sim 578 \text{ m}$, both obtained from a manually drawn best-fitting ellipse, where the major axis corresponds to the cone's maximum diameter (Wood, 1980b) (Fig. 3.7d, Table 3.4). The average cone basal diameter varies from 584 m (W_{co}) to 553 m (W_{co_A}) depending if calculated as the arithmetic mean of $W_{co_{max}}$ and $W_{co_{min}}$ (i.e., W_{co}) (e.g., Pedrazzi et al., 2020; Wood, 1980b) or estimated as the diameter of a circle with an area equivalent to A_{co} (i.e., W_{co_A}) (e.g., Favalli et al., 2009; Kervyn et al., 2012). Maximum cone height ($H_{co_{max}}$) is $\sim 77 \text{ m}$ but rises up to $\sim 80 \text{ m}$ ($H_{co_{maxSb}}$) when considering it as the difference between the average basal elevation ($Z_{b_{ave}}$) and the minimum water depth observed at the cone's rim crest or summit ($Z_{b_{min}}$) (Table 3.4 and Fig. 3.7d) (Settle, 1979). This results in similar height and width ratios regardless of the calculation method, ranging between ~ 0.132 ($H_{co_{max}}/W_{co}$) and 0.145 ($H_{co_{maxSb}}/W_{co_A}$), and a cone volume (V_{co}) of 0.06 km^3 .

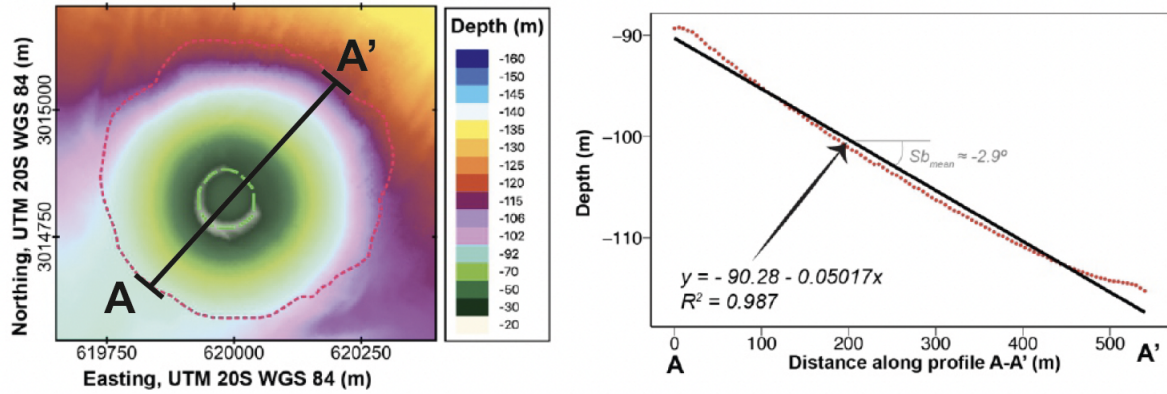


Figure 4.1. 4×4 m grid size Digital Elevation Model (DEM) of Stanley Patch volcano. Elevation points obtained along A-A' profile aligned along the maximum dip direction of the basal surface. The average slope of the basal plane (Sb_{mean}) is then obtained by applying a linear regression.

The crater rim has a shallow crest with maximum (Wcr_{max}) and minimum (Wcr_{min}) diameters of 123 m and 117 m, respectively. The average crater diameter ranges from 113 m (Wcr_A) to 120 m (Wcr), depending on the calculation method (Table 4). This results in a Wcr and cone basal diameter ratio in the range of ~ 0.193 (Wcr_A/Wco) to 0.217 (Wcr/Wco_A). The crater floor is flat with a diameter (Wcf) of ~ 39 m and a maximum depth (Dcr) of ~ 13 m (Table 3.4, Fig. 3.7d).

The cone is characterized by steep upper flanks, separated by a break-in slope from a gentle sloping apron (Fig. 4.2). The cone slope angle histogram shows two major slope angle modes centered at $\sim 25^\circ$ (Fig. 4.3b I) and a broad feature between 8° and 20° (Fig. 4.3b II). The intra-crater slopes are generally less steep (Figs. 4.2, 4.3b III), partially due to the filling of the crater floor by sediment (Fig. 4.3a I). The Stanley Patch cone is also characterized by the following morphological features (Fig. 4.2): (1) a flat to gentle sloping wide crest of the crater rim ($5 - 15^\circ$) on the northeast side; (2) a break-in-slope between the uniformly inclined flanks and a gentle sloping apron surrounding the Stanley Patch volcano; and (3) two arcuate troughs running from N to S on the flanks.

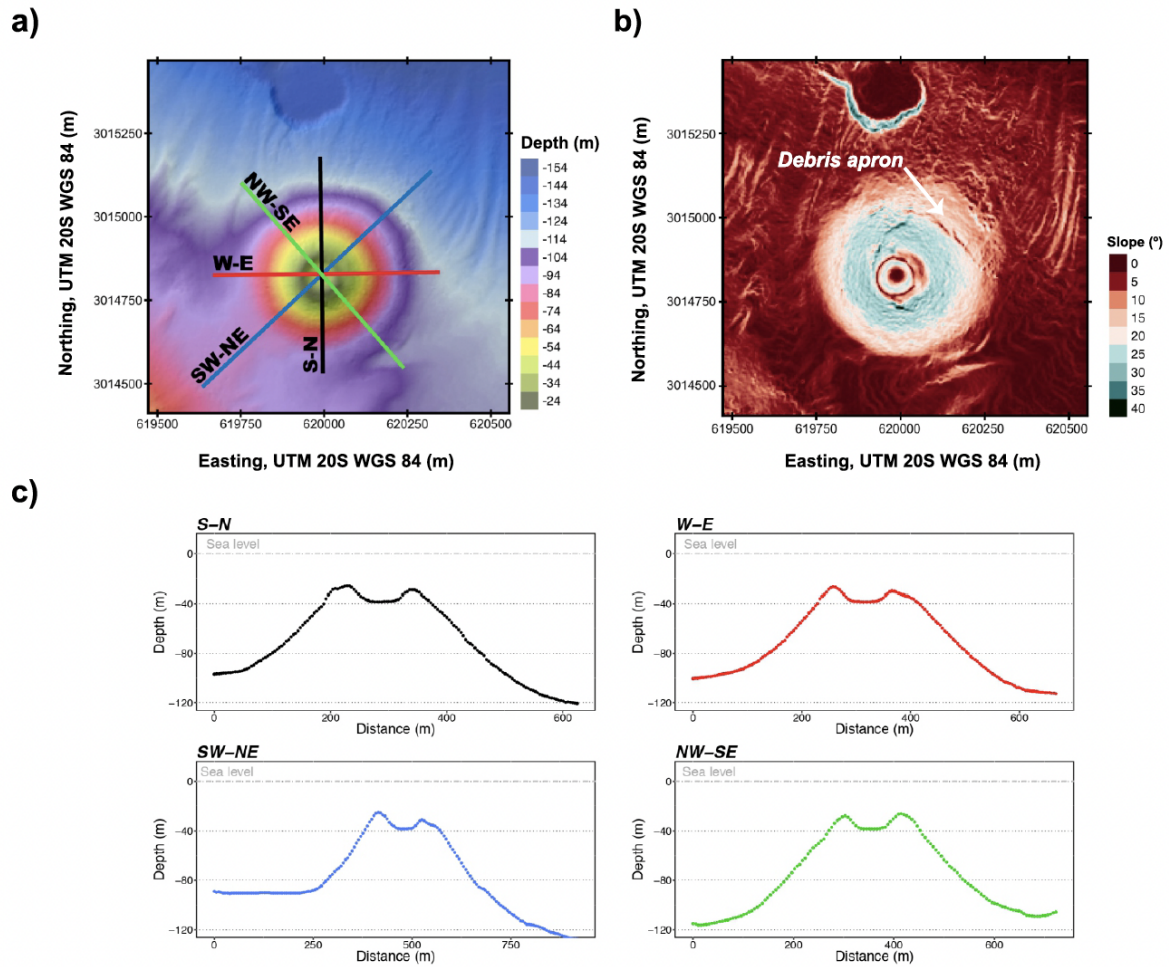


Figure 4.2. a) Depth map of Stanley Patch volcano. Cross sections marked for c). b) Slope map of Stanley Patch volcano, the debris apron around the NE side of the cone are clearly observed. c) Cross sections of Stanley Patch volcano.

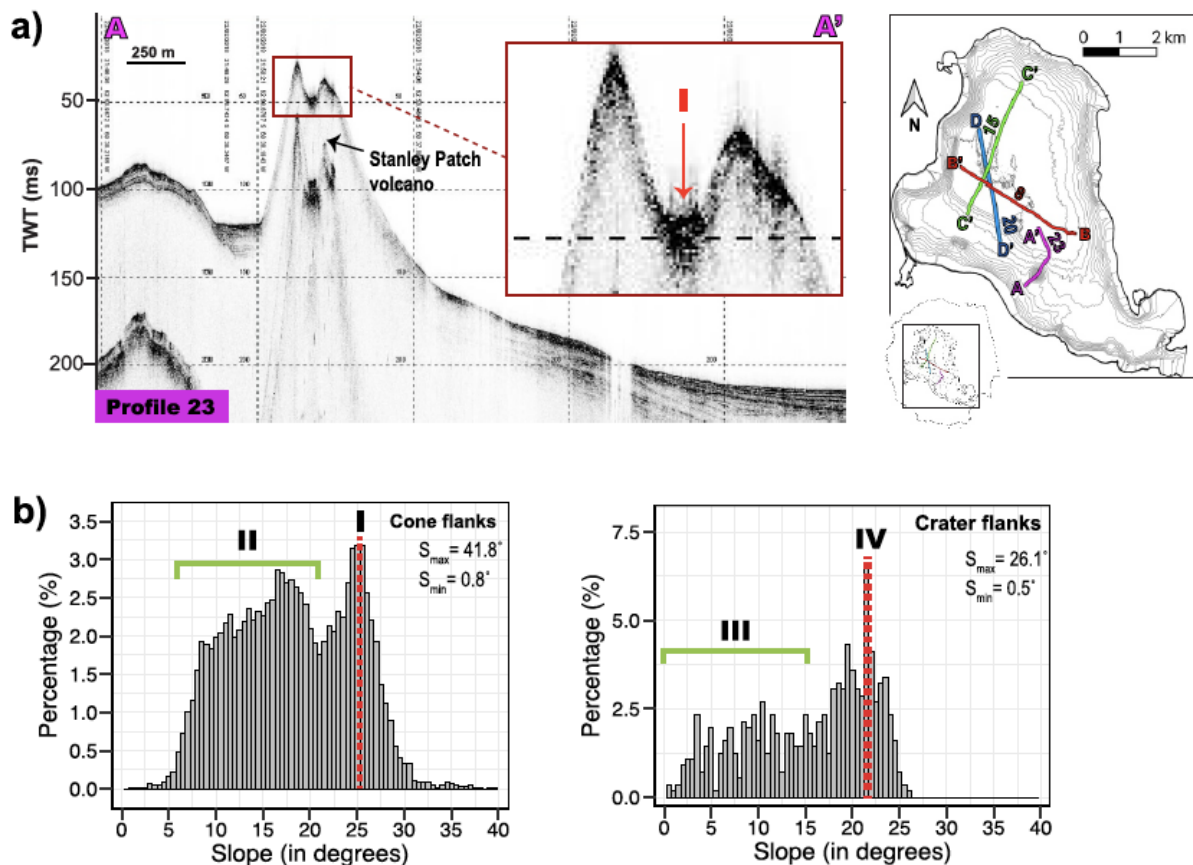


Figure 4.3. NW-SE high resolution seismic profiles across Stanley Patch volcano (available at Gómez-Ballesteros et al., 2018). TWT: Two-way-time proxy for depth. The map on the right indicates the location of the profile A - A' (Profile 23) and of those included in Fig. 6a–c of Hopfenblatt et al., 2021. b) Density slope diagrams of the cone (left) and crater inner flanks (right).

4.2 Petrographic and geochemical analyses

The rock samples collected on the crater rim of Stanley Patch correspond to low density and poorly vesicular (25 – 35% vesicle volume; Houghton & Wilson, 1989) scoriaceous fragments from 2 to 15 cm in size (Fig. 4.4). Vesicle sizes are normally smaller than 1 mm, rarely reaching up to 3 – 4 mm, and are fairly elongated to irregular in shape. In hand specimens, the fragments are usually black, with local reddish-brown oxidized zones. Most samples show a < 0.5 mm thick, yellow to green carbonate crust corresponding to encrusting coralline algae (Fig. 4.4).

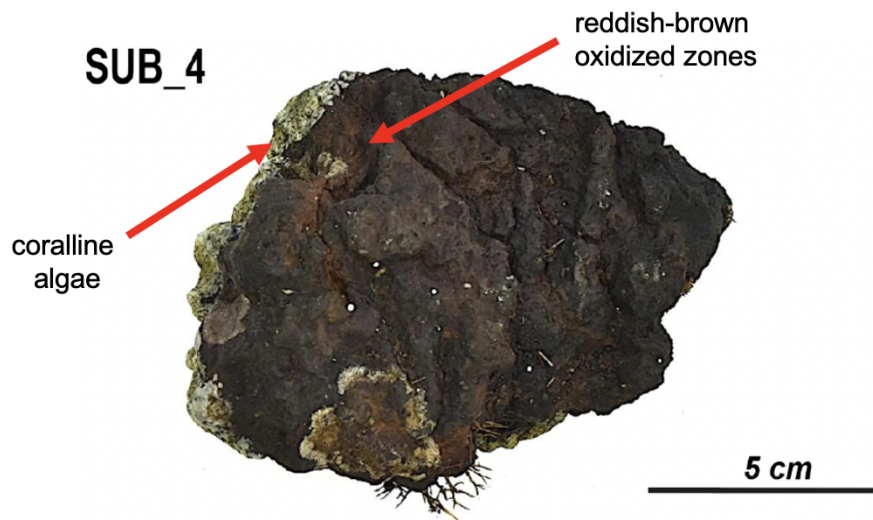


Figure 4.4. SUB_4 sample of Stanley Patch volcano with features described in the text.

At microscopic scale, the studied samples are porphyritic with phenocryst content below 1 - 2 vol% immersed in a hyalopilitic textured groundmass consisting of plagioclase, pyroxene, Fe-Ti oxides, and interstitial glass. Phenocrysts are dominated by euhedral plagioclase crystals from 0.5 to 1.0 mm in diameter, with minor subhedral phenocrysts of clinopyroxene and olivine ranging from 0.3 to 0.5 mm (Fig. 4.5). Quenching textures such as skeletal or dendritic shapes are not observed. Spiky crystals with swallow-tailed terminations are scarce, whereas sideromelane is mainly present as micrometric glass fragments filling the vesicles.

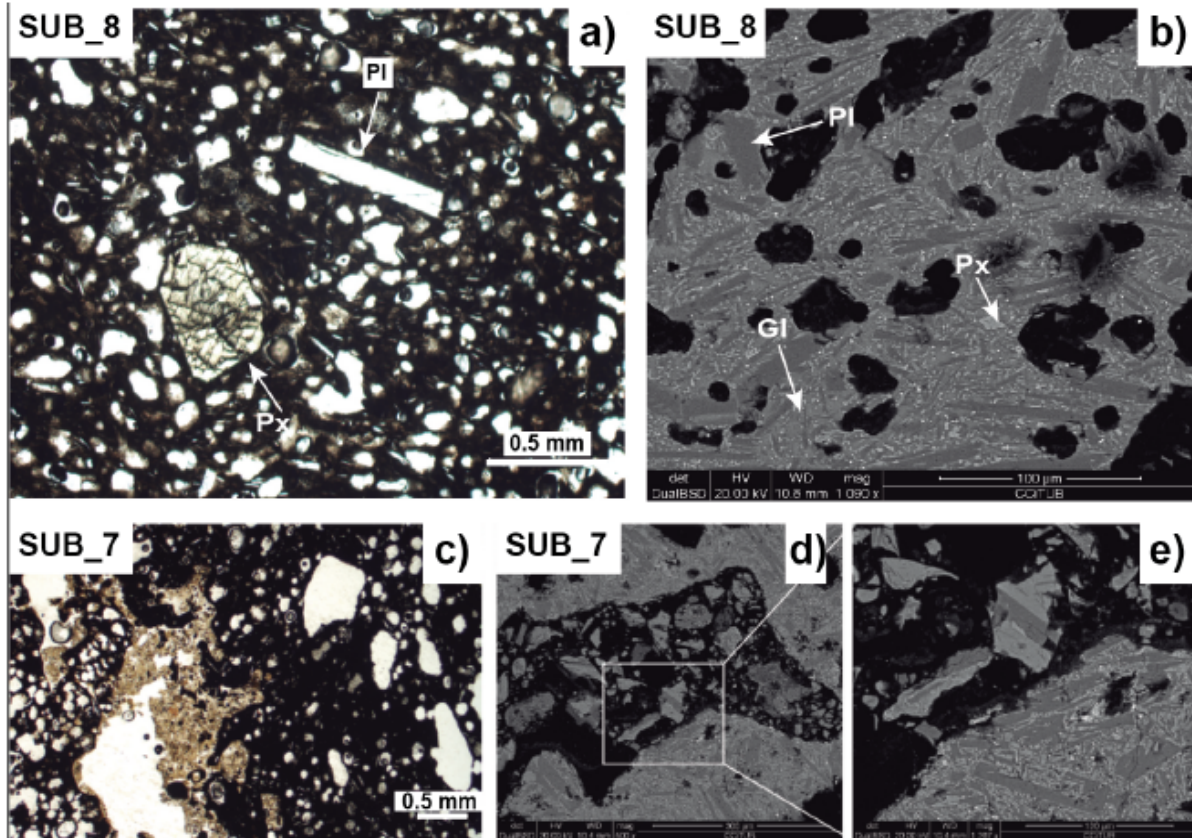


Figure 4.5. Plane light optical microscope (a, and c) and SEM (b, d, and e) images of Stanley Patch juvenile samples. SUB_8 consists of a highly vesiculated scoriaceous volcanic fragment with phenocrysts of plagioclase (Pl) and pyroxene (Px) and with interstitial glass (Gl). Images of sideromelane fragments filling vesicles in sample SUB_7 (c and d) and b) correspond to a porphyritic sample with plagioclase phenocrysts immersed in a dark crystalline groundmass of plagioclase (Pl), pyroxene (Px), and oxides (Ox).

Based on whole rock geochemistry, the sampled rocks classify as subalkaline basaltic trachyandesites and basaltic andesites (53 – 55 wt.% SiO₂) (Fig. 4.6, Table S3 of Hopfenblatt et al., 2021). Despite their small range in composition, they present slightly negative correlations of MgO and CaO with SiO₂ and positive correlations of K₂O and Na₂O (Fig. 4.7). REE contents depict nearly straight trends in a chondrite-normalized diagram without significant anomalies (Fig. 4.8). In contrast, marked positive anomalies (Cs and Pb) and negative anomalies (Nb) occur in the primitive-mantle normalized diagram (Fig. 4.9).

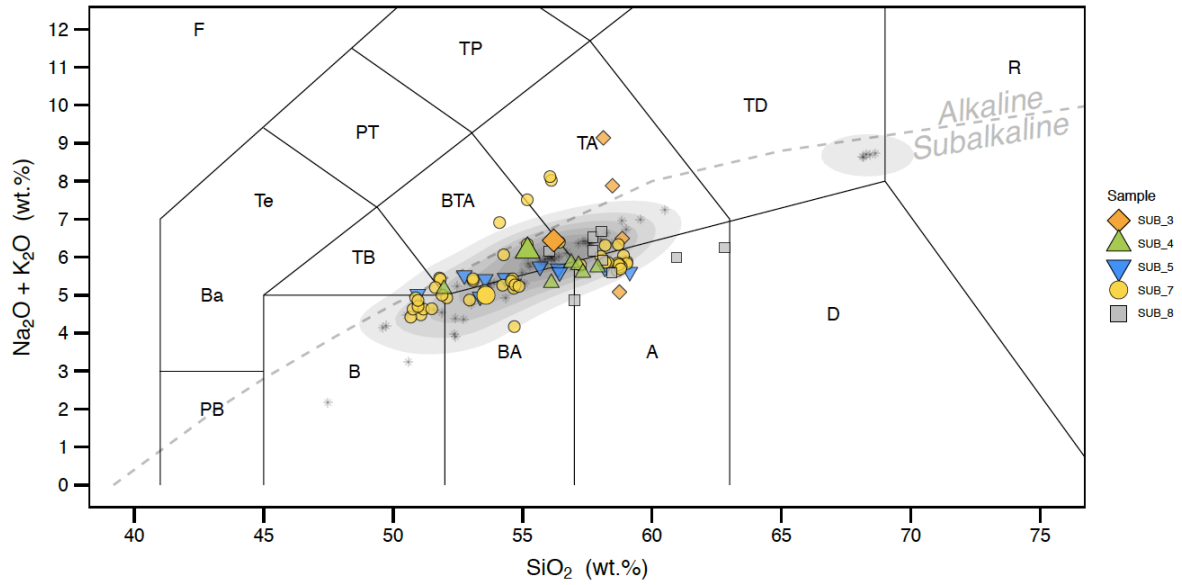


Figure 4.6. Total Alkali vs. Silica diagram (TAS) (Le Bas et al., 1986) for the rock samples considered in this work (See Hopfenblatt et al., 2021 for analyzed data). For comparison, gray shaded areas and asterisks correspond to the post-caldera rock samples presented by Geyer et al. (2019). Major elements normalized to 100% (anhydrous) with Fe distributed between FeO and Fe₂O₃ following Middlemost (1989). The gray dashed line discriminates between the alkaline-subalkaline fields (Irvine & Baragar, 1971).

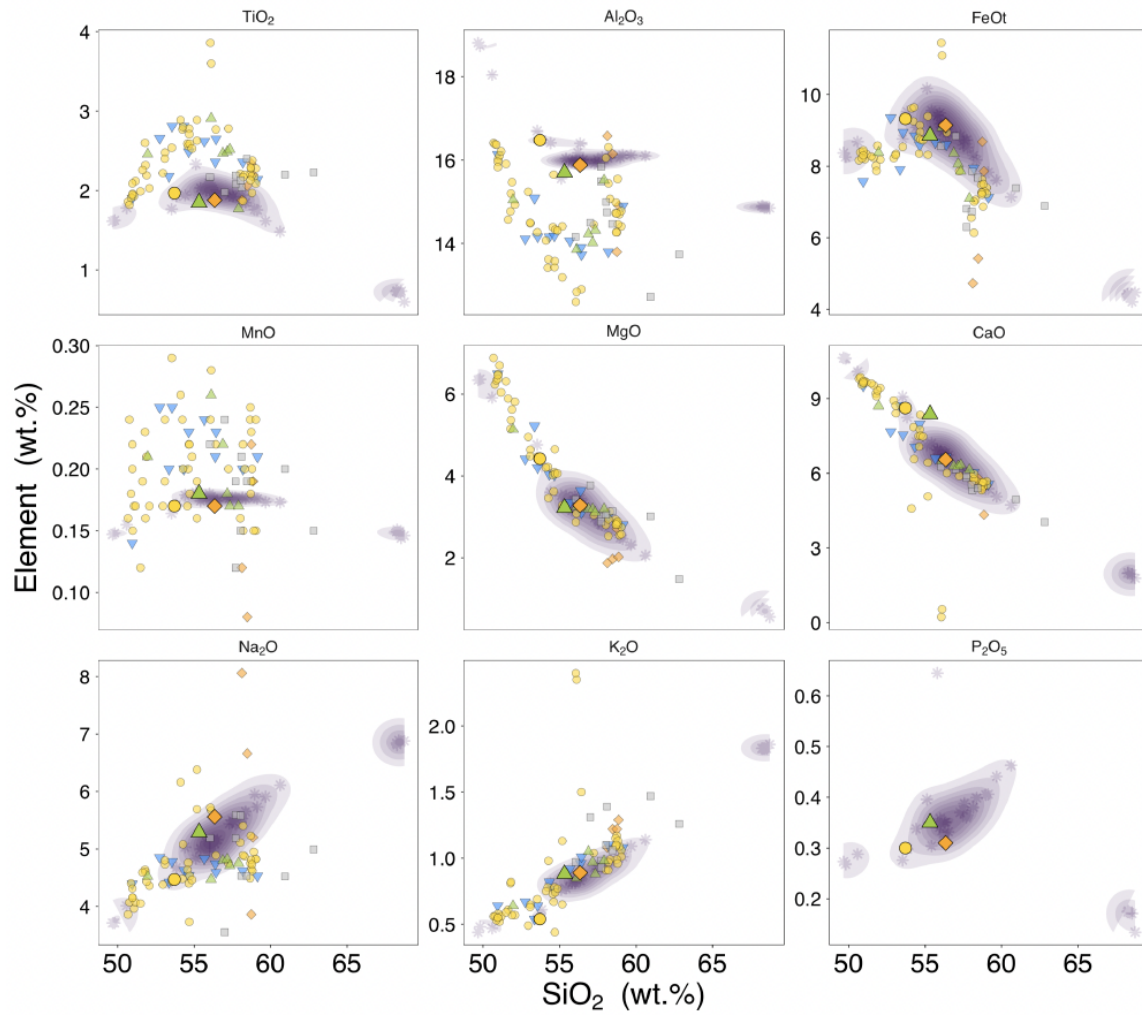


Figure 4.7. Major element vs. SiO_2 content Harker Diagrams for the rock samples considered in this study. For comparison, gray–purple shaded areas and asterisks correspond to the post-caldera rock samples presented by Geyer et al. (2019). Major element compositions have been normalized to 100% in an anhydrous base with Fe as FeO_t . Legend, as per Figure 28 (See Hopfenblatt et al., 2021 for analyzed data).

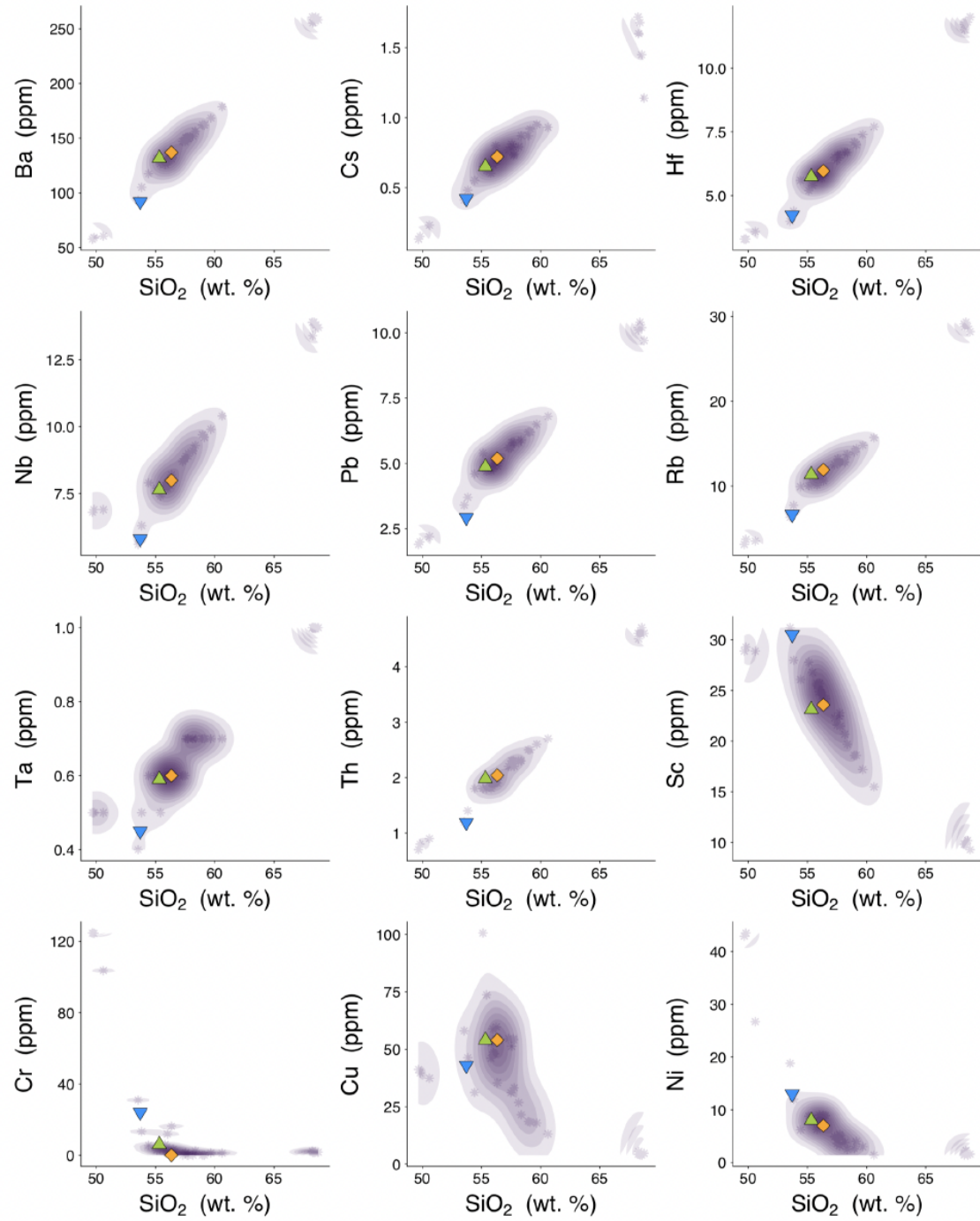


Figure 4.8. Harker diagrams of trace and Rare Earth elements vs. SiO_2 content for the rock samples considered in this work. For comparison, gray–purple shaded areas and asterisks correspond to the post-caldera rock samples presented by Geyer et al. (2019). Major element compositions have been normalized to 100% in an anhydrous base with Fe as FeO_t . Legend, as per Figure 4.6 (See Hopfenblatt et al., 2021 for analyzed data).

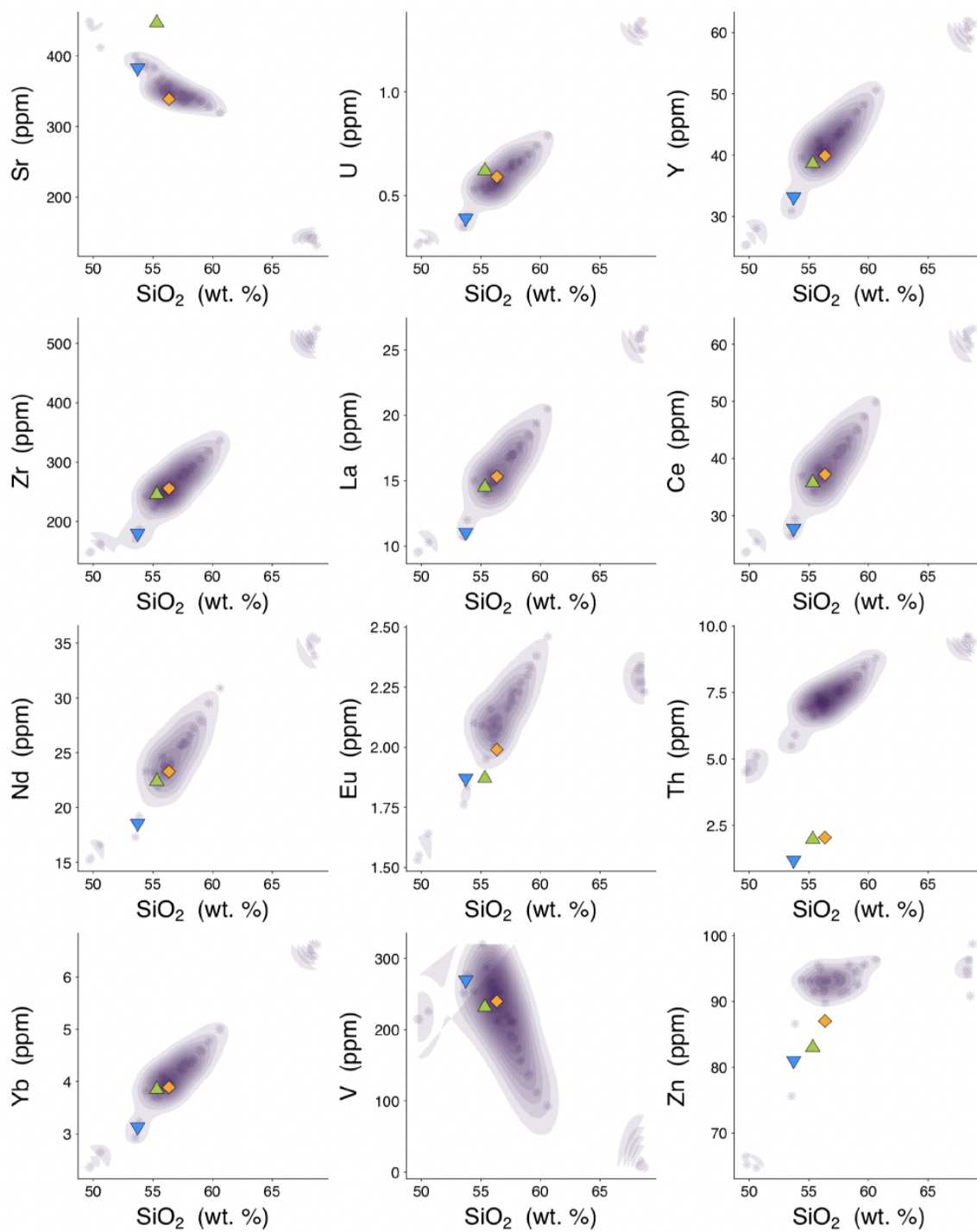


Figure 4.8. Continuation.

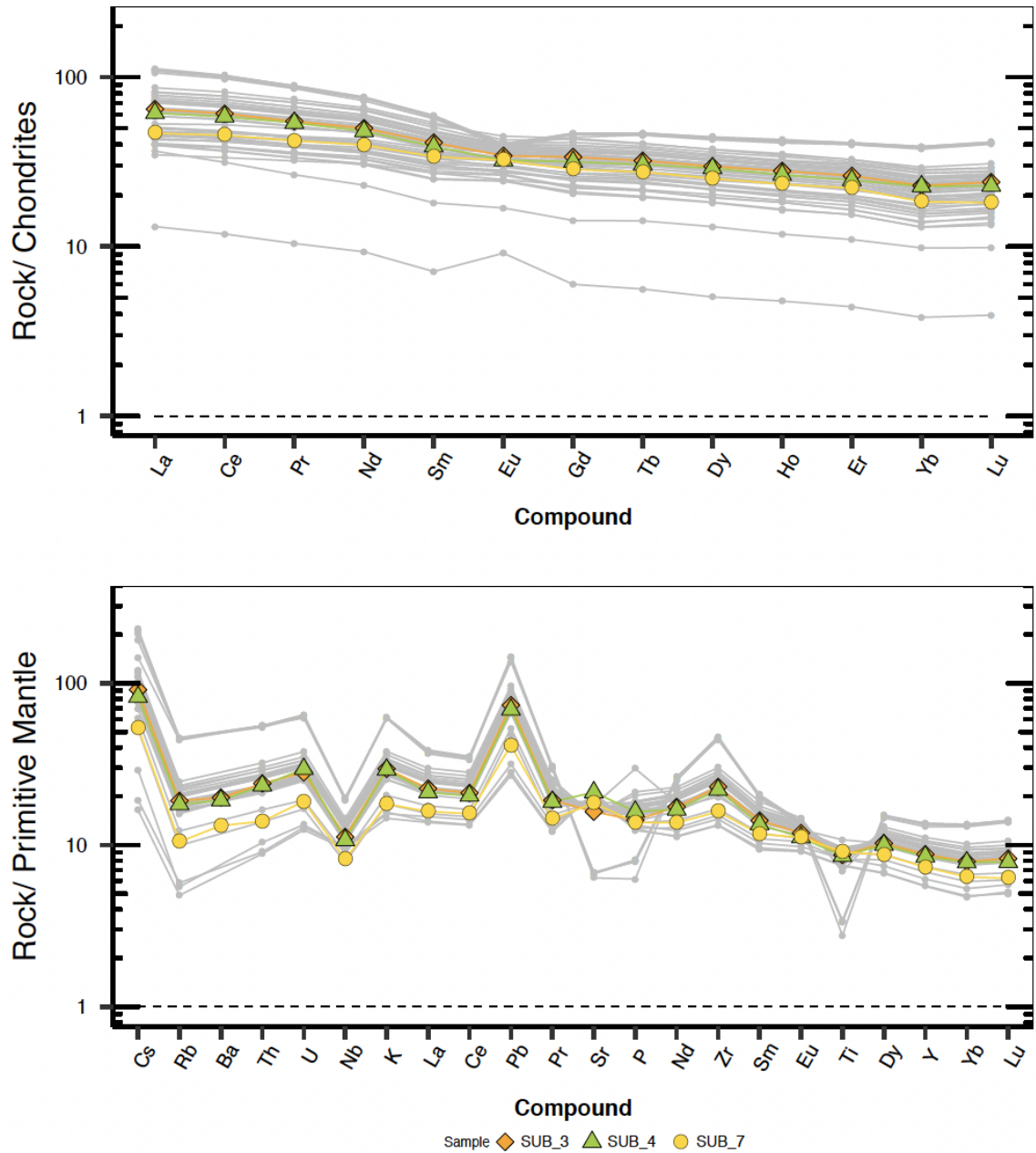


Figure 4.9. Whole Rock compositions normalized to chondrites (top) and primitive mantle (bottom) compositions of Sun and McDonough (1989). Major element compositions have been normalized to 100% in an anhydrous base with Fe as FeO_t (See Hopfenblatt et al., 2021 for analyzed data).

Olivine micropheno- and microcrystals show forsterite contents ranging from Fo₄₉ to Fo₇₂ (Fig. 4.10a) and Ni contents varying from 33 to 563 ppm. Microphenocrysts and phenocrysts of pyroxenes (augites), show compositions of Wo_{25–44}, En_{37–52}, Fs_{10–22} (Fig. 4.10b). Plagioclases are mainly labradorites and andesines, with An₆₂ – An₃₈ (Fig. 4.10c, Table S7 of Hopfenblatt et al., 2021). In sample SUB_7, plagioclase ranges from bytownite to oligoclase (An₇₅ to An₁₀). In addition, samples SUB_4 and SUB_7 display local ilmenite and titanomagnetite (Fig. 4.10d, Table S8 of Hopfenblatt et al., 2021). Glass compositions are notably variable, going from basaltic to trachyandesitic with SiO₂ contents of 51 – 59 wt.% and 56 – 62 wt.% in samples SUB_5, SUB_7, and SUB_8, respectively (Fig. 4.6). In contrast, regarding silica content, glass is mostly homogeneous in samples SUB_3 and SUB_4. In general, glasses show a negative correlation of MgO and CaO with SiO₂, and a positive correlation of K₂O and Na₂O. Contents of TiO₂, FeO_t, Al₂O₃, and MnO show a notable chemical dispersion (Figs. 4.6, 4.7). This significant variation in the compositional ranges of phenocrystals and glasses is consistent with the mixing mechanisms occurring at depth, which are widely observed in the products of the entire island (e.g., Smellie, 2001, 2002b; Geyer et al., 2019, 2021).

D/H ratios of the Stanley Patch samples range from –58.4 to –99.5 ‰ (Fig. 4.11) with homogeneous water content of 0.1 – 0.2 wt.% (See Table S9 of Hopfenblatt et al., 2021). All samples fall within the range of regular primary magmatic fluids (i.e., igneous waters in Fig. 4.11), slightly above and immediately below the isotopic composition of the N-MORB mantle (–60 ‰; Clog et al., 2013). $\delta^{18}\text{O}$ values show small variation from 5.0 to 6.3 ‰ within the usual values of basaltic rocks on Earth ($\approx 3.5 - 7$ ‰) (Bindeman, 2008), and are in line with the onland samples of the island (Álvarez-Valero et al., 2020).

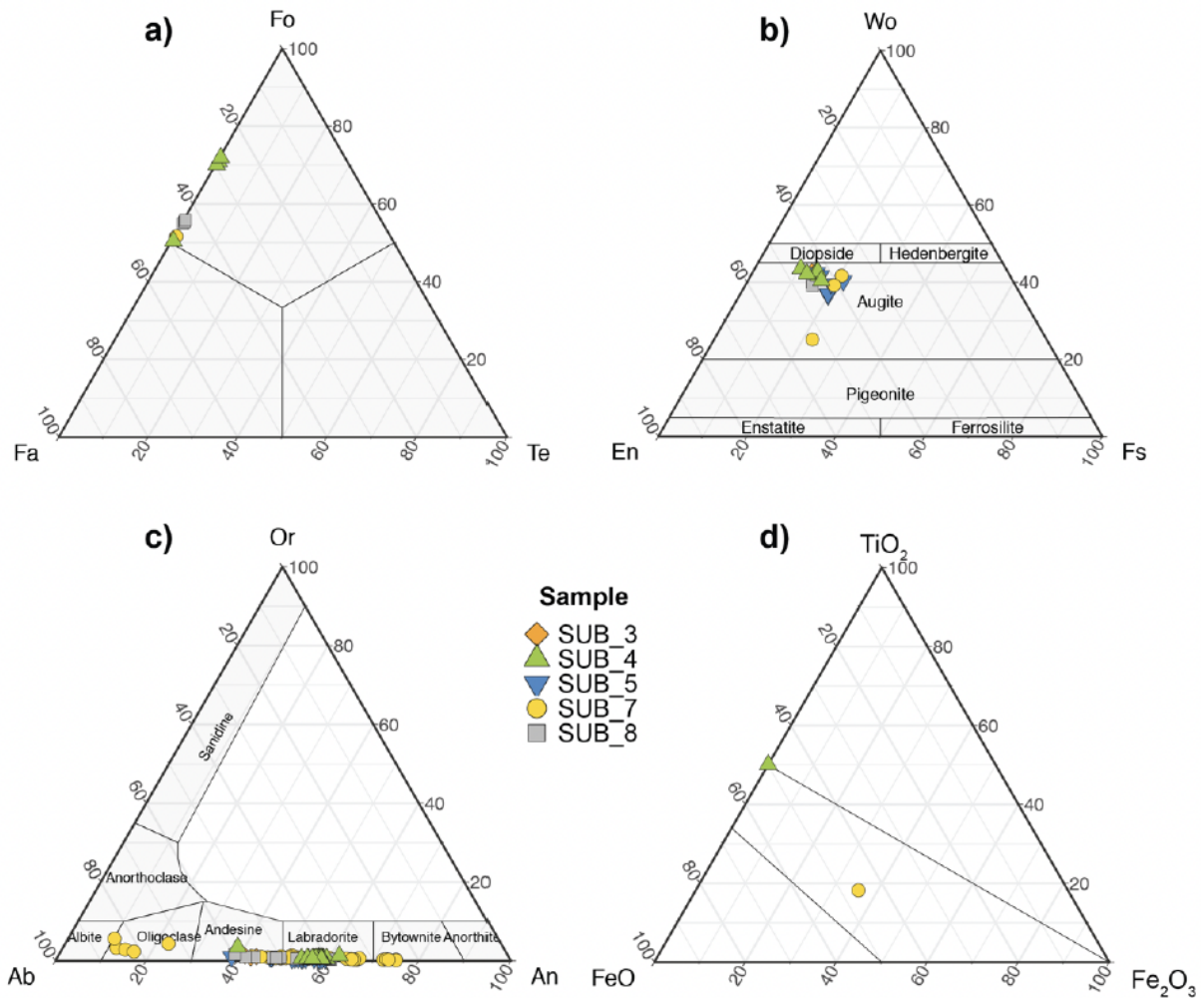


Figure 4.10. a) Forsterite (Fo) - Fayalite (Fa) - Tephroite (Te) ternary diagram for olivine classification; b) Wollastonite (Wo) - Enstatite (En) - Ferrosilite (Fs) ternary diagram for the classification of Ca-Mg-Fe pyroxenes (Morimoto, 1989); c) Orthoclase (Or) - Albite (Ab) - Anorthite (An) ternary diagram for the classification of feldspars (Deer et al., 2001); d) Ternary classification diagram for Fe-Ti oxides (See Hopfenblatt et al., 2021 for analyzed data).

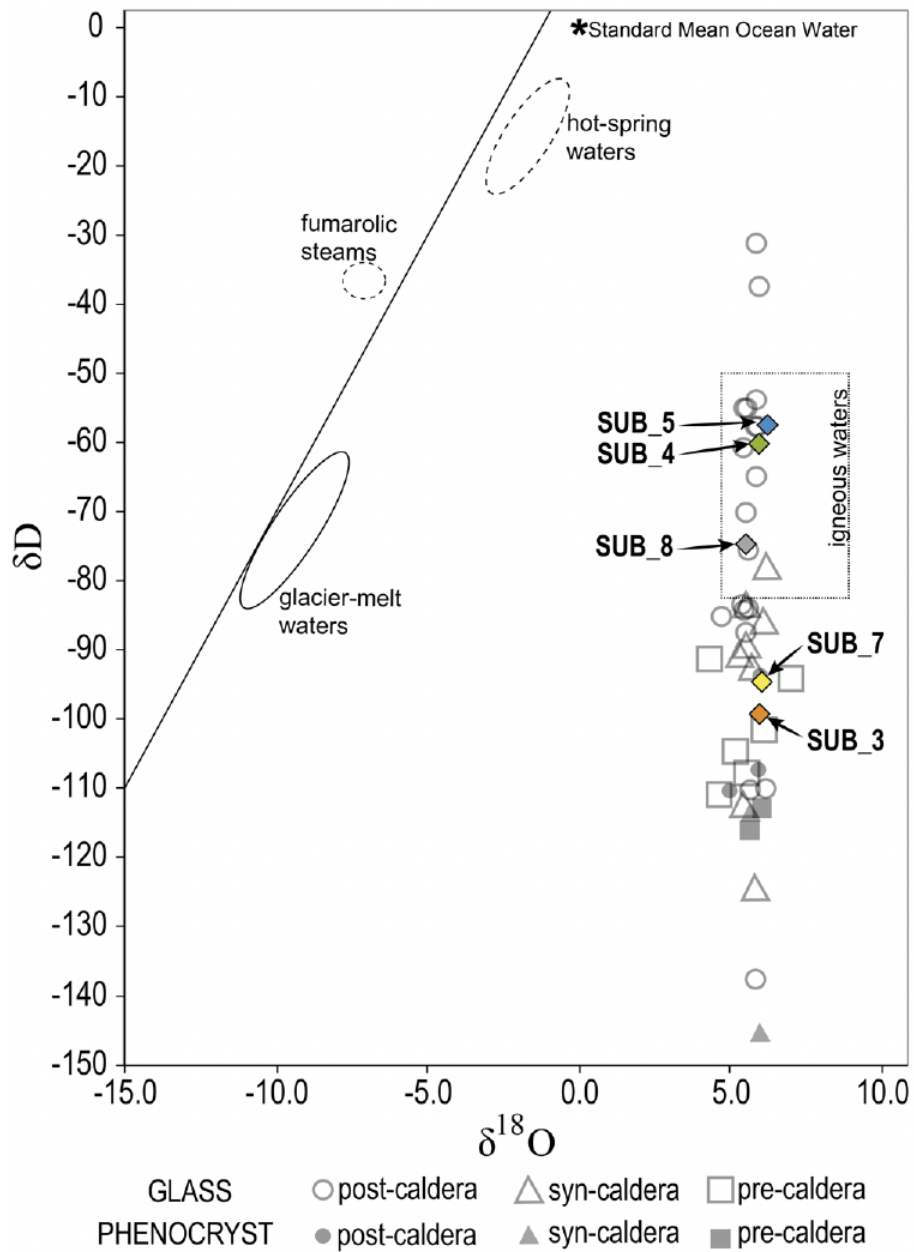


Figure 4.11. Plot of D vs. O stable isotopes for Stanley Patch samples. Deception Island samples are also represented according to their stratigraphic position (pre-, syn-, and post-caldera). Hot spring, fumarolic, and glacier-melt waters data (ellipses) correspond to the local values at Deception Island from Kusakabe et al. (2009) (See Hopfenblatt et al., 2021 for analyzed data).

4.3 Discussion: Stanley Patch, a submerged subaerial volcanic cone

The height and width ratios for the edifice and its crater show an overlap with terrestrial scoria cones (e.g., Kervyn et al., 2012; Settle, 1979; Wood, 1980b) (Fig. 4.12a). The obtained values, independent of the calculation method applied, match with young cone populations from Mt. Etna (Italy) (Favalli et al., 2009), Lanzarote (Canary Island) (Kervyn et al., 2012), and Mauna Kea (Hawaii) (Kervyn et al., 2012). The morphometric values of Stanley Patch, however, are in contrast with onshore monogenetic edifices, which are mostly tuff cones and tuff rings with much wider craters and lower edifice height/width ratios (Pedrazzi et al., 2020). In general, submarine pyroclastic cone populations show a much larger range of edifice height and width ratios, and typically they are larger in volume (Fig. 4.12) (e.g., Mitchell et al., 2012; Weiß et al., 2015).

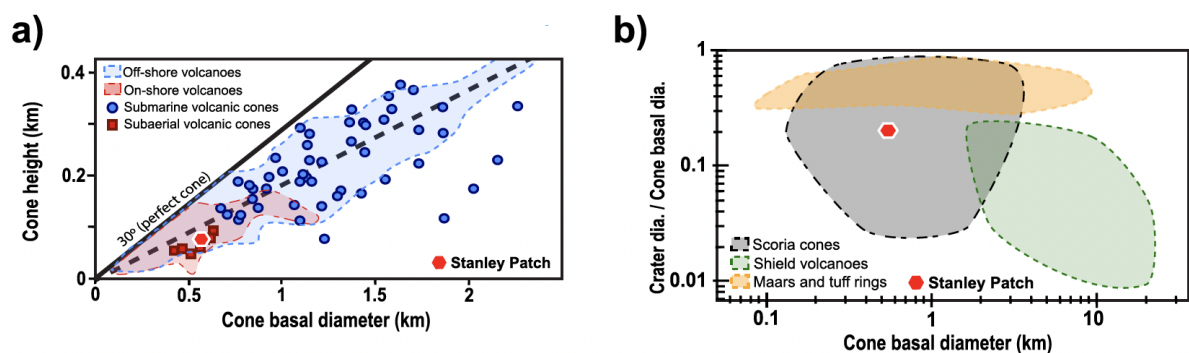


Figure 4.12. a) Average cone basal diameter vs height for Stanley Patch volcano compared to well-studied on-shore and off-shore volcanic edifices observed at Pico Island (Azores) (blue circles and red squares, data from Mitchell et al., 2012) and Terceira Rift/São Miguel island (blue and red area, data from Weiß et al., 2015). b) Crater diameter/cone basal diameter ratio vs cone basal diameter of Stanley Patch volcano compared to the values for several other types of terrestrial volcanic edifices according to Brož and Hauber (2013).

The bimodal slope angle distribution of the cone flanks (Fig. 4.3b I, II) can correspond to hillslope erosion and sediment transport. The gentle sloping areas around the cone (Figs. 3.7b, c, 4.2) are interpreted to be a debris apron formed due to syn-eruptive reworking and

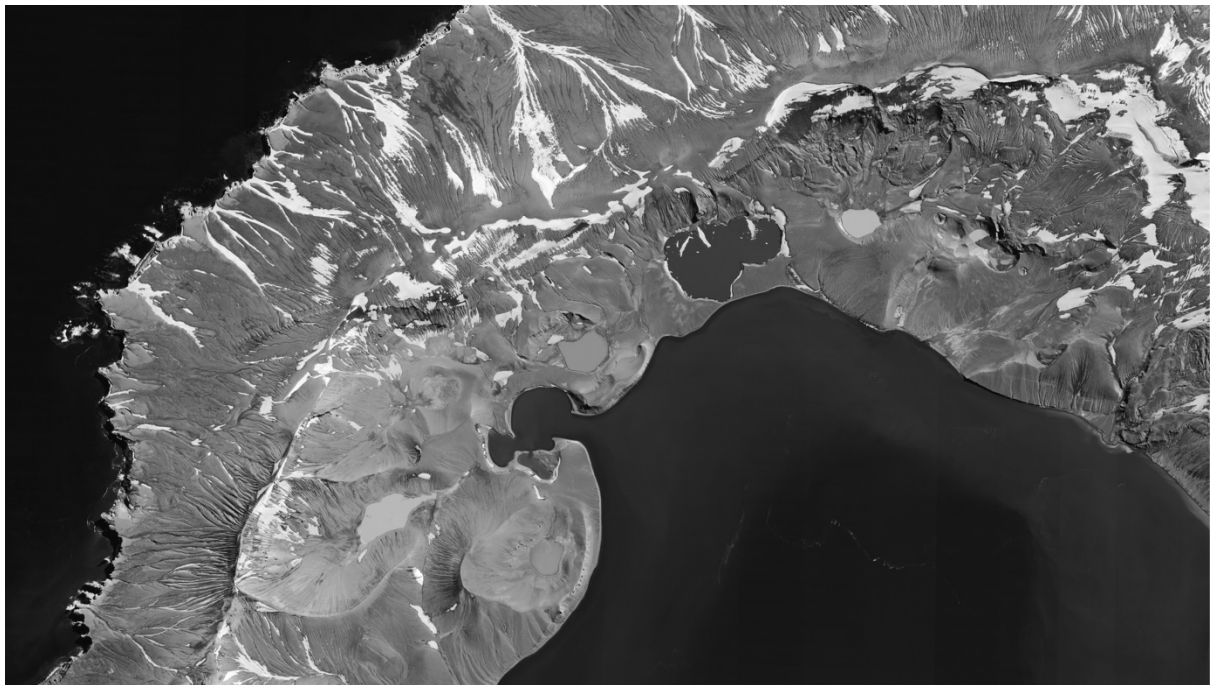
post-eruptive erosional processes (e.g., debris flows) (e.g., Dohrenwend et al., 1986; Ferrucci et al., 2005; Kereszturi & Németh, 2016a; McGetchin et al., 1974). The steeper ($\sim 25^\circ$) upper cone flanks have a slope angle lower than the typical angle of repose value ($30 - 35^\circ$) (Wood, 1980a, 1980b), indicating eruption-related deviation of the pyroclastic successions, including grain size, welding, and agglutination differences among flank sectors (e.g., Kereszturi et al., 2012; Kereszturi & Németh, 2016b; Kervyn et al., 2012; Valentine et al., 2005), and/or erosional processes (e.g., Hooper and Sheridan, 1998). The arcuate troughs on the flank of Stanley Patch resemble discontinuity surfaces and small-stepped scars due to partial cone collapse (Figs. 3.7c, 4.2). These features are present at many unwelded scoria cones (e.g., Németh et al., 2011; Riggs & Duffield, 2008; Sumner, 1998), and also observed in analogue experiments (Grosse et al., 2012). The geomorphology of the crater rim also suggests erosional rounding (e.g., Pelletier & Cline, 2007). The lower intra crater wall slope angles are interpreted to be caused by erosional modification, suggesting a post-eruptive rim-to-crater sediment transport combined with marine sedimentation.

Basaltic magma cooled by surface water forms a rim of pale brown glass (sideromelane) that transitions to black glass (tachylite) with slower cooling. Tachylite has a glassy groundmass with abundant cryptocrystalline microlites/nanolites of Fe-Ti oxides (White et al., 2015). It also forms quenching textures in crystals, such as skeletal, dendritic, or globular shapes. Magma-water interaction can fragment magma via hydromagmatic processes or hyaloclastite formation (underwater only). Magma-water interaction also affects vesicle shape and volume (Mastin et al., 2004; Stovall et al., 2011; Ross & White, 2012). After emplacement, sideromelane alters into palagonite when wet and hot (Stroncik & Schmincke, 2002). These key features of magma-water interactions are absent in the Stanley Patch samples, thus supporting negligible magma-water contact during the eruption (e.g., Bryan, 1972; Jercinovic et al., 1990; Walton & Schiffman, 2003).

Direct contact between seawater and magma or volcanic rocks during eruption or cooling can modify the original δD ratios of the glass towards heavier values (e.g., Friedman

et al., 1993). δD ratios (in the range of -58.4 to -99.5 ‰) and water contents ($0.1 - 0.2$ wt%) of the studied samples are consistent with an initial magma composition within the range of the N-MORB mantle ($\delta D = -60 \pm 5$ ‰; Clog et al., 2013) and show no significant isotope contribution from seawater into the studied rocks. Thus, δD ratios and water contents preclude significant magma-seawater interaction during eruption or cooling, further supporting the subaerial origin of Stanley Patch. The numerous analytical and technical limitations of the K-Ar dating method makes it inapplicable for samples younger than 2000 years (e.g., Miyoshi et al., 2012; Mori & Mashima, 2005; Nagao et al., 1984; Nagao et al., 1996; Nier, 1950; Orihashi et al., 2004; Schaeffer & Zähringer, 1966; Solé, 2009). The $^{40}\text{Ar}/^{36}\text{Ar}$ ratios of the glasses (Table S9 of Hopfenblatt et al., 2021) are lower than the atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ (296.0) ratio. This yields negative $^{40}\text{Ar}^*$ (non-atmospheric ^{40}Ar) values that in turn imply negative K-Ar ages, i.e., less than 2000 years. This agrees with the age of the caldera collapse of 3980 ± 125 calibrated years BP based on tephrochronology, sedimentology studies and ^{14}C dates (Antoniades et al., 2018) as well as the fact that the volcanic edifice is built on top of over a ~ 100 m thick pile of post-caldera sediments (at least, sub-units B1 to B3) (Rey et al., 1995, 1997, 2002; Somoza et al., 2004), suggesting a considerable time period between the caldera collapse and the Stanley Patch's formation.

Therefore, we state that the results of the morphological analysis, supported by the petrographic and isotopic geochemical data from the collected rock samples, suggest a subaerial origin for Stanley Patch despite its current subaqueous location, and the complete flooding of Port Foster by seawater likely occurred during the last 2000 years. These results have direct implications for the evolution of the caldera depression since collapse and consequences on the typology of the post-caldera volcanic activity as controlled by the magma-water interaction. These aspects are discussed further in PART IV.



PART III

5 CHAPTER 5

Tephra Studies

In this chapter, we present a summary of the results of the DecTephra database and the physicochemical characterization of tephra samples of the latest eruptive event on Deception Island (1970) and from the marine sediments at the Bransfield Strait (< 40 km from Deception Island). Results obtained have allowed to: (i) assess the available information tephra layers sourced in Deception Island; (ii) expand the database content with new information related to the 1970 and previous eruptive events; and (iii) provide a better understanding of the most common characteristic of Deception Island's emitted tephras to be used as a starting point for future studies on tephra layers found in different environments (e.g., sea, ice, lakes). Further details can be found on Hopfenblatt et al. 2022a (See Appendix 3).

5.1 DecTephra Database

5.1.1 Analysis of the DecTephra database content

The DecTephra database compiles published information on all (crypto)tephra layers potentially sourced in Deception Island. These occur in ice cores, marine and lacustrine sediments, and glaciers located at the South Shetland Islands, Antarctic Peninsula, Antarctic Continent, South Orkney Islands, Bransfield Strait, and Scotia Sea (Fig. 5.1). The geographical distribution of the recorded tephras is explained in this section, together with sampling locations, and available geochemical data.

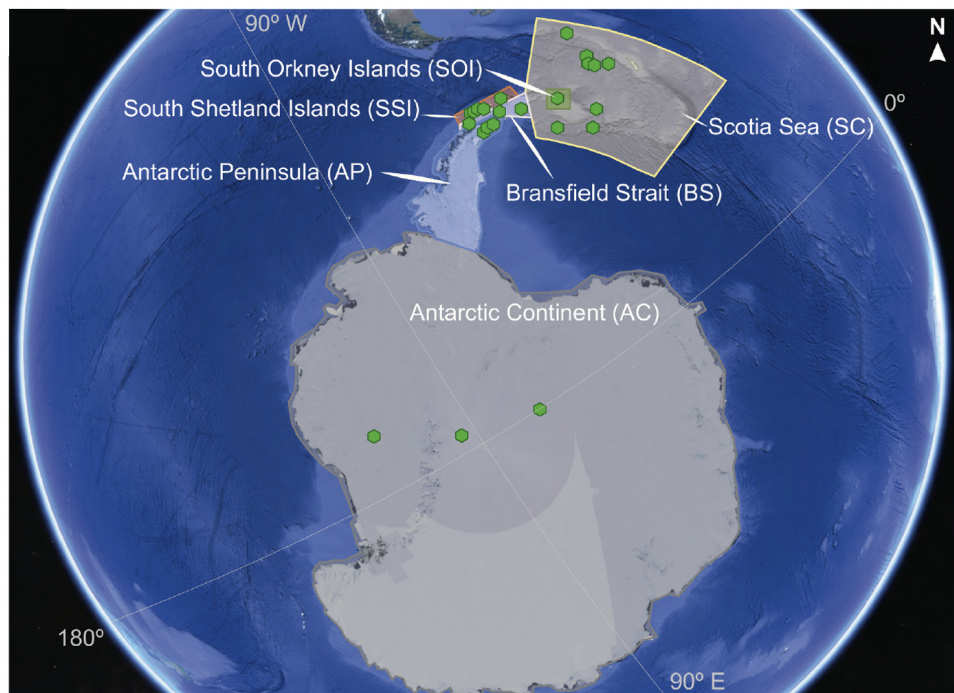


Figure 5.1. Google Earth Pro image showing the location and extension of the six geographical regions used to classify the sampling sites (green hexagons). These are: South Shetland Islands (SSI, red polygon), Antarctic Peninsula (AP, light blue polygon), Antarctic Continent (AC, gray polygon), South Orkney Islands (SOI, green rectangle), Bransfield Strait (BS, white polygon), and Scotia Sea (SC, yellow polygon). Image sources: Landsat/Copernicus; U.S. Geological Survey; PGC/NASA.

5.1.1.1 Geographical distribution and sampling locations

The 362 tephra layers included in the DecTephra database were identified at 86 different sampling sites (including sediment/ice cores and englacial sampling sites), mostly distributed throughout the South Shetland Islands (50%, $n = 43$) and the Bransfield Strait (22%, $n = 18$) (Figs. 5.2a, 5.3, 5.4, 5.5a). The closest sampling sites (~ 30 km distance) correspond to marine sediment cores from Bransfield Strait (Matthies et al., 1988) (Fig. 5.5a) and the most distant (> 3000 km) are ice cores from the South Pole (Palais et al., 1989; Kurbatov et al., 2006) (Fig. 5.6b). Nearly 80% of the sampling sites correspond either to lake (47%, $n = 40$) or marine sediment cores (31%, $n = 27$) (Fig. 5.2b). Considering all this, almost half of the tephra layers included in the DecTephra database (48%, $n = 177$), were recovered from lake sediment cores obtained in the South Shetland Islands ($n = 149$) (e.g., Liu et al.,

2016), Antarctic Peninsula ($n = 21$) (e.g., Sterken et al., 2012; Roberts et al., 2017) or the South Orkney Islands ($n = 7$) (e.g., Hodgson et al., 1998) (Fig. 5.2c; Hopfenblatt et al., 2022b). Tephra layers obtained in marine sediment cores, corresponding to about one third of all DecTephra records (34%, $n = 118$), were largely obtained from sites within Bransfield Strait ($n = 58$) (e.g., Fretzdorff & Smellie, 2002) and the Scotia Sea ($n = 60$) (e.g., Moreton & Smellie, 1998) (Fig. 5.2c, Hopfenblatt et al., 2022b). In the following sections, we provide a more detailed description of the tephra layers found in each of the defined regions with a particular focus on likely isochronous tepthrostratigraphic horizons.

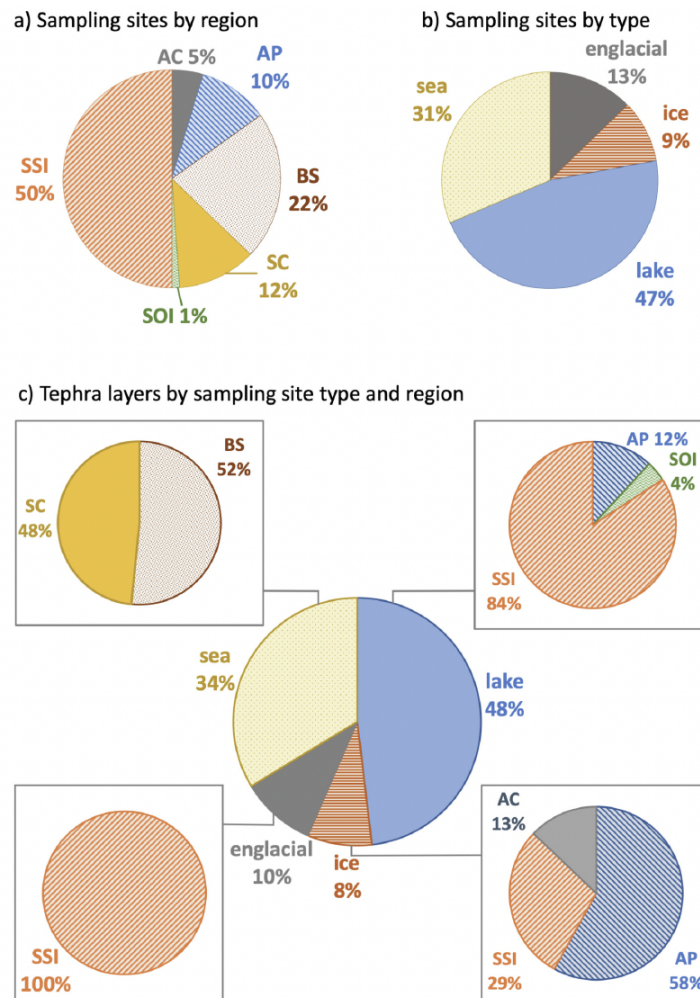


Figure 5.2. Pie charts illustrating the distribution of the tephra sampling sites by region (a) and type (b). (c) Pie charts representing the distribution of tephra layers by sampling site type and, within each type, also by region. AP: Antarctic Peninsula; AC: Antarctic Continent; BS: Bransfield Strait; SC: Scotia Sea; SOI: South Orkney Islands; SSI: South Shetland Islands.

5.1.1.1.1 South Shetlands Islands

Deception Island tephra layers are present in numerous lakes and glaciers at localities scattered along the South Shetland Islands (Fig. 5.3). On Livingston Island, a total of 57 tephra layers have been described in sediment cores retrieved from seven different lakes on Byers Peninsula (Åsa, Cerro Negro, Chester Cone, Domo, Escondido, Limnopolar, and Midge lakes) and 36 englacial tephra layers were obtained from ice cliffs and ice cores from Hurd and Perunika glaciers (Fig. 5.3, Hopfenblatt et al., 2022b). The estimated age of the tephra layers is based on available ^{14}C dating on sediments (e.g., Liu et al., 2016) or historic records (e.g., Pallàs et

al., 2001). Geochemical comparisons were made with volcanic deposits in situ on Deception Island, thus permitting limited age control and defining isochronous tephra horizons for a few layers (Fig. 5.4). As interpreted by Liu et al. (2016), the oldest layer has been correlated with tephra *T3* (5400 cal yr BP) found in sediment cores from the Cerro Negro, Escondido, and Limnopolar lakes. However, the layer has recently been correlated more robustly, using a wide range of supportive criteria, with Deception Island's caldera-forming event, established as 3980 ± 125 cal yr BP (Antoniades et al., 2018). Two additional tephra layers can be traced between the same three lakes (Liu et al., 2016; Oliva et al., 2016) and are dated as 2370 ± 100 (T2) cal yr BP and 1890 ± 140 (T1) cal yr BP (Antoniades et al., 2018). The youngest tephra horizons described for Livingston Island are *TPH1* (1970 CE) and *TPH2* (< 1829 CE), both observed in the Hurd and Perinuka glaciers (Pallàs et al., 2001; Molina Castiella, 2014; Velev et al., 2018). Based on geochemical comparisons and evidence from aerial photographs of the British Antarctic Survey taken in 1956, *TPH1* and *TPH2* correspond to deposits associated with eruptions in 1970 and 1829 (Pallàs et al., 2001).

About 120 km northeast of Deception Island, more than 90 tephra layers have been identified in sediment and ice cores retrieved from eleven lakes on King George Island (Geographensee, Hotel, Jurasee, Kiteschsee, Kitezsh, Long, Mondsee, L6, Rudy, Tiefersee, and Yanou lakes), Ardley Lake on Ardley Island, and from the Collins Ice Cap (Fig. 5.3; Hopfenblatt et al., 2022b). Many of the layers can be traced between two or more sites, and at least 17 isochronous tephra horizons have been defined, with ages ranging from 8700 ± 300 yr BP (tephra horizon *e* from Matthies et al., 1990) to < 500 cal yr BP (tephra horizon *T1b* from Roberts et al., 2017) (Fig. 5.4). Additional younger tephra layers also occur in other sediment cores retrieved from several of the lakes on Fildes Peninsula (Watcham et al., 2011) and in ice cores of the Collins Ice Cap (Jiankang et al., 1999). The Collins Ice Cap layers may correspond to eruptive events that occurred on Deception Island between 1812 and 1956 CE (Jiankang et al., 1999).

Finally, in the outer reach of the South Shetland archipelago, tephra studies at Walker Point (Elephant Island) (Björck et al., 1991b,c) identified a total of 5 cryptotephra with ages ranging from 3500 ± 60 to 1850 ± 50 yr BP (Figs. 5.3, 5.4; Hopfenblatt et al., 2022b).

5.1.1.1.2 Bransfield Strait

A total of 58 tephra layers were observed in 16 marine sediment cores from Bransfield Strait (Fig. 5.5a; Hopfenblatt et al., 2022b). The sediment core locations vary from 30 km southwest of Deception Island to 360 km northeast of the volcano (southwest of Elephant Island; Matthies et al., 1988) (Fig. 5.5a). The youngest dated layers, described by Monien et al. (2011), have been correlated with tephras *AP-2* (c. 450 cal yr BP) and *AP-3* (c. 750 cal yr BP) present in lacustrine sediment cores from Livingston Island (Björck et al., 1991a,b; Fig. 39). Two additional layers observed by Matthies et al. (1988) were correlated with tephras *a* (c. 3550 yr BP) and *d* (5,190 yr BP) on King George Island (Matthies et al., 1990; Fig. 39). Finally, based on their similar geochemical composition and stratigraphic position, Fretzdorff & Smellie (2002) interpreted the topmost tephra layers in their sediment cores to be equivalent to *TPH1* and *TPH2* tephras present in Livingston Island glaciers (Pallàs et al., 2001; Fig. 5.4).

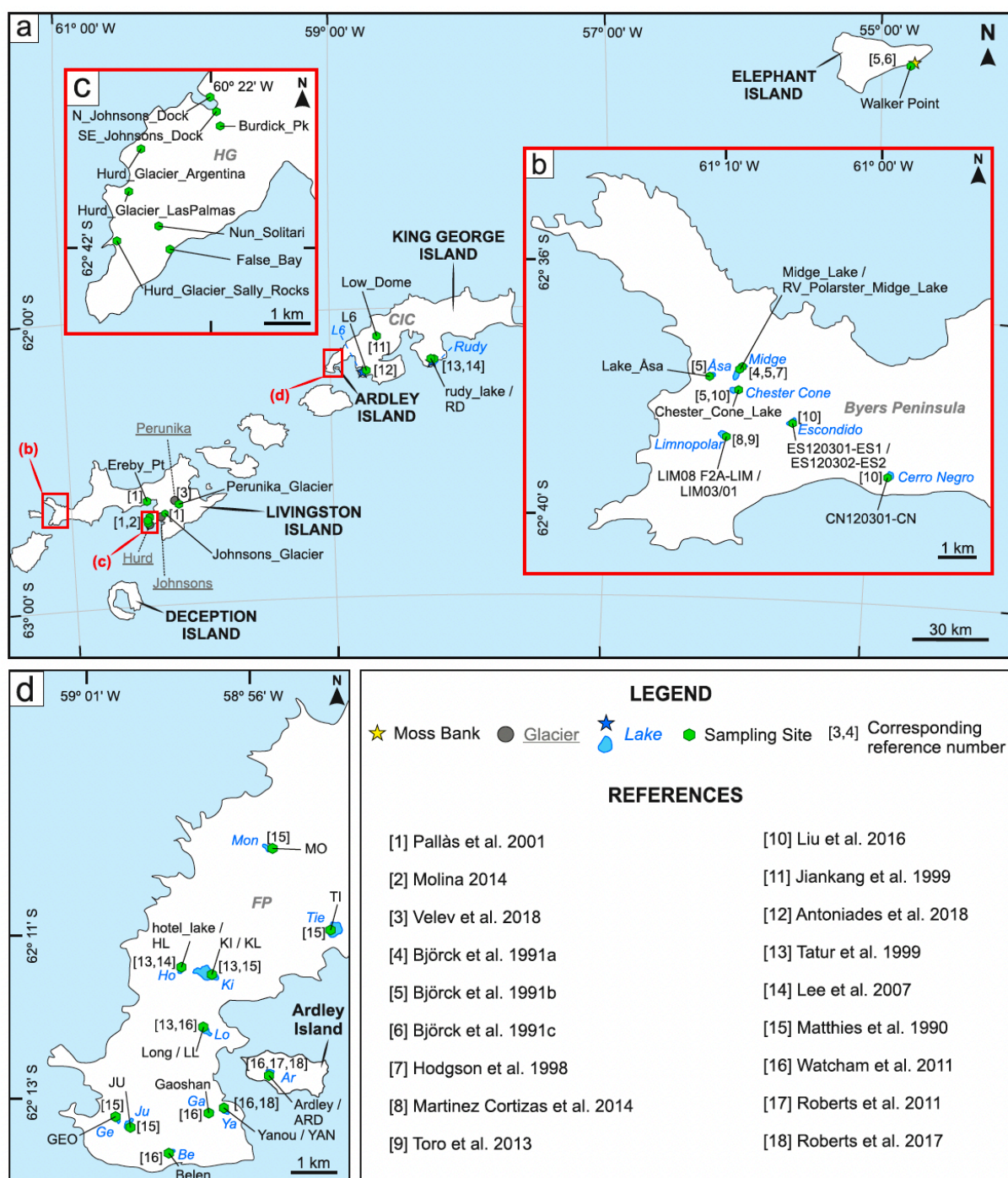


Figure 5.3. Location of the tephra sampling sites in lakes, glaciers, and moss banks of the South Shetland Islands. Sampling_site_ID and published sources are indicated for each site (See Supplementary Material 1 of Hopfenblatt et al. (2022a) for bibliographic details and geographical coordinates of site locations).

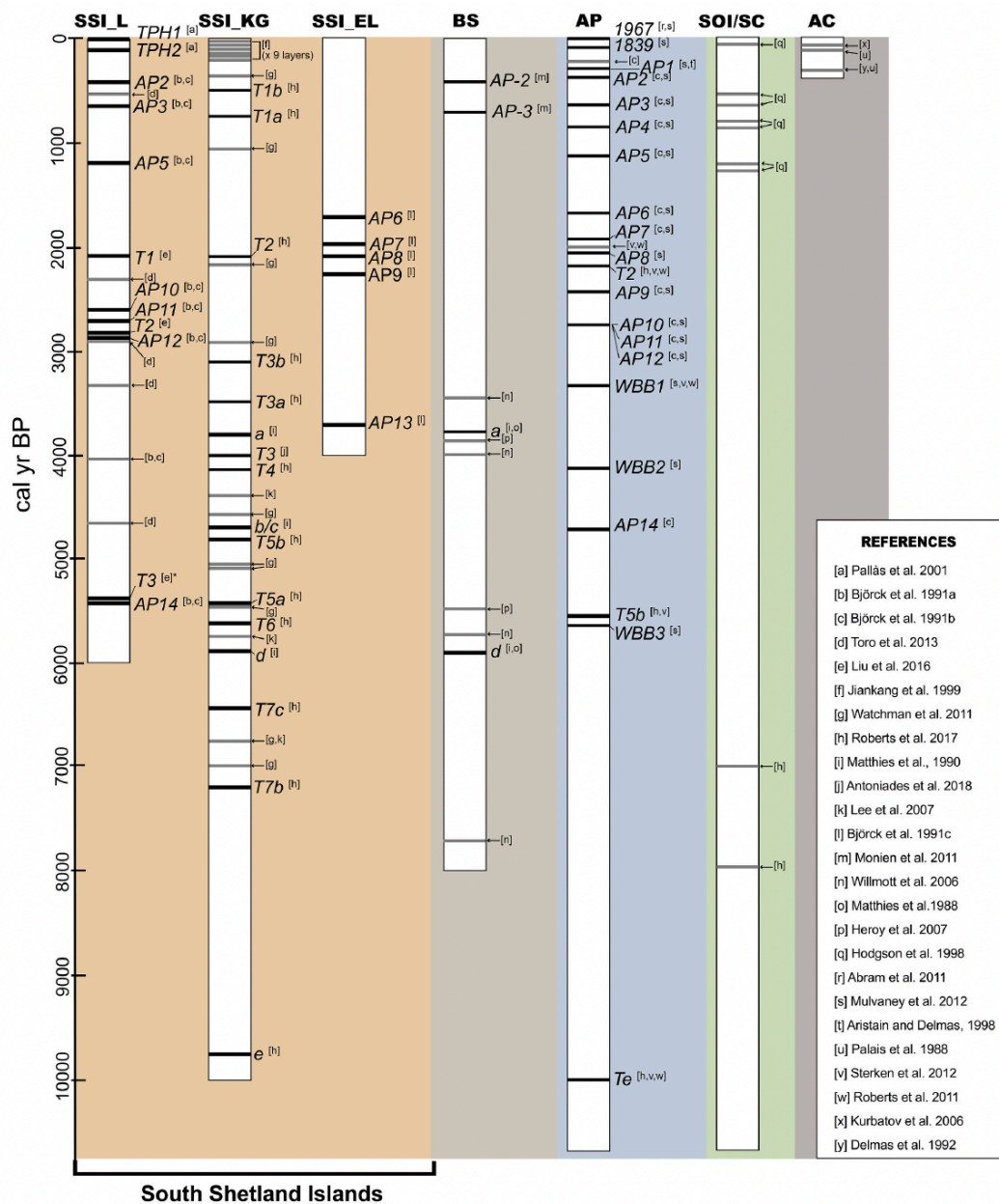


Figure 5.4. Tephra layers (grey) included in the DecTephra database with a reported age (See Hopfenblatt et al. (2022b) for further details regarding the location of the corresponding sampling sites, tephra dating method and errors). Only Holocene tephra layers are included in this figure. If an age interval is provided for a specific tephra layer, we have estimated the average age. In this case, only those layers with an age interval comprising 1000 years or less are considered. Errors are not illustrated in this figure for the sake of simplicity, but can be found in Hopfenblatt et al. (2022b). In the case where a tephra layer is correlated among two or more sampling sites, it is considered to be a tephra horizon and is represented as a black line in this graph. AC: Antarctic Continent; AP: Antarctic Peninsula; BS: Bransfield Strait; SC: Scotia Sea; SSi_E: South Shetland Islands – Elephant Island; SOI: South Orkney Islands; SSi_K: South Shetland Islands – King George Island; SSi_L: South Shetland Islands – Livingston Island.

5.1.1.1.3 Antarctic Peninsula

The DecTephra database includes 15 cryptotephra and 23 tephra layers observed in lacustrine sediment and ice cores situated on the Antarctic Peninsula and neighboring islands (Fig. 5.5b). The youngest layer observed in the James Ross Island (JRI) ice core has been correlated with the 1967 CE Deception Island eruption (Abram et al., 2011; Mulvaney et al., 2012) (Fig. 5.5). The tephra horizon *Te* (c. 9975 cal yr BP), defined by Roberts et al. (2011), is the oldest described from the Antarctic Peninsula and it can be observed in the JRI ice core and sediments in Beak lake on Beak Island (Roberts et al., 2011, 2017; Mulvaney et al., 2012). Between the 1967 CE and *Te* tephra horizons, several other tephra layers can be correlated between the Antarctic Peninsula and King George Island (e.g., T5b; Roberts et al., 2017) or Livingston Island (e.g., AP2, AP3, AP14, etc.; Björck et al., 1991b) (Sterken et al., 2012)

5.1.1.1.4 Scotia Sea and South Orkney Islands

Over 800 km east of Deception Island, seven tephra layers are identified in lacustrine sediment cores recovered from Sombre lake on Signy Island (South Orkney Islands) (Hodgson et al., 1998) (Fig. 5.6a). Estimated ages range from 30 to 1470 yr BP, and the high Na₂O contents make it very likely that Deception Island was the source (Hodgson et al., 1998; Fig. 5.4; Hopfenblatt et al., 2022b).

In the Scotia Sea, a total of 60 tephra layers have been described throughout ten different marine sediment cores with ages ranging between 7020 yr BP and 35,400 yr BP (Moreton & Smellie, 1998; Moreton, 1999; Roberts et al., 2017) (Fig. 5.6a; Hopfenblatt et al., 2022b). One of these, a megascopic ash layer (~ 10,670 yr BP) of bimodal composition ranging from basalt to rhyolite, was described by Moreton & Smellie, (1998) and Moreton (1999), and was correlated across six sampling sites (GC027, PC029, GC037, PC078, PC079, and KC081) (Figs. 5.4, 5.6a), making it the second-most widely correlated tephra layer after the caldera-collapse layer correlated by Antoniadou et al. (2018).

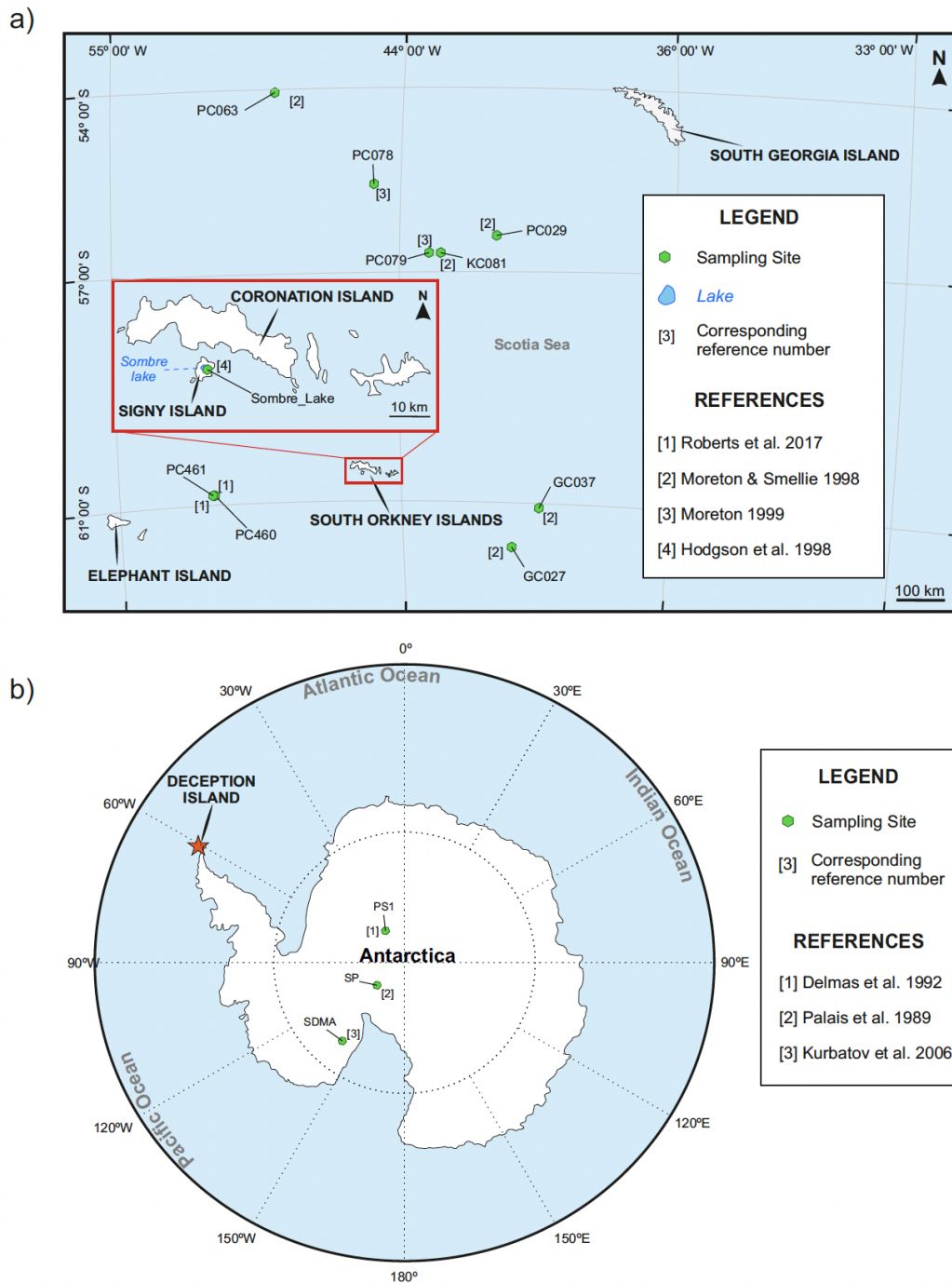


Figure 5.6. Location of the tephra sampling sites in the Scotia Sea and South Orkney Islands (a) and the Antarctic Continent (b). Sampling_site_ID and consulted reference are indicated for each site (See Supplementary Material 1 of Hopfenblatt et al. (2022a) for details and exact geographical coordinates).

5.1.1.1.5 Antarctic Continent

On the Antarctic continent, (crypto)tephra layers potentially sourced at Deception Island have been found in the Simple Dome ice core in West Antarctica (Kurbatov et al., 2006) and in the three ice cores closest to the South Pole (Palais et al., 1989; Delmas et al., 1992) (Fig. 5.6). The two youngest tephra layers (1819–1829 CE and 1879 CE, respectively; Palais et al., 1989; Kurbatov et al., 2006), have been interpreted as the deposits of historic eruptions occurring on Deception Island during the same period (Fig. 5.4). The oldest layers at each site could potentially be correlated, as they have ages of 1641 CE and 1632–1638 CE (Palais et al., 1989; Delmas et al., 1992).

5.1.1.2 Geochemistry of the tephra layers

Geochemical data are available for 85% ($n = 309$) of the tephra layers included in the DecTephra database (Fig. 5.7a). The data were provided in the original publications either as compositional graphs (47%, $n = 144$) or as analyses (53%, $n = 165$). All published major and trace element data are included in the DecTephra database (See Hopfenblatt et al., 2022b). Within the 165 tephra layers with major element analyses listed in the Major_elements table, 35 layers (i.e., 21%) also include trace element compositions (Fig. 5.7b). Major and trace elements have been both mostly obtained from glass shards (99% and 81%, respectively) (Fig. 5.7c). Geochemical analyses were carried out using different techniques (e.g., Electron Probe Microanalysis (EPMA), X-ray fluorescence (XRF) or Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) among others.); in a few cases, the data were presented as normalized major element concentrations (Lee et al., 2007; Antoniadou et al., 2018).

Tephra layers with accompanying analyses have been sampled mainly in the South Shetland Islands (39%, $n = 65$), the Scotia Sea (36%, $n = 60$), and Bransfield Strait (19%, $n = 31$). Bulk tephra analyses are restricted to tephra layers in the glaciers of Livingston Island (South Shetland Islands; Pallàs et al., 2001 ($n = 18$); Molina Castiella, 2014 ($n = 10$)). Trace element data are uncommon and are restricted to grain-specific analyses of glass shards from

the Scotia Sea (84%), analyzed by ion probe (Moreton, 1999), and bulk-sample tephra analyses of layers in Livingston Island glaciers (16%) (Pallàs et al., 2001).

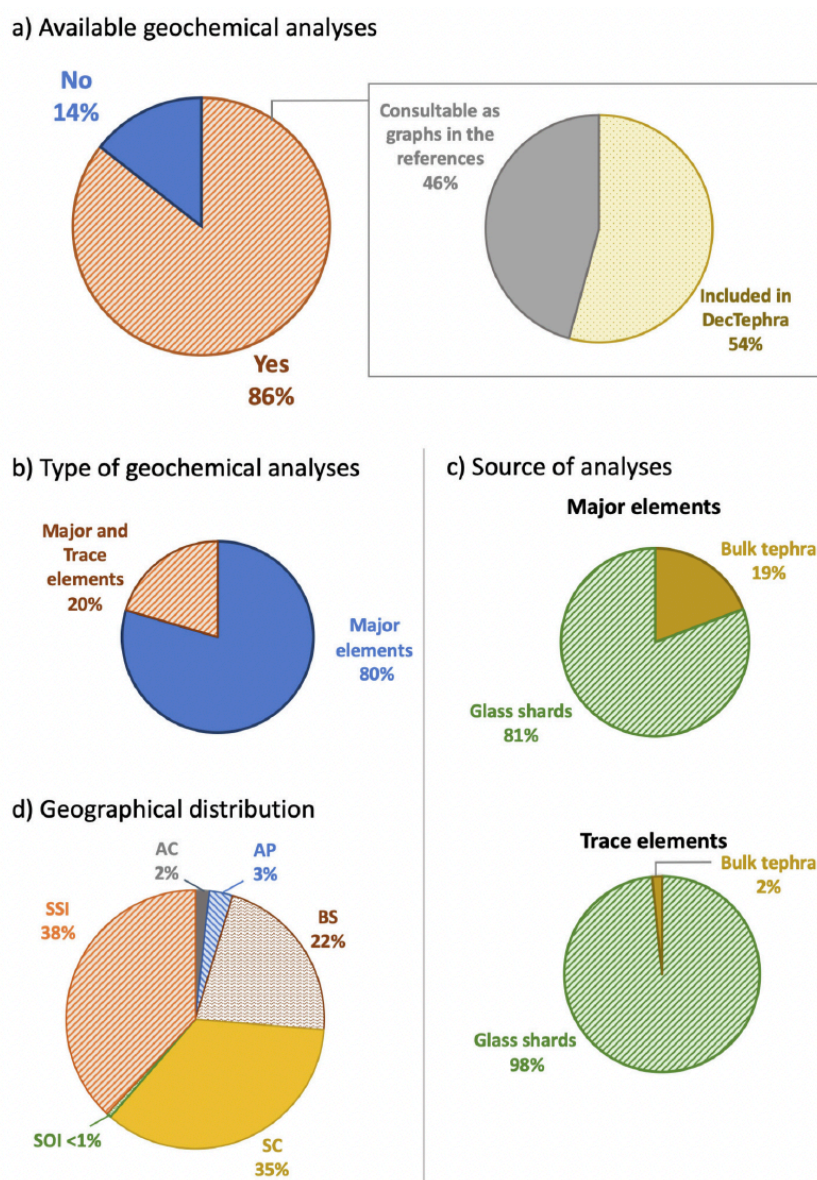


Figure 5.7. Pie charts illustrating the availability (a), type (b), source (c), and geographical location (d) of geochemical analyses of tephra layers included in the DecTephra database. In (b–d) percentages refer only to those analyses listed in the Major_elements and the Trace_elements tables of the DecTephra database, excluding those simply published as graphs. AP: Antarctic Peninsula; AC: Antarctic Continent; BS: Bransfield Strait; SC: Scotia Sea; SOI: South Orkney Islands; SSI: South Shetland Islands.

