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Major-Minor-Trace Element Analyses and Oceanographic Modeling Confirms Circumpolar Transport of the 1962 Protector Shoal Pumice Raft

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Key Points:

- Pumice clasts found on Falkland Islands shorelines are linked with the 1962 eruption of Protector Shoal seamount using geochemistry
- Oceanographic modeling confirms that the 1962 Protector Shoal pumice raft circumnavigated Antarctica
- Protector Shoal seamount is more volcanically diverse than previously thought

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Pumice rafts derived from submarine eruptions can remain afloat for months or even years, traveling thousands of kilometers on ocean currents. These natural phenomena disperse marine organisms and provide important evidence for submarine volcanism yet are not fully understood. Here, we describe pumice clasts from Falkland Islands shorelines and use major-minor-trace element analyses to trace their provenance to the 1962 volcanic eruption on Protector Shoal, a large seamount in the South Sandwich Islands, Scotia Sea. Compositional variability between rafted and dredged pumice from Protector Shoal suggests eruptions have varied from explosive to non- or mildly explosive (the latter from lava domes and during neptunian events) and the seamount is volcanically diverse. Oceanographic modeling simulations and historical observations show that clasts from the 1962 eruption reached the Falkland Islands via the Antarctic Circumpolar Current, a journey of ~20,000 km that took approximately three years. Although oceanographic variability strongly affects modeled transport pathways, in all simulations particles consistently reach the Falkland Islands from Protector Shoal seamount, suggesting a persistent long-distance connection. The results highlight the potential for pumice rafting to disperse non-native, potentially invasive, marine organisms throughout the Southern Ocean as climate warms.

Plain Language Summary Pumice rafts are floating mats of buoyant volcanic rock derived from the eruptions of underwater or coastal volcanoes. These rafts occur in nearly all the world's major oceans and can transport marine plants and animals over large distances. Here, we analyze the chemical composition of pumice fragments collected from shorelines in the Falkland Islands and trace their origin to Protector Shoal seamount in the South Sandwich Islands, Scotia Sea. Variation in the composition of rafted and dredged pumice suggests that eruptions have ranged from explosive to non- or mildly explosive and the seamount is volcanically diverse. Computer modeling simulations that are tested against real-world observations suggest the pumice reached the Falkland Islands by circumnavigating Antarctica; a journey of ~20,000 km that took approximately three years following the well-documented eruption in 1962. The results show that pumice rafts could disperse potentially invasive plants and animals throughout the Southern Ocean as the region warms.

1. Introduction

Pumice rafts are floating mats composed of vesicular, silicic rock formed during eruptions of submarine or coastal volcanoes. This common natural phenomenon affects nearly all the world's major oceans and can produce rafts that cover thousands of square kilometers, including pumice clasts as large as >1 m (Bryan et al., 2012; Carey et al., 2014; Yoshida et al., 2022). These floating mats can persist for months or even years and travel large distances on ocean currents. In doing so, they disperse plants and animals well beyond their typical ranges, linking marine and coastal ecosystems that would otherwise remain separated. For example, pumice produced during the 2006 eruption of Home Reef Volcano, in Tonga, carried >80 species 5,000 km in following 7–8 months (Bryan et al., 2012). Pumice rafts also provide key evidence for submarine eruptions that may otherwise go undetected (e.g., Carey et al., 2014, 2018)—a vital data source given that around 75% of volcanic eruptions occur beneath the ocean (Carey et al., 2025) and can pose substantial hazards (e.g., Hunga Tonga-Ha'apai 2022 ashfall and tsunami; Carn et al., 2022). Rafted pumice can pose hazards by impacting ports, fisheries, and coastal ecosystems (e.g.,

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2021 Fukutoku-Oka-no-Ba eruption; Ishimura & Hiramine, 2025). Despite this, our understanding of long-distance pumice rafting is limited. Once detected, satellite imagery can now track pumice rafts at almost real time (e.g., Chen et al., 2022; Iskandar et al., 2023) and clast-studies have improved understanding of pumice production and buoyancy (Jutzeler et al., 2014; Mitchell et al., 2021; Yoshida et al., 2022). However, it is likely that many rafts go unobserved (Zheng et al., 2022) and data come from a narrow observation window that may not encompass the full range of marine-volcanic interactions. Examples from historical or paleoenvironmental records (e.g., Farnsworth et al., 2020; Pattan et al., 2008; Risso et al., 2002; Simkin & Fiske, 1983; Yu et al., 2022) can provide long-term records of pumice rafting, but these are often not available from remote volcanic arcs. This is especially true in the Southern Ocean where access is difficult and historical records are rare and often seasonal.

One of the best-known examples of long-distance pumice dispersal in the Southern Ocean is the 1962 Protector Shoal pumice raft (see sect. 1.1). Risso et al. (2002) showed that trace element compositions of pumice clasts collected from Tierra del Fuego and the South Shetland Islands had strong similarities with those of the 1962 eruption of Protector Shoal in the South Sandwich Islands, Scotia Sea (Figure 1) although differed in some elements. Based on observations of Protector Shoal pumice in Australia and New Zealand, the authors hypothesized that these clasts reached Drake Passage by circumnavigating Antarctica over a period of around 18 months. However, they did not have access to today's sophisticated global ocean-sea ice models that allow transport pathways to be accurately determined. In this study, we analyze the major-minor-trace element composition of pumice clasts collected from shorelines in the Falkland Islands, South Atlantic that are likely derived from the 1962 eruption on Protector Shoal seamount. We then use oceanographic modeling to examine the movement of pumice clasts throughout the Southern Ocean. Guided by historical observations and geochemistry, our study places new spatial and temporal limits on pumice raft dispersal and, for the first time, quantitatively models the transport path of the 1962 Protector Shoal pumice raft.

1.1. The 1962 Protector Shoal Pumice Raft

The 1962 pumice raft was derived from Protector Shoal seamount, a broad shoal area around 10 km in diameter that, together with Nimrod Bank, comprises the most northerly volcanic seamount of the South Sandwich Islands volcanic arc (Figure 1). The shoal has an uneven hummocky surface composed of several conical and dome like features. It has a general depth of <400 m and rises to 27 m beneath the ocean surface at its maximum (Leat et al., 2014). Pumice rafts from the 1962 eruption were first encountered by the Royal Navy ship HMS Protector on the 14th of March 1962 close to Visokoi Island (Figure 2a). Rafts formed elongate mats trending east-west, away from Protector Shoal seamount (Figure S1 in Supporting Information S1), along the prevailing wind/surface currents and included clasts up to 1.5 m across. Subsequent dredging by HMS Protector, on the flank of one of the submarine features on Protector Shoal seamount summit, revealed abundant pumice and confirmed Protector Shoal as the raft source (Gass et al., 1963), but the exact location of the source vent responsible for the 1962 pumice raft is still unknown. In the months following the eruption, pumice assumed to be sourced from Protector Shoal seamount was reported from beaches in Australia and New Zealand and in the Southern Ocean, south of Macquarie Island by the Royal New Zealand Navy vessel HMNZS Piikai (Coombs & Landis, 1966; Sutherland, 1965). Subsequently, pumice collected from Marion Island, Bouvet Island, Kerguelen Island, and Hawaii has been linked with the 1962 Protector Shoal raft based on geochemistry (Jokiel & Cox, 2003; Kent & Frick, 1984; Nougier, 1970). The nature of eruptions on Protector Shoal seamount have never been assessed, although an explosive origin for the 1962 event is implicit in the early publications.

1.2. Pumice in the Falkland Islands

The Falklands archipelago lies around 500