5.1.2 Discussion

5.1.2.1 Geochemistry of DecTephra layers: comparison with Deception Island eruptive products

A reliable correlation between tephra layers and their volcanic sources requires a comprehensive geochemical record, including not only major and trace element analyses of the volcanic glasses but also of any magmatic minerals present (Lowe, 2011; Lowe et al., 2017). Because of the often unpredictable effects of alteration, which can be prevalent in marine tephra in particular due to the rapidity with which highly reactive glass becomes altered, immobile elements and isotopes unaffected by secondary processes are most important for achieving successful correlations (e.g., Hopkins et al., 2015; Petrosino et al., 2019).

Although a full geochemical characterization is not available for all tephra layers included in the DecTephra database, the existing published major element compositions enable a first-order geochemical comparison between the tephra and eruptive products on Deception Island. In order to maximize the reliability of the analyses and to make tephra and Deception Island datasets comparable, we have treated the geochemical data in the following way (Fig. 5.8):

- (i) only major element analyses of volcanic glasses are considered since bulk tephra/rock analyses may be affected by variable phenocryst, xenocryst and xenolith contents (Shane, 2000). For comparison with Deception Island volcanic rocks, we have used EPMA data provided by Geyer et al. (2019);
- (ii) only analyzes with total major elements (including Loss on Ignition - LOI) that fall within the range ≥ 95 to ≤ 101 wt.% are considered (Lowe, 2011);

- (iii) for each sample all major elements are recalculated on a volatile-free basis (Shane, 2000; Lowe, 2011) to avoid secondary hydration effects (Lowe, 2011; Lowe et al., 2017);
- (iv) the analyses available for each sample have been normalized to ensure that each tephra layer/volcanic rock is treated equally in order to avoid giving undue prominence to multiple analyses of single grains. However, we also wished to preserve information suggesting geochemical variability or bimodality within individual samples.

Then, we have (Fig. 5.8):

* Categorized each analysis based on silica content, i.e. felsic (> 63 wt.% SiO_2), intermediate ($52\% < \text{SiO}_2 \text{ wt.\%} \leq 63\%$), mafic ($45\% < \text{SiO}_2 \text{ wt.\%} \leq 52\%$) and ultramafic ($\leq 45\%$ wt.% SiO_2) following Le Bas et al. (1986).

* For each tephra layer/volcanic rock, all available geochemical analyses are grouped based on their assigned compositional category (See Supplementary Materials 3 and 4 of Hopfenblatt et al., 2022a).

* Mean and standard deviations were calculated for each compositional group present within the individual tephra layers or volcanic rocks (i.e., felsic, intermediate, mafic, ultramafic) (See Supplementary Materials 3 and 4 of Hopfenblatt et al., 2022a). Hence, the individual tephra layers/volcanic rocks are represented in variation diagrams by only up to four data points (one per compositional group). This avoids the plotted data being swamped by large numbers of analyses that are available for multiple shards in some individual tephra layers/rock samples, but it preserves the evidence for any compositional diversity present.

* The major element compositions were then plotted on total alkalis—silica (TAS) (Fig. 5.9), bivariate diagrams (Fig. 5.10), and as density histograms (Fig. 5.11).

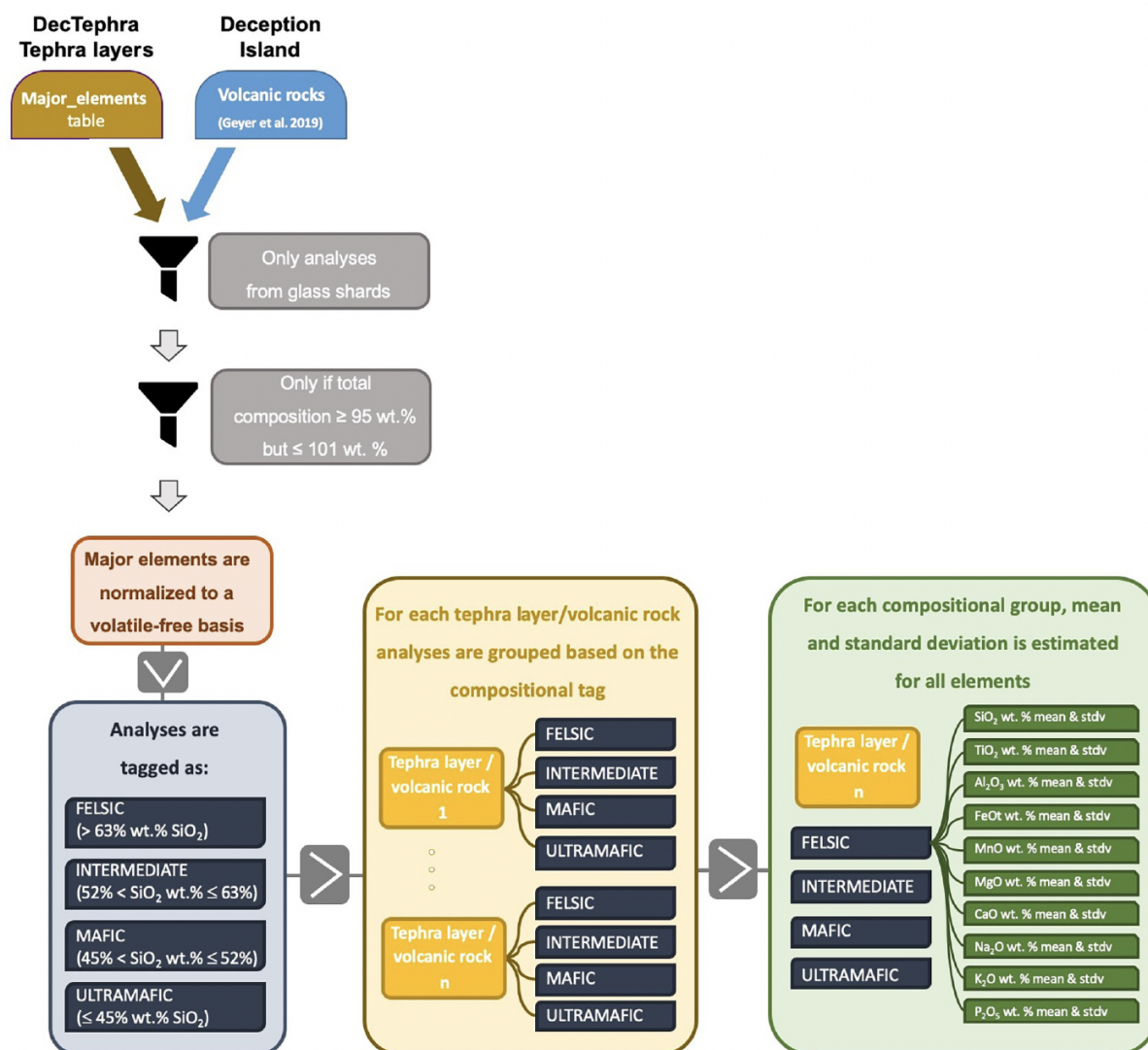


Figure 5.8. Scheme of the procedure followed to normalize available geochemical data of major elements for tephra layers included in the DecTephra database as well as the EPMA analyses of volcanic glass in Deception Island volcanic rocks (original data from Geyer et al., 2019).

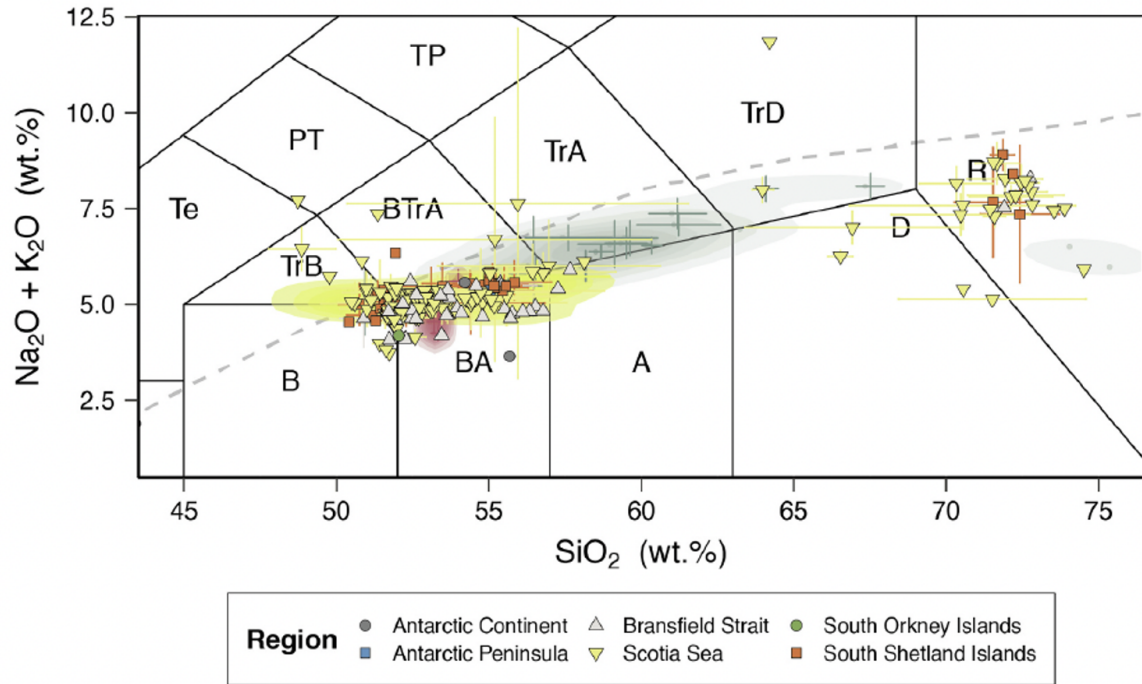


Figure 5.9. Total Alkali vs. Silica diagram (TAS) (Le Bas et al., 1986) for the glass shard analyses included in the DecTephra database. Major elements normalized to 100% (anhydrous) with Fe distributed between FeO and Fe₂O₃ following Middlemost (1989). Grey dashed line discriminates between the alkaline subalkaline fields, according to Irvine and Baragar (1971). Background density clouds and semi-transparent points correspond to glass analyses of in situ Deception Island rock samples reported by Geyer et al. (2019).

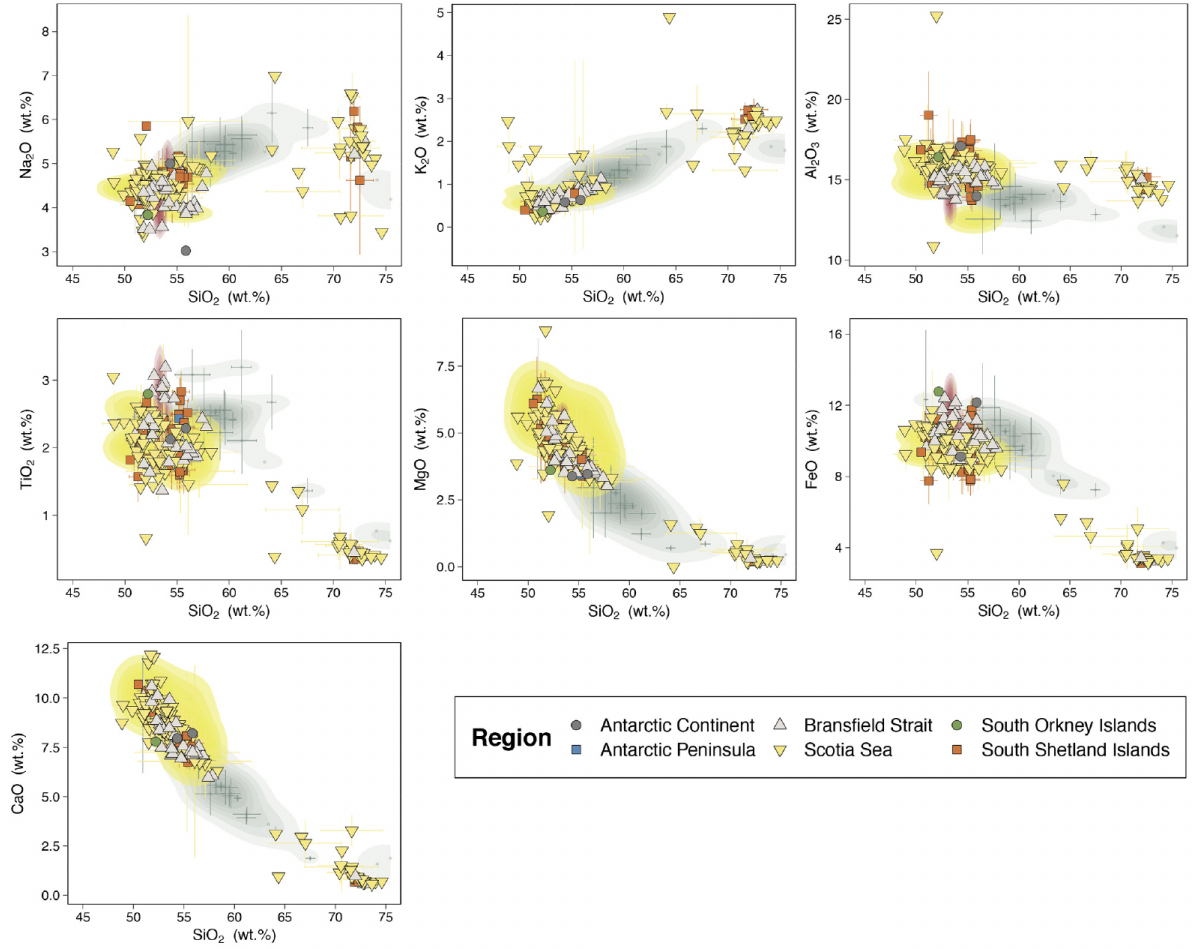


Figure 5.10. Major element vs. SiO_2 content Harker Diagrams for glass shard analyses obtained after normalization based on the criteria illustrated in Fig. 5.9 and detailed in the main text (See Supplementary Materials 3 and 4 of Hopfenblatt et al., 2022a for further detail on the data). Major element compositions have been normalized to 100% in anhydrous base with Fe as FeO_t . Background density clouds and semi-transparent points correspond to glass analyses of in situ Deception Island rock samples reported by Geyer et al. (2019).

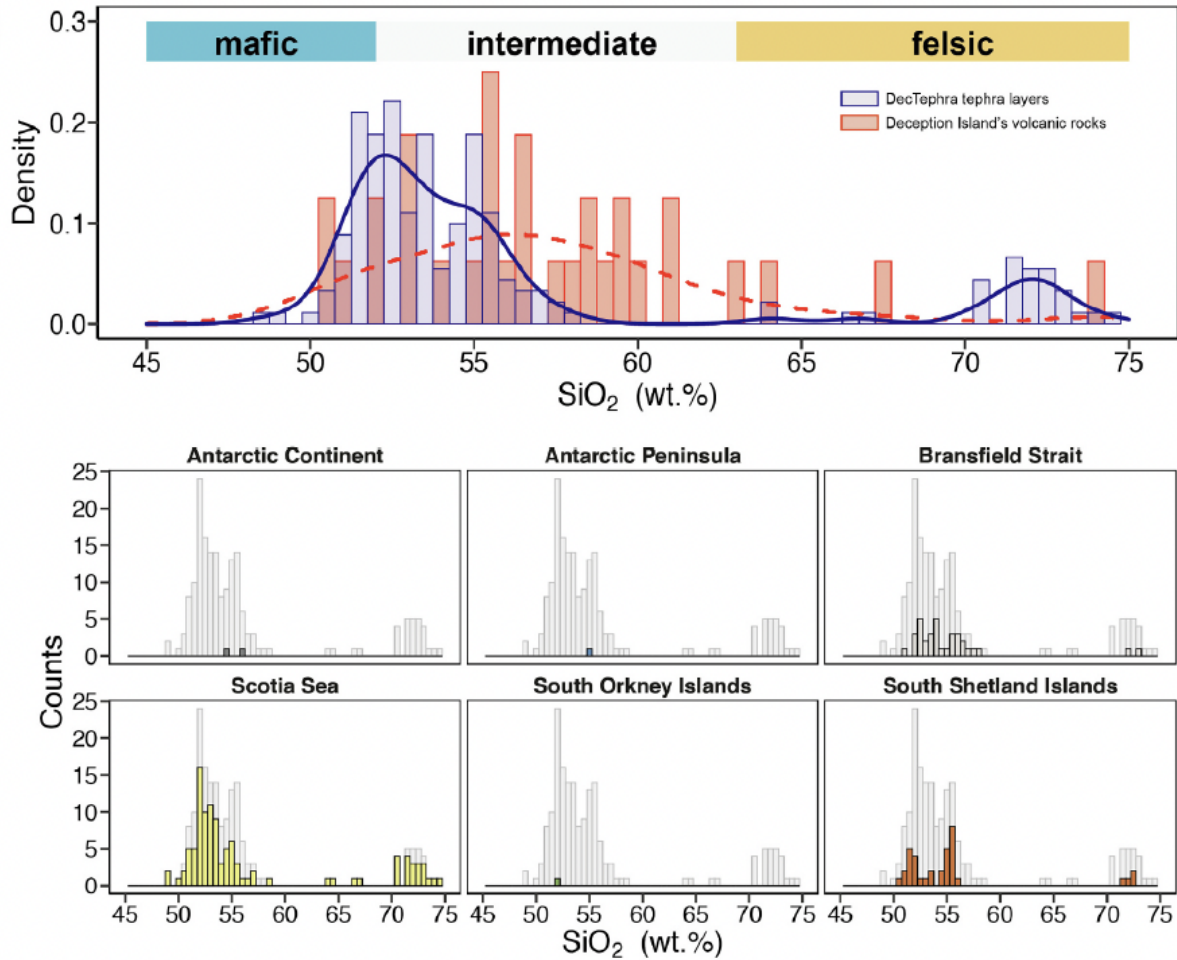


Figure 5.11. (Top) Frequency histogram of SiO₂ wt.% of those glass shard analyses included in the DecTephra database and of Deception Island's volcanic products (See Supplementary Materials 3 and 4 of Hopfenblatt et al., 2022a). A bandwidth of 0.5 has been applied and the SiO₂ wt. % intervals used to tag the analyses as being acid (> 63 wt.% SiO₂), intermediate (52% < SiO₂ wt.% ≤ 63%) and basic (45% < SiO₂ wt.% ≤ 52%) are also indicated. (Bottom) Frequency histograms of SiO₂ wt.% for those glass shard analyses included in the DecTephra database are separated by regions. The gray histogram in the background corresponds to the general histogram represented in b) that includes all available analyses. Analyses considered in a), b), and c) are those obtained after normalization based on the criteria illustrated in Fig. 5.8 and detailed in the main text. (See Supplementary Materials 3 and 4 of Hopfenblatt et al., 2022a for further details).

A full statistical analysis and correlation between the datasets is beyond the scope of this paper, but preliminary comparisons are suggested based on a visual analysis. Deception Island glass compositions range from basalt to trachyandesite in the TAS diagram, within the upper subalkaline field, similar to whole-rock (bulk sample) analyses from Deception Island (Fig. 5.9; cf. Smellie, 2002b; Geyer et al., 2019). The pre-caldera glasses show the narrowest

compositional variation (52 – 54 SiO₂ wt.%) although the number of analyses is also few, whereas the syn-caldera and post-caldera glasses have a much wider range (SiO₂ from 50 to 58 wt.% and from 50 to 75 wt.%, respectively) (Geyer et al., 2019) (Figs. 5.9, 5.10). Trachydacites and rhyolites are also present in a few post-caldera eruptions (Geyer et al., 2019). Analyzed DecTephra tephra layers also range from basalts to rhyolites, defining a less pronounced differentiation trend of increasing alkalinity, especially for intermediate compositions (Fig. 5.9). Some glasses plot outside the main trend and show dispersed compositions with either very high or very low alkali contents, particularly for tephra in marine sediment cores from the Scotia Sea (Figs. 5.9, 5.10) (Supplementary Materials 3 and 4 of Hopfenblatt et al., 2022a). Based on SiO₂ content, bimodal compositions are also evident. The most common compositions are mafic to intermediate (50 – 58 wt.% SiO₂) (Fig. 5.11), but a minor cluster of evolved compositions (70 – 75 wt.% SiO₂) is also present in glasses in Scotia Sea marine sediments (e.g., Moreton, 1999; Moreton & Smellie, 1998; Lee et al., 2007; Roberts et al., 2017), South Shetland Islands (e.g., Lee et al., 2007) and, to a lesser extent, Bransfield Strait (e.g., Fretzdorff & Smellie, 2002) (Fig. 5.11). Only glass shards found in the Scotia Sea have SiO₂ contents falling between 58 and 70 wt.% (Fig. 5.11). By contrast, Deception Island shows a more continuous compositional range, with a modal peak at ~ 56 wt.% SiO₂; rhyolitic compositions are uncommon (Fig. 5.11). Both datasets show negative correlations of MgO, TiO₂, FeO, and CaO with SiO₂, and a positive correlation for K₂O (Fig. 5.10) for most of the analyzed tephra layers and volcanic rocks. However, anomalous compositions are shown by a few glasses from the Scotia Sea (for Al₂O₃, TiO₂, FeO, MgO and K₂O) (Fig. 5.10). There is a general overlap between the major elements of DecTephra tephra layers and Deception Island for mafic and intermediate compositions, for SiO₂ values ranging from ~ 50 to 58 wt.% and corresponding to the main compositional cluster (Figs. 5.9, 5.11). In contrast, the compositional similarity for intermediate and felsic samples (59 to > 70 wt.% SiO₂) is less evident, with much greater scatter for tephra data from the Scotia Sea and, to a lesser degree, South Shetland Islands evident in Na₂O and K₂O vs. SiO₂, in particular (Fig. 5.10). It is also notable that trachydacites and, especially, rhyolites are poorly represented on Deception Island, with only two eruptions recording the most evolved compositions (i.e., Cross Hill volcanic edifice). In any case, the lack of a complete record of the evolved compositions (i.e., the most felsic) at Deception Island makes a robust compositional correlation difficult. Considering all of this, we conclude that Deception Island is the most

probable source for the majority of mafic to intermediate (≤ 58 wt.% SiO_2) tephras but a similar correlation for more felsic glasses is not so evident for the evolved tephras ($\text{SiO}_2 > 60$ wt.%). Additional geochemical constraints (i.e., trace element analyses on glass shards and mineral compositions) on the ash layers should help to resolve this anomaly.

5.1.2.2 Towards a more complete tephra record

Tephra-related studies should ideally incorporate: (i) granulometric data; (ii) petrographic and morphological descriptions; (iii) geochemical analyses (including major and trace elements and, if possible, mineral analyses); and (iv) the use of statistical tools for tephra correlation (e.g., principal component analysis, scatterplot matrix) (Lowe, 2011; Lowe et al., 2017). Having a complete tephra characterization makes it easier to establish possible correlations between layers, especially in conjunction with stratigraphic and chronologic criteria. It is therefore obvious that tephra layers included in the DecTephra database are incompletely characterized. Firstly, there is a lack of morphological descriptions of the glass shards (only provided by Liu et al., 2016) and less than 50% of the tephra layers include granulometric analysis (See Hopfenblatt et al., 2022a, b). Information from glass shard morphologies, together with grain size data, are essential to determine the eruption type (i.e., magmatic versus phreatomagmatic), explosivity, size and potential impact (i.e., distances traveled by the tephras). Secondly, the DecTephra's compositional dataset is largely complete for major elements ($\sim 85\%$ of the tephra layers contain major element data) but trace elements and isotope ratios are poorly represented. Additionally, only half of the publications (53%) present the data in tables and not many publications include full data sets for all the grains analyzed, often depending on average values.

Future tephra studies on the area should strive to obtain a full physicochemical characterization of the tephra layers by incorporating granulometric data, and petrographic and morphological information in their description. Additionally, geochemical analyses should try to include major and trace elements and, whenever possible, mineral analyses.

5.2 Tephras of the 1970 Deception Island eruption found at Livingston Island glaciers

Textural and morphological features of pyroclasts generated during explosive eruptions, together with mineral and glass geochemical compositions, may contribute to define and quantify the processes that occur before, during and immediately after an eruption (i.e., magma evolution, degassing, ascent, crystallization, fragmentation and alteration). In this section, we present the results of the physicochemical description of the 1970 Deception Island eruption tephras deposited at Livingston Island glaciers. The performed characterization includes a petrographic and morphological description, granulometric analyses, and mineral and glass geochemical analyses. Note that during previous studies, six of the tephra samples originally collected (N70A, N70B, J70A, J70B, FB70 and PB70) were divided in two subsamples (e.g., J70A-1, J70A-2, FB70-1, FB70-2) (Pallàs et al., 2001; Geyer et al., 2006, 2008). Given the absence of proper documentation regarding the reasons for subsampling, we have decided to separately analyze each subsample. As a consequence, this section reports the results of 25 samples (Supplementary Material 1).

5.2.2 Granulometry

According to granulometric data, tephra samples correspond to coarse ash with grain sizes ranging between -1 and 4Φ ($2 - 0.06$ mm) and medians (Me) between 1.3 and 3.5Φ ($0.41 - 1.79$ mm) (Figs. 5.12, 5.13, 5.14, 5.15). Seven samples (70-200, GJ2, N70B-2, N70A, FB70-2, J70A-2, J70B-2) contain more than 25 % of the volume of fine ash particles (Figs. 5.12, 5.13). Tephra sample 70-200 displays the highest content of fine particles, almost reaching the 50% of differential volume, whereas samples J70B-1 and N70B-1 have the highest coarse ash content ($> 90\%$) (Figs. 5.12, 5.13).

Most samples are poorly sorted ($1 < \sigma < 2$, Fig. 5.14; Tables 5.1, 5.2). Samples J70B-1 and N70B-1, with a sorting coefficient close to 0.5 (Tables 5.1, 5.2), exhibit the highest degree of sorting among all the well-sorted tephra samples. Samples 70-200 and N70A have the

highest sorting coefficient (2.0 and 1.8 σ respectively; Tables 5.1, 5.2) (Fig. 5.14), corresponding to the poorest sorted samples.

Sorting Coefficient (σ)	Characterization
> 4	extremely poor
2 - 4	very poor
1 - 2	poor
0.71 - 1	moderate
0.5 - 0.71	moderately well
0.35 - 0.5	well
< 0.35	very well

Table 5.1. Classification of the degree of sorting coefficient according to Folk & Ward (1957).

Grain-size analyses show a bimodal distribution for 13 (52%) of the analyzed tephra samples (70-1, 70-21, 70-69, CA-4, CA-11, E70, FB70-2, GJ2, GJ3, J70A-2, J70B-2, N70A-1, N70B-1) (Figs. 5.16a-f; Supplementary Figure S1, with modes ranging from 0.5 to 1 Φ and from 2.5 to 4.5 Φ . These finer modes (2.5 - 4.5 Φ) present a positive skewness (Fig. 5.16, Supplementary Figure S1). Additionally, 6 samples (70-200, PB-70-ASH1, E70, FB70-1, N70A, N70B-2) present a polymodal distribution (Figs. 5.16a, e; Supplementary Figure S1). The remaining 7 samples (70-6, 70-11, PB-70, CA-4, CA-7, J70A-1, J70B-1) show a unimodal distribution with a positive skewness with modes ranging from 1 to 2 Φ (Figs. 5.16g, h; Supplementary Figure S1).

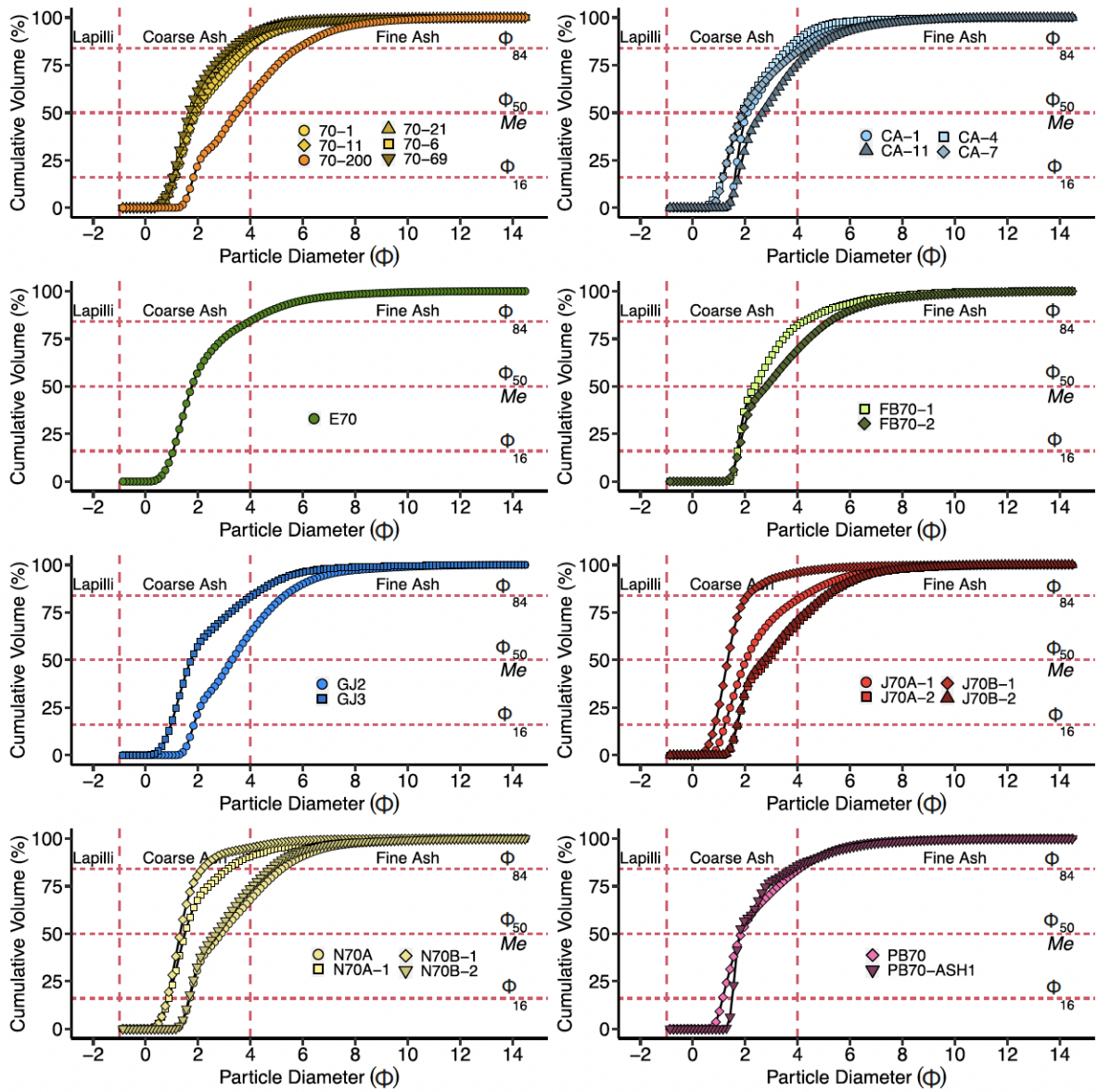


Figure 5.12. Granulometry curves of the 25 analyzed tephra samples. The vertical dashed red lines represent the lapilli-coarse ash and coarse-fine ash limits according to Lockwood and Hazlett (2010). The horizontal dotted red lines represent percentiles 84 and 16 employed to calculate the sorting coefficient according to Heiken & Wohletz (1992). Samples are grouped according to their proximity within the same sampling site (Fig. 3.4).

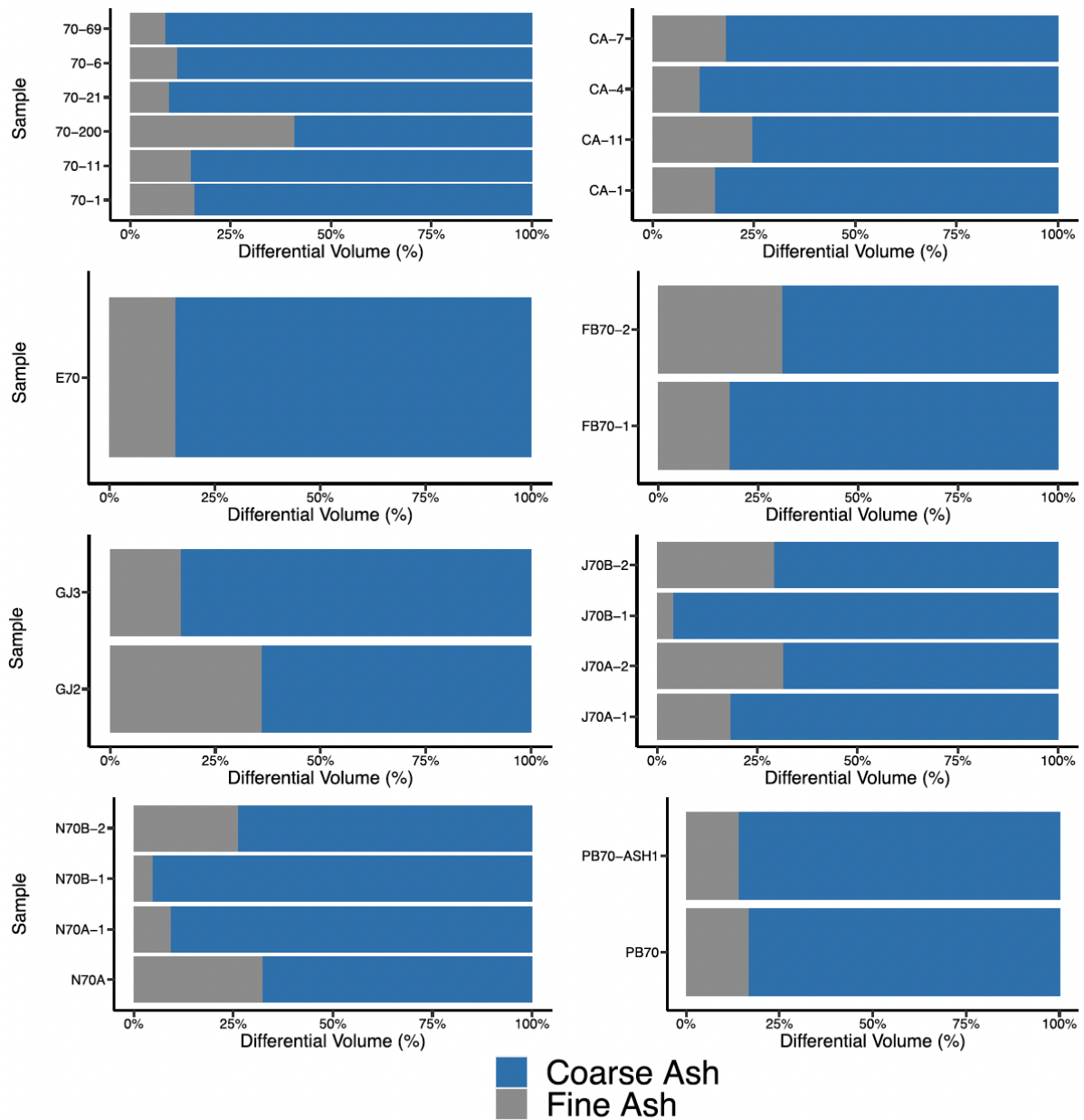


Figure 5.13. Coarse (-1 to 4Φ or 0.06 to 2 mm) and fine ash ($> 4 \Phi$ or < 2 mm) proportions in each studied tephra sample. The limits between coarse and fine ash were defined according to Lockwood & Hazlett (2010). Samples are grouped according to their proximity within each sampling site and sample code name.

Sample	Sorting Coefficient (σ)	Median Grain Size (Φ)	Distance to Deception Island (km)
70-1	1.4	2.0	36
70-6	1.3	1.7	36
70-11	1.4	1.9	36
70-21	1.1	1.8	36
70-69	1.1	1.6	36
70-200	2.0	3.5	36
CA-1	1.2	2.1	36
CA-4	1.3	1.9	36
CA-7	1.5	1.9	36
CA-11	1.5	2.7	36
E70	1.5	1.8	38
FB70-1	1.3	2.4	40
FB70-2	1.7	2.8	40
GJ2	1.7	3.3	34
GJ3	1.6	1.7	34
J70A-1	1.5	2.0	36
J70A-2	1.7	2.9	36
J70B-1	0.6	1.3	36
J70B-2	1.7	2.7	36
N70A	1.8	2.9	32
N70A-1	1.1	1.5	32
N70B-1	0.7	1.3	32
N70B-2	1.5	2.7	32
PB70	1.5	1.9	33
PB70-ASH1	1.1	1.8	33

Table 5.2. Sorting and median values obtained for each tephra sample studied. Distance between samples and the center of Deception Island (Coordinates: -62.957° / -60.643° , Hopfenblatt et al., 2022a).

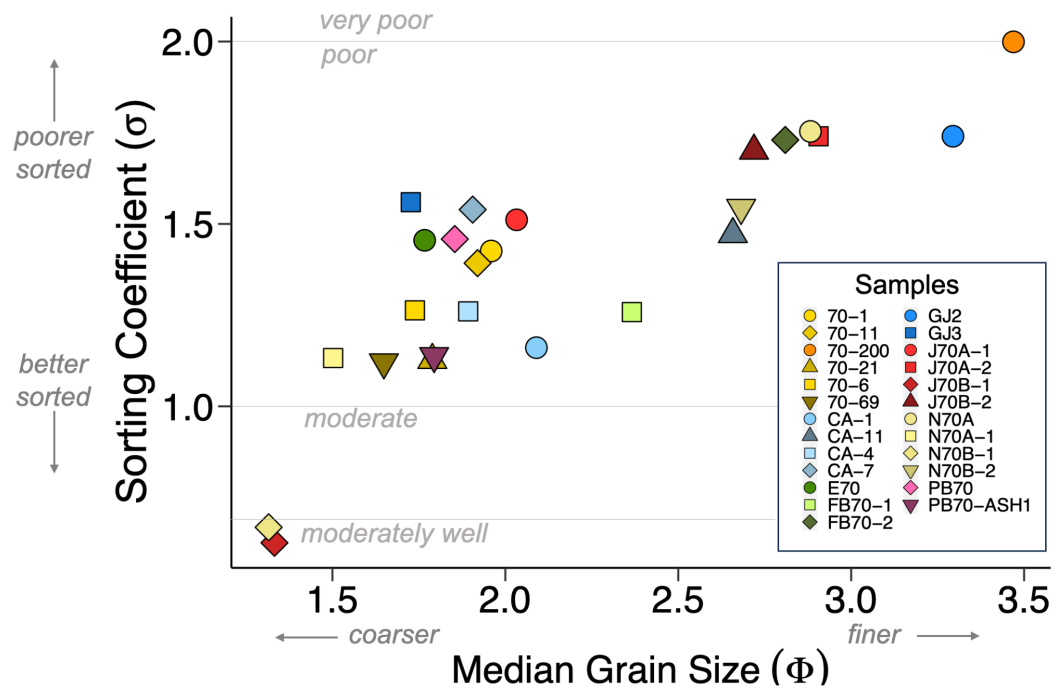


Figure 5.14. Median-sorting coefficient scatter plot.

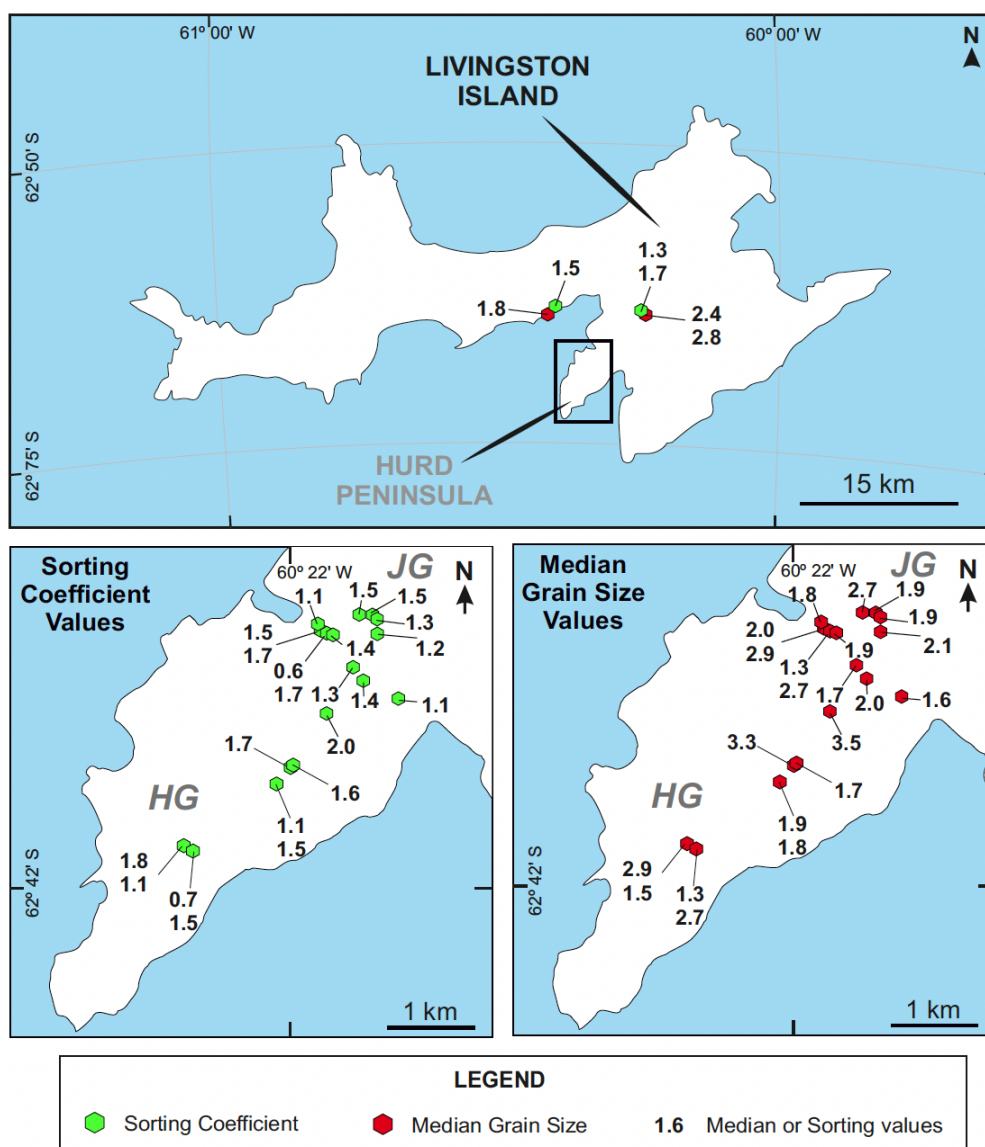


Figure 5.15. Sorting coefficient and median grain sizes values map. HG: Hurd Glacier; JG: Johnsons Glacier. The two maps at the bottom correspond to the area delineated by the black rectangle marked in the Hurd Peninsula on the Livingston Island map (top).

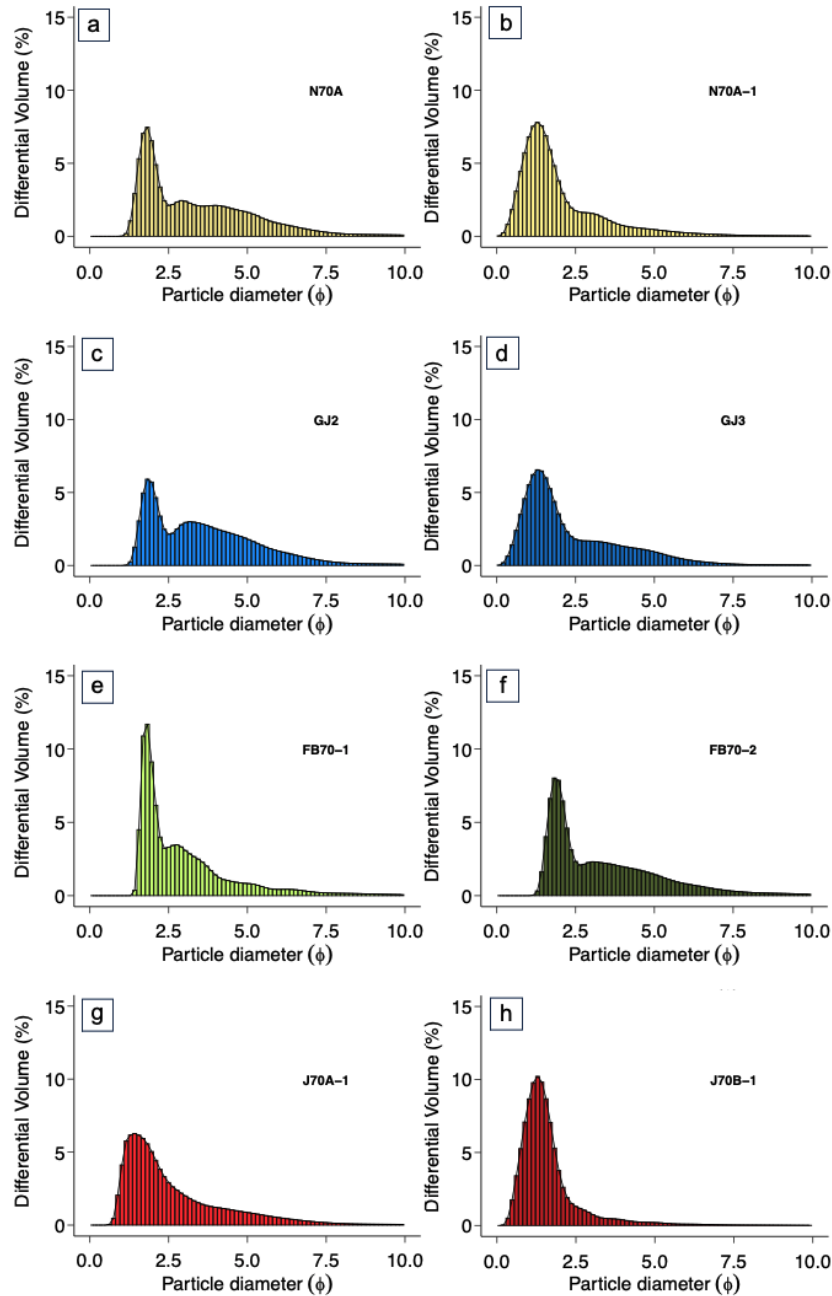


Figure 5.16. Total grain size distribution of selected samples of the 1970 eruption of Deception Island. a) Polymodal distribution with positive skewness of sample N70A. b) Bimodal distribution with positive skewness of sample N70A-1. c) Bimodal distribution with positive skewness of sample GJ2. d) Bimodal distribution with positive skewness of sample GJ3. e) Polymodal distribution with positive skewness of sample FB70-1. f) Bimodal distribution with positive skewness of sample FB70-2. g) Unimodal distribution with positive skewness of sample J70A-1. h) Unimodal distribution with positive skewness of sample J70B-1. See Supplementary Figure S1 for the grain size distribution graphs of the remaining samples.

5.2.3 Petrography and morphology of juvenile & lithics fragments

In the context of fragment composition, juvenile elements collectively comprise 88%, while lithic materials and free crystals (< 1%) constitute the remaining 12%. Juvenile tephra fragments exhibit spongy, blocky, and fluidal morphologies, along with variations in vesicularity and curvilinear surfaces (Fig. 5.17). Vesicularity of glass shards ranges from poor (< 10%), medium (10 - 30%), up to high (> 30 %) (Fig. 5.18). Spongy fragments are highly vesiculated with vesicles (particle long axis ranging in size between 20 and 125 μm) intersecting with the external surface of the fragment (Fig. 5.16a). There is a predominance of blocky fragments with curvilinear surfaces and concave shapes, a variable content of circular vesicles of various sizes (50 - 200 μm) —ranging from poorly to highly vesiculated—, and occasionally with dust adhered on the fragment and/or within the vesicles (Heiken, 1974) (Figs. 5.17b, 5.19). Furthermore, dense, non-vesiculated blocky fragments (Wohletz & Kinsley, 1982) are also presented (Fig. 5.19c). Fluidal fragments are smooth and glassy, highly vesiculated, roughly circular in shape with sharpened edges due to circular, elongated, and fluidal terminations, with dust adhered in the vesicles walls. Sometimes these terminations resemble a Pele's tear (Figs. 5.17c, 5.19a, b; Heiken & Wohletz, 1985). Finally, fragments with elongated vesicles are also observable (Dellino & La Volpe, 1996) (Figs. 5.19c, d).

We can discern up to three main types of juvenile fragments (Type I, II and III) based on their color under the optical microscope, and the degree of crystallinity and/or glass content observed with the SEM (Fig. 5.18). A short description of all three juvenile types is provided below. Note that according to Mackenzie et al. (1982) the term microcryst refers to crystals smaller than 0.05 mm, microphenocrysts between 0.05 and 0.5 mm, and phenocryst larger than 0.5 mm.

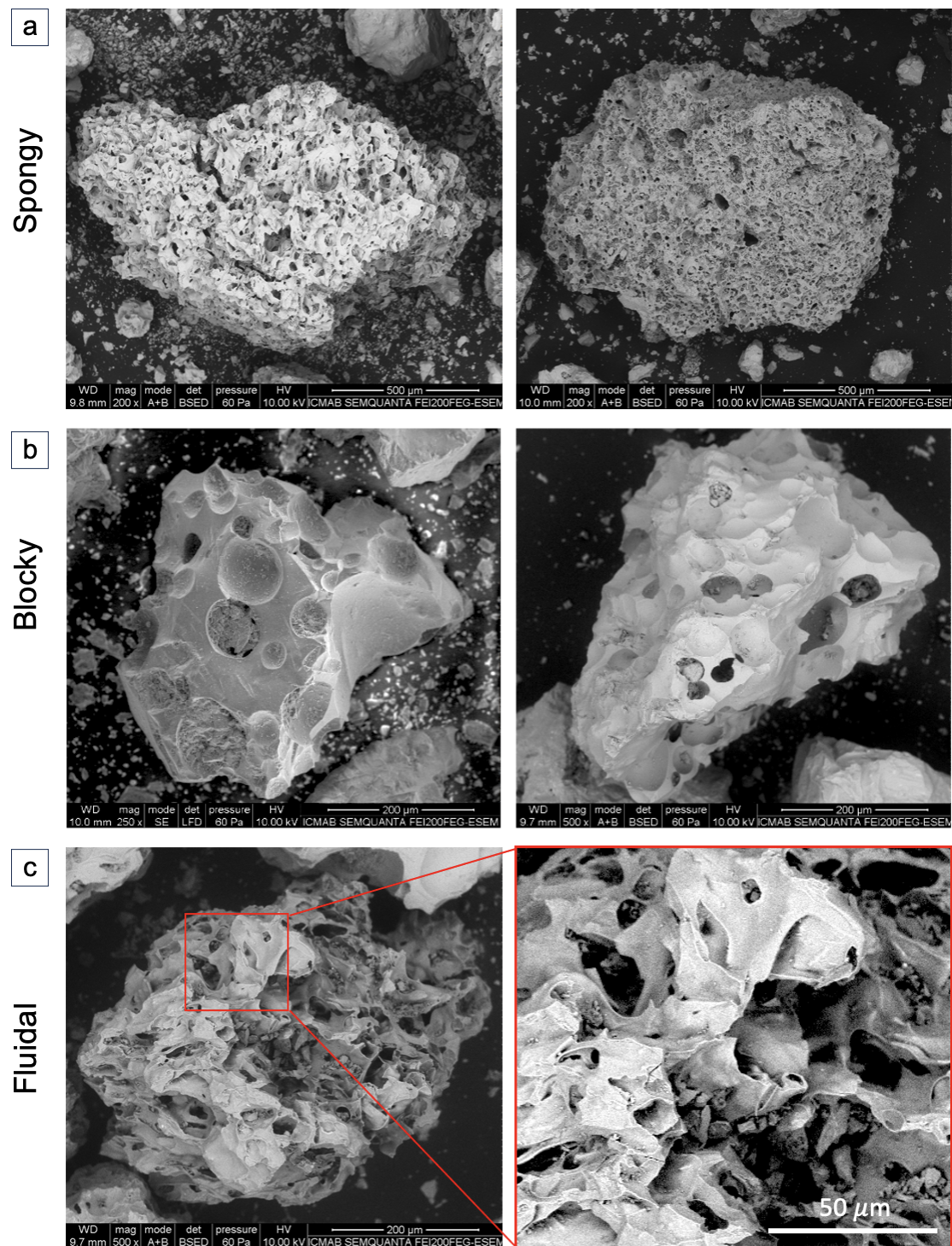


Figure 5.17. Different types of external morphology (spongy, blocky and fluidal) present in the tephra fragments of the 1970 eruption. a) Spongy fragment with high content of vesicles intersecting with the external surface of the fragment. b) Blocky fragment with curvilinear surfaces and a medium to high vesicle content. c) Fluidal fragment with high content of vesicles, smooth and glassy surfaces with sharpened edges due to vesicle walls and fluidal terminations.

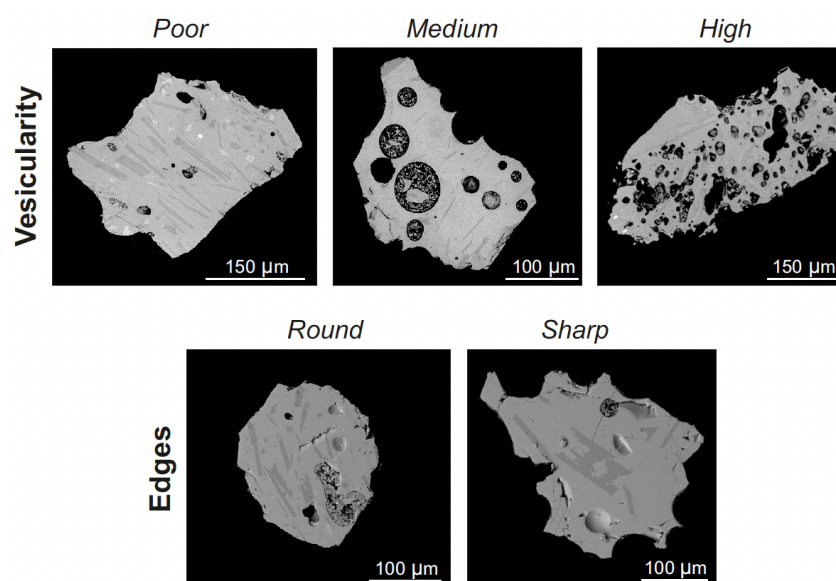


Figure 5.18. Backscattered image of vesicularity (top) and shape of the edges of glass shards (bottom). Poor vesicularity (< 10 % vesicles). Medium vesicularity (10 - 30 % vesicles). High vesicularity (> 30 % vesicles).

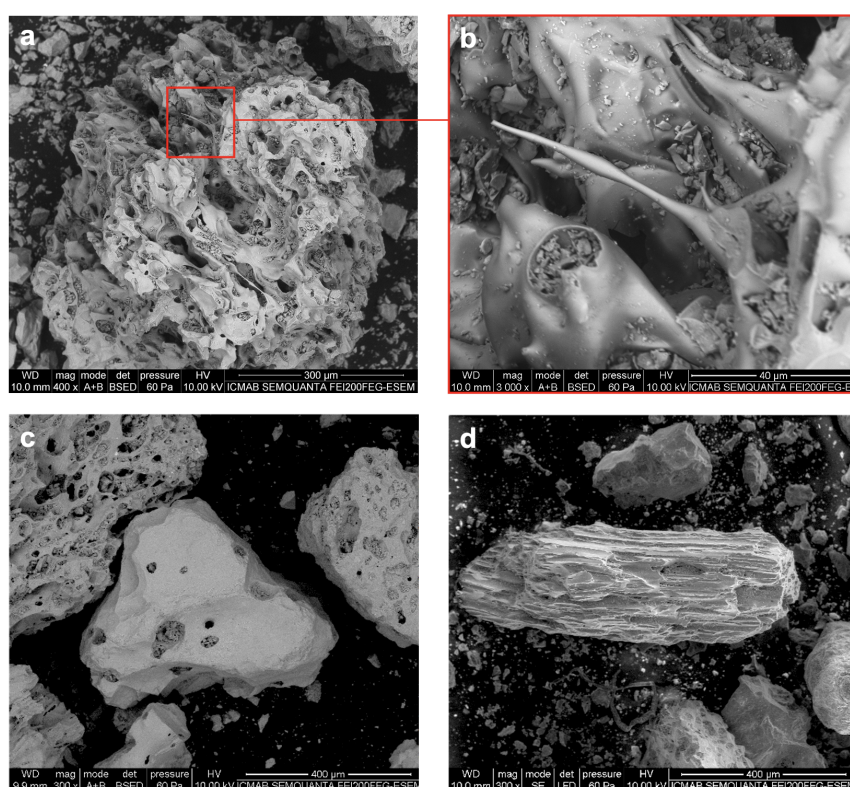


Figure 5.19. a) Vesicular fragment with fluidal texture of sample FB70-2. b) Zoom of a) showing a Pele's tear. c) Dense fragment of sample FB70-2. d) Fluid fragment with elongated and parallel vesicles of sample FB70-2.

- **Type I** juvenile fragments (Fig. 5.20) are commonly irregularly shaped with more rounded edges compared to other fragments (Fig. 5.18). They have a dark brownish color and show moderate (15 – 20 %) vesicularity and blocky morphology (Fig. 5.18). These fragments are particularly characterized by: (i) a high (40 - 50 %) crystal content mostly consisting of plagioclase microphenocrysts with quenching textures and minor pyroxene (Fig. 5.20); (ii) having a glassy matrix which hosts a high content of plagioclase microliths and minor pyroxene microcrysts; and (iii) presenting a high (2 – 8 %) Fe-Ti oxide content (compared to Type II and III fragments).
- **Type II** juvenile fragments are irregularly shaped with sharpened edges (Fig. 5.18), exhibit a color range that extends from dark brown (Fig. 5.21a) to light brown color (Fig. 5.21b), and show moderate (20 - 30 %) vesicularity (Fig. 5.18) with round and elongated vesicles (Fig. 5.21). These fragments present a blocky and spongy morphology. The crystal content (30 - 40 %) mainly consists of plagioclase microphenocrysts with quenching textures, and microcryst of pyroxene and minor olivine (Fig. 5.21). The glassy matrix hosts a 10 to 25 % content of pyroxene and plagioclase microcrysts (Fig. 5.21). The content of Fe-Ti oxide varies between 2 and 3 %. Locally, several fragments displayed fluidal textures with aligned plagioclase microcrysts (Fig. 5.22).
- **Type III** juveniles (Fig. 5.23) consist of blocky fragments of irregular shapes with sharpened edges (Fig. 5.18) owing to the vesicles, similarly to Type II. They consist of red colored fragments with moderate content of vesicles (10 – 15 %), which are either elongated or rounded (Fig. 5.18). These fragments have a crystal content that ranges between 20 and 30 %, consisting of plagioclase, pyroxene and minor olivine microphenocrysts. The glassy matrix presents microcrysts (10 – 15 %) (similarly to Type II), which are mainly pyroxene and plagioclase (Fig. 5.23).

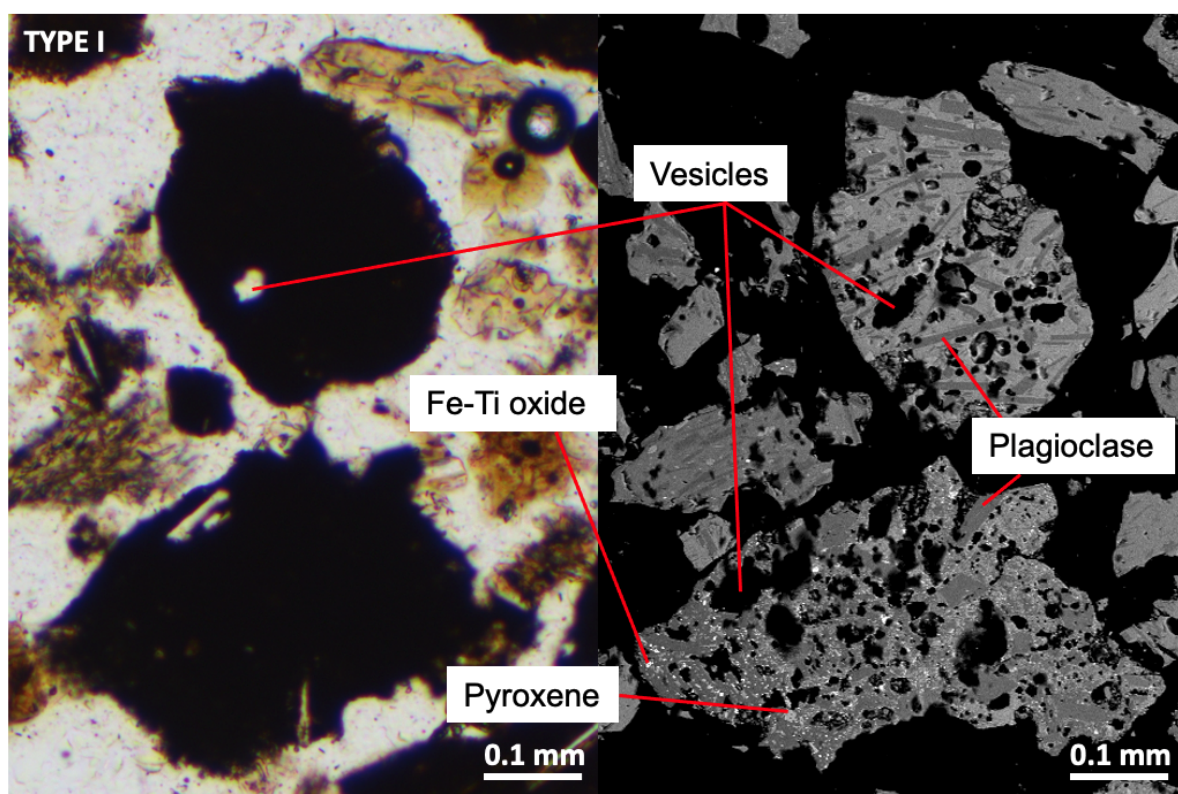


Figure 5.20. Type I Juvenile fragments of sample 70-69 with microphenocrysts of plagioclase and microcrysts of pyroxene. Plane-polarized optical microscope image (left) and EPMA image (right).

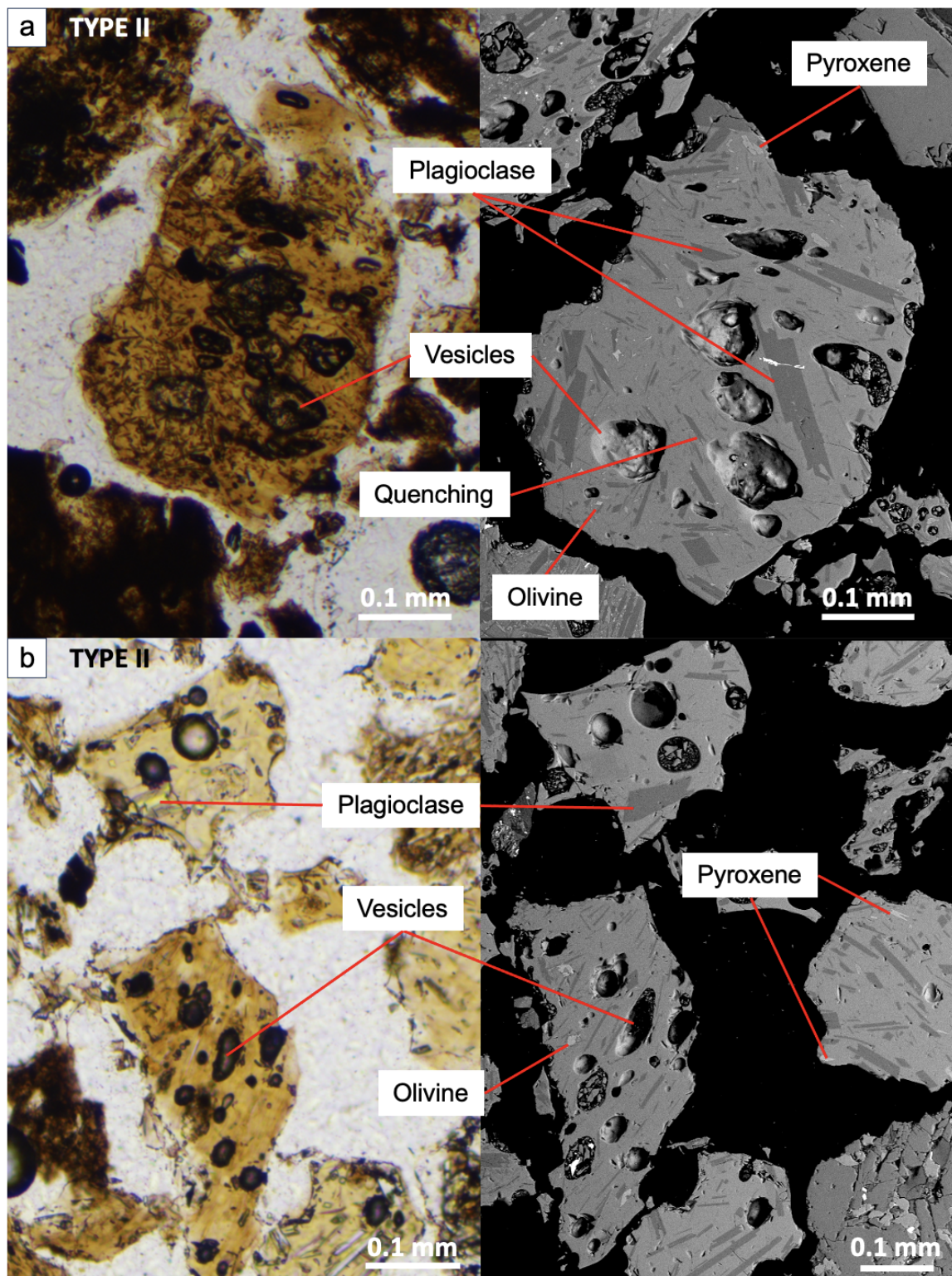


Figure 5.21. a) Type II Juvenile fragments of sample 70-21 with microphenocrysts of plagioclase and microcrysts of olivine and pyroxene. Optical microscope image (up left) and EPMA image (up right). b) Type II Juvenile fragments of sample 70-69. Optical microscope image (bottom left) and EPMA image (bottom right).

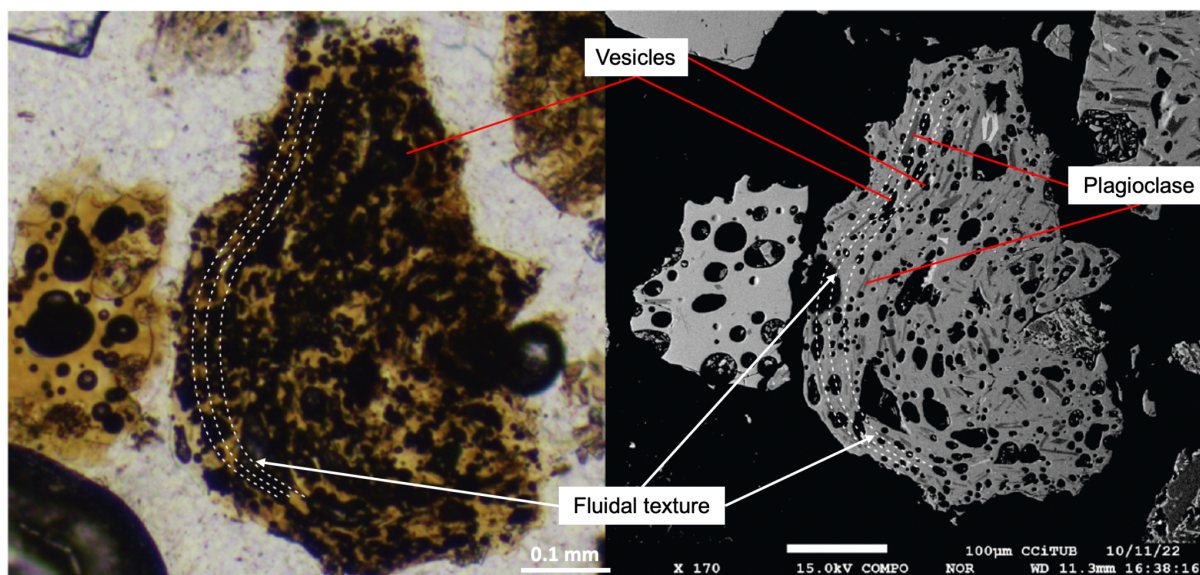


Figure 5.22. Type II Juvenile fragments with fluidal textures of sample J70B-1. Optical microscope image (left) and EPMA image (right).

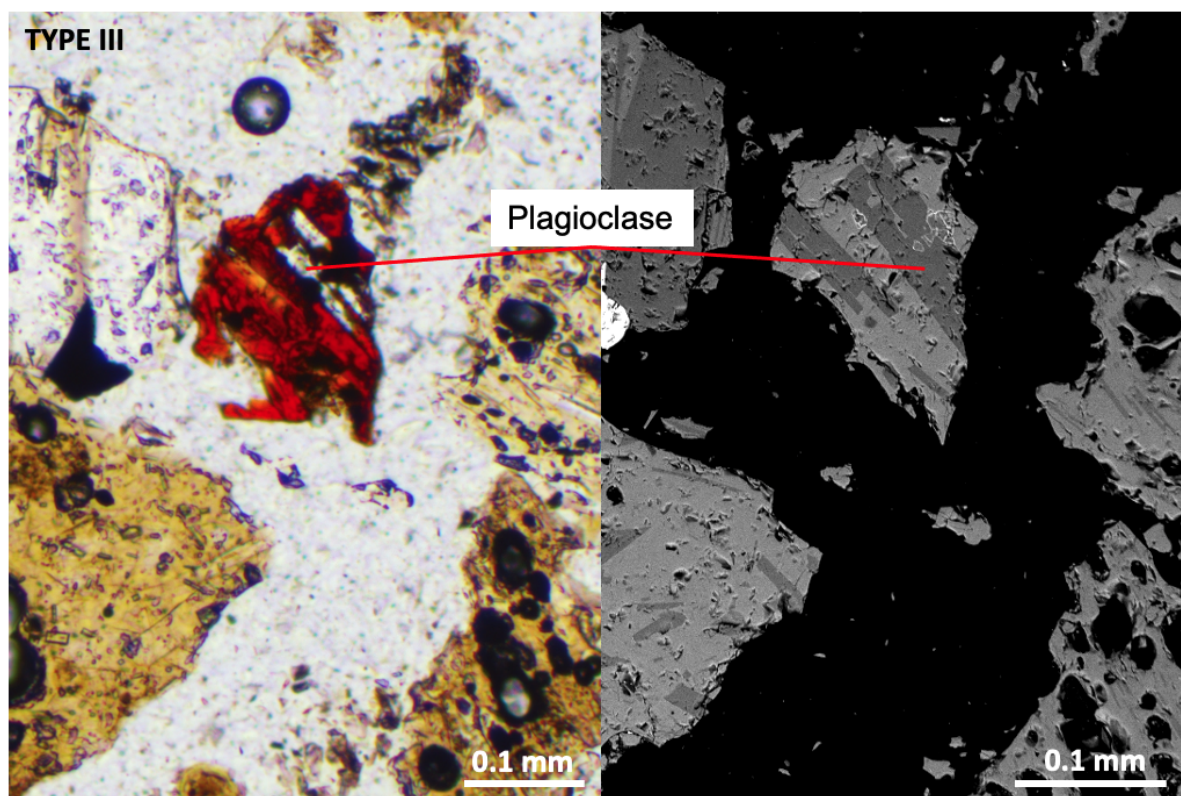


Figure 5.23. Type III Juvenile fragments of sample E70 with microphenocryst of plagioclase. Optical microscope image (left) and EPMA image (right).

Among all three types of juvenile fragments, Type II is the most abundant (77%) followed by Type I (22%). Type III fragments are sparingly represented, making up just 1% of the overall juvenile fragment composition. It is important to clarify that these percentages are derived from an average across six samples selected from each sampling site (1 sample selected per sampling site). In the analysis of each individual sample, the percentage count varies between 1% and 2%, indicating minimal variation when calculating the overall average for each component (e.g., lithic, juvenile).

In addition to lithics and juvenile fragments, free crystals, mostly subhedral plagioclase and pyroxene, are also present (< 1%) in all tephra samples (Fig. 5.24). These are commonly plagioclases (80%) with sizes ranging from 0.1 to 0.5 mm, and frequently displaying twin planes and local zoning (Figs. 5.24e, f). Pyroxenes, present in different sizes (0.2 to 0.4 mm), are less common (20%) than plagioclases, and in some cases, they are surrounded by a very thin glass coat (Figs. 5.24a, d). Subhedral to anhedral olivines (0.2 to 0.3 mm) are also presented as free crystals (Figs. 5.24b, c), but in smaller proportions (10%).

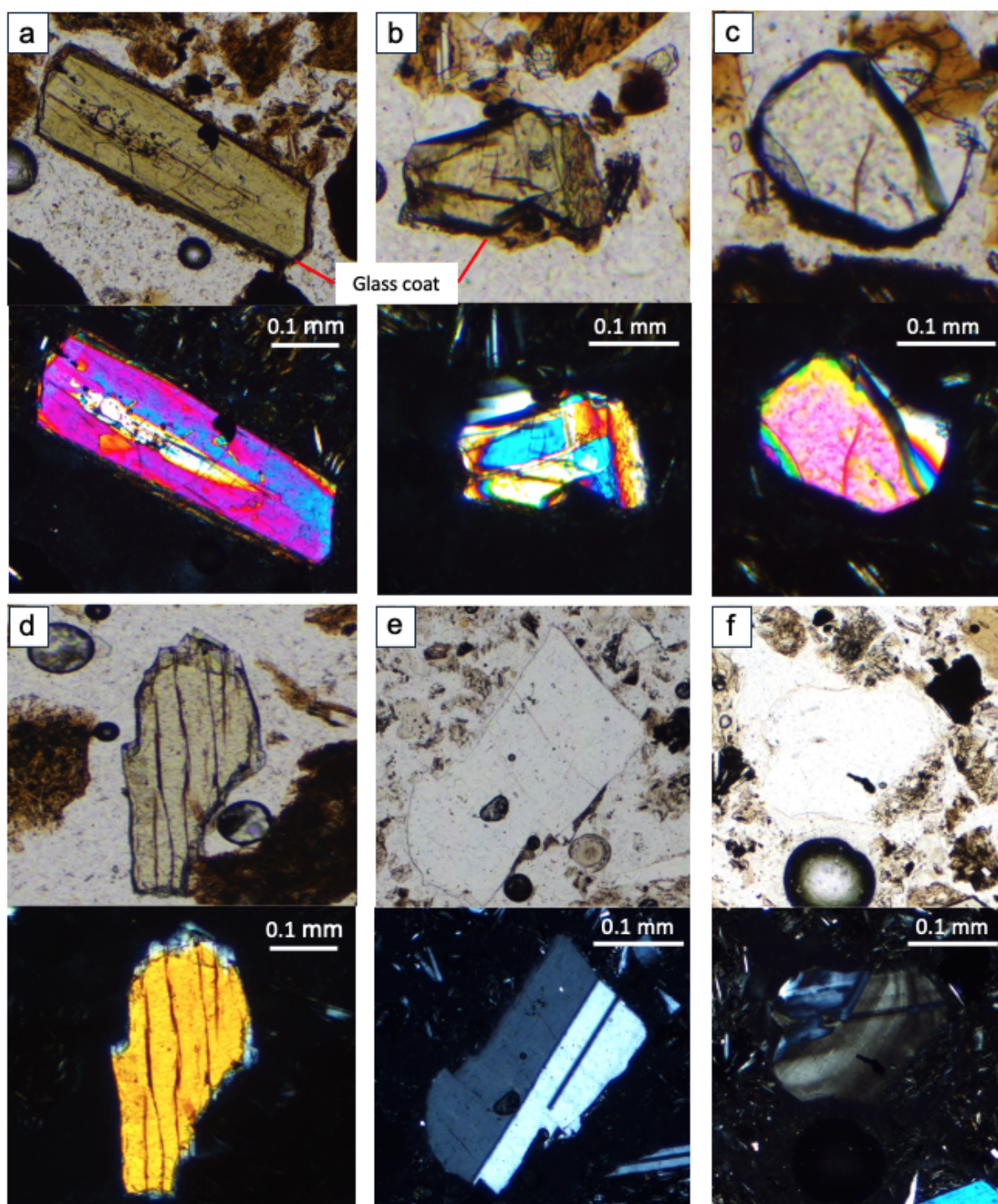


Figure 5.24. Optical microscope images of free crystals. For each example: plane-polarized (top) and crossed-polarized light (bottom). a) Pyroxene of sample 70-21. b) Olivine of sample J70B-1. c) Olivine of sample J70B-1 d) Pyroxene of sample CA-4. e) Plagioclase of sample GJ3. f) Plagioclase of sample N70B-2.

Among the great diversity of lithics observed in the studied tephra samples, the most abundant ones are (Fig. 5.25):

(i) black colored fragments with a crystallized matrix (Figs. 5.25a, b) hosting microphenocrysts of plagioclase, pyroxene, and abundant Fe-Ti oxides (Fig. 5.25c). Observed under an optical microscope, this type of lithics can be confused with Type I juvenile fragments (compare Fig. 5.25a, b with Fig. 5.20), but using backscattered images of SEM or EPMA, volcanic glass is easily identified within the matrix of Type I juvenile fragments.

(ii) lithics with a browner color and some oxide tones (Fig. 5.25d) characterized by a crystalline matrix with presence of Fe-Ti oxide. Due to their resemblance in color, this type of lithics can be confused with Type II fragments when observed under the optic microscope. However, when using backscattered images of SEM or EPMA, juvenile fragments present a glassy matrix not altered.

(iii) highly crystalline lithics of granular texture, mainly composed of plagioclase and pyroxene (90 - 98 %) (Fig. 5.25e) and with 2 to 10 % of Fe-Ti oxides (Fig. 5.25f). In some cases, alteration minerals such as analcime or smectite are filling the vesicles (Figs. 5.26a, b).

(iv) lithics with a browner color and oxide to red tones (Figs. 5.25g, h) characterized by a completely altered matrix where it is hard to identify crystals (Fig. 5.25h). Also, secondary minerals are commonly filling the vesicles (Fig. 5.25g). Due to their resemblance in color, this type of lithics can be confused with Type II and Type III fragments when observed under the optic microscope. However, when using backscattered images of SEM or EPMA, juvenile fragments present a glassy matrix not altered and no presence of secondary minerals within the vesicles.

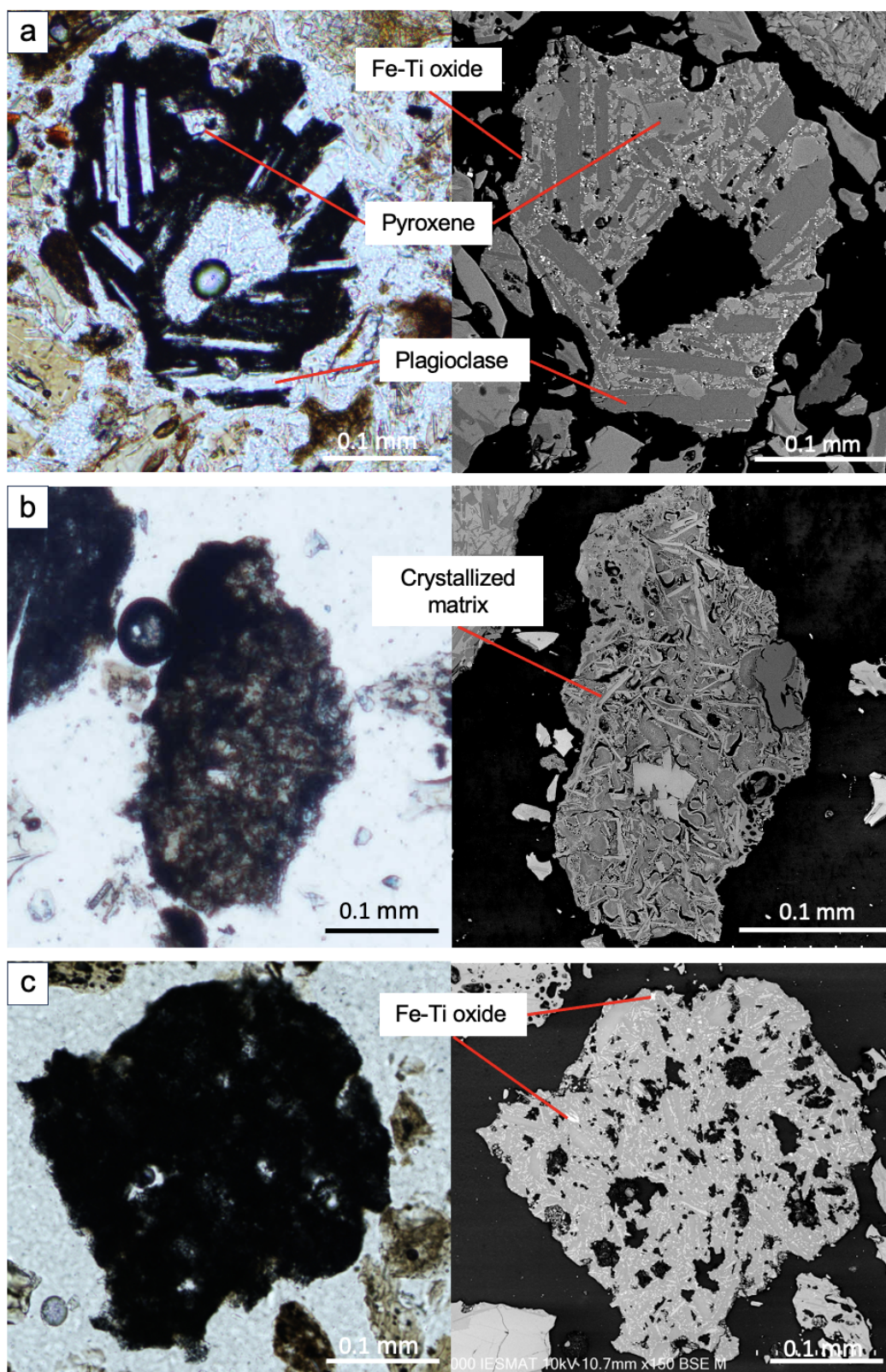


Figure 5.25. Examples of lithic fragments. Plane-polarized light optical microscope image (left) and EPMA image (right). a) Black colored lithic fragment of sample 70-1. b) Black colored lithic fragment of sample 70-1. c) Black colored lithic fragment of sample J70B-1.

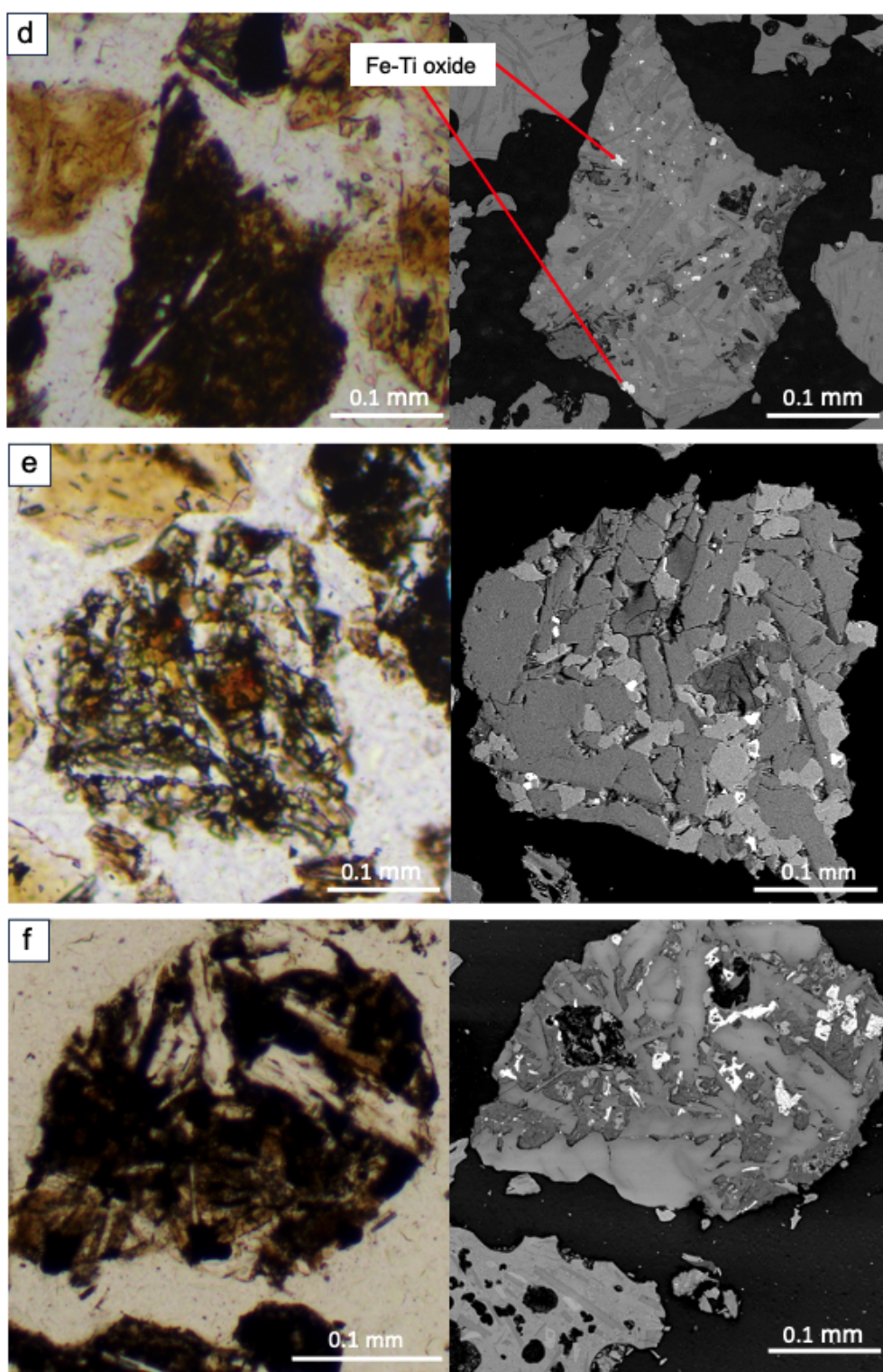


Figure 5.25. Continuation. Plane-polarized light optical microscope image (left) and EPMA image (right). Examples of lithic fragments. d) Brown colored lithic fragment of sample J70B-1. e) Crystalline lithic fragment of sample 70-69. f) Crystalline lithic fragment of sample 70-21.

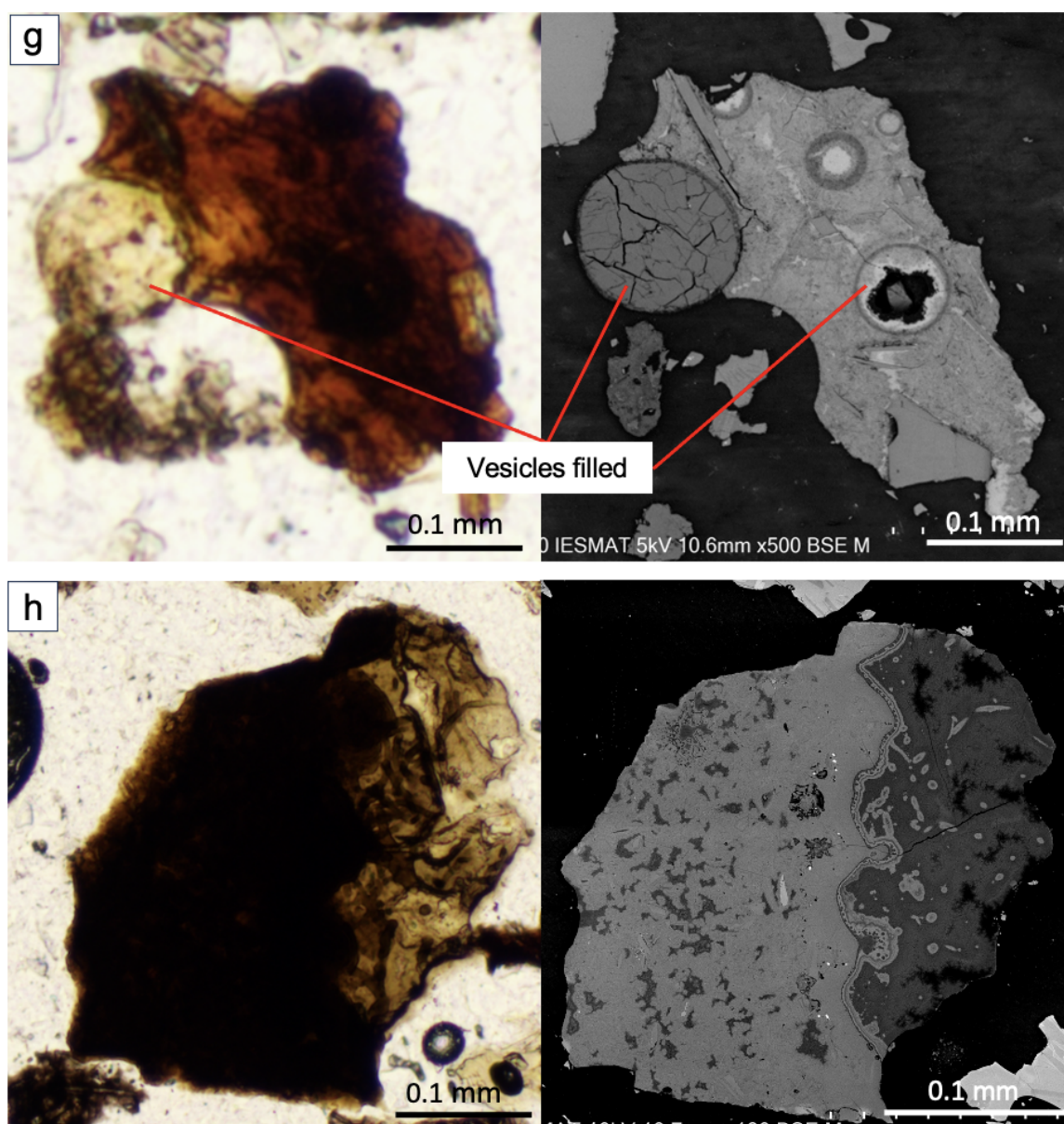


Figure 5.25. Continuation. Plane-polarized light optical microscope image (left) and EPMA image (right). Examples of lithic fragments. g) Red colored lithic fragment with vesicles filled by secondary minerals of sample CA-4. h) Black to brownish colored lithic fragment of sample 70-69.

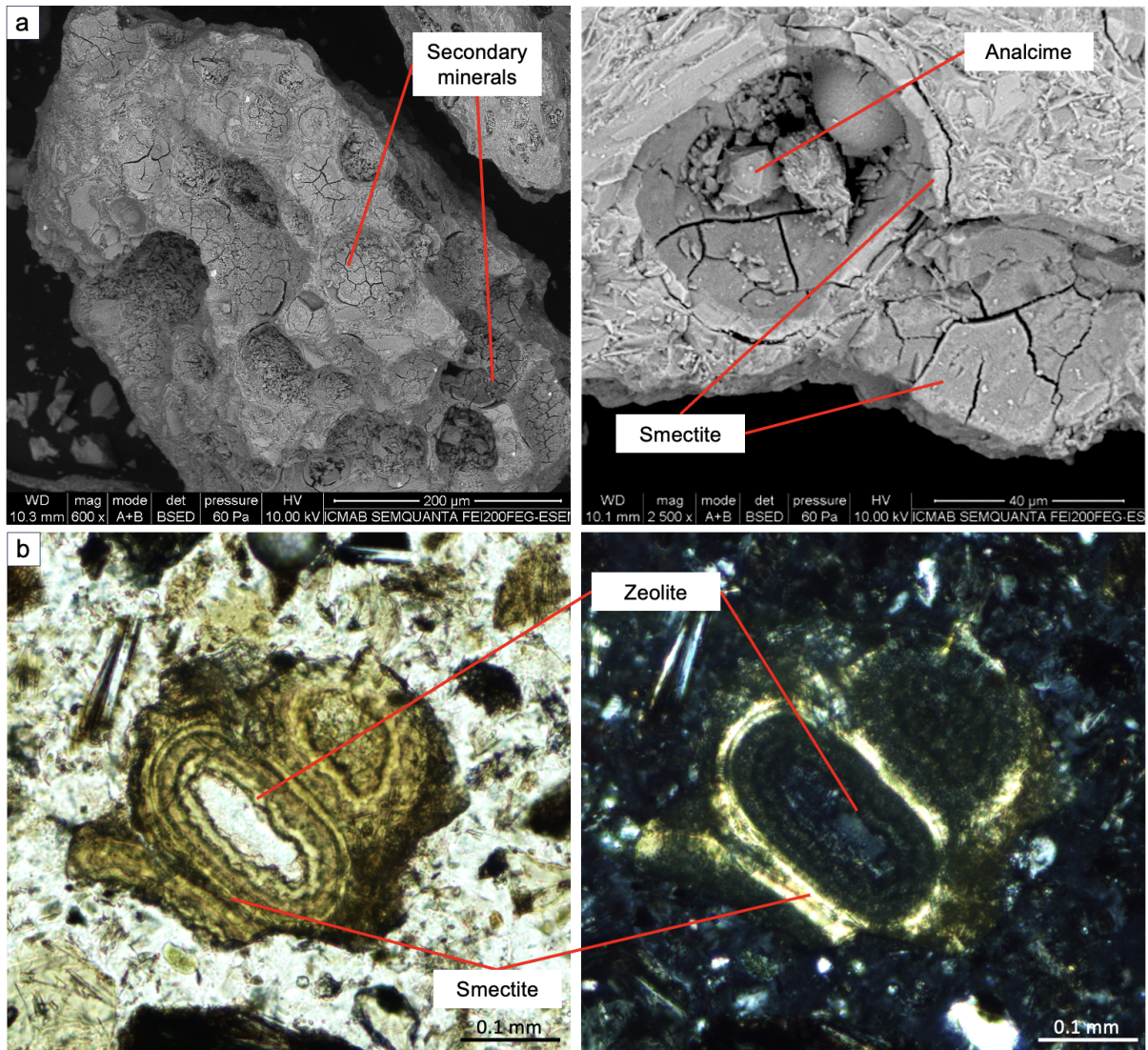


Figure 5.26. a) SEM images of lithic fragments of sample E70. b) Optic microscope images of a lithic fragment of sample 70-200 in plane-polarized (left) and crossed-polarized light (right).

5.2.4 Glass geochemistry

Juvenile glass compositions (Type I-III) plot all in the subalkaline field ranging from basalt to trachyandesite, with minor abundance of andesites (Fig. 5.27). The SiO_2 content of the tephra samples varies from 51 to 62 wt.%, with the majority of the analyzed glasses falling within the 51 and 59 wt.% interval. The most evolved volcanic glasses (from 59.9 to 60.9 wt.% in SiO_2) have been measured in Type I and II juvenile fragments of samples FB-70, 70-1, N70B-1, and J70B-1 (Figs. 5.27, S2). The volcanic glasses of the last four tephra samples also cover the widest range of SiO_2 content (from 49.58 to 60.89 wt.% in SiO_2). Type II fragments cover the entire spectrum of SiO_2 content represented by the complete set of samples (Figs. 5.27, S2). However, Type I fragments are limited to basaltic andesite, basaltic trachyandesite, and trachyandesite compositions. Type III fragments are exclusively concentrated within the basaltic trachyandesite field (Figs. 5.27, S2).

Considering all glass geochemical analyses, these follow a similar evolutionary trend as the Deception Island magmas, defining a distinctive differentiation trend of increasing alkalinity produced by uncommonly high Na_2O (between 2 and 8 wt.% Na_2O ; Geyer et al., 2019) (Figs. 5.27, 5.28). Binary variation diagrams of major elements show a negative correlation of MgO and CaO with SiO_2 , as well as a positive correlation of K_2O and Na_2O with SiO_2 (Fig. 5.28). There is no evident correlation of TiO_2 , FeO_t or Al_2O_3 with SiO_2 (Fig. 5.28).

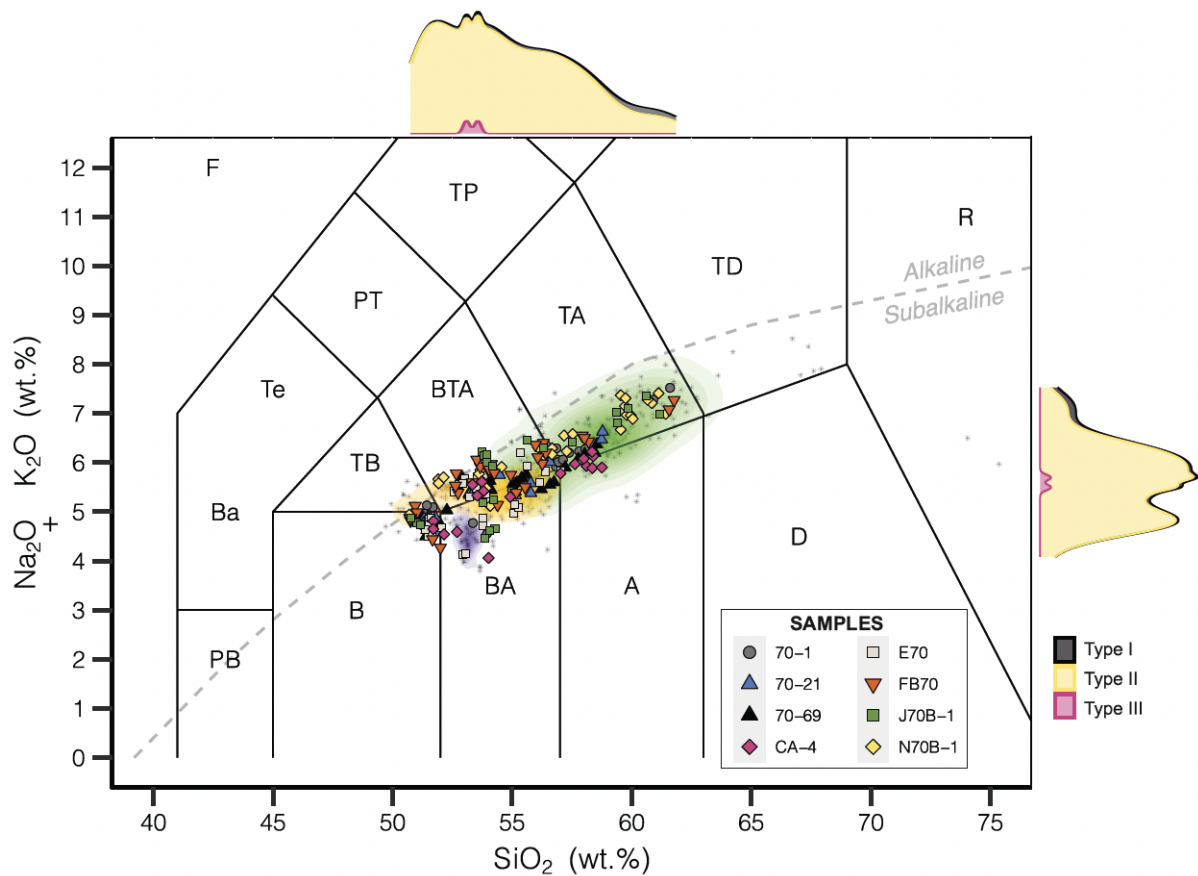


Figure 5.27. Total alkalis versus silica diagram (TAS) (Le Bas et al., 1986) for glass of tephra samples. The major elements were normalized to 100% (anhydrous), with Fe distributed between FeO and Fe₂O₃ following Middlemost (1989). Data available in Supplementary Material 2. Each point plot corresponds to a single EPMA analysis, i.e. different points may belong to the same juvenile fragment. Gray asterisks correspond to the geochemical analyses of Deception Island glass shards provided by Geyer et al. (2019). Blue, yellow and green color clouds correspond to glass composition of pre-, syn- and post-caldera rock samples of Deception Island, respectively. Density diagrams for each fragment Type (I-III) showing the distribution of each type of fragment along each axis.

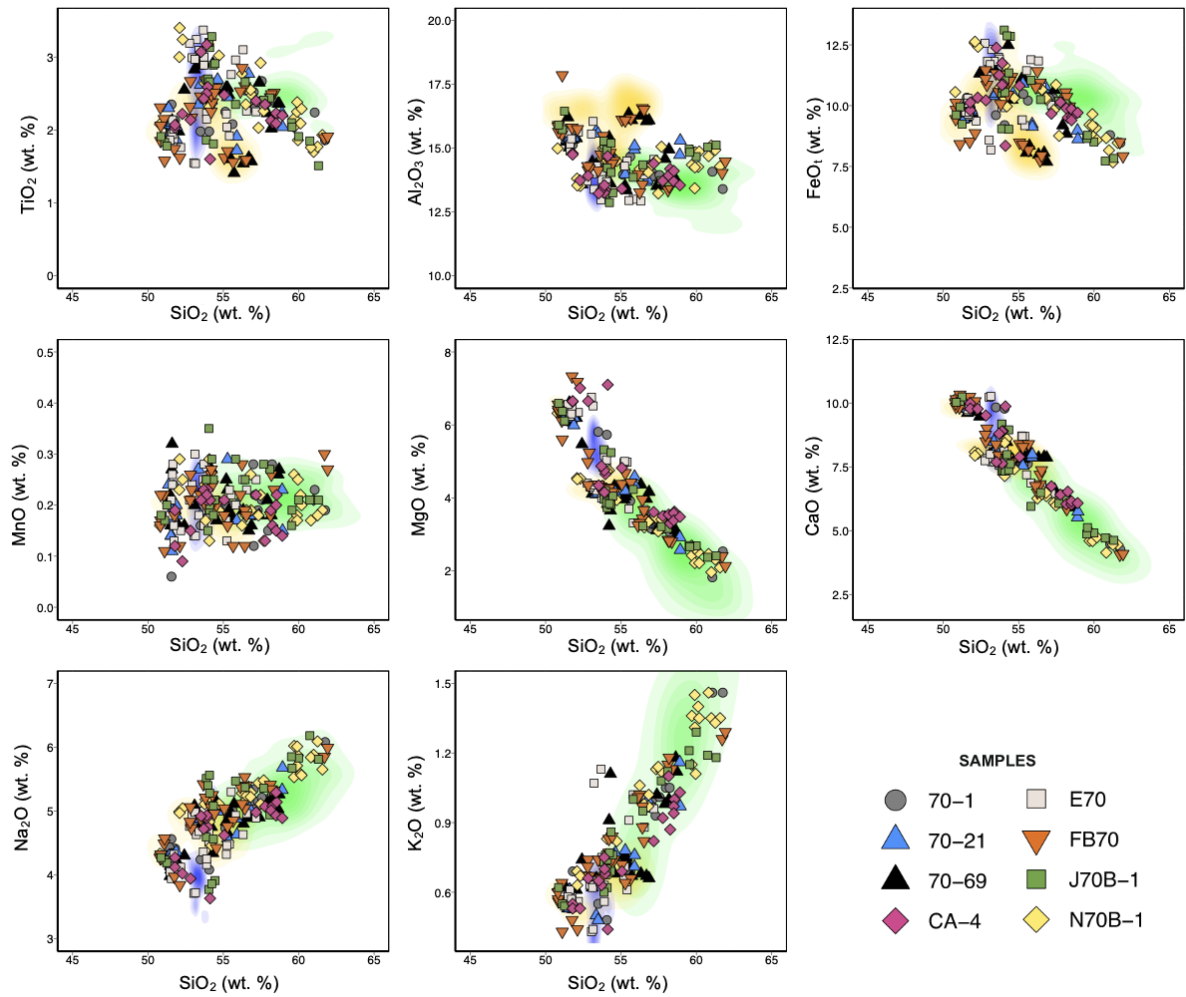


Figure 5.28. Major element vs. SiO_2 content Harker Diagrams for the glass shard of tephra samples. The major element compositions were normalized to 100% in an anhydrous base, with Fe as FeO_t . Each point plot corresponds to a single EPMA analysis, i.e. different points may belong to the same juvenile fragment. Data available in Supplementary Material 2. Geochemical analyses of Deception Island glass shards provided by Geyer et al. (2019) marked as blue, yellow and green color clouds correspond to glass composition of pre-, syn- and post-caldera rock samples of Deception Island, respectively.

5.2.5 Mineral chemistry

Regarding the composition of the minerals of the juvenile fragments, all minerals analyzed are presented in all samples and fragment types (I-III), with the exception of Type I fragments where there is no olivine present.

Plagioclases cover a wide range of compositions, from andesine to bytownite (An_{32-83}) (Fig. 5.29a), being the most frequent ones andesines and labradorites. Bytownites have been only observed in one single crystal from a Type I fragment of sample 70-69 and one single crystal from a Type II fragment of sample CA-4. Pyroxenes are mainly augite (Wo_{39-44} , En_{41-45} , Fs_{15-20}) and diopside (Wo_{45-47} , En_{46-48} , Fs_{9-10}) (Fig. 5.29b). Olivines plot in the Forsterite field, with crystals from sample 70-21 displaying the widest compositional range (Fo_{59-82}) and the highest Mg content (Fo_{80-82}) (Fig. 5.29c).

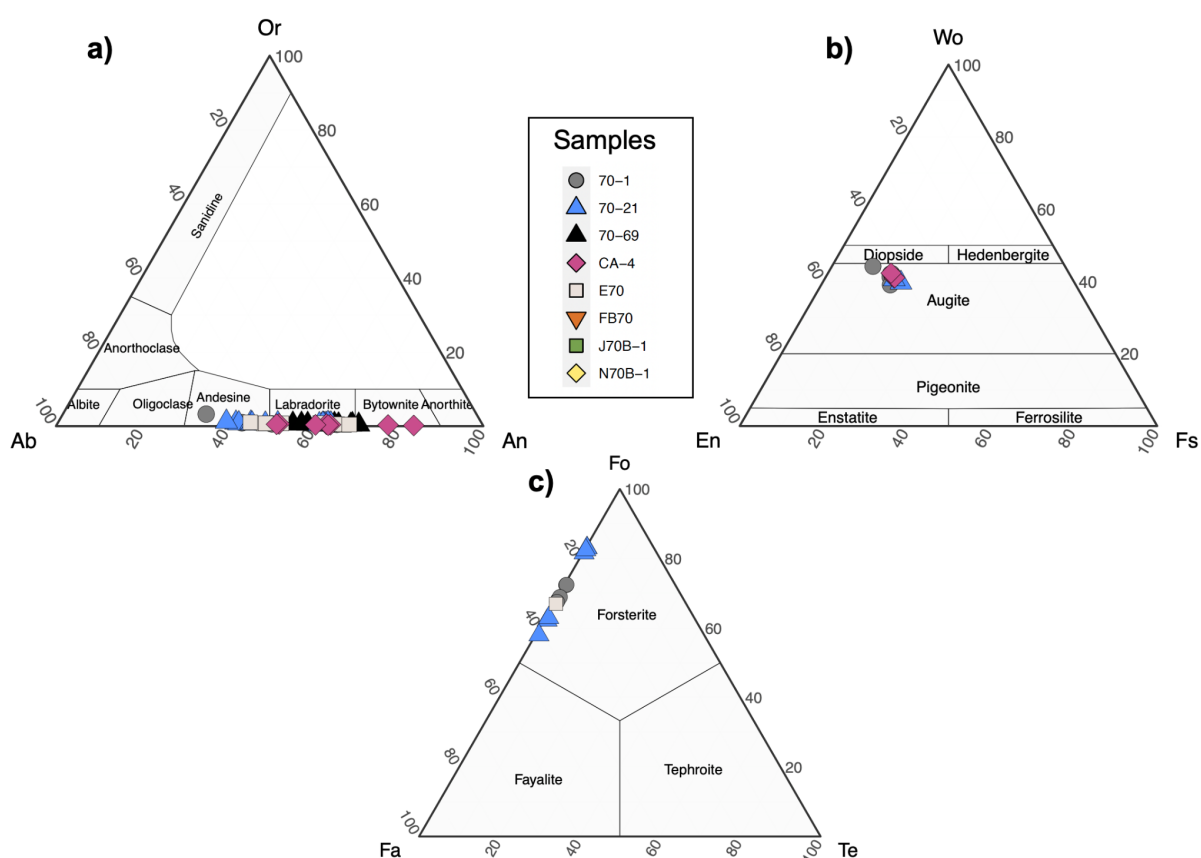


Figure 5.29. a) Orthoclase (Or) - Albite (Ab) - Anorthite (An) ternary diagram for the classification of feldspars (Deer et al., 2001); b) Wollastonite (Wo) - Enstatite (En) - Ferrosilite (Fs) ternary diagram for the classification of Ca-Mg-Fe pyroxenes (Morimoto, 1989); c) Forsterite (Fo) - Fayalite (Fa) - Tephroite (Te) ternary diagram for olivine classification. Data available in Supplementary Material 2.

5.2.6 Discussion

5.2.6.1 Physicochemical characteristics of the 1970 tephra: Insights on eruptive style and eruption dynamics.

5.2.6.1.1 Morphology and tephra grain size distribution

The physicochemical properties of the magma, along with the circumstances in which it rises and erupts, play a role in determining the shape and texture of volcanic ash fragments (e.g., Heiken & Wohletz, 1985). For example, the interaction of the ascending magma with water (e.g., aquifers, lakes, sea water) leads to its rapid cooling, generating glassy tephra grains with highly variable vesicularity (e.g., Sheridan & Wohletz, 1983; Liu et al., 2015). In the same sense, blocky tephra fragments, with more or less vesicles content (i.e., spongy or dense, respectively), are typical of phreatomagmatic eruptions (e.g., Heiken, 1974; Wohletz & Krinsley, 1982; Heiken & Wohletz, 1985). Contrarily, fluidal textures, including Pele's tears (Fig. 5.19a, b) are characteristic of magmatic eruptions (Heiken & Wohletz, 1985). Considering all this and the morphologies of the 1970 tephra fall deposits on Livingston Island (See section 5.2.2), it is possible to confirm the diversity of eruptive styles (phreatomagmatic and magmatic) during the volcanic event. Even if the phreatomagmatic products stand out (i.e., blocky fragments), more than one eruptive style was involved. Indeed, Pedrazzi et al. (2014) identified deposits formed from base-surge-type explosions at the base of the eastern craters. The high degree of fragmentation of these deposits could be an indicator of phreatomagmatic activity, matching with the morphologic features of the tephra fragments.

In addition, granulometric results of the studied tephra samples show three main distributions: i) unimodal with a positive skewness; ii) bimodal with the peak of the coarser mode being higher than the one corresponding to the finer mode with a positive skewness; and iii) polymodal with a positive skewness (Figs. 5.16, 5.30). According to different total grain size distributions from diverse mafic, intermediate, dacitic, rhyolitic and alkaline eruptions, intermediate magmas (andesitic) eruptions tend to have a more significant bimodality than rhyolitic/dacitic and basaltic eruptions (see Costa et al., 2016). In the case of the 1970

eruption tephra fall deposits, the majority of analyses plot within the basaltic andesite and basaltic trachyandesite field (Fig. 5.27). Yet, a smaller proportion of glasses plot in the andesitic field, which may contribute to bimodality in the tephras from the 1970 eruption (e.g., samples CA-4, 70-69; Figs. 5.27, 5.30, Supplementary Figure S1). Aside of the potential differences in the grain size distribution based on the chemical composition of the juvenile fragments, bimodality in tephra fall deposits can be an indicator of plume bifurcation, ash aggregation, rainfall, or due to subtle changes in the eruptive style, wind velocities and direction, or to local instabilities of atmospheric conditions (e.g., humidity) (e.g., Bonadonna et al., 2011; Taddeucci et al., 2011; Cioni et al., 2014; Eychenne et al., 2022). Indeed, tephra fall-out deposits are strongly controlled by the characteristics of transporting winds. Strong winds at the moment of the eruption may result in a better sorting of fragments owing to a more effective velocity decrease, resulting in low values of the sorting coefficient (σ) (Walker, 1971). In addition, one of the commonly recognized processes that lead to polymodality in tephra deposits is a change in wind direction during the eruption. This alteration results in a change in the direction of the plume dispersal, which consequently causes a shift in the tephra depositional axis (Eychenne et al., 2022). As a result, different particle sizes become intermingled on the ground (e.g., 2008 Chaitén eruption; Watt et al., 2009). In the case of the 1970 tephras, bimodal and polymodal grain size distribution can be caused by the strong winds and changes in the eruptive style during the eruption. But to corroborate this, a future detailed study of additional 1970 tephra samples collected in Livingston, Greenwich and/or King George islands (Fig. 5.33) would be necessary. The characterization of the tephra fragments related to the 1970 eruption deposited on Greenwich and/or King George Island would shed some light on the particle distribution in even more “distal” locations compared to Livingston Island. In addition, a study of the meteorological conditions during the eruption integrated with the available total grain size distribution data could be used as a starting point for a simulation of the eruption to enhance possible location of 1970 tephras across the South Shetland Islands.

The sorting coefficient and median grain size values (Figure 5.15; Table 5.2) demonstrate that there is no difference in variation when moving away from Deception Island. Each sample's values have some variation, even at the same sampling site (Table 5.2). Additionally, the median grain size values are quite similar, with no noticeable variation in the

distance from the sampling site to Deception Island. Therefore, we cannot identify the process(es) leading to these differences, even in the same sampling site. One explanation may be that is due to previous analyses (e.g., sieving) on the same samples by Pallàs et al. (2001), Geyer, (2002) and Geyer et al. (2006, 2008), samples could be have been mixed and divided into subsamples (See section 5.2).

5.2.5.1.2 Geochemistry of the 1970 eruption tephras deposited on Livingston Island

The 1970 tephra samples collected in Livingston show an evolutionary pattern similar to that of Deception Island, displaying a distinct trend compared to nearby volcanic centers (e.g., Penguin Island, Sail Rock, Bridgeman Island) (Fig. 5.31). This is also observable both in the TAS diagram and the Harker diagrams of the major elements versus SiO_2 (Fig. 5.28; Geyer et al., 2019). Results obtained align with previous studies (Pallàs et al., 2001; Geyer et al. 2006, 2008) on the same tephra fragments and confirm Deception Island as the source of the sampled tephra layer (Supplementary Figure S3). In addition, the analyzed volcanic glasses plot in the compositional fields of pre-, syn and post-caldera samples (basalt, basaltic-andesitic, and basaltic-trachyandesite), but in less proportion at the more intermediate and evolved compositions of Deception Island's post-caldera magmas (trachyandesite) (Fig. 5.27; Geyer et al., 2019).

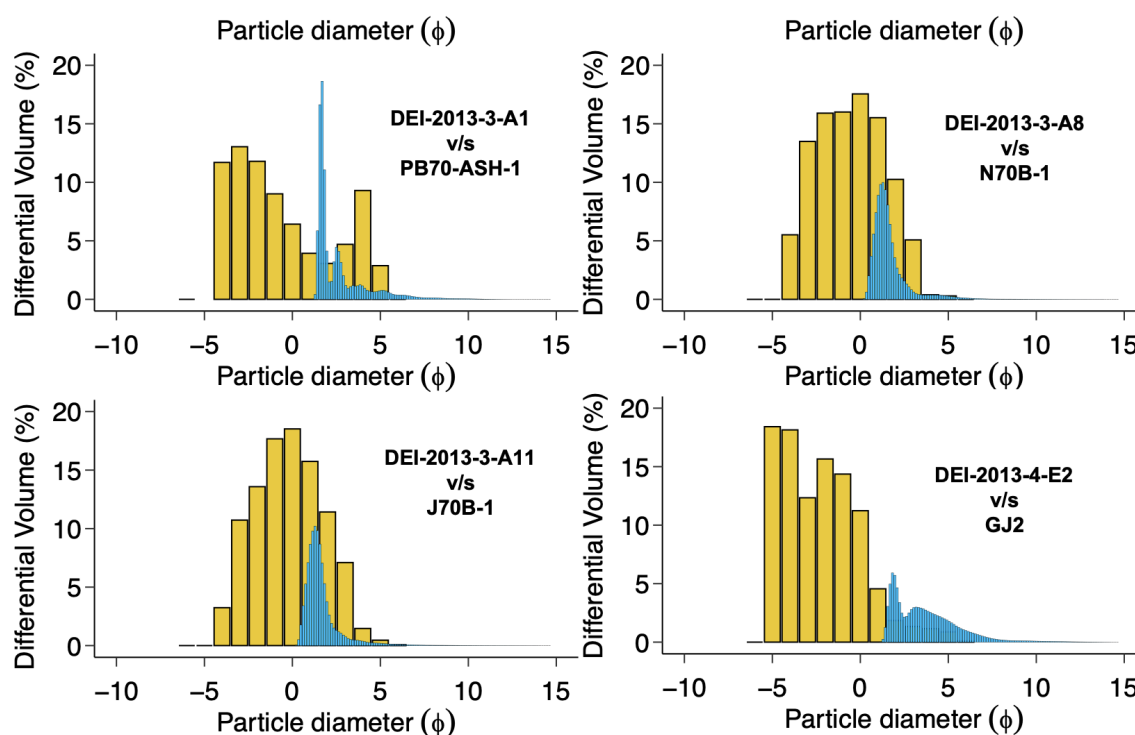


Figure 5.30. Total grain size distribution of selected samples of the 1970 eruption of Deception Island (blue) compared to data from Pedrazzi et al. (2014) (yellow) of the eruption site at Deception Island. Note that for this figure unimodal/ bimodal samples from Pedrazzi et al. (2014) were selected to be compared with unimodal/bimodal tephra samples from the 1970. For further remaining graphs on total grain size distribution of tephra samples from the 1970 See Supplementary Figure S1 and for the rest of graphs of Pedrazzi et al. (2014) See Supplementary Material of Pedrazzi et al. (2014). Note that Pedrazzi et al. (2014) analyzes are represented in wt. %, while Coulter analyzes from tephra fragments correspond to volume %.

Note that it is important to consider the significance of result bias, which arises from constraints associated with the inability to analyze every juvenile tephra fragment and with the possibility of having more than one analysis per fragment. These constraints stem from the high crystal proportion within the matrix, variations in fragment sizes, and the limited content of glass suitable for EPMA analysis.

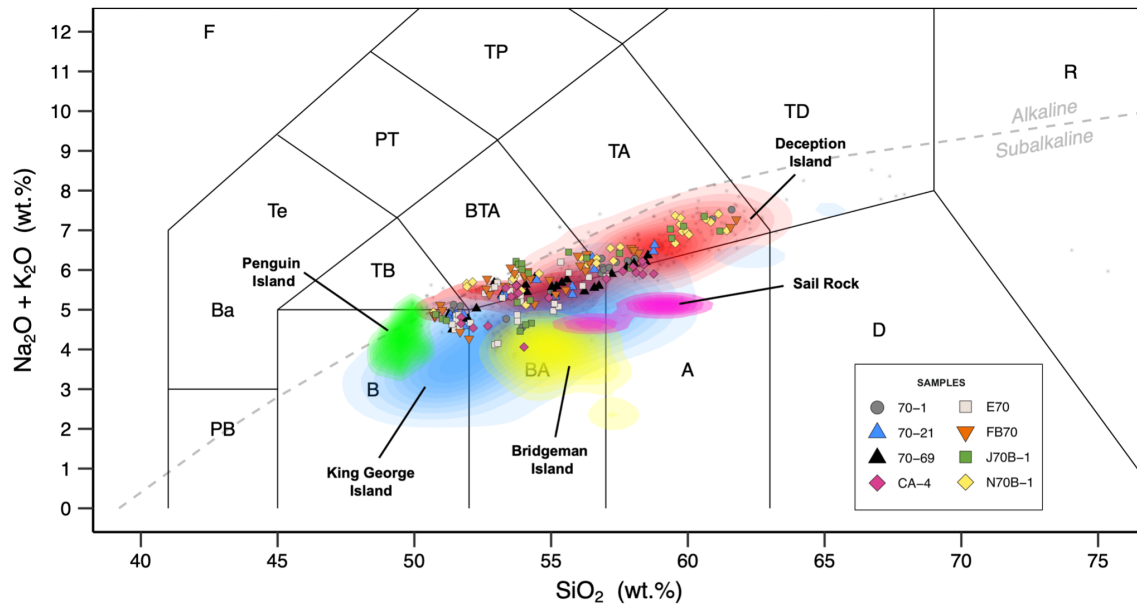


Figure 5.31. Total alkalis versus silica diagram (TAS) (Le Bas et al., 1986) for glass of tephra samples. The major elements were normalized to 100% (anhydrous), with Fe distributed between FeO and Fe₂O₃ following Middlemost (1989). Each point plot corresponds to a single EPMA analysis, i.e. different points may belong to the same juvenile fragment. Bulk rock data from Antoniadou et al. (2018) composition of nearby volcanic centers marked as follows: Deception Island (red) and gray asterisks, Penguin Island (green), King George Island (blue), Bridgeman Island (yellow) and Sail Rock (purple).

5.2.6.2 The 1970 eruptive products: Distal tephra fall-out layers vs. near-vent pyroclastic deposits

5.2.6.2.1 1970 eruption: An overview

The phreatomagmatic 1970 eruptive event on Deception Island had at least 13 active vents (Fig. 5.32) during the course of the eruption (Baker et al., 1975; Pedrazzi et al., 2014). Depending on their location (onshore ice-free locations) and sea water interaction, eruptive activity resulted in conical edifices or maar-like shaped edifices (Pedrazzi et al., 2014). During the eruption, tephra fall out was reported in Greenwich and King George Island (Baker et al., 1975) (Fig. 5.33), and an ash-coated iceberg was reported close to Elephant Island (200 km to the NE of Deception Island) (Roobol et al., 1975).

For the 1970 eruption site, an exhaustive stratigraphical and granulometric work was conducted by Pedrazzi et al. (2014), by analyzing different outcrops levels from separated vents (Figs. 5.32, 5.34). These granulometric analyses conducted on the in situ deposit at the eastern part of the craters and Lago Escondido (Figs. 5.32, 5.34) revealed coarser grain sizes (-5 to 5 Φ) (compared to tephra fall out deposits of Livingston Island) of pyroclastic materials with unimodal and bimodal distribution, similarly to the one describer for some of the analyzed tephra samples (Fig. 5.30). In any case, this comparison should be done with caution since the studied tephra layers may be the result of the deposition of the pyroclastic material ejected during the whole eruption and from different vents.

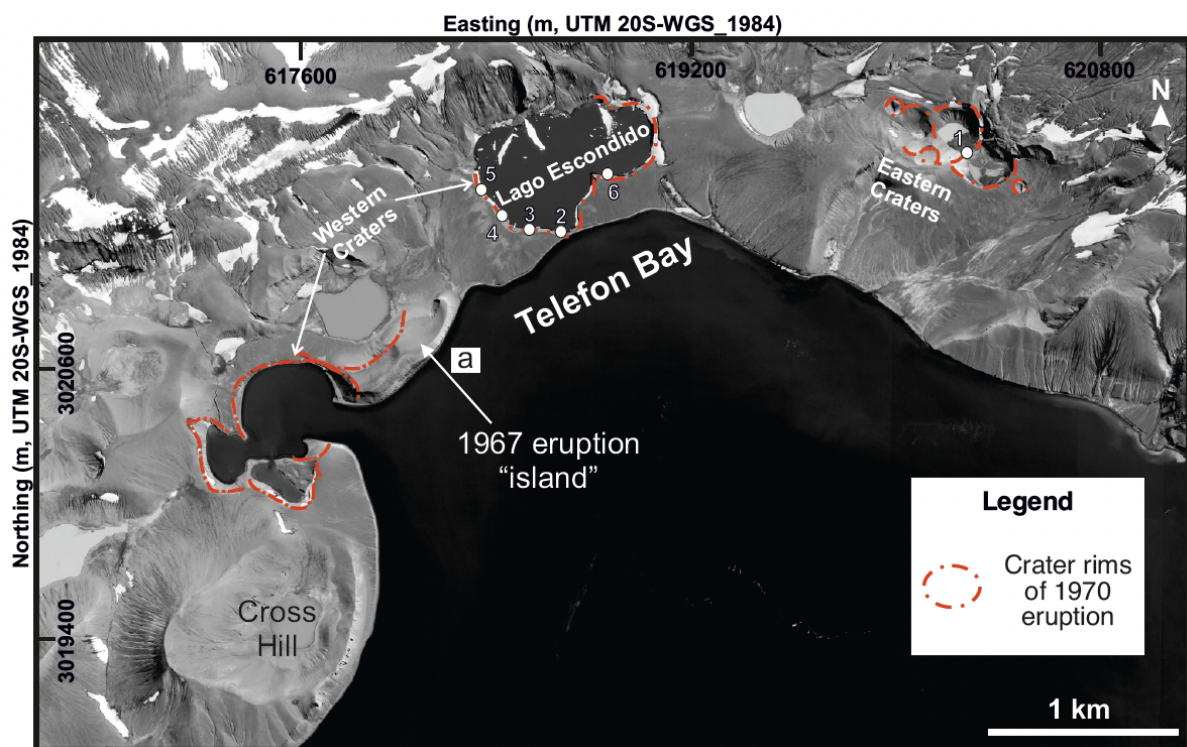


Figure 5.32. Orthophotomap of Deception Island (Torrecillas et al., 2006), indicating crater rims from the 1970 eruption according to Pedrazzi et al. (2014). Stratigraphic logs numbers (1-6) refer to Fig. 5.34.

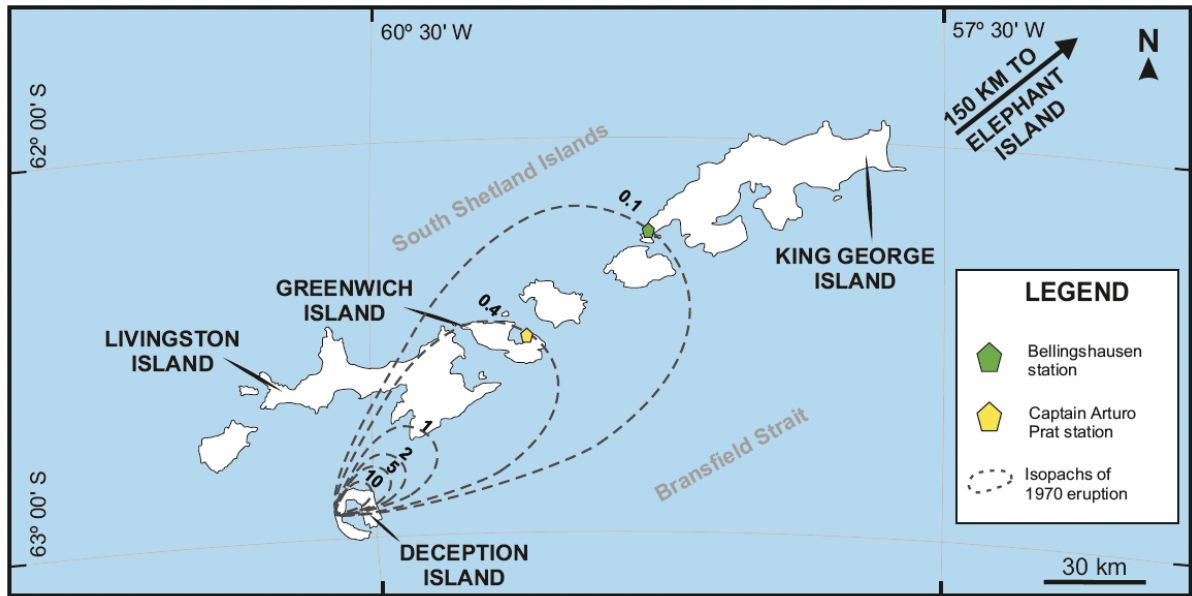


Figure 5.33. Isopachs (dashed lines; in cm) of the 1970 eruption in the South Shetland Islands (modified from Baker & McReath 1975).

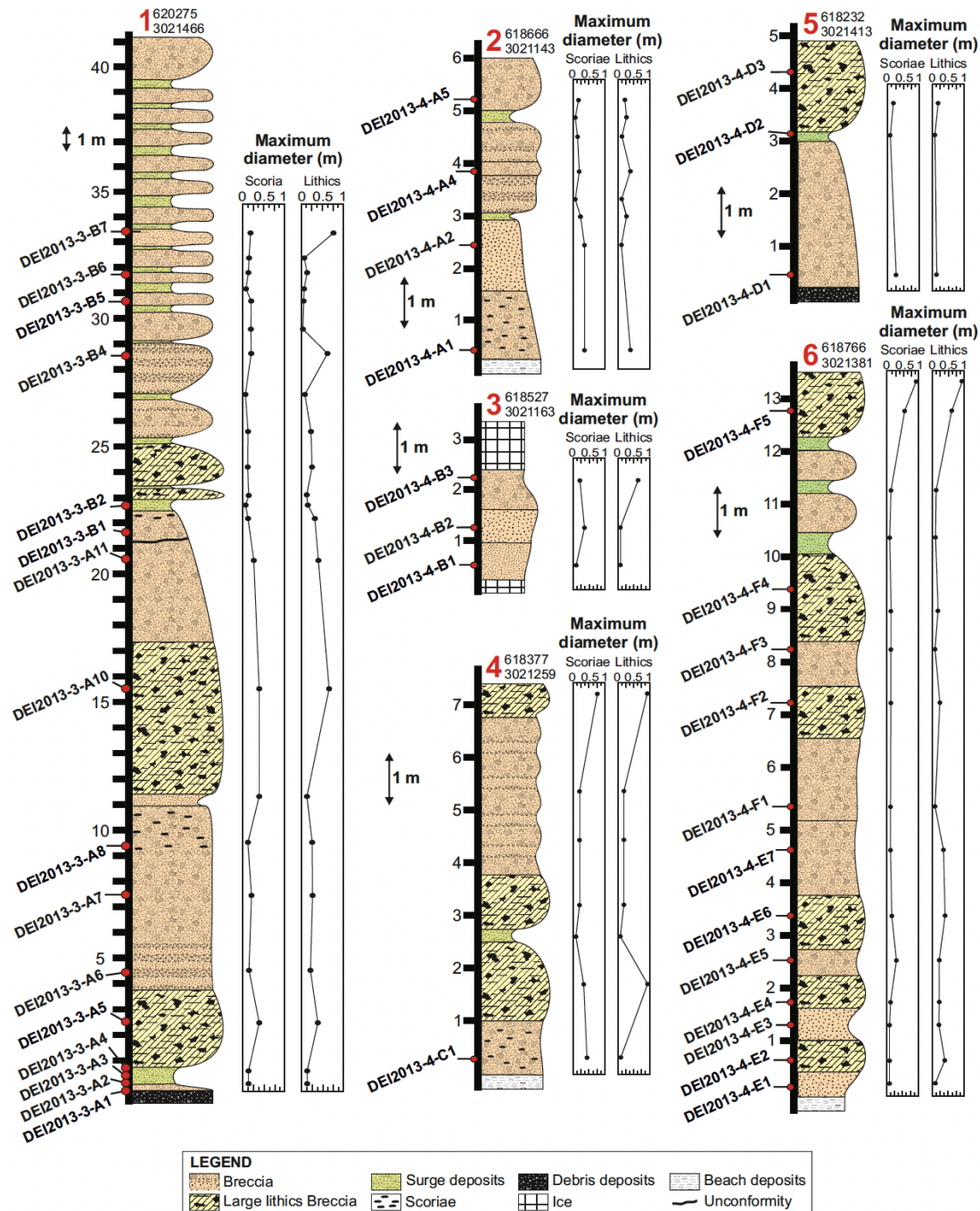


Figure 5.34. Composite stratigraphic logs of the deposits modified from Pedrazzi et al. (2014) (log numbers refer to the position in Fig. 5.35) and component analysis of the most representative samples. Stratigraphic log 1 refers to the eastern craters, and stratigraphic logs 2–6 are located around Lago Escondido (western craters) (Fig. 5.35). Black numbers above the columns refer to UTM coordinates (WGS 1984 Zone 20 S). Vertical variations in grain size and the maximum diameter of lithic and scoria clasts are also indicated.

Tephra fall deposits tend to thin exponentially away from the source, which is clearly shown by the differences between grain sizes from the near-vent pyroclastic deposits and the tephra fragments studied. The median grain sizes of the analyses performed on fall deposits by Pedrazzi et al. (2014) are bigger (-5 to 5Φ) than the tephra fragments found at Livingston Island Glacier (Fig. 5.35). As previously explained, 1970 tephra fragments present median grain sizes that vary from 1.4 to 3.5Φ with a sorting coefficient from 0.8 to 2.0 (the higher the sorting coefficient the poorer is the selection). Based on the diagram of Walker (1971) with the main fields of different pyroclastic deposits added by Brown & Andrews, (2015), tephra fragments of the 1970 eruption are plotted within the field of Fall Deposits (Fig. 5.29), which confirms the nature of the deposits. Furthermore, the samples analyzed by Pedrazzi et al. (2014) have a wider dispersion in the same diagram (Figs. 5.30, 5.35), covering a wider range of median grain sizes and sorting coefficients and smaller values of median grain size (Φ), indicating larger grain sizes. Therefore, the wider dispersion of near-vent pyroclastic material studied by Pedrazzi et al. (2014) can be explained as a combination of the nature of each studied deposit (e.g., surge deposits, large lithic breccia; Fig. 5.34) generated by different phases of the eruption and the degree of fragmentation level depending on the location (western or eastern craters) (Fig. 5.34; Pedrazzi et al., 2014). Furthermore, the 10 km height of the eruptive column together with the wind effects are responsible for depositing the smaller grain sizes in tephra fall-out layers in distal locations, explaining the coarser pyroclasts in proximal or near vent locations.

described by Pedrazzi et al. (2014). The mineral phases present in the near-vent pyroclastic deposit closely resembled those found in the tephra fragments, primarily comprising plagioclase, pyroxene, and olivine (Geyer et al., 2019). However, locating glass within the pyroclasts from the eruption site proved to be a challenge in comparison to the amount of glass shards observed in the tephra fall-out deposits on Livingston Island. But the primary similarity lies in their color under the optical microscope.

The content of Fe-Ti oxides in the near-vent deposits is similar to the one of the distal tephras; predominantly higher in fragments similar to type I. Additionally, some fragments exhibit a color change within the fragment (Fig. 5.39), suggesting a transition between Type I and II fragments or vice versa. Finally, some juvenile fragments present a red color (Type III fragments) that may be due to an hydromagmatic fluid alteration or to crystallization of Fe-bearing phases on the external surfaces in oxidizing conditions (D’Oriano et al. 2014).

Establishing a correlation between the different eruptive vents and the various tephra fragments found on Livingston Island is challenging. As reported by D’Oriano et al. (2014), recycling ash during an eruption can induce a series of changes, such as alteration in color in pyroclasts owing to their reworking during an eruption. This phenomenon may explain the diverse tonalities of the fragments observed in the tephras of the 1970 eruption.

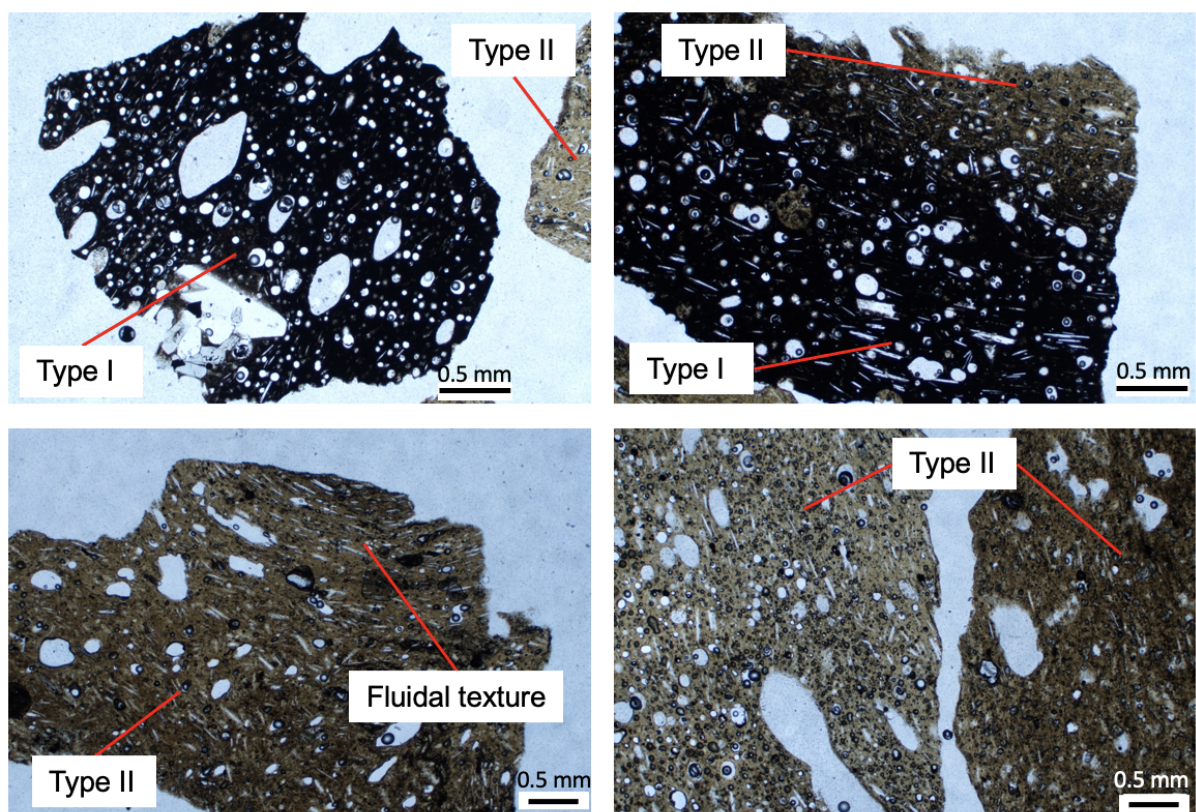


Figure 5.39. Optical microscope images of pyroclasts from sample DEI-2013-3-B2 corresponding to the near-vent pyroclastic deposits at the Easter Craters site of the 1970 eruption as described by Pedrazzi et al. (2014).

During recycling (Fig. 5.40), fragments acquire distinctive features such as a color shift, loss of glassy luster, and crystallization of the groundmass (D’Oriano et al. 2014). Furthermore, Fe-oxides can form in reheated fragments through heterogeneous nucleation under highly oxidizing conditions (D’Oriano et al., 2013, 2014), a phenomenon previously observed in the products of violent Strombolian eruptions and attributed to magma oxidation before fragmentation (Genareau et al., 2010). In the 1970 near-vent samples, we discerned different colors within the juvenile fragments, ranging from black to light brown (Fig. 5.39), which is likely attributed to the recycling of intra-crater ash fragments. Also, during the 1970 event, there were at least 13 active vents (e.g., Baker et al., 1975; Pedrazzi et al., 2014) during the eruption, which can lead to recycling into different vents due to their close location (Fig. 5.31). Moreover, having more than one vent active during the eruption may have led to

changes in the content of vesicles and microlites. In addition, changes in the morphology of the fragments may be related due to different eruptive styles and variations in magma viscosity, explained for different vents active during the 2016 eruption at Piton de la Fournaise (La Réunion Island, France) (Thivet et al., 2020). Yet, in order to verify these affirmations, it is essential to integrate the characterization of the eruption, tephra fragmented together with monitoring of the ongoing eruption, which for the last case, was impossible for the 1970 eruptive event.

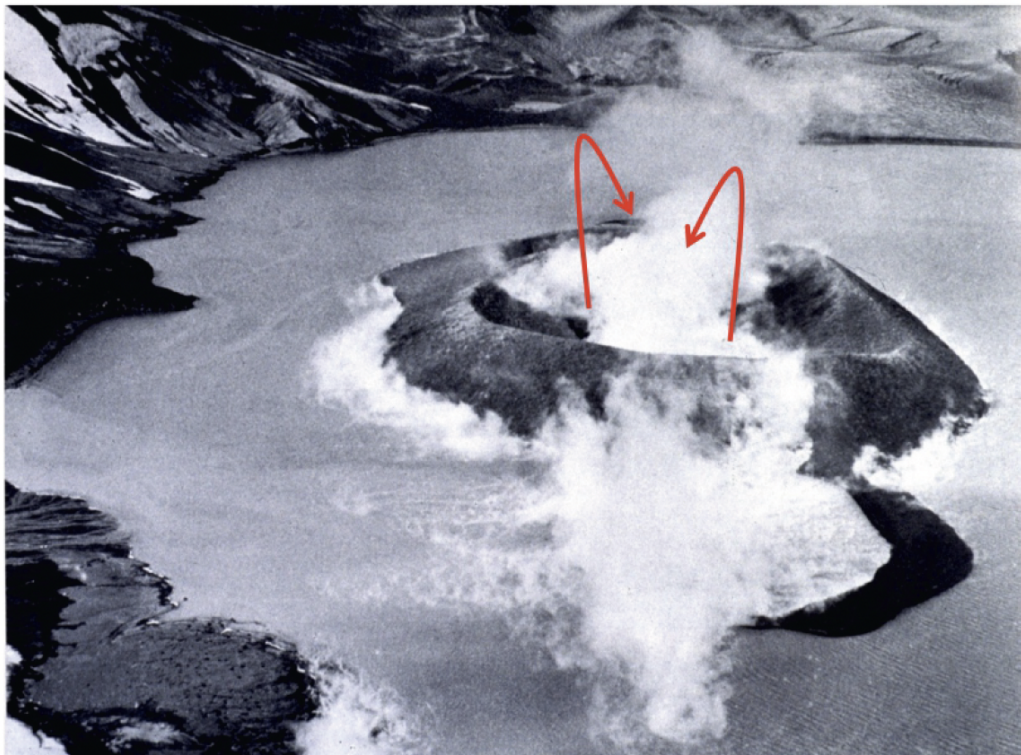


Figure 5.40. Example of tephra fragments recycling. a) Image of the 1967 eruption at Deception Island with a possible trajectory for recycled fragments marked with red arrows. Recycled tephra fragments refer to when a significant volume of juvenile material, characterized by varying sizes, is ejected during discrete explosive events. Subsequently, this material descends into the crater area, rendering it available for subsequent incorporation and expulsion during ensuing activity within the same eruptive event.

Finally, Type I fragments exhibit a higher content of Fe-Ti oxides (Fig. 5.41), potentially also related to the highly oxidizing conditions in the ash recycling process (D’Oriano et al. 2014). If this is the case, we propose that tephra fragments corresponding to Type II (brown to light brown color) may represent fragments that have not undergone recycling in the eruptive process. They also exhibit a "cleaner", or more suitable, glass for chemical analysis because of their unaltered and/or lower mineral content in the matrix. Nevertheless, lithic fragments, especially those easily confused with juvenile fragments, also display a higher content of Fe-Ti oxides, indicating past recycling processes from previous eruptions, such as the 1967 event, which occurred in the same area as the 1970 eruption.

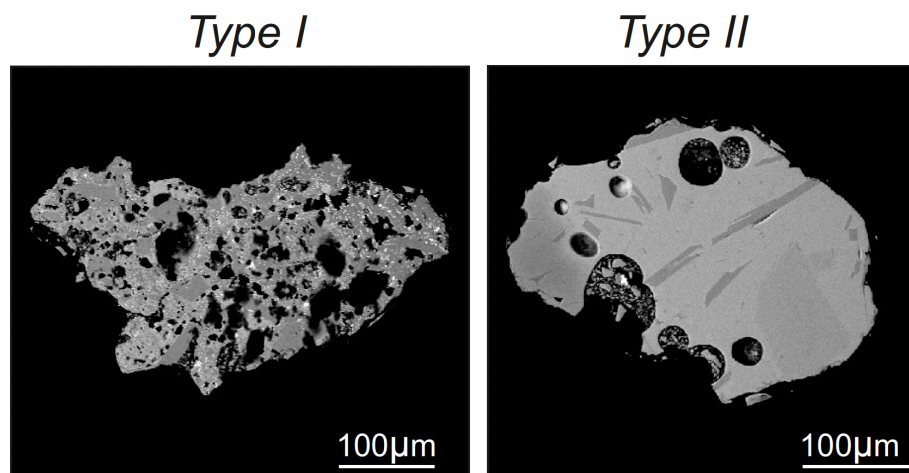


Figure 5.41. Backscattered image of Type I (sample 70-69) and II (sample 70-21) fragments showing the differences between Fe-Ti oxides content.

5.2.6.2.3 Geochemical comparison of distal tephra fall-out deposits and near vent pyroclasts

When comparing the 1970 tephra samples collected in Livingston with the near-vent (easter and western craters) pyroclasts on Deception Island, we observed that the glasses from the easter craters (Fig. 5.32) exhibited the most evolved composition (up to 63.3 wt. % in SiO_2), plotting mostly within the trachyandesite field and reaching the beginning of the dacite and trachydacite field (Fig. 5.42). Glass compositions of the western craters (Fig. 5.32)

also plot in the trachydacite field (Fig. 5.42). Tephra fall-out found at Livingston Island plot in the subalkaline field, ranging from basalt to trachyandesite, with a minor abundance of andesites (Fig. 5.42) being, in general, less evolved than the glasses from the eastern and western craters.

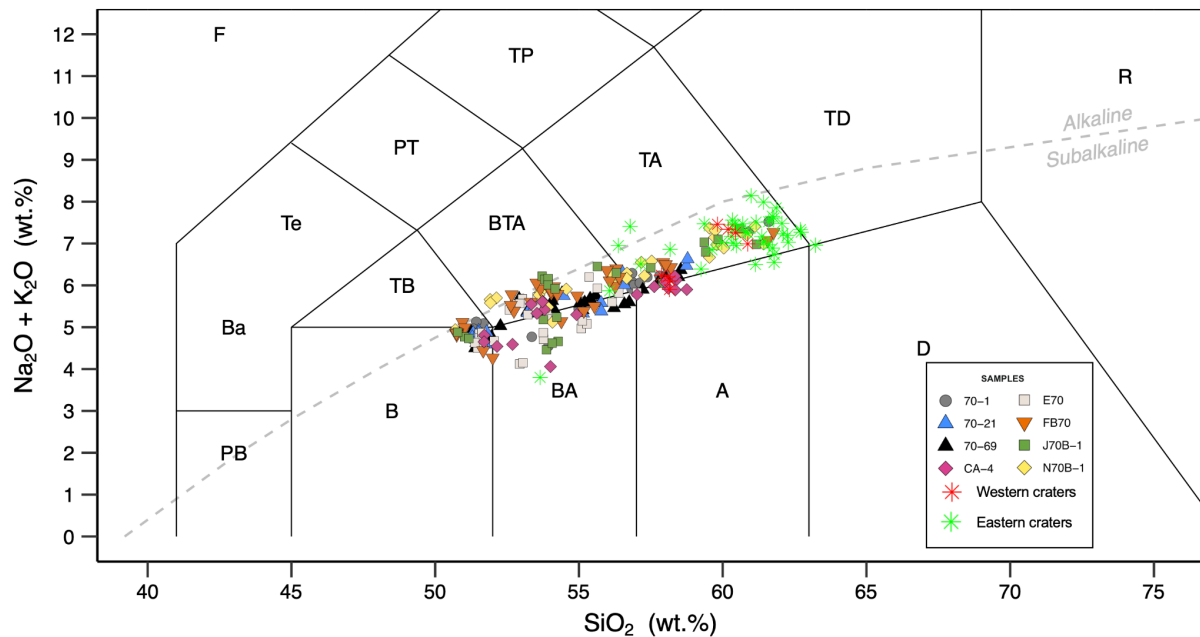


Figure 5.42 Total alkalis versus silica diagram (TAS) (Le Bas et al., 1986) for glass of tephra samples. The major elements were normalized to 100% (anhydrous), with Fe distributed between FeO and Fe₂O₃ following Middlemost (1989). Data available in Supplementary Material 2. Each point plot corresponds to a single EPMA analysis, i.e. different points may belong to the same juvenile fragment. Geochemical analyses of Deception Island 1970 eruption of western and eastern craters (marked as green and red asterisks) glass shards provided by Geyer et al. (2019).

Binary variation diagrams (Fig. 5.43) of major elements show that glasses from the eastern and western craters show a similar dispersion for MnO with SiO₂ and similar trend for CaO and MgO with SiO₂. The eastern craters show higher values of TiO₂, FeOt, and K₂O and lower values of Al₂O₃ and Na₂O than the tephra fall-out deposits from the 1970 eruption (Fig. 5.43). The western craters show similar major element values and correlation with the tephra

fragments of the 1970 eruption (Fig. 5.43), with the exception of one analysis that shows the highest value of Al_2O_3 (18.6 wt.%) (Fig. 5.43).

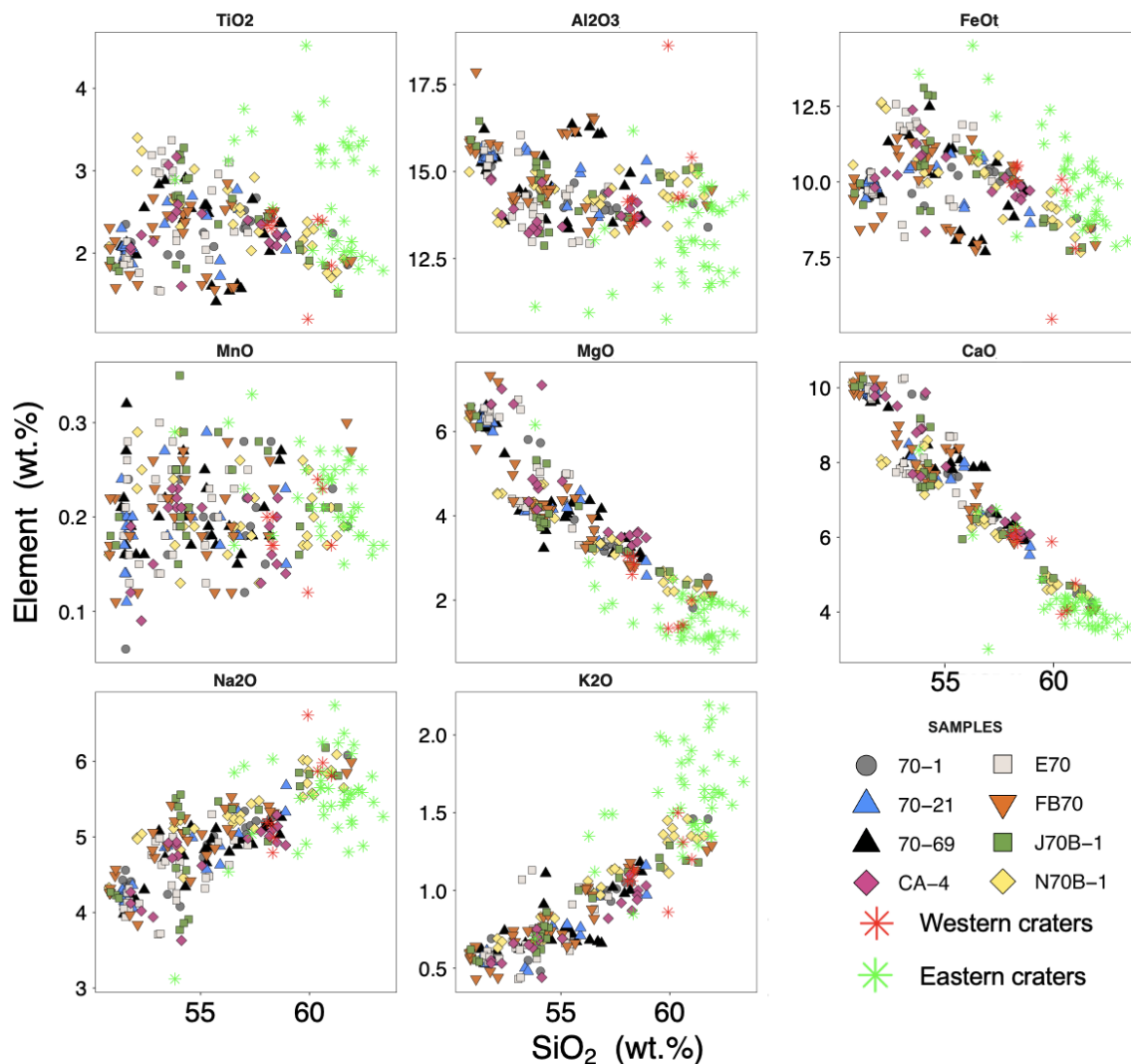


Figure 5.43. Major element vs. SiO_2 content Harker Diagrams for the glass analyzed in the distal tephra fall-out and near-vent pyroclastic deposits of the 1970 eruption. The major element compositions were normalized to 100% in an anhydrous base, with Fe as FeO_t . Each point plot corresponds to a single EPMA analysis, i.e. different points may belong to the same juvenile fragment. Data available in Supplementary Material S3. Geochemical analyses of Deception Island 1970 eruption of western and eastern craters (marked as green and red asterisks) glass shards as provided by Geyer et al. (2019).

Between the eastern and western craters, there is no larger difference besides the higher concentration in wt. % of SiO_2 and some higher or lower contractions of elements

observed in the Harkers diagrams (Figs. 5.42, 5.43). Therefore, it is not possible to correlate the different samples of the distal tephra fall-out products with a specific source vent on the island solely based on the available geochemical data. Further geochemical analyses (e.g., trace elements), together with more analyses of glasses from each crater site (easter and western), are required to try to narrow the possible correlation between distal tephra fall-out layers and near-vent pyroclastic materials and to understand why tephra samples tend to show less evolved compositions (i.e., lower SiO₂ wt. %).

5.3 Bransfield Strait Tephra

In this section, we present the preliminary results of the physicochemical characterization of the tephra layers found in the marine sediment cores retrieved along the Bransfield Strait less than 40 km distance from Deception Island. The performed characterization includes a brief petrographic and morphological description, as well as granulometric and geochemical analyses.

5.3.1 Granulometry

According to granulometric data, most of the tephra samples correspond to coarse ash with a particle size ranging between -1 and 4 Φ (2 - 0.06 mm) (Figs. 5.44, 5.45). Only four samples (TG-40-30, TG-48-45, TG-48-69_70, TG-50-43_50) contain high amounts of fine ash (up to 60% volume) (Figs. 5.44, 5.45) and a significant (up to 60% volume) content of lapilli has been measured in samples TG-40-31, TG-48-120, TG-50-17, TG-50-30 (Figs. 5.44, 5.45).

Most samples are poorly to moderately well sorted ($0.5 < \sigma < 2$, Fig. 5.46; Table 5.2). Samples TG-40-31, TG-50-17 and TG-50-30 present a sorting coefficient higher than 2.5, being the less sorted tephra samples (Fig. 5.46; Table 5.1). There is no significant variation between the sorting coefficient and grain size values with the depth of layers of each core (Fig. 5.46)

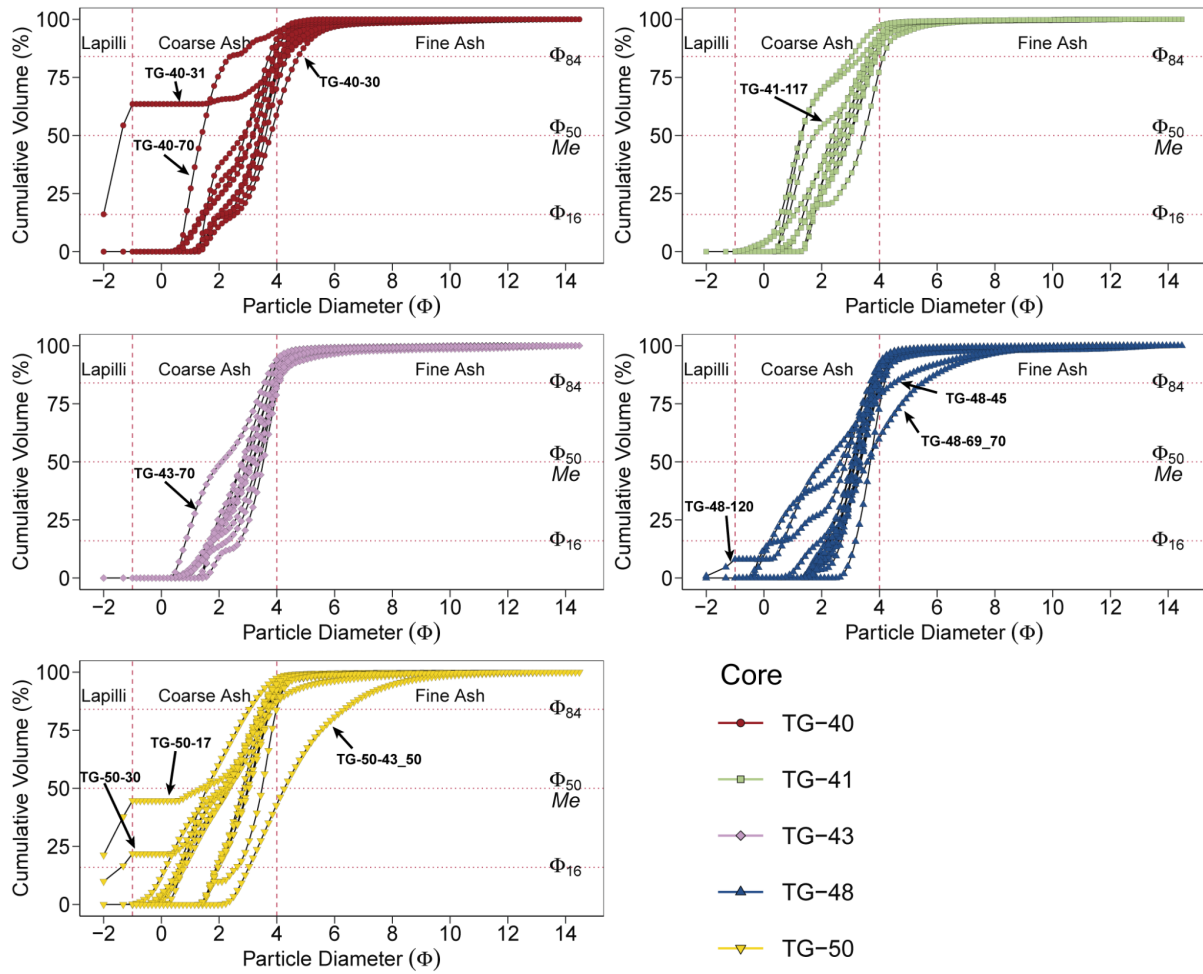


Figure 5.44. Each granulometry curve represents a different tephra sample. The vertical dashed lines represent the lapilli-coarse ash and coarse-fine ash, and the limits were defined according to Lockwood and Hazlett (2010). The horizontal dotted lines represent percentiles 84 and 16 employed to calculate the sorting coefficient. Samples are grouped by the different sediment cores (Fig. 3.6).

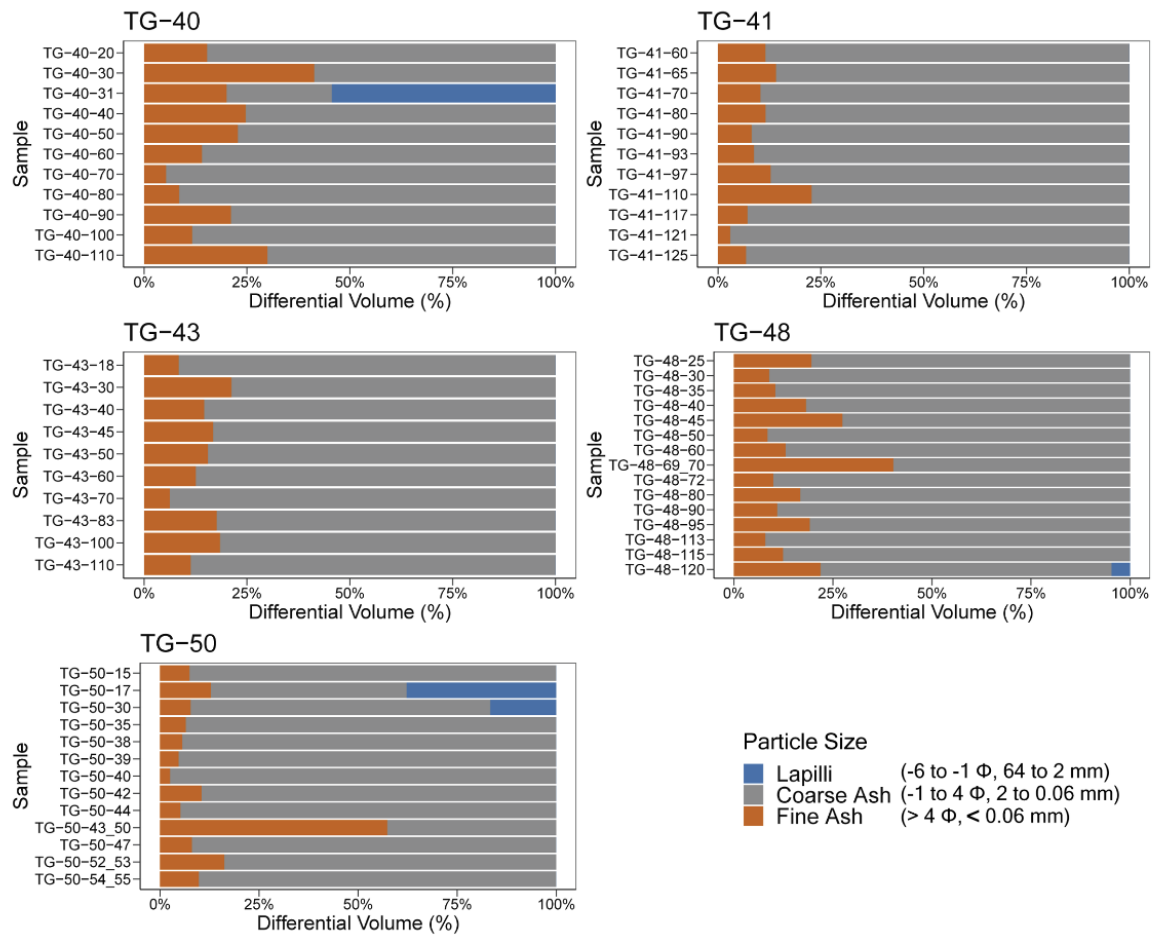


Figure 5.45. Lapilli, Coarse and Fine Ash proportions in each sample. The limits were defined according to Lockwood and Hazlett (2010). Samples are grouped by sediment cores (Fig. 3.6).

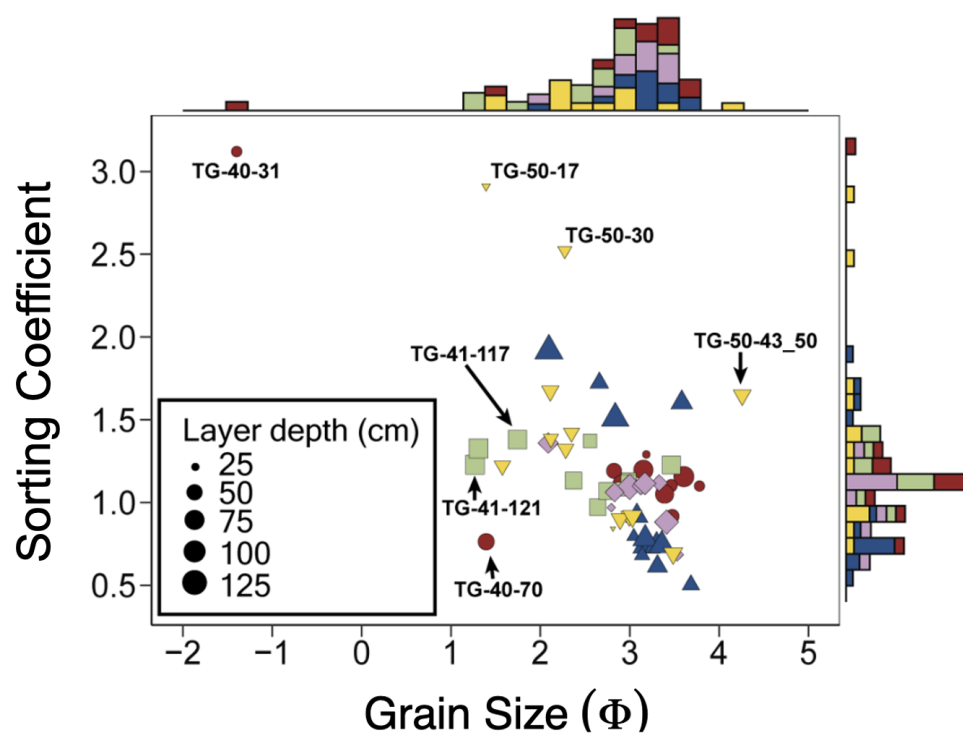


Figure 5.46. Grain size-sorting coefficient scatter plot of the samples sorted by depth of the sample along the sediment core.

5.3.2 Morphology of tephra fragments

In general, there is a predominance of blocky fragments with curviplanar surfaces and concave shapes, and a variable content of circular and elongated vesicles of various sizes (30 - 150 μm). Vesicularity ranges from moderate (Fig. 5.475a) to high (Figs. 5.47b, c, d) and, occasionally, dust is adhered on their walls (Heiken, 1974) (Figs. 5.47b, c).

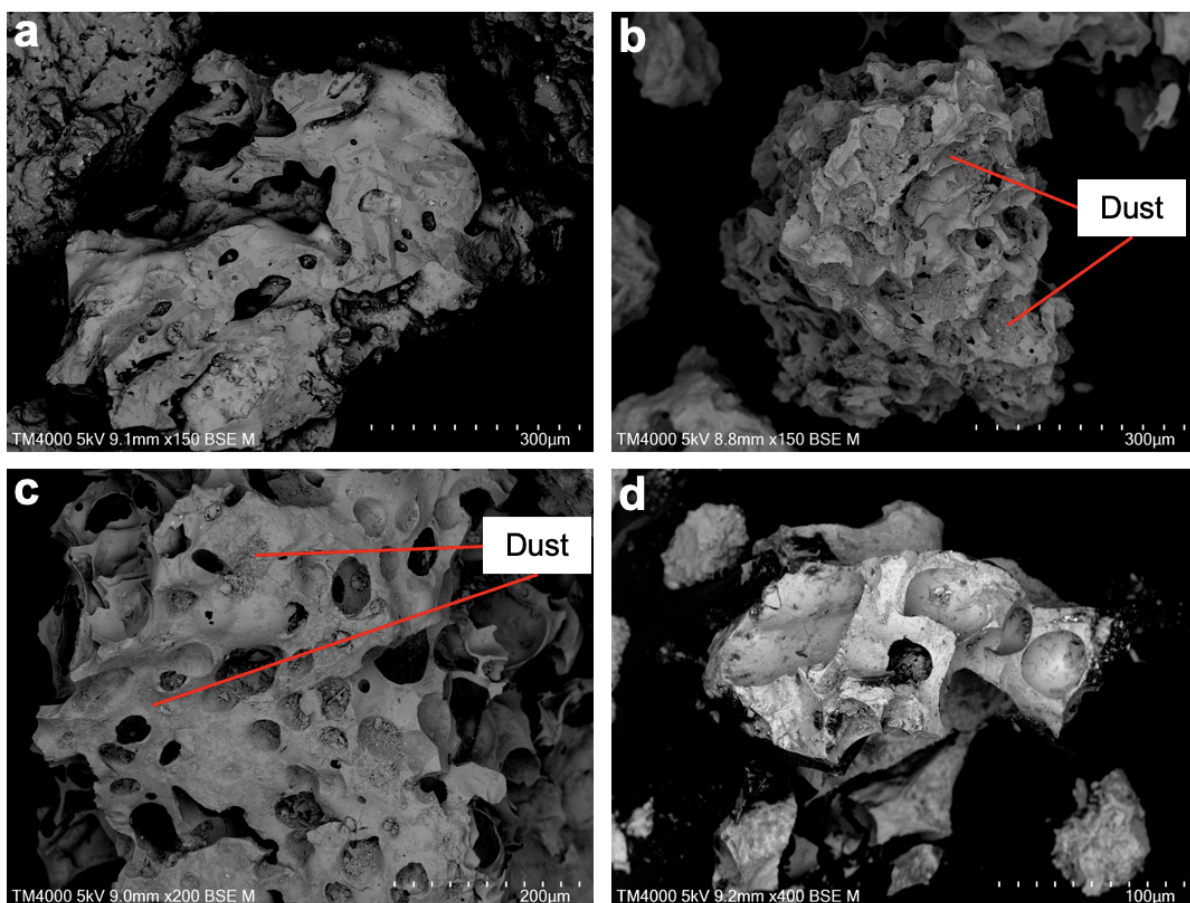


Figure 5.47. Backscattered SEM images of different blocky fragments. a) Blocky fragment of sample TG-41-125 with moderate vesicularity. b) Blocky fragment of sample TG-43-83 with adhered dust. c) Blocky fragment of sample TG-41-110 with adhered dust. d) Blocky fragment of sample TG-43-60.

5.3.3 Petrography of juveniles and lithic fragments

In the context of fragment composition, a preliminary counting of the different components observed indicate that juvenile elements collectively comprise approximately 85%, while lithic materials and free crystals (2%) constitute the remaining 15%.

We can discern up to the same three main types of juvenile fragments (Type I-III) previously described for the 1970 eruption tephra, based on their color under the optical microscope, the degree of crystallinity and/or glass content observed with the electronic microscope:

- **Type I** juvenile fragments observed in the tephra layers from the sediment cores (Fig. 5.48) are also commonly irregularly shaped with more rounded edges compared to other fragments. They have a dark brownish color and show moderate (15 – 20 %) vesicularity and blocky morphology. Type I fragments are characterized by: (i) a moderate to high (27 - 40 %) crystal content, mostly consisting of plagioclase microphenocrysts and minor pyroxene (Fig. 5.48); (ii) having a glassy matrix, which hosts a moderate (30 %) content of plagioclase microliths and minor pyroxene microcrysts; and (iii) presenting a high (2 – 8 %) Fe-Ti oxide content (compared to Type II and III fragments).

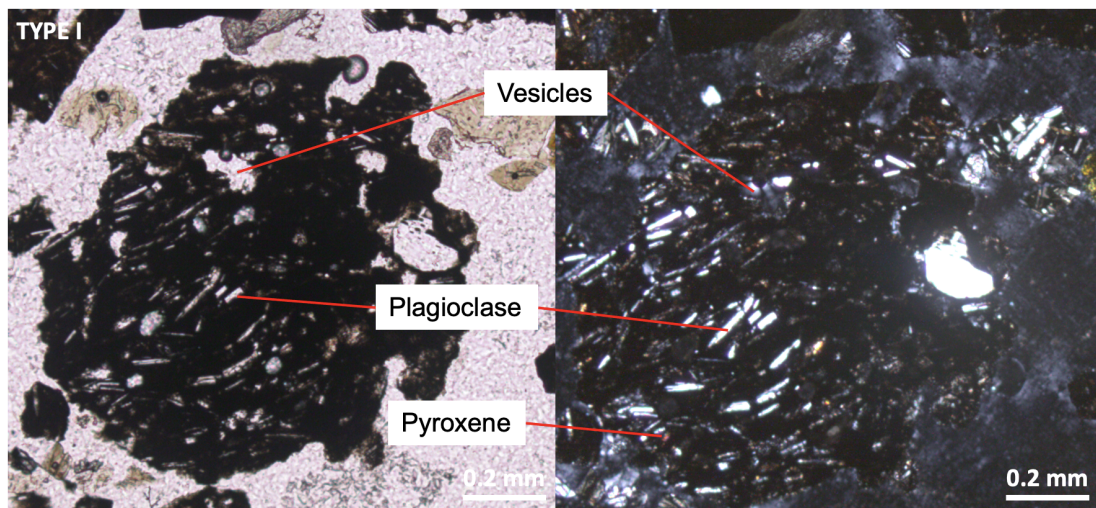


Figure 5.48. Optical microscope image of a Type I Juvenile fragment of sample TG-41-97. Microphenocrysts of plagioclase and microcrysts of pyroxene can be observed. Images in plane-polarized (left) and crossed-polarized light (right).

- **Type II** juvenile fragments are irregularly shaped with sharpened and rounded edges and they exhibit a color range that extends from dark brown (Fig. 5.49a) to light brown color (Fig. 5.49b), and show moderate (20 - 30 %) vesicularity with circular and elongated vesicles (Fig. 5.49). Fragments present a blocky and spongy morphology. The crystal content (30 - 50 %) mainly consists of plagioclase microphenocrysts, microcrysts of pyroxene and minor olivine (Fig. 5.19). The glassy matrix hosts a 10 to 25 % content of pyroxene and plagioclase microcrysts (Fig. 5.49). The content of Fe-Ti oxide varies between 2 and 3 %.

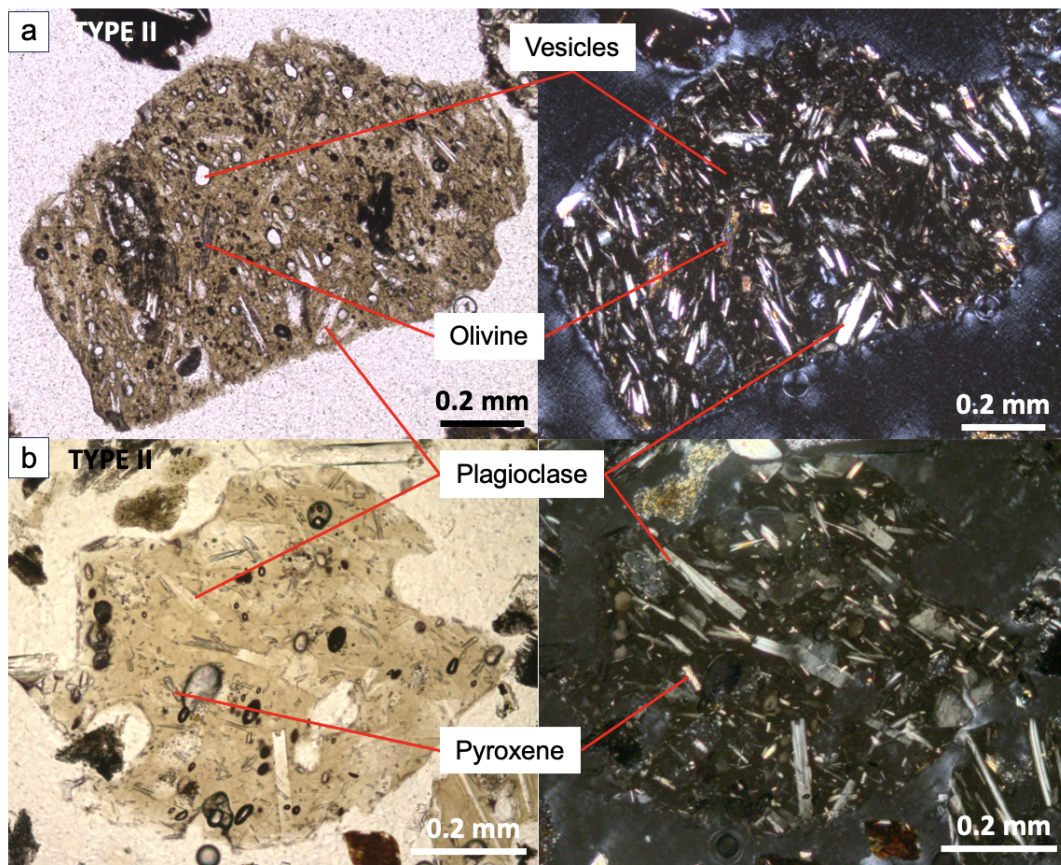


Figure 5.49. a) Type II Juvenile fragments of sample TG-41-50 with microphenocrysts of plagioclase and microcrysts of olivine and pyroxene. b) Type II Juvenile fragments of sample TG-41-80. Images in plane-polarized (left) and crossed-polarized light (right).

- **Type III** juvenile fragments (Fig. 5.50) have irregular shapes with sharpened edges owing to the vesicles (similar to Type II). They consist of red colored fragments with moderate content of vesicles (10 – 15 %), which are usually elongated and rounded. Fragments present a blocky shape, and the crystal content ranges between 20 and 30 %, and consists of plagioclase, pyroxene and minor olivine microphenocrysts. The glassy matrix presents microcrysts (10 – 15 %) (similar to Type II), which are mainly pyroxene and plagioclase (Fig. 5.50).

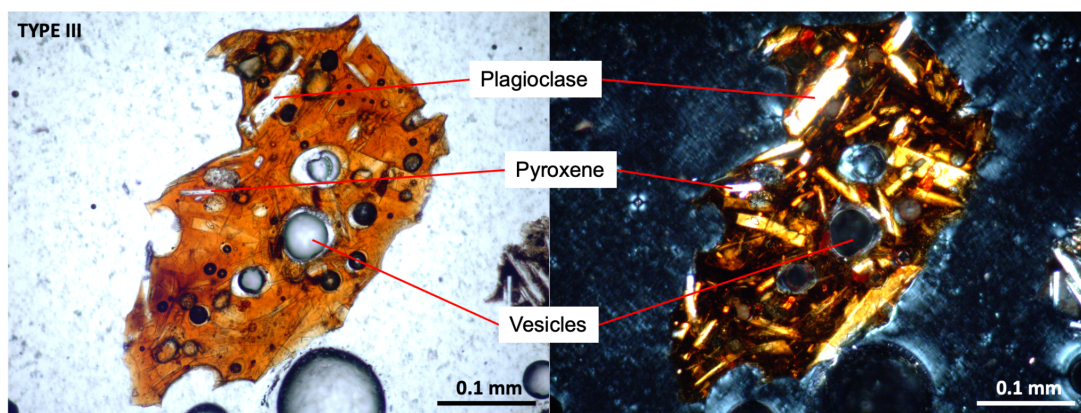


Figure 5.50. Type III Juvenile fragments of sample TG-50-44 with microphenocrysts of plagioclase. Images in plane-polarized (left) and crossed-polarized light (right).

5.3.4 Glass geochemistry

Juvenile glass compositions (Type I-III) plot in their majority in the subalkaline field including basalt, trachyandesite, and andesites (Fig. 5.51), within color clouds of the pre-, syn- and post-caldera samples (Geyer et al., 2019), but not covering the entire post-caldera field (trachydacite and rhyolite fields). The SiO_2 content of the samples ranges from 50 to 59 wt.% SiO_2 (excluding potential outliers). Note that those points escaping from the main evolutionary trend described by the majority of samples will not be considered in the main description of the preliminary results (Fig. 5.51). These correspond to the points: (i) corresponding to TG-41 and TG-43 samples and plotting within the TB, BTA and TA fields of

the TAS diagram, showing a higher compositions of alkali ($\text{Na}_2\text{O} + \text{K}_2\text{O}$ wt. %); (ii) of sample TG-48 falling within the B-Ba field of the TAS diagram and with low compositions of alkali ($\text{Na}_2\text{O} + \text{K}_2\text{O}$ wt. %); and (iii) of sample TG-50 that plot within the rhyolite field of the TAS diagram.

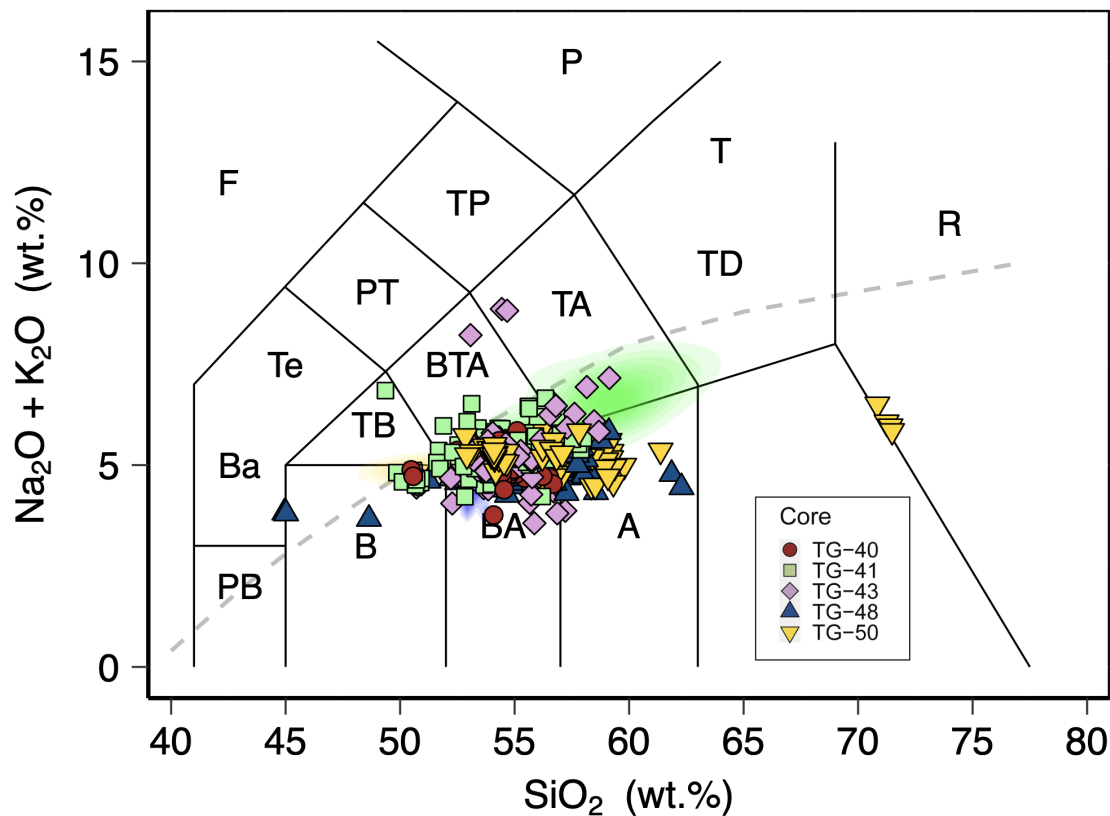


Figure 5.51. Total alkalis versus silica diagram (TAS) (Le Bas et al., 1986) for analyzed glass from the Bransfield Strait tephra samples. The major elements were normalized to 100% (anhydrous), with Fe distributed between FeO and Fe_2O_3 following Middlemost (1989). Data available in Supplementary Material 3. Each point plot corresponds to a single EPMA analysis, i.e. different points may belong to the same juvenile fragment. Deception Island glass shards data from Geyer et al. (2019) marked with blue, yellow and green color clouds correspond to pre-, syn- and post-caldera samples, respectively.

Samples analyzed follow an evolutionary trend which is more linear in the alkali content ($\text{Na}_2\text{O} + \text{K}_2\text{O}$ wt. %) and that differ from the one followed by the Deception Island magmas, which defines a distinctive differentiation trend of increasing alkalinity produced by uncommonly high Na_2O (between 2 – 8 wt. % Na_2O ; Geyer et al., 2019) (Figs. 5.51, 5.52). In

the case of the Bransfield samples, the increase of alkalinity is not as clearly defined as for Deception Island magmas. Bransfield tephra fragments show a negative correlation of MgO and CaO with SiO_2 , as well a positive correlation of K_2O with SiO_2 (Fig. 5.52). Contents of Na_2O , MnO , TiO_2 , FeO_t , and Al_2O_3 show a chemical dispersion. (Fig. 5.52).

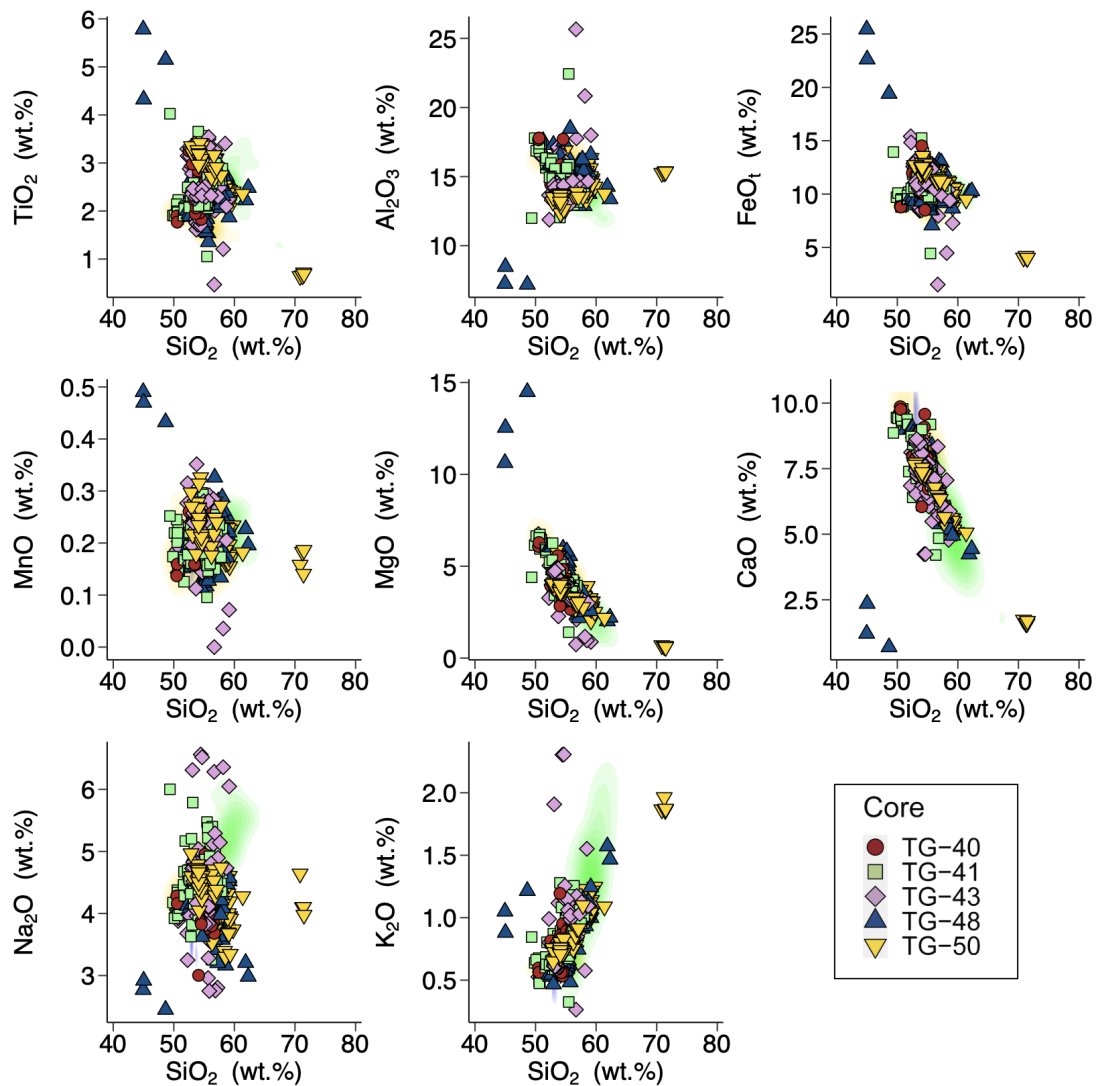


Figure 5.52. Major element vs. SiO_2 content Harker Diagrams for the glass shards of the Bransfield Strait tephra samples. The major element compositions were normalized to 100% in an anhydrous base, with Fe as FeO_t . Each point plot corresponds to a single EPMA analysis, i.e. different points may belong to the same juvenile fragment. Data available in Supplementary Material 3. Deception Island glass shards data from Geyer et al. (2019) marked with blue, yellow and green color clouds correspond to pre, syn and post-caldera samples respectively.

5.3.5 Discussion

Bransfield Strait tephra layers: Main conclusions and future work

The exhaustive description of tephra fragments of the 1970 eruption (see section 5.2.2) has enabled us to identify three different types of fragments (Type I-III) along with various lithic fragments, for which we know Deception Island was the source (See section 5.2). This allows us to discern the same three types of fragments among the tephra samples retrieved from the Bransfield Strait. Regarding lithic fragments, further analyses are conducted on the Bransfield Strait tephras to clearly identify the different types of lithics and determine if they are similar to those described for tephra deposits sourced from Deception Island. Further analyses are required in order to corroborate these observations of juvenile and lithic fragments.

Granulometric results indicate that the tephra layers correspond mainly to coarse ash, with some samples having a coarser fraction (lapilli size). In addition, the morphologic results of the studied layers indicate a predominance of blocky fragments (similar to the 1970 tephra morphologies), which indicates phreatomagmatic activity (e.g., Heiken, 1974; Wohletz & Krinsley, 1982; Heiken & Wohletz, 1985), at least for the studied layers (See section 5.3.2). A more detailed study regarding grain size is needed to establish a full total grain size distribution for the tephra layers. This additional information will shed light on the possible correlations between layers among the studied cores that follow the same grain size pattern. Furthermore, a more detailed study on the morphologies of the fragments is needed to determine all morphologies present in each tephra layer. This will help to determine more, or corroborate, the possible eruptive styles of the eruptive events responsible for the different tephra layers present in the studied cores.

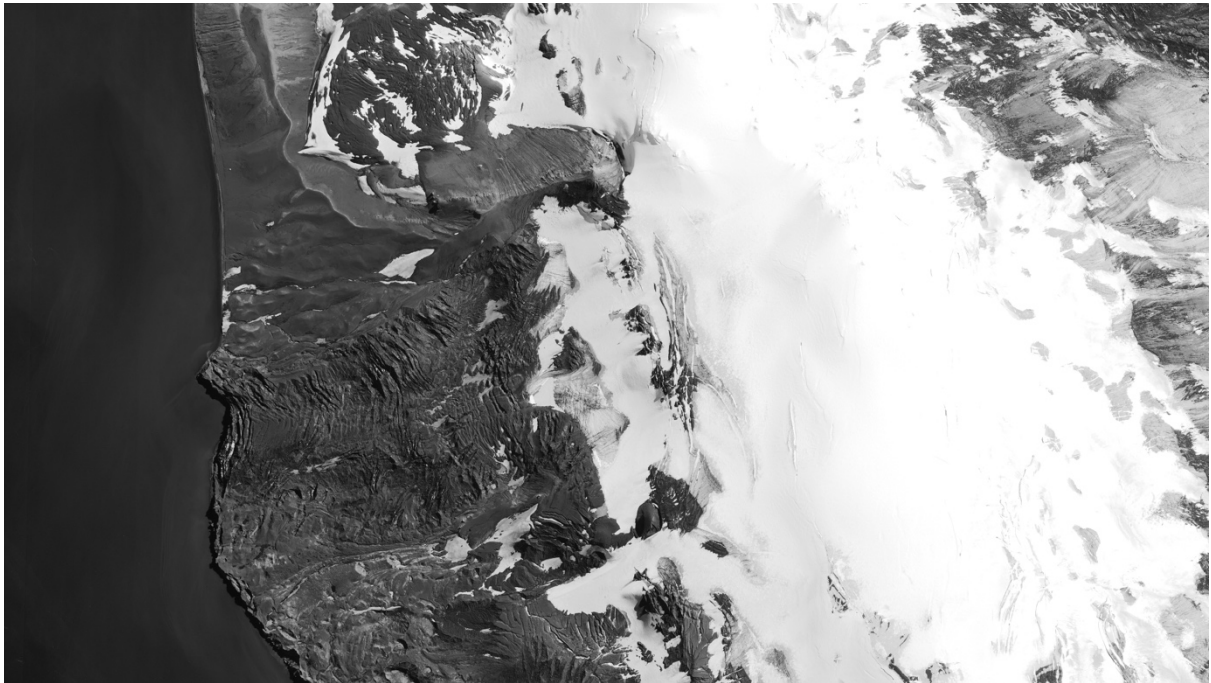
According to chemical analyses, the glasses of the Bransfield Strait tephras follow an evolutionary trend that is more linear in alkali content ($\text{Na}_2\text{O} + \text{K}_2\text{O}$ wt. %) and that differs from the one followed by the Deception Island magmas (Figs. 5.51, 5.52). A more detailed

study is needed regarding the points that escape the main trend depicted by the Bransfield Strait glasses. Considering the short distance (< 40 km) to Deception Island, which is the active volcano closer to the studied tephra layers, it could be considered their potential source. However, this geochemical trend may indicate otherwise. This can be due to the following: (i) Deception Island is not the source of the tephra and another eruptive center may be considered (e.g., volcanic centers in King George) (See figure 5.31); (ii) tephra layers are sourced from Deception Island, and the chemical differences are related to an analytical problem with the EPMA. The latter may be connected to calibration problems with the volcanic glass experienced by the EPMA at the CCI-TUB at the time the Bransfield Strait tephra were analyzed. This second explanation is considered to be the most plausible one since chemical differences between the Bransfield Strait and Deception Island deposits are mainly observed in the alkali content (i.e., $\text{Na}_2\text{O} + \text{K}_2\text{O}$ wt. %) and not in the other major elements; suggesting an analytical problem during the estimation of Na (Fig. 5. 52). Without a doubt, further geochemical analyses (e.g., trace elements), including the remaining tephra layers, are needed.

Briefly, the preliminary results of the 65 tephra layers sampled from five marine sediment cores retrieved from the Bransfield Strait show a potential future research goal for tephra studies in Antarctica, specially related to Deception Island activity and volcanic record. However, further studies need to be carried out in order to: (i) undoubtedly establish the volcanic source of the tephra layers; (ii) try to date the different tephra layers to contribute to complete the tephra chronostratigraphic framework for the Bransfield Strait; (iii) complete the eruptive record of Deception Island; (iv) correlate the tephra layers between cores; and (v) contribute to volcanic hazards assessment related to Deception Island or Antarctic volcanoes.

These future studies need to include:

- A more detailed physicochemical characterization of the 65 tephra layers, including petrographic, morphologic, and geochemical analyses. This will help to identify differences and similarities between layers and to establish correlations between them.
- Date the tephras with different methods, for example, ^{14}C dating in the sediment present in the cores. Alternatively, this age could be compared with studies of sediment rates in the Bransfield Strait region (e.g., Bárcena et al., 2006).
- Future results regarding the remaining tephra layers from the Bransfield Strait, will be included in the DecTephra database, adding and improving new information about Bransfield Strait tephra layers with a possible Deception Island eruptions origin.
- Expand these future work to more available cores in more distal locations from Deception Island, which also several tephra layers are found in them, with the idea of comparing different results and try to correlate them.



PART IV

6 CHAPTER 6

General Discussion

In this chapter, we present the general discussion that integrates the results and discussion outcomes presented in chapters 4 and 5, which contribute to: (i) a better comprehension of the Deception Island's volcanic evolution and caldera formation (including the flooding event); (ii) a first order estimate of the eruptive recurrence of Deception Island volcanic events; and (iii) shed light regarding the evolution of the magmatic system beneath the island. At the end of this chapter, and based on the main outcomes of this general discussion, guidelines and roadmap for future work are also provided.

6.1 Reconstructing the past history of Deception Island's caldera

Our results back the hypothesis that Stanley Patch volcano grew in a subaerial environment, thus showing that Port Foster's southern sector (i.e., sub-basins 2 and 3) was not submerged after the caldera collapse. This implies that Deception Island's caldera was completely flooded by seawater after Stanley Patch volcano formed. This, combined with prior stratigraphic, sedimentological, geophysical, and petrological data, provides a comprehensive geologic evolution of Deception Island. We identify five evolutionary stages and events: (i) pre-caldera; (ii) caldera collapse; (iii) early post-caldera; (iv) caldera flooding; and (v) late post-caldera (Fig. 6.1).

6.1.1 Pre-caldera Stage

Most of the pre-caldera volcanic activity likely originated from several vents, representing a period of shoaling and emergence of the volcanic island (Fig. 6.1a) (e.g., Baker et al., 1975; Baraldo et al., 2003; Birkenmajer, 1992; Hawkes, 1961; Holtedahl, 1929; Martí & Baraldo, 1990; Olsacher, 1956; Smellie, 2001, 2002c). The most recent paleo-topographic reconstruction of the island suggests the presence of a paleo-edifice with a paleo-summit

height of about 640 m.a.s.l and parasitic volcanoes (< 650 m height) in the locations presently known as Neptunes Bellows and Macaroni Point (Fig. 6.1a) (Torrecillas et al., 2013).

6.1.2 Caldera collapse event

During the caldera collapse, the OCTF was emplaced radially from the caldera borders, mantling older deposits and progressively infilling the caldera depression (e.g., Martí et al., 2013; Smellie, 2001, 2002a). Most probably, the caldera collapse took place through distinct caldera blocks that subsided (likely synchronous) into the emptying magma chamber (e.g., Martí et al., 2013) (Fig. 6.1b). In this sense, the fault-related monocline currently separating the bay's sub-basins may represent the limit of -at least- two subsiding blocks (Fig. 6.1b). The caldera collapse can therefore be subdivided into a central zone (main block, current sub-basin 1) and a marginal zone tilted towards the caldera interior (secondary block(s), current sub-basins 2 and 3). Subsidence difference between the two main described blocks at the moment of the caldera collapse is still uncertain. This collapse mechanism and structure is similar to other calderas worldwide (e.g., Rotorua, New Zealand; Milner et al., 2002) and consistent with the modeling results of sand-box analogues (e.g., Acocella, 2006, 2007; Geyer et al., 2006; Roche & Druitt, 2001). Based on our present findings, the secondary block, corresponding to sub-basins 2 and 3, should have stayed “dry” at least until the construction of Stanley Patch volcano ($< \sim 2000$ years ago). The caldera should have remained closed to the sea and, most probably, was only filled by fresh water coming from rainfall, and snow and ice melting, which accumulated in the deepest parts of the northern sub-block or sub-basin 1 (Fig. 6.1b, c).

6.1.3 Early (pre-flooding) post-caldera stage

After the caldera-forming event, volcanic activity was characterized by (e.g., Smellie, 2001, 2002c): (i) the formation of scoria cones aligned along previous active fissures (Fig. 6.1c I); (ii) abundant effusive activity on the outer slopes leading to prominent lava platforms (Fig. 6.1c II); (iii) occasional lava flows within the caldera (Fig. 6.1c III) and over the caldera wall

(Fig. 6.1c IV); and (iv) hydromagmatic activity from centers distributed both outside (e.g., Baily Head (Fig. 6.1c V)) and within the caldera (Fig. 6.1c VI). During this period, volcanic activity also occurred inside the bay in sub-basins 2 and 3 as previously interpreted from the seismic profiles across Port Foster and as evidenced by the presence of Stanley Patch volcano (Fig. 6.1c VII).

6.1.4 Caldera sea flooding event

At some time after the formation of Stanley Patch volcano, the caldera became open to the sea leading to its complete flooding. The ultra-high resolution seismic stratigraphy of the uppermost (< 300 ms) deposits infilling Port Foster shows two distinct sedimentary units abutting the monoclinical structure (Figs. 6.2 and S1 of Hopfenblatt et al., 2021). The Lower Unit (LU) represents a striking and relatively thick seismically transparent body that occupies an extensive part of sub-basin 1, onlapping its margins (Fig. 6.2). This unit reaches its maximum thickness of ~ 38 ms (i.e., ~ 30 – 36 m) in the northwest, at the base of (or even beneath) the western submerged flank of Wensleydale Beacon's volcanic edifice (Fig. 6.3d I); it becomes thinner towards the north and northeast of the bay (Fig. 6.3d II). The volume of this unit is estimated to be >0.055 km³. The LU, which correlates to sub-unit C1 of Rey et al. (1995, 1997) (Figs. 2.8d, e) and Kowalewski et al. (1990), is overlaid by an Upper Unit (UU) (up to c. 50 ms thick). The UU, equivalent to sub-unit C2 of Rey et al. (1995, 1997) and C2 plus D of Kowalewski et al. (1990), is made up of the vertically stacked even-layered deposits separated by irregular transparent bodies (a few ms thick), which resemble smaller-scale mass-flow deposits (Fig. 6.2). In line with the observations made by Kowalewski et al. (1990), our ultra-high resolution seismic stratigraphy indicates a sharp change in the sedimentary history of the bay after the deposition of the LU.

The shape, seismic facies, boundaries and thickness distribution of this unit, all point to a large mass-flow deposit (e.g., Casas et al., 2013; Masson et al., 1996) sourced from the southeast (Whalers Bay and/or Neptunes Bellows area) (Fig. 6.1d I). The seismic characteristics of the LU displayed by the ultra-high resolution TOPAS profiles show transparent facies resembling an amalgamated deposit with local lack of penetration of the

acoustic signal. The LU has been previously interpreted as the result of the sudden deposition of pyroclastic materials carried down by large onshore-generated lahars (Kowalewski et al., 1990). However, since it is the thickest and most voluminous sedimentary unit compared to the ones composing the UU, we state that it originated due to an extreme and unique event, not since repeated. We propose that the LU corresponds to the materials deposited by an exceptional mass flow event that occurred during the outburst flood that inundated the caldera to its present sea level. Likewise, the distribution of the slide sediment is in general governed by the nature of the landslide material, the flow process and/ or the emplacement speed (e.g., Masson et al., 2002). Both considerations would imply that the process responsible of the LU could have initiated as a debris avalanches evolving to a debris flow due to disaggregation occurred during the transport that extends to the interior of Port Foster. Similar processes have been considered to occur in the Canary Islands (e.g., Masson et al., 1998).

Accounting with all the sedimentological and morphological features of the LU pointing its source at the southeast of the bay, and the fact that the volume of this body ($> 0.055 \text{ km}^3$) can be roughly correlated with the “missing” material from Neptunes Bellows (Figs. 6.4a, b). We conclude that it resulted from the sudden collapse of the caldera wall at that precise location. This opened the inner area of the island at that time below sea level- to the ocean (Fig. 6.1d I). This argument agrees with the stratigraphic observations by Kowalewski et al. (1990), who concluded that the flooding of the caldera by seawater may have occurred after the deposition of their unit B (our LU), and that C and D (composing our UU) were undoubtedly deposited in submarine conditions.

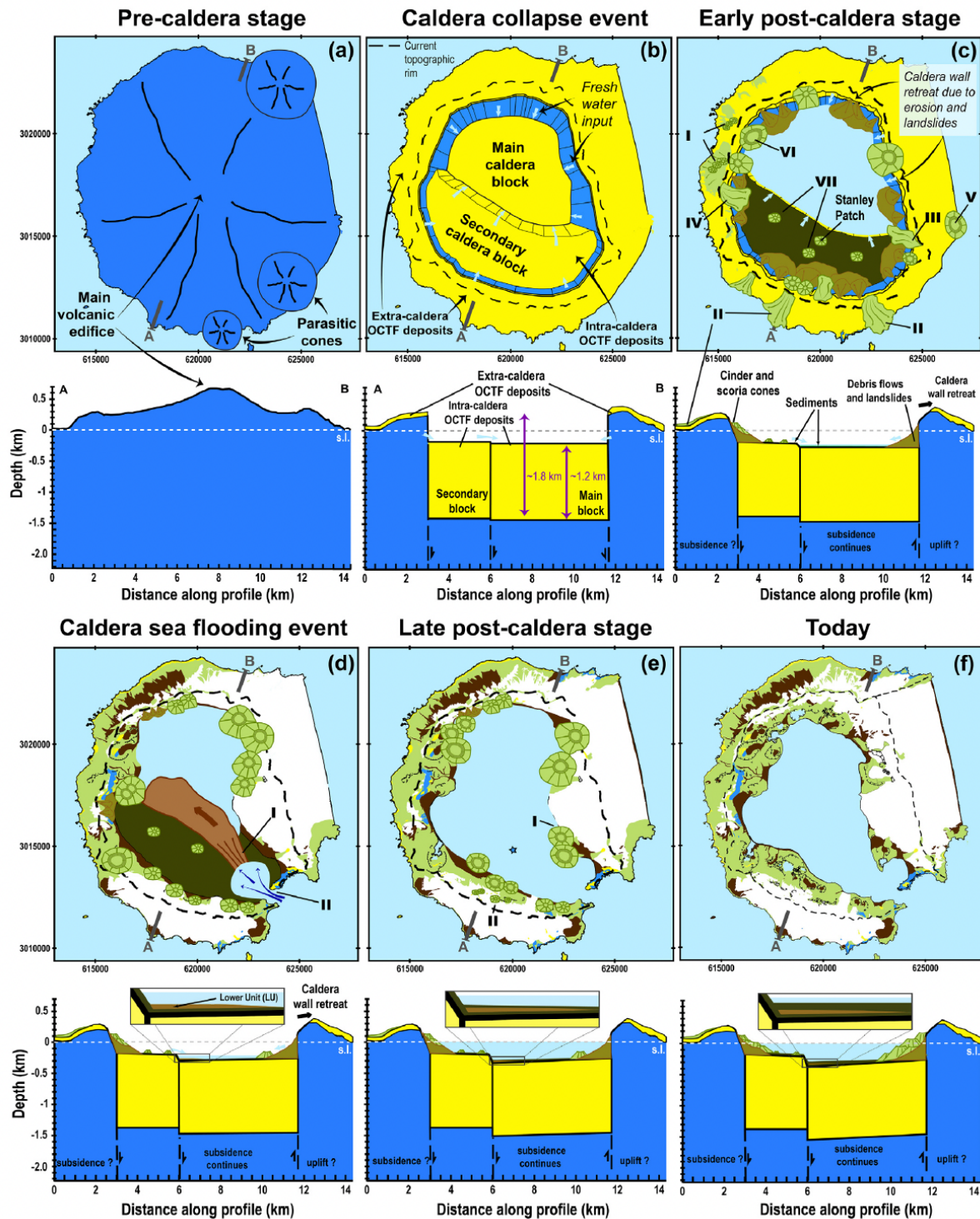


Figure 6.1. Conceptual model of the evolution of Deception Island based on the review of available geological and geophysical data and new results presented in this work. Main phases and events include: a) pre-caldera stage; b) caldera-forming event; c) early post-caldera phase; d) caldera flooding event; e) post-flooding phase; and f) current stage.

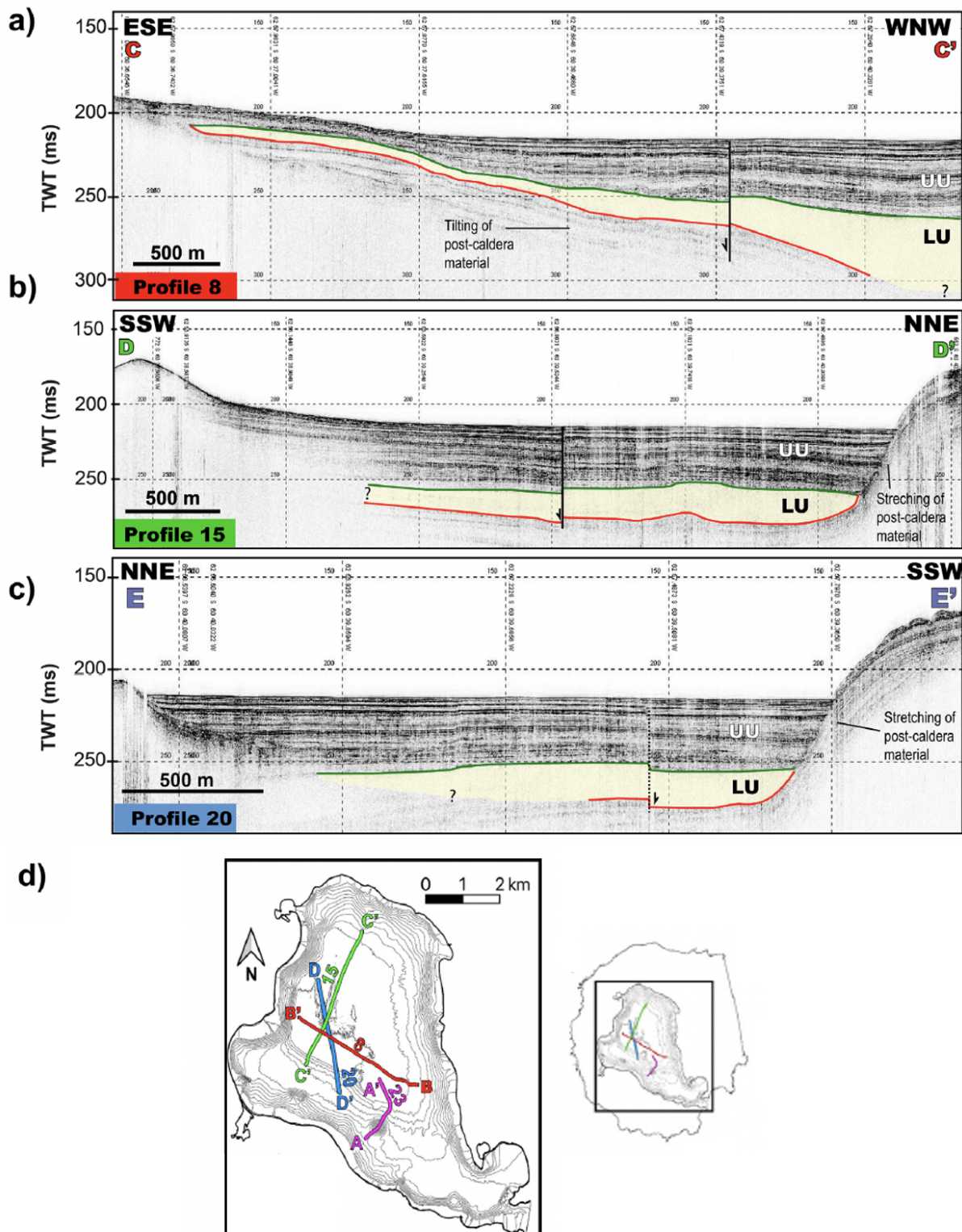


Figure 6.2. a) to c) Seismic profiles obtained within Port Foster (available at Gómez-Ballesteros et al., 2018). The Lower Unit (LU) is colored in yellow with its top and base highlighted in green and red, respectively. If clearly visible, faults are also indicated. UU: Upper Unit. See text for further details. d) Map indicating the location of the profiles.

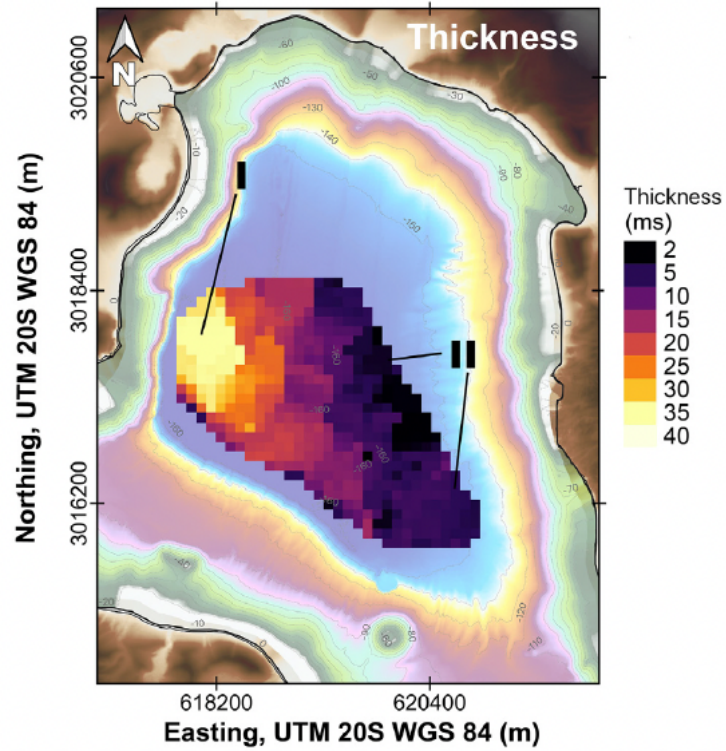


Figure 6.3. Thickness map (in ms) estimated for the Lower Unit.

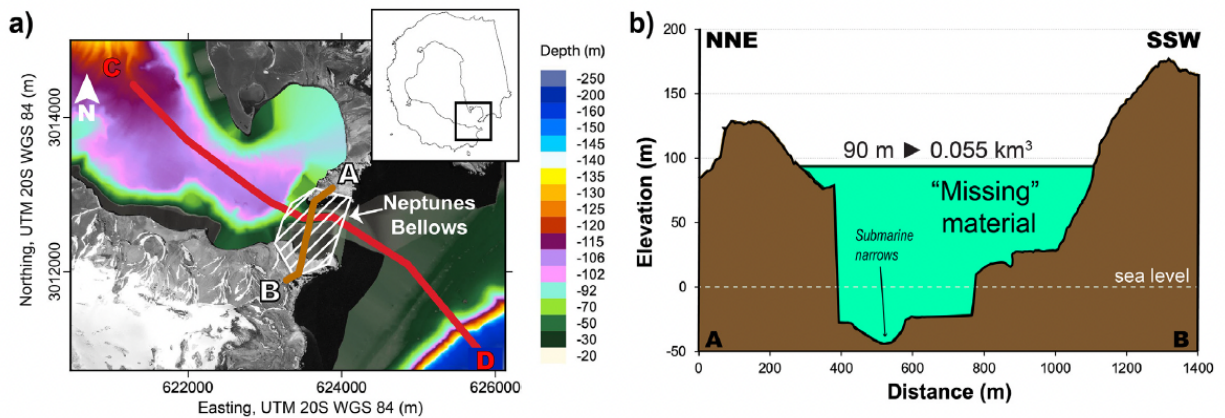


Figure 6.4. DEM of Port Foster and orthophotomap of Deception Island showing in plan view (white dashed area) and cross sectional view (green colored area in b) of the area used to estimate the volume “missing” from Neptunes Bellows.

6.1.5 Late (post-flooding) post-caldera stage

After the flooding, volcanic activity continued on the island until historical times and as recently as 1970, around the shores of Port Foster (Fig. 6.1e I), and along on-land fissures (Fig. 6.1e II). Since the caldera flooding episode, the volcanic activity in the deepest parts of Port Foster has been apparently limited to hydrothermal venting with no clear evidence of submarine or Surtseyan activity (Somoza et al., 2004).

6.1.6 Estimating the timing of the outburst flood and caldera refilling

Three main, yet not mutually exclusive, processes may have initiated the caldera wall breach and hence, triggered a sea flooding event (Fig. 6.5): (i) a flank instability and major collapse of the pre-caldera edifice to the open sea or the caldera interior (e.g., Acosta et al., 1992); (ii) the occurrence of an explosive eruption at the caldera wall (e.g., Aparicio et al., 1997; Baraldo & Rinaldi, 2000); or (iii) overtopping of the sea potentially facilitated by the weakening of the caldera wall due to water infiltration leading to minor collapses.

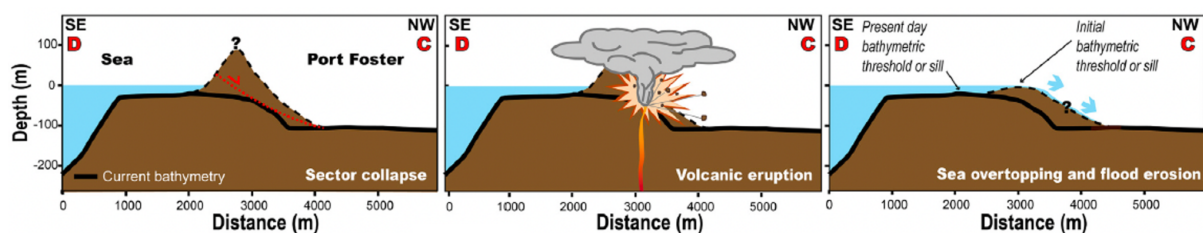


Figure 6.5. Sketch of the three different, yet not mutually exclusive processes, that may have led to the opening of the caldera to the sea and consequently, to the outburst flood. See Figure 6.2 for exact location of the represented cross-section.

Once the oceanic water overtops the caldera wall, the erosion caused by the water influx gradually (but with initial rates increasing potentially; Figs. 6.6 and S13 of Hopfenblatt et al., 2021) enlarges and deepens the spillway (e.g., Kataoka, 2011). Among these three scenarios, the overtopping is the most conservative in terms of flood duration and peak

discharge, because it assumes that the initial inflow of water is small and only its own erosion contributes to enlarge the inlet, thus progressively increasing the inflow rate. The smooth U-shape of the seaway floor and the seeming retrogressive erosion suggested by its bathymetry (the submarine bathymetric sill lays today out of the island) (Figs. 6.5, 6.7) argues for the third of these mechanisms, by similarity with other scenarios where the overtopping mechanism is well determined (e.g., Lake Bonneville, Abril-Hernández et al., 2018). Assuming this mechanism is followed by ever-increasing water erosion of the topographic barrier separating the bay from the ocean, we can estimate a minimum peak water inflow and filling time (Fig. 6.7). The mechanism is similar to other floods taking place due to the overtopping of lakes (O'Connor et al., 2013). However, in our case, contrary to floods sourced at natural lakes or breaching artificial dams, the water source (upper reservoir: the ocean) was effectively infinite. Hence, the flooding is limited by the size of the sink (the lower reservoir: the caldera), which is filled up to sea level.

To estimate the timing of the caldera refilling by overtopping of the sea at the Neptunes Bellows, we assume that: i) Port Foster was empty up to, at least, the base of the Stanley volcano, which remained exposed in an endorheic evaporitic basin at a depth below sea level similar to today's (i.e., 90–120 m b.s.l.) (Fig. 6.7); (ii) the present depth of Neptunes Bellows has not been modified by subsidence of the island or eustatic sea level changes; and (iii) the present depth of the submarine bathymetric threshold between the caldera and the open ocean (30 m b.s.l.) is at least partially related to the erosion produced during the refilling flood (Figs. 6.5 and 6.7). The latter is supported by the absence of comparable sea level changes since the formation of Stanley Patch volcano (Hallmann et al., 2018). Post-volcanic subsidence (of a tectonic or thermal nature) of the threshold area (or of the entire island), may undermine this assumption.

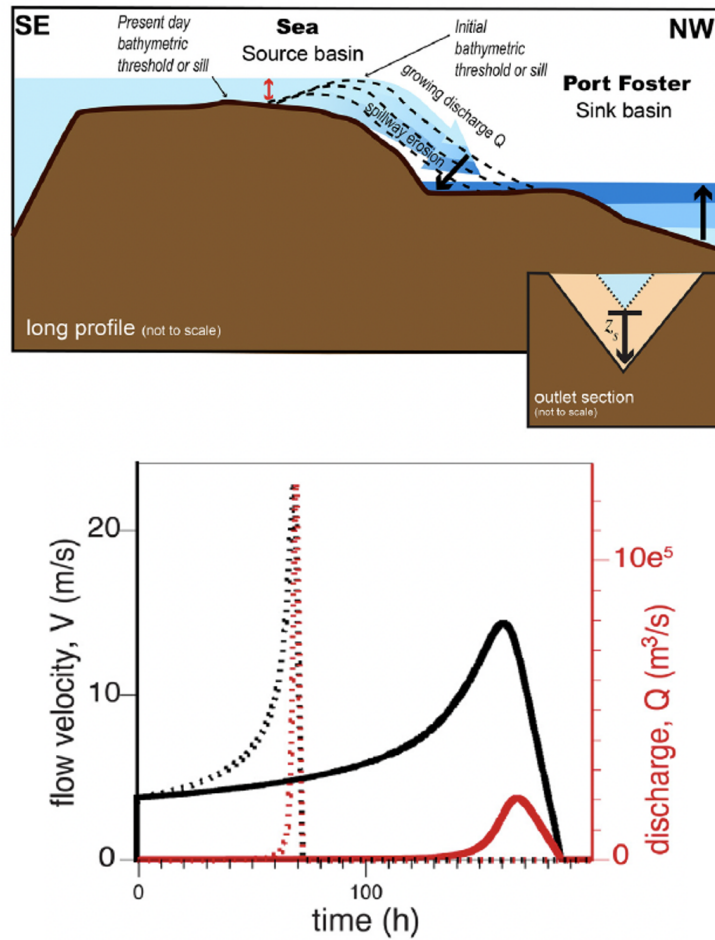


Figure 6.6. Conceptual model (section along the inlet) of sea overtopping and outburst flood development as a result of water discharge and inlet erosion at the threshold (top). For the parameters involved see the text. Numerical model results of flood development after breaching or overtopping. Curves for water velocity V (in black) and discharge Q (in red) are shown for two final sill depths (final depth of the threshold below sea level): 15 m (solid lines) and 30 m (dashed lines) (bottom). See main text and Fig. S13 of Hopfenblatt et al., 2021 for further details.

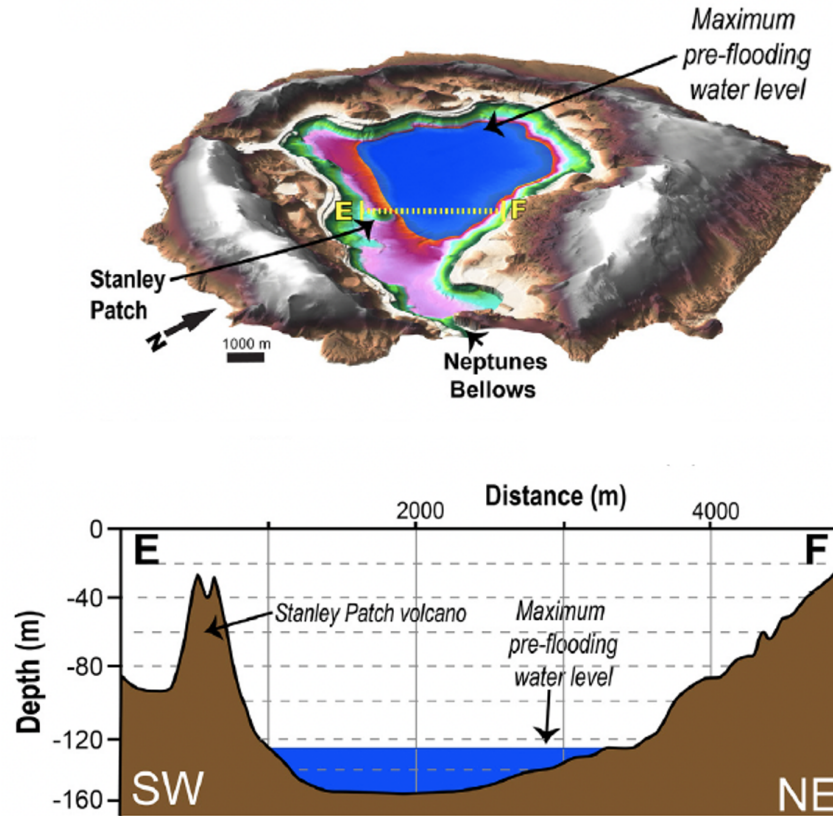


Figure 6.7. 3D shaded relief map of Deception Island (top) and bathymetric profile of Port Foster (bottom). The maximum pre-flooding water level is indicated. Vertical exaggeration: $\times 1.5$.

We use the present depth of the bathymetric threshold or sill (30m; Figs. 6.5 and S12 of Hopfenblatt et al., 2021) as a constraint on the erosion produced during refilling, and apply a coupled erosion/hydrodynamic model to estimate the progress of the refill (Garcia-Castellanos & O'Connor, 2018). The numerical model spillover (available at <https://github.com/danigeos/spillover>) iteratively calculates the water discharge across a certain threshold as a function of its depth below a source water body (the global ocean in our scenario), and for a lower basin (sink) of known area and depth (Fig. 6.6). This is coupled to a progressive deepening of the threshold due to erosion exerted by the water flow, following a basal shear-stress power law (Howard and Kerby, 1983).

$$\frac{dz_s}{dt} = -k_e \tau^a \quad (1)$$

where $z_s(t)$ is the depth of the sill (Fig. 6.6), t is time, k_e is the erodibility of the rock, and τ is the shear stress at the base of the flow, proportional to water velocity, with an $a=1.5$ (See Garcia-Castellanos & O'Connor (2018) for a detailed formulation). For the calculation of basal shear stress and water velocity we adopt a critical flow at the sill where overtopping takes place and a sill widening that is proportional to its depth. We adjust the width's linear dependence on depth such as to fit the final model's width to the present observed width of the submarine narrows (120 m; Figs. 6.4 and S12 of Hopfenblatt et al., 2021).

With the aim of showing the sensitivity of the flood evolution to the total cumulative erosion at the inlet, results show two floods calculated for an initial one-meter deep breach of the ocean into the caldera, reaching a final erosion depth of 15 and 30 m, respectively (Fig. S13 of Hopfenblatt et al., 2021). These two scenarios aim to show the sensitivity of our results to the assumption that most of this depth originated during the refill process. The rock erodibilities required for both scenarios are $k_e = 1.8e^{-3} \text{ m yr}^{-1} \text{ Pa}^{-1.5}$ and $4.2e^{-3} \text{ myr}^{-1} \text{ Pa}^{-1.5}$; these values are consistent with the relatively weak volcanic lithology of the barrier, considering that linking erodibility to lithology involved orders of magnitude of uncertainty (Garcia-Castellanos and O'Connor, 2018). Increasing the initial breach depth only advances the timing of the flood and vice versa, while keeping the peak discharge values largely unchanged. In the first scenario, the basin (Port Foster) is refilled in 180 h, although most of the flow is concentrated in the last 40 h. The second scenario evolves faster due to the weaker barrier and the refill takes place in only 100 h, with 95% of the flow concentrated in the last 10 h. Peak discharge changes from $1.92 \cdot 10^4$ to $1.24 \cdot 10^5 \text{ m}^3 \text{ s}^{-1}$. Erosion rates (Fig. S13 of Hopfenblatt et al., 2021) reach values 15 times faster in the second scenario. Thus, the first scenario, causing an erosion of only half of the present depth of the threshold, represents an estimation of the slowest refill mechanisms considered in this work. We can therefore conclude that, if most of the present depth of the threshold is related to erosion during the refill rather than to eustatic changes, then the process was very rapid, in the form of an outburst flood lasting a few days or less. Our results indicate that the filling of Deception

Island's empty basin, only 3.5 km³ in volume, may have proceeded to completion at peak rates of at least thousands of m³ s⁻¹, thus completing the bulk of the flooding in a time period of a few days or less (Figs. 6.6 and S13 of Hopfenblatt et al., 2021). This is comparable in order of magnitude to the estimates by Nomikou et al. (2016), the ~ 20 km³ Santorini caldera was filled in <2 days, involving a water velocity larger than 19 m/s and a water discharge above 2.5 · 10⁵ m³ s⁻¹.

6.2 Eruptive recurrence of Deception Island volcanic events

After compiling data on tephra and cryptotephra layers in the DecTephra database, including the location, simple description of the sampling site, petrologic and geochemical features, dating ages of each tephra layer, and meticulous dataset filtration of the radiocarbon ages can provide information about the eruptive recurrence of Deception Island.

About 78% ($n = 283$) of all the tephra layers included in the database have information regarding their age, derived using ¹⁴C, ice accumulation rates, historical information or correlation with dated tephra layers in other sampling sites nearby (e.g., Hodgson et al., 1998; Jiankang et al., 1999; Pallàs et al., 2001; Liu et al., 2016). Due to the difficulty of combining age data of diverse accuracy derived from different methodologies, in order to make a first order estimate of the eruptive recurrence of Deception Island, we have filtered our dataset according to the following: (i) uncalibrated radiocarbon dates have been calibrated using the most recent online CALIB software (<http://calib.org/calib/calib.html>) employing the last Southern Hemisphere calibration curve (SHCal20) (Hogg et al., 2020) and a 2-sigma confidence interval (See Supplementary Material 2 of Hopfenblatt et al., 2022a); (ii) only those tephra layers with an assigned age interval smaller than 1000 years (Fig. 6.8), i.e., with a dating uncertainty of ≤ 500 years, were considered; and (iii) tephra layers observed in two or more sampling sites were counted only once to avoid overestimating the number of eruptive events within a selected time period. For the last step, we resampled the tephra record using time-window bins of 25, 50 and 100 years, and combined as a single layer (represented with a new average age) those tephra layers with average ages separated by fewer years than the time windows chosen above. Historic eruptions (younger than 1820 CE)

were excepted from this procedure and all layers separately identified were included since a higher accuracy for the published ages is assumed.

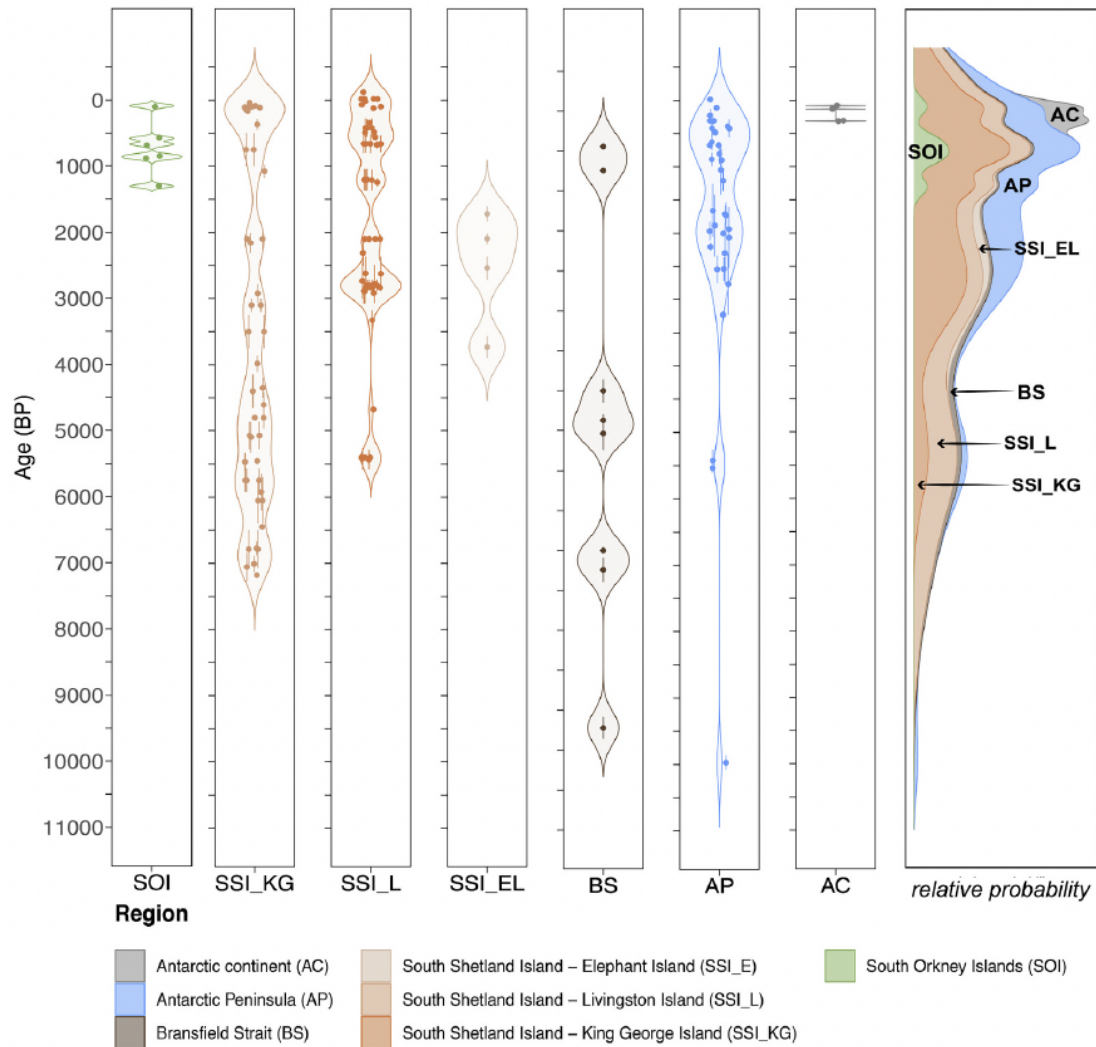


Figure 6.8. Violin plots and relative probability for the ages of the tephra layers reported in the DecTephra database separated by region. Points and vertical bars represent individual tephra ages and errors as included in the Tephra_layers table (See Supplementary Material 2 of Hopfenblatt et al., 2022a for further detail on the data).

The results of our analysis indicate that, using a conservative time window of 100 years, 58 tephra layers are identified in DecTephra that potentially correspond to independent explosive eruptive events (Fig. 6.9). This number increases to 82 if a time window of 25-years is used. Thus, on the basis of these two time windows, the recurrence of

explosive eruptions on Deception Island is estimated to be about 1–2 eruptions per 300 years during the $\sim 10,000$ cal yr BP – 1820 CE period. The estimate is significantly higher for the historic period, when at least 15 explosive eruptive events in the last ~ 150 years can be identified from sites across the region and this figure is slightly lower than that estimated from outcrops of various types in the region (Smellie, 2002d). Since some eruptive events in Deception Island were effusive (i.e., most probably without related tephra layers; Smellie, 2002b) and not all explosive eruptions leave a recognizable record in lakes, glaciers or the sea, these recurrence values should be considered as minima.

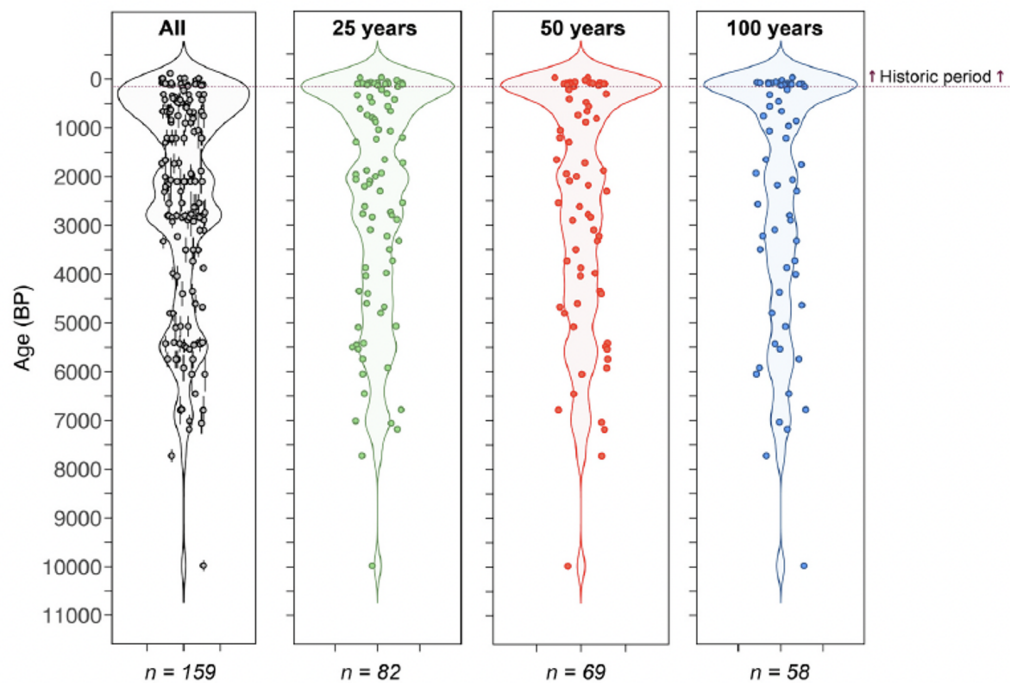


Figure 6.9. Violin plots for the ages of the tephra layers (in cal yr BP) reported in the DecTephra using time-window bins of 25, 50 and 100 years. After filtering, n indicates the number of tephra samples in each bin (See Supplementary Material 5 of Hopfenblatt et al., 2022a for further detail on the data).

Besides all the information included in DecTephra database, there is still need to improve about dating tephras, specially with the ones related to Deception Island explosive eruptions. Without a doubt, new data obtained in this thesis regarding the 1970 eruption of Deception Island (See section 5.2) will help to better understand future tephra studies that could be related to Deception Island as a source, especially when these studies include dating methods that could improve the eruptive recurrence of Deception Island.

6.3 Evolution of Deception Island's magmatic system

6.3.1 Magmas feeding the caldera-forming eruptive event

According to previous research works, the magmas from the caldera-forming eruptive event can be categorized into two groups (e.g., Smellie et al., 2002; Geyer et al., 2019): one aligns with the primary geochemical trend for Deception Island, and the other deviates from the main trend, representing the "*second magma series*" proposed by Smellie et al. (2002) (Fig. 5.31). This series exhibits lower TiO_2 and FeO_t values and, for the same SiO_2 , slightly higher concentrations of MgO , Al_2O_3 , and CaO than the pre- and post-caldera rocks in major elements versus SiO_2 Harker diagrams (Figs. 5.28, 6.10; Antoniadou et al., 2018; Geyer et al., 2019).

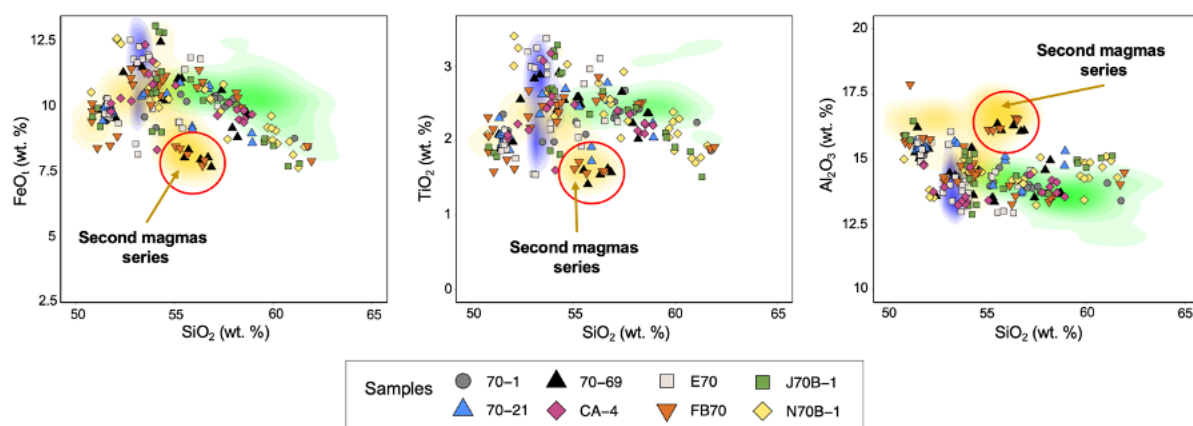


Figure 6.10. Major element vs. SiO_2 content Harker Diagrams for the glass shard of tephra samples. The major element compositions were normalized to 100% in an anhydrous base, with Fe as FeO_t . Each point plot corresponds to a single EPMA analysis, i.e. different points may belong to the same juvenile fragment. Deception Island bulk rock data from Antoniades et al. (2018) and Geyer et al. (2019) marked with blue, yellow and green color clouds correspond to pre-, syn- and post-caldera samples respectively. Second magmas series described for the syn caldera eruption samples from OCTF and tephra fragments indicated with yellow arrow and a red circle.

Based on XRF and EPMA geochemical data, and the application of rhyolite-MELTS software v.1.2.0 (Asimow & Ghiorso, 1998; Gualda et al., 2012) to analyze the thermodynamic geochemical database, Geyer et al. (2019) revealed that OCTF magmas came from two reservoirs (R2, ~10–11 km depth, $P \sim 3$ kbar) and (R1, > 15 km depth) (Fig. 6.11). As suggested by Smellie et al. (2002), the arrival of these hotter and more primitive magmas (i.e., R1) into reservoir R2 may have triggered the explosive eruption leading to caldera formation (Sparks et al., 1977; Pallister et al., 1996), later discussed by Geyer et al. (2019).

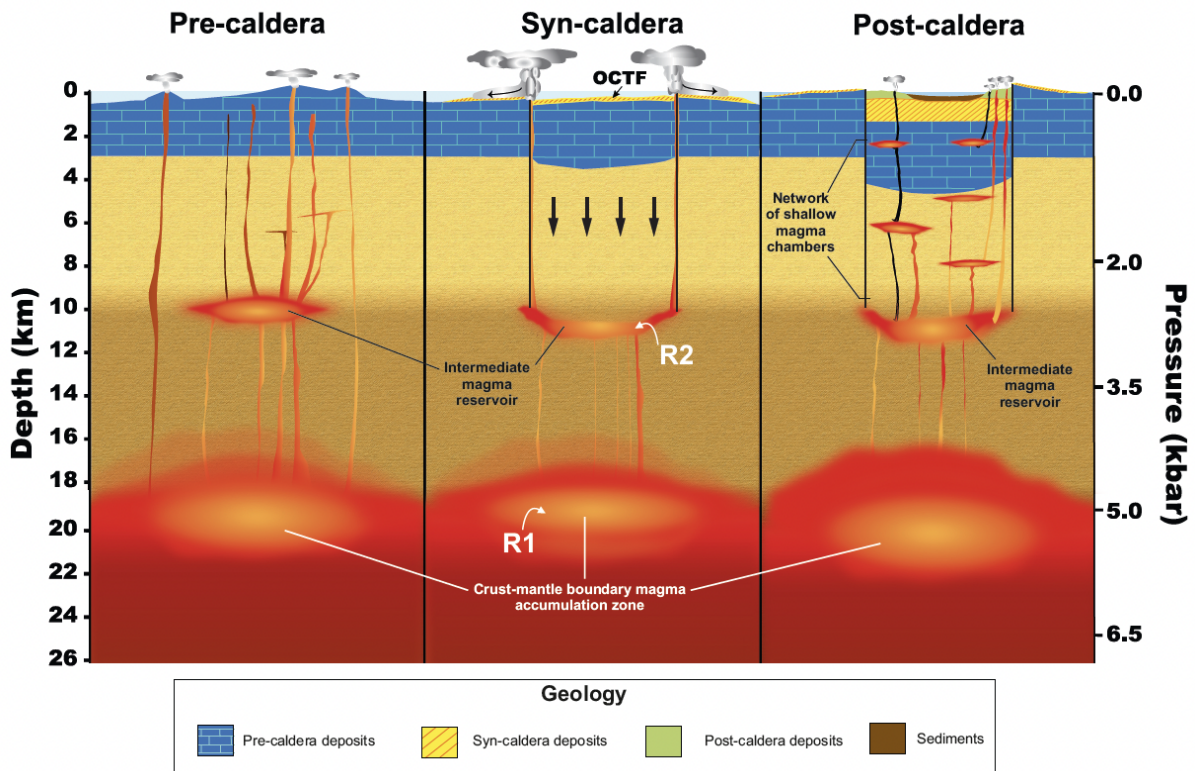


Figure 6.11. Conceptual model of the magmatic system of Deception Island modified from Geyer et al. (2019) based on P-T estimates. R1 and R2 correspond to the magmatic reservoirs. See Geyer et al. (2019) for further information.

Until this PhD, the distinct geochemical pattern of the second magma series had solely been identified in syn-caldera samples from Deception Island (Smellie et al., 2002; Geyer et al., 2019). Regarding tephra studies related with Deception as a source, Antoniadou et al. (2018) correlated a tephra layer (“T3”) found on several lakes of Livingston Island with the caldera collapse event based on the fact that juvenile fragments displayed the same geochemical pattern as the OCTF magmas.

As seen in section 5.2.3, glass compositions of the 1970 tephra samples from Livingston Island plot both along the main evolutionary trend of Deception Island's magmas and on the compositional field of the *second magma series* (Fig. 6.10). This is the first occurrence of such geochemical features in samples (rocks, tephra, or cryptotephra) not directly linked to the colossal caldera collapse event and the OCTF deposit. Indeed, this

characteristic geochemical pattern (with two distinct magmas) has never been identified before in the pre- and post-caldera volcanic materials deposited on the island (Smellie et al., 2002; Geyer et al., 2019) or in tephra/cryptotephra samples related to explosive eruptions on Deception Island (Hopfenblatt et al., 2022a).

For the 1970 tephra samples collected on Livingston Island glaciers, Type II fragments of samples 70-69 and FB70 exhibit similar values of the major elements as the *second magma series*. These fragments show no textural, morphological and mineral differences when compared to other Type II fragments. In addition, glass compositions of other tephra samples (e.g., J70B-1, 70-21 and 70-1) fall within the main compositional trend and the second magma series cluster. When comparing the composition of the 1970 tephra samples with the one of the 1970 near-vent pyroclastic deposits, the latter do not plot on the field of the *second magma series* as the Type II fragments from samples 70-69 and FB70 (Figs. 5.42, 5.43)

One explanation for the presence of the *second magma series* on 1970 tephra samples may be related to the fact that the analyzed fragments are not juveniles but OCTF fragments dragged by the magma and incorporated as lithics in the 1970 deposit. However, this option has been ruled out due to extensive petrographic work focused on distinguishing between juvenile and lithic fragments to ensure that only glass of juvenile fragments of the 1970 eruptions were analyzed. The fresh looking appearance of the 1970 eruption Type II glass shards clearly contrast with the more altered one of the OCTF fragments, which have the vesicles filled with secondary minerals, and the volcanic glass commonly displays signs of bioalteration and an alteration rind of diverse thickness (compare Fig. 5.21 with Fig. 6.12). In addition, OCTF glass shards are coated by a glassy matrix hosting microcrysts of diverse minerals (Fig. 6.12), this is not observable in Type II tephra fragments. Considering all the petrographic evidence, it is concluded that the Type II glass shards of the 1970 eruption plotting in the compositional field are juveniles from this historic eruption and not lithics of the OCTF.

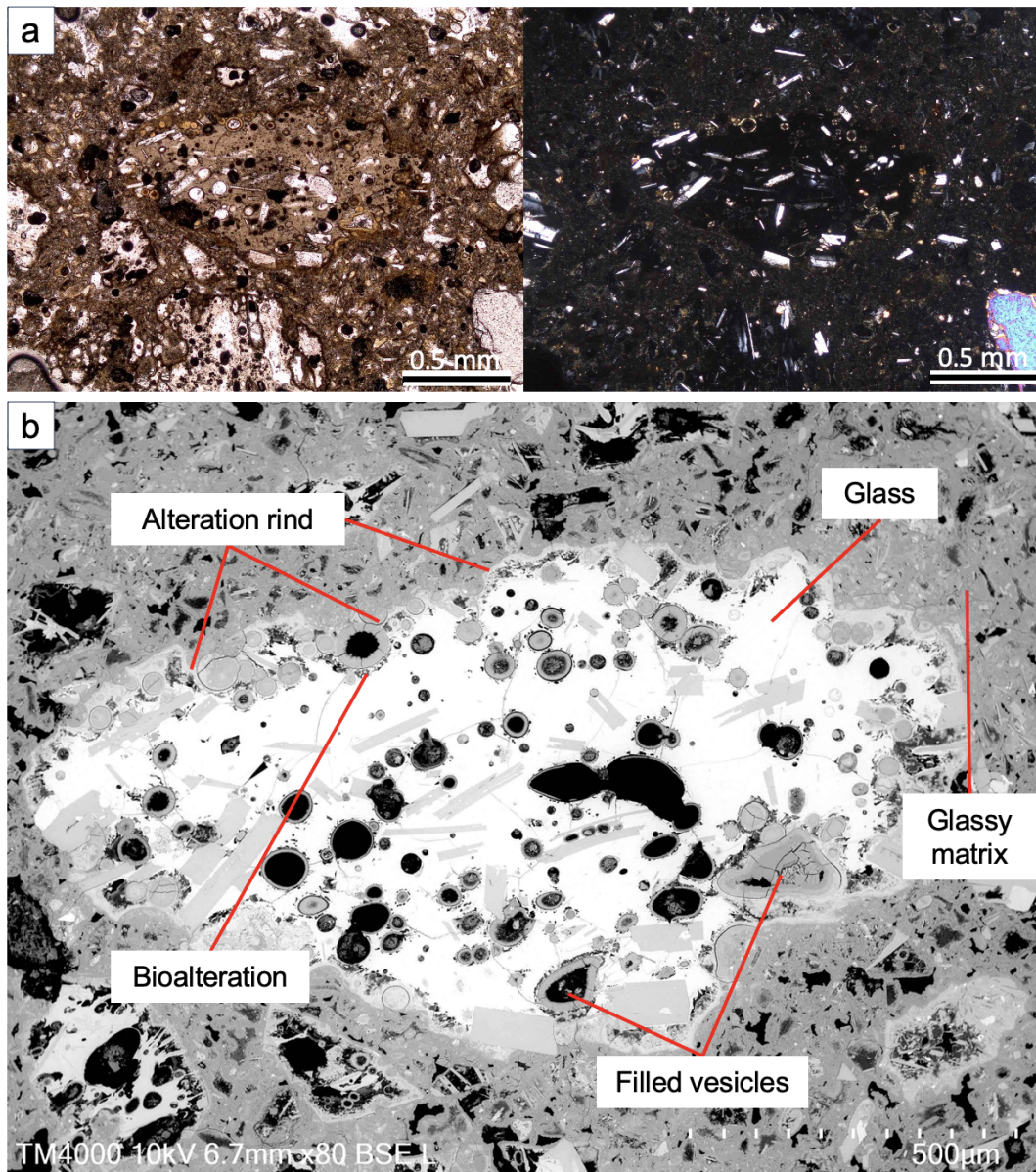


Figure 6.12. Juvenile ignimbrite fragment (OCTF) of sample DI-28 (Oriol Vilanova). a) Images in plane-polarized (left) and crossed-polarized light (right). b) SEM image (bottom).

Hence, the presence of glasses similar in composition to the *second magma series* may have the following potential explanations (Fig. 6.13):

(1) The source of the *second magma series* has always been present beneath the island (even before the caldera collapse) but there has been a strong observational bias when studying both pre- and post-caldera deposits.

(2) The source of the *second magma series* developed close in time to the caldera - forming event (this would explain its absence in pre-caldera deposits), was drained during the OCTF event but has been being replenished and active (i.e., potentially eruptable) since then, but only seen in the 1970 deposits due to observational bias on the post-caldera deposits.

(3) The source of the *second magma series* developed close in time to the caldera - forming event (this would explain its absence in pre-caldera deposits), was almost fully drained during the OCTF event and has been only replenished and active (i.e., potentially eruptable) since shortly before the 1970 (or even 1967) event (this would explain its absence in the other post-caldera deposits).

(4) The source of the *second magma series* was present beneath the island (even potentially long before the caldera collapse) before the caldera-forming event but there is a strong observational bias in the pre-caldera samples. After the caldera collapse, the reservoir corresponding to the *second magma series* was almost fully drained/destroyed and has been only replenished, and active (i.e., potentially eruptable), since before the 1970 (or even 1967) event (this would explain its absence in the other post-caldera deposits).

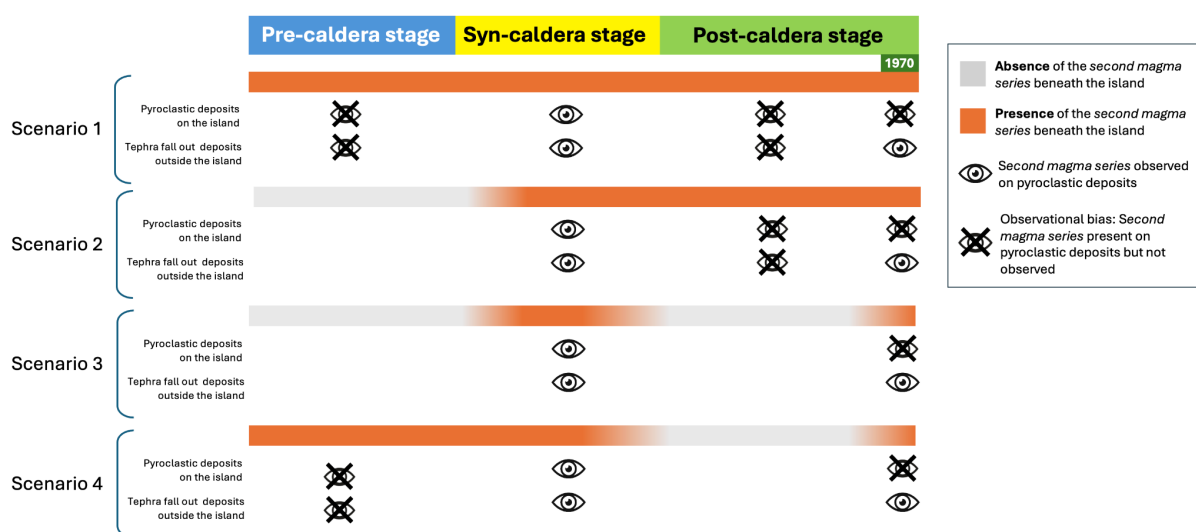


Fig. 6.13. Scheme of the different possible scenarios to explain the presence/absence of the second magma series in the near-vent pyroclastic deposits of Deception Island or distal tephra fall out layers found elsewhere outside the island.

Regardless of which explanation from those presented above is the most probable, the observation of the *second magma series* raises two important questions:

- Why is the *second magma series* only observed in the distal tephra fall-out deposits of the 1970 event and not in the near-vent pyroclastic deposits?
- Is the presence of the *second magma* a singular event in time, or will it be present from now on in all future eruptions on Deception Island?"

The response to the first question could be related to an observational bias and lack of sufficient glass geochemical analyses of the near-vent pyroclastic deposits. This could be sorted out by performing more geochemical analyses in the near-vent pyroclast to see if the second magma series pattern appears in other samples located among the western and eastern craters that have not been analyzed yet. So far the analyzed samples from the eastern and western craters comprise only information and samples of 2 craters (log1 and log6; See figures 5.32 and 5.34) of the, at least, 13 vents of the 1970 event.

Concerning the second question, and in connection to the scenarios presented before, it is not possible to rule out the appearance of the *second magma series* in future eruptive events on the island. Furthermore, in connection to the third and fourth scenarios presented before, the question is if the reappearance of the *second magma series* in the 1970 deposits (assuming its absence since the caldera-forming event and in the pre-1970 eruptive materials is not related to observational biases) may represent a new level of maturity of the magmatic system, which may potentially correspond to a new (caldera?) cycle after the collapse event, as occurred in other volcanic systems worldwide (e.g., Bouvet De Maisonneuve et al., 2021).

Indeed, it has been repeatedly demonstrated that some caldera systems are polycycles and can involve multiple collapses in the same approximate location (e.g., Kos-Nisyros Volcanic Complex (Greece), Long Valley (USA), Campi Flegrei (Italy), Rabaul (Papua

New Guinea), Okataina (New Zealand)). These cycles can be reflected in their chemistry, for example, at Long Valley (United States of America) there was a transition from three geochemical series of trachy-basalts to dacites) to a single geochemical series of rhyolites (Bailey, 2004; Hildreth, 2004) or Rabaul caldera (Papua New Guinea) with cycles in the order of the few thousands of years (4-6 ka) (e.g., Bouvet de Maisonneuve et al., 2021)

According to Bouvet De Maisonneuve et al. (2021), caldera cycles comprise: (i) the period of pre-collapse activity (incubation, maturation, and widespread presence of a magmatic volatile phase); (ii) the catastrophic caldera eruption; and (iii) post-collapse recovery (resurgence, renewed eruptions, and subsequent maturation) or the possible cessation of the cycle. Within post-caldera activity, subvolcanic intrusion and hydrothermal activity typically continue even if the magma supply decreases; however, if the magma supply remains abundant, the system may recover (Bouvet de Maisonneuve et al., 2021). This can reactivate the reservoirs involved in caldera-forming eruptions, recharging shallow reservoirs that could start to grow and mature again (Bouvet de Maisonneuve et al., 2021).

The possibility that Deception Island is entering (or has already entered) in a caldera cycle has never been proposed so far. However, the presence of the *second magma series* in the 1970 deposit, a chemical characteristic (apparently) only of the caldera-forming event deposits, opens the door to such possibility, although the duration of the cycle remains uncertain, yet. More information is needed to complete the full picture of Deception Island's magmatic evolution, including (but not restricted to): extensive field work to seek for complementary pre-caldera and post-caldera outcrops; detailed petrologic studies of near-vent and distal fall-out pyroclastic deposits; extend the available geochronological data; geophysical data; and monitoring information.

6.4 Future steps

Finally, there are still important aspects to be developed for further exploration and in-depth investigation to fully comprehend the volcanic history of Deception Island. It is essential to enhance the multidisciplinary methodologies used in this study to shed light on the possibility of a caldera cycle. Geophysics, isotopes, monitoring, and tephra studies remain the focal points for future research.

The development and application of geophysical techniques are crucial for enhancing subsurface imaging and identifying potential magmatic reservoirs. Additionally, isotopic studies hold promise for providing further constraints on magma sources and crustal processes contributing to volcanic activity. To effectively capture changes in volcanic parameters over time, it is crucial to implement continuous monitoring efforts through the development of reliable geodetic networks and real-time data-acquisition systems.

A detailed analysis of tephra and/or cryptotephra layers, encompassing physicochemical characterization such as grain size distribution, morphologies, and geochemical analyzes, will provide valuable insights into eruption dynamics and potential shifts in magmatic and eruptive behavior. Further exploration and expansion of study zones within the spatial range of where Deception Island tephras are found (e.g., Hopfenblatt et al., 2022a) will create a more comprehensive dataset, extend the temporal resolution, and enhance the tephrostratigraphic record.

In addition, continued refinement of age dating techniques and incorporation of advancements (e.g., radiocarbon dating), together with advanced numerical and computational modeling approaches, will aid in simulating volcanic processes, such as past eruptions, contribute to the interpretation of geophysical data, enhance the precision of age estimates, and refine our understanding of volcanic hazards.

These proposed future steps collectively aim to propel our understanding of the volcanic system of Deception Island, laying the groundwork for comprehensive insights into its geological evolution and potential hazards.

7 CHAPTER 7

Conclusions

This Doctoral Thesis has allowed us to enhance our overall comprehension of Deception Island's post-caldera volcanic activity, its past and future evolution, and the potential impact of future eruptive events. The following main findings and conclusions from this Ph.D. thesis can be highlighted:

Port Foster Bay most relevant eruptive episode

The new geophysical data (bathymetric data and ultra-high resolution parametric seismic profiles of Port Foster) obtained during the 2017–2018 Spanish Antarctic Campaign, and the juvenile rock samples collected from Stanley Patch by SCUBA diving have allowed shedding new light on the eruptive event that lead to the formation of the largest volcanic edifice within Port Foster.

The morphological characterization of Stanley Patch volcanic edifice and the petrographic description and chemical analyses of the collected rock samples, all point to a subaerial monogenetic explosive eruption as responsible for the formation of this scoria cone. This reveals that the caldera could have opened to the sea leading to its complete flooding only after the construction of Stanley Patch volcano ($< \sim 2000$ years ago).

The caldera wall breach could have been triggered by a sector collapse of the pre-caldera edifice, the occurrence of an explosive eruption and/or overtopping of the sea with gradual erosion of the spillway. Anyhow, Deception Island's empty basin may have been completely flooded in a few days or less, leading to an important inflection point in the island's geological evolution. The flooding event not only changed the sedimentary dynamics within the caldera depression, but it also changed the eruptive style of post-caldera volcanic activity, increasing the potential of phreatomagmatic eruptions. This highlights the complex temporal

and spatial aspects of a changing hazard landscape that must be incorporated into any volcanic hazard assessment of volcanic islands.

Database on tephra and cryptotephra layers sourced at Deception Island

DecTephra database, an up-to-date compilation of all published information used to identify tephra layers potentially erupted from Deception Island, one of the most active volcanoes in Antarctica and a source of numerous datums widely used in environmental studies. The lack of a rigorous statistical appraisal of the methods used to characterize individual tephras has prevented their more widespread use as datums. Currently, the database includes 362 tephra layers described in multiple sources (> 20 scientific publications and 2 PhD theses).

A preliminary geographical analysis of the DecTephra database shows that putative Deception Island tephras have been identified in numerous proximal (< 150 km) sampling sites distributed between the South Shetland Islands and Bransfield Strait, but also much further afield in the Scotia Sea and the South Pole (> 1000 km and > 3000 km distant, respectively).

The tephra layers occur in ice cores, marine and lacustrine sediments and glaciers. They are Holocene in age and their major element chemistry completely overlaps with mafic to intermediate tephras from the pre, syn and post-caldera evolutionary stages of Deception Island volcano.

A preliminary analysis of the information included in the new database has determined that explosive eruptive activity on the island varied during the Holocene. For example, the eruptive recurrence prior to 1820 CE was 1–2 eruptions per 300 years, which increased significantly to at least 15 eruptions in 150 years during the period between 1820 and present.

Despite current drawbacks due to the lack of trace element data and inaccessible major element data, the DecTephra database represents a novel key tool for studies of

volcanology, petrology and geochemistry, tephrochronology and regional ash transport associated with the volcanic activity of Deception Island.

Tephra of the 1970 Deception Island eruption found at Livingston Island glaciers

New physical characterization of the tephra fragments from the 1970 eruption of Deception Island indicates that there are three Types of juvenile fragments (I-III) and various different lithic fragments with grain sizes ranging from fine to coarse ash. The morphologies of juvenile fragments indicate magmatic and phreatomagmatic eruptive styles for the 1970 eruptive event. Geochemical characterization demonstrates that juvenile fragments follow a similar trend of the Deception Island glasses, but less evolved than the glasses from the eastern and western craters in their majority.

Glass compositions of the 1970 tephra samples analyzed plot on the compositional field of the *second magma series*, being the first occurrence of such features in samples (rocks, tephra, or cryptotephra) not directly linked to the colossal caldera collapse event and the OCTF deposit. The presence of the *second magma series* can be due to:

- (1) a strong observational bias when studying both pre- and post-caldera deposits;
- (2) the magmatic source has been replenished and active since the collapse (fully drained), but only seen in the 1970 deposits due to observational bias on the post-caldera deposits.
- (3) the magmatic source has been replenished and active since the collapse (almost fully drained), but shortly before the 1970 (or even 1967) event, explaining the absence in the other post-caldera deposits.
- 4) A strong observational bias in the pre-caldera samples and after the caldera collapse, the reservoir corresponding to the *second magma series* was almost fully drained/destroyed and has been only replenished and active since before the 1970 (or even 1967) event.

Assuming absence of the *second magma series* since the caldera-forming event and that in the pre-1970 eruptive materials is not related to observational biases may represent a new level of maturity of the magmatic system, which may potentially correspond to a new caldera cycle after the collapse event as occurred in other volcanic systems worldwide.

The physicochemical characterization of the 1970 eruption tephra fragments can be used as a starting point for future studies of tephra layers found in glaciers and marine/lacustrine sediment cores outside the island, improving our capacity to reconstruct the eruptive dynamics of past eruptions.

Preliminary study of Bransfield Strait tephras

In the Bransfield Strait tephra layers we can identify the same three Types of fragments (I-III) described for the 1970 event with grain sizes ranging from fine ash to lapilli and the morphologic features indicate a phreatomagmatic eruptive style for the studied layers.

Geochemical analyses, the glasses of the Bransfield Strait tephras follow an evolutionary trend that is more linear in alkali content and that differs from the one followed by the Deception Island magmas. While these chemical disparities might suggest a source beyond Deception Island (such as King George), we posit that they are more likely attributable to an analytical bias requiring further examination. Moreover, the close proximity of the analyzed sites (< 40 km) to Deception Island suggests that the origin of the Bransfield tephras is linked to this island.

The combination of different research lines about Port Foster together with tephra studies show key advances for the understanding of Deception Island's post-caldera volcanic activity, its potential future evolution and the potential impact of future eruptive events.

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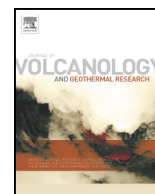
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Appendix 1

Formation of Stanley Patch volcanic cone: New insights into the evolution of Deception Island caldera (Antarctica).

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Formation of Stanley Patch volcanic cone: New insights into the evolution of Deception Island caldera (Antarctica)

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ABSTRACT

Deception Island (South Shetland Islands) is one of the most active volcanoes in Antarctica, with more than 20 explosive eruptive events registered over the past centuries. Recent eruptions (1967, 1969, and 1970) and volcanic unrest episodes (1992, 1999, and 2014–2015) demonstrate that volcanic activity is likely occurring in the future. This is of special concern for scientists, logistic personnel, and tourists, since the South Shetland Islands are an important tourist destination and host numerous year-round and seasonal scientific stations and base camps. Significant efforts have been made to understand the complex magmatic and volcanic evolution of Deception Island with special interest on its subaerial part. However, studies on submerged volcanic cones within Port Foster, the sea-flooded part of Deception Island's caldera depression, are comparatively scarce. Here, we provide a full characterization of Stanley Patch volcano, the largest of these volcanic edifices. Estimated morphometric parameters based on new multibeam bathymetric data, supported by petrographic and chemical observations from rock samples collected on the crater rim, reveal that Stanley Patch volcano grew in a subaerial environment. This result, combined with previous findings and new sedimentological evidence from our ultra-high resolution seismic profiles, allow to further detail the island's geologic evolution since the caldera collapse. We conclude that the complete flooding of Port Foster could have only occurred after the formation of Stanley Patch volcano, i.e. during the last ~2000 years, and in a time period of a few days or less.

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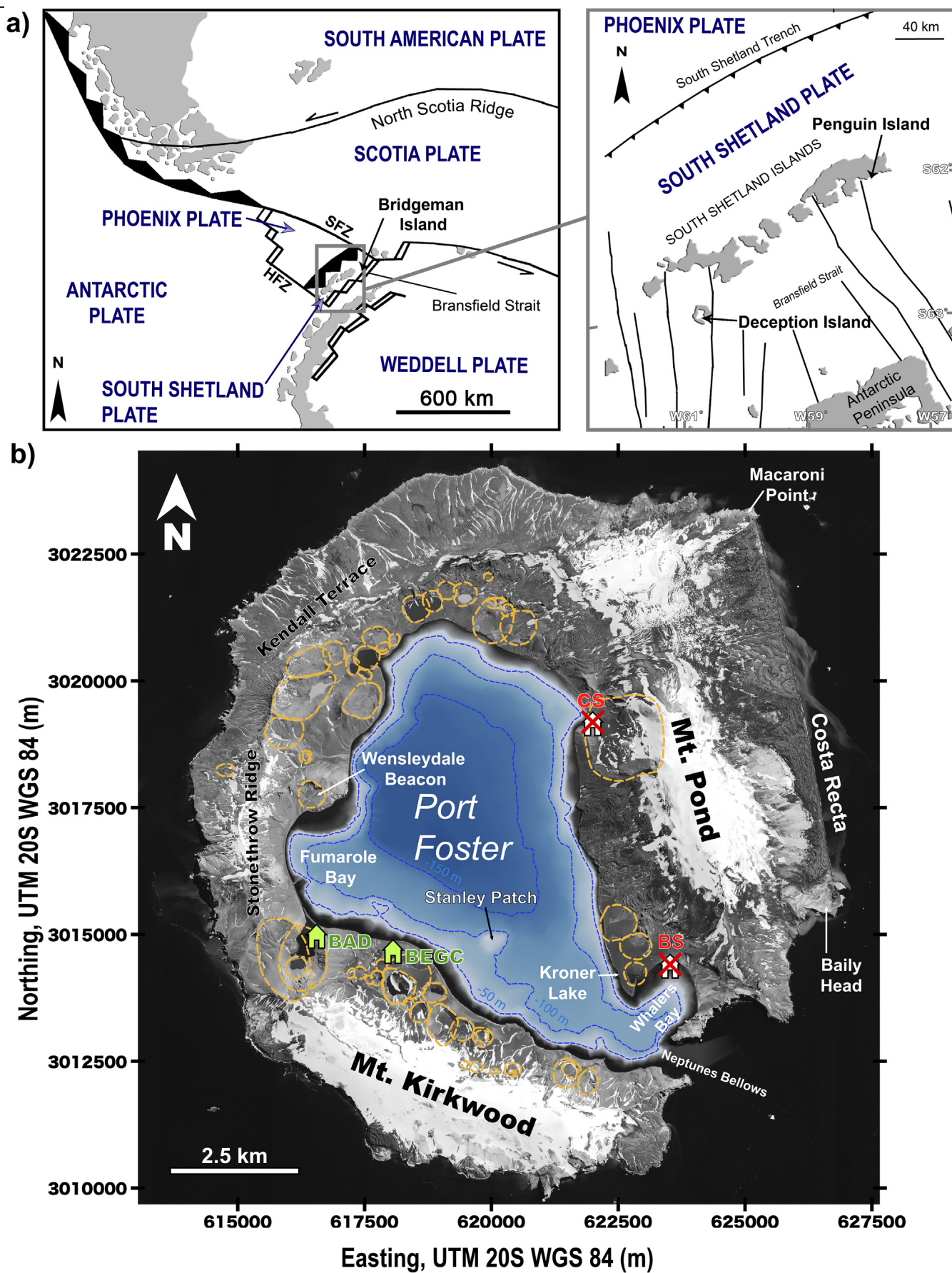
1. Introduction

Deception Island (South Shetland Islands) is among the most active volcanoes in Antarctica with a record of more than 20 explosive eruptions in the last centuries (e.g., Orheim, 1972; Roobol, 1982; Smellie, 2002a; Geyer, 2021). It consists of a composite volcano, whose central part is occupied by a c. 8.5 × 10 km collapse caldera, elongated in NW-SE direction (Fig. 1a). The caldera-forming eruption, with 30–60 km³ of erupted magma (dense rock equivalent), has been estimated to be comparable in size to some of the largest eruptions occurring on Earth

over the past several millennia (e.g., 1883 Krakatoa eruption) (Martí et al., 2013). Port Foster, the sea-flooded part of the caldera depression, has smaller dimensions (c. 6 × 10 km) due to the numerous post-caldera eruptions occurred around the caldera wall margins (e.g., Pedrazzi et al., 2020; Smellie, 1988, 2002a; Geyer et al., 2021) (Fig. 1b). The recorded historical volcanic activity, the most recent eruptive events (1967, 1969, and 1970), and the episodes of unrest which occurred in 1992 (Ibáñez et al., 2003b), 1999 (Ibáñez et al., 2003a), and 2014–2015 (Almendros et al., 2018; Berrocoso et al., 2018), undoubtedly categorize Deception Island as a very active volcano. This leads directly to a

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significant socio-economic problem since the South Shetland Islands are an important tourist destination and host numerous year-round and seasonal scientific stations and base camps (e.g., Bartolini et al., 2014; Bender et al., 2016). Hence, even a moderate eruption (e.g., Volcanic Explosivity Index - VEI of 3–4) occurring in the near future on the island will pose far-reaching volcanic hazards and substantial economic losses and consequences for global aviation safety in the Southern Hemisphere (e.g., Bartolini et al., 2014; Geyer et al., 2017; Smellie, 2002c). Therefore, completing our knowledge about the island's evolution is fundamental to untangle the potential for future volcanic activity, and to significantly improve our understanding of the monitoring data recorded during a volcanic crisis in order to better forecast future unrest.

Important efforts have been made to understand the complex magmatic and volcanic evolution of Deception Island with special interest on its subaerial part (e.g., Agosto et al., 2007; Aparicio et al., 1997; Baker, 1969; Baker et al., 1969, 1975; Baker and McReath, 1971; Baraldo and Rinaldi, 2000; Birkenmajer, 1992; Galé et al., 2014; Geyer et al., 2019; González-Ferrán et al., 1971; González-Ferrán and Katsui, 1970; Hawkes, 1961; Martí et al., 1996; Roobol, 1980; Smellie, 1988, 2001, 2002b; Smellie et al., 2002). However, studies on submerged cones within the Port Foster are comparatively scarce (e.g., Barclay et al., 2009; López-Martínez et al., 2000; López-Martínez and Serrano, 2002; Rey et al., 1995, 1997; Somoza et al., 2004; Smellie, 2021).

During the 2017–2018 Spanish Antarctic Campaign, a geophysical study was carried out in Port Foster with special focus on Stanley Patch volcano, the largest volcanic cone located in the southern sector of the bay (Figs. 1b and 2a). A new multibeam swath bathymetry was obtained together with several high-resolution parametric seismic profiles of Port Foster's shallow sub-bottom structure (Gómez-Ballesteros et al., 2018). Additionally, and for the first time, juvenile rock samples were collected from Stanley Patch by SCUBA diving (Angulo-Preckler et al., 2021). In this study, we present a morphological characterization of this volcanic edifice based on these new multibeam bathymetric data. Results obtained, supported by the petrographic description and chemical analyses of the collected rock samples, allow us to shed new light on the eruptive event that led to the formation of Stanley Patch volcano. Then, this information is combined with sedimentological evidence from our new ultra-high resolution seismic profiles and numerical flood models, to further detail the geological evolution of Deception Island since the caldera collapse.

2. Deception Island's geological overview

2.1. Geological setting, magmatic and volcanic evolution

Deception Island is located at the south-western end of the Bransfield Strait (e.g., Catalán et al., 2013, 2014; Grad et al., 1992) (Fig. 1a), a ~4 Ma old extensional structure interpreted to be the consequence of back-arc extension linked to subduction of the Phoenix Plate beneath the Antarctic Plate (Barker, 1982; McCarron and Larter, 1998). Quaternary magmatism, connected to rifting and back-arc basin formation, is mostly concentrated on Deception, Penguin, and Bridgman Islands (e.g., Birkenmajer et al., 1990; Haase et al., 2012; Hole et al., 1994; Smellie, 2021). The normal magnetic polarity of all Deception Island's exposed rocks indicates that these are younger than 0.75 Ma (Valencio et al., 1979), and K–Ar data (Keller et al., 1992) point to 0.2 Ma. Paleomagnetic data suggest ages of c. 8300 years for the caldera collapse that strongly marked the island's morphology and subsequent volcanic evolution (Oliva-Urcia et al., 2015). However, more recent findings

indicate that the most likely age for the caldera-forming event is 3980 ± 125 calibrated years Before Present (BP) based on tephrochronology, sedimentology studies and ^{14}C dates (Antoniades et al., 2018).

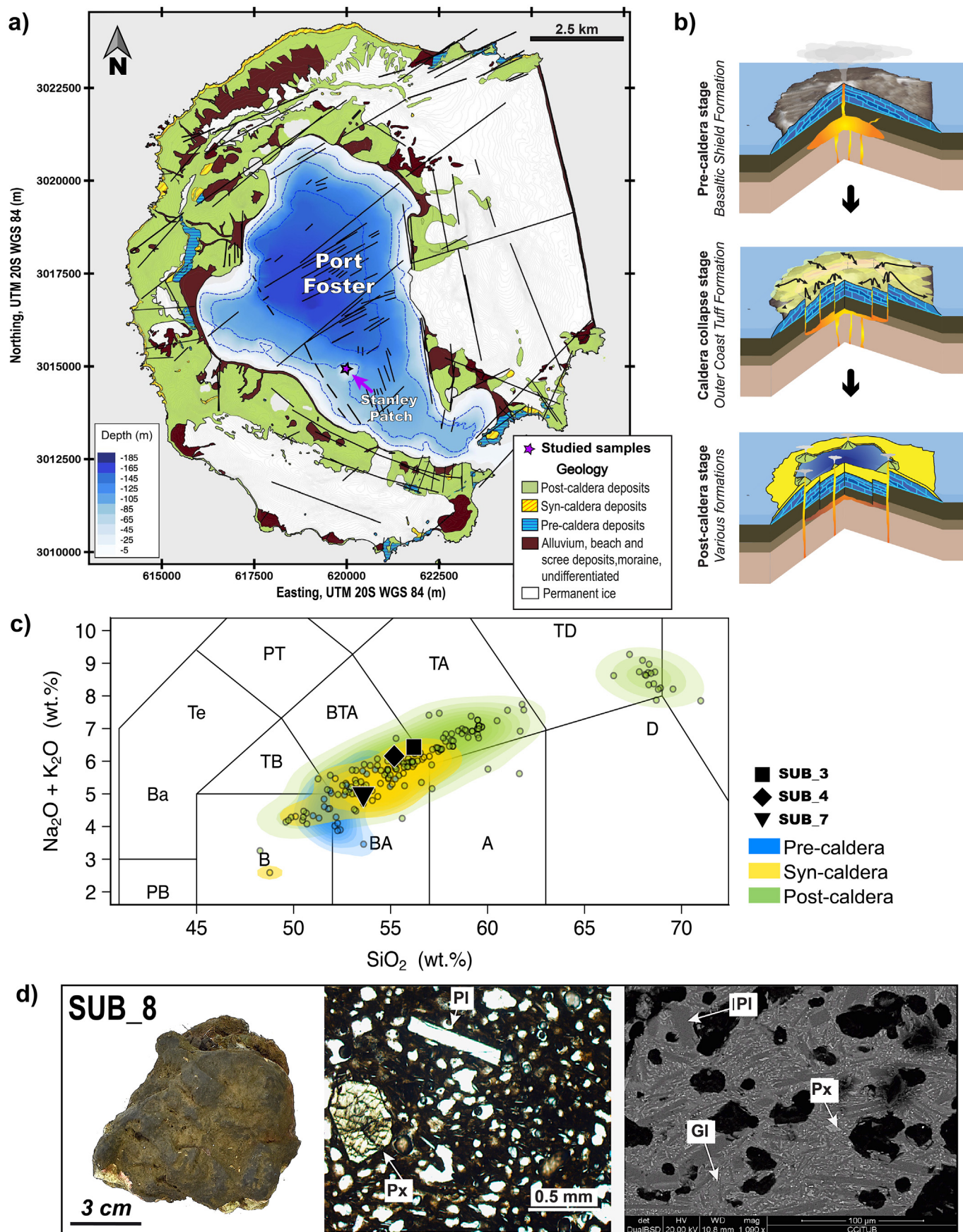
Previous to the caldera collapse, volcanic activity led to the formation of multiple shoaling seamounts and a main subaerial volcanic edifice (Smellie, 2002a) (Fig. 2b). During the caldera-forming event, a several tens of meters thick sequence of pyroclastic density current deposits, known as the Outer Coast Tuff Formation (OCTF) was emplaced (Martí et al., 2013; Smellie, 2001, 2002a) (Fig. 2a and b). Post-caldera eruptive events, predominantly located along the structural borders of the caldera and the interior of Port Foster (Fig. 1b), have mainly consisted of hydromagmatic eruptions with variable intensity and explosivity degree mostly depending on the amount and provenance of water (i.e., aquifer, sea, and/or ice/snow melting) that interacted with the rising or erupting magma (e.g., Baker et al., 1975; Pedrazzi et al., 2014, 2018, 2020; Smellie, 2002b). Historic eruptions, generally $<0.1 \text{ km}^3$ in volume and a VEI of 2–3 (Baker et al., 1975), have been concentrated in eruptive clusters (e.g., 1818–1828, 1906–1912) with several temporally closely spaced events, separated by decades of quiescence (e.g., 1912–1967) (Orheim, 1972; Roobol, 1982; Smellie, 2002a).

2.2. Port Foster: geomorphology and internal structure

Port Foster is assumed to have formed just after the caldera-forming event by marine inundation of the collapsed depression via gaps in the caldera rim created by local sector collapse and/or volcanic events (e.g., Aparicio et al., 1997; Smellie and López-Martínez, 2002a). The bay is open to the sea by a narrow and shallow entrance ($<500 \text{ m}$ wide and $<25 \text{ m}$ deep) at Neptunes Bellows (Fig. 1b) and is composed of three sub-basins (Cooper et al., 1998; Paredes et al., 2006; Rey et al., 2002; Fig. 3): (i) sub-basin 1 (165 m maximum water depth) that occupies the entire northern half of the bay; (ii) sub-basin 2 ($<110 \text{ m}$ water depth) that extends from east of Stanley Patch into Whalers Bay; and (iii) sub-basin 3 (100–120 m water depth), a smaller basin in the Fumarole Bay. Whereas the limit between the sub-basins 2 and 3 is subdued, sub-basin 1 is delimited on its south and south-western side by a striking ENE-dipping monoclinical structure related to a major NNW-SSE-trending fault (Cooper et al., 1998; López-Martínez and Serrano, 2002) (Fig. 3a–c).

Previous seismic studies within Port Foster have imaged geological structures at the topmost 300 m below the sea floor in the central part of the caldera depression (e.g., Kowalewski et al., 1990; López-Martínez and Serrano, 2002; Rey et al., 1995, 1997, 2002; Somoza et al., 2004). The basin infilling comprises three seismic units A, B, and C, from older to younger (Rey et al., 1995, 1997), separated by unconformities interpreted to be individual deformation events that disturbed the geometry of the sedimentary materials (Fig. 3d and e) (Kowalewski et al., 1990; López-Martínez and Serrano, 2002; Rey et al., 1995, 1997). Unit A is interpreted as the intra-caldera facies of the OCTF deposited during the caldera-forming eruption (e.g., Martí et al., 2013; Rey et al., 2002). It gently dips to the south-west and is overlain by two major post-caldera sedimentary units B and C, both divided into several sub-units (Fig. 3d and e). Their distribution and strata pattern suggest either that basinal subsidence occurred along the monocline at greater rates than local sedimentation, or that subsidence in the south-western part of the basin was accompanied by uplift in the north-east (Fig. 3e) (Kowalewski et al., 1990; Rey et al., 2002). Indeed, during the last decades, ground deformation monitoring (e.g., Almendros et al., 2015; Fernandez-Ros et al., 2007; Rosado et al., 2019) and the analysis of bathymetric variations (Barclay

Fig. 1. a) Simplified regional tectonic map and location of the South Shetland Islands (modified from Martí et al., 2013). HFZ (Hero Fracture Zone), SFZ (Shetland Fracture Zone). b) Deception Island orthophotomap with bathymetric data (data obtained from Spatial Data Infrastructure for Deception Island SIMAC, Torrecillas et al., 2006). BAD: Base Antártica Decepción (Argentinean scientific base); BEGC: Base Española Gabriel de Castilla (Spanish scientific base); BS: Remains of the British scientific base; and CS: Remains of the Chilean scientific base. Post-caldera volcanic craters (orange lines) are indicated based on Smellie and López-Martínez (2002b).



et al., 2009; Cooper et al., 1998) have shown that, in the past, the basin's floor has experienced notorious deformation episodes including uplift/subsidence stages.

Several submarine pyroclastic cones dot the Port Foster seafloor (López-Martínez and Serrano, 2002; Rey et al., 1995, 1997). These volcanic edifices show an arcuate NNW-SSE alignment and are characterized by relatively steep slopes and a dome-like or cone morphology, the largest one being Stanley Patch volcano first identified as a volcanic edifice in 1987 (Figs. 1, 3 and 4) (British Antarctic Survey, 1987; López-Martínez and Serrano, 2002).

3. Methods

3.1. Fieldwork and geophysical study

Fieldwork, including rock sample collection and the geophysical study, was carried out during the 2017–2018 Spanish Antarctic Campaign and the Antarctic GALILEO-IHM cruise aboard the R/V Hespérides (2017/2018) (Gómez-Ballesteros et al., 2018; Angulo-Preckler et al., 2021). The swath bathymetry was acquired by a multibeam echosounder system (Kongsberg EM-1002) operating 111 beams at 95 kHz frequency, with approximately 2° beam width. Surveys were carried out by the Marine Hydrographic Institute (IHM) in 2012, 2017, and 2018. Undertaken to meet International Hydrographic Organization (IHO) standards for multibeam surveying, the different surveys were positioned to insonify 100% of the seafloor with a 33% overlap between them. The resulting data set was processed using Caris Hips & Sips V.7.1 software and interpolated to an 8 × 8 m sided regular grid in Port Foster and a 4 × 4 m sided regular grid for Stanley Patch volcano, providing virtually continuous coverage of the entire survey area with high spatial resolution. Then, Digital Elevation Models (DEM) surfaces were created with QGIS software version 3.10 “A Coruña” (<http://www.qgis.org/>) and GRASS GIS software version 7.6 (<http://grass.osgeo.org>) (Figs. 3a and 4a).

Parametric seismic profiles were obtained with a hull-mounted TOPAS PS 018 high-resolution parametric sounder designed for sub-bottom profiling with very high spatial resolution in water depths from less than 20 m to full ocean depth. The +80% relative bandwidth, low frequency signal is generated in the water column by non-linear interaction between two high frequency signals (centered symmetrically around 18 kHz). The seismic profiles obtained were recorded working in high-penetration mode, by transmission of a Chirp wave (LFM), trying at all times not to interfere with the EM122 multibeam echosounder signal. Normal transmission frequencies vary from 2.0 kHz for the initial and 5 kHz for the final, with a pulse length of 10 ms, and transmitted at a 1500 ms internal mode trigger interval (Table S1). The record length was 400 ms at a sampling rate of 16.0 kHz. The deconvolution and initial 2 kHz filtering (HP filter) of the signal have always been applied in this Chirp mode. The TVG ramps normally used during the acquisition have been 0.78 d/ms between the bottom and 5.4 ms depth, 0.77 d/ms between 5.4 and 25.9 ms, and 0.14 d/ms after 35.6 ms. The seismic profiles (Figs. 5a, 6a–c and S1) are presented in two-way time and have been analyzed with the Kingdom Suite (Version 8.4) software to identify, define the top and base, and interpret sedimentary units and acoustical facies. For conversion depth in double-time depth (TWT) to depths (in distance), seismic velocities between 1600 and 1900 m/s as typical for volcanic sediments (Hamilton, 1970; Johnston et al., 2015) have been

considered. For specific seismic units, the depth points (in ms) of base and top extracted from the seismic profiles are imported into GRASS GIS and interpolated to 3D surfaces with the *v.surf.bspline* function, which performs a bilinear/bicubic spline interpolation with Tykhonov regularization (e.g., Fathi and Maleki Shoja, 2018). Then, the *r.contour* function is applied to calculate the isobaths (Fig. S2). Additionally, isopach maps (in ms) of the sedimentary units can be created by difference from the generated base and top 3D surfaces (Fig. 6d).

3.2. Geomorphometrical methods

The morphological parameters of Stanley Patch volcano were obtained from the 4 × 4 m grid size DEM. Shaded relief (Fig. 4b and d) and slope angle maps (Fig. 4c) were created with QGIS from the DEM to manually delineate the cone base outline and crater rim both identified by a break-in-slope (Fig. 4a). The pre-eruptive basal surface was obtained by interpolating the elevation data points around the volcanic cone (Fig. S3) with the *v.surf.bspline* function of GRASS GIS. The average slope of the basal plane ($S_{b,mean}$) was obtained by applying a linear regression to the elevation points obtained along a profile aligned along the maximum dip direction of the basal surface (Fig. S3). Complementarily, a statistical analysis with the R-Studio software (<https://www.rstudio.com/>) (R Core Team, 2014) was carried out to obtain data of mean, median, maximum and minimum slopes, and standard deviation, for both the crater and cone flanks. The morphometric parameters estimated from the DEM are summarized in Table 1 and Figs. 4d and e.

3.3. Geochemical, petrological and stable isotopes analyses

We collected a total of 21 rock samples of 3–15 cm in diameter size at the southern side of the crater rim (Angulo-Preckler et al., 2021). From these, we have selected only those juvenile fragments of larger size (> 5 cm) and less weathered appearance (5 in total, SUB_3 to SUB_5, SUB_7, and SUB_8) for geochemical and petrographic analyses (Table S2, Fig. S4). Petrographic characteristics of all samples were determined using an optical microscope, a Zeiss Axiophot at the Universitat de Barcelona (UB). Detailed studies of microtextures were performed using a scanning electron microscope SEM Quanta 200 FEI, XTE 325/D8395 at the Scientific and Technological Centre of UB (CCiTUB) (<http://www.ccitub.edu/EN/home.html>). Whole rock major and trace element compositions were analyzed by X-Ray Fluorescence (XRF) using a ThermoARL Advant'XP+ sequential X-ray spectrometer at the GeoAnalytical Lab at Washington State University (WSU) (<https://environment.wsu.edu/facilities/geoanalytical-lab/>). Trace elements and Rare Earth Elements (REE) were also analyzed on the same samples by Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) using an Agilent 7700 at WSU. Major element glass and mineral chemistry was also analyzed on thin sections using a JEOL JXA-8230 electron microprobe at the CCiTUB. The instrument was calibrated previous to each session using primary natural and synthetic standards from P and H developments Ltd. (<https://www.pandhdevelopments.com/>). Diopside or albite (Si), corundum (Al), orthoclase (K), rutile (Ti), wollastonite (Ca), periclase (Mg), albite (Na), Fe₂O₃ (Fe), rhodonite (Mn) and Cr₂O₃ (Cr), NiO (Ni) and celestine (Sr) were used as primary standards. In the case of mineral phases, detection limit of most elements at 2sigma confidence level is below 0.03 wt% with exception of Na (0.04 wt%), Cr (0.08 wt%) and Sr (0.14 wt%). Detection limits for glass are below 0.05

Fig. 2. a) Simplified geological map of Deception Island (modified from Martí et al., 2013; Smellie and López-Martínez, 2002b) showing the distribution of the two main tectonic fault sets, NW-SE and NE-SW according to De Rosa et al. (1995). Data obtained from Spatial Data Infrastructure for Deception Island SIMAC (Torrecillas et al., 2006) and López-Martínez et al. (2000). b) The three cartoons present the volcanic evolution of the island starting with the composite volcano formation, followed by the caldera collapse, and finishing with the post-caldera eruptive episodes (modified from Martí et al., 2013). c) Total Alkali vs. Silica diagram (TAS) (Le Bas et al., 1986) for Deception Island rock samples (see Geyer et al., 2019) and the rock samples of Stanley Patch volcano (See Table S3). Major elements are normalized to 100% (anhydrous) with Fe distributed between FeO and Fe₂O₃ following Middlemost (1989). d) Example of one of the rock samples collected at Stanley Patch volcano. Plane light (center) and scanning electron (right) microscope images of the samples are also included. Gl: Interstitial glass; Pl: Plagioclase; Px: Pyroxene.

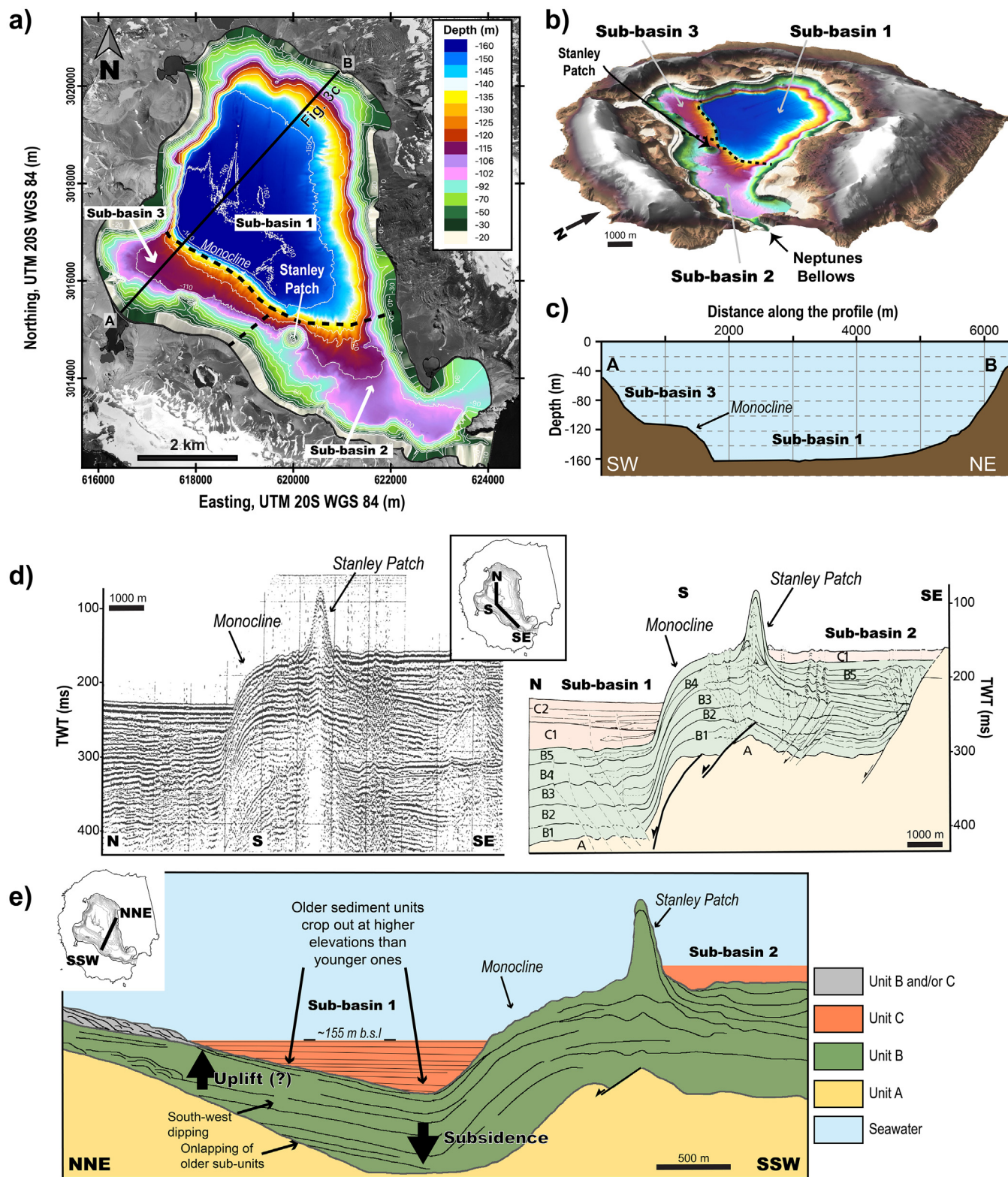


Fig. 3. a) Deception Island orthophotomap (data obtained from Spatial Data Infrastructure for Deception Island SIMAC, [Torrecillas et al., 2006](#)) and Digital Elevation Model of Port Foster obtained during the 2012 and 2017–2018 Spanish Antarctic Campaign by the Marine Hydrographic Institute. The limits of the different sub-basins are also indicated. b) 3D shaded relief map of Port Foster and Deception Island. Vertical exaggeration is $\times 1.5$; c) bathymetric profile of Port Foster. The location is shown in a); d) composite seismic reflection profile (Sparker) (left) and its interpretation (right) obtained across Port Foster, showing the seismo-acoustic depositional units A, B and C described in the text (after [Rey et al., 1995](#)); e) simplified schematic composite section across Port Foster (modified from [Kowalewski et al., 1990](#); [Rey et al., 1995](#); [Smellie, 2002a](#)).

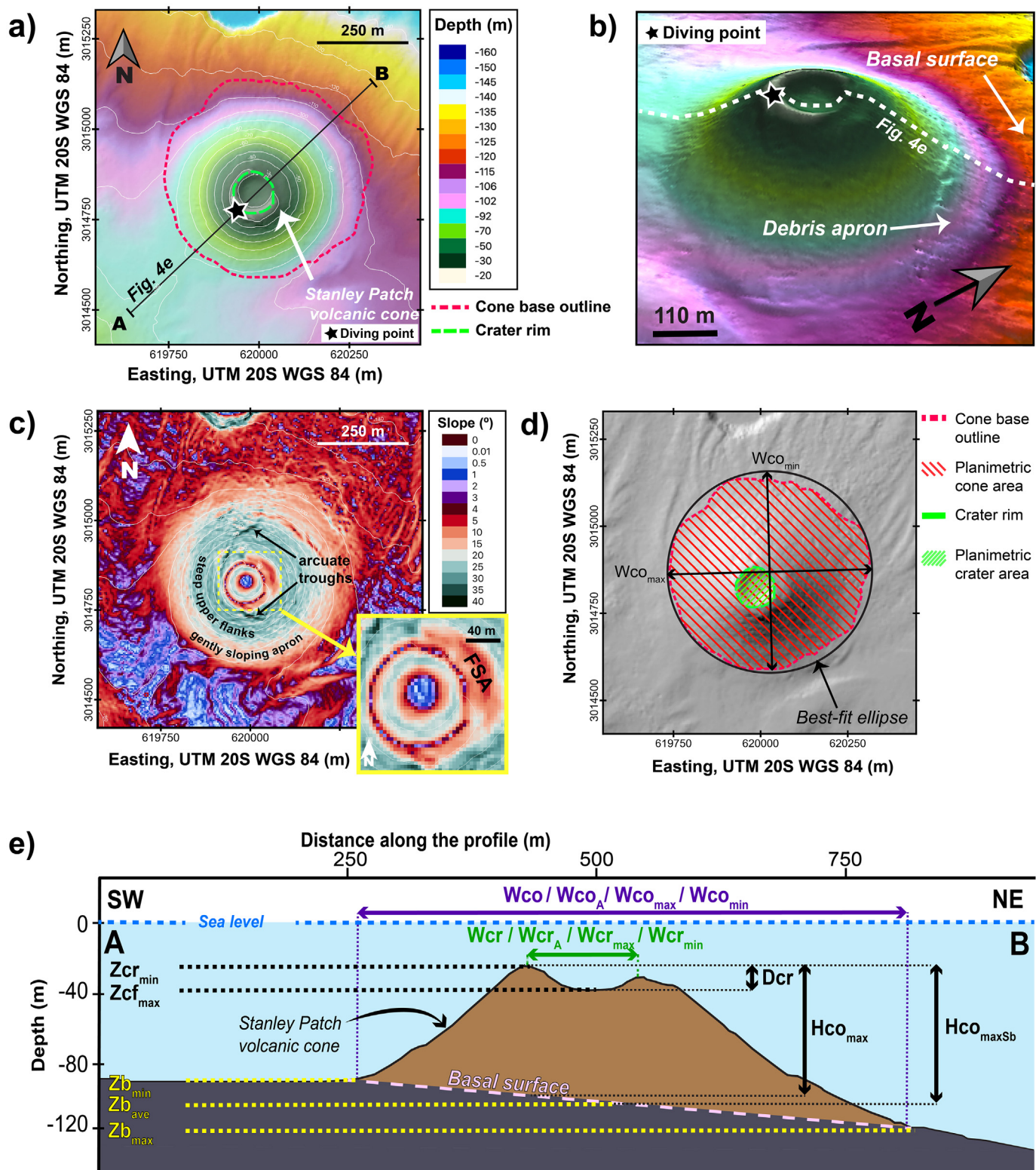


Fig. 4. a) Bathymetric map of Stanley Patch volcano, showing the location of the profiles displayed at e) as well as the cone base outline and crater rim. b) 3D shaded relief map of Stanley Patch volcano: the debris apron around the NE side of the cone are clearly observed. c) Slope map of Stanley Patch volcano, showing the location of the flat summit area (FSA), the arcuate flank troughs and the surrounding debris apron. d) DEM-derived upper view of Stanley Patch volcano. Cone and crater planimetric area, cone base outline and crater rim are also indicated. e) Bathymetric profile across SW-NE direction (see a) and b) for location). The morphological parameters measured at the cone are also indicated (see Table 1 for further explanation) (modified from Angulo-Preckler et al., 2021).

wt% for Si, Al, Na, Mg, Mn, Fe and Ni and below 0.03 wt% for Ca and K. Ti, Cr and Sr show higher detection limits (0.08 wt%, 0.14 wt% and 0.3 wt%, respectively). An up to 20- μ m-diameter defocused beam was used for groundmass analyses in order to minimize Na migration.

We also analyzed the stable isotopic ratios (δD , $\delta^{18}O$) of the selected samples. To prepare the samples for analysis we removed several centimeters of material from the surface of each sample to avoid late isotopic modification by weathering. Absence of secondary minerals such as

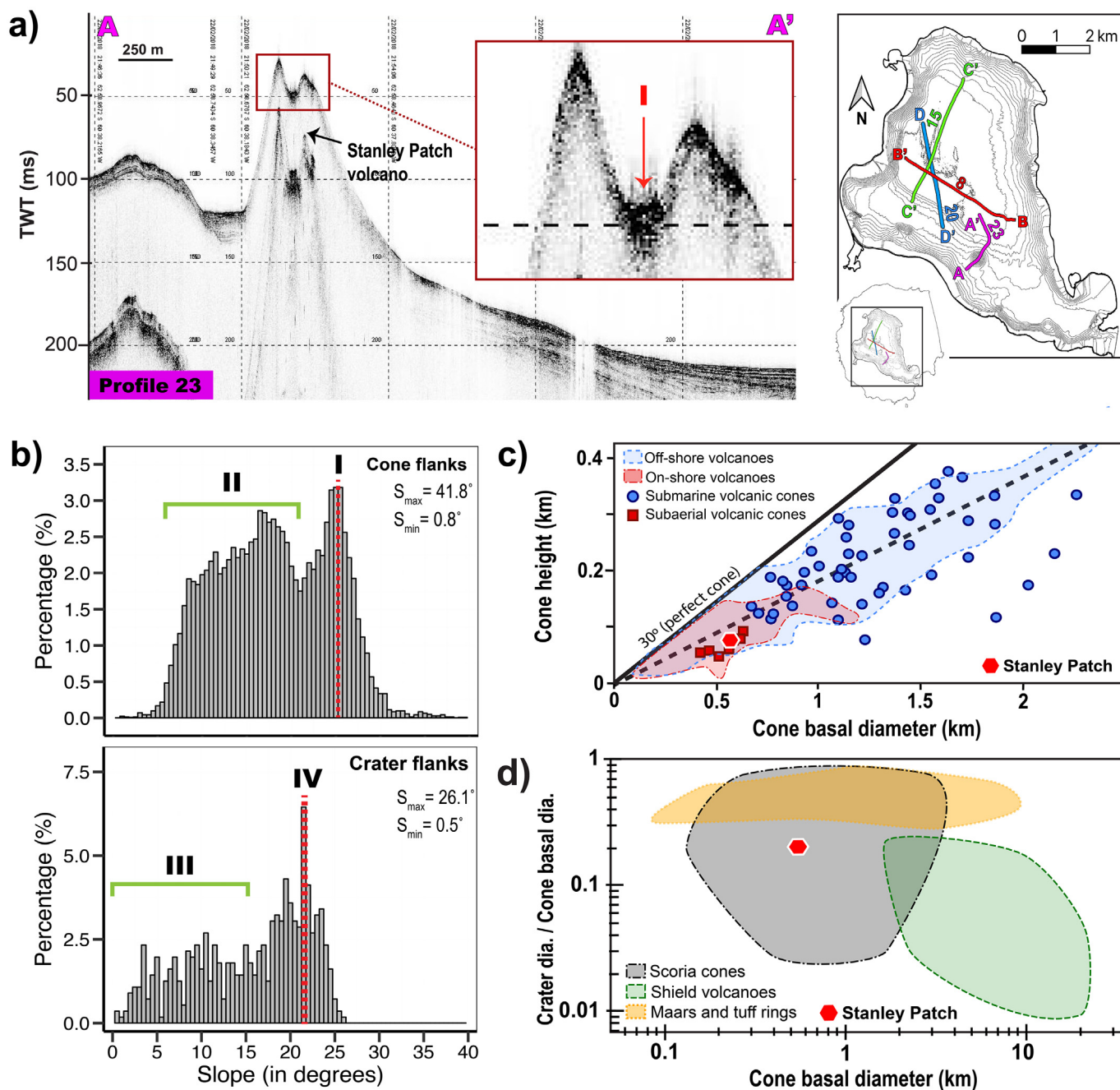


Fig. 5. NW-SE high resolution seismic profiles across Stanley Patch volcano (available at Gómez-Ballesteros et al., 2018). TWT: Two-way-time proxy for depth. The map on the right indicates the location of the profile A - A' (Profile 23) and of those included in Fig. 6a–c. b) Density slope diagrams of the cone (top) and crater inner flanks (bottom). c) Average cone basal diameter vs height for Stanley Patch volcano compared to well-studied on-shore and off-shore volcanic edifices observed at Pico Island (Azores) (blue circles and red squares, data from Mitchell et al., 2012) and Terceira Rift/São Miguel island (blue and red area, data from Weiß et al., 2015). d) Crater diameter/cone basal diameter ratio vs cone basal diameter of Stanley Patch volcano compared to the values for several other types of terrestrial volcanic edifices according to Brož and Hauber (2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

zeolite group minerals was confirmed through an exhaustive petrographic analysis. The hydrogen and oxygen isotopic analyses were carried out at the Servicio General de Análisis de Isótopos Estables (NUCLEUS - Universidad de Salamanca, <https://nucleus.usal.es/en/isotopes>) following the detailed extraction procedures, standards and equipment used, as well as reproducibility determination, described in Álvarez-Valero et al. (2020).

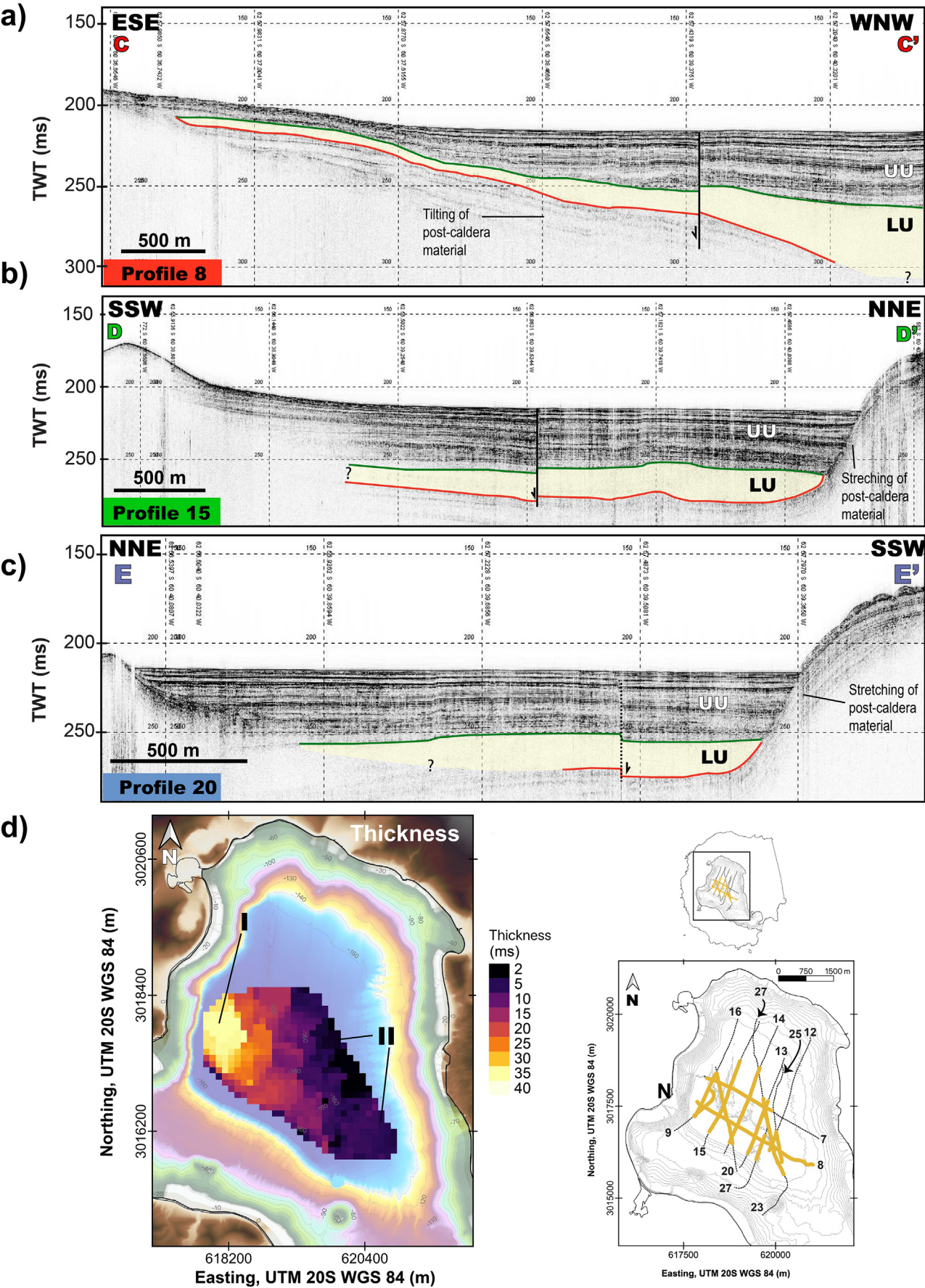
Argon isotopic ratios of the groundmass materials already analyzed by XRF in samples SUB_3, SUB_4, and SUB_7 were measured using a noble-gas mass spectrometer MS-IV (a modified VG-5400) in the Department of General Systems Studies, Graduate School of Arts and Sciences, The University of Tokyo. K% is obtained by the K_2O wt% content through the

XRF analysis described above. The analytical procedure in detail and calculation method are described by Miyoshi et al. (2012), Mori and Mashima (2005), Nagao et al. (1984, 1996) and Orihashi et al. (2004).

4. Results

4.1. Morphological analysis

Stanley Patch rises sharply from the north-east trending and gently dipping ($\sim 3^\circ$) seafloor (Figs. 4e and S3). The overall shape of both crater and base is very circular with a planimetric basal (Aco) and crater area (Acr) of $\sim 2.4 \times 10^5 \text{ m}^2$ and $\sim 0.1 \times 10^5 \text{ m}^2$, respectively. The volcanic



cone presents a maximum basal diameter ($W_{co,max}$) of ~589 m and a minimum diameter ($W_{co,min}$) of ~578 both obtained from a manually drawn best-fitting ellipse, where the major axis corresponds to the cone's maximum diameter (Wood, 1980b) (Fig. 4d, Table 1). The average cone basal diameter varies from 584 m (W_{co}) to 553 m ($W_{co,A}$) depending if calculated as the arithmetic mean of $W_{co,max}$ and $W_{co,min}$ (i.e., W_{co}) (e.g., Pedrazzi et al., 2020; Wood, 1980b) or estimated as the diameter of a circle with an area equivalent to A_{co} (i.e., $W_{co,A}$) (e.g., Favalli et al., 2009; Kervyn et al., 2012). Maximum cone height ($H_{co,max}$) is ~77 m but rises up to ~80 m ($H_{co,maxSb}$) when considering it as difference between the average basal elevation ($Z_{b,ave}$) and the minimum water depth observed at the cone's rim crest or summit ($Z_{b,min}$) (Table 1 and Fig. 4d) (Settle, 1979). This results in similar height and width ratios regardless of the calculation method, ranging between ~0.132 ($H_{co,max}/W_{co}$) and 0.145 ($H_{co,maxSb}/W_{co,A}$), and a cone volume (V_{co}) of 0.06 km³.

The crater rim has a shallow crest with a maximum ($W_{cr,max}$) and minimum ($W_{cr,min}$) diameter of 123 and 117 m, respectively. The average crater diameter ranges from 113 m ($W_{cr,A}$) to 120 m (W_{cr}) depending on the calculation method (Table 1). This results in a W_{cr} and cone basal diameter ratio in the range of ~0.193 ($W_{cr,A}/W_{co}$) to 0.217 ($W_{cr}/W_{co,A}$). The crater floor is flat with a diameter (W_{cf}) of ~39 m and a maximum depth (D_{cr}) of ~13 m (Table 1, Fig. 4d).

The cone is characterized by steep upper flanks, separated by a break-in-slope from a gentle sloping apron (Figs. 4b and c). The cone slope angle histogram shows two major slope angle modes centered at ~25° (Fig. 5b I) and a broad feature between 8 and 20° (Fig. 5b II). The intra-crater slopes are generally less steep (Figs. 4c and 5b III), partially due to the crater floor being filled up by sediments (Fig. 5a I). The Stanley Patch cone is also characterized by the following morphological features (Fig. 4b and c): (1) a flat to gentle sloping wide crest of the crater rim (5–15°) on the northeast side; (2) a break-in-slope between the uniformly inclined flanks and a gentle sloping apron surrounding the Stanley Patch volcano; and (3) two arcuate troughs running from N to S on the flanks.

4.2. Petrographic and geochemical analyses

The rock samples collected on the crater rim of Stanley Patch correspond to low density and poorly vesicular (25–35% vesicles volume; Houghton and Wilson, 1989) scoriaceous fragments from 2 to 15 cm in size (Figs. 2e and S4). Vesicle sizes are normally smaller than 1 mm, rarely reaching up to 3–4 mm, and fairly elongated to irregular in shape. In hand specimens, the fragments are usually black, with local reddish-brown oxidized zones. Most samples show a < 0.5 mm thick, yellow to green carbonate crust corresponding to encrusting coralline algae.

At microscopic scale, the studied samples are porphyritic with phenocrysts content below 1–2 vol% immersed in a hyalopilitic textured groundmass consisting of plagioclase, pyroxene, Fe—Ti oxides, and interstitial glass. Phenocrysts are dominated by euhedral plagioclase crystals from 0.5 to 1.0 mm in diameter, with minor subhedral phenocrysts of clinopyroxene and olivine ranging from 0.3 to 0.5 mm (Figs. 2e and S4). Quenching textures such as skeletal or dendritic shapes are not observed. Spiky crystals with swallow-tailed terminations are scarce, whereas sideromelane is mainly present as micrometric glass fragments filling vesicles.

Based on whole rock geochemistry, the sampled rocks classify as subalkaline basaltic trachyandesites and basaltic andesites (53–55 wt% SiO₂) (Figs. 2c and S6, Table S3). Despite their small range in composition, they present slightly negative correlations of MgO and CaO with

SiO₂, and positive ones of K₂O and Na₂O (Fig. S7). REE contents depict nearly straight trends in a chondrite-normalized diagram without significant anomalies (Fig. S8). In contrast, marked positive anomalies (Cs and Pb) and negative (Nb) anomalies occur in the primitive-mantle normalized diagram (Fig. S9).

Olivine micropheno- and microcrystals show forsterite contents ranging from Fo₄₉ to Fo₇₂ and Ni contents varying from 33 to 563 ppm. Microphenocrysts and phenocrysts of pyroxenes (augites), show composition of Wo_{25–44}, En_{37–52}, Fs_{10–22}. Plagioclases are mainly labradorites and andesines with An₆₂–An₃₈ (Fig. S10c and Table S7). In sample SUB_7, plagioclase ranges from bytownite to oligoclase (An₇₅ to An₁₀). In addition, samples SUB_4 and SUB_7 display local ilmenite and titanomagnetite (Fig. S10d and Table S8). Glass compositions are notably variable, going from basaltic to trachyandesitic with SiO₂ contents of 51–59 wt% and 56–62 wt% in samples SUB_5, SUB_7, and SUB_8, respectively (Fig. S6). In contrast, regarding silica content, glass is mostly homogeneous in samples SUB_3 and SUB_4. In general, glasses show a negative correlation of MgO and CaO with SiO₂, and a positive correlation of K₂O and Na₂O. Contents of TiO₂, FeO, Al₂O₃, and MnO show a notable chemical dispersion (Figs. S6 and S7). This significant variation in the compositional ranges of phenocrystals and glasses is consistent with the mixing mechanisms occurring at depth, which are widely observed in the products of the entire island (e.g. Smellie, 2001, 2002a; Geyer et al., 2019, 2021).

D/H ratios of the Stanley Patch samples range from –58.4 to –99.5‰ (Fig. S11) with homogeneous water contents of 0.1–0.2 wt% (Table S9). All samples fall within the range of regular primary magmatic fluids (i.e., igneous waters in Fig. S11), slightly above and immediately below the isotopic composition of N-MORB mantle (–60‰; Clog et al., 2013). $\delta^{18}O$ values show small variation from 5.0 to 6.3‰ within the usual values of basaltic rocks on Earth ($\approx$ 3.5–7‰) (Bindeman, 2008), and in line with the onland samples of the island (Álvarez-Valero et al., 2020).

4.3. Shallow seismic sub-bottom structure of Port Foster

The ultra-high resolution seismic stratigraphy of the uppermost (< 300 ms) deposits infilling Port Foster (Figs. 6 and S1) show two distinct sedimentary units abutting the monoclinical structure. The Lower Unit (LU) represents a striking and relatively thick seismically transparent body that occupies an extensive part of sub-basin 1, overlapping its margins (Figs. 6 and S1). This unit reaches its maximum thickness of ~38 ms (i.e., ~30–36 m) in the northwest, at the base of (or even beneath) the western submerged flank of Wensleydale Beacon's volcanic edifice (Fig. 6d I); it gets thinner towards the north and north-east of the bay (Fig. 6d II). The volume of this unit is estimated to be >0.055 km³. The LU, which correlates to sub-unit C1 of Rey et al. (1995, 1997) (Figs. 3d and e) and Kowalewski et al. (1990), is overlaid by an Upper Unit (UU) (up to c. 50 ms thick). The UU, equivalent to sub-unit C2 of Rey et al. (1995, 1997) and C2 plus D of Kowalewski et al. (1990), is made up of the vertically stacked even-layered deposits separated by irregular transparent bodies (a few ms thick), which resemble smaller-scale mass-flow deposits (Fig. 6).

5. Discussion

5.1. Stanley Patch: a submerged subaerial volcanic cone

The height and width ratios for the edifice and its crater show an overlap with terrestrial scoria cones (e.g., Kervyn et al., 2012; Settle,

Fig. 6. (a) to (c) Seismic profiles obtained within Port Foster (available at Gómez-Ballesteros et al., 2018). See Fig. 5a for location. The Lower Unit (LU) is colored in yellow with its top and base highlighted in green and red, respectively. If clearly visible, faults are also indicated. UU: Upper Unit. See text for further details. d) Thickness map (in ms) estimated for the Lower Unit. The orange colour indicates the lateral coverage where the Lower Unit is observable in the seismic profile included in a) to c) and in Figs. 5a and S1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Morphometric parameters measured for Stanley Patch volcano. b.s.l. Below sea level.

Parameter	Unit	Description	Value
Aco	m ²	Planimetric area of the cone including crater and outer flanks (see Fig. 4d).	$2.4 \cdot 10^5$
Acr	m ²	Planimetric area of the cone crater including crater floor and inner flanks (see Fig. 4d).	$1 \cdot 10^4$
Dcr	m	Crater depth calculated as (Hooper and Sheridan, 1998; Wood, 1980a): $Dcr = Z_{cf_{max}} - Z_{cr_{min}}$	13
Hco _{max}	m	Maximum cone height calculated as the maximum elevation of the crater rim above the 3D basal surface (see Fig. 3e) (Favalli et al., 2009).	77
Hco _{maxSb}	m	Maximum cone height calculated as Settle (1979): $Hco_{maxSb} = Zb_{ave} - Z_{cr_{min}}$	80
Sb _{mean}	degree	Slope of the basal plane obtained by applying a linear regression to the points obtained along a profile aligned along the maximum dip direction of the basal surface (Fig. S3c and g).	3
Vco	km ³	Cone volume enclosed between the DEM surface and the 3D base surface determined from the surrounding topography and the bilinear/bicubic spline interpolation with Tykhonov regularization (see Fig. S3e).	0.06
Wcr _{max}	m	Maximum crater diameter measured along four profiles spaced 45° azimuthally, with one of them aligned along the maximum dip direction of the basal surface (Wood, 1980b)	123
Wcr _{min}	m	Minimum crater diameter measured along four profiles spaced 45° azimuthally, with one of them aligned along the maximum dip direction of the basal surface (Wood, 1980b)	117
Wcr	m	Average crater diameter calculated as (Wood, 1980b): $Wcr = (Wcr_{max} + Wcr_{min})/2$	120
Wcr _A	m	Average crater diameter calculated as (Favalli et al., 2009): $Wcr_A = (4 \cdot Acr/\pi)^{0.5}$	113
Wco _{max}	m	Maximum cone basal diameter obtained from a manually drawn best-fitting ellipse, where the major axis corresponds to the cone's maximum diameter (Wood, 1980b) (see Fig. 4d).	589
Wco _{min}	m	Maximum cone basal diameter obtained from a manually drawn best-fitting ellipse, where the major axis corresponds to the cone's maximum diameter (Wood, 1980b) (see Fig. 4d).	578
Wco	m	Average cone basal diameter calculated as (Wood, 1980b): $Wco = (Wco_{max} + Wco_{min})/2$	584
Wco _A	m	Average cone basal diameter calculated as (Favalli et al., 2009): $Wco_A = (4 \cdot Aco/\pi)^{0.5}$	553
Zb _{max}	m	Maximum basal depth b.s.l. (in absolute value).	120
Zb _{min}	m	Minimum basal depth b.s.l. (in absolute value).	90
Zb _{ave}	m	Average basal depth b.s.l. (in absolute value) calculated as: $Zb_{ave} = (Zb_{max} - Zb_{min})/2$	105
Zcf _{max}	m	Maximum depth b.s.l. (in absolute value) of the cone crater floor.	38
Zcr _{min}	m	Minimum depth b.s.l. (in absolute value) of the cone crater rim.	25

1979; Wood, 1980b) (e.g., Fig. 5d). The obtained values, independent of the calculation method applied, match with young cone populations from Mt. Etna (Italy) (Favalli et al., 2009), Lanzarote (Canary Island) (Kervyn et al., 2012), and Mauna Kea (Hawaii) (Kervyn et al., 2012). The morphometric values of Stanley Patch, however, are in contrast with onshore monogenetic edifices, which are mostly tuff cones and tuff rings with much wider craters and lower edifice height/width ratios (Pedrazzi et al., 2020). In general, submarine pyroclastic cone populations show a much larger range of edifice height and width ratios, and typically they are larger in volume (Fig. 5c) (e.g., Mitchell et al., 2012; Weiß et al., 2015).

The bimodal slope angle distribution of the cone flanks (Fig. 5b I and II) can correspond to hillslope erosion and sediment transport. The gentle sloping areas around the cone (Fig. 4b and c) are interpreted to be a debris apron formed due to syn-eruptive reworking and post-eruptive erosional processes (e.g. debris flows) (e.g., Dohrenwend et al., 1986; Ferrucci et al., 2005; Kereszturi and Németh, 2016a; McGetchin et al., 1974). The steeper (~25°) upper cone flanks have a slope angle lower than the typical angle of repose value (30–35°) (Wood, 1980a, 1980b), indicating eruption-related deviation of the pyroclastic successions, including grain size, welding, and agglutination differences among flank sectors (e.g., Kereszturi et al., 2012; Kereszturi and Németh, 2016b; Kervyn et al., 2012; Valentine et al., 2005), and/or erosional processes (e.g., Hooper and Sheridan, 1998). The arcuate troughs on the flank of Stanley Patch resemble discontinuity surfaces and small-stepped scars due to partial cone collapse (Fig. 4c). These features are present at many unwelded scoria cones (e.g., Németh et al., 2011; Riggs and Duffield, 2008; Sumner, 1998), and also observed in analogue experiments (Grosse et al., 2012). The geomorphology of the crater rim also suggests erosional rounding (e.g., Pelletier and Cline, 2007). The lower intra crater wall slope angles are interpreted to be caused by erosional modification, suggesting a post-eruptive rim-to-crater sediment transport combined with marine sedimentation.

Quenching of basaltic magma by surface water commonly forms a rim of pale brown glass (sideromelane) that progressively grades inward into more crystalline black glass (tachylite). Tachylite is the product of slower cooling rates, which yield a glass groundmass that hosts abundant cryptocrystalline microlites and/or nanolites of opaque

mineral phases, commonly Fe—Ti oxides (e.g., White et al., 2015). In addition, it also typically produces quenching textures in crystals, such as skeletal, dendritic, or globular shapes. On the other hand, interaction of magma with external water may enhance fragmentation either by hydromagmatic processes (which may also occur in subaerial settings) or hyaloclastite formation (exclusive from underwater conditions). In addition, it is widely accepted that magma-water interaction also affects the shape and volume of the vesicles (e.g. Mastin et al., 2004; Stovall et al., 2011; Ross and White, 2012). After emplacement, under wet and hot conditions, sideromelane quickly alters into palagonite (Stroncik and Schmincke, 2002). These key features of magma-water interactions are absent in the Stanley Patch samples, thus supporting negligible magma-water contact during the eruption (e.g., Bryan, 1972; Jercinovic et al., 1990; Walton and Schiffman, 2003).

Direct contact between seawater and magma -or volcanic rocks- during eruption or cooling can modify the original δD ratios of the glass towards heavier values (e.g., Friedman et al., 1993). δD ratios (in the range of −58.4 to −99.5‰) and water contents (0.1–0.2 wt%) of the studied samples are consistent with an initial magma composition within the range of the N-MORB mantle ($\delta D = -60 \pm 5\%$; Clog et al., 2013), and show no significant isotope contribution from seawater into the studied rocks. Thus, δD ratios and water contents preclude significant magma-seawater interaction during eruption or cooling, further supporting the subaerial origin of Stanley Patch.

Therefore, we state that the results of the morphological analysis, supported by the petrographic and isotopic geochemical data from the collected rock samples, suggest a subaerial origin for Stanley Patch despite its current subaqueous location.

5.2. Dating of Stanley Patch volcano

The numerous analytical and technical limitations of the K—Ar dating method makes it inapplicable for samples younger than 2000 years (e.g., Miyoshi et al., 2012; Mori and Mashima, 2005; Nagao et al., 1984; Nagao et al., 1996; Nier, 1950; Orihashi et al., 2004; Schaeffer and Zähringer, 1966; Solé, 2009). However, it is a useful age constraint test for the upper age limit of the Stanley Patch volcano. The $^{40}Ar/^{36}Ar$ ratios of the glasses (Table S9) are lower than the atmospheric $^{40}Ar/^{36}Ar$

(296.0) ratio. This yields negative $^{40}\text{Ar}^*$ (non-atmospheric ^{40}Ar) values that in turn imply negative K–Ar ages, i.e., less than 2000 years. Consequently, considering the subaerial origin of Stanley Patch cone and the proposed ages for its formation, the complete flooding of Port Foster by seawater likely happened during the last 2000 years. This agrees with the age of the caldera collapse of 3980 ± 125 calibrated years BP based on tephrochronology, sedimentology studies and ^{14}C dates (Antoniades et al., 2018) as well as the fact that the volcanic edifice is built on top of over a ~ 100 ms thick pile of post-caldera sediments (at least, sub-units B1 to B3) (Rey et al., 1995, 1997, 2002; Somoza et al., 2004), suggesting a considerable time period between the caldera collapse and the Stanley Patch's formation (Fig. 3d).

5.3. Reconstructing the past history of Deception Island's caldera

Our results support the hypothesis that Stanley Patch volcano grew in a subaerial environment, hence indicating that at least the southern (shallower) sector of Port Foster (i.e., sub-basins 2 and 3) was not covered by water immediately after the caldera collapse. This reveals that the complete flooding of Deception Island caldera by seawater could only have occurred after the formation of Stanley Patch volcano. This, combined with the previously published stratigraphic, sedimentological, geophysical and petrological data, allows us to depict a comprehensive geologic evolution of Deception Island. We distinguish the following major evolutionary stages and events: (i) pre-caldera stage; (ii) caldera collapse event; (iii) early (pre-flooding) post-caldera stage; (iv) caldera sea flooding event; and (v) late (post-flooding) post-caldera stage (Fig. 7).

5.3.1. Pre-caldera stage

Most of the pre-caldera volcanic activity likely originated from several vents, representing a period of shoaling and emergence of the volcanic island (Fig. 7a) (e.g., Baker et al., 1975; Baraldo et al., 2003; Birkenmajer, 1992; Hawkes, 1961; Holtedahl, 1929; Martí and Baraldo, 1990; Olsacher, 1956; Smellie, 2001, 2002a). The most recent paleo-topographic reconstruction of the island suggests the presence of a paleo-edifice with a paleo-summit height of about 640 m.a.s.l and parasitic volcanoes (< 650 m height) in the locations presently known as Neptunes Bellows and Macaroni Point (Fig. 7a) (Torrecillas et al., 2013).

5.3.2. Caldera collapse event

During the caldera collapse, the OCTF was emplaced radially from the caldera borders, mantling older deposits and progressively infilling the caldera depression (e.g., Martí et al., 2013; Smellie, 2001, 2002a). Most probably, the caldera collapse took place through distinct caldera blocks that subsided (likely synchronous) into the emptying magma chamber (e.g., Martí et al., 2013) (Fig. 7b). In this sense, the fault-related monocline currently separating the bay's sub-basins may represent the limit of -at least- two subsiding blocks (Fig. 7b). The caldera collapse can therefore be subdivided into a central zone (main block, current sub-basin 1) and a marginal zone tilted towards the caldera interior (secondary block(s), current sub-basins 2 and 3). Subsidence difference between the two main described blocks at the moment of the caldera collapse is still uncertain. However, the current deformation, stretching and tilting of the post-caldera sedimentary units observed in the seismic profiles (Unit B in Figs. 3d, e and 6) indicate that the main block has been continuously subsiding in a trap-door manner since the caldera collapse (Rey et al., 2002). This collapse mechanism and structure is similar to other calderas worldwide (e.g., Rotorua, New Zealand; Milner et al., 2002) and consistent with the modelling results of sand-box analogues (e.g., Acocella, 2006, 2007; Geyer et al., 2006; Roche and Druitt, 2001). Considering the figures presented by Martí et al. (2013) based on available geophysical data (e.g., Ben-Zvi et al., 2009; Grad et al., 1992; Luzón et al., 2011; Rey et al., 1995; Zandomenighi et al., 2009), the caldera floor may

have subsided ~1.8 km, whereas the intra-caldera OCTF deposits would be as thick as ~1.2 km (Fig. 7b). Based on our present findings, the secondary block, corresponding to sub-basins 2 and 3, should have stayed "dry" at least until the construction of Stanley Patch volcano (< ~ 2000 years ago). The caldera should have remained closed to the sea and, most probably, was only filled by fresh water coming from rainfall, and snow and ice melting, which accumulated in the deepest parts of the northern sub-block or sub-basin 1 (Fig. 7b and c). During decades and even centuries after the collapse, the water level of this shallow lake may have varied as seen in other caldera systems potentially hosting internal lacustrine ecosystems (e.g., Sete Cidades-Azores; Rull et al., 2017; Vázquez-Loureiro et al., 2019).

5.3.3. Early (pre-flooding) post-caldera stage

After the caldera-forming event, volcanic activity was characterized by (e.g., Smellie, 2001, 2002a): (i) the formation of scoria cones aligned along previous active fissures (Fig. 7c I); (ii) abundant effusive activity on the outer slopes leading to prominent lava platforms (Fig. 7c II); (iii) occasional lava flows within the caldera (Fig. 7c III) and over the caldera wall (Fig. 7c IV); and (iv) hydromagmatic activity from centers distributed both outside (e.g., Baily Head (Fig. 7c V)) and within the caldera (Fig. 7c VI). During this period, volcanic activity also occurred inside the bay in sub-basins 2 and 3 as previously interpreted from the seismic profiles across Port Foster and as evidenced by the presence of Stanley Patch volcano (Fig. 7c VII).

5.3.4. Caldera sea flooding event

At some time after the formation of Stanley Patch volcano, the caldera became open to the sea leading to its complete flooding. Our ultra-high resolution seismic stratigraphy of the uppermost (< 300 ms) deposits infilling Port Foster (see Figs. 6 and S1), in line with the observations made by Kowalewski et al. (1990), indicates a sharp change in the sedimentary history of the bay after the deposition of the LU. The shape, seismic facies, boundaries and thickness distribution of this unit, all point to a large mass-flow deposit (e.g., Casas et al., 2013; Masson et al., 1996) sourced from the southeast (Whalers Bay and/or Neptunes Bellows area) (Fig. 7d I). The seismic characteristics of the LU displayed by the ultra-high resolution TOPAS profiles show transparent facies resembling an amalgamated deposit with local lack of penetration of the acoustic signal. An irregular blocky character with hyperbolic echoes is not observed. The LU has been previously interpreted as the result of the sudden deposition of pyroclastic materials carried down by large onshore-generated lahars (Kowalewski et al., 1990). However, since it is the thickest and most voluminous sedimentary unit compared to the ones composing the UU, we state that it originated due to an extreme and unique event, not since repeated. We propose that the LU corresponds to the materials deposited by an exceptional mass flow event that occurred during the outburst flood that inundated the caldera to its present sea level. Here, we use the term mass flow as a generic expression that involves different types of sediment-gravity flows, e.g., debris flow, debris avalanches. Nevertheless, those processes on volcanic environments are not distinct and/or separate but may be part of a process continuum (Mulder and Cochonat, 1996; Masson et al., 1998). Likewise, the distribution of the slide sediment is in general governed by the nature of the landslide material, the flow process and/or the emplacement speed (e.g., Masson et al., 2002). Both considerations would imply that the process responsible of the LU could have initiated as a debris avalanches evolving to a debris flow due to disaggregation occurred during the transport that extends to the interior of Port Foster. Similar processes have been considered to occur in the Canary Islands (e.g., Masson et al., 1998). We have not evidences/information about the mechanical behaviour of the slope failure at the headwall/source area, only evidences of the distal domain (depositional) of that sediment gravity-driven event. A mass flow event that in any case is unique in the area based on its magnitude, as it is well reflected by the stratigraphic divisions and their deposits.

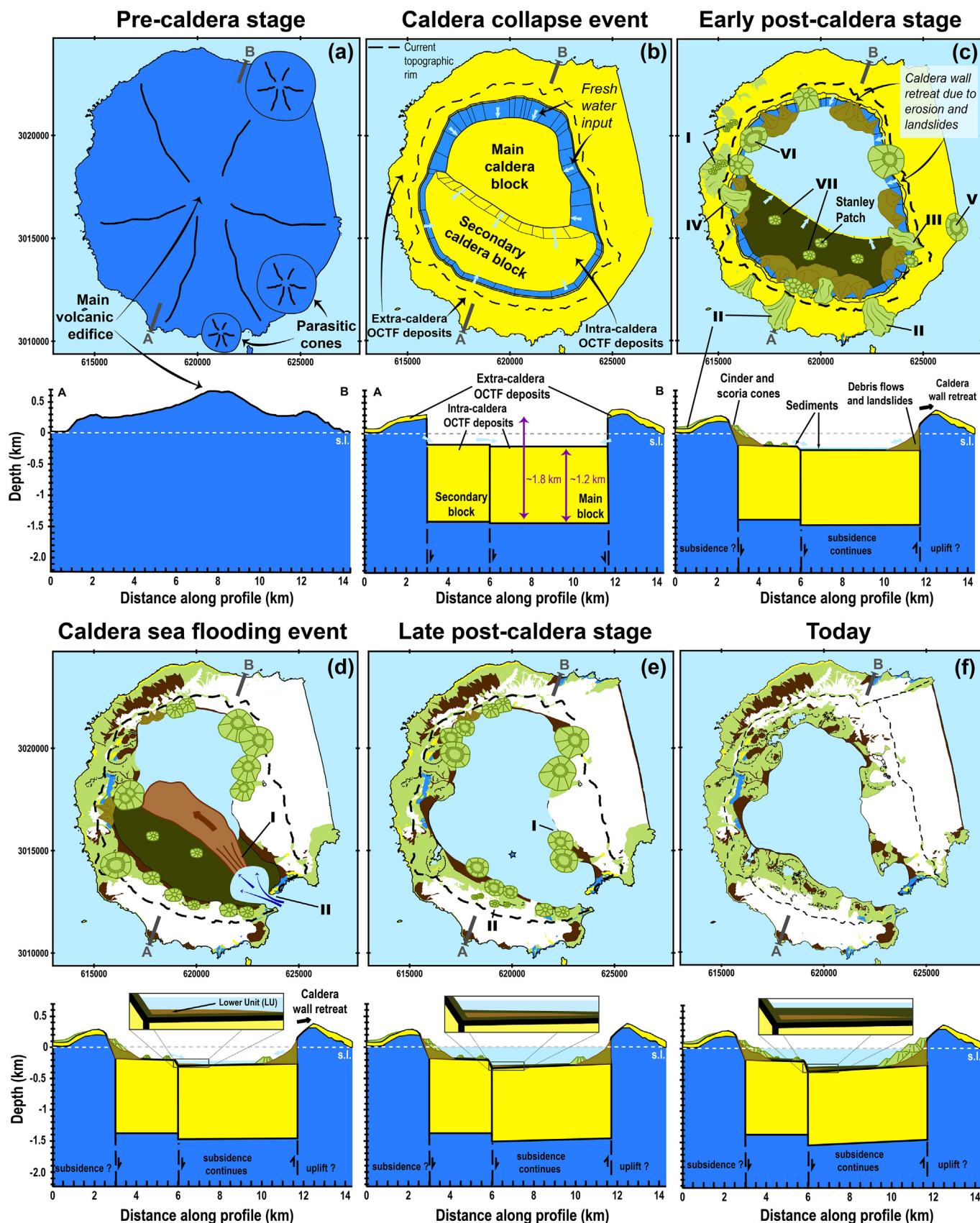


Fig. 7. Conceptual model of the evolution of Deception Island based on the review of available geological and geophysical data and new results presented in this work. Main phases and events include: a) pre-caldera stage; b) caldera-forming event; c) early post-caldera phase; d) caldera flooding event; e) post-flooding phase; and f) current stage. Legend as per Fig. 2a.

Accounting with all the sedimentological and morphological features of the LU pointing its source at the southeast of the bay, and the fact that the volume of this body ($> 0.055 \text{ km}^3$) can be roughly correlated with the “missing” material from Neptunes Bellows

(Figs. 8a and b). We conclude that it resulted from the sudden collapse of the caldera wall at that precise location. This opened the inner area of the island – at that time below sea level – to the ocean (Fig. 7d I). This argument agrees with the stratigraphic observations by Kowalewski

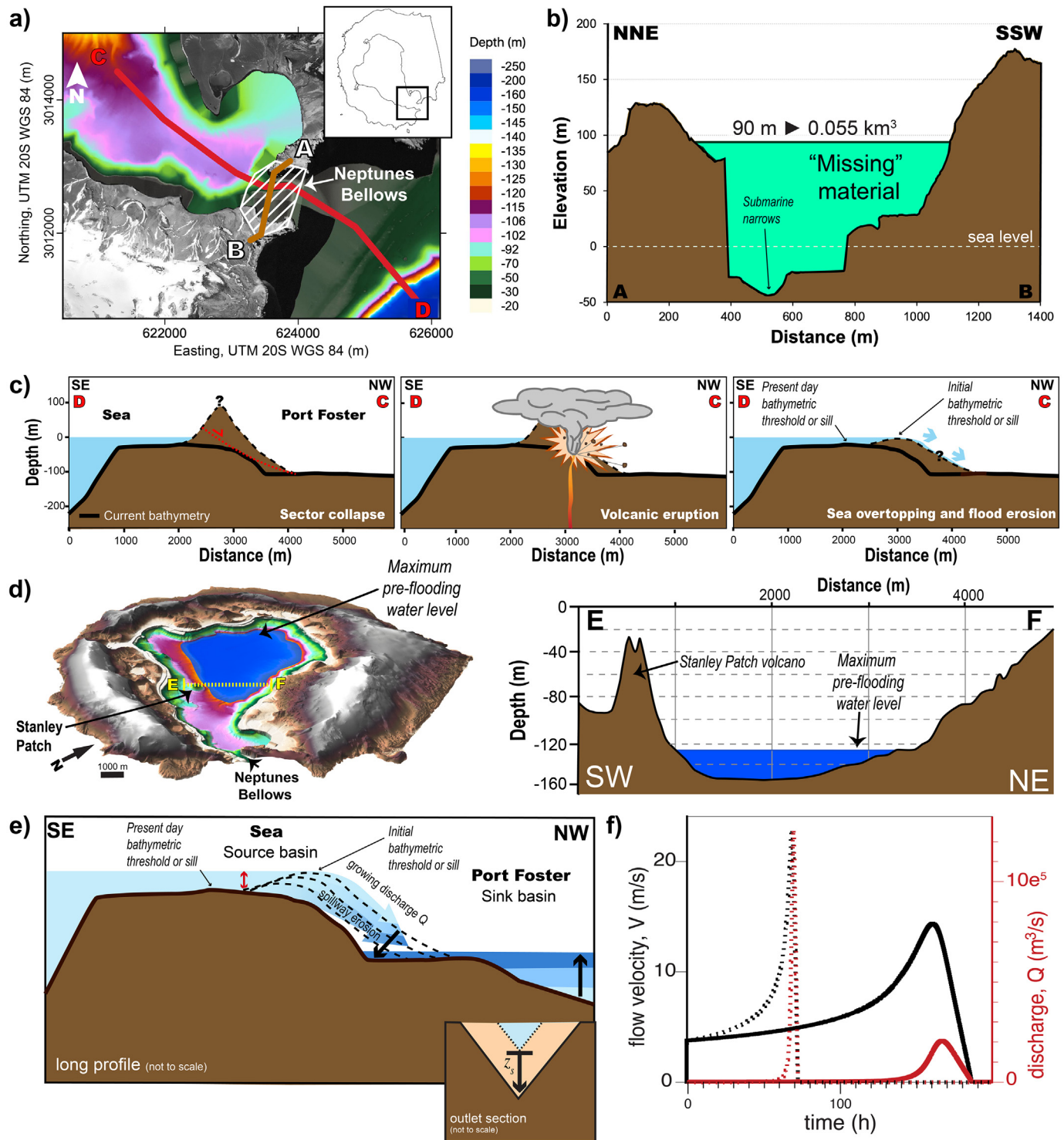


Fig. 8. DEM of Port Foster and orthophotomap of Deception Island showing in plan view (white dashed area) and cross sectional view (green colored area in b) of the area used to estimate the volume “missing” from Neptunes Bellows; c) Sketch of the three different, yet not mutually exclusive processes, that may have led to the opening of the caldera to the sea and consequently, to the outburst flood. d) 3D shaded relief map of Deception Island (left) and bathymetric profile of Port Foster (right). The maximum pre-flooding water level is indicated. Vertical exaggeration: $\times 1.5$. e) Conceptual model (section along the inlet) of sea overtopping and outburst flood development as a result of water discharge and inlet erosion at the threshold. For the parameters involved see the text. f) Numerical model results of flood development after breaching or overtopping. Curves for water velocity V (in black) and discharge Q (in red) are shown for two final sill depths (final depth of the threshold below sea level): 15 m (solid lines) and 30 m (dashed lines). See main text and Fig. S13 for further details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al. (1990), who concluded that the flooding of the caldera by seawater may have occurred after the deposition of their unit B (our LU), and that C and D (composing our UU) were undoubtedly deposited in submarine conditions.

5.3.5. Late (post-flooding) post-caldera stage

After the flooding, volcanic activity continued on the island until historical times and as recently as 1970, around the shores of Port Foster (Fig. 7e I), and along on-land fissures (Fig. 7e II). Since the caldera flooding episode, the volcanic activity in the deepest parts of Port Foster has been apparently limited to hydrothermal venting with no clear evidence of submarine or Surtseyan activity (Somoza et al., 2004). The shallow seismic sub-bottom stratigraphy and facies of the UU point to a significant change in the sedimentation of Port Foster, as it is suggested by the unconformity dividing the UU of the LU, and the distinctive expression of UU seismic facies.

5.4. Estimating the timing of the outburst flood and caldera refilling

Three main, yet not mutually exclusive, processes may have initiated the caldera wall breach and hence, triggered a sea flooding event (Fig. 8c): (i) a flank instability and major collapse of the pre-caldera edifice to the open sea or the caldera interior (e.g., Acosta et al., 1992); (ii) the occurrence of an explosive eruption at the caldera wall (e.g., Aparicio et al., 1997; Baraldo and Rinaldi, 2000); or (iii) overtopping of the sea potentially facilitated by the weakening of the caldera wall due to water infiltration leading to minor collapses. Once the oceanic water overtops the caldera wall, the erosion caused by the water influx gradually (but with initial rates increasing potentially; Figs. 8e and S13) enlarges and deepens the spillway (e.g., Kataoka, 2011). Among these three scenarios, the overtopping is the most conservative in terms of flood duration and peak discharge, because it assumes that the initial inflow of water is small and only its own erosion contributes to enlarge the inlet, thus progressively increasing the inflow rate. The smooth U-shape of the seaway floor and the seeming retrogressive erosion suggested by its bathymetry (the submarine bathymetric sill lays today out of the island) (Figs. 8c and d) argues for the third of these mechanisms, by similarity with other scenarios where the overtopping mechanism is well determined (e.g., Lake Bonneville, Abril-Hernández et al., 2018). Assuming this mechanism followed by ever-increasing water erosion of the topographic barrier separating the bay from the ocean, we can estimate a minimum peak water inflow and filling time (Fig. 8d). The mechanism is similar to other floods taking place due to the overtopping of lakes (O'Connor et al., 2013). However, in our case, contrary to floods sourced at natural lakes or breaching artificial dams, the water source (upper reservoir: the ocean) was effectively infinite. Hence, the flooding is limited by the size of the sink (the lower reservoir: the caldera), which is filled up to sea level.

To estimate the timing of the caldera refilling by overtopping of the sea at the Neptunes Bellows, we assume that: i) Port Foster was empty up to, at least, the base of the Stanley volcano, which remained exposed in an endorheic evaporitic basin at a depth below sea level similar to today's (i.e., 90–120 m b.s.l.) (Fig. 8d); (ii) the present depth of Neptunes Bellows has not been modified by subsidence of the island or eustatic sea level changes; and (iii) the present depth of the submarine bathymetric threshold between the caldera and the open ocean (30 m b.s.l.) is at least partially related to the erosion produced during the refilling flood (Figs. 8c and d). The latter is supported by the absence of comparable sea level changes since the formation of Stanley Patch volcano (Hallmann et al., 2018). Post-volcanic subsidence (of a tectonic or thermal nature) of the threshold area (or of the entire island), may undermine this assumption.

We use the present depth of the bathymetric threshold or sill (30 m; Figs. 8c and S12) as a constraint on the erosion produced during refilling, and apply a coupled erosion/hydrodynamic model to estimate the progress of the refill (García-Castellanos and O'Connor, 2018). The

numerical model spillover (available at <https://github.com/danigeos/spillover>) iteratively calculates the water discharge across a certain threshold as a function of its depth below a source water body (the global ocean in our scenario), and for a lower basin (sink) of known area and depth (Fig. 8e). This is coupled to a progressive deepening of the threshold due to erosion exerted by the water flow, following a basal shear-stress power law (Howard and Kerby, 1983).

$$\frac{dz_s}{dt} = -k_e \tau^a \quad (1)$$

where $z_s(t)$ is the depth of the sill (Fig. 8e), t is time, k_e is the erodibility of the rock, and τ is the shear stress at the base of the flow, proportional to water velocity, with an $a = 1.5$ (See García-Castellanos and O'Connor (2018) for a detailed formulation). For the calculation of basal shear stress and water velocity we adopt a critical flow at the sill where overtopping takes place and a sill widening that is proportional to its depth. We adjust the width's linear dependence on depth such as to fit the final model's width to the present observed width of the submarine narrows (120 m; Figs. 8b and S12).

With the aim of showing the sensitivity of the flood evolution to the total cumulative erosion at the inlet, results in Fig. S13 show two floods calculated for an initial one-meter deep breach of the ocean into the caldera, reaching a final erosion depth of 15 and 30 m, respectively. These two scenarios aim to show the sensitivity of our results to the assumption that most of this depth originated during the refill process. The rock erodibilities required for both scenarios are $k_e = 1.8e^{-3} \text{ m yr}^{-1} \text{ Pa}^{-1.5}$ and $4.2e^{-3} \text{ m yr}^{-1} \text{ Pa}^{-1.5}$; these values are consistent with the relatively weak volcanic lithology of the barrier, considering that linking erodibility to lithology involved orders of magnitude of uncertainty (García-Castellanos and O'Connor, 2018). Increasing the initial breach depth only advances the timing of the flood and vice versa, while keeping the peak discharge values largely unchanged. In the first scenario, the basin (Port Foster) is refilled in 180 h, although most of the flow is concentrated in the last 40 h. The second scenario evolves faster due to the weaker barrier and the refill takes place in only 100 h, with 95% of the flow concentrated in the last 10 h. Peak discharge changes from $1.92 \cdot 10^4$ to $1.24 \cdot 10^5 \text{ m}^3 \text{ s}^{-1}$. Erosion rates (Fig. S13) reach values 15 times faster in the second scenario. Thus, the first scenario, causing an erosion of only half of the present depth of the threshold, represents an estimation of the slowest refill mechanisms considered in this work. We can therefore conclude that, if most of the present depth of the threshold is related to erosion during the refill rather than to eustatic changes, then the process was very rapid, in the form of an outburst flood lasting a few days or less. Our results indicate that the filling of Deception Island's empty basin, only 3.5 km^3 in volume, may have proceeded to completion at peak rates of at least thousands of $\text{m}^3 \text{ s}^{-1}$, thus completing the bulk of the flooding in a time period of a few days or less (Figs. 8f and S13). This is comparable in order of magnitude to the estimates by Nomikou et al. (2016), the $\sim 20 \text{ km}^3$ Santorini caldera was filled in <2 days, involving a water velocity larger than 19 m/s and a water discharge above $2.5 \cdot 10^5 \text{ m}^3 \text{ s}^{-1}$.

6. Summary and conclusions

Significant efforts have been made to understand the complex magmatic and volcanic evolution of Deception Island. However, very few studies exist about the submerged volcanic edifices within Port Foster. The new geophysical data (bathymetric data and ultra-high resolution parametric seismic profiles of Port Foster) obtained during the 2017–2018 Spanish Antarctic Campaign, and the juvenile rock samples collected from Stanley Patch by SCUBA diving have allowed shedding new light on the eruptive event that lead to the formation of the largest volcanic edifice within Port Foster. The morphological characterization of this volcanic edifice, and the petrographic description and chemical analyses of the collected rock samples, all point to a subaerial

monogenetic explosive eruption as responsible for the formation of this scoria cone. This reveals that the caldera could have opened to the sea leading to its complete flooding only after the construction of Stanley Patch volcano ($< \sim 2000$ years ago). The caldera wall breach could have been triggered by a sector collapse of the pre-caldera edifice, the occurrence of an explosive eruption and/or overtopping of the sea with gradual erosion of the spillway. Anyhow, Deception Island's empty basin, may have been completely flooded in a few days or less, leading to an important inflexion point in the island's geological evolution. The flooding event not only changed the sedimentary dynamics within the caldera depression, but it also changed the eruptive style of post-caldera volcanic activity incrementing the potential of phreatomagmatic eruptions. This highlights the complex temporal and spatial aspects of a changing hazard landscape that must be incorporated into any volcanic hazard assessment of volcanic islands.

Data availability

Bathymetric data supporting this research, obtained by the Spanish Marine Hydrographic Institute, belong to the Ministry of Defense of Spain and are restricted to the public due to security reasons.

Seismic profiles for this research are available in Gómez-Ballesteros et al. (2018). Seismic Profiles from Port Foster, Deception Island (Antarctica). SEANOE. doi:[10.17882/77208](https://doi.org/10.17882/77208)

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jvolgeores.2021.107249>.

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Appendix 2

Volcanism and rapid sedimentation affect the benthic communities of Deception Island, Antarctica.

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Volcanism and rapid sedimentation affect the benthic communities of Deception Island, Antarctica

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ABSTRACT

Deception Island is amongst the most active volcanoes in the Southern Ocean, with over 20 explosive eruptions in the last ca. 200 years. The eruption that formed the caldera at Deception Island occurred 3980 ± 125 calendar years Before Present, and it is the largest eruptive event documented in Antarctica during Holocene. Since then, post-caldera volcanic activity has comprised many scattered eruptive vents across the island. Mortality of benthic organisms has been reported during the most recent eruptions occurred on the island, in 1967, 1969, and 1970 Common Era (CE), with very low abundances of organisms during the 1967–1973 CE period. Within the sea-flooded part of the caldera depression, named Port Foster, a submarine volcanic axis with several volcanic cones is observed. An interdisciplinary team sampled the best morphologically preserved volcanic edifice within Port Foster, the so-called Stanley Patch. Geophysical data traced the volcano and characterized its morphology and inner structure. Underwater scuba sampling allowed to acquire sediment and rock samples, photographs and video images of the benthic organisms and seascape. Morphology of Stanley Patch cone and textural characteristics of the collected pyroclastic rocks indicate that the volcanic edifice was originated during an explosive eruption. Furthermore, the lack of palagonitization, quenched pyroclast margins, and hyaloclastite deposits indicate that this cone has formed on-land, before the caldera floor became inundated by the seawater, highlighting the complex intra-caldera evolution of Deception Island. A sediment core from the crater was collected for sedimentological, and geochemical analysis. Antarctic climate and seasonal sea ice, together with organic degradation due to high sedimentation rates, explain the low total organic carbon data measured. The volcanic history of the island has probably avoided the development of a stable benthic community over time, similar to other Antarctic shallow communities. Moreover, the current geomorphological conditions still shape different benthic communities than in the surrounding coastal ecosystems. Stanley Patch, and the whole Port Foster, provide a natural laboratory for benchmarking the reestablishment of benthic communities on a volcanic-influenced shallow marine environment, offering relevant data for future studies evaluating global climate change effects on the Antarctic seabed.

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1. Introduction

Antarctic volcanoes are extremely active and have produced multiple volcanic eruptions in historical times (LeMasurier and Thomson 1990). Deception Island, located in the South Shetland Islands, is amongst the most active volcanoes in the Southern Ocean, with a record of over 20 explosive eruptions in the last two centuries (e.g. Orheim et al., 1972; Roobol, 1982; Smellie et al., 2002). Indeed, the eruption record from the eighteenth to the twentieth centuries comprises periods of high activity (e.g. 1818–1828 CE, 1906–1912 CE, 1967–1970 CE) with numerous eruptions closely spaced in time, followed by decades of dormancy (e.g. 1912–1967 CE) (Orheim 1972; Roobol 1980, 1982; Smellie 2002).

Periodic disturbance is a key factor in most ecosystems and is a selective force influencing species composition and assemblage structure (Dell et al., 2019; Robinson et al., 2020). While in shallow coastal areas of Antarctica, the benthic communities are mainly influenced by ice disturbance (Smale 2008), in Deception Island, factors such as volcanic activity and sedimentation may impose the distribution and abundance of macroinvertebrates (Brierley, 1999; Barnes et al., 2008). However, there is still a lack of knowledge on how natural disturbance processes with such disparate time scales can be influencing the composition and structure of current communities on a small spatial scale. Thus, it is important to understand the underlying mechanisms linking species composition, disturbance, and other drivers of assemblage structure.

During January 2018, a multidisciplinary team worked together to

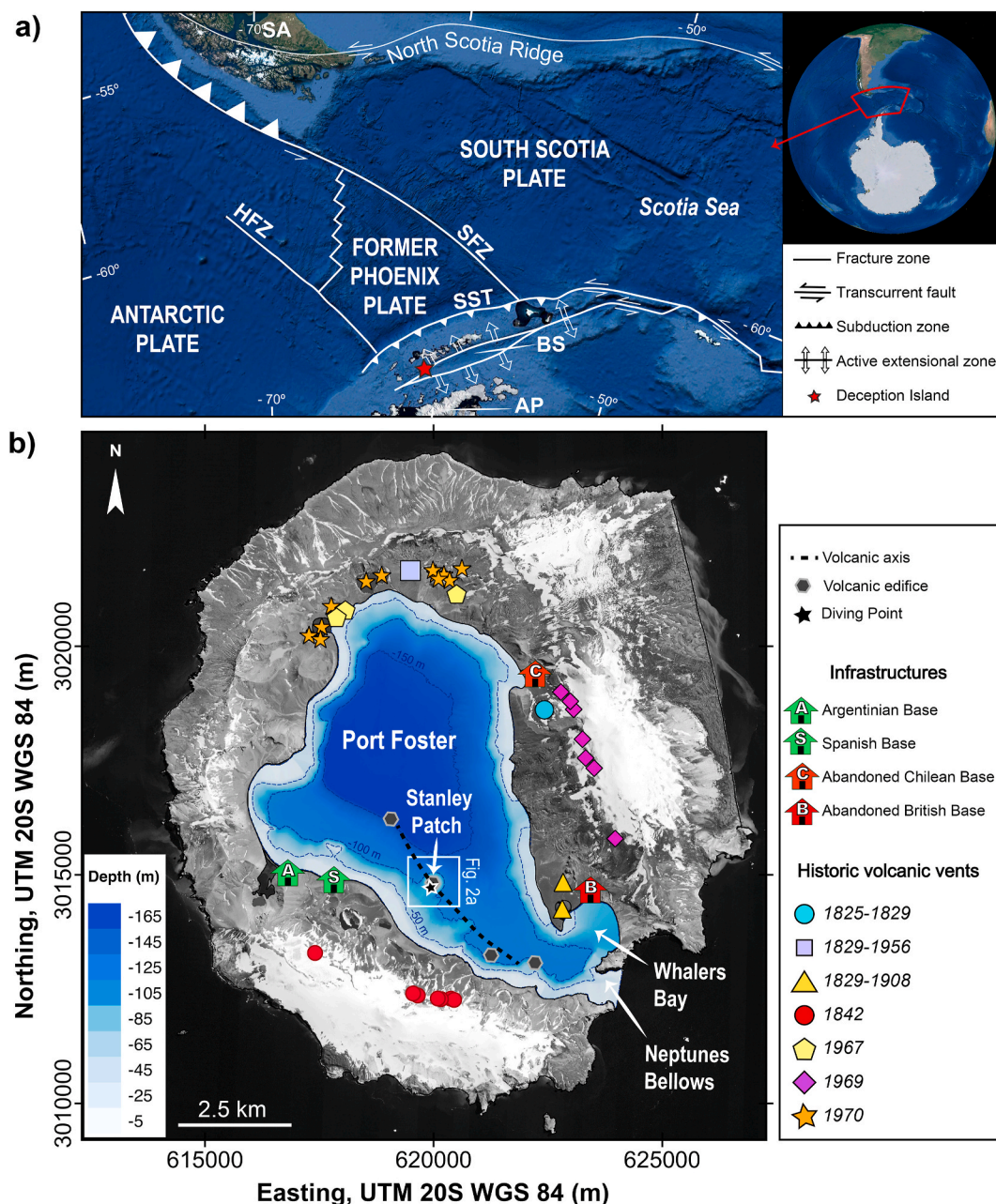


Fig. 1. (a) Simplified regional tectonic map and location of the South Shetland Islands (modified from Martos et al., 2014). AP: Antarctic Peninsula, BS: Bransfield Strait, HFZ Hero Fracture Zone, SFZ Shetland Fracture Zone, SST: South Shetland Trench. Google Earth image source: Landsat/Copernicus – U.S. Geological Survey (b) Deception Island orthophotomap (data obtained from Spatial Data Infrastructure for Deception Island SIMAC, Torrecillas et al., 2006) where active and abandoned scientific stations, as well as historic volcanic vents (data from Roobol, 1973, 1980, 1982; Baker et al., 1975, Smellie, 2002; Baker and McReath, 1971) and submarine volcanic edifices along volcanic axis (Rey et al., 1995) are indicated.

sample Stanley Patch for the first time. Stanley Patch is the largest and best morphologically preserved volcanic cone inside Port Foster. The study allows for an integrative understanding of this volcanic system from environmental, ecological, and volcanological perspectives. We also highlight the importance of multidisciplinary studies to advance in the general understanding of the bio-geological knowledge of submarine volcanic terrains, and at Deception Island in particular.

1.1. Site description

Deception Island is located at the southwestern end of the Bransfield Strait, an actively extending young (probably <4 My old; Barker, 1982) marginal basin between the Antarctic Peninsula and South Shetland Islands. The volcanic and magmatic evolution of the island is marked by a large eruption that occurred 3980 ± 125 calibrated years Before Present (BP) (Antoniades et al., 2018). This event led to the catastrophic collapse and sinking of the major volcanic edifice that generated the current caldera (Rey et al., 1995; Smellie, 2002). Port Foster bay, which opens onto the sea through the narrow strait of Neptunes Bellows, occupies the central part of the island and corresponds to the sea-flooded part of the caldera depression. Volcanic activity occurring after the caldera-forming event, which includes the recent historical eruptions (Fig. 1), comprises several tens of scattered eruptive vents across the whole island (e.g., Smellie et al., 2002; Martí et al., 2013). Within Port Foster, a submarine volcanic axis composed of several volcanic cones can be distinguished (Rey et al., 1995; Somoza et al., 2004). Some of these volcanic edifices, mainly located at the southern part of the bay, are morphologically well-preserved and rise up to more than 50 m from the seafloor.

Port Foster constitutes a closed natural sedimentary basin, with lateral contributions of terrigenous, fine volcanogenic sediments of fluvioglacial, periglacial, aeolian and marine origin with bioterritic components (Baldwin and Smith, 2003). The coastal and submarine deposits are regulated by processes related to the steep slopes covered by glaciers surrounding the caldera (López-Martínez et al., 1999). The interaction of volcanic material and ice results in the establishment of active torrential streams during the austral summer that carry sediment to the basin. Long-term volcanic tremors also promote avalanches of sedimentary fillings on the steep slopes (Rey et al., 1992). The submarine morphologies and the depositional characteristics of Port Foster suggest a strong tectonic control over the submarine geomorphology, which affects the intensity of the fluvioglacial processes. The sediment particulate flux in Port Foster is considerably higher than that in the nearby Bransfield Strait, with winter fluxes up to five orders of magnitude larger (Baldwin and Smith, 2003).

The composition of the seafloor communities is the product of numerous biological and physical processes acting across multiple spatial and temporal scales (Pickett and Kolasa, 1991). Significant inputs of freshwater, sediments, and associated minerals are observed in areas in proximity to ice shelves and glaciers, and the associated runoff with melting (Pasotti et al., 2015; Dayton et al., 2016; Monien et al., 2017). Nearshore communities, often rich in primary production, are at the boundary between terrestrial and open ocean systems. The volcanic eruptions of 1967, 1969, and 1970 CE, led to a complete mortality of local marine benthic organisms (Gallardo and Castillo 1968; Gallardo et al., 1977). These communities suffered an enormous impact that lasted several years, when the abundance of macroorganisms was reported to be very low from 1967 to 1973 CE (Lovell and Trego, 2003). Shallow benthic communities inside Port Foster have since apparently recovered, with a dominance of vagile invertebrates, particularly echinoderms such as brittle stars, sea stars, and sea urchins (Cranmer et al., 2003; Angulo-Preckler et al., 2017b). Furthermore, an important community of suspension-feeders (mainly sponges, bryozoans, and ascidians) are found in the scarce hard bottoms described within Port Foster (Angulo-Preckler et al., 2018). Also, bivalves contribute to the suspension feeding communities established in the soft-bottoms at Deception

Island (Angulo-Preckler et al., 2018).

2. Material & methods

Fieldwork during the 2017–2018 Antarctic season targeted the shallowest point of Stanley Patch, the cone summit at the southern side of the crater rim located at 25 m depth below sea level. The objective was to access and observe the general submarine scenario, to identify the macrobenthic communities living on it, as well as to collect both a sediment core and rock samples by SCUBA diving. To complete the study, the divers took underwater photographs and videos. Selected invertebrates were collected to identify the species forming the benthic community that inhabits the volcano. Samples for sedimentological analysis provide information about the environmental evolution since the cone formation and a minimum age for the volcano based on radiocarbon dating. Furthermore, the morphology of Stanley Patch volcano has been mapped in detail using the bathymetry data (IHM, 2018) collected in the bay, aboard the R.V. BIO-Hesperides, by the Instituto Español de Oceanografía (IEO) and Instituto Hidrográfico de la Marina (IHM). Bathymetric data was obtained with a multibeam echosounder system, including a Kongsberg EM-12, operating 191 beams at a 12 kHz frequency and a GeoSwath system in the shallowest areas. From these data, a 9×9 m resolution digital elevation model (DEM) of Stanley Patch volcano (Fig. 2a and b) was constructed with Caris Hips & Sips software.

Volcanology and Petrology. Twenty-one rock samples of 3–15 cm in diameter size were collected at the southern side of the crater rim. A subset of three less weathered representative samples were selected for the sedimentological, petrographic, and geochemical descriptions. Thin sections were prepared and whole rock major and trace elements were analyzed for each sample using x-ray fluorescence (XRF) and inductively coupled plasma - mass spectrometry (ICP-MS), respectively. For XRF analysis a ThermoARL Advant'XP + sequential X-ray spectrometer was used at the GeoAnalytical Lab at Washington State University (WSU) (<https://environment.wsu.edu/facilities/geoanalytical-lab/technical-notes/xrf-method/>). Loss on ignition (LOI) as a proxy for volatile content was measured using standard thermogravimetric methods at WSU. Trace elements and rare Earth elements (REE) were also analyzed for the same samples by ICP-MS using an Agilent 7700 at WSU (<https://environment.wsu.edu/facilities/geoanalytical-lab/technical-notes/icp-ms-method/>). Relative precision was in general better than 1% (RSD) for major oxides and trace elements, under 5% for REE, and under 10% for the remaining trace elements.

Morphometric parameters of Stanley Patch volcanic cone were manually measured using Quantum GIS, version 3.10 A Coruña (<http://www.qgis.org/en/site/>). A shaded relief model was created from the DEM to delineate the extent of the crater and cone based on break-slopes. The morphometric parameters obtained were the following (Fig. 2c): (i) cone height (Hco) calculated as the difference between the maximum elevation of the cone rim (i.e. shallowest point below sea level) and the average basal depth of the cone (Settle, 1979); (ii) average diameter of the cone crater (Wcr) obtained from the planimetric area of the crater (Acr) as $(4 \cdot Acr / \pi)^{0.5}$ (Favalli et al., 2009); and (iii) average basal diameter of the cone (Wco) obtained from the planimetric projection of the cone basal area (Aco) as $(4 \cdot Aco / \pi)^{0.5}$.

Sedimentological and geochemical analysis. A push core from the crater rim was collected (62.98°S, 60.63°W). The sample was taken manually, and the rocky substrate was not reached. The sediment core (4 cm in diameter and 8 cm in length) was subsampled every centimetre for sedimentological and geochemical analysis. In order to minimize the oxidation of sediment material, samples were frozen at -20°C until the physico-chemical analyses were performed. The pH and redox potential (Eh) were determined *in situ* with portable electrodes (HANNA instruments INC, Woonsocket, RI, U.S.A.). The Eh values were corrected by adding the potential of a reference electrode (+244 mV). Oxidation

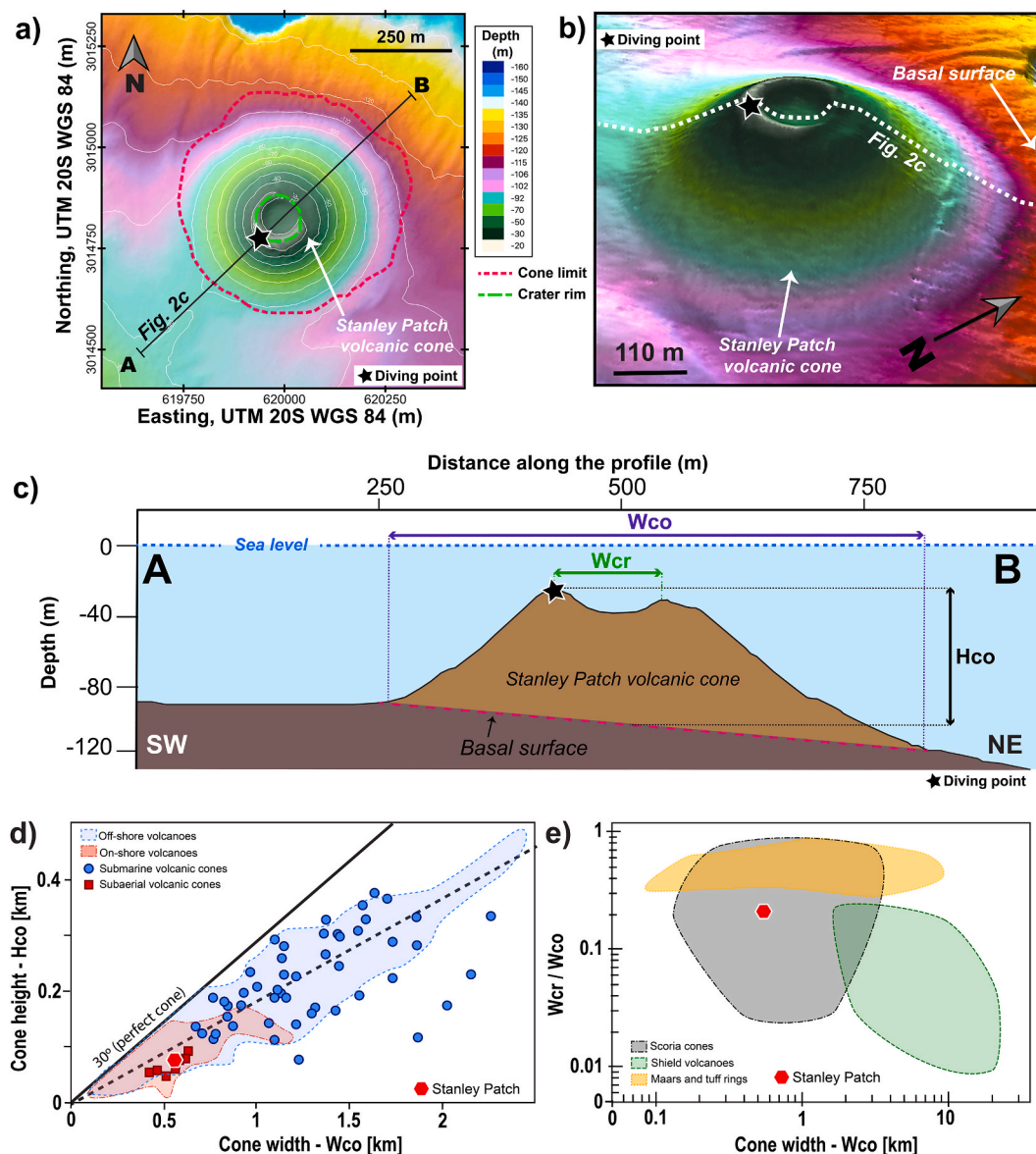


Fig. 2. Bathymetric (a) and 3D shaded relief map (b) of Stanley Patch volcano, showing the location of the profiles displayed at c). (c) Terrain profile crossing Stanley Patch volcano along the line A-B (see (a) for location). At the profile are marked the morphological parameters measured at the cone (W_{co} , W_{cr} , and H_{co}); (d) Average basal width (W_{co}) vs height (H_{co}) for Stanley Patch volcano compared to well-studied on-shore and off-shore volcanic edifices observed at Pico Island (Açores) (blue circles and red squares, data from Mitchell et al., 2012) and Terceira Rift/San Miguel island (blue and red area, data from Weiß et al., 2015). (e) W_{cr}/W_{co} ratio vs. height H_{co} of Stanley Patch volcano compared to the values for several other types of terrestrial volcanic edifices according to Brož and Hauber (2013).

microsites (i.e. presence of molecular oxygen) were considered when $E_h > 350$ mV, suboxic (i.e. reduction of oxyhydroxides of Fe (III)/Mn(IV)) when $E_h = 350$ –100 mV, and anoxic (i.e. reduction of sulphate) when $E_h > 100$ mV (see Ponnamperuma, 1972; Ferreira et al., 2006). Particle sizes were separated using the Robinson pipette method (Gee and Bauder, 1986). Twenty grams of dry sample were subjected to attack by hydrogen peroxide (15%) for 72 h to remove organic matter; 50 ml HCl (1M) were then added and left for 20 min, occasionally shaking, to remove Fe and Al oxides and hydroxides. Organic substances and Fe/Al oxides were removed because they act as sediment particle aggregating components. The sample was then washed until free from chlorides, and sodium hexametaphosphate was added as a dispersing agent. Mechanical agitation (2 h) used in combination with chemical treatments enhances dispersal. After dispersal, the sand fraction (0.05–2 mm) was separated by sieving through a 0.05 mm mesh size, while particles with diameter <0.05 mm (silt and clay) were separated by sedimentation in

water. During sand particle separation, the solution and particles (silt + clay) were collected in a bucket after passing through the sieve and were then transferred to a 1 L beaker. This solution was thoroughly stirred to achieve suspension of all soil particles. Immediately after stirring, 20 mL of the suspension were extracted at 10 cm depth using a Robinson pipette. This subsample contained both fractions: silt and clay. The sample was dried at 105 °C and weighed. After leaving to rest for 8 h, the silt fraction had sedimented and the clay fraction could be extracted following the same procedure. The subsample was dried at 105 °C and weighed. To calculate the amount of clay present in the total sediment sample, the amount of clay present in 20 mL was multiplied by 50 to yield the amount of clay in 1 L of suspension and, therefore, in the sediment sample. The amount of silt was calculated by subtracting the amount of clay from the subsample (silt + clay) and following the same procedure as with the clay fraction. The weight in grams was finally obtained for the sand, silt, and clay fractions. The three fractions were

added (=100%) and the % weight of the individual fractions was calculated based on the weight of each one.

The total organic carbon (TOC) and total nitrogen (TN) contents were determined in a TruSpec CHNS analyser (LECO Corp., St Joseph, MI, USA), while total sulfur (TS) were measured in an SC-144DR analyser. Prior to the TOC determination, the samples were attacked with 1M HCl at 60 °C until dry in order to eliminate the carbonates (Huerta-Díaz and Morse, 1992). Calibration was realized with different LECO standards and percentage of recovery obtained: $100.1 \pm 1.3\%$ for C, $99.7 \pm 1.7\%$ and $99.9 \pm 1.3\%$ for S ($n = 4$). The ratio TOC/TN was used as a proxy of organic matter origin (terrigenous organic matter C/N > 20, Emerson and Hedges, 1988).

The concentration of metastable Fe sulphides fraction (acid volatile sulphides AVS = $\sum \text{FeS}, \text{Fe}_3\text{S}_4$) was determined in duplicate using 0.5–1 g of wet sample, according to the method described by Kostka and Luther (1994). Sulphide from AVS was liberated with 20 ml 6N HCl previously deaerated for 40–50 min. The sample was digested in a gas-tight reaction flask for 40–50 min under a continuous flow of nitrogen, which was bubbled through the flask as slowly as possible. The evolved H_2S was then received in a trap containing 25 ml of 3% Zn acetate, 1 mL of concentrated H_2SO_4 , and 4 mL of diamine reagent, and precipitated as ZnS. Sulphide was then measured colorimetrically with a UV-VIS spectrophotometer at a wavelength of 670 nm using the methylene blue method of Cline (1969). The concentration of Fe-AVS was calculated from the concentration of AVS-S, assuming a ratio of S:Fe of 1.1 (Kostka and Luther, 1994). The concentrations were always expressed in terms of dry weight of soil (dw), the moisture content being determined from two subsamples dried at 105 °C to constant weight. In addition, the color of the sediment samples was characterized by using the Munsell Color Chart.

Biodiversity. Underwater photographs were taken by scuba-diving. The specimens were identified to species level, when possible. Due to the difficulties of the dive operation (depth, low visibility, currents, cold waters), the bottom time was limited to 15 min, and only one video transect was recorded. The distance of the transect was 50 m long. All organisms detected on half meter at each side of the central line of the video transect were counted to measure the abundance for each macrobenthic species. The density of benthic organisms was ranked in three different groups, 1) **low abundance**; species present at least one time in the transect but lower than 5 organisms per m^2 , 2) **medium abundance**; between 5 and 50 organisms per m^2 , and 3) **high abundance**; species with densities higher than 50 organisms per m^2 .

3. Results

Volcanology and Petrology. Stanley Patch rises sharply from the north-east trending and gently dipping ($\sim 3^\circ$) seafloor at 90–120 m water depth (Fig. 2a, b and c). The edifice has a height (Hco) of 80 m and a basal diameter of ~ 553 m (Wco) (Fig. 2c). The crater (Wcr) has a circular shape and a diameter of 113 m. This results in an average Hco/Wco ratio of ~ 0.15 (Fig. 2d) and Wcr/Wco of ~ 0.2 (Fig. 2e). The cone has relatively uniform slope angle values of $20\text{--}30^\circ$. The morphology of the cone is well defined and hardly affected by underwater erosion (e.g. turbidites).

Based on the macroscopic observations, the Stanley Patch volcanic samples are mostly low-density scoriaceous fragments (Fig. 3, Appendix A). They display aphyric textures with phenocryst and microphenocryst contents below 1–2%. Plagioclase and minor clinopyroxene and olivine phenocrysts are set in a brown to black groundmass mostly composed of microlites of plagioclase, clinopyroxene, and Fe–Ti oxides, and

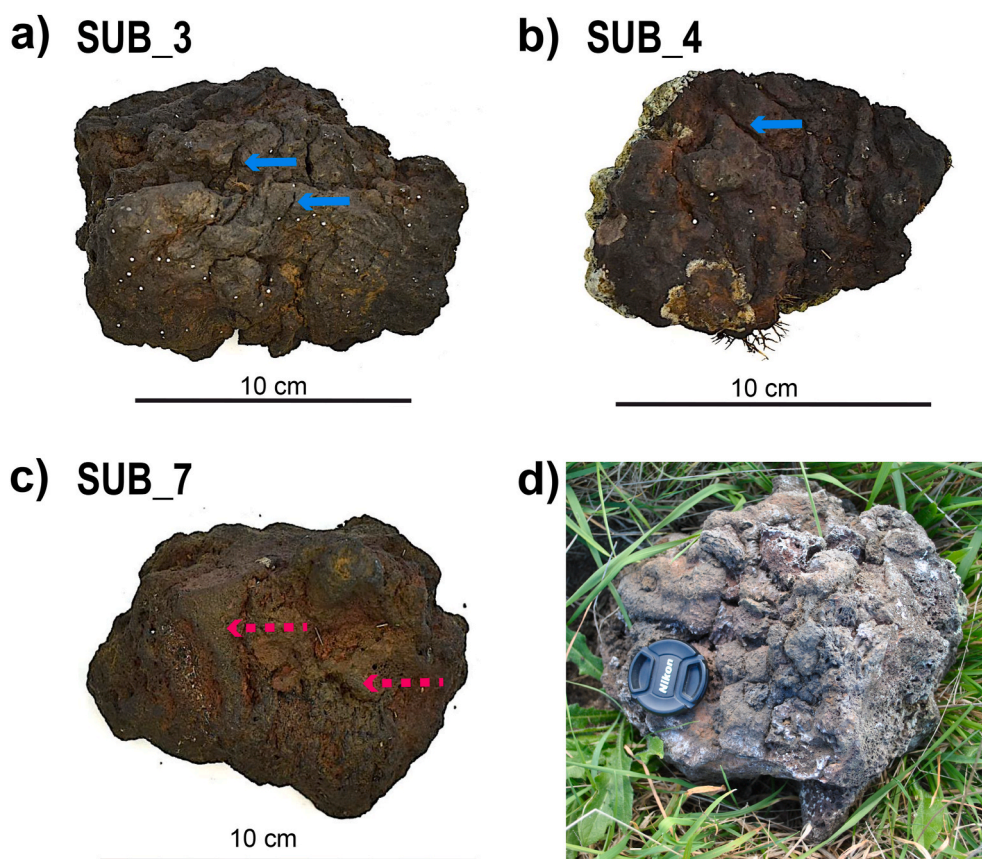


Fig. 3. Examples of hand-specimens collected at Stanley Patch volcano (a–c). Textural features such as cooling cracks (blue solid arrows) and deformation structures (red dashed arrows), are also indicated. d) Block fragment formed through subaerial lava fountaining activity in the Otuaatua scoria cone (-36.985189° , 174.753150°) from the Quaternary Auckland Volcanic Field, New Zealand.

interstitial glass (Hopfenblatt, 2019). The vesicles are randomly distributed displaying collapsed and coalescent structures with vesicularity, ranging from c. 20 to 50 vol %. Vesicular patterns are typical to nucleation of a segregated gas phase within an ascending magma causing degassing and fragmentation at shallow depths (Valentine et al., 2005; Shea et al., 2010; Kereszturi and Nemeth, 2016). The samples show lack of palagonitization, quenched rims, and hyaloclastites, which are typical for underwater and emerging volcanoes, such as Surtsey Island near Iceland (e.g. Van Otterloo, 2015; Jackson et al., 2019). This suggests that the samples have not experienced excessive hydration, oxidation and zeolitization processes. The whole-rock geochemistry indicates that the Stanley Patch products are subalkaline basaltic andesites to basaltic trachyandesites (53–55 wt% SiO_2) falling within the compositional trend described by the Deception Island magmas (Fig. 4) (e.g., Aparicio 1997; Smellie 2002; Geyer et al., 2019).

Geochemistry of the sediments. The properties and composition of the sediment column are homogeneous and do not change substantially with depth (Fig. 5, Appendix B). Textural composition is clearly dominated by the sand fraction (66–77%), followed by the silt fraction (22–34%), and by clay in a very low proportion (generally <1%). The overall TOC is very low (generally <0.03%) and, consequently, TN and TS contents are also low (generally, TN <0.01% and TS < 0.05%). The ratio TOC/TN was always less than 20, indicating a marine origin of the organic matter (Emerson and Hedges, 1988).

Sediment reaction shows values close to neutral ($\text{pH} = 6.6\text{--}7.3$), and the grey color of the matrix (5Y3/2, Munsell Color Chart) suggest iron-reducing redox conditions (suboxic conditions), while the sparse reddish spots (2.5 YR 3/6) associated with bioturbation channels suggest the presence of oxic microsystems related to benthic faunal activity. Additionally, the presence of metastable iron sulphide forms at very low concentrations (acid volatile sulphides, AVS: $0.09\text{--}0.20 \mu\text{mol g}^{-1}$) indicates the presence of anoxic microsystems in the sediment column, where organic matter is mineralized by sulphate-reducing bacteria (SRB). The low AVS and pyrite (FeS_2) contents indicate the absence of metal sulphides released by volcanic activity, as occurs in other oceanic

hydrothermal environments (e.g. Otero et al., 2003).

Macrobenthic biodiversity. Most of the macrobenthic organisms observed during collection were vagile (Fig. 6). A total of 11 species (species richness) were identified, belonging to 5 phyla (Table 1). High densities of the two most common echinoderms of Deception Island were observed, the brittle star *Ophionotus victoriae* Bell, 1902, and the sea urchin *Sterechnus neumayeri* (Meissner, 1900), along with the bivalve mollusc *Laternula elliptica* (King, 1832). All of them showed a uniform distribution in the sampled area, whereas the sea star *Odontaster Validus* Koehler, 1906 and the nemertean *Parborlasia corrugatus* (McIntosh, 1876) displayed medium abundances with patchy distributions. The abundances of the brittle stars and sea urchins range in hundreds of individuals ($200\text{--}400 \text{ m}^{-2}$), while the abundance of bivalves are an order of magnitude less ($50\text{--}80 \text{ m}^{-2}$). When occasional boulders were found, sessile filter and suspension feeders were present (Fig. 6), such as the demosponges *Dendrilla antarctica* Topsent, 1905, *Kirkpatrickia variolosa* (Kirkpatrick, 1907), *Hemigellius pilosus* (Kirkpatrick, 1907), and *Mycale (Oxymycale) acerata* Kirkpatrick, 1907, the tunicate *Cnemidocarpa verrucosa* (Lesson, 1830), and some smaller animals that live on these megabenthic organisms, such as annelid polychaetes (Terebellidae, Polynoidea), crustaceans (Isopoda and Amphipoda), and the nudibranch mollusc *Doris kerguelensis* (Bergh, 1884).

4. Discussion

Stanley Patch volcanic cone presents many challenging features for interpreting its origin due to the semi-enclosed nature of Port Foster, the presence of hydrothermal activity, the variations in topography, and basin morphological features. The morphology and size of the Stanley Patch cone (e.g. Wcr/Wco and Hco/Wco) and the textural characteristics of the recovered pyroclastic rocks (e.g. vesicles volume and shape) indicate that this volcanic edifice was constructed during a monogenetic explosive volcanic eruption (e.g. Németh and Kereszturi, 2015). A monogenetic origin for Stanley Patch volcano is also in agreement with the rest of post-caldera volcanic features observed onshore on Deception

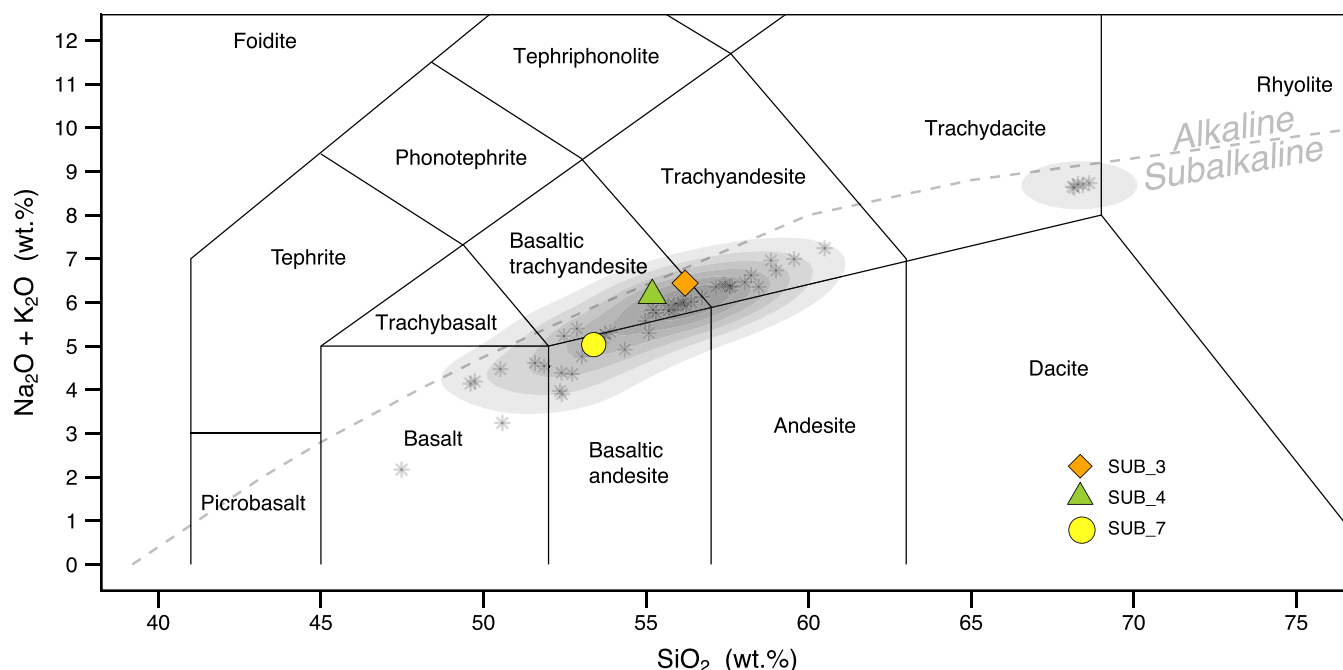


Fig. 4. Total alkalis versus silica diagram (TAS) (Le Bas et al., 1986) for the three geochemically analyzed Stanley Patch rock samples: SUB_3, SUB_4 and SUB_7 (see Appendix A for details on composition and latitude-longitude coordinates of the rock samples). For comparison grey shaded areas and asterisks correspond to the post-caldera rock samples presented by Geyer et al. (2019). Major elements normalized to 100% (anhydrous) with Fe distributed between FeO and Fe_2O_3 following Middlemost (1989). Grey dashed line discriminates between the alkaline-subalkaline fields (Irvine et al., 1971). See main text for more details.

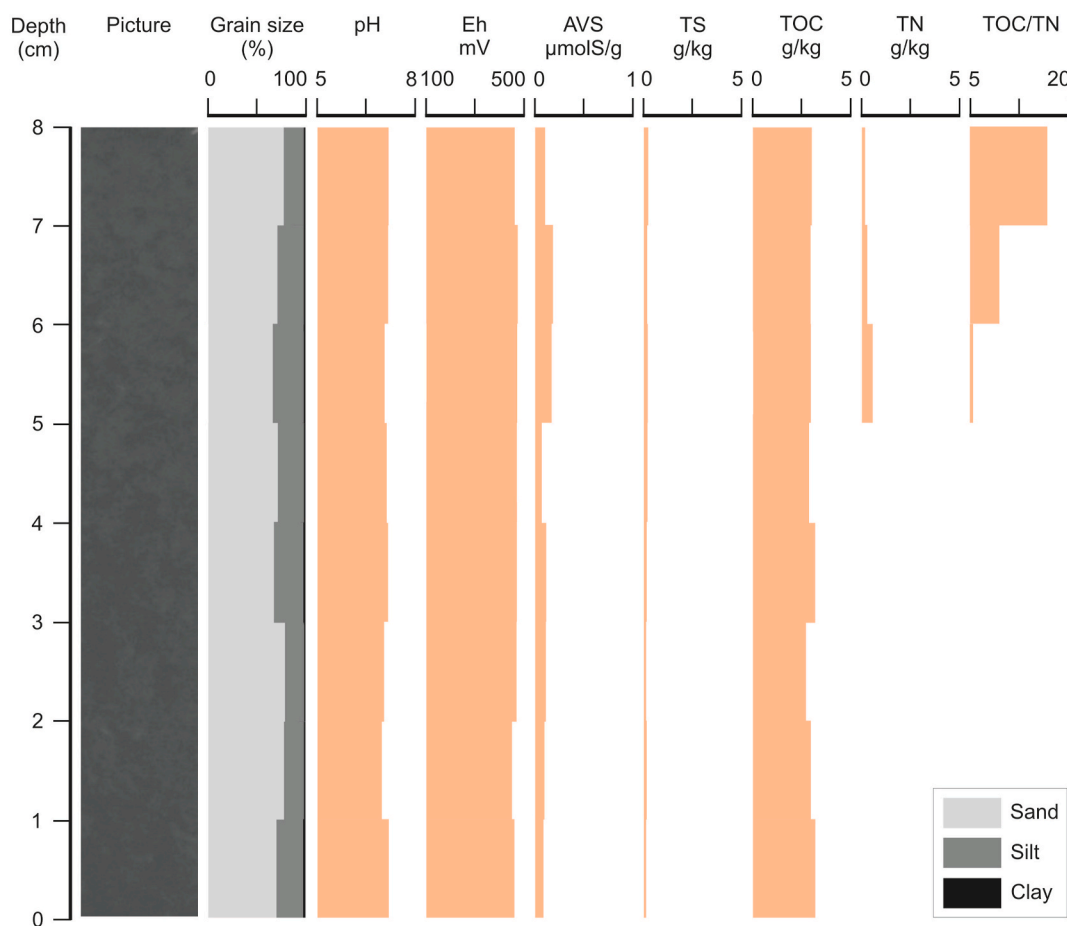


Fig. 5. Schematic log of the core, indicating sedimentological and geochemical characteristics. AVS: Acid volatile sulphide (FeS , Fe_3S_4); TS: total sulfur; TOC: total organic carbon; TN: total nitrogen; TOC/TN: ratio organic carbon to total N.

Island, such as tuff rings, tuff cones, and scoria cones (Bartolini et al., 2014; Pedrazzi et al., 2014, 2020). The Hco/Wco ratio of 0.13 is in line with both submarine (e.g. Cavallaro and Coltelli, 2019; Weiß et al., 2015) (Fig. 2d), and subaerial pyroclastic cones when: (1) the cone flank is immature, or (2) the cone has been partially eroded (Riedel et al., 2003; Kereszturi and Németh, 2012). The slope and major geometry of the flank are usually maintained due to the angle of repose of natural scoria that is 33° (e.g. Wood, 1980). This repose angle value yields a Hco/Wco ratio of 0.2. However, when there is limited scoria available, the growing cone never reaches 33° (e.g. McGetchin et al., 1974) thus maintaining the value of 0.2. This can explain the relatively small size and apparent low Hco/Wco ratio of Stanley Patch volcano. However, the Wcr/Wco ratio, and flank morphology are in the same range as for terrestrial scoria cones (e.g., Kervyn et al., 2012; Settle, 1979; Wood, 1980b) (Fig. 2e).

Additionally, the lack of palagonitization (i.e. significant alteration of the volcanic glass by water interaction) and quenched rims of the collected samples and apparent absence of hyaloclastites suggest that the explosive eruptions leading to the growth of Stanley Patch, must have taken place under “dry”-subaerial conditions, despite the common phreatic and phreatomagmatic activity described in the island (Pedrazzi et al., 2018; Álvarez-Valero et al., 2020). This may reveal changes of the sea level within Port Foster, subsidence processes of the caldera floor since the caldera-forming event until present day, and/or even that the caldera depression was enclosed for a certain time (Hopfenblatt, 2019).

Geochemical and petrologic analysis of the Stanley Patch rocks (e.g. fine-grained textures, similar geochemistry to the subaerial volcanoes) support a similar petrogenesis compared to the on-shore post-caldera volcanoes. Bulk rock geochemistry fits within the post-caldera magmatic

trend (Smellie, 2002; Geyer et al., 2019). Geyer et al. (2019) revealed the existence of a complex plumbing system beneath Deception Island, composed of several shallow reservoirs (≤ 10 km depth) fed by magmas directly from the mantle, or from a magma accumulation zone located at the crust-mantle boundary (15–20 km). According to these authors, during the post-caldera stage, erupted magma can be either directly supplied by the reservoir located at the crust-mantle boundary or by magma batches located at different depths (at 10–11 km and < 10 km). In the case of the Stanley Patch magmas whole-rock compositions suggest that the erupted material is compatible to magma reservoirs located at depths greater than 10 km (Geyer et al., 2019). Further detailed studies on geochemistry and petrology in the Stanley Patch rocks (stable isotopes, mineral chemistry, and pressure-temperature estimates) are necessary to precisely determine the origin and evolution of magma beneath Stanley Patch cone (Hopfenblatt, 2019).

Low TOC content in the sediments reflects the subpolar climatic conditions and the presence of sea-ice, due to its effects on primary productivity rates. On the other hand, several studies showed a decrease of TOC and an increase of mineral content in the coldest periods when there is a more extensive sea-ice coverage (Domack et al., 1995; Shevenell et al., 1996; Yoon et al., 2007). Moreover, organic degradation is less efficient at higher burial rates. Above a critical sedimentation rate, TOC typically decreases with increasing sedimentation rate owing to classic dilution of the organic input (Johnson, 1982). In Port Foster, sedimentation rates are high due to several factors: (1) fine volcanic sedimentary particles (e.g. ash and lapilli), and (2) melting of snow cover during the austral summer, causing run-off, with the presence of active gullies, alluvial fans, debris flows, and mudflows (Inbar, 1995; López-Martínez et al., 1999). In the volcanic eruptions of the 1960s and

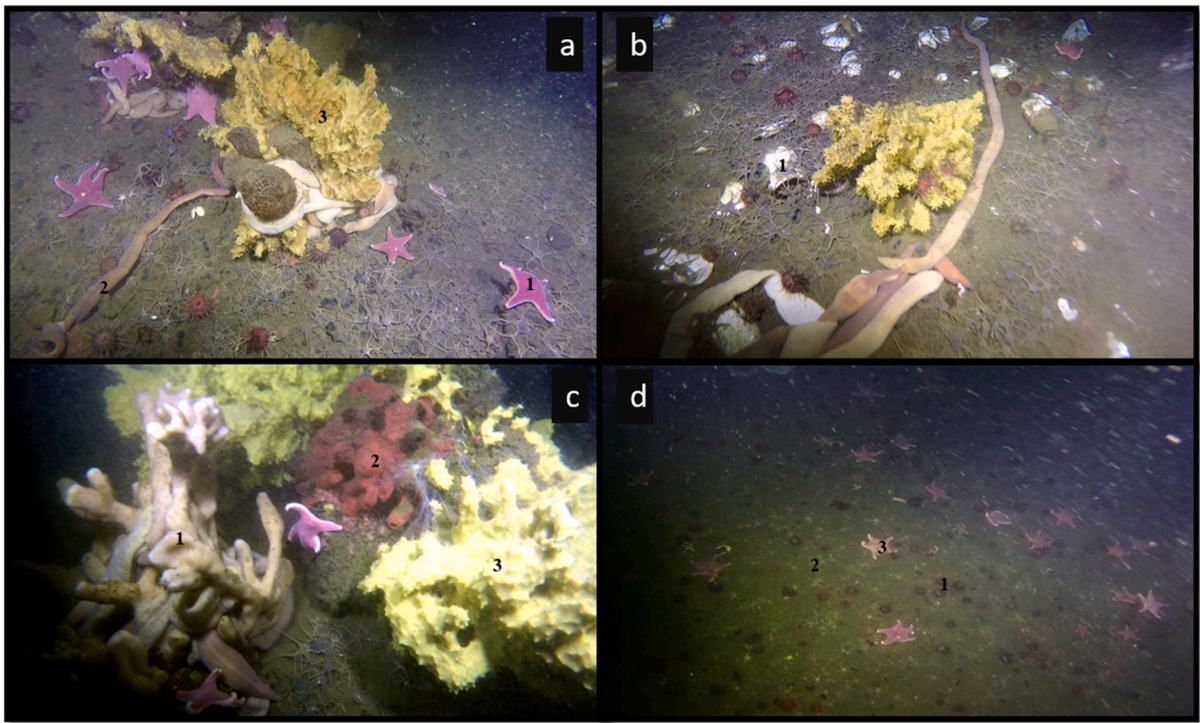


Fig. 6. Photographs taken by divers on the top of the crater. (a) The sea star *Odontaster validus* (1), the worm *Parborlasia corrugatus* (2), and the sponge *Dendrilla antarctica* (3). (b) *Dendrilla antarctica*, cluster of *P. corrugatus*, and shells of the mollusc *Laternula elliptica* (1). (c) The sponges *Hemigellius pillosus* (1), *Kirkpatrickia variolosa* (2), and *Dendrilla antarctica* (3). (d) High densities of the sea urchin *Sterechinus neumayeri* (1), the brittle star *Ophionotus victoriae* (2), and the sea star *Odontaster validus* (3).

Table 1
Species identified in the video transect, ordered by semi-quantitative abundances.

Phylum	Class or Order	Taxa	Density	Abundance
Echinodermata	Ophiuroidea	<i>Ophionotus victoriae</i> Bell, 1902	high	200-500/m ²
Echinodermata	Echinoidea	<i>Sterechinus neumayeri</i> (Meissner, 1900)	high	100-200/m ²
Mollusca	Bivalvia	<i>Laternula elliptica</i> (P.P. King, 1832)	high	50-100/m ²
Echinodermata	Asteroidea	<i>Odontaster validus</i> Koehler, 1906	medium	10/m ²
Nemertean	Heteronemertea	<i>Parborlasia corrugatus</i> (McIntosh, 1876)	medium	10/m ²
Porifera	Demospongia	<i>Dendrilla antarctica</i> Topsent, 1905	low	<1/m ²
Porifera	Demospongia	<i>Mycale (Oxymycale) acerata</i> Kirkpatrick, 1907	low	<1/m ²
Porifera	Demospongia	<i>Hemigellius pilosus</i> (Kirkpatrick, 1907)	low	<1/m ²
Porifera	Demospongia	<i>Kirkpatrickia variolosa</i> (Kirkpatrick, 1907)	low	<1/m ²
Mollusca	Gastropoda	<i>Doris kerguelenensis</i> (Bergh, 1884)	low	<1/m ²
Chordata	Ascidacea	<i>Cnemidocarpa verrucosa</i> (Lesson, 1830)	low	<1/m ²

1970s, the formation of lahars and pyroclastic density currents has been observed in various areas of Deception Island (Bartolini et al., 2014). These events give rise to a rapid sediment flux. Moreover, the degradation of permafrost, increased by the geothermal activity of the volcano (Goyanes et al., 2014), also contributes to the mobilization of water and sediment.

Similarly, those glacial fronts reaching the coastal areas also play a key role in coastal erosion and sedimentation processes (Griffith and Anderson, 1989). In the studied sediment core, the reddish mottles and high Eh values (Eh > 400 mV) may be connected with oxic microsystems due to the high densities of infaunal organisms found in sediment cores of the shallow-water (5–15 m depth) of Deception Island (Angulo-Preckler et al., 2017a). Iron-reduction redox conditions (suboxic conditions) were also identified, yet low sulphate-reduction activity in these sediments could favor the flux of Fe to the water column. This process can be very important considering that iron is a key delimiting or co-limiting micronutrient for biological production in most oceans, including the Southern Ocean (Moore et al., 2009, 2013).

Port Foster receives a massive sediment discharge into the seawater through glacier activity, and surface wash combined with seismic tremors that drive remobilization of water-saturated sediments (Inbar, 1995). Although there are other sources of nutrients involved in productivity, the low organic content in the sediment reflects the subpolar climate and the present-day morphodynamics, related to volcanism and the glacial, periglacial and slope landforms and processes that affect the basin sedimentation. All these physical factors produce oxic microsystems (probably due to the high densities of infaunal organisms), and suboxic conditions that favor the flux of Fe to the water column.

The current benthic community was apparently established since the last eruptions that devastated all of the sea bottom community of Deception Island during 1967–1970 (Elderfield, 1972). This local devastation of the fauna is one of the most severe disturbances, especially because recovery in the Antarctic ecosystem is slow due to its low

productivity (Gutt et al., 1996). This recolonization process seems to be recurrent along the history of Deception Island since the caldera was flooded for the first time. Many taxa are poorly represented, and the colonizers are mainly opportunistic species with planktrophic larvae (Barnes et al., 2008). In fact, it has been suggested that the modern benthic community has reached the highest level of organization that the temporal frequency of the volcanic activity of the island allows (Lovell and Trego, 2003; Angulo-Preckler et al., 2017a, 2018).

The extreme habitat conditions that characterize Antarctic ecosystems provide many opportunities to study how benthic species and communities respond to physical disturbance, underlining the importance of substratum stability as the structuring factor of the benthic communities in Deception Island. Punctuated disturbance (volcanic eruptions and degassing) and chronic disturbance (high sedimentation rates and sediment instability) seem to be the key fundamental factors that shape the macrobenthic communities at Deception Island. Concerning the former, there is evidence of direct relationships between volcanic emissions (e.g. gas) and organism reactions in other submarine volcanoes (Fraile-Nuez et al., 2012; Álvarez-Valero et al., 2018). Antarctic ecosystems are described to have great resilience, since they are subject to continuous physical impacts (Peck et al., 2009; Kapsenberg and Hofmann, 2014). Due to the strong instability of the soft sediment bottoms on Deception Island slopes (Inbar, 1995; Melo et al., 2012), the development of a sessile filter feeder community is difficult, thus favoring opportunistic detritivores (Angulo-Preckler et al., 2018). Furthermore, a community dominated by infauna, with surface and subsurface feeders, is related to a high biogenic sedimentation rate (Ravaoli et al., 1999). This opens the chance for well-developed epibenthic and infaunal communities (Angulo-Preckler et al., 2017a, 2017b). In addition, the high abundance of some predator species, such as *Odontaster validus* (sea star) and *Parborlasia corrugatus* (nemertean) requires high amounts of available food. This is reinforced by the important presence of dead shells of the bivalve *Laternula elliptica*, probably the main prey of these voracious predators. Typically, Antarctic community assemblages include huge densities of mainly opportunistic deposit feeders, with mobile deposit feeders dominated by echinoderms, and a very abundant infauna (Gutt, 2007; Angulo-Preckler et al., 2017a). Moreover, the high concentrations of suspended particulate matter, the poor availability of light, and the sediment instability could be the reasons for the absence of macroalgae on this volcano.

A positive correlation between hard-substrates and biodiversity of macrobenthic species has been described in Deception Island (Angulo-Preckler et al., 2018). Dropstones provide hard substrate, increasing habitat heterogeneity, and may function as island habitats surrounded by sand. A random distribution of dropstones on the seafloor creates an heterogeneous distribution of fragmented hard substrata, forming the already mentioned island habitats. High rates of burial disturbance would not allow for a high diversity of benthic organisms, yet the competition is less severe for those species capable of coping with sediment instability. Moreover, the abrasion caused by sand and gravel put in motion by the waves and on an inclined slope, hinders sessile organisms from becoming permanently established in the shallow sublittoral zone.

5. Concluding remarks

Stanley Patch cone built up during an explosive monogenetic volcanic event. The apparent absence of typical petrologic features of submarine volcanic eruption in the studied samples such as palagonitization, quenched rims, and hyaloclastites suggest that Stanley Patch

formed under “dry”-subaerial conditions, and subsequently partially eroded. When Neptunes Bellows collapsed, a massive influx of seawater entered into Port Foster, opening up for the first time a new area for marine benthic colonization. The volcanic history of the island has probably avoided the development of a stable benthic community over time, similar to other Antarctic shallow communities. Moreover, the current geomorphological conditions still shape different benthic communities than in the surrounding coastal ecosystems. This volcanic cone, and even the entire Port Foster, is a unique and special natural laboratory for benchmarking the rates of reestablishment of benthic communities on a volcanological-influenced shallow marine environment, offering data of great relevance for future studies evaluating the effects of global change on the seabed communities in Antarctica.

Ethical statement

The research reported here has been conducted in an ethical and responsible manner, and complies with all relevant legislation. We have no potential conflict of interest.

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Author contribution

M.G-B. identified the submarine cone through the real time bathymetry and contributed to design the logistic plan for sampling the cone with C.A-P., C.A., G.K., and A.A-V. C.A-P., P.P., and C.A. sampled the submerged volcano by scuba-diving. G.K., A.A-V., J.H-H., and A.G. studied the hand-specimens and carried out the morphometric, volcanic, petrologic and geochemical analysis. J.R-F. sample macroanalysis of the sediment, and J. C.: laboratory work, C.G-H. and X.L.O.: performed the geochemical analysis. C.A. and C.A-P. identified taxonomically the invertebrates, and C.A-P. studied the images and the video transect. All the authors contributed to write and review the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. List of collected rock samples (62.98°S, 60.63°W). IGSN: International Geosample Number

Sample name	IGSN	Sample description
SUB_1	IED1800SUB1	Scoria fragment
SUB_2	IED1800SUB2	Scoria fragment
SUB_3	IED1800SUB3	Scoria fragment
SUB_4	IED1800SUB4	Scoria fragment
SUB_5	IED1800SUB5	Scoria fragment
SUB_6	IED1800SUB6	Scoria fragment
SUB_7	IED1800SUB7	Scoria fragment
SUB_8	IED1800SUB8	Scoria fragment
SUB_9	IED1800SUB9	Scoria fragment
SUB_10	IED1800SUB10	Scoria fragment
SUB_11	IED1800SUB11	Scoria fragment
SUB_12	IED1800SUB12	Scoria fragment
SUB_13	IED1800SUB13	Scoria fragment
SUB_14	IED1800SUB14	Scoria fragment
SUB_15	IED1800SUB15	Scoria fragment
SUB_16	IED1800SUB16	Scoria fragment
SUB_17	IED1800SUB17	Scoria fragment
SUB_18	IED1800SUB18	Scoria fragment
SUB_19	IED1800SUB19	Scoria fragment
SUB_20	IED1800SUB20	Scoria fragment
SUB_21	IED1800SUB21	Scoria fragment

Appendix B. Sedimentological and geochemical characterization of the sedimentary column. The concentrations are expressed in terms of dry weight of sediment (dw)

Sample	Depth (cm)	pH	Eh mV	AVS μmolS/g	TS g/kg	TOC g/kg	TN g/kg	TOC/TN	Sand %	Silt %	Clay %	Sedimentary texture
1	0–1	7.37	452	0.1259	0.46	3.05	0.18	16.66	77.00	22.92	0.08	loamy sand
2	1–2	7.28	467	0.1963	0.39	2.97	0.31	9.45	70.44	29.47	0.09	loamy sand
3	2–3	6.87	461	0.1743	0.44	3	0.57	5.28	65.91	33.99	0.10	sandy loam
4	3–4	7.08	459	0.0736	0.43	2.91	< LD	–	70.48	29.43	0.09	loamy sand
5	4–5	7.22	461	0.1407	0.36	3.24	< LD	–	67.37	32.52	0.10	sandy loam
6	5–6	6.82	459	0.1379	0.33	2.75	< LD	–	77.56	22.36	0.08	loamy sand
7	6–7	6.57	436	0.1051	0.36	3.01	< LD	–	76.85	23.07	0.08	loamy sand
8	7–8	7.28	449	0.0931	0.31	3.24	< LD	–	70.56	29.33	0.11	loamy sand

AVS: Acid volatile sulphide (FeS, Fe₃S₄); TOC: total organic carbon; TN: total nitrogen, LD: limit of detection; TS: total sulfur, TOC/TN: ratio organic carbon to total N.

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Appendix 3

Hopfenblatt, J., Geyer, A., Aulinas, M., Álvarez-Valero, A. M., Sánchez, A. P., Giralt, S., & Smellie, J. L. (2022). DecTephra: A new database of Deception Island's tephra record (Antarctica).

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DecTephra: A new database of Deception Island's tephra record (Antarctica)

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ABSTRACT

Deception Island (South Shetland Islands) is one of the most active volcanoes in Antarctica, with more than 20 explosive eruptive events registered over the past few centuries. Recent eruptions (1967, 1969, and 1970) and volcanic unrest episodes (1992, 1999, and 2014–2015) demonstrate that volcanic activity will likely occur in the future. Despite this, there has been a considerable increase in the number of scientific bases, tourist activities and air and vessel traffic in the region during the last several decades. The escalation in interest has increased the amount of infrastructure and population numbers exposed to a future eruption. Thus, there is an urgent need to develop an accurate long-term assessment of the volcanic hazard of the island. However, past attempts have always been limited by the incompleteness of the eruptive record. Volcanic ash layers found in marine and lacustrine sediment cores and glaciers outside Deception Island are a fundamental source of information for reconstructing the explosive eruptive record of the volcano. The spatial distribution of the tephra layers, as well as their physicochemical analysis are invaluable for determining the size and explosiveness of past eruptive events, as well as for assessing the extent and impact of their related hazards (e.g., ash fall out). In order to overcome the dispersion of existing data among numerous publications and to facilitate the analysis of available information on tephra layers sourced in Deception Island, we present the DecTephra (Deception Island Tephra Record) database. The current database version contains 362 tephra layers (including cryptotephra) located at sites up to 3115 km distant from the island. For each tephra layer, the database includes: (i) the location and simple description of the sampling site; and (ii) the key petrologic and geochemical features of each tephra layer. A preliminary analysis of the information contained in the DecTephra database (e.g., magma composition, explosiveness, eruptive recurrence, etc.), validates it as a key tool for evaluating past explosive activity of the volcano. In addition, it can function as a valuable resource for paleoenvironmental and paleoclimatic studies requiring tephrostratigraphical and tephrochronological control at local and regional scales. DecTephra also has the potential to help to assess the contribution of volcanic forcing to Holocene climate variability in the Southern Hemisphere.

1. Introduction

Deception Island (South Shetland Islands) is one of the most active volcanoes in Antarctica with more than 20 eruptions over the last two centuries (e.g., Orheim, 1972; Roobol, 1980; Pallàs et al., 2001; Smellie and López-Martínez, 2002) and three episodes of volcanic unrest since 1990 (1992, 1999 and 2014–2015) (e.g., Ortiz et al., 1992, 1997; Vila et al., 1992; Ibáñez et al., 2003; Almendros et al., 2018; Berrococo et al., 2018; Rosado et al., 2019). It is a composite volcano, with a substantial

collapse caldera measuring c. 8.5–10 km in diameter (Fig. 1a and b). The caldera-forming eruption, with 30–60 km³ of ejected magma, has been estimated to be comparable in size to some of the largest eruptions occurring on Earth over the past several millennia (e.g., 1883 eruption of Krakatoa) (Martí et al., 2013).

Since the discovery of Deception Island in 1820, the number of scientific bases, tourist activities, and air and vessel traffic in the region have increased considerably. The Antarctic Peninsula region alone, together with the South Shetland Islands, hosts 25 research stations

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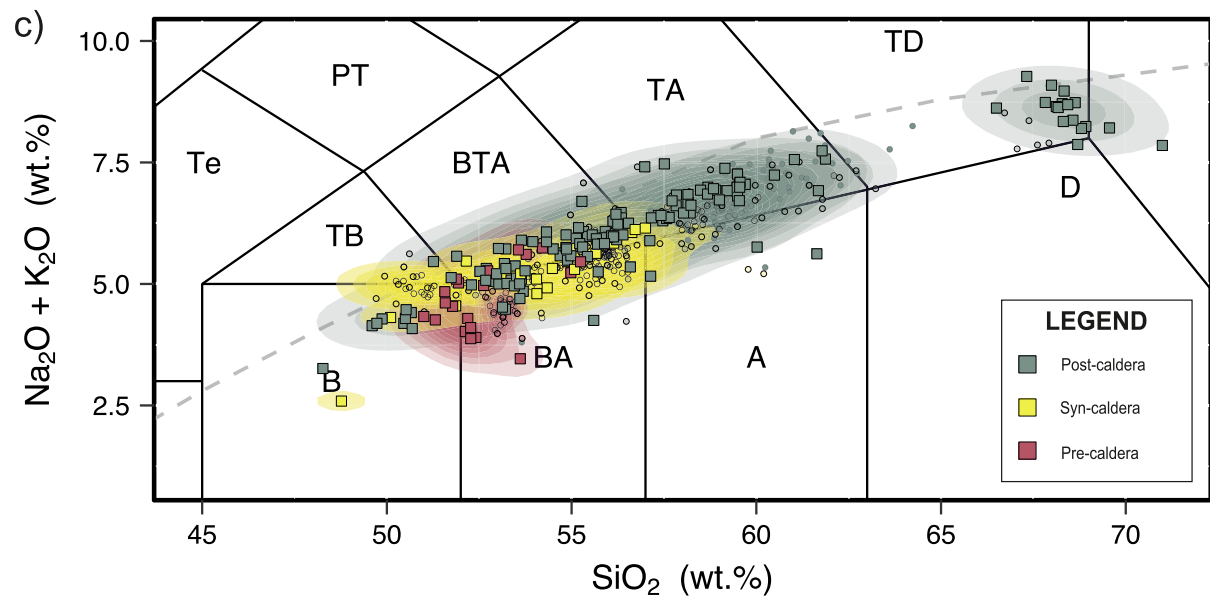
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Fig. 1. a) Simplified regional tectonic map and location of the South Shetland Islands (modified from Martos et al., 2014). AP: Antarctic Peninsula, BS: Bransfield Strait, HFZ Hero Fracture Zone, SFZ Shackleton Fracture Zone, SST: South Shetland Trench. Google Earth image source: Landsat/Copernicus – U.S. Geological Survey. b) Simplified geological map of Deception Island (after Smellie and López-Martínez, 2002; modified from Martí et al., 2013). c) Total alkalis vs. Silica diagram (TAS) (Le Bas et al., 1986) for Deception Island rock samples and glass shards (data from Geyer et al., 2019). Major elements are normalized to 100% (anhydrous) with Fe distributed between FeO and Fe₂O₃ following Middelmost (1989).

(both temporary and year-round) and three summer field camps, which are located inside (e.g., Gabriel de Castilla Base—Spain) or within a 150 km radius of this active volcano (e.g., Geyer, 2021; Geyer et al., 2021). Nearby, the Palmer Archipelago and the north-western coast of the Antarctic Peninsula are both important tourist destinations exceeding 30,000 visitors per year (IAATO, <https://iaato.org/>) largely restricted to the short tourist season (Bender et al., 2016).

The escalation in the amount of infrastructure and a vulnerable static and vagrant population to a future eruption of Deception Island emphasizes a clear need for improved long-term volcanic hazard assessments. However, past attempts have always been limited by the incompleteness of the island's eruption record (Roobol, 1982; Smellie, 2002a; Bartolini et al., 2014). Volcanic ash layers found in glaciers and marine/lacustrine sediment cores outside Deception Island can provide valuable information to: (i) determine the size and explosiveness of past eruptive events (e.g., Iverson et al., 2017); (ii) assess the spatial extent and potential impact of their related hazards (e.g., ash fallout) (e.g., Costa et al., 2014); (iii) complete the eruption record of the island (e.g., Harpel et al., 2008; Wulf et al., 2020); and (iv) estimate the island's eruptive recurrence over time (e.g., Bartolini et al., 2014).

During the last three decades, several studies have contributed to the reconstruction of the tephra record of Deception Island and to establishing a regional tephrostratigraphic framework. Hence, it has been possible to identify numerous tephra layers sourced at Deception Island in proximal (< 150 km) ice and sediment cores in the South Shetland Islands (e.g., Jiankang et al., 1999; Pallàs et al., 2001; Roberts et al., 2017) and Bransfield Strait (e.g., Fretzdorff and Smellie, 2002), and also in distal (> 800 km) marine sediments of the Scotia Sea (Moreton and Smellie, 1998). However, to date all the available information regarding the physicochemical characterization (and dating) of these tephra layers is dispersed and has neither been merged nor analysed within a common framework.

In this paper we present the DecTephra (Deception Island Tephra Record) database, which compiles the published information on all tephra layers potentially sourced in Deception Island. Geochemical analyses of the sampled layers are also provided, where available. The database is kept updated by the Research group on Volcanism and Magmatism of Deception Island (<http://voldec.es/>) and the latest version is freely accessible for download at the DecTephra web page (<http://voldec.es/dectephra/>) and at Zenodo open-access repository (Hopfenblatt et al., 2022; <https://doi.org/10.5281/zenodo.6077062>). A contact e-mail to propose corrections or updates facilitating the incorporation of new tephra layers into the database is also available on the same webpage.

DecTephra database seeks to become a key tool to: (i) construct a robust eruptive record for Deception Island; (ii) evaluate the island's past explosive volcanic activity (e.g., magma composition, explosiveness, eruptive recurrence, etc.); and (iii) to assess the extent and impact of the volcanic hazards. All three aspects are essential to improve existing volcanic scenarios and hazard maps of the island—a mandatory task for such an active volcano, given the increasing number of tourists and scientific expeditions visiting the island and its surroundings. As an example of the utility of the database, we use a preliminary analysis of the information to show how: (i) the composition and spatial extent of Deception Island's eruptive products can be depicted more completely; and (ii) the main periods of higher explosive eruptive activity on the island can be determined for the Holocene. Finally, we expect that the information included in DecTephra will also be of use for paleoenvironmental and paleoclimatic studies that require tephrochronological

information on local and regional scales. Finally, volcanic eruptions have always been considered one of the main forcing mechanisms that contribute to climate variability at several timescales, playing a key role in the short-term evolution of climate modes (Hernandez et al., 2020). The relationship between volcanic eruptions and climate variability has been characterized for the Northern Hemisphere (e.g., Sigl et al., 2015) whereas a similar characterization for the Southern Hemisphere is still in its infancy (e.g., Zhuo et al., 2021). Therefore, DecTephra also aims to improve our knowledge and characterization of Southern Hemisphere volcanism and its relationship to climate.

2. Geological overview of Deception Island

Deception Island is located at the southwestern end of Bransfield Strait (Lawver et al., 1995), a young (< 1.4 Ma) marginal basin separating the South Shetland Islands from the Antarctic Peninsula (Fig. 1a). Bransfield Strait formed as a consequence of the subduction of the Phoenix plate under the Antarctic plate during the Late Mesozoic–Cenozoic (Dalziel, 1984) combined with back-arc extension (González-Ferrán, 1985), although the precise nature and causes of the extension are debated (summarized in Smellie, 2021). According to K–Ar age estimations (Keller et al., 1992) and paleomagnetic studies, the island's subaerial exposed rocks are younger than 0.75 Ma (Valencio et al., 1979). The caldera-forming event, which dominates the evolution of the island, has been dated at c. 8300 years, according to paleomagnetic data, (Oliva-Urcia et al., 2015) and 3980 ± 125 calibrated years Before Present (cal yr BP) based on tephrochronology, sedimentological studies and ¹⁴C dating (Antoniades et al., 2018).

Deception Island magmas range from basaltic to trachydacitic and rhyolitic compositions, defining a distinctive differentiation trend of increasing alkalinity produced by uncommonly high Na₂O contents (mainly >4 wt% even in basalts; varying between 2 and 8 wt% overall, Fig. 1c) (e.g., Aparicio et al., 1997; Smellie, 2002b; Geyer et al., 2019). The pre-caldera phase was characterized by the construction of a volcanic shield and is represented by the Basaltic Shield Formation (Fig. 1b), in which most of the units correspond to lava flows, Strombolian deposits and palagonitized hyaloclastite breccias (e.g., Smellie, 2001, 2002b; Martí et al., 2013). The widespread Outer Coast Tuff Formation, formed during the caldera-forming eruption, comprises a thick sequence of massive dense pyroclastic density current deposits, several tens of meters thick and forms an almost continuous outcrop that encircles most of the island (e.g., Smellie, 2001, 2002a, 2002b; Martí et al., 2013) (Fig. 1b). The post-caldera phase, which includes the more recent historical eruptions (1829–1970), includes at least 70 dispersed eruptive vents inside the caldera and around the rim (e.g., Baker et al., 1975; Smellie, 2002c; Smellie and López-Martínez, 2002; Martí et al., 2013; Pedrazzi et al., 2020). Recent post-caldera activity consists of small volume eruptions (< 0.1 km³) with eruptive columns rising up to 10 km in height (Baker et al., 1975; Smellie, 2001, 2002c; Bartolini et al., 2014; Martí et al., 2013; Pedrazzi et al., 2014) and most of them are classified as VEI (Volcanic Explosivity Index) 2 or 3 magnitude events influenced both by the amount of water that interacted with the rising or erupting magma and its source (aquifer, ice melt, sea) (e.g., Baker et al., 1975; Smellie, 2002a; Pedrazzi et al., 2014, 2018, 2020).

3. Database architecture

The DecTephra database has been constructed based on an extensive review of 30 peer-reviewed scientific articles and 2 PhD theses

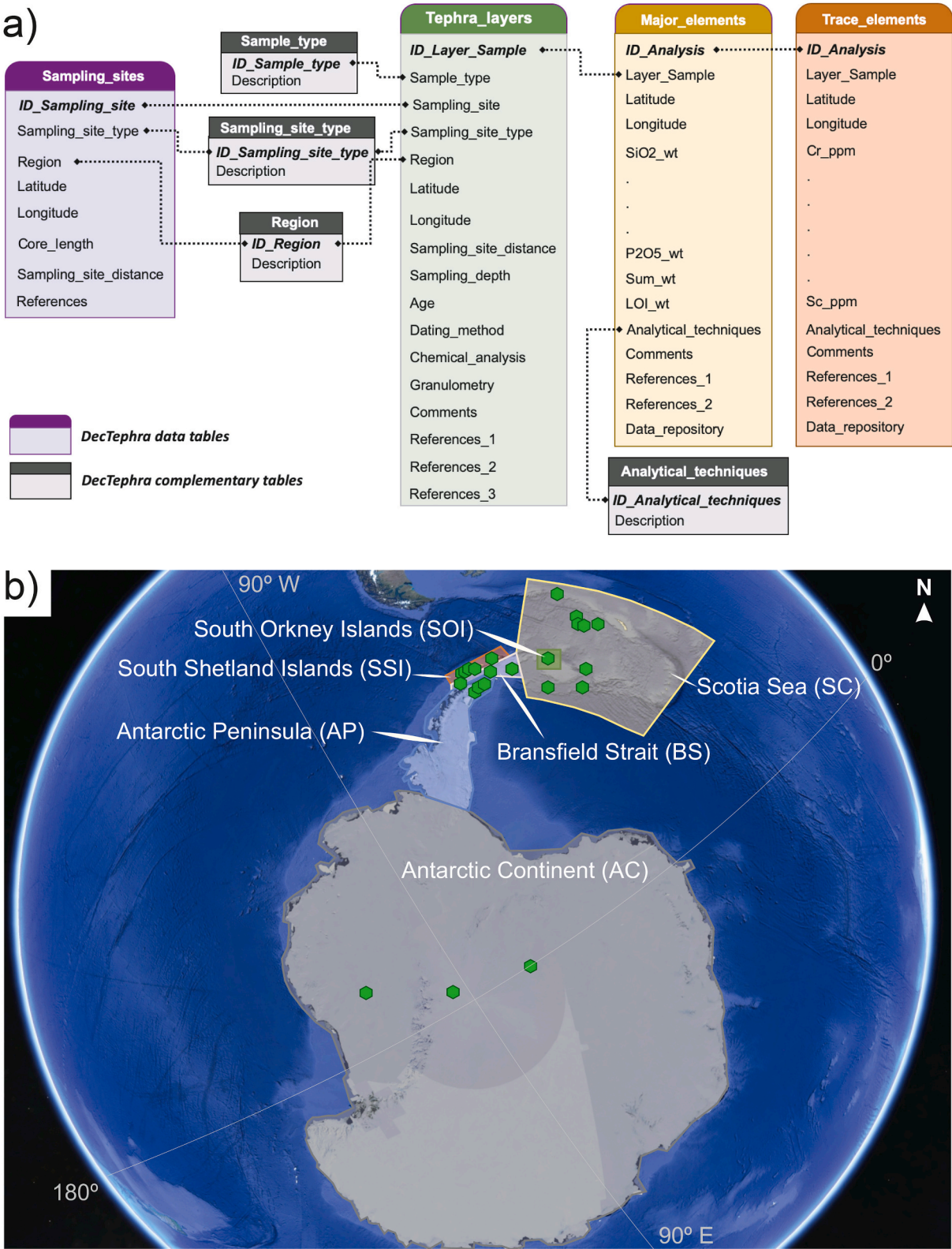


Fig. 2. a) Structure of the DecTephra database, comprising principal data tables (Sampling_sites, Tephra_layers, Major_elements and Trace_elements) and complementary tables (Sample_type, Sampling_site_type, Region, and Analytical_techniques). The References table is not included for clarity. Black dashed lines indicate connections between tables. b) Google Earth Pro image showing the location and extension of the six geographical regions used to classify the sampling sites (green hexagons). Image sources: Landsat/Copernicus; U.S. Geological Survey; PGC/NASA. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

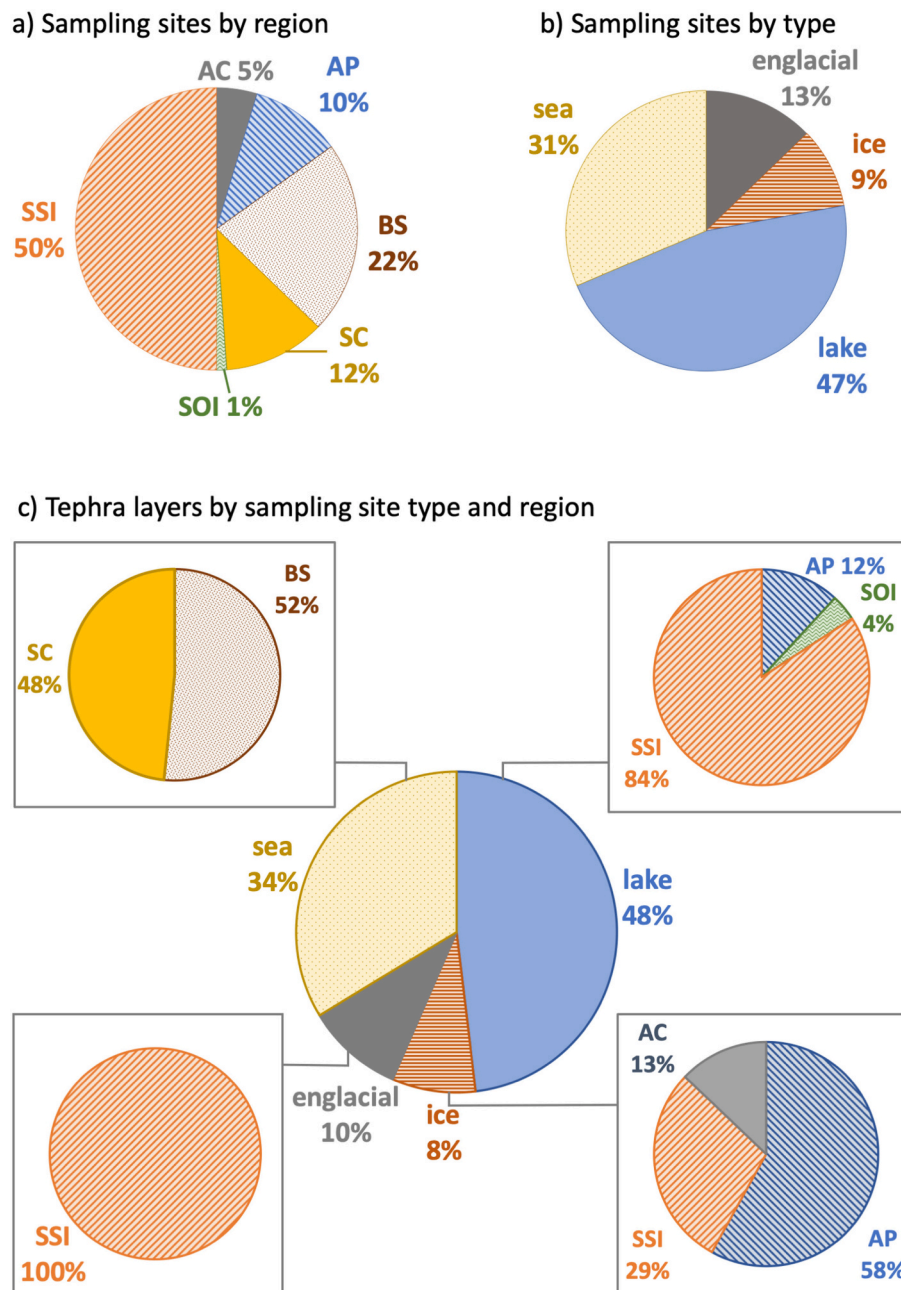


Fig. 3. Pie charts illustrating the distribution of the tephra sampling sites by region (a) and type (b). (c) Pie charts representing the distribution of tephra layers by sampling site type and, within each type, also by region. AP: Antarctic Peninsula; AC: Antarctic Continent; BS: Bransfield Strait; SC: Scotia Sea; SOI: South Orkney Islands; SSI: South Shetland Islands.

(Moreton, 1999; Molina Castiella, 2014) published between 1988 and 2020. For a tephra layer to be included in the DecTephra database, its Deception Island origin needs to be confirmed (or highly suspected) based on the geochemical similarity between the tephra layer and Deception Island's erupted materials (e.g., Pallàs et al., 2001). The proximity of the observed tephra layer to Deception Island, or to another sampling site with tephra layers known to be sourced at Deception Island (e.g., Watcham et al., 2011), are also considered potential evidence, particularly if no geochemical analyses are available. If this is the case, it is clearly indicated in the DecTephra record.

The current version of the DecTephra database comprises records for 362 tephra layers, including: (i) 12 layers described by Hodgson et al. (1998) and listed in the Antarctic Tephra Database (<http://www.tephrochronology.org/AntT>); (ii) 60 studied by Moreton and Smellie (1998)

and Moreton (1999), uploaded in the PANGAEA Repository (<http://www.pangaea.de>); (iii) 254 tephra layers found in marine/lacustrine sediments and ice cores; and (iv) 36 sampled englacial tephras. In this way, the database substantially updates the compilation by Smellie (1999) that listed c. 65 Upper Cenozoic tephra layers in the south polar region sourced at Deception Island. For each tephra layer included in the database, we have compiled information regarding: (i) location (e.g., latitude, longitude, region) and sample details such as position within a sediment or ice core; and (ii) tephra layer characteristics (e.g., age, chemistry, granulometry). The latest version of the database is included in Supplementary Material 1 in MS Excel format, and it is also available for download at the DecTephra web page (<http://voldec.es/dectephra/>) and at Zenodo open-access repository (Hopfenblatt et al., 2022; <https://doi.org/10.5281/zenodo.6077062>).

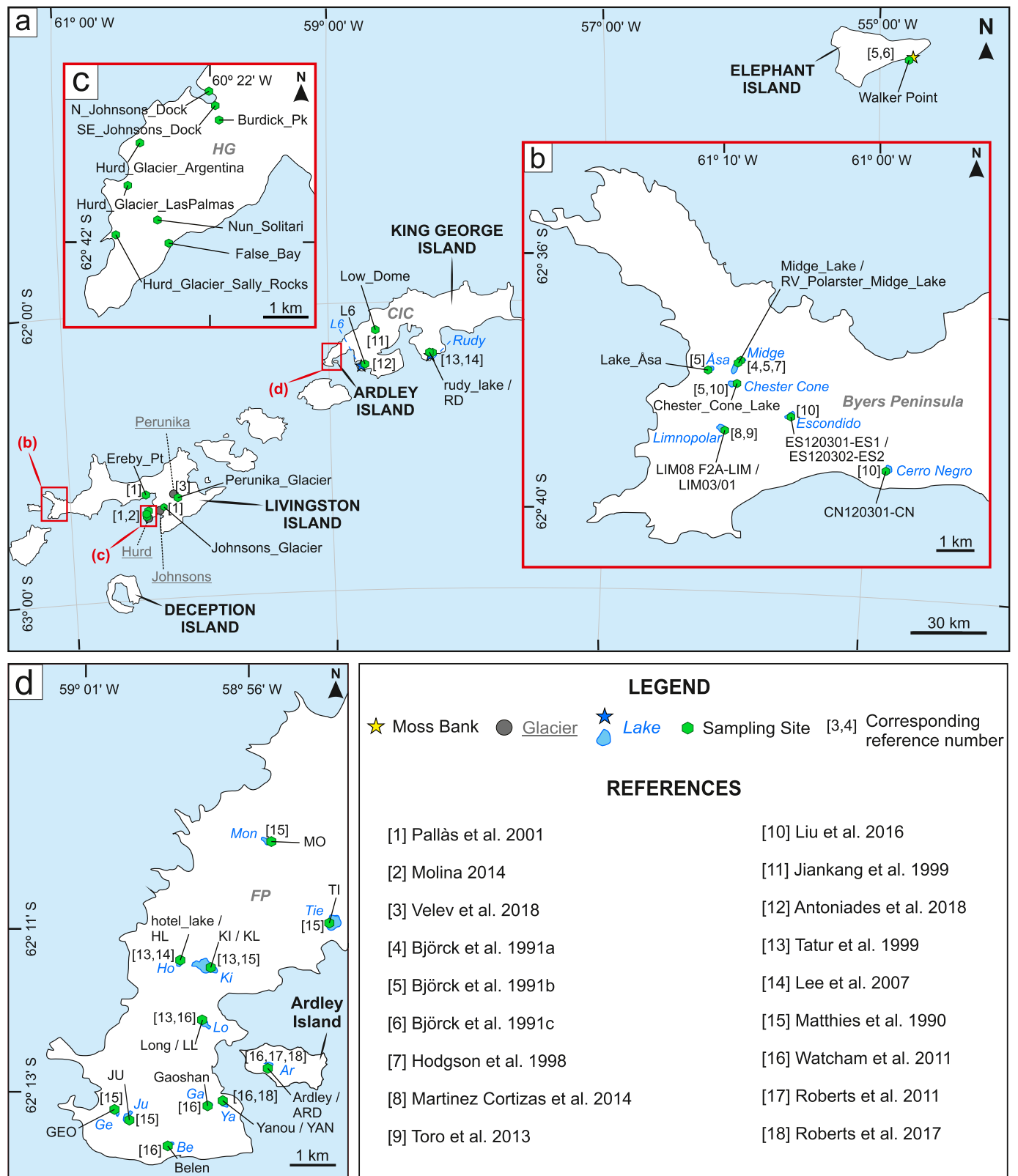


Fig. 4. Location of the tephra sampling sites in lakes, glaciers, and moss banks of the South Shetland Islands. Sampling site_ID and published sources are indicated for each site (See Supplementary Material 1 for bibliographic details and geographical coordinates of site locations).

The DecTephra database is composed of four main Excel-based data tables containing the following information (Fig. 2a): (i) a list of the tephra layers included in the DecTephra database and their most relevant details (Tephra_layers table); (ii) glass and bulk chemical analyses of the tephra layers, where available (Major_elements and Trace_elements tables); and (iii) information for each sampling site (Sampling_sites table). Four complementary tables (Region, Sample_type, Sampling_site_type, and Analytical_techniques) provide descriptions of

Table 1

Summary of the tephra layers included in the DecTephra database, the published sources, and the sampling site types.

Reference	Sampling site type	No. of layers	Age range*	Tephra/ Cryptotephra**	Geochemistry***
South Shetland Islands - SSI					
<i>Livingston Island (~40 km distance from Deception Island)</i>					
Björck et al., 1991a	Lake	6	< 650–3985 yr BP ^[3] /(516–4655 cal yr BP)	Tephra	-
Björck et al., 1991b	Lake	23	360–4790 yr BP ^[1] /(285–5589 cal yr BP)	Tephra	Major elements ^[c, d]
Hodgson et al., 1998	Lake	5	1970 CE – 1440 yr BP ^[1, 4] /(1970 CE – 1367 cal yr BP)	Tephra	Major elements ^[a]
Martínez Cortizas et al., 2014	Lake	3	1450–1860 CE ^[2]	Tephra	Major elements ^[i]
Molina Castiella, 2014	Englacial	10	> 1829–1970 CE ^[4]	Tephra	Major elements ^[e]
Liu et al., 2016	Lake	14	2100–5400 cal yr BP ^[1]	Tephra	Major elements ^[a]
Pallàs et al., 2001	Ice	16	< 1829–1970 CE ^[4]	Tephra	Major and trace elements ^[e, f, g, h]
Toro et al., 2013	Lake	7	525–4630 cal yr BP ^[1]	Tephra and Cryptotephra	Major elements ^[d, e]
Velev et al., 2018	Englacial	10	< 1829–1970 CE ^[4]	Tephra	Crystal phases ^[j]
<i>King George Island (~155 km distance from Deception Island)</i>					
Antoniades et al., 2018	Lake	2	3855–4105 cal yr BP	Tephra	Major elements ^[a]
Jiankang et al., 1999	Ice	9	1817–1955 CE ^[2]	Tephra	Major elements ^[a]
Lee et al., 2007	Lake	6	3900–6120 yr BP ^[1] /(4146–7076 cal yr BP)	Tephra	Major elements ^[a]
Matthies et al., 1990	Lake	18	3100–9000 yr BP ^[1] /(2843–10,507 cal yr BP)	Tephra	Major elements ^[a]
Roberts et al., 2017	Lake	18	< 500–7216 cal yr BP ^[1]	Tephra	Major elements ^[a]
Tatur et al., 1999	Lake	7	4000–6000 yr BP ^[1]	Tephra	Major and trace elements ^[b]
Watcham et al., 2011	Lake	35	977–7413 cal yr BP ^[1]	Tephra	Major elements ^[a]
<i>Elephant Island (~353 km distance from Deception Island)</i>					
Björck et al., 1991b, 1991c	Lake	5	1800–3560 yr BP ^[1] /(1608–3897 cal yr BP)	Cryptotephra	Major elements ^[c, d]
South Orkney Islands - SOI					
Hodgson et al., 1998	Lake	7	1920 CE – 1473 yr BP ^[1] /(1920 CE – 1320 cal yr BP)	Tephra	Major elements ^[a]
Bransfield Strait - BS					
Fretzdorff and Smellie, 2002	Sea	29	-	Tephra	Major elements ^[a]
Heroy et al., 2008	Sea	2	3793–5545 cal yr BP ^[1]	Tephra	-
Matthies et al., 1988	Sea	19	-	Tephra	Major elements ^[a]
Monien et al., 2011	Sea	2	442–744 cal yr BP	Tephra	-
Moreton, 1999	Sea	2	-	Tephra	Major elements ^[a]
Willmott et al., 2006	Sea	4	3.24–6.99 ka ^[5] /(3356–7858 cal yr BP)	Tephra	-
Antarctic Peninsula - AP					
Abram et al., 2011	Ice	1	1967 CE	Tephra	-
Aristarain and Delmas, 1998	Ice	1	1638–1644 CE ^[7]	Tephra	Major soluble ions ^[k]
Björck et al., 1991b	Lake	15	190–4770 yr BP ^[1] /(125–5589 cal yr BP)	Cryptotephra	Major elements ^[c, d]
Mulvaney et al., 2012	Ice	15	106–10,580 yr BP ^[4] /(1834 CE – 12,848 cal yr BP)	Tephra	Major elements ^[a] ; unpublished EMPA data of JL Smellie
Palais et al., 1989	Ice	1	1590–1690 CE ^[6]	Tephra	Major elements ^[i]
Roberts et al., 2011	Lake	3	2260–10,556 yr BP ^[1] /(2141–12,693 cal yr BP)	Tephra	-
Sterken et al., 2012	Lake	3	1981–10,081 cal yr BP ^[1]	Tephra	-
Scotia Sea - SC					
Moreton, 1999	Sea	22	7300–35,400 yr BP ^[1] /(6392 – > 43,005 cal yr BP)	Tephra	Major and trace elements ^[a, i]
Moreton and Smellie, 1998	Sea	36	7300–35,400 yr BP ^[1] /(6392 – > 43,005 cal yr BP)	Tephra	Major elements ^[a]
Roberts et al., 2017	Sea	2	7020–7990 cal yr BP ^[1]	Tephra	Major elements ^[a]
Antarctic Continent - AC					
<i>West Antarctica</i>					
Kurbatov et al., 2006	Ice	1	1871 CE ^[7]	Cryptotephra	-
<i>South Pole</i>					
Delmas et al., 1992	Ice	1	1641 CE ^[6]	Cryptotephra	Major soluble ions ^[i, k]
Palais et al., 1989	Ice	2	1632–1821 CE ^[6]	Tephra	Major elements ^[i]

* Age range covered by all dated tephra layers expressed either in ka, uncalibrated (yr) or calibrated (cal yr) years Before Present (BP), or Common Era (CE). The selected age format (yr BP, cal yr BP, CE or ka) is in agreement with the one used in the references. Errors have been considered when estimating the maximum and minimum ages. Dating methods: [1] ¹⁴C sediment dating; [2] ice dating with the Dansgaard-Johnsen model; [3] AMS sediment dating; [4] correlation; [5] geomagnetic paleointensity age model; [6] ice core dating; [7] glaciological model. In brackets, age provided as *cal yr BP* following the methodology described in Section 5.2 and Supplementary Material 2.

**Cryptotephra is defined as fine or very fine ash sized ($\leq 125 \mu\text{m}$) not visible as a layer to the naked eye.

- No chemical analysis reported/available.

*** Geochemical analysis methods: [a] Electron Probe Microanalysis (EPMA); [b] Atomic Absorption Spectrophotometry (AAS); [c] Atomic Emission Spectroscopy (AES); [d] Mass spectrometry (MS); [e] X-Ray Fluorescence (XRF); [f] Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES); [g] Inductively Coupled Plasma Mass Spectrometry (ICP-MS); [h] Instrumental Neutron Activation Analysis (INAA); [i] Scanning Electron Microscopy - Energy Dispersive X-Ray Spectroscopy (SEM-EDS); [j] X-Ray Diffraction (XRD); [k] Ion Chromatography (IC); [l] Ion Microprobe (IM).

^^ No calibration possible; uncertainty too large (see Section 5.2 and Supplementary Material 2 for more details).

the content of specific columns in the data tables (Fig. 2a). The last table, References, contains full bibliographic details for all references cited in each table. A detailed description of the content of all four main DecTephra data tables is provided below.

Each entry in the Tephra_layers table corresponds to a tephra layer identified at specific sampling sites (including sediment and ice cores, and ice cliff sites) although it cannot currently be shown that each is a unique isochronous tephrostratigraphic horizon (or eruptive episode). Consequently, some of the tephra layers separately identified may be the same horizon sampled at different locations. If known, potential correlations between diverse tephra layers are indicated.

In the following section we describe parameters used in tables that make up the DecTephra database. Parameters that are self-explanatory and do not require further description are omitted.

3.1. Tephra_layers table

ID_Layer_Sample (Column A): this is a primary key in the Tephra_layer table. It is used to link with the Tephra_layers, Major_elements, and Trace_elements data tables. The layer name included in this column uniquely identifies each record shown. The layer name is commonly given in the reference(s) cited. If this is not the case, we have named them as *Sampling_site* (Column C) followed by the *Sampling_depth* (Column I) (e.g., Gaoshan_220cm, Watcham et al., 2011). If the latter is not available, we use a numerical sequence (e.g., PS1_1, Delmas et al., 1992). In case of duplicity in the original layer names, we have added a unique suffix related to the *Sampling_site* (e.g., AP7_walker_point and AP7_hidden_lake, Björck et al., 1991b and c).

Sample_type (Column B): describes the type of layer based on the definition by Lowe (2011): (i) tephra layer (i.e., ash particle size $\geq 125 \mu\text{m}$ with tephra layer visible to the naked eye); (ii) cryptotephra (i.e., fine or very fine ash particle size $\leq 125 \mu\text{m}$ with tephra layer not visible to the naked eye); or not defined (n.d). All available options are listed and described in the Sample_type complementary table.

Sampling_site (Column C): corresponds to the primary key of the Sampling_sites data table, and it is used to correlate the Tephra_layers and Sampling_sites data tables. In the case of sediment and ice cores, the *Sampling_site* corresponds to the core name as provided by the consulted references. For englacial samples, or those cores without a specific given name, the *Sampling_site* name is given after its geographical location.

Sampling_site_type (Column D): describes if the tephra layer has been identified in: (i) a marine sediment core (sea); (ii) a lacustrine sediment core (lake); or (iii) an ice core (ice). It also indicates if the sampled/studied layer corresponds to an englacial tephra (englacial). All available options are listed and described in the Sampling_site_type complementary table.

Region (Column E): classifies the tephra layer into six main geographical regions (see Fig. 2b): Antarctic Continent (AC), Antarctic Peninsula (AP), Bransfield Strait (BS), South Orkney Islands (SOI), Scotia Sea (SC), and South Shetland Islands (SSI).

3.2. Major_elements data table

ID_Analysis (Column A): indicates the primary key of the Major_elements data table. It is used to link the Major_elements and Trace_elements data tables. The analysis name (as in the consulted references) included in this column uniquely identifies each record in the table and hence, cannot be the same for two or more entries and can never be null.

Layer_Sample_ID (Column B): refers to *ID_Layer_Sample* from the Tephra_layers data table. It is used to link the Major_elements and Tephra_layers data tables.

3.3. Trace_elements data table

ID_Analysis (Column A): indicates the primary key of the Trace_elements data table. The analysis name (as in the consulted references) included in this column uniquely identifies each record in the table and hence, cannot be the same for two or more entries and never null.

Layer_Sample (Column B): refers to *ID_Layer_Sample* from the Tephra_layers data table. It is used to link the Trace_elements and Tephra_layers data tables.

3.4. Sampling_sites table

ID_Sampling_site (Column A): indicates the primary key of the Sampling_sites table. See *Sampling_site* of the Tephra_layers data table for description.

4. Overview of the DecTephra content

4.1. Geographical distribution and sampling locations

The 362 tephra layers included in the DecTephra database have been identified at 86 different sampling sites (including sediment/ice cores and englacial sampling sites), mostly distributed throughout the South Shetland Islands (50%, $n = 43$) and Bransfield Strait (22%, $n = 18$) (Figs. 2b and 3a). The closest sampling sites ($\sim 30 \text{ km}$ distance) correspond to marine sediment cores from Bransfield Strait (Matthies et al., 1988) (Fig. 4) and the most distant ($> 3000 \text{ km}$) are ice cores from South Pole (Kurbatov et al., 2006; Palais et al., 1989) (Fig. 2b). Nearly 80% of the sampling sites correspond either to lake (47%, $n = 40$) or marine sediment cores (31%, $n = 27$) (Fig. 3b). Considering all this, almost half of the tephra layers included in the DecTephra database (48%, $n = 177$), were recovered from lake sediment cores obtained in the South Shetland Islands ($n = 149$) (e.g., Liu et al., 2016), Antarctic Peninsula ($n = 21$) (e.g., Roberts et al., 2017; Sterken et al., 2012) or the South Orkney Islands ($n = 7$) (e.g., Hodgson et al., 1998) (Fig. 3c, Table 1 and Supplementary Material 1). Tephra layers obtained in marine sediment cores, corresponding to about one third of all DecTephra records (34%, $n = 118$), were largely obtained from sites within Bransfield Strait ($n = 58$) (e.g., Fretzdorff and Smellie, 2002) and the Scotia Sea ($n = 60$) (e.g., Moreton and Smellie, 1998) (Fig. 3c, Table 1 and Supplementary Material 1). In the following section, we provide a more detailed description of the tephra layers found in each of the defined regions, with particular focus on likely isochronous tephrostratigraphic horizons.

4.1.1. South Shetland Islands

Deception Island tephra layers are present in numerous lakes and glaciers at localities scattered along the South Shetland Islands (Fig. 4). On Livingston Island, a total of 57 tephra layers have been described in sediment cores retrieved from seven different lakes on Byers Peninsula (Åsa, Cerro Negro, Chester Cone, Domo, Escondido, Limnopolar, and Midge lakes) and 36 englacial tephra layers were obtained from ice cliffs and ice cores from Hurd and Perunika glaciers (See Table 1, Fig. 4). The estimated age of the tephra layers is based on available ^{14}C dating on sediments (e.g., Liu et al., 2016) or historic records (e.g., Pallàs et al.,

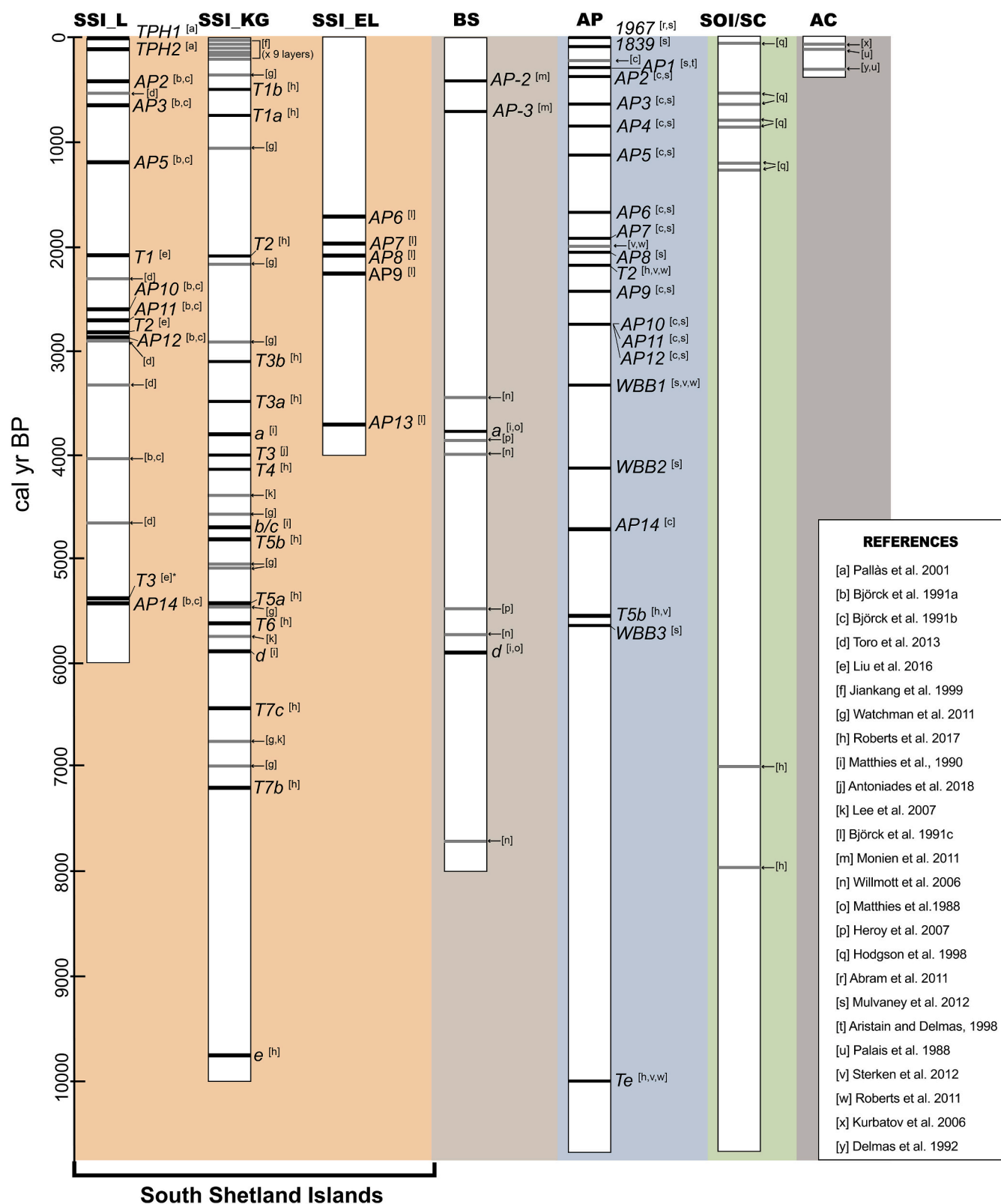


Fig. 5. Tephra layers (grey) included in the DecTephra database with a reported age (see Supplementary Material 1 for details on the location of the corresponding sampling sites, tephra dating method and error). Only Holocene tephra layers are included in this figure. Age in cal yr BP for all tephra layers is provided in Supplementary Material 2. If an age interval is provided for a specific tephra layer, we have estimated the average age. In this case, only those layers with an age interval comprising 1000 years or less are considered. Errors are not illustrated in this figure for the sake of simplicity, but can be found in Supplementary Materials 1 and 2. In the case where a tephra layer is correlated among two or more sampling sites, it is considered to be a tephra horizon and is represented as a black line in this graph. Ages of the tephra horizons “a” and “d” represented in BS are assigned based on the correlations made by Matthies et al. (1990). AC: Antarctic Continent; AP: Antarctic Peninsula; BS: Bransfield Strait; SC: Scotia Sea; SSI_E: South Shetland Islands – Elephant Island; SOI: South Orkney Islands; SSI_K: South Shetland Islands – King George Island; SSI_L: South Shetland Islands – Livingston Island.

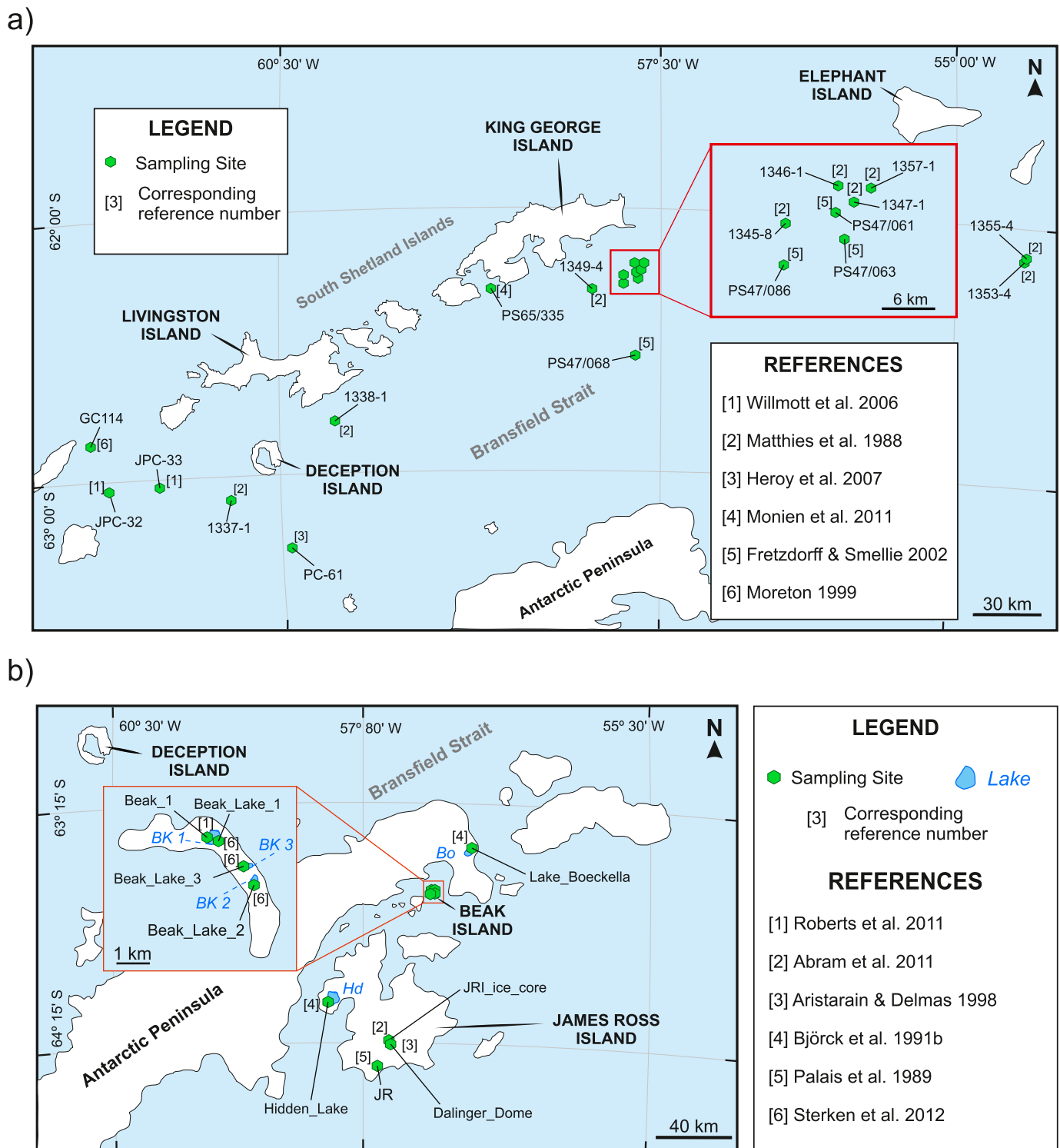


Fig. 6. Locations of tephra sampling sites in Bransfield Strait (a) and the Antarctic Peninsula (b). Sampling_site_ID and consulted reference are indicated at each site (see Supplementary Material 1 for details and exact geographical coordinates).

2001). Geochemical comparisons have been made with volcanic deposits in situ on Deception Island, thus permitting limited age control and defining isochronous tephra horizons for a few layers (Fig. 5). As interpreted by Liu et al. (2016), the oldest layer has been correlated with tephra T3 (5400 cal yr BP) found in sediment cores from the Cerro Negro, Escondido, and Limnopolar lakes. However, the layer has recently been correlated more robustly, using a wide range of supportive criteria, with Deception Island's caldera-forming event, established as

3980 ± 125 cal yr BP (Antoniades et al., 2018). Two additional tephra layers can be traced between the same three lakes (Liu et al., 2016; Oliva et al., 2016) and are dated as 2370 ± 100 (T2) cal yr BP and 1890 ± 140 (T1) cal yr BP (Antoniades et al., 2018). The youngest tephra horizons described for Livingston Island are TPH1 (1970 CE) and TPH2 (< 1829 CE), both observed in the Hurd and Perinuka glaciers (Molina Castiella, 2014; Pallàs et al., 2001; Velev et al., 2018). Based on geochemical comparisons and evidence from aerial photographs from the British

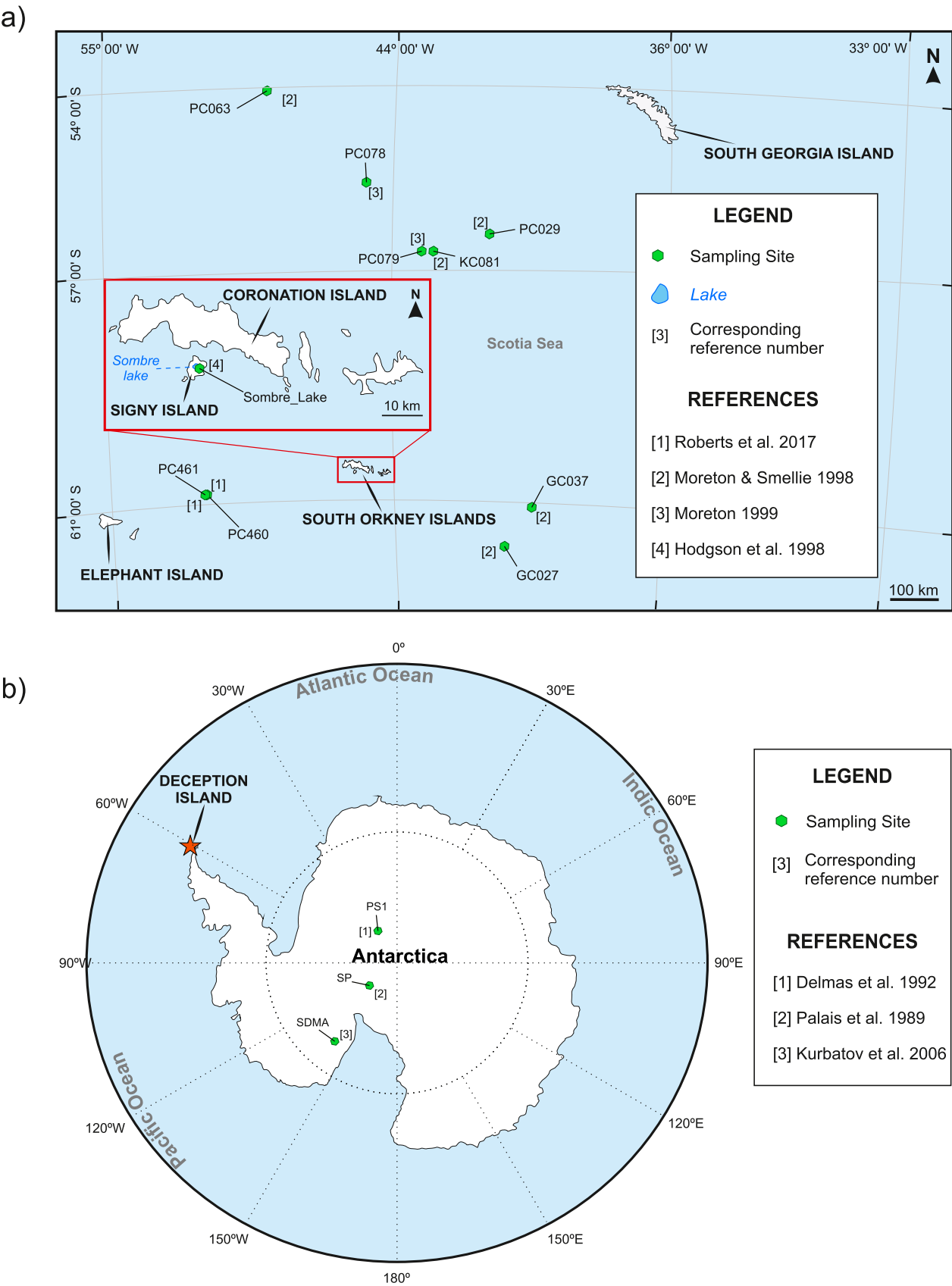
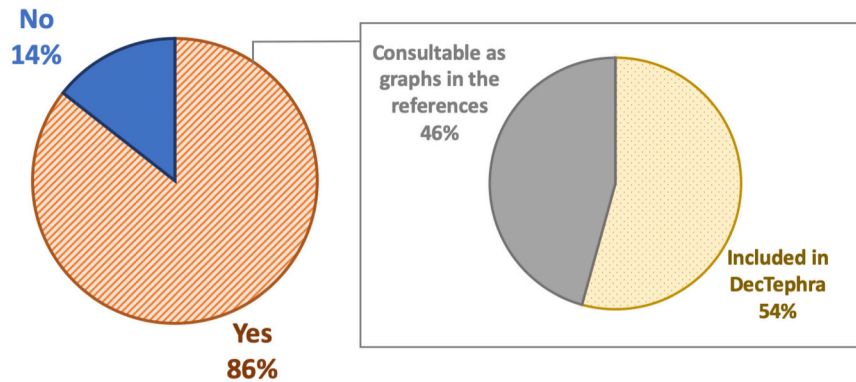
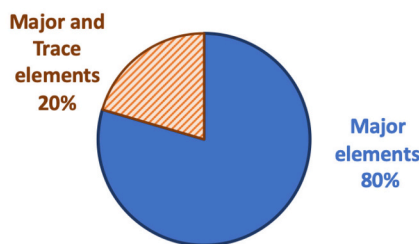


Fig. 7. Location of the tephra sampling sites in the Scotia Sea and South Orkney Islands (a) and the Antarctic Continent (b). Sampling_site_ID and consulted reference are indicated for each site (See Supplementary Material 1 for details and exact geographical coordinates).

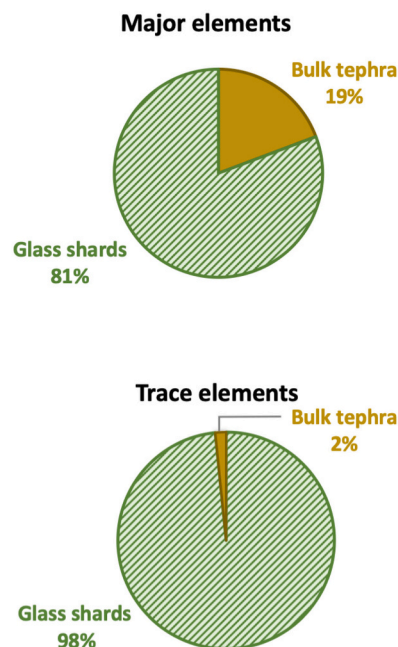
a) Available geochemical analyses



b) Type of geochemical analyses



c) Source of analyses



d) Geographical distribution

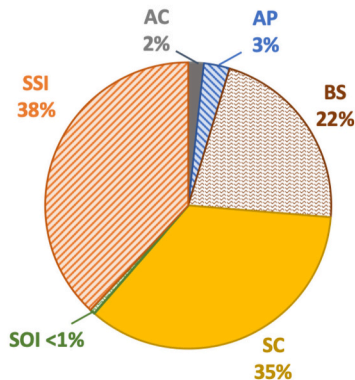


Fig. 8. Pie charts illustrating the availability (a), type (b), source (c), and geographical location (d) of geochemical analyses of tephra layers included in the DecTephra database. In (b–d) percentages refer only to those analyses listed in the Major_elements and the Trace_elements tables of the DecTephra database, excluding those simply published as graphs. AP: Antarctic Peninsula; AC: Antarctic Continent; BS: Bransfield Strait; SC: Scotia Sea; SOI: South Orkney Islands; SSI: South Shetland Islands.

Antarctic Survey taken in 1956, *TPH1* and *TPH2* correspond to deposits associated with eruptions in 1970 and 1829 (Pallàs et al., 2001).

About 120 km northeast of Deception Island, more than 90 tephra layers have been identified in sediment and ice cores retrieved from eleven lakes on King George Island (Geographensee, Hotel, Jurasee, Kiteschsee, Kitezsh, Long, Mondsee, L6, Rudy, Tiefersee, and Yanou lakes), Ardley Lake on Ardley Island, and from the Collins Ice Cap (Fig. 4, Table 1 and Supplementary Material 1). Many of the layers can be traced between two or more sites and at least 17 isochronous tephra horizons have been defined, with ages ranging from 8700 ± 300 yr BP (tephra horizon *e* from Matthies et al., 1990) to <500 cal yr BP (tephra horizon *T1b* from Roberts et al., 2017) (Fig. 5). Additional younger tephra layers also occur in other sediment cores retrieved from several of the lakes on Fildes Peninsula (Watcham et al., 2011) and in ice cores of the Collins Ice Cap (Jiankang et al., 1999). The Collins Ice Cap layers may correspond to eruptive events that occurred on Deception Island

between 1812 and 1956 CE (Jiankang et al., 1999).

Finally, in the outer reach of the South Shetland archipelago, tephra studies at Walker Point (Elephant Island) (Björck et al., 1991b; Björck et al., 1991c) identified a total of 5 cryptotephra with ages ranging from 3500 ± 60 to 1850 ± 50 yr BP (Figs. 4 and 5, Table 1 and Supplementary Material 1).

4.1.2. Bransfield Strait

A total of 58 tephra layers have been observed in 16 marine sediment cores from Bransfield Strait (Fig. 6a; Table 1 and Supplementary Material 1). The sediment core locations vary from 30 km southwest of Deception Island to 360 km northeast of the volcano (southwest of Elephant Island; Matthies et al., 1988) (Fig. 6a). The youngest dated layers, described by Monien et al. (2011), have been correlated with tephra layers *AP-2* (c. 450 cal yr BP) and *AP-3* (c. 750 cal yr BP) present in lacustrine sediment cores from Livingston Island (Björck et al., 1991a,

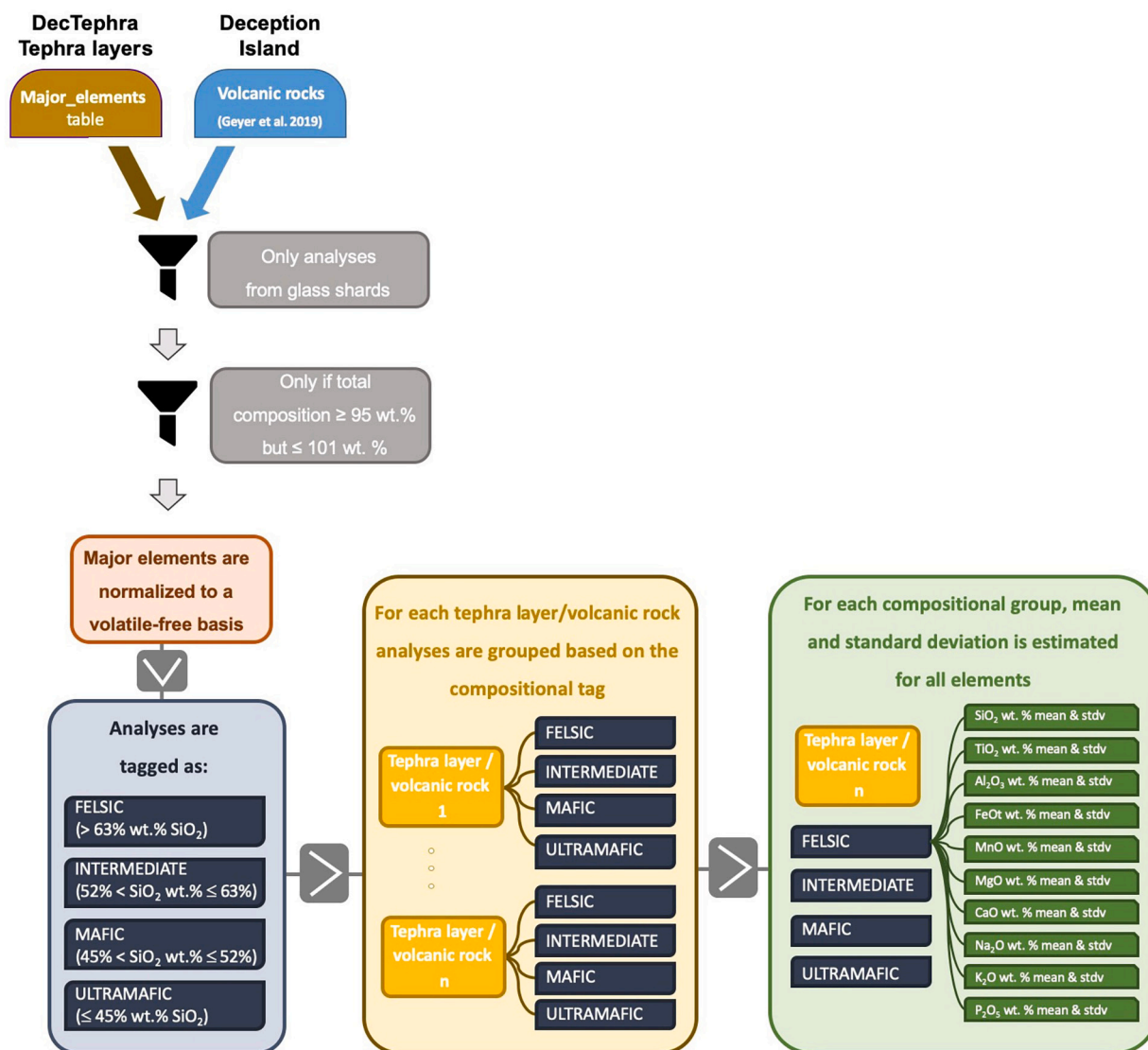


Fig. 9. Scheme of the procedure followed to normalize available geochemical data of major elements for tephra layers included in the DecTephra database as well as the EPMA analyses of volcanic glass in Deception Island volcanic rocks (original data from Geyer et al., 2019).

1991b; Fig. 5). Two additional layers observed by Matthies et al. (1988) were correlated with tephra *a* (c. 3550 yr BP) and *d* (5,190 yr BP) on King George Island (Matthies et al., 1990; Fig. 5). Finally, based on their similar geochemical composition and stratigraphic position, Fretzdorff and Smellie (2002) interpreted the topmost tephra layers in their sediment cores to be equivalent to *TPH1* and *TPH2* tephra present in Livingston Island glaciers (Pallàs et al., 2001; Fig. 5).

4.1.3. Antarctic Peninsula

The DecTephra database includes 15 cryptotephra and 23 tephra layers observed in lacustrine sediment and ice cores situated on the Antarctic Peninsula and neighbouring islands (Fig. 6b). The youngest layer, observed in the James Ross Island (JRI) ice core, has been correlated with the 1967 CE Deception Island eruption (Abram et al., 2011; Mulvaney et al., 2012) (Fig. 5). The tephra horizon *Te* (c. 9975 cal yr BP), defined by Roberts et al. (2011), is the oldest described from the Antarctic Peninsula and it can be observed in the JRI ice core and sediments in Beak lake on Beak Island (Mulvaney et al., 2012; Roberts et al., 2011, 2017). Between the 1967 CE and *Te* tephra horizons, several other tephra layers can be correlated between the Antarctic Peninsula and King George Island (e.g., T5b; Roberts et al., 2017) or Livingston Island (e.g., AP2, AP3, AP14, etc.; Björck et al., 1991b) (Sterken et al., 2012)

(Fig. 5).

4.1.4. Scotia Sea and South Orkney Islands

Over 800 km east of Deception Island, seven tephra layers are identified in lacustrine sediment cores recovered from Sombre lake on Signy Island (South Orkney Islands) (Hodgson et al., 1998) (Fig. 7a). Estimated ages range from 30 to 1470 yr BP, and the high Na₂O contents make it very likely that Deception Island was the source (Hodgson et al., 1998; Fig. 5, Table 1 and Supplementary Material 1).

In the Scotia Sea, a total of 60 tephra layers have been described throughout ten different marine sediment cores with ages ranging between 7020 yr BP and 35,400 yr BP (Moreton and Smellie, 1998; Moreton, 1999; Roberts et al., 2017) (Fig. 7a, Table 1 and Supplementary Material 1). One of these, a megascopic ash layer (~ 10,670 yr BP) of bimodal composition ranging from basalt to rhyolite, was described by Moreton & Smellie, (1998) and Moreton (1999), and was correlated across six sampling sites (GC027, PC029, GC037, PC078, PC079, and KC081) (Figs. 5 and 7a), making it the second-most widely correlated tephra layer after the caldera-collapse layer correlated by Antoniadou et al. (2018).

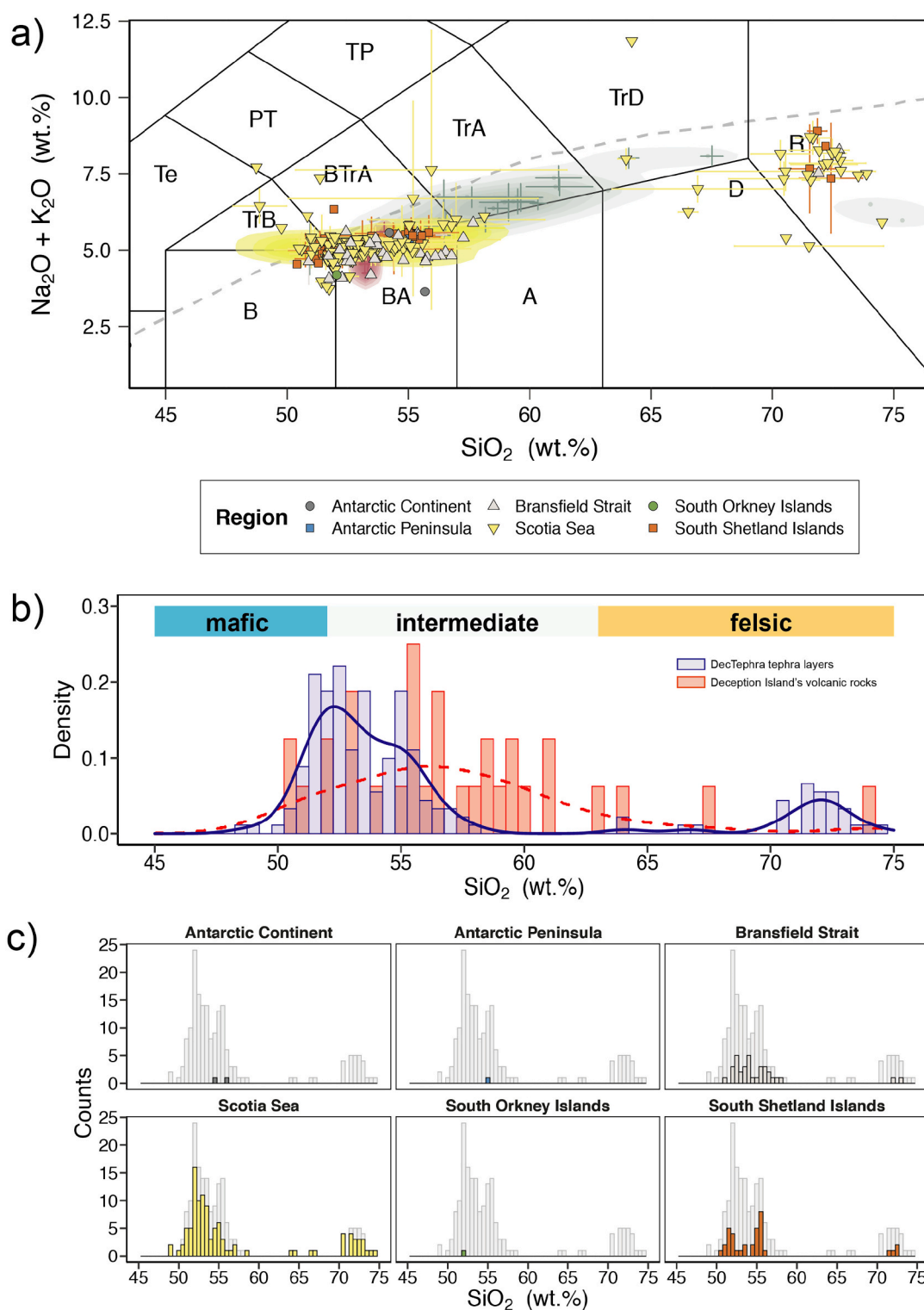


Fig. 10. a) Total Alkali vs. Silica diagram (TAS) for the glass shard analyses included in the Major_elements table of the DecTephra database. Major elements normalized to 100% (anhydrous) with Fe distributed between FeO and Fe_2O_3 following Middelmost (1989). Grey dashed line discriminates between the alkaline-subalkaline fields, according to Irvine and Baragar (1971). Background density clouds and semi-transparent points correspond to glass analyses of in situ Deception Island rock samples reported by Geyer et al. (2019). Legend as per Figure 1c. b) Frequency histogram of SiO_2 wt% of those glass shard analyses included in the Major_elements table of the DecTephra database and of Deception Island's volcanic products (See Supplementary Materials 3 and 4). A bandwidth of 0.5 has been applied and the SiO_2 wt% intervals used to tag the analyses as being acid ($> 63\%$ wt% SiO_2), intermediate ($52\% < \text{SiO}_2$ wt% $\leq 63\%$) and basic ($45\% < \text{SiO}_2$ wt% $\leq 52\%$) are also indicated. c) Frequency histograms of SiO_2 wt% for those glass shard analyses included in the Major_elements table of the DecTephra database are separated by regions. The grey histogram in the background corresponds to the general histogram represented in b) that includes all available analyses. Analyses considered in a), b), and c) are those obtained after normalization based on the criteria illustrated in Fig. 9 and detailed in the main text. See Supplementary Materials 3 and 4 for further details.

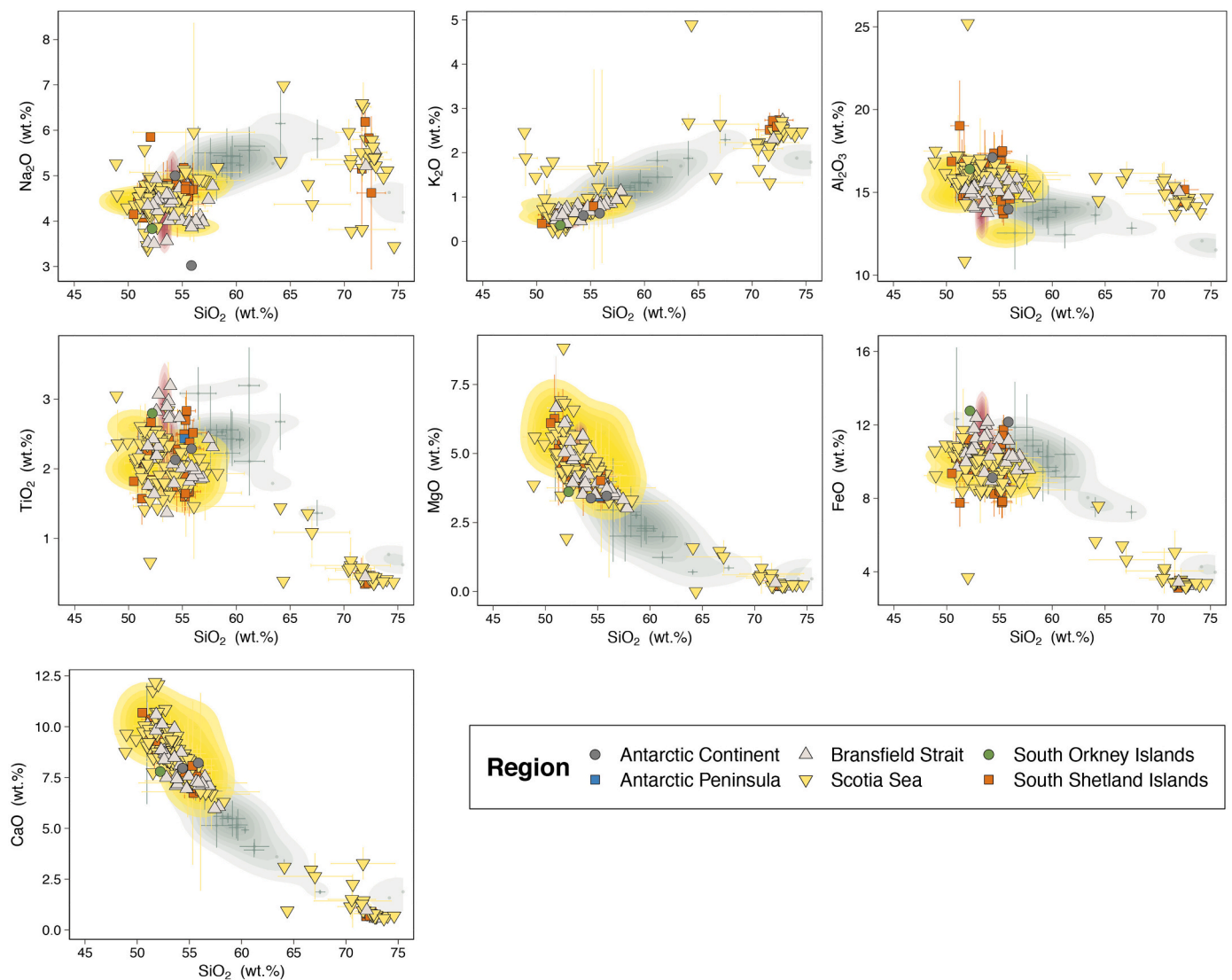


Fig. 11. Major element vs. SiO_2 content Harker Diagrams for glass shard analyses obtained after normalization based on the criteria illustrated in Fig. 10 and detailed in the main text (see Supplementary Materials 3 and 4 for further detail on the data). Major element compositions have been normalized to 100% in anhydrous base with Fe as FeO. Background density clouds and semi-transparent points correspond to glass analyses of in situ Deception Island rock samples reported by Geyer et al. (2019). Legend as per Figure 1c.

4.1.5. Antarctic Continent

On the Antarctic continent, (crypto)tephra layers potentially sourced at Deception Island have been found in the Simple Dome ice core in West Antarctica (Kurbatov et al., 2006) and the three ice cores closest to the South Pole (Palais et al., 1989; Delmas et al., 1992) (Fig. 7). The two youngest tephra layers (1819–1829 CE and 1879 CE, respectively; Palais et al., 1989; Kurbatov et al., 2006), have been interpreted as the deposits of historic eruptions occurring on Deception Island during the same period (Fig. 5). The oldest layers at each site could potentially be correlated, as they have ages of 1641 CE and 1632–1638 CE (Palais et al., 1989; Delmas et al., 1992).

4.2. Geochemistry

Geochemical data are available for 85% ($n = 309$) of the tephra layers included in the DecTephra database (Fig. 8a). The data were provided in the original publications either as compositional graphs (47%, $n = 144$) or as analyses (53%, $n = 165$). All the published major and trace element data are included in the DecTephra database (See Supplementary Material 1). Within the 165 tephra layers with major

element analyses listed in the Major_elements table, 35 layers (i.e., 21%) also include trace element compositions (Fig. 8b). Major and trace elements have been both mostly obtained from glass shards (99% and 81%, respectively) (Fig. 8c). The geochemical analyses were carried out using different techniques (e.g., Electron Probe Microanalysis (EPMA), X-ray fluorescence (XRF), Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES), etc.); in a few cases, the data were presented as normalized major element concentrations (Lee et al., 2007; Antoniadis et al., 2018).

Tephra layers with accompanying analyses have been sampled mainly in the South Shetland Islands (39%, $n = 65$), the Scotia Sea (36%, $n = 60$) and Bransfield Strait (19%, $n = 31$). Bulk tephra analyses are restricted to tephra layers in the glaciers of Livingston Island (South Shetland Islands; Pallàs et al., 2001 ($n = 18$); Molina Castiella, 2014 ($n = 10$)). Trace element data are uncommon and are restricted to grain-specific analyses of glass shards from the Scotia Sea (84%), analysed by ion probe (Moreton, 1999), and bulk-sample tephra analyses of layers in Livingston Island glaciers (16%) (Pallàs et al., 2001).

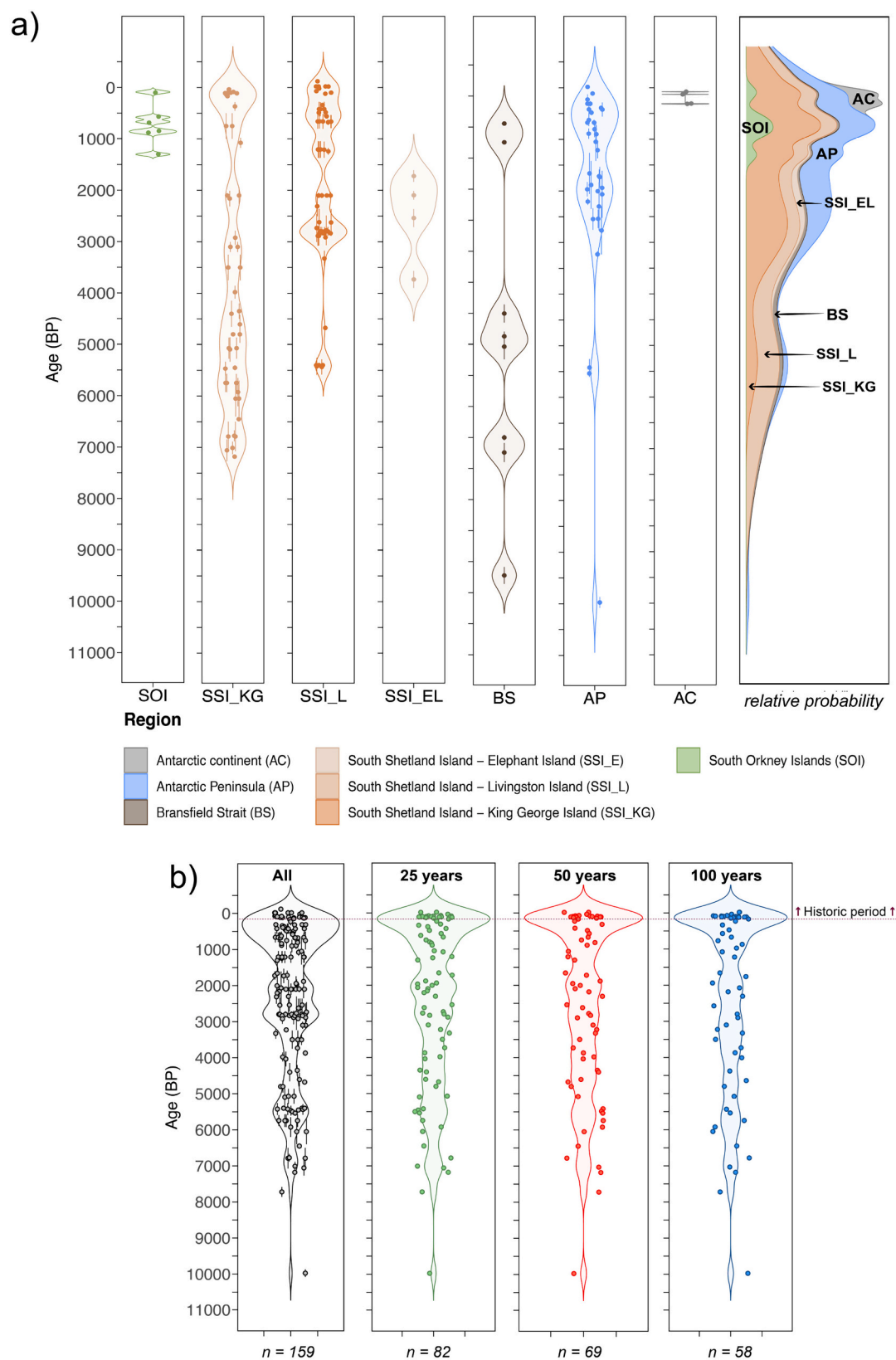


Fig. 12. (a) Violin plots and relative probability for the ages of the tephra layers reported in the DecTephra database separated by region. Points and vertical bars represent individual tephra ages and errors as included in the Tephra_layers table (See Supplementary Material 2 for further detail on the data). (b) Violin plots for the ages of the tephra layers (in cal yr BP) reported in the DecTephra using time-window bins of 25, 50 and 100-years. After filtering, n indicates the number of tephra samples in each bin (See Supplementary Material 5 for further detail on the data).

5. Discussion

5.1. Geochemistry of DecTephra layers: comparison with Deception Island eruptive products

A reliable correlation between tephra layers and their volcanic sources requires a comprehensive geochemical record, including not only major and trace element analyses of the volcanic glasses but also of any magmatic minerals present (Lowe, 2011; Lowe et al., 2017). Because of the often unpredictable effects of alteration, which can be prevalent in marine tephra in particular due to the rapidity with which highly reactive glass becomes altered, immobile elements and isotopes unaffected by secondary processes are most important for achieving successful correlations (e.g., Hopkins et al., 2015; Petrosino et al., 2019).

Although a full geochemical characterization is not available for all tephra layers included in the DecTephra database, the existing published major element compositions enable a first-order geochemical comparison between the tephra and eruptive products on Deception Island. In order to maximize the reliability of the analyses and to make tephra and Deception Island datasets comparable, we have treated the geochemical data in the following way (Fig. 9):

- (i) only major element analyses of volcanic glasses are considered since bulk tephra/rock analyses may be affected by variable phenocryst, xenocryst and xenolith contents (Shane, 2000). For comparison with Deception Island volcanic rocks, we have used EPMA data provided by Geyer et al. (2019);
- (ii) only analyses with total major elements (including Loss on Ignition - LOI) that fall within the range ≥ 95 to ≤ 101 wt% are considered (Lowe, 2011);
- (iii) for each sample all major elements are recalculated on a volatile-free basis (Shane, 2000; Lowe, 2011) to avoid secondary hydration effects (Lowe, 2011; Lowe et al., 2017);
- (iv) the analyses available for each sample have been normalized to ensure that each tephra layer/volcanic rock is treated equally in order to avoid giving undue prominence to multiple analyses of single grains. However, we also wished to preserve information suggesting geochemical variability or bimodality within individual samples. Thus, we have (Fig. 9):

* Categorized each analysis based on silica content, i.e. felsic ($> 63\%$ wt% SiO_2), intermediate ($52\% < \text{SiO}_2 \text{ wt}\% \leq 63\%$), mafic ($45\% < \text{SiO}_2 \text{ wt}\% \leq 52\%$) and ultramafic ($\leq 45\% \text{ wt}\% \text{SiO}_2$) following Le Bas et al. (1986).

* For each tephra layer/volcanic rock, all available geochemical analyses are grouped based on their assigned compositional category (See Supplementary Materials 3 and 4).

* Mean and standard deviations were calculated for each compositional group present within the individual tephra layers or volcanic rocks (i.e., felsic, intermediate, mafic, ultramafic) (See Supplementary Materials 3 and 4). Hence, the individual tephra layers/volcanic rocks are represented in variation diagrams by only up to four data points (one per compositional group). This avoids the plotted data being swamped by large numbers of analyses that are available for multiple shards in some individual tephra layers/rock samples, but it preserves the evidence for any compositional diversity present.

* The major element compositions were then plotted on total alkalis—silica (TAS) and other bivariate diagrams, and as density histograms (Figs. 10 and 11).

A full statistical analysis and correlation between the datasets is beyond the scope of this paper, but preliminary comparisons are suggested based on a visual analysis. Deception Island glass compositions range from basalt to trachyandesite in the TAS diagram, within the upper subalkaline field, similar to whole-rock (bulk sample) analyses from Deception Island (Fig. 10a; cf. Smellie, 2002b; Geyer et al., 2019). The pre-caldera glasses show the narrowest compositional variation

(SiO_2 from 52 to 54 wt%) although the number of analyses is also few, whereas the syn-caldera and post-caldera glasses have a much wider range (SiO_2 from 50 to 58 wt% and from 50 to 75 wt%, respectively) (Geyer et al., 2019) (Figs. 10a and 11). Trachydacites and rhyolites are also present in a few post-caldera eruptions (Geyer et al., 2019). Analysed DecTephra tephra layers also range from basalts to rhyolites, defining a less pronounced differentiation trend of increasing alkalinity, especially for intermediate compositions (Fig. 10a). Some glasses plot outside the main trend and show dispersed compositions with either very high or very low alkali contents, particularly for tephra in marine sediment cores from the Scotia Sea (Figs. 10a and 11a) (Supplementary Materials 3 and 4).

Based on SiO_2 content, bimodal compositions are also evident. The most common compositions are mafic to intermediate (50–58 wt% SiO_2) (Fig. 10b), but a minor cluster of evolved compositions (70–75 wt% SiO_2) is also present in glasses in Scotia Sea marine sediments (e.g., Moreton, 1999; Moreton and Smellie, 1998; Lee et al., 2007; Roberts et al., 2017), South Shetland Islands (e.g., Lee et al., 2007) and, to a lesser extent, Bransfield Strait (e.g., Fretzdorff and Smellie, 2002) (Fig. 10c). Only glass shards found in the Scotia Sea have SiO_2 contents falling between 58 and 70 wt% (Fig. 10c). By contrast, Deception Island shows a more continuous compositional range, with a modal peak at $\sim 56 \text{ SiO}_2 \text{ wt}\%$; rhyolitic compositions are uncommon (Fig. 10b).

Both datasets show negative correlations of MgO , TiO_2 , FeO , and CaO with SiO_2 , and a positive correlation for K_2O (Fig. 11) for most of the analysed tephra layers and volcanic rocks. However, anomalous compositions are shown by a few glasses from the Scotia Sea (for Al_2O_3 , TiO_2 , FeO , MgO and K_2O) (Fig. 11).

There is a general overlap between the major elements of DecTephra tephra layers and Deception Island for mafic and intermediate compositions, for SiO_2 values ranging from ~ 50 to 58 wt% and corresponding to the main compositional cluster (Figs. 10 and 11). In contrast, the compositional similarity for intermediate and felsic samples (59 to $>70 \text{ wt}\% \text{SiO}_2$) is less evident, with much greater scatter for tephra data from the Scotia Sea and, to a lesser degree, South Shetland Islands evident in Na_2O and K_2O vs. SiO_2 , in particular (Fig. 11). It is also notable that trachydacites and, especially, rhyolites are poorly represented on Deception Island, with only two eruptions recording the most evolved compositions (i.e., Cross Hill volcanic edifice). In any case, the lack of a complete record of the evolved compositions (i.e., the most felsic) at Deception Island makes a robust compositional correlation difficult.

Considering all of this, we conclude that Deception Island is the most probable source for the majority of mafic to intermediate ($\leq 58 \text{ wt}\% \text{SiO}_2$) tephra but a similar correlation for more felsic glasses is not so evident for the evolved tephra ($\text{SiO}_2 > 60 \text{ wt}\%$). Additional geochemical constraints (i.e., trace element analyses on glass shards and mineral compositions) on the ash layers should help to resolve this anomaly.

5.2. Eruptive recurrence of Deception Island volcanic events

About 78% ($n = 283$) of all the tephra layers included in the database have information regarding their age, derived using ^{14}C , ice accumulation rates, historical information or correlation with dated tephra layers in other sampling sites nearby (e.g., Hodgson et al., 1998; Jiankang et al., 1999; Pallàs et al., 2001; Liu et al., 2016).

Due to the difficulty of combining age data of diverse accuracy derived from different methodologies, in order to make a first order estimate of the eruptive recurrence of Deception Island, we have filtered our dataset according to the following: (i) uncalibrated radiocarbon dates have been calibrated using the most recent online CALIB software (<http://calib.org/calib/calib.html>. Last accessed: 01.09.2021) employing the last Southern Hemisphere calibration curve (SHCal20) (Hogg et al., 2020) and a 2-sigma confidence interval (See Supplementary Material 2); (ii) only those tephra layers with an assigned age interval smaller than 1000 years (Figs. 5 and 12), i.e., with a dating uncertainty of ≤ 500 years, were considered; and (iii) tephra layers observed in two

or more sampling sites were counted only once to avoid overestimating the number of eruptive events within a selected time period. For the last step, we resampled the tephra record using time-window bins of 25, 50 and 100 years, and combined as a single layer (represented with a new average age) those tephra layers with average ages separated by fewer years than the time windows chosen above. Historic eruptions (younger than 1820 CE) were excepted from this procedure and all layers separately identified were included since a higher accuracy for the published ages is assumed.

The results of our analysis indicate that, using a conservative time window of 100 years, 58 tephra layers are identified in DecTephra that potentially correspond to independent explosive eruptive events (Fig. 12b). This number increases to 82 if a time window of 25-years is used. Thus, on the basis of these two time windows, the recurrence of explosive eruptions on Deception Island is estimated to be about 1–2 eruptions per 300 years during the ~10,000 cal yr BP – 1820 CE period. The estimate is significantly higher for the historic period, when at least 15 explosive eruptive events in the last ~150 years can be identified from sites across the region and this figure is slightly lower than that estimated from outcrops of various types in the region (Smellie, 2002d). Since some eruptive events in Deception Island were effusive (i.e., most probably without related tephra layers; Smellie, 2002b) and not all explosive eruptions leave a recognizable record in lakes, glaciers or the sea, these recurrence values should be considered as minima.

5.3. Towards a more complete tephra record

Tephra-related studies should ideally incorporate: (i) granulometric data; (ii) petrographic and morphological descriptions; (iii) geochemical analyses (including major and trace elements and, if possible, mineral analyses); and (iv) the use of statistical tools for tephra correlation (e.g., principal component analysis, scatterplot matrix) (Lowe, 2011; Lowe et al., 2017). Having a complete tephra characterization makes it easier to establish possible correlations between layers, especially in conjunction with stratigraphic and chronologic criteria. It is therefore obvious that tephra layers included in the DecTephra database are incompletely characterized. Firstly, there is a lack of morphological descriptions of the glass shards (only provided by Liu et al., 2016) and less than 50% of the tephra layers include granulometric analyses (See Supplementary Material 1). Information from glass shard morphologies, together with grain size data, are essential to determine the eruption type (i.e., magmatic versus phreatomagmatic), explosivity, size and potential impact (i.e., distances travelled by the tephtras). Secondly, the DecTephra's compositional dataset is largely complete for major elements (~85% of the tephra layers contain major element data) but trace elements and isotope ratios are poorly represented. Additionally, only half of the publications (53%) present the data in tables and not many publications include full data sets for all the grains analysed, often depending on average values.

Future tephra studies on the area should strive to obtain a full physicochemical characterization of the tephra layers by incorporating granulometric data, and petrographic and morphological information in their description. Additionally, geochemical analyses should try to include major and trace elements and, whenever possible, mineral analyses.

6. Summary

We present the DecTephra database, an up-to-date compilation of all published information used to identify tephra layers potentially erupted from Deception Island, one of the most active volcanoes in Antarctica and a source of numerous datums widely used in environmental studies. The lack of a rigorous statistical appraisal of the methods used to characterise individual tephtras has prevented their more widespread use as datums. Currently, the database includes 362 tephra layers described in multiple sources (> 20 scientific publications and 2 PhD theses). A

preliminary geographical analysis of the database shows that putative Deception Island tephtras have been identified in numerous proximal (< 150 km) sampling sites distributed between the South Shetland Islands and Bransfield Strait, but also much further afield in the Scotia Sea and the South Pole (> 1000 km and > 3000 km distant, respectively). The tephra layers occur in ice cores, marine and lacustrine sediments and glaciers. They are Holocene in age and their major element chemistry completely overlaps with mafic to intermediate tephtras from the *pre*, *syn* and *post-caldera* evolutionary stages of Deception Island volcano. A preliminary analysis of the information included in the new database has determined that explosive eruptive activity on the island varied during the Holocene. For example, the eruptive recurrence prior to 1820 CE was 1–2 eruptions per 300 years, which increased significantly to at least 15 eruptions in 150 years during the period between 1820 and present.

Despite current drawbacks due to the lack of trace element data and inaccessible major element data, the DecTephra database represents a novel key tool for studies of volcanology, petrology and geochemistry, tephrochronology and regional ash transport associated with the volcanic activity of Deception Island. The latest version of the database will be available to download at the DecTephra web page (<http://voldec.es/dectephra/>) and at Zenodo open-access repository (Hopfenblatt et al., 2022; <https://doi.org/10.5281/zenodo.6077062>) and it will be continuously updated.

Author's statement

The latest version of the DecTephra database at Zenodo open-access repository (Hopfenblatt et al., 2022; <https://doi.org/10.5281/zenodo.6077062>).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jvolgeores.2022.107516>.

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Supplementary Figures

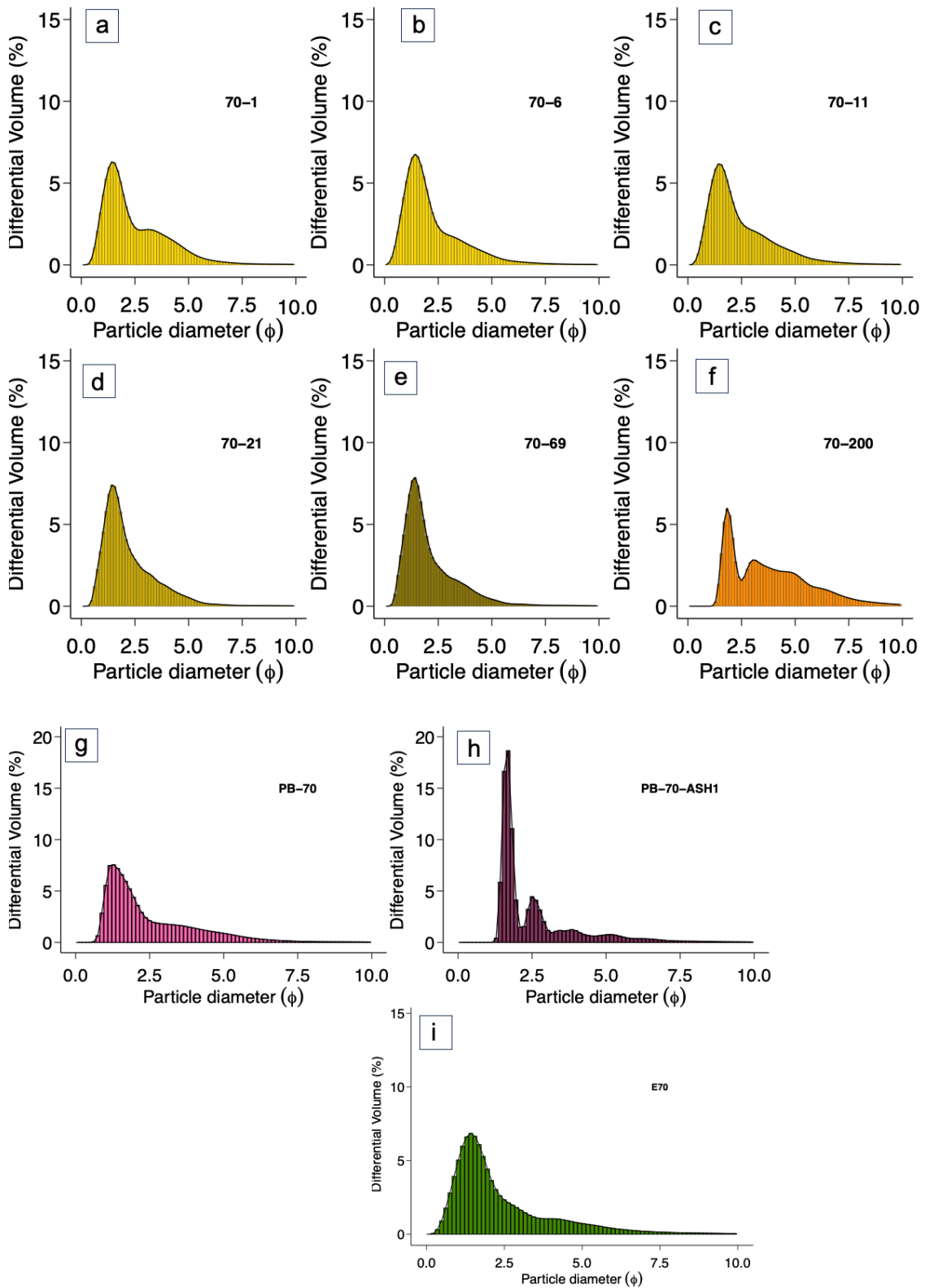


Figure S1: Total grain size distribution of samples from the 1970 eruption of Deception Island.

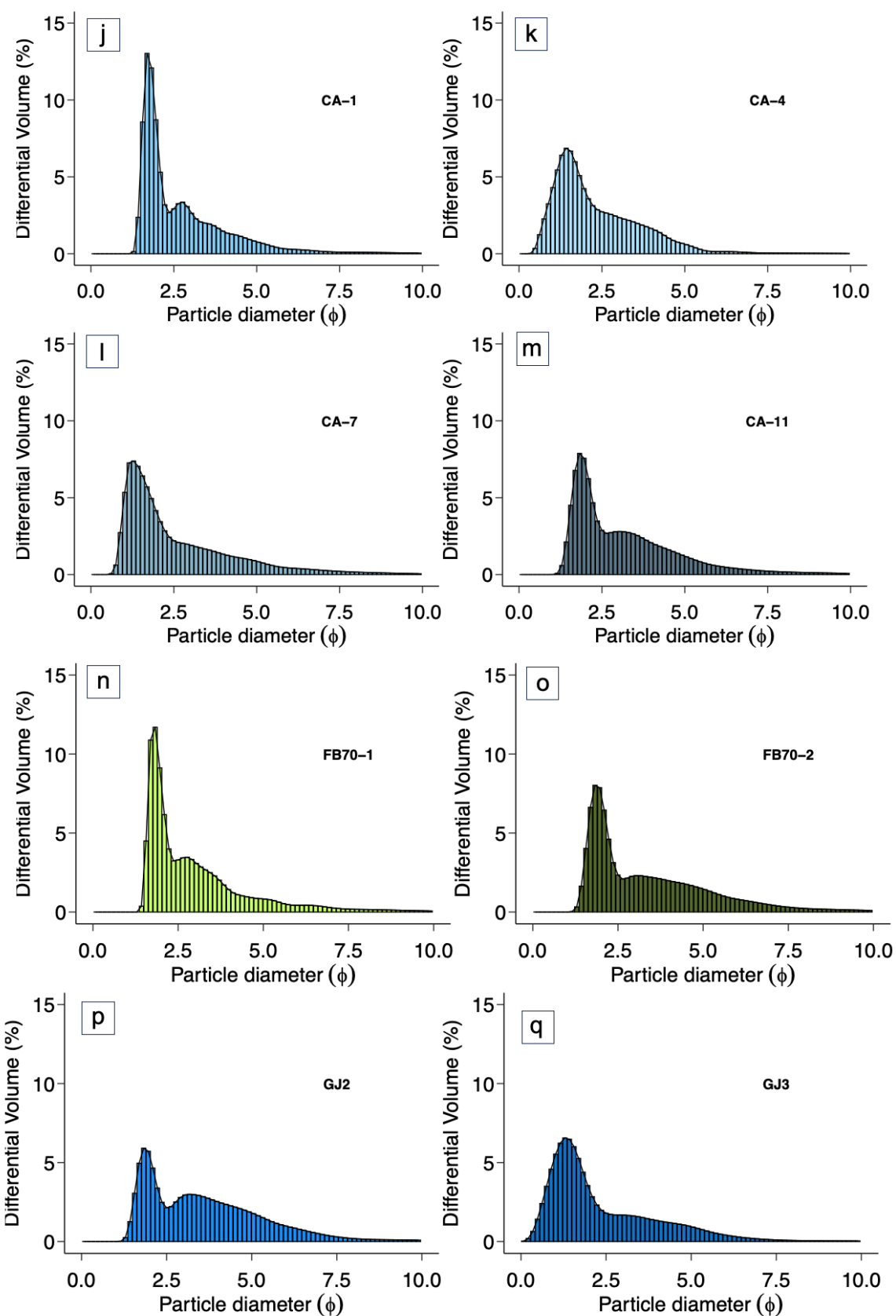


Figure S1: Continuation.

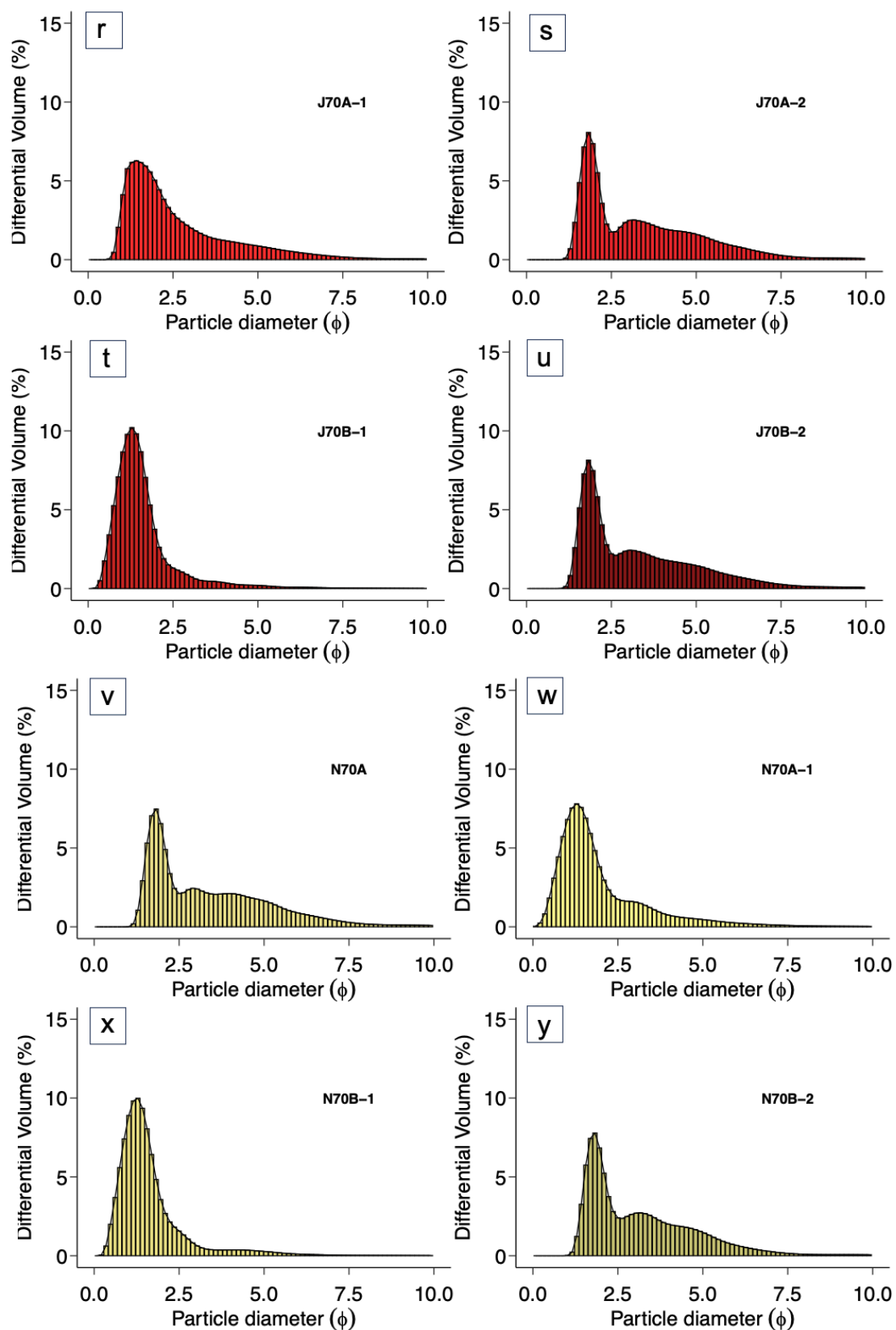


Figure S1: Continuation.

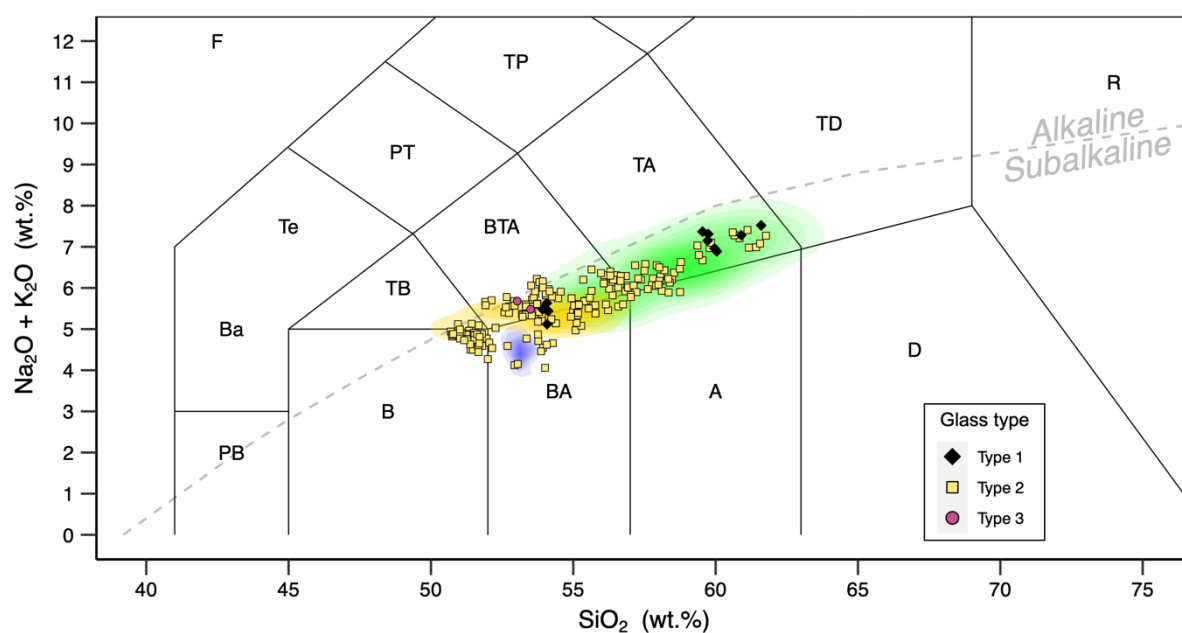


Figure S2: Total alkalis versus silica diagram (TAS) (Le Bas et al., 1986) for glass of tephra samples divided by fragment Types. The major elements were normalized to 100% (anhydrous), with Fe distributed between FeO and Fe₂O₃ following Middlemost (1989). Data available in Supplementary Material 2. Each point plot corresponds to a single EPMA analysis, i.e. different points may belong to the same juvenile fragment. Gray asterisks correspond to the geochemical analyses of Deception Island glass shards provided by Geyer et al. (2019). Blue, yellow and green color clouds correspond to glass composition of pre-, syn- and post-caldera rock samples of Deception Island, respectively.

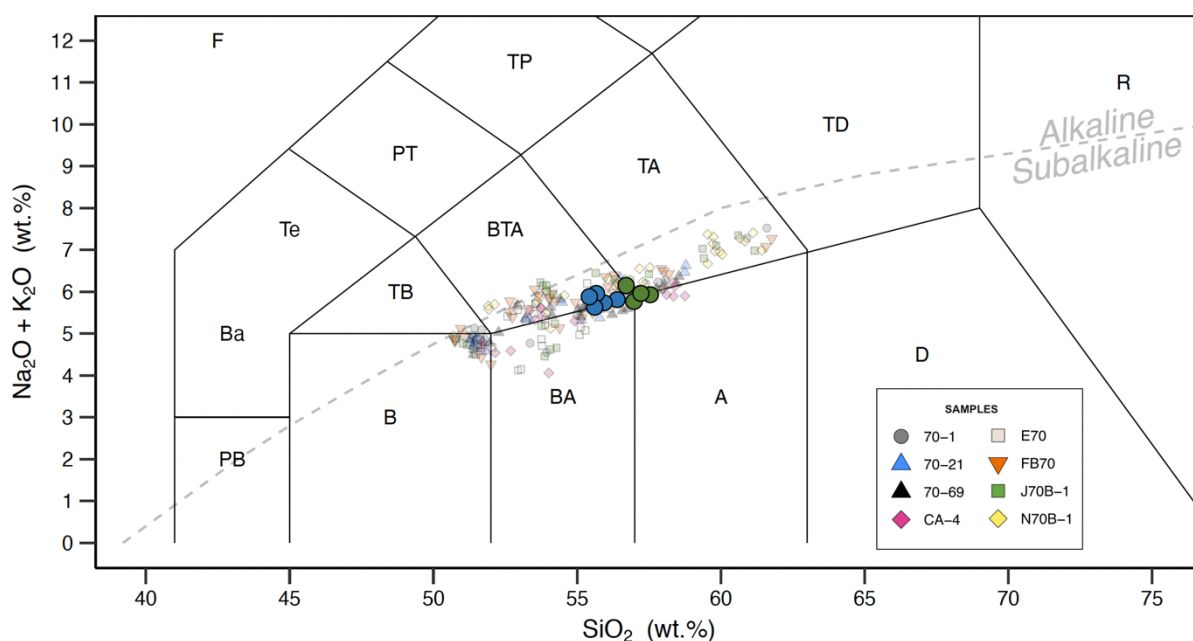


Figure S3. Total alkalis versus silica diagram (TAS) (Le Bas et al., 1986) for glass of tephra samples. The major elements were normalized to 100% (anhydrous), with Fe distributed between FeO and Fe₂O₃ following Middlemost (1989). Each point plot corresponds to a single EPMA analysis, i.e. different points may belong to the same juvenile fragment. Green (Pallàs et al., 2001) and blue (Geyer et al., 2006, 2008) dots correspond to previous analyses from the same tephra fragments of the 1970 eruption found at Livingston Island.

Supplementary Material 1

Total number of samples used in the doctoral thesis

		UTM WGS84 20S			
Samples	Location	x	y	thin section	coulter
CA-1	Livingston Island	636034	3049080	x	x
CA-4	Livingston Island	636121	3049208	x	x
CA-7	Livingston Island	636159	3049314	x	x
CA-11	Livingston Island	635971	3049398	x	x
70-6	Livingston Island	635732	3048752	x	x
GJ2	Livingston Island	634759	3046822	x	x
70-69	Livingston Island	636033	3047818	x	x
70-11	Livingston Island	635600	3049167	x	x
70-200	Livingston Island	634365	3047972	x	x
N70A-1	Livingston Island	633703	3046036	x	x
N70A	Livingston Island	633703	3046036	x	x
GJ3	Livingston Island	634759	3046822	x	x
70-1	Livingston Island	635788	3048364	x	x
70-21	Livingston Island	635443	3049304	x	x
E70	Livingston Island	630538	3053034	x	x
PB-70	Livingston Island	634600	3046750	x	x
PB-70 ASH-1	Livingston Island	634600	3046750	x	x
J70A-1	Livingston Island	635519	3049234	x	x
J70A-2	Livingston Island	635519	3049234	x	x
N70B-1	Livingston Island	633703	3046036	x	x
N70B-2	Livingston Island	633703	3046036	x	x
J70B-1	Livingston Island	635519	3049234	x	x
J70B-2	Livingston Island	635519	3049234	x	x
FB70-1	Livingston Island	639994	3052544	x	x
FB70-2	Livingston Island	639994	3052544	x	x
SUB_1	Stanley Patch	619988	3014884		no coulter analysis
SUB_2	Stanley Patch	619988	3014884		no coulter analysis
SUB_3	Stanley Patch	619988	3014884	x	no coulter analysis
SUB_4	Stanley Patch	619988	3014884	x	no coulter analysis
SUB_5	Stanley Patch	619988	3014884	x	no coulter analysis
SUB_6	Stanley Patch	619988	3014884		no coulter analysis
SUB_7	Stanley Patch	619988	3014884	x	no coulter analysis
SUB_8	Stanley Patch	619988	3014884	x	no coulter analysis
SUB_9	Stanley Patch	619988	3014884		no coulter analysis
SUB_10	Stanley Patch	619988	3014884		no coulter analysis

SUB_11	Stanley Patch	619988	3014884		no coulter analysis
SUB_12	Stanley Patch	619988	3014884		no coulter analysis
SUB_13	Stanley Patch	619988	3014884		no coulter analysis
SUB_14	Stanley Patch	619988	3014884		no coulter analysis
SUB_15	Stanley Patch	619988	3014884		no coulter analysis
SUB_16	Stanley Patch	619988	3014884		no coulter analysis
SUB_17	Stanley Patch	619988	3014884		no coulter analysis
SUB_18	Stanley Patch	619988	3014884		no coulter analysis
SUB_19	Stanley Patch	619988	3014884		no coulter analysis
SUB_20	Stanley Patch	619988	3014884		no coulter analysis
SUB_21	Stanley Patch	619988	3014884		no coulter analysis
TG40-20	Bransfield Strait	613239	2986534	x	x
TG40-30	Bransfield Strait	613239	2986534	x	x
TG40-31	Bransfield Strait	613239	2986534		x
TG40-40	Bransfield Strait	613239	2986534		x
TG40-50	Bransfield Strait	613239	2986534		x
TG40-60	Bransfield Strait	613239	2986534		x
TG40-70	Bransfield Strait	613239	2986534		x
TG40-80	Bransfield Strait	613239	2986534	x	x
TG40-90	Bransfield Strait	613239	2986534		x
TG40-100	Bransfield Strait	613239	2986534	x	x
TG40-110	Bransfield Strait	613239	2986534		x
TG41-30	Bransfield Strait	622591	2988539		not enough sample to be analyzed
TG41-40	Bransfield Strait	622591	2988539		not enough sample to be analyzed
TG41-50	Bransfield Strait	622591	2988539		not enough sample to be analyzed
TG41-60	Bransfield Strait	622591	2988539		x
TG41-65	Bransfield Strait	622591	2988539		x
TG41-70	Bransfield Strait	622591	2988539	x	x
TG41-80	Bransfield Strait	622591	2988539	x	x
TG41-90	Bransfield Strait	622591	2988539		x
TG41-93	Bransfield Strait	622591	2988539		x
TG41-97	Bransfield Strait	622591	2988539		x
TG41-110	Bransfield Strait	622591	2988539		x
TG41-117	Bransfield Strait	622591	2988539	x	x
TG41-121	Bransfield Strait	622591	2988539	x	x
TG41-125	Bransfield Strait	622591	2988539		x
TG43-18	Bransfield Strait	639831	2985214		x
TG43-30	Bransfield Strait	639831	2985214	x	x
TG43-40	Bransfield Strait	639831	2985214		x
TG43-45	Bransfield Strait	639831	2985214	x	x
TG43-50	Bransfield Strait	639831	2985214		x
TG43-60	Bransfield Strait	639831	2985214		x
TG43-70	Bransfield Strait	639831	2985214	x	x

TG43-83	Bransfield Strait	639831	2985214		x
TG43-90	Bransfield Strait	639831	2985214		not enough sample to be analyzed
TG43-100	Bransfield Strait	639831	2985214	x	x
TG43-110	Bransfield Strait	639831	2985214		x
TG48-20	Bransfield Strait	636624	3023581		not enough sample to be analyzed
TG48-25	Bransfield Strait	636624	3023581		x
TG48-30	Bransfield Strait	636624	3023581	x	x
TG48-35	Bransfield Strait	636624	3023581		x
TG48-40	Bransfield Strait	636624	3023581		x
TG48-45	Bransfield Strait	636624	3023581		x
TG48-50	Bransfield Strait	636624	3023581		x
TG48-60	Bransfield Strait	636624	3023581		x
TG48-69/70	Bransfield Strait	636624	3023581	x	x
TG48-72	Bransfield Strait	636624	3023581	x	x
TG48-80	Bransfield Strait	636624	3023581		x
TG48-90	Bransfield Strait	636624	3023581		x
TG48-95	Bransfield Strait	636624	3023581		x
TG48-113	Bransfield Strait	636624	3023581	x	x
TG48-115	Bransfield Strait	636624	3023581		x
TG48-120	Bransfield Strait	636624	3023581	x	x
TG50-15	Bransfield Strait	642559	3010500		x
TG50-17	Bransfield Strait	642559	3010500	x	x
TG50-30	Bransfield Strait	642559	3010500		x
TG50-35	Bransfield Strait	642559	3010500		x
TG50-38	Bransfield Strait	642559	3010500		x
TG50-39	Bransfield Strait	642559	3010500		x
TG50-40	Bransfield Strait	642559	3010500		x
TG50-42	Bransfield Strait	642559	3010500		x
TG50-44	Bransfield Strait	642559	3010500	x	x
TG50-47	Bransfield Strait	642559	3010500		x
TG50-52-53	Bransfield Strait	642559	3010500		x
TG50-54-55	Bransfield Strait	642559	3010500		x
TG50-57	Bransfield Strait	642559	3010500	x	x

Supplementary Material 2

Chemical analyzes of the glasses analyzed in tephra fragments from the 1970 eruption at Deception Island collected at Livingston Island

code_sample	sample	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Sum
70-1_punto1_A_vidre_1	70_1	51.12	2.10	14.94	9.79	0.20	5.98	9.53	4.35	0.69	98.72
70-1_punto1_A_vidre_2	70_1	51.02	2.01	15.02	10.00	0.16	6.07	9.61	4.51	0.58	98.99
70-1_punto1_A_vidre_3	70_1	50.75	2.31	14.76	10.17	0.06	6.00	9.61	4.17	0.59	98.47
70-1_punto1_A_vidre_4	70_1	51.44	2.10	15.18	9.98	0.23	6.01	9.71	4.33	0.53	99.56
70-1_punto1_B_vidre_1	70_1	55.16	2.06	14.55	10.13	0.20	3.88	7.56	4.97	0.69	99.27
70-1_punto1_B_vidre_2	70_1	54.40	2.22	13.77	10.79	0.19	4.30	7.61	4.67	0.72	98.67
70-1_punto1_B_vidre_3	70_1	54.50	2.50	13.90	10.33	0.18	4.09	7.49	4.83	0.71	98.62
70-1_punto1_E_vidre_1	70_1	60.46	1.82	13.12	8.29	0.19	2.48	4.17	5.95	1.43	97.92
70-1_punto1_E_vidre_2	70_1	60.32	2.21	13.91	8.68	0.22	1.80	4.44	5.77	1.44	98.86
70-1_punto1_F_vidre_1	70_1	55.77	2.25	14.06	10.18	0.27	3.09	6.43	4.86	0.95	97.90
70-1_punto1_F_vidre_2	70_1	55.99	2.31	13.67	10.23	0.17	3.22	6.54	5.02	0.95	98.20
70-1_punto1_F_vidre_3	70_1	56.32	2.27	13.83	10.30	0.22	3.26	6.49	4.96	0.99	98.67
70-1_punto1_F_vidre_4	70_1	56.34	2.35	13.65	10.15	0.19	3.28	6.41	5.06	0.92	98.40
70-1_punto1_F_vidre_5	70_1	56.26	2.49	13.70	10.18	0.12	3.34	6.35	5.27	0.95	98.76
70-1_punto2_B_vidre_1	70_1	53.22	1.97	14.27	9.56	0.16	5.78	9.78	4.22	0.54	99.58
70-1_punto2_B_vidre_2	70_1	53.63	1.96	14.33	9.13	0.24	5.68	9.70	4.05	0.48	99.25
70-1_punto3_C_vidre_1	70_1	56.94	2.34	13.45	10.13	0.14	3.09	5.99	5.10	1.03	98.24
70-1_punto3_C_vidre_2	70_1	56.92	2.64	13.80	9.90	0.21	3.20	6.09	5.15	1.00	99.00
70-1_punto3_C_vidre_3	70_1	57.48	2.39	13.41	9.90	0.28	3.02	6.01	5.18	1.04	98.71
70-1_punto3_D_vidre_1	70_1	51.14	1.87	15.31	9.79	0.21	6.24	9.95	4.41	0.53	99.58
70-1_punto3_D_vidre_2	70_1	50.86	1.93	15.25	9.33	0.20	6.41	9.87	4.28	0.52	98.71
70-69_punto1_A_vidre_1	70_69	54.14	2.41	15.41	10.30	0.27	3.23	8.46	4.74	0.91	99.94
70-69_punto1_A_vidre_2	70_69	53.88	2.89	13.50	12.39	0.20	3.62	7.34	4.31	1.10	99.29
70-69_punto1_C_vidre_2	70_69	52.00	2.53	13.47	11.23	0.16	5.43	9.40	4.27	0.73	99.30
70-69_punto2_A_vidre_1	70_69	57.35	2.31	13.39	9.46	0.26	2.91	5.77	5.14	1.10	97.70
70-69_punto2_A_vidre_2	70_69	58.03	2.34	13.51	9.70	0.25	3.08	5.91	4.98	1.17	99.07
70-69_punto2_B_vidre_1	70_69	55.55	1.59	15.74	7.90	0.15	3.89	7.73	4.79	0.66	98.01
70-69_punto2_B_vidre_2	70_69	54.64	1.57	16.09	7.93	0.18	4.23	8.20	4.89	0.71	98.48
70-69_punto2_B_vidre_3	70_69	55.54	1.52	16.05	7.87	0.18	4.30	7.75	4.73	0.67	98.79
70-69_punto2_B_vidre_4	70_69	56.33	1.56	15.94	7.62	0.16	4.12	7.79	4.91	0.65	99.24
70-69_punto2_B_vidre_5	70_69	54.55	1.38	15.77	8.18	0.17	4.32	7.90	5.00	0.65	98.00
70-69_punto2_C_vidre_2	70_69	51.62	2.13	15.53	9.81	0.32	6.28	9.61	4.18	0.55	100.08
70-69_punto2_C_vidre_3	70_69	50.84	2.06	15.31	9.62	0.16	6.39	9.73	4.03	0.54	98.79
70-69_punto2_D_vidre_1	70_69	57.24	1.99	14.71	8.70	0.18	3.20	6.28	5.10	0.98	98.39
70-69_punto2_D_vidre_2	70_69	57.37	2.21	14.44	9.10	0.21	3.43	6.26	5.07	0.97	99.12
70-69_punto2_E_vidre_1	70_69	53.93	2.51	14.38	10.12	0.17	4.27	7.71	5.08	0.68	98.84

70-69_punto3_B_vidre_1	70_69	51.67	1.91	16.27	9.55	0.22	6.40	9.84	4.00	0.53	100.40
70-69_punto3_B_vidre_2	70_69	51.39	2.05	14.98	9.95	0.17	6.59	9.76	4.19	0.58	99.77
70-69_punto3_C_vidre_1	70_69	54.54	2.55	13.34	10.81	0.22	3.99	7.88	4.60	0.75	98.73
70-69_punto3_C_vidre_2	70_69	54.41	2.54	13.26	10.93	0.24	3.90	7.80	4.76	0.75	98.68
70-69_punto3_C_vidre_3	70_69	54.81	2.46	13.22	10.98	0.19	4.07	7.73	4.81	0.74	99.06
70-69_punto3_D_vidre_1	70_69	56.47	2.61	13.30	10.47	0.17	3.06	6.50	4.82	1.01	98.52
70-69_punto4_C_vidre_1	70_69	52.98	2.86	14.26	11.44	0.21	4.08	8.09	4.70	0.65	99.31
70-69_punto4_C_vidre_2	70_69	52.59	2.80	14.32	11.53	0.20	4.07	7.91	5.03	0.62	99.06
70-69_punto4_D_vidre_1	70_69	51.20	2.03	15.28	9.91	0.27	6.03	9.70	4.27	0.56	99.30
70-69_punto4_D_vidre_2	70_69	51.00	2.07	15.15	9.81	0.21	6.39	9.84	4.24	0.61	99.33
70-69_punto4_E_vidre_1	70_69	52.01	1.98	15.38	9.55	0.16	6.19	9.89	4.16	0.61	100.01
70-69_punto4_E_vidre_2	70_69	51.49	2.06	15.25	9.85	0.19	6.20	9.59	4.20	0.57	99.47
70-21_punto1_A_vidre_1	70_21	51.02	1.93	15.45	9.64	0.17	6.47	9.73	4.11	0.57	99.12
70-21_punto1_A_vidre_2	70_21	51.42	1.96	15.51	9.76	0.10	6.39	9.77	4.20	0.53	99.76
70-21_punto1_A_vidre_3	70_21	51.52	2.04	15.38	9.69	0.18	6.16	9.76	4.03	0.54	99.36
70-21_punto1_A_vidre_4	70_21	51.17	2.06	15.27	9.88	0.20	6.28	9.83	4.28	0.57	99.71
70-21_punto1_A_vidre_5	70_21	51.26	2.01	15.48	9.75	0.13	6.32	9.79	4.12	0.52	99.39
70-21_punto2_B_vidre_1	70_21	51.07	2.01	15.22	9.63	0.20	6.15	9.83	4.26	0.61	99.07
70-21_punto2_B_vidre_2	70_21	51.16	1.96	15.29	9.97	0.14	6.14	9.90	4.19	0.55	99.29
70-21_punto2_C_vidre_1	70_21	54.41	2.68	14.45	10.46	0.20	4.14	7.54	4.97	0.77	99.62
70-21_punto2_C_vidre_2	70_21	54.60	2.42	13.81	10.78	0.28	4.14	7.45	4.51	0.77	98.83
70-21_punto3_B_vidre_1	70_21	55.23	1.89	14.76	9.13	0.17	4.32	7.79	4.82	0.71	98.86
70-21_punto3_B_vidre_2	70_21	54.24	1.67	14.64	8.86	0.19	4.44	7.75	4.49	0.74	97.12
70-21_punto3_C_vidre_1	70_21	58.58	2.22	14.66	8.93	0.23	2.90	5.49	5.30	1.15	99.46
70-21_punto3_C_vidre_2	70_21	58.55	2.03	15.20	8.56	0.15	2.55	5.71	5.64	0.96	99.42
70-21_punto4_C_vidre_1	70_21	51.23	2.06	15.56	9.60	0.18	6.25	9.87	4.11	0.57	99.43
70-21_punto4_C_vidre_2	70_21	50.74	2.27	15.48	9.33	0.23	6.20	9.81	4.14	0.56	98.79
70-21_punto4_D_vidre_1	70_21	56.23	2.75	13.57	10.61	0.18	3.24	6.36	5.32	0.95	99.21
70-21_punto4_D_vidre_2	70_21	56.12	2.50	13.61	10.68	0.18	3.35	6.49	4.98	0.99	98.95
70-21_punto5_A_vidre_1	70_21	52.51	2.31	15.42	10.24	0.26	4.04	8.36	4.78	0.49	98.42
70-21_punto5_A_vidre_2	70_21	52.62	2.58	15.32	10.33	0.18	4.05	8.03	4.80	0.48	98.39
70-21_punto5_A_vidre_3	70_21	51.09	1.84	15.18	9.67	0.19	5.90	9.80	4.29	0.53	98.49
70-21_punto5_A_vidre_4	70_21	50.91	2.07	15.20	9.56	0.19	6.31	9.65	4.20	0.60	98.73
E70_punto1_A_vidre_1	E70	52.31	3.19	13.16	12.10	0.21	4.17	7.57	4.55	1.05	98.44
E70_punto1_A_vidre_2	E70	51.69	3.25	12.50	11.55	0.24	4.11	7.68	4.20	1.09	96.37
E70_punto1_B_vidre_1	E70	53.21	2.20	14.41	9.79	0.19	5.22	9.05	4.11	0.55	98.76
E70_punto1_B_vidre_2	E70	52.89	2.11	13.88	10.36	0.25	5.06	8.81	4.17	0.62	98.15
E70_punto1_C_vidre_1	E70	54.60	2.90	12.72	11.63	0.20	3.24	6.72	4.82	1.00	97.83
E70_punto1_C_vidre_2	E70	55.38	3.05	12.72	11.64	0.25	3.19	6.59	4.55	0.98	98.40
E70_punto1_D_vidre_1	E70	52.98	2.85	13.80	11.65	0.27	3.93	7.48	4.91	0.74	98.61
E70_punto1_D_vidre_2	E70	52.71	2.94	13.51	11.70	0.16	4.06	7.42	4.91	0.72	98.14
E70_punto1_D_vidre_3	E70	52.64	3.05	14.10	11.66	0.18	4.14	7.59	4.61	0.64	98.78
E70_punto1_D_vidre_4	E70	52.07	2.94	14.08	11.64	0.24	4.23	7.70	4.86	0.62	98.44

E70_punto2_A_vidre_1	E70	51.73	2.57	12.07	10.66	0.21	3.45	6.70	4.94	0.85	93.18
E70_punto2_A_vidre_2	E70	55.78	2.23	13.76	10.62	0.23	3.63	6.65	4.89	0.87	98.73
E70_punto2_B_vidre_1	E70	53.60	2.58	13.58	10.73	0.19	4.79	8.40	4.63	0.68	99.28
E70_punto2_B_vidre_2	E70	53.51	2.56	13.36	11.15	0.25	4.99	8.04	4.47	0.70	99.06
E70_punto2_B_vidre_3	E70	56.52	2.22	14.39	9.91	0.25	3.41	6.38	4.83	0.95	98.89
E70_punto2_C_vidre_2	E70	54.55	2.19	14.19	9.29	0.17	4.91	8.61	4.27	0.65	98.89
E70_punto2_C_vidre_3	E70	54.60	1.89	14.29	9.05	0.23	4.91	8.57	4.41	0.60	98.61
E70_punto2_C_vidre_4	E70	54.34	2.01	14.07	9.27	0.13	4.92	8.55	4.39	0.69	98.37
E70_punto3_A_vidre_1	E70	52.03	3.15	13.52	12.40	0.20	4.34	7.63	4.69	0.66	98.62
E70_punto3_A_vidre_2	E70	51.98	2.91	13.70	11.44	0.29	4.26	7.82	4.87	0.60	97.93
E70_punto3_C_vidre_1	E70	51.45	1.74	15.42	9.24	0.14	6.25	9.77	4.06	0.55	98.63
E70_punto3_C_vidre_2	E70	51.29	1.85	15.58	9.51	0.13	6.30	9.80	4.11	0.58	99.20
E70_punto3_C_vidre_3	E70	51.10	1.92	15.64	9.60	0.21	6.25	9.93	3.91	0.56	99.21
E70_punto4_A_vidre_1	E70	51.14	1.91	15.52	9.55	0.27	6.40	9.59	4.09	0.53	99.01
E70_punto4_A_vidre_2	E70	50.77	1.84	15.09	9.62	0.17	6.39	9.75	3.95	0.54	98.22
E70_punto4_B_vidre_1	E70	52.74	1.55	15.47	8.53	0.14	6.72	10.17	3.69	0.42	99.46
E70_punto4_B_vidre_2	E70	52.85	1.53	15.96	8.13	0.14	6.48	10.20	3.70	0.44	99.65
E70_punto4_C_vidre_1	E70	51.39	1.93	14.82	10.26	0.26	6.20	9.87	4.24	0.59	99.63
E70_punto4_C_vidre_2	E70	51.44	2.13	15.11	10.07	0.24	6.22	9.71	4.12	0.61	99.80
E70_punto4_D_vidre_1	E70	50.66	1.83	15.36	9.58	0.17	6.46	9.80	3.99	0.57	98.45
E70_punto4_D_vidre_2	E70	51.25	1.99	15.23	9.64	0.16	6.24	9.77	4.28	0.56	99.22
N70B-1_punto1_B_vidre_1	N70B_1	55.10	2.29	13.81	10.41	0.18	3.28	6.46	5.05	0.96	97.57
N70B-1_punto1_B_vidre_2	N70B_1	55.14	2.42	13.79	9.94	0.19	3.24	6.16	5.13	0.99	97.18
N70B-1_punto1_B_vidre_3	N70B_1	54.65	2.69	13.78	10.43	0.16	3.23	6.08	5.13	1.03	97.17
N70B-1_punto1_C_vidre_1	N70B_1	59.71	1.67	14.78	7.99	0.20	1.92	4.56	5.76	1.32	97.91
N70B-1_punto1_C_vidre_2	N70B_1	60.04	1.88	13.93	8.26	0.19	2.04	4.34	5.51	1.32	97.57
N70B-1_punto1_C_vidre_3	N70B_1	58.48	2.00	14.61	8.55	0.25	2.64	4.89	5.42	1.13	98.01
N70B-1_punto1_C_vidre_4	N70B_1	58.90	1.83	14.58	8.58	0.25	2.54	4.71	5.77	1.09	98.32
N70B-1_punto1_D_vidre_1	N70B_1	49.58	2.03	14.63	10.31	0.16	6.17	9.91	4.23	0.60	97.71
N70B-1_punto1_D_vidre_2	N70B_1	53.33	2.94	14.13	10.05	0.19	3.84	7.22	4.98	0.80	97.48
N70B-1_punto1_D_vidre_3	N70B_1	52.77	2.59	14.71	10.33	0.17	4.14	7.59	5.08	0.67	98.10
N70B-1_punto1_D_vidre_4	N70B_1	52.67	2.52	14.09	11.35	0.28	3.65	6.95	5.08	0.81	97.40
N70B-1_punto1_D_vidre_5	N70B_1	52.69	2.59	14.31	10.54	0.23	4.24	7.73	5.01	0.66	98.00
N70B-1_punto2_A_vidre_1	N70B_1	58.79	2.13	14.13	9.07	0.17	2.38	4.53	5.93	1.34	98.47
N70B-1_punto2_A_vidre_2	N70B_1	58.46	2.03	13.88	8.84	0.21	2.44	4.59	5.43	1.36	97.35
N70B-1_punto2_A_vidre_4	N70B_1	52.77	2.30	14.39	9.71	0.19	4.62	8.37	4.34	0.66	97.40
N70B-1_punto2_A_vidre_5	N70B_1	52.44	2.25	14.07	9.99	0.13	4.59	8.19	4.68	0.65	96.99
N70B-1_punto2_B_vidre_1	N70B_1	55.07	2.49	13.84	10.38	0.19	3.11	6.26	5.10	0.96	97.48
N70B-1_punto2_B_vidre_2	N70B_1	55.43	2.49	13.71	10.07	0.25	3.26	6.32	5.09	0.94	97.59
N70B-1_punto3_A_vidre_2	N70B_1	58.48	2.20	13.11	9.42	0.18	2.55	4.71	5.58	1.42	97.68
N70B-1_punto3_A_vidre_3	N70B_1	58.48	2.32	13.91	8.96	0.16	2.16	4.48	5.87	1.28	97.63
N70B-1_punto3_A_vidre_4	N70B_1	58.56	2.23	14.47	8.36	0.19	2.15	4.61	5.41	1.31	97.53
N70B-1_punto3_B_vidre_1	N70B_1	50.63	2.92	13.42	12.23	0.23	4.41	7.85	4.85	0.67	97.26

N70B-1_punto3_B_vidre_2	N70B_1	51.11	3.17	13.21	12.14	0.24	4.43	7.84	4.93	0.66	97.83
N70B-1_punto3_B_vidre_3	N70B_1	51.09	3.33	13.28	12.39	0.28	4.42	7.79	4.87	0.62	98.09
N70B-1_punto3_B_vidre_6	N70B_1	55.60	1.97	14.07	9.52	0.18	3.36	5.91	5.28	1.09	96.98
N70B-1_punto3_B_vidre_7	N70B_1	55.82	2.19	14.58	8.48	0.13	3.30	5.90	5.30	1.08	96.93
N70B-1_punto4_A_vidre_1	N70B_1	55.78	2.83	12.84	10.54	0.21	2.99	5.81	4.96	1.11	97.08
N70B-1_punto4_A_vidre_2	N70B_1	58.90	1.70	14.36	7.38	0.18	2.22	4.28	5.86	1.28	96.22
N70B-1_punto4_A_vidre_3	N70B_1	58.89	1.70	14.23	8.40	0.16	2.38	4.01	5.66	1.41	96.84
FB70_punto1_A_vidre_1	FB70	50.02	2.11	15.23	9.73	0.21	5.99	9.63	4.40	0.63	97.97
FB70_punto1_A_vidre_2	FB70	55.56	2.56	13.37	10.78	0.19	3.38	6.72	4.96	0.95	98.55
FB70_punto1_A_vidre_3	FB70	50.64	1.56	17.70	8.34	0.11	5.55	10.24	4.53	0.43	99.24
FB70_punto1_B_vidre_1	FB70	52.58	2.62	15.13	9.84	0.20	4.02	7.52	5.09	0.72	97.72
FB70_punto1_B_vidre_2	FB70	52.38	2.39	14.40	10.31	0.21	4.21	7.76	5.29	0.64	97.67
FB70_punto2a_A_vidre_1	FB70	53.56	1.58	15.68	8.25	0.18	4.26	8.16	4.90	0.70	97.36
FB70_punto2a_A_vidre_2	FB70	54.03	1.51	15.70	7.94	0.12	4.29	8.15	4.71	0.64	97.09
FB70_punto2a_A_vidre_3	FB70	54.17	1.68	15.77	8.23	0.15	4.59	8.11	4.66	0.63	97.99
FB70_punto2a_A_vidre_4	FB70	52.56	2.18	14.07	10.49	0.25	4.15	7.63	4.91	0.74	97.03
FB70_punto2a_A_vidre_5	FB70	53.13	2.51	14.13	10.89	0.20	4.04	7.49	4.31	0.72	97.46
FB70_punto2a_A_vidre_6	FB70	53.43	2.34	14.59	10.29	0.24	3.91	7.74	5.17	0.72	98.44
FB70_punto2a_B_vidre_1	FB70	57.06	2.45	13.31	9.75	0.22	2.74	5.92	5.20	1.11	97.84
FB70_punto2a_B_vidre_2	FB70	56.90	2.40	13.08	10.33	0.18	2.79	5.80	5.30	1.13	97.93
FB70_punto2a_B_vidre_3	FB70	57.36	2.45	13.32	10.21	0.25	2.78	5.77	5.26	1.17	98.62
FB70_punto2a_B_vidre_4	FB70	51.70	2.61	13.84	11.22	0.26	4.26	8.32	4.95	0.72	98.06
FB70_punto2a_B_vidre_5	FB70	52.01	2.39	13.74	11.02	0.22	4.24	8.15	4.74	0.72	97.24
FB70_punto2a_C_vidre_1	FB70	49.58	2.01	15.25	9.58	0.21	6.21	9.90	4.21	0.55	97.57
FB70_punto2b_A_vidre_1	FB70	54.04	1.53	15.87	7.42	0.12	3.78	6.89	5.30	0.84	95.78
FB70_punto2b_A_vidre_2	FB70	54.72	1.54	15.99	7.70	0.18	3.54	7.14	5.23	0.79	96.83
FB70_punto2b_A_vidre_3	FB70	51.09	2.10	13.72	10.49	0.23	5.06	8.69	4.57	0.65	96.65
FB70_punto2b_A_vidre_4	FB70	50.79	2.23	13.76	10.68	0.20	4.79	8.43	4.65	0.68	96.32
FB70_punto2b_A_vidre_5	FB70	51.00	1.71	15.58	8.40	0.17	7.22	10.09	3.91	0.47	98.57
FB70_punto2b_A_vidre_6	FB70	51.02	1.58	15.42	8.68	0.12	7.03	9.86	3.76	0.44	97.92
FB70_punto2b_B_vidre_1	FB70	55.31	2.80	13.05	11.23	0.28	3.26	6.39	5.03	1.00	98.49
FB70_punto2b_B_vidre_2	FB70	54.78	2.47	13.64	10.50	0.22	3.16	6.59	5.25	0.98	97.64
FB70_punto3_A_vidre_1	FB70	52.99	2.42	13.84	11.03	0.27	4.17	7.30	4.94	0.81	97.77
FB70_punto3_A_vidre_2	FB70	52.98	2.44	14.01	10.74	0.20	4.05	7.30	4.83	0.82	97.41
FB70_punto3_A_vidre_3	FB70	50.17	1.83	15.70	9.99	0.17	6.34	9.72	4.20	0.57	98.71
FB70_punto3_A_vidre_4	FB70	49.95	2.27	15.57	9.29	0.16	6.45	9.82	4.19	0.59	98.36
FB70_punto3_B_vidre_1	FB70	60.39	1.85	13.73	8.32	0.30	2.35	3.97	5.72	1.23	97.99
FB70_punto3_B_vidre_2	FB70	60.89	1.88	14.24	7.79	0.27	2.09	4.02	5.89	1.27	98.34
J70B-1_punto1_A_vidre_1	J70B_1	52.52	2.62	14.75	10.26	0.24	3.86	7.15	5.37	0.72	97.49
J70B-1_punto1_A_vidre_2	J70B_1	52.79	2.64	14.43	10.48	0.14	4.11	7.20	5.28	0.75	97.82
J70B-1_punto1_A_vidre_3	J70B_1	58.32	1.86	14.26	8.27	0.21	2.61	4.77	5.67	1.25	97.30
J70B-1_punto1_A_vidre_4	J70B_1	58.01	2.05	14.58	8.43	0.15	2.62	4.75	5.70	1.18	97.70
J70B-1_punto1_A_vidre_5	J70B_1	58.08	1.99	14.47	8.56	0.18	2.59	4.99	5.53	1.12	97.55

J70B-1_punto1_D_vidre_1	J70B_1	56.62	2.38	13.33	9.83	0.26	3.08	6.06	4.82	1.10	97.63
J70B-1_punto1_D_vidre_2	J70B_1	56.62	2.37	13.48	10.00	0.28	3.15	5.96	5.26	1.06	98.18
J70B-1_punto1_D_vidre_3	J70B_1	55.12	2.60	14.01	10.01	0.24	3.15	6.34	5.24	0.93	97.65
J70B-1_punto2_A_vidre_1	J70B_1	54.38	2.29	13.51	10.76	0.28	4.12	5.80	5.33	0.97	97.49
J70B-1_punto2_B_vidre_1	J70B_1	53.13	2.61	14.68	10.35	0.19	3.66	7.55	5.46	0.61	98.24
J70B-1_punto2_B_vidre_2	J70B_1	52.94	3.06	13.93	10.83	0.20	3.84	7.18	5.17	0.73	97.91
J70B-1_punto2_B_vidre_3	J70B_1	53.04	2.82	13.71	11.08	0.24	3.72	7.20	4.96	0.84	97.61
J70B-1_punto3_A_vidre_1	J70B_1	53.04	1.83	15.04	8.91	0.25	5.24	9.04	4.52	0.59	98.48
J70B-1_punto3_A_vidre_2	J70B_1	53.02	1.77	14.83	8.81	0.18	5.11	8.73	4.45	0.67	97.57
J70B-1_punto3_A_vidre_3	J70B_1	59.51	1.81	14.74	7.56	0.21	2.32	4.61	6.05	1.17	98.03
J70B-1_punto3_A_vidre_4	J70B_1	59.94	1.48	14.78	7.65	0.20	2.36	4.52	5.68	1.15	97.84
J70B-1_punto4_A_vidre_1	J70B_1	52.87	3.13	12.93	12.83	0.35	3.79	7.57	3.69	0.69	97.92
J70B-1_punto4_A_vidre_2	J70B_1	53.02	2.83	12.90	12.51	0.21	3.94	7.42	3.81	0.74	97.51
J70B-1_punto4_A_vidre_3	J70B_1	52.53	3.18	12.47	12.47	0.28	3.72	7.73	3.74	0.75	96.87
J70B-1_punto4_B_vidre_1	J70B_1	49.79	1.78	15.32	9.69	0.17	6.21	9.81	4.12	0.53	97.52
J70B-1_punto4_B_vidre_2	J70B_1	50.00	1.74	16.05	9.01	0.20	5.96	9.99	4.09	0.52	97.60
J70B-1_punto4_B_vidre_3	J70B_1	49.94	1.88	15.62	9.45	0.17	6.47	9.85	4.19	0.61	98.24
CA-4_5_glass1	CA_4	52.49	2.52	13.00	10.59	0.22	4.52	8.66	4.62	0.66	97.33
CA-4_5_glass2	CA_4	51.85	2.41	12.76	10.44	0.20	4.57	8.55	4.70	0.73	96.21
CA-4_5_glass3	CA_4	52.13	2.36	12.98	10.93	0.22	4.73	8.54	4.58	0.61	97.08
CA-4_3_glass1	CA_4	55.85	2.27	13.26	9.80	0.13	3.38	6.20	4.90	0.89	96.67
CA-4_3_glass2	CA_4	55.02	2.31	13.86	9.31	0.21	3.47	6.49	4.79	0.79	96.35
CA-4_3_glass3	CA_4	55.94	2.02	13.63	9.13	0.15	3.17	6.27	4.88	0.83	96.03
CA-4_1_glass1	CA_4	56.31	2.06	13.49	9.58	0.19	3.43	5.85	4.85	1.06	96.82
CA-4_1_glass2	CA_4	56.80	2.14	13.30	9.26	0.21	3.51	5.84	4.99	0.97	97.13
CA-4_1_glass3	CA_4	56.55	2.16	13.24	9.53	0.19	3.46	5.83	4.77	0.94	96.67
CA-4_2_glass1.1	CA_4	50.57	1.98	14.45	9.58	0.12	6.48	9.75	4.17	0.54	97.64
CA-4_2_glass1.2	CA_4	51.12	2.04	14.56	10.00	0.18	6.56	9.65	4.07	0.52	98.71
CA-4_2_glass2.1	CA_4	57.17	2.04	13.79	9.19	0.14	3.30	6.01	5.17	0.92	97.84
CA-4_2_glass2.2	CA_4	57.51	2.15	13.23	9.48	0.14	3.40	5.94	4.77	1.01	97.63
CA-4_2_glass3.1	CA_4	51.24	2.18	13.47	10.12	0.09	6.87	9.58	3.94	0.52	98.05
CA-4_2_glass3.2	CA_4	51.01	2.07	13.44	9.87	0.15	6.42	9.18	3.81	0.63	96.68
CA-4_4_glass1	CA_4	52.93	1.57	14.37	8.17	0.20	6.94	9.65	3.55	0.43	97.81
CA-4_4_glass2.1	CA_4	52.62	3.09	13.23	11.47	0.22	4.05	7.45	4.81	0.69	97.63
CA-4_4_glass2.2	CA_4	52.36	3.00	12.94	12.11	0.21	4.25	7.52	4.81	0.63	97.83
CA-4_4_glass3	CA_4	54.37	2.45	13.24	10.68	0.21	4.76	7.79	4.56	0.68	98.74

**Chemical analyzes of the plagioclase crystals analyzed in tephra fragments from the 1970 eruption at
Deception Island collected at Livingston Island**

code_sample	sample	SiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Na ₂ O	MgO	MnO	Fe ₂ O ₃	K ₂ O	CaO	TiO ₂	Sum
70-1_punto1_A_plg_1	70-1	50.78	29.24	0.04	4.03	0.19	0.01	0.74	0.09	13.41	0.10	98.59
70-1_punto1_A_plg_2	70-1	50.54	29.30	0.00	3.93	0.22	0.01	0.96	0.09	13.67	0.10	98.80
70-1_punto1_B_plg_1	70-1	54.80	26.91	0.04	5.70	0.14	0.00	0.95	0.11	10.54	0.18	99.32
70-1_punto4_C_plg_1	70-1	57.09	25.97	0.05	6.54	0.03	0.00	0.79	0.16	9.09	0.09	99.76
70-1_punto4_C_plg_2	70-1	59.81	21.57	0.02	6.91	0.43	0.02	2.62	0.54	6.63	0.62	99.13
70-69_punto1_A_plg_1	70-69	53.20	28.49	0.00	4.78	0.24	0.00	1.07	0.11	12.42	0.15	100.45
70-69_punto1_A_plg_3	70-69	54.24	26.96	0.00	5.13	0.25	0.03	1.25	0.12	11.56	0.12	99.62
70-69_punto1_C_plg_1	70-69	51.58	29.20	0.07	4.09	0.18	0.02	1.08	0.09	13.43	0.07	99.71
70-69_punto1_C_plg_2	70-69	51.57	29.84	0.01	3.98	0.19	0.00	0.93	0.11	13.52	0.12	100.25
70-69_punto2_C_plg_1	70-69	52.30	29.39	0.01	4.39	0.22	0.00	0.72	0.10	13.37	0.15	100.64
70-69_punto3_A_plg_1	70-69	50.78	30.18	0.02	3.52	0.17	0.01	0.76	0.09	14.48	0.08	100.07
70-69_punto3_A_plg_2	70-69	50.67	30.26	0.00	3.64	0.19	0.00	0.64	0.06	14.68	0.04	100.18
70-69_punto3_A_plg_3	70-69	50.13	30.94	0.00	3.35	0.18	0.02	0.68	0.07	14.78	0.07	100.19
70-69_punto3_B_plg_1	70-69	51.53	29.70	0.00	3.86	0.16	0.00	0.80	0.07	13.69	0.13	99.94
70-69_punto3_C_plg_2	70-69	53.32	28.27	0.00	4.92	0.26	0.01	1.00	0.11	12.04	0.05	99.97
70-69_punto4_B_plg_1	70-69	50.93	29.58	0.10	3.89	0.17	0.00	0.81	0.07	13.74	0.10	99.29
70-69_punto4_B_plg_2	70-69	51.95	29.35	0.00	4.16	0.22	0.02	0.99	0.10	13.37	0.07	100.20
70-69_punto4_E_plg_1	70-69	52.01	28.88	0.01	4.32	0.22	0.06	0.89	0.07	12.92	0.11	99.41
70-21_punto1_B_plg_1	70-21	57.30	25.63	0.00	6.79	0.18	0.00	1.22	0.16	8.91	0.11	100.31
70-21_punto1_C_plg_1	70-21	51.35	29.19	0.05	4.22	0.18	0.00	0.86	0.10	13.14	0.13	99.17
70-21_punto1_C_plg_2	70-21	51.37	27.91	0.01	4.08	0.67	0.00	1.27	0.12	13.36	0.26	99.04
70-21_punto1_C_plg_3	70-21	51.88	29.48	0.00	4.34	0.20	0.05	0.77	0.08	13.30	0.08	100.14
70-21_punto1_D_plg_1	70-21	56.94	25.82	0.00	6.68	0.12	0.00	1.12	0.13	9.02	0.16	100.00
70-21_punto1_D_plg_2	70-21	56.29	26.03	0.00	6.29	0.13	0.05	1.03	0.17	9.53	0.11	99.57
70-21_punto1_D_plg_3	70-21	57.86	25.23	0.00	7.10	0.16	0.02	1.04	0.21	8.48	0.13	100.21
70-21_punto2_B_plg_1	70-21	51.21	28.27	0.06	4.14	0.66	0.06	1.65	0.15	13.18	0.21	99.46
70-21_punto2_C_plg_1	70-21	54.60	27.76	0.00	5.61	0.11	0.00	1.10	0.14	10.96	0.12	100.40
70-21_punto3_B_plg_1	70-21	52.39	29.03	0.00	4.45	0.20	0.00	0.95	0.09	12.96	0.07	100.14
70-21_punto4_A_plg_1	70-21	55.59	27.15	0.03	5.83	0.05	0.00	0.61	0.11	10.13	0.05	99.53
70-21_punto4_B_plg_1	70-21	56.03	26.73	0.00	6.42	0.08	0.00	0.50	0.13	9.84	0.02	99.75
70-21_punto4_C_plg_1	70-21	52.13	28.65	0.00	4.33	0.40	0.01	1.06	0.11	13.08	0.18	99.94
E70_punto1_A_plg_1	E70	54.63	27.05	0.01	5.36	0.17	0.03	1.00	0.13	10.83	0.13	99.31
E70_punto1_A_plg_2	E70	55.27	27.13	0.00	6.00	0.07	0.02	0.63	0.13	10.28	0.08	99.59
E70_punto1_A_plg_3	E70	55.24	27.18	0.03	5.92	0.09	0.03	0.58	0.14	10.32	0.07	99.54
E70_punto3_A_plg_1	E70	56.05	26.09	0.02	6.39	0.18	0.04	1.21	0.18	9.62	0.24	99.95
E70_punto3_B_plg_1	E70	51.14	29.59	0.07	3.95	0.22	0.03	0.84	0.08	13.64	0.12	99.58
E70_punto3_B_plg_2	E70	50.45	30.00	0.00	3.72	0.15	0.02	0.71	0.06	13.96	0.04	99.10
E70_punto3_C_plg_1	E70	51.22	29.22	0.00	3.83	0.61	0.00	1.00	0.09	13.36	0.14	99.47
E70_punto4_C_plg_1	E70	51.79	28.56	0.04	4.28	0.34	0.00	0.88	0.15	12.62	0.21	98.83

E70_punto4_C_plg_2	E70	50.34	30.24	0.00	3.60	0.16	0.02	0.74	0.08	14.31	0.04	99.49
CA-4_3_pl1	CA-4	55.02	27.41	0.09	5.48	0.07	0.00	0.63	0.11	10.84	0.02	99.58
CA-4_3_pl2	CA-4	55.45	27.55	0.08	5.54	0.07	0.01	0.57	0.09	10.70	0.00	99.96
CA-4_2_pl_1	CA-4	47.49	32.99	0.06	1.84	0.15	0.04	0.60	0.03	17.19	0.00	100.30
CA-4_2_pl_2	CA-4	48.76	31.79	0.05	2.52	0.17	0.00	0.63	0.05	15.96	0.00	99.88
CA-4_2_pl_3	CA-4	52.81	28.81	0.14	4.13	0.19	0.00	0.74	0.10	12.91	0.02	99.70
CA-4_4_pl_1	CA-4	52.45	29.40	0.09	4.10	0.17	0.03	0.80	0.07	13.35	0.02	100.36
CA-4_4_pl_2	CA-4	52.64	29.65	0.09	4.14	0.14	0.04	0.74	0.05	13.16	0.03	100.56
CA-4_4_pl_3	CA-4	53.49	28.95	0.10	4.52	0.18	0.00	0.83	0.06	12.66	0.00	100.69

Chemical analyzes of the olivine crystals analyzed in tephra fragments from the 1970 eruption at Deception Island collected at Livingston Island

code_sample	sample	SiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Na ₂ O	MgO	MnO	FeOt	K ₂ O	CaO	TiO ₂	Sum
70-1_punto1_B_sill_1	70-1	37.23	0.07	0.07	0.01	36.75	0.40	23.44	0.02	0.32	0.03	99.64
70-1_punto1_B_sill_2	70-1	37.52	0.03	0.08	0.07	36.45	0.43	24.21	0.03	0.33	0.13	99.21
70-1_punto1_F_sill_1	70-1	36.93	0.07	0.02	0.04	33.72	0.50	27.61	0.01	0.30	0.09	99.37
70-1_punto1_F_sill_2	70-1	37.66	0.19	0.04	0.07	34.25	0.52	26.96	0.01	0.34	0.09	100.04
70-1_punto1_F_sill_3	70-1	37.12	0.09	0.03	0.08	33.45	0.52	28.16	0.01	0.37	0.07	99.82
70-1_punto4_B_sill_1	70-1	36.77	0.00	0.00	0.02	32.41	0.69	29.70	0.01	0.16	0.03	100.62
70-1_punto4_B_sill_2	70-1	36.94	0.00	0.00	0.05	32.45	0.72	29.90	0.00	0.19	0.03	100.92
70-21_punto1_A_sill_1	70-21	39.81	0.62	0.04	0.17	42.35	0.29	16.77	0.01	0.64	0.03	100.55
70-21_punto1_A_sill_3	70-21	39.04	0.06	0.04	0.03	44.58	0.28	14.26	0.00	0.23	0.03	100.31
70-21_punto1_A_sill_4	70-21	39.03	0.02	0.00	0.03	44.68	0.29	14.11	0.01	0.25	0.05	100.48
70-21_punto1_B_sill_1	70-21	37.27	1.11	0.05	0.40	28.66	0.64	30.39	0.14	0.62	0.29	99.03
70-21_punto1_D_sill_1	70-21	36.75	0.32	0.04	0.17	30.71	0.71	31.49	0.03	0.38	0.11	100.51
70-21_punto1_D_sill_2	70-21	36.04	0.37	0.05	0.20	27.33	0.74	34.60	0.05	0.36	0.09	99.58
70-21_punto2_B_sill_1	70-21	39.27	0.03	0.05	0.04	44.08	0.28	15.44	0.02	0.27	0.11	100.63
E70_punto1_C_sill_1	E70	36.38	0.05	0.01	0.02	32.97	0.54	27.78	0.02	0.36	0.10	98.94

Chemical analyzes of the pyroxene crystals analyzed in tephra fragments from the 1970 eruption at Deception Island collected at Livingston Island

code_sample	sample	SiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Na ₂ O	MgO	MnO	FeOt	K ₂ O	CaO	TiO ₂	Sum
70-1_punto1_C_sill_1	70-1	50.54	2.26	0.02	0.39	14.98	0.29	9.25	0.01	20.59	0.93	99.27
70-1_punto1_C_sill_2	70-1	50.81	2.29	0.00	0.40	15.16	0.34	10.11	0.01	19.81	0.89	99.85
70-1_punto1_C_sill_3	70-1	51.05	2.15	0.00	0.40	15.16	0.36	9.12	0.00	20.69	0.84	99.82
70-1_punto1_D_sill_1	70-1	51.56	1.73	0.05	0.42	15.32	0.38	9.28	0.03	20.28	0.71	99.77
70-1_punto1_D_sill_2	70-1	51.11	1.96	0.04	0.41	14.99	0.30	9.35	0.03	20.70	0.74	99.63
70-1_punto2_A_sill_1	70-1	50.36	2.46	0.01	0.47	14.77	0.31	9.80	0.02	20.10	0.97	99.27

70-1_punto2_A_sill_2	70-1	51.89	1.51	0.06	0.35	15.74	0.40	10.05	0.00	19.26	0.68	99.95
70-1_punto4_A_sill_1	70-1	51.79	2.24	0.00	0.32	16.50	0.14	6.14	0.02	22.05	0.82	100.03
70-69_punto4_A_sill_1	70-69	50.73	0.54	0.01	0.11	19.59	1.17	24.26	0.00	1.99	0.32	98.74
70-69_punto4_A_sill_2	70-69	51.50	0.51	0.00	0.10	19.74	1.15	24.10	0.00	1.75	0.41	99.29
70-21_punto2_A_sill_1	70-21	50.78	1.62	0.00	0.45	14.64	0.55	11.24	0.04	19.42	0.53	99.26
70-21_punto2_A_sill_2	70-21	50.38	2.48	0.00	0.46	14.96	0.31	10.13	0.02	19.73	1.01	99.51
70-21_punto3_A_sill_1	70-21	50.79	3.75	0.87	0.36	16.38	0.13	4.25	0.03	22.79	0.50	99.86
CA-4_3_sili_1	CA-4	51.22	2.35	0.04	0.41	14.87	0.37	9.67	0.00	20.19	1.04	100.17
CA-4_3_sili_2	CA-4	51.58	2.45	0.00	0.45	14.86	0.33	9.92	0.00	19.90	1.05	100.57
CA-4_1_sili_1	CA-4	51.34	2.21	0.00	0.45	14.88	0.41	9.37	0.01	20.26	0.96	99.93
CA-4_1_sili_2	CA-4	51.17	1.95	0.00	0.35	14.92	0.31	8.71	0.01	20.29	0.91	98.61
CA-4_1_sili_3	CA-4	51.79	3.66	1.05	0.35	16.44	0.10	4.20	0.01	22.10	0.60	100.34
CA-4_1_sili_4	CA-4	52.19	3.08	0.82	0.29	16.78	0.07	4.16	0.01	21.82	0.43	99.75
CA-4_1_sili_5	CA-4	52.25	3.22	0.90	0.27	16.81	0.09	4.20	0.01	22.34	0.53	100.69
CA-4_2_sili_1	CA-4	51.70	2.25	0.01	0.41	14.72	0.39	9.90	0.02	19.84	1.09	100.33
CA-4_2_sili_2	CA-4	51.94	2.01	0.05	0.42	14.91	0.25	9.16	0.01	20.60	0.78	100.14

Supplementary Material 3

Chemical analyzes of the glasses analyzed in tephra layers collected at the Bransfield Strait

ID Analysis Point	Core	SiO ₂	TiO ₂	Al ₂ O ₃	FeO _t	MnO	MgO	CaO	Na ₂ O	K ₂ O	Sum
TG43-100-V1	TG-43	54.50	2.80	13.80	12.17	0.20	3.89	7.31	4.14	0.69	99.51
TG43-100-V2	TG-43	55.12	2.48	15.19	10.42	0.17	3.42	7.83	4.12	0.59	99.34
TG43-100-V3	TG-43	54.37	2.97	13.97	11.80	0.20	3.63	7.30	3.95	0.68	98.88
TG43-100-V4	TG-43	54.58	2.70	13.74	11.98	0.23	4.12	7.11	3.96	0.70	99.12
TG43-100-V5	TG-43	54.53	2.94	14.07	11.99	0.24	3.80	7.25	4.28	0.69	99.79
TG43-100-4-v1	TG-43	54.92	2.93	12.96	12.64	0.23	3.48	7.20	2.92	1.09	98.38
TG43-100-4-v2	TG-43	55.70	3.13	13.35	12.20	0.24	3.15	6.81	3.54	1.17	99.29
TG43-100-4-v3	TG-43	55.59	2.70	14.58	12.03	0.25	3.44	6.78	3.83	0.92	100.12
TG43-100-4-v4	TG-43	56.19	3.01	13.46	12.07	0.26	2.92	6.42	3.48	1.20	99.00
TG43-100-5-v1	TG-43	55.90	2.91	13.93	11.23	0.22	3.04	6.79	3.23	1.06	98.30
TG43-100-5-v2	TG-43	56.50	2.76	14.04	11.37	0.23	2.93	6.81	2.77	1.05	98.46
TG43-100-5-v3	TG-43	56.00	3.00	14.16	11.66	0.24	2.81	6.60	3.59	1.07	100.12
TG43-100-5-v4	TG-43	55.32	2.94	13.64	11.53	0.24	2.91	6.61	3.52	1.07	99.00
TG43-100-5-v5	TG-43	56.53	2.00	17.70	7.93	0.16	2.09	7.40	4.85	0.77	99.13
TG43-100-5-v6	TG-43	55.18	2.86	14.37	11.27	0.25	2.76	6.95	3.73	1.02	97.78
TG43-100-5-v7	TG-43	56.07	3.21	13.96	11.65	0.25	2.74	6.70	2.72	1.03	98.30
TG43-100-5-v8	TG-43	55.13	2.62	15.01	10.76	0.26	2.77	6.94	4.58	0.98	98.46
TG43-100-7-v1	TG-43	50.61	1.95	16.77	9.39	0.20	6.42	9.66	3.99	0.57	99.56
TG43-100-7-v2	TG-43	51.20	1.99	16.73	9.53	0.19	6.50	9.59	4.14	0.55	100.42
TG43-100-7-v4	TG-43	50.60	2.02	16.77	9.58	0.16	6.33	9.71	3.87	0.56	99.61
TG43-100-7-v5	TG-43	50.44	1.90	16.62	9.57	0.16	6.43	9.64	3.90	0.59	99.25
TG43-100-7-v6	TG-43	51.03	2.02	16.73	9.62	0.14	6.75	9.77	4.05	0.53	100.65
TG43-100-7-v7	TG-43	50.61	2.00	16.78	9.50	0.19	6.77	9.67	4.07	0.53	100.12
TG43-100-7-v8	TG-43	51.29	2.02	16.65	9.56	0.19	6.53	9.76	4.02	0.54	100.56
TG-48-30-V2	TG-48	56.70	2.62	13.89	11.20	0.25	3.30	5.78	3.79	1.01	98.54
TG-48-30-V3	TG-48	56.88	2.53	14.08	11.09	0.25	3.39	6.02	3.73	0.92	98.89
TG-48-30-V4	TG-48	56.73	2.57	13.94	10.92	0.28	3.22	5.95	3.92	0.94	98.47
TG-48-30-V5	TG-48	56.87	2.51	13.66	11.22	0.21	3.19	5.83	3.97	0.95	98.40
TG-48-30-V6	TG-48	53.85	2.51	13.80	11.60	0.18	4.66	7.91	3.68	0.67	98.88
TG-48-30-V7	TG-48	53.96	2.35	15.06	10.63	0.19	4.08	7.80	4.24	0.67	98.98
TG-48-30-V8	TG-48	53.15	2.27	14.74	10.46	0.25	4.26	7.57	4.27	0.65	97.62
TG-48-30-V9	TG-48	53.49	2.36	14.69	10.79	0.17	4.25	7.68	3.89	0.65	97.96
TG-48-30-V12	TG-48	56.67	2.61	13.90	10.53	0.23	3.16	5.85	4.10	0.90	97.94
TG-48-30-V14	TG-48	56.46	2.76	13.80	10.63	0.13	3.29	6.01	4.07	0.94	98.10
TG-48-30-V15	TG-48	60.59	2.18	13.97	9.92	0.22	1.97	4.15	3.14	1.54	97.68
TG-48-30-V17	TG-48	61.18	2.44	13.14	10.10	0.19	2.17	4.36	2.93	1.44	97.95
TG-48-30-V21	TG-48	56.30	2.90	12.70	12.29	0.21	3.20	5.84	3.64	1.08	98.16
TG-48-30-V22	TG-48	57.07	2.79	13.20	12.08	0.28	3.04	5.76	3.80	1.17	99.19
TG-48-30-V23	TG-48	57.08	2.94	13.37	11.93	0.24	2.76	6.05	4.13	1.02	99.52
TG-48-30-V24	TG-48	57.03	2.52	13.54	11.15	0.21	3.30	5.89	4.08	1.03	98.74

TG-48-30-V25	TG-48	56.96	2.65	13.54	11.60	0.19	3.08	5.92	3.87	1.03	98.85
TG-48-30-V26	TG-48	56.19	2.51	13.71	10.98	0.19	3.18	6.10	4.19	0.94	97.99
TG-48-30-V27	TG-48	58.61	2.57	14.17	9.78	0.18	2.77	5.29	4.48	0.99	98.84
TG-48-30-V28	TG-48	57.70	2.66	13.99	10.13	0.25	2.71	5.31	4.20	1.05	98.01
TG-48-30-V29	TG-48	57.55	2.69	14.04	10.52	0.20	2.70	5.47	3.69	1.07	97.92
TG-48-30-V30	TG-48	57.35	2.63	14.03	10.41	0.26	2.87	5.56	4.16	0.92	98.19
TG-48-69-V1	TG-48	55.42	1.86	16.35	8.96	0.17	5.38	7.92	4.28	0.60	100.95
TG-48-69-V2	TG-48	55.25	1.94	14.99	9.63	0.14	5.65	7.90	4.09	0.65	100.24
TG-48-69-V3	TG-48	55.04	1.77	15.26	9.38	0.19	5.40	7.97	4.37	0.67	100.05
TG-48-69-V4	TG-48	55.69	1.86	15.25	9.20	0.19	5.72	8.17	4.06	0.59	100.74
TG-48-69-V5	TG-48	55.28	1.75	14.73	9.63	0.14	5.72	8.19	3.91	0.60	99.95
TG-48-69-V6	TG-48	55.58	1.97	15.43	9.28	0.15	5.82	7.97	4.10	0.61	100.91
TG-48-69-V7	TG-48	54.68	1.93	14.89	9.38	0.20	5.70	8.24	3.84	0.62	99.48
TG-48-69-V8	TG-48	55.09	1.70	14.93	9.06	0.14	5.66	8.15	4.23	0.61	99.57
TG-48-69-V9	TG-48	55.20	1.87	14.89	9.15	0.12	5.64	8.07	4.00	0.62	99.56
TG-48-69-V10	TG-48	54.93	1.79	15.26	9.34	0.12	5.71	8.18	4.01	0.58	99.92
TG-48-69-V11	TG-48	55.25	1.78	15.41	9.23	0.11	6.04	8.27	4.42	0.56	101.07
TG-48-69-V12	TG-48	55.79	1.54	15.98	8.53	0.17	5.58	7.88	3.99	0.62	100.10
TG-48-113-V1	TG-48	57.57	2.61	13.74	11.03	0.24	2.90	5.69	3.11	1.14	98.03
TG-48-113-V3	TG-48	55.28	2.43	14.08	10.64	0.24	3.87	7.06	3.74	0.77	98.10
TG-48-113-V4	TG-48	54.99	2.27	14.03	10.95	0.22	4.02	7.09	3.95	0.75	98.27
TG-48-113-V5	TG-48	55.67	2.90	13.65	12.80	0.24	2.32	5.54	3.30	1.16	97.57
TG-48-113-V6	TG-48	56.16	2.80	14.30	12.09	0.21	2.15	5.30	3.70	1.18	97.89
TG-48-113-V7	TG-48	55.96	2.88	13.77	12.67	0.18	2.45	5.27	3.13	1.08	97.39
TG-48-113-V8	TG-48	57.88	2.34	13.53	10.19	0.21	3.33	5.61	3.85	1.18	98.12
TG-48-113-V9	TG-48	57.84	2.39	14.77	9.64	0.23	2.83	5.86	4.35	1.04	98.95
TG-48-113-V13	TG-48	56.11	2.13	14.75	10.97	0.26	3.22	5.59	3.79	1.12	97.95
TG-48-113-V14	TG-48	56.39	2.48	13.75	10.99	0.28	3.07	5.34	3.48	1.16	96.94
TG-48-113-V15	TG-48	56.94	2.80	12.64	11.60	0.23	3.10	5.87	3.56	1.09	97.83
TG-48-113-V16	TG-48	55.14	2.41	14.48	10.76	0.26	3.67	6.74	3.82	0.76	98.04
TG-48-113-V17	TG-48	55.47	2.34	14.10	10.76	0.19	3.61	6.72	3.91	0.78	97.87
TG-48-113-V18	TG-48	51.53	1.98	15.61	9.66	0.19	5.98	8.87	4.07	0.54	98.42
TG-48-113-V19	TG-48	51.73	1.91	15.72	9.40	0.20	5.96	8.91	3.99	0.52	98.34
TG-48-113-V20	TG-48	51.98	1.87	15.61	9.61	0.18	5.95	8.74	4.03	0.54	98.50
TG-48-113-V21	TG-48	50.99	1.87	17.49	8.93	0.20	6.34	8.94	4.03	0.56	99.35
TG-48-113-V22	TG-48	55.86	1.36	18.51	7.10	0.13	3.91	8.40	4.33	0.49	100.08
TG-48-113-V23	TG-48	55.16	1.56	16.29	8.57	0.16	4.71	7.96	4.51	0.65	99.57
TG-48-113-V24	TG-48	56.10	1.77	16.68	8.59	0.17	5.08	7.81	4.38	0.62	101.21
TG-48-113-V25	TG-48	55.48	2.08	15.61	9.32	0.23	4.75	7.52	4.25	0.66	99.89
TG-48-113-V26	TG-48	55.24	1.83	15.19	9.30	0.19	5.19	7.51	4.22	0.75	99.42
TG-48-113-V27	TG-48	56.68	2.51	14.47	10.57	0.20	3.48	6.38	4.11	0.74	99.13
TG-48-113-V28	TG-48	55.83	2.41	14.39	10.63	0.22	3.95	6.23	3.52	0.96	98.15
TG-48-113-V29	TG-48	55.78	2.60	14.27	11.10	0.23	3.87	6.28	3.62	0.91	98.66
TG-48-113-V30	TG-48	55.33	1.71	15.48	8.87	0.17	5.83	8.12	3.97	0.61	100.09
TG-48-113-V31	TG-48	54.82	1.68	15.67	9.36	0.20	5.44	8.04	4.00	0.56	99.77
TG-48-113-V32	TG-48	55.13	1.65	15.55	9.38	0.21	5.42	7.90	4.35	0.58	100.16

TG-48-113-V33	TG-48	54.58	1.75	15.49	8.92	0.22	5.26	7.88	3.99	0.63	98.72
TG50-30-1-V6	TG-50	54.66	1.90	15.51	9.80	0.18	5.24	8.69	4.19	0.56	100.72
TG50-30-1-V1	TG-50	54.16	2.72	13.30	11.83	0.26	4.05	8.26	4.36	0.79	99.73
TG50-30-1-V2	TG-50	53.87	2.85	12.29	12.38	0.30	4.18	8.45	3.92	0.81	99.04
TG50-30-1-V3	TG-50	54.54	2.78	12.49	12.05	0.26	4.35	8.13	3.89	0.77	99.26
TG50-30-1-V4	TG-50	55.03	2.68	13.48	11.04	0.24	3.98	7.75	4.42	0.89	99.51
TG50-30-1-V5	TG-50	54.68	2.82	12.66	11.97	0.28	4.31	8.21	4.28	0.77	99.98
TG50-30-3-V1	TG-50	54.31	2.55	14.83	10.86	0.18	3.90	7.02	4.47	0.69	98.80
TG50-30-3-V2	TG-50	54.72	2.39	14.66	10.96	0.24	3.94	7.13	4.43	0.67	99.14
TG50-30-3-V3	TG-50	54.36	2.56	14.29	10.91	0.19	4.70	7.98	4.20	0.66	99.84
TG50-30-3-V4	TG-50	53.74	2.26	14.58	10.64	0.18	5.45	7.88	4.40	0.60	99.75
TG50-30-3-V5	TG-50	54.29	2.26	14.34	10.88	0.25	4.92	7.96	4.16	0.62	99.68
TG50-30-2-V1	TG-50	54.08	2.37	14.66	10.81	0.23	4.71	8.06	4.60	0.65	100.16
TG50-30-2-V2	TG-50	53.46	2.38	15.10	10.87	0.24	4.68	8.08	4.50	0.65	99.97
TG50-30-2-V3	TG-50	53.82	2.31	14.57	10.76	0.21	4.45	7.94	4.44	0.64	99.15
TG50-30-2-V4	TG-50	58.72	2.44	14.44	10.17	0.16	2.72	5.28	4.30	1.13	99.35
TG50-30-2-V5	TG-50	58.78	2.35	14.62	9.74	0.18	2.75	5.28	4.16	1.13	98.98
TG50-30-2-V6	TG-50	59.04	2.13	15.87	9.27	0.16	2.78	5.55	4.70	0.99	100.49
TG50-30-2-V7	TG-50	53.59	2.44	13.31	11.60	0.19	5.86	8.07	4.34	0.62	100.01
TG50-30-2-V8	TG-50	52.96	2.03	14.79	10.68	0.21	5.17	8.10	4.50	0.65	99.09
TG50-30-2-V9	TG-50	53.93	2.06	14.98	10.37	0.20	5.56	8.31	4.24	0.57	100.22
TG50-30-2-V10	TG-50	55.35	2.60	14.31	12.25	0.26	3.51	6.51	3.95	0.85	99.59
TG50-30-4-V1	TG-50	56.51	3.07	13.52	11.81	0.24	2.90	6.03	3.90	0.92	98.90
TG50-30-4-V2	TG-50	56.12	2.99	13.82	12.01	0.26	2.95	5.98	3.95	0.93	99.01
TG50-30-4-V3	TG-50	56.05	2.78	13.66	12.24	0.20	2.84	6.00	4.00	0.99	98.76
TG50-30-4-V4	TG-50	56.11	3.05	13.76	12.14	0.21	2.70	6.02	3.59	0.94	98.52
TG50-30-4-V5	TG-50	70.23	0.64	15.12	4.00	0.16	0.68	1.72	4.60	1.85	99.00
TG50-30-4-V6	TG-50	70.39	0.65	15.10	4.14	0.18	0.63	1.58	4.05	1.94	98.66
TG50-30-4-V7	TG-50	71.02	0.71	15.29	3.97	0.14	0.66	1.59	4.08	1.85	99.31
TG50-30-4-V8	TG-50	70.66	0.68	15.17	3.97	0.18	0.59	1.67	3.93	1.85	98.71
TG50-30-4-V9	TG-50	54.41	2.09	14.89	10.51	0.17	4.53	7.83	4.45	0.63	99.51
TG50-30-4-V10	TG-50	54.28	2.27	14.75	10.28	0.18	4.48	7.74	4.47	0.66	99.11
TG50-30-4-V11	TG-50	55.31	2.21	17.02	9.56	0.19	3.24	7.46	4.93	0.61	100.53
TG50-30-4-V12	TG-50	53.99	2.21	13.85	10.69	0.23	5.03	8.64	4.03	0.66	99.33
TG50-30-4-V13	TG-50	54.28	2.63	13.09	12.04	0.22	5.29	8.20	4.02	0.78	100.55
TG50-30-4-V14	TG-50	53.68	2.14	14.89	10.94	0.18	5.38	8.46	4.10	0.64	100.41
TG50-57-2-v1	TG-50	55.85	2.22	15.02	10.23	0.17	3.75	6.72	4.41	0.80	99.15
TG50-57-2-v2	TG-50	55.99	2.27	14.81	10.56	0.19	4.15	6.53	4.35	0.83	99.68
TG50-57-2-v3	TG-50	55.47	2.35	15.14	10.10	0.16	3.66	6.72	4.31	0.81	98.72
TG50-57-2-v4	TG-50	55.94	2.53	14.51	10.73	0.24	3.39	6.45	4.65	0.87	99.31
TG50-57-2-v5	TG-50	56.45	2.75	14.28	10.93	0.22	3.26	6.32	4.18	0.83	99.21
TG50-57-2-v6	TG-50	56.48	2.61	14.03	10.94	0.17	3.59	6.06	4.14	0.89	98.91
TG50-57-2-v7	TG-50	56.22	2.94	13.45	12.15	0.26	2.99	5.93	4.72	1.13	99.78
TG50-57-2-v8	TG-50	56.91	2.93	14.24	11.69	0.19	2.70	5.85	4.65	1.12	100.28
TG50-57-2-v9	TG-50	56.47	2.91	13.39	12.37	0.26	3.05	5.89	4.78	1.10	100.23
TG50-57-2-v10	TG-50	54.57	2.65	14.05	11.33	0.21	4.31	7.56	3.88	0.85	99.42

TG50-57-1-v1	TG-50	56.58	2.61	14.23	11.18	0.21	3.74	6.47	4.25	0.79	100.06
TG50-57-1-v2	TG-50	56.24	2.45	14.44	11.17	0.23	3.66	6.40	4.14	0.85	99.58
TG50-57-1-v3	TG-50	55.82	2.34	14.33	11.04	0.21	3.60	6.41	3.93	0.95	98.64
TG50-57-1-v4	TG-50	56.15	2.68	14.29	11.12	0.19	3.57	6.46	4.07	0.93	99.46
TG50-57-1-v5	TG-50	55.89	2.42	15.01	10.12	0.23	3.66	6.35	3.85	0.79	98.31
TG50-57-1-v6	TG-50	55.71	2.39	14.85	10.21	0.21	3.48	6.49	4.05	0.77	98.15
TG50-57-1-v7	TG-50	56.48	2.62	14.25	10.74	0.21	3.53	6.26	3.82	0.84	98.75
TG50-57-1-v8	TG-50	56.20	2.73	14.22	10.85	0.22	3.64	6.69	4.28	0.82	99.65
TG50-57-1-v9	TG-50	56.52	2.42	14.98	10.37	0.26	3.48	6.57	4.17	0.82	99.59
TG50-57-1-v10	TG-50	55.78	2.41	14.86	10.50	0.21	3.52	6.55	4.42	0.79	99.04
TG50-57-1-v11	TG-50	56.52	2.77	13.30	12.17	0.23	2.99	6.40	3.71	1.06	99.15
TG50-57-1-v12	TG-50	56.29	2.90	13.37	12.24	0.20	3.15	6.64	3.78	1.05	99.62
TG50-57-1-v13	TG-50	56.73	2.83	13.75	11.69	0.28	3.08	6.56	3.74	0.98	99.64
TG50-57-1-v14	TG-50	56.08	2.95	14.02	12.02	0.15	3.32	6.62	4.12	0.94	100.22
TG50-57-4-v5	TG-50	55.87	2.47	14.85	10.47	0.16	3.80	6.44	4.21	0.85	99.12
TG50-57-4-v6	TG-50	55.93	2.61	14.47	10.70	0.22	3.56	6.59	4.39	0.79	99.26
TG50-57-4-v7	TG-50	55.99	2.63	14.06	11.50	0.23	3.93	6.25	3.77	0.89	99.25
TG50-57-4-v8	TG-50	55.80	2.44	14.71	11.15	0.21	3.60	6.14	4.06	0.88	99.00
TG50-57-4-v9	TG-50	55.02	2.76	14.19	11.14	0.22	3.64	6.15	3.98	0.94	98.05
TG50-17-1-v1	TG-50	58.98	2.06	16.29	8.76	0.20	2.03	5.58	4.59	1.00	99.49
TG50-17-1-v2	TG-50	58.12	2.39	13.98	10.47	0.15	2.61	5.07	3.88	1.20	97.88
TG50-17-1-v3	TG-50	57.60	2.50	13.08	11.11	0.23	3.77	5.70	3.35	1.08	98.42
TG50-17-1-v4	TG-50	58.97	2.37	14.07	10.33	0.23	2.47	5.01	3.69	1.23	98.37
TG50-17-1-v6	TG-50	57.99	2.44	13.62	11.02	0.18	3.88	5.21	3.27	1.18	98.79
TG50-17-1-v7	TG-50	58.49	2.20	14.65	10.41	0.22	2.77	5.10	3.30	1.20	98.34
TG50-17-1-v8	TG-50	57.92	2.33	14.53	10.04	0.21	2.93	5.31	3.63	1.17	98.07
TG50-17-1-v9	TG-50	59.31	2.11	15.36	9.67	0.23	3.20	5.37	4.60	0.99	100.85
TG50-17-1-v10	TG-50	59.07	2.15	15.59	9.18	0.16	2.72	5.46	4.46	1.01	99.80
TG50-17-1-v11	TG-50	58.55	2.12	14.78	9.72	0.23	3.23	5.27	3.97	1.11	98.99
TG50-17-1-v13	TG-50	55.39	2.90	13.67	11.93	0.28	3.38	6.20	3.69	0.83	98.27
TG50-17-2-v1	TG-50	54.78	2.64	14.27	11.55	0.21	3.73	6.13	3.95	0.73	97.99
TG50-17-2-v2	TG-50	55.32	2.69	14.44	11.60	0.23	3.63	6.05	3.81	0.78	98.55
TG50-17-2-v3	TG-50	55.19	2.62	14.38	11.23	0.19	3.66	6.15	3.46	0.85	97.73
TG50-17-4-v1	TG-50	58.09	2.23	14.17	9.71	0.17	3.01	5.36	3.83	1.03	97.60
TG50-17-4-v2	TG-50	57.80	2.19	15.25	9.44	0.20	3.08	5.63	4.16	0.99	98.74
TG50-17-4-v3	TG-50	58.22	2.25	14.55	9.83	0.22	3.08	5.55	3.89	1.00	98.58
TG50-17-4-v4	TG-50	58.13	2.19	14.77	9.79	0.17	3.02	5.42	3.62	1.02	98.14
TG50-17-4-v5	TG-50	58.05	2.21	14.48	11.04	0.19	3.75	5.56	4.48	1.03	100.79
TG50-17-4-v6	TG-50	57.62	2.20	14.37	10.78	0.21	3.33	5.27	3.96	1.22	98.97
TG48-120-4-v1	TG-48	45.19	4.34	8.51	22.71	0.47	12.59	2.36	2.93	0.88	99.98
TG48-120-4-v2	TG-48	44.77	5.76	7.22	25.34	0.49	10.59	1.21	2.76	1.05	99.19
TG48-120-4-v3	TG-48	48.44	5.13	7.16	19.33	0.43	14.43	0.69	2.44	1.21	99.26
TG48-120-3-v4	TG-48	53.14	2.36	17.36	9.40	0.15	3.72	8.82	4.71	0.47	100.13
TG48-120-3-v5	TG-48	52.74	2.68	14.99	11.20	0.23	4.76	7.92	4.13	0.63	99.27
TG48-120-3-v6	TG-48	53.00	2.36	14.91	10.80	0.17	4.66	7.92	4.38	0.64	98.84
TG48-120-3-v7	TG-48	53.14	2.35	14.18	10.45	0.20	5.02	8.47	3.81	0.63	98.25

TG_43_60_M1_vi-1	TG-43	57.29	0.47	25.93	1.54	0.00	0.76	8.43	6.35	0.27	101.03
TG_43_60_M1_vi-2	TG-43	58.68	2.24	17.85	7.21	0.07	0.87	4.98	6.00	1.10	99.01
TG_43_60_M1_vi-3	TG-43	58.42	3.40	15.39	10.38	0.22	0.96	4.78	4.53	1.55	99.63
TG_43_60_M1_vi-4	TG-43	58.64	1.22	21.01	4.52	0.04	1.17	7.12	6.41	0.58	100.70
TG_43_60_M1_vi-6	TG-43	51.96	2.26	15.37	10.43	0.20	4.62	8.24	4.26	0.66	98.00
TG_43_60_M1_vi-7	TG-43	52.52	2.19	15.65	10.58	0.18	4.59	8.32	4.33	0.69	99.05
TG_43_60_M1_vi-8	TG-43	52.53	2.14	15.55	10.18	0.17	4.54	8.26	4.41	0.68	98.47
TG_43_60_M2_vi-1	TG-43	54.87	2.62	14.96	10.61	0.24	3.53	6.72	4.06	0.85	98.46
TG_43_60_M2_vi-2	TG-43	55.36	2.54	14.89	10.57	0.19	3.43	6.86	3.77	0.88	98.50
TG_43_60_M2_vi-3	TG-43	55.55	2.49	14.79	10.56	0.29	3.59	7.00	4.13	0.82	99.22
TG_43_60_M2_vi-5	TG-43	54.61	2.29	14.95	10.61	0.25	3.44	6.91	3.88	0.80	97.74
TG_43_60_M3_vi-1	TG-43	53.05	1.59	16.78	8.33	0.17	5.29	8.77	4.00	0.59	98.58
TG_43_60_M3_vi-2	TG-43	52.86	1.81	16.87	8.39	0.17	5.24	8.63	3.78	0.58	98.33
TG_43_60_M3_vi-3	TG-43	53.52	1.71	16.77	8.52	0.20	5.19	8.90	3.77	0.60	99.18
TG_43_60_M3_vi-4	TG-43	53.45	1.75	17.06	8.71	0.11	5.12	8.60	3.96	0.64	99.39
TG_43_60_M3_vi-5	TG-43	53.53	1.70	16.56	8.40	0.20	5.34	8.62	3.95	0.60	98.90
TG_43_60_M4_vi-1	TG-43	53.33	1.94	16.05	9.02	0.20	4.92	8.47	3.97	0.73	98.63
TG_43_60_M4_vi-2	TG-43	53.20	1.67	15.60	8.94	0.28	5.13	8.27	3.79	0.66	97.54
TG_43_60_M4_vi-3	TG-43	53.19	1.80	15.75	9.16	0.21	4.98	8.38	3.94	0.65	98.06
TG_43_60_M5_vi-1	TG-43	54.43	2.79	14.40	10.84	0.25	3.36	6.42	4.11	0.99	97.59
TG_43_60_M5_vi-2	TG-43	55.21	2.70	14.52	11.01	0.17	3.12	6.34	3.88	0.96	97.92
TG_43_60_M5_vi-3	TG-43	55.06	2.96	14.71	11.03	0.21	3.34	6.29	4.14	0.95	98.70
TG_43_60_M5_vi-4	TG-43	55.15	2.92	14.66	10.82	0.24	3.37	6.60	4.02	0.93	98.71
TG_43_60_M5_vi-5	TG-43	51.95	2.84	14.44	12.41	0.16	3.93	8.01	3.91	0.77	98.42
TG_43_60_M5_vi-6	TG-43	52.98	3.28	14.47	13.30	0.35	2.24	6.61	3.90	1.10	98.23
TG_43_60_M5_vi-7	TG-43	51.10	3.22	13.36	15.08	0.27	3.20	6.70	3.60	0.97	97.50
TG_43_60_M5_vi-8	TG-43	51.01	3.07	11.59	14.47	0.31	4.91	7.92	3.17	0.78	97.23
TG_41_97_M3_vi-9	TG-41	50.49	2.22	17.32	9.31	0.23	5.92	9.26	4.02	0.62	99.40
TG_41_97_M3_vi-10	TG-41	50.20	2.13	16.96	9.41	0.24	6.16	9.48	4.02	0.67	99.27
TG_41_97_M3_vi-11	TG-41	50.23	1.86	16.77	9.33	0.15	6.03	9.65	3.92	0.59	98.53
TG_41_97_M4_vi-12	TG-41	49.44	1.89	17.63	9.62	0.17	6.10	9.37	4.14	0.63	99.00
TG_41_97_M4_vi-13	TG-41	49.43	1.88	16.64	9.96	0.22	6.55	9.29	3.87	0.65	98.49
TG_41_97_M5_vi-1	TG-41	52.82	2.69	14.24	12.22	0.17	3.86	7.71	3.63	0.80	98.15
TG_41_97_M5_vi-2	TG-41	53.11	2.69	14.79	11.41	0.22	3.74	7.70	3.65	0.80	98.12
TG_41_97_M5_vi-3	TG-41	52.77	3.05	14.36	12.79	0.21	4.02	7.44	3.80	0.83	99.26
TG_41_97_M5_vi-4	TG-41	54.47	3.14	14.97	10.86	0.29	2.86	7.64	4.03	0.87	99.14
TG_41_97_M5_vi-5	TG-41	53.26	2.69	14.84	11.50	0.17	3.28	7.22	3.98	0.85	97.79
TG_41_97_M5_vi-6	TG-41	56.05	1.06	22.66	4.48	0.10	1.42	9.28	5.53	0.33	100.92
TG_40_40_M1_vi-1	TG-40	55.46	2.82	15.67	10.20	0.23	3.03	6.73	4.18	0.74	99.06
TG_40_40_M1_vi-2	TG-40	55.13	2.92	14.48	11.34	0.24	3.11	6.39	4.13	0.86	98.60
TG_40_40_M1_vi-3	TG-40	55.24	2.68	14.58	10.75	0.20	3.02	6.43	3.78	0.81	97.49
TG_40_40_M1_vi-4	TG-40	55.90	2.71	14.50	11.14	0.27	3.07	6.32	3.63	0.84	98.38
TG_40_40_M2_vi-1	TG-40	54.12	2.92	13.77	12.02	0.20	3.08	6.65	3.67	0.90	97.33
TG_40_40_M2_vi-2	TG-40	54.43	3.15	14.18	12.15	0.14	3.06	6.74	3.87	0.85	98.58
TG_40_40_M2_vi-3	TG-40	54.68	2.84	13.99	11.88	0.27	3.24	6.73	3.94	0.93	98.50
TG_40_40_M3_vi-1	TG-40	54.51	3.29	14.38	11.76	0.26	3.48	6.84	3.88	0.85	99.25

TG_40_40_M3_vi-2	TG-40	53.98	3.03	14.30	11.92	0.18	3.30	6.81	3.89	0.87	98.28
TG_40_40_M3_vi-3	TG-40	54.17	3.12	13.87	12.11	0.24	3.44	6.70	3.93	0.85	98.43
TG_40_40_M5_vi-1	TG-40	53.92	2.95	14.30	11.96	0.23	3.10	6.57	4.00	0.80	97.83
TG_40_40_M5_vi-2	TG-40	54.97	2.92	14.10	11.45	0.20	3.09	6.49	3.84	0.82	97.88
TG_40_40_M5_vi-3	TG-40	55.23	2.99	14.12	11.77	0.20	2.72	6.27	3.73	0.91	97.95
TG_40_40_M5_vi-4	TG-40	54.89	3.08	14.24	11.93	0.26	2.61	6.10	4.11	0.93	98.15
TG_48_40_M1_vi-1	TG-48	57.81	2.34	15.05	9.44	0.17	2.70	5.09	4.40	1.11	98.10
TG_48_40_M1_vi-2	TG-48	58.42	1.85	16.38	8.56	0.22	2.53	4.89	4.52	1.23	98.60
TG_48_40_M2_vi-1	TG-48	57.74	2.30	15.51	9.32	0.17	3.34	5.63	4.06	1.05	99.11
TG_48_40_M2_vi-2	TG-48	56.05	2.36	14.66	10.18	0.20	3.68	5.95	4.38	1.04	98.50
TG_48_40_M2_vi-3	TG-48	55.88	2.42	15.12	9.80	0.32	3.31	5.97	4.39	1.03	98.24
TG_48_40_M3_vi-1	TG-48	53.11	2.07	16.16	9.61	0.23	4.31	7.92	4.03	0.64	98.07
TG_48_40_M3_vi-2	TG-48	54.90	1.95	17.61	9.22	0.16	4.09	8.00	3.64	0.64	100.21
TG_48_40_M3_vi-3	TG-48	53.36	2.27	16.31	9.19	0.24	4.46	7.99	4.05	0.63	98.49
TG_48_40_M4_vi-1	TG-48	56.90	2.10	15.95	9.82	0.17	3.19	5.72	4.30	0.97	99.13
TG_48_40_M4_vi-2	TG-48	56.97	2.04	15.95	9.15	0.13	3.20	5.82	4.17	1.01	98.45
TG_48_40_M4_vi-3	TG-48	57.10	2.11	15.92	9.06	0.20	3.14	5.69	4.36	0.98	98.56
TG_48_40_M4_vi-4	TG-48	57.21	2.49	15.22	9.36	0.22	3.12	5.53	4.24	1.12	98.50
TG_48_40_M4_vi-5	TG-48	57.76	2.26	16.24	9.35	0.26	3.15	5.76	3.98	1.02	99.79
TG_48_40_M4_vi-6	TG-48	57.05	2.58	14.29	9.99	0.19	3.53	5.55	4.16	1.13	98.47
tg-41-117-2-vi1	TG-41	53.31	2.64	14.26	11.28	0.20	4.32	7.90	4.83	0.83	99.57
tg-41-117-2-vi2	TG-41	52.69	2.48	14.00	11.39	0.18	3.99	7.79	4.99	0.85	98.36
tg-41-117-2-vi3	TG-41	52.89	2.46	14.48	11.46	0.24	4.35	7.67	5.20	0.87	99.62
tg-41-117-2-vi4	TG-41	53.27	2.75	14.51	11.41	0.24	4.11	7.74	4.96	0.70	99.70
tg-41-117-3-vi1	TG-41	50.43	1.92	16.72	9.51	0.15	6.49	9.66	3.95	0.53	99.36
tg-41-117-3-vi2	TG-41	50.17	1.98	16.91	9.36	0.20	6.20	9.39	4.34	0.49	99.04
tg-41-117-4-vi1	TG-41	52.87	2.13	16.27	10.25	0.16	6.26	7.68	3.63	0.59	99.84
tg-41-117-4-vi2	TG-41	52.12	2.11	15.86	10.23	0.15	6.28	7.42	5.19	0.81	100.17
tg-41-117-4-vi3	TG-41	51.52	2.06	15.58	9.84	0.13	5.75	9.20	4.66	0.68	99.42
tg-41-117-4-vi4	TG-41	52.17	2.06	15.87	11.79	0.19	5.09	6.36	4.67	0.79	98.99
tg-41-117-5-vi1	TG-41	55.59	2.69	14.45	11.16	0.18	4.20	6.19	3.22	0.96	98.63
tg-41-117-5-vi2	TG-41	56.28	2.69	14.46	10.30	0.15	3.91	4.80	4.95	1.18	98.71
tg-41-117-5-vi3	TG-41	56.54	2.77	14.44	11.13	0.26	3.98	4.22	5.42	1.26	100.02
tg-41-117-6-vi1	TG-41	50.97	1.91	17.43	8.87	0.15	6.48	9.48	4.09	0.58	99.96
tg-41-117-6-vi2	TG-41	49.63	1.79	17.21	8.67	0.14	6.58	9.15	4.06	0.47	97.70
tg-41-117-6-vi3	TG-41	50.29	1.96	17.27	8.74	0.22	6.51	9.45	4.31	0.47	99.22
tg-41-117-7B-vi1	TG-41	54.12	3.00	13.19	12.44	0.24	3.13	6.68	4.40	1.00	98.20
tg-41-117-8-vi1	TG-41	54.66	3.36	12.90	12.83	0.21	3.07	6.50	4.40	1.06	98.99
tg-41-117-8-vi2	TG-41	55.00	3.36	13.07	12.49	0.27	3.12	6.81	4.26	1.06	99.44
tg-41-117-8-vi3	TG-41	54.23	3.54	12.87	13.24	0.25	3.05	6.62	4.06	1.12	98.99
tg-41-121-1-vi1	TG-41	52.97	3.06	13.79	12.26	0.27	3.42	7.11	5.77	0.73	99.39
tg-41-121-3-vi1	TG-41	53.22	3.60	11.86	15.02	0.24	3.04	6.00	3.91	1.26	98.15
tg-41-121-3-vi2	TG-41	53.87	3.15	12.85	13.77	0.28	2.99	6.09	4.79	1.07	98.85
tg-41-121-4-vi1	TG-41	55.12	2.50	14.27	10.77	0.19	3.30	6.30	5.33	1.07	98.84
tg-41-121-4-vi2	TG-41	55.51	2.82	14.11	10.73	0.23	3.12	6.17	5.06	1.09	98.84
tg-41-121-4-vi3	TG-41	54.90	2.72	13.93	10.92	0.23	3.19	6.19	5.15	1.17	98.40

tg-41-121-5-vi1	TG-41	53.22	3.06	13.30	11.94	0.25	3.82	7.35	4.59	0.77	98.30
tg-41-121-5-vi2	TG-41	54.15	2.90	13.84	12.03	0.23	4.01	7.16	4.56	0.85	99.73
tg-41-121-5-vi3	TG-41	53.83	2.98	13.80	11.89	0.25	3.90	7.61	4.85	0.86	99.97
tg-41-121-5-vi4	TG-41	54.34	2.68	13.92	11.92	0.25	3.83	7.68	4.77	0.81	100.19
tg-41-121-6-vi1	TG-41	54.15	2.77	12.75	11.94	0.27	5.09	6.92	4.96	0.80	99.66
tg-41-121-6-vi2	TG-41	53.82	2.85	13.46	12.03	0.26	3.72	7.17	4.90	0.89	99.10
tg-41-121-6-vi3	TG-41	53.94	2.91	13.48	11.60	0.21	3.77	7.01	4.94	0.91	98.76
tg-41-121-6-vi4	TG-41	54.02	2.98	13.97	11.61	0.21	3.62	7.02	4.59	0.86	98.89
tg-41-121-6-vi5	TG-41	53.79	2.92	13.32	11.95	0.25	3.63	7.22	4.69	0.78	98.56
tg-43-30-2-vi1	TG-43	55.23	3.46	13.49	12.71	0.28	3.30	6.11	3.25	0.98	98.81
tg-43-30-2-vi2	TG-43	55.25	3.34	13.69	12.54	0.23	3.30	6.74	2.72	0.80	98.61
tg-43-30-2-vi3	TG-43	54.96	3.49	13.55	12.40	0.24	3.35	5.41	3.97	0.91	98.28
tg-43-30-2-vi4	TG-43	55.49	3.33	13.60	12.37	0.26	3.39	6.09	3.82	0.86	99.21
tg-43-30-4-vi1	TG-43	52.52	3.35	13.18	13.15	0.25	3.73	7.07	4.02	0.77	98.05
tg-43-30-4-vi2	TG-43	52.43	3.27	12.91	13.07	0.25	3.93	7.13	4.32	0.80	98.10
tg-43-30-4-vi3	TG-43	55.79	2.69	13.79	10.70	0.28	2.94	6.03	5.05	1.11	98.39
tg-43-30-4-vi4	TG-43	55.66	2.91	13.96	10.66	0.26	3.02	5.73	4.48	1.05	97.72
tg-43-30-4-vi5	TG-43	56.14	2.75	13.90	10.47	0.20	3.03	5.65	5.23	1.16	98.54
tg-43-30-4-vi6	TG-43	57.34	2.48	14.08	10.33	0.20	2.90	5.65	5.12	1.12	99.23
tg-43-30-4-vi7	TG-43	55.71	2.91	13.51	10.65	0.18	3.18	5.91	4.38	0.90	97.33
tg-43-30-4-vi8	TG-43	55.56	3.06	13.23	11.14	0.26	3.03	6.08	4.27	0.83	97.45
tg-43-30-5-vi1	TG-43	54.13	2.94	13.77	11.76	0.28	3.82	6.32	4.37	0.85	98.24
tg-43-30-5-vi2	TG-43	54.09	3.00	13.91	12.01	0.20	3.55	5.94	4.13	0.91	97.74
tg-43-30-5-vi3	TG-43	53.94	2.99	13.51	12.22	0.24	3.36	6.68	4.74	0.74	98.42
tg-43-30-5-vi4	TG-43	53.99	3.14	13.70	12.22	0.23	3.38	6.75	4.93	0.73	99.06
tg-43-30-5-vi5	TG-43	54.00	2.87	13.74	12.28	0.21	3.57	6.94	4.64	0.77	99.02
tg-43-30-5-vi6	TG-43	53.34	3.01	13.52	12.21	0.21	3.62	6.74	4.97	0.75	98.37
tg-43-45-1-vi1	TG-43	54.34	2.60	15.25	10.59	0.15	3.49	4.23	6.55	2.30	99.50
tg-43-45-1-vi2	TG-43	54.28	2.80	14.92	10.56	0.18	3.26	4.21	6.47	2.29	98.96
tg-43-45-1-vi3	TG-43	53.15	2.39	14.75	10.77	0.21	3.81	6.54	6.32	1.91	99.85
tg-43-45-1-vi4	TG-43	52.32	3.03	13.15	12.38	0.19	4.15	7.63	4.53	0.62	97.99
tg-43-45-1-vi5	TG-43	52.34	3.17	13.08	12.93	0.19	4.10	7.80	4.42	0.63	98.65
tg-43-45-1-vi6	TG-43	52.41	2.91	13.33	12.56	0.24	4.16	7.96	4.54	0.59	98.70
tg-43-45-1-vi7	TG-43	52.39	3.12	13.23	12.80	0.22	4.21	8.01	4.55	0.61	99.14
tg-43-45-2-vi1	TG-43	51.98	2.68	13.77	12.12	0.24	4.21	7.35	4.35	0.60	97.30
tg-43-45-2-vi2	TG-43	52.33	2.74	14.11	12.37	0.22	4.05	7.34	4.53	0.68	98.37
tg-43-45-4-vi1	TG-43	54.00	2.25	15.73	9.62	0.24	4.06	7.24	4.52	0.70	98.36
tg-43-45-4-vi2	TG-43	54.17	2.15	15.80	9.68	0.17	4.00	6.95	4.67	0.66	98.25
tg-43-45-4-vi3	TG-43	54.28	2.00	15.76	9.91	0.14	4.15	7.26	4.79	0.69	98.98
tg-43-45-5-vi1	TG-43	53.82	2.94	13.39	12.00	0.19	3.41	6.68	4.71	0.81	97.96
tg-43-45-5-vi2	TG-43	53.84	3.16	13.49	12.16	0.26	3.46	6.68	4.63	0.80	98.49
tg-43-45-8-vi1	TG-43	54.39	2.96	14.78	11.41	0.21	3.69	6.28	4.43	1.15	99.30
tg-43-45-8-vi2	TG-43	54.82	2.73	14.86	11.24	0.23	3.83	6.33	3.80	1.14	98.98
tg-43-45-8-vi3	TG-43	54.58	2.67	14.83	11.24	0.20	3.64	6.54	4.26	1.25	99.21
TG-40-20-vidre-1	TG-40	54.45	2.13	14.07	10.34	0.25	4.26	7.46	4.74	0.80	98.50
TG-40-20-vidre-2	TG-40	53.76	2.27	14.30	10.49	0.19	4.03	7.48	4.66	0.85	98.03

TG-40-20-vidre-1	TG-40	54.43	2.14	14.50	10.50	0.23	3.79	7.56	4.64	0.84	98.63
TG-40-20-vidre-2	TG-40	53.80	2.33	14.02	10.53	0.19	3.90	7.62	4.35	0.80	97.54
TG-40-20-vidre-3	TG-40	53.79	2.33	13.85	10.52	0.17	4.08	7.73	4.37	0.77	97.61
TG-40-20-vidre-5	TG-40	54.56	2.23	14.23	10.24	0.26	4.09	7.54	4.38	0.80	98.32
TG-40-20-1-vidre-1	TG-40	53.14	2.75	13.42	11.51	0.23	3.69	7.33	4.49	0.84	97.39
TG-40-20-1-vidre-2	TG-40	52.93	2.69	13.49	11.85	0.26	3.88	7.29	4.40	0.84	97.63
TG-40-20-1-vidre-3	TG-40	53.19	2.83	13.28	11.66	0.21	3.80	7.15	4.66	0.82	97.60
TG-40-20-1-vidre-4	TG-40	53.69	2.71	13.62	11.49	0.21	3.62	7.17	4.27	0.78	97.55
TG-40-20-3-vidre-1	TG-40	53.50	2.46	13.88	9.77	0.19	4.75	8.92	4.00	0.52	97.99
TG-40-20-3-vidre-2	TG-40	53.79	2.82	12.68	13.22	0.26	3.66	7.28	3.82	0.94	98.47
TG-40-20-3-vidre-3	TG-40	54.01	1.81	17.53	8.41	0.20	3.03	9.48	3.79	0.56	98.82
TG-40-20-3-vidre-4	TG-40	52.99	2.78	13.48	14.24	0.23	2.78	5.93	4.09	1.17	97.70
TG-40-20-3-vidre-6	TG-40	53.13	3.02	13.69	12.92	0.17	3.73	7.57	2.95	0.75	97.92
TG-40-20-4-vidre-1	TG-40	53.25	2.09	15.26	9.94	0.22	4.57	8.08	4.54	0.69	98.64
TG-40-20-4-vidre-2	TG-40	52.90	2.19	14.99	10.32	0.20	4.82	8.28	4.44	0.65	98.79
TG-40-20-4-vidre-3	TG-40	52.72	1.97	15.07	10.16	0.24	4.47	8.15	4.10	0.65	97.53
TG-40-20-4-vidre-4	TG-40	53.33	1.93	15.61	9.85	0.18	4.05	8.15	4.44	0.55	98.08
TG-40-80-3-vidre-1	TG-40	54.77	2.70	14.16	10.89	0.18	3.42	6.88	4.48	0.91	98.39
TG-40-80-3-vidre-2	TG-40	54.42	2.56	14.56	10.98	0.22	3.30	6.64	4.89	0.88	98.45
TG-40-80-3-vidre-3	TG-40	54.84	2.46	13.73	11.01	0.21	3.47	6.60	4.43	0.94	97.69
TG-40-80-4-vidre-4	TG-40	52.33	1.90	15.10	9.99	0.18	4.54	8.66	4.20	0.62	97.51
TG-40-80-5-vidre-1	TG-40	53.28	2.05	14.37	10.14	0.16	5.53	8.64	4.23	0.59	98.99
TG-40-100-1-vidre-1	TG-40	49.51	1.86	17.32	8.68	0.13	5.96	9.67	4.20	0.59	97.93
TG-40-100-1-vidre-2	TG-40	50.33	1.76	17.70	8.75	0.16	6.26	9.71	4.14	0.56	99.37
TG-40-100-5-vidre-1	TG-40	51.51	3.19	14.15	11.76	0.26	3.86	7.80	4.46	0.80	97.78
TG-40-100-5-vidre-2	TG-40	52.06	2.92	13.94	11.59	0.24	3.82	7.76	4.73	0.75	97.81
TG-40-100-5-vidre-3	TG-40	52.73	2.50	14.59	11.11	0.19	4.12	8.35	4.33	0.77	98.69
TG-40-100-5-vidre-4	TG-40	52.20	2.50	14.73	10.80	0.16	3.59	8.49	4.25	0.76	97.48
TG-41-80-1-vidre-2	TG-41	52.35	2.41	14.76	10.62	0.25	4.26	8.30	4.33	0.70	97.98
TG-41-80-2-vidre-1	TG-41	52.51	2.39	15.35	10.70	0.21	3.93	8.32	4.47	0.58	98.47
TG-41-80-2-vidre-2	TG-41	52.18	2.53	14.39	11.31	0.19	4.21	8.05	4.07	0.74	97.68
TG-41-80-3-vidre-1	TG-41	49.19	4.01	11.95	13.89	0.25	4.38	8.83	5.98	0.84	99.32
TG_41_70_A_vidre_1	TG-41	55.66	2.60	13.76	11.18	0.21	3.39	6.61	4.50	0.87	98.78
TG_41_70_A_vidre_2	TG-41	55.71	2.75	13.60	11.18	0.21	3.43	6.56	4.60	0.83	98.88
TG_41_70_A_vidre_3	TG-41	55.96	2.74	14.09	10.89	0.21	3.49	6.86	4.58	0.89	99.71
TG_41_70_A_vidre_4	TG-41	55.62	2.66	13.75	11.11	0.24	3.39	6.85	4.63	0.86	99.11
TG_41_70_B_vidre_1	TG-41	55.37	2.19	15.71	9.66	0.16	3.94	7.40	4.56	0.68	99.68
TG_41_70_B_vidre_3	TG-41	55.51	2.18	15.57	9.89	0.20	4.13	7.36	4.70	0.72	100.25
TG_41_70_B_vidre_4	TG-41	55.11	2.05	15.50	9.66	0.22	3.86	7.45	4.25	0.70	98.80
TG_41_70_B_vidre_5	TG-41	55.32	2.39	15.03	10.13	0.17	4.04	7.42	4.59	0.70	99.79
TG_41_70_B_vidre_6	TG-41	55.67	2.23	14.85	10.25	0.16	3.95	7.23	4.62	0.74	99.70
TG_41_70_B_vidre_7	TG-41	56.00	2.45	14.59	10.57	0.21	3.91	6.85	4.61	0.87	100.07
TG_41_70_C_vidre_1	TG-41	55.42	2.05	15.51	9.61	0.15	3.79	7.35	4.63	0.72	99.24
TG_41_70_C_vidre_2	TG-41	54.67	2.08	15.30	9.58	0.17	3.83	7.58	4.76	0.69	98.66
TG_41_70_C_vidre_3	TG-41	54.98	2.21	15.75	9.64	0.17	3.80	7.27	4.68	0.67	99.17
TG_41_70_C_vidre_4	TG-41	55.21	2.04	15.25	9.59	0.14	3.93	7.50	4.58	0.71	98.95

TG_41_70_C_vidre_5	TG-41	57.26	2.62	13.46	10.82	0.22	2.89	6.03	4.31	1.01	98.62
TG_41_70_C_vidre_6	TG-41	56.69	2.68	13.47	11.05	0.18	2.88	6.21	4.47	1.05	98.68
TG_41_70_C_vidre_7	TG-41	56.22	2.96	13.25	11.14	0.20	2.83	6.06	4.66	1.01	98.33
TG_41_70_C_vidre_8	TG-41	57.22	2.70	13.34	10.90	0.17	2.89	6.03	4.47	0.99	98.72
TG_41_70_D_vidre_1	TG-41	55.47	2.12	15.51	9.52	0.17	3.62	7.47	4.62	0.72	99.22
TG_41_70_D_vidre_2	TG-41	55.23	2.19	15.46	9.74	0.21	3.78	7.22	4.36	0.71	98.89
TG_41_70_D_vidre_3	TG-41	55.32	2.10	15.61	9.70	0.16	3.87	7.24	4.69	0.72	99.40
TG_41_70_D_vidre_4	TG-41	55.42	2.13	15.58	9.79	0.21	4.09	7.48	4.44	0.71	99.86
TG_41_70_D_vidre_5	TG-41	55.30	3.01	12.74	11.59	0.22	3.09	6.74	4.40	1.00	98.10
TG_41_70_D_vidre_6	TG-41	55.75	2.97	12.83	11.70	0.23	3.20	6.82	4.27	0.98	98.75
TG_41_70_D_vidre_7	TG-41	57.23	3.00	13.23	11.58	0.26	3.03	6.51	4.39	1.00	100.22
TG_41_70_D_vidre_8	TG-41	55.45	2.18	15.84	9.71	0.21	3.84	7.35	4.37	0.69	99.63
TG_41_70_D_vidre_9	TG-41	55.15	2.12	15.64	9.75	0.18	3.89	7.41	4.87	0.74	99.75
TG_41_70_D_vidre_11	TG-41	52.81	2.49	15.09	10.67	0.22	5.22	8.46	4.58	0.66	100.20
TG_41_70_D_vidre_12	TG-41	52.03	2.48	14.87	10.49	0.18	5.19	8.68	4.67	0.62	99.20
TG_41_70_D_vidre_13	TG-41	52.17	2.29	14.70	10.56	0.23	5.27	8.49	4.27	0.64	98.62
TG_41_70_E_vidre_1	TG-41	55.30	2.52	13.82	11.23	0.16	3.60	6.61	4.42	0.87	98.52
TG_41_70_E_vidre_2	TG-41	55.30	2.73	13.52	11.53	0.23	3.84	6.86	4.52	0.80	99.33
TG_41_70_E_vidre_3	TG-41	56.14	2.35	14.43	10.72	0.22	3.66	6.88	4.94	0.80	100.14
TG_41_70_E_vidre_4	TG-41	53.44	2.12	14.38	10.24	0.21	4.36	8.89	4.25	0.74	98.63
TG_41_70_E_vidre_5	TG-41	53.68	2.09	14.73	10.63	0.21	4.57	8.21	4.14	0.77	99.03
TG_41_70_E_vidre_6	TG-41	51.23	1.89	16.06	9.43	0.17	5.93	9.31	4.43	0.60	99.04
TG_41_70_E_vidre_7	TG-41	51.80	2.05	16.36	9.57	0.17	5.89	9.20	4.29	0.63	99.96
TG_41_70_F_vidre_1	TG-41	57.35	2.85	13.59	10.20	0.22	2.85	5.92	4.60	1.00	98.60
TG_41_70_F_vidre_2	TG-41	56.86	2.75	13.58	11.03	0.22	2.93	6.29	4.48	1.00	99.15
TG_41_70_F_vidre_3	TG-41	57.48	2.64	13.75	10.76	0.23	3.09	6.05	4.68	0.95	99.64
TG_41_70_G_vidre_1	TG-41	55.68	2.38	14.00	10.56	0.21	3.75	6.85	4.57	0.82	98.82
TG_41_70_G_vidre_2	TG-41	55.97	2.55	13.88	10.74	0.20	3.64	6.93	4.55	0.88	99.34
TG_41_70_G_vidre_3	TG-41	55.65	2.55	13.83	10.62	0.21	3.53	6.99	4.28	0.79	98.44
TG_41_70_G_vidre_4	TG-41	55.56	2.68	13.87	10.68	0.20	3.59	6.96	4.48	0.80	98.82
TG_43_70_A_vidre_1	TG-43	54.58	2.88	12.93	12.35	0.27	3.20	6.89	4.18	1.05	98.34
TG_43_70_A_vidre_2	TG-43	54.91	2.91	12.86	12.17	0.20	3.24	6.92	4.03	0.97	98.21
TG_43_70_A_vidre_3	TG-43	55.55	2.98	12.99	12.30	0.28	3.19	6.96	4.10	1.02	99.37
TG_43_70_C_vidre_1	TG-43	53.82	2.38	14.22	11.27	0.21	4.44	8.07	4.69	0.81	99.91
TG_43_70_C_vidre_2	TG-43	53.02	2.38	14.11	10.63	0.26	4.23	8.08	4.74	0.77	98.23
TG_43_70_C_vidre_3	TG-43	53.13	2.42	13.90	10.78	0.26	4.15	7.94	4.55	0.80	97.92
TG_43_70_F_vidre_1	TG-43	52.85	2.23	14.39	10.55	0.22	4.87	8.41	4.44	0.58	98.55
TG_43_70_F_vidre_2	TG-43	52.72	2.28	14.37	10.38	0.20	4.84	8.33	4.58	0.60	98.30
TG_43_70_F_vidre_3	TG-43	53.17	2.32	14.43	10.38	0.19	4.79	8.49	4.64	0.61	99.01
TG_43_70_F_vidre_4	TG-43	52.64	2.32	14.23	10.98	0.24	4.80	8.40	4.47	0.60	98.68
TG_43_70_F_vidre_5	TG-43	52.50	2.44	14.13	10.70	0.19	4.71	8.33	4.76	0.63	98.39
TG_43_70_F_vidre_6	TG-43	52.62	2.34	14.31	11.07	0.19	4.64	8.51	4.69	0.61	98.99
TG_43_70_F_vidre_7	TG-43	53.53	2.31	14.25	10.91	0.21	4.85	8.44	4.15	0.68	99.32
TG_43_70_F_vidre_8	TG-43	53.07	2.46	14.16	10.84	0.26	4.73	8.61	4.73	0.61	99.47
TG_43_70_G_vidre_1	TG-43	54.70	2.27	14.09	10.61	0.24	3.98	7.54	4.53	0.77	98.72
TG_43_70_G_vidre_2	TG-43	54.38	2.48	13.89	10.72	0.21	3.91	7.59	4.35	0.78	98.31

TG_43_70_G_vidre_3	TG-43	54.40	2.44	14.12	11.17	0.22	3.80	7.57	4.68	0.78	99.18
TG_43_70_G_vidre_4	TG-43	54.07	2.30	14.22	10.95	0.20	3.99	7.51	4.66	0.82	98.71
TG_43_70_H_vidre_1	TG-43	57.32	2.30	14.70	9.85	0.20	3.35	6.14	4.90	1.03	99.80
TG_43_70_H_vidre_2	TG-43	58.29	2.08	14.57	9.34	0.20	2.98	5.83	4.70	1.09	99.08
TG_43_70_H_vidre_3	TG-43	56.32	2.33	14.74	10.48	0.19	3.23	7.14	4.82	0.81	100.06
TG_50_44_A_vidre_3	TG-50	55.53	2.63	13.31	10.92	0.24	3.21	6.33	4.61	0.89	97.67
TG_50_44_vidre_1	TG-50	53.32	3.12	13.49	11.64	0.20	3.96	7.10	4.56	0.70	98.09
TG_50_44_vidre_2	TG-50	52.85	3.11	13.49	11.62	0.27	3.78	7.14	4.69	0.67	97.62
TG_50_44_vidre_3	TG-50	53.32	3.05	13.57	11.57	0.26	4.03	7.16	4.64	0.69	98.30
TG_50_44_vidre_4	TG-50	55.34	2.86	13.47	11.23	0.19	3.30	6.68	4.38	0.74	98.19
TG_50_44_vidre_5	TG-50	55.99	2.70	13.62	11.39	0.18	3.28	6.75	4.61	0.80	99.31
TG_50_44_C_vidre_1	TG-50	53.20	3.05	13.59	12.15	0.18	3.96	7.23	4.69	0.73	98.78
TG_50_44_C_vidre_2	TG-50	53.78	3.14	13.48	11.93	0.21	3.79	7.38	4.68	0.68	99.07
TG_50_44_C_vidre_3	TG-50	53.48	3.15	13.63	11.80	0.24	3.84	7.41	4.67	0.69	98.90
TG_50_44_C_vidre_4	TG-50	57.82	2.74	13.56	11.07	0.27	2.76	5.65	4.74	1.10	99.71
TG_50_44_C_vidre_5	TG-50	53.30	3.36	12.13	13.34	0.24	3.50	7.42	3.98	0.79	98.07
TG_50_44_C_vidre_6	TG-50	53.90	3.38	12.29	12.86	0.27	3.69	7.37	4.68	0.80	99.23
TG_50_44_C_vidre_7	TG-50	54.20	3.33	12.53	12.74	0.21	3.55	7.28	4.20	0.82	98.87
TG_50_44_D_vidre_1	TG-50	52.13	3.19	13.00	12.53	0.29	3.89	7.63	4.90	0.74	98.31
TG_50_44_D_vidre_2	TG-50	52.63	3.17	13.43	12.60	0.21	3.79	7.66	4.56	0.72	98.77
TG_50_44_D_vidre_3	TG-50	52.50	3.32	13.39	12.60	0.27	4.01	7.58	4.56	0.64	98.88
TG_50_44_D_vidre_4	TG-50	53.44	3.36	13.20	11.83	0.23	3.76	7.19	4.36	0.74	98.12
TG_50_44_D_vidre_5	TG-50	53.36	3.08	13.28	11.84	0.32	3.74	7.03	4.38	0.73	97.76
TG_50_44_E_vidre_1	TG-50	53.38	3.01	13.15	12.31	0.24	3.62	7.12	4.50	0.75	98.09
TG_50_44_E_vidre_2	TG-50	53.67	3.03	13.46	12.14	0.23	3.62	7.28	4.57	0.71	98.71
TG_50_44_E_vidre_3	TG-50	53.26	3.22	13.42	12.31	0.24	3.60	7.14	4.47	0.71	98.36
TG_50_44_E_vidre_4	TG-50	55.90	3.12	13.45	11.01	0.21	3.05	6.40	4.47	0.85	98.46
TG_50_44_E_vidre_5	TG-50	55.93	2.80	13.66	11.21	0.24	2.90	6.28	4.22	0.90	98.14
TG_50_44_E_vidre_6	TG-50	56.31	2.87	13.35	11.11	0.24	3.00	6.25	4.32	0.90	98.35
TG_50_44_E_vidre_7	TG-50	60.44	2.32	13.55	9.33	0.18	2.15	4.98	4.21	1.07	98.23
TG_50_44_F_vidre_1	TG-50	53.57	2.97	13.32	12.00	0.21	3.70	7.20	4.33	0.69	97.99
TG_50_44_F_vidre_2	TG-50	54.15	2.96	13.47	11.79	0.20	3.70	7.23	4.56	0.72	98.78
TG_50_44_F_vidre_3	TG-50	53.79	3.04	13.45	11.96	0.21	3.70	7.19	4.31	0.71	98.36
TG_50_44_F_vidre_4	TG-50	53.46	2.92	13.51	12.25	0.24	3.73	7.27	4.36	0.75	98.49
TG_50_44_F_vidre_5	TG-50	53.67	3.17	12.80	12.45	0.31	3.68	7.46	4.52	0.71	98.78
TG_50_44_F_vidre_6	TG-50	53.59	3.15	13.33	12.43	0.25	3.55	7.25	4.46	0.73	98.74
TG_50_44_F_vidre_7	TG-50	53.52	2.93	13.04	12.39	0.23	3.94	7.28	4.61	0.70	98.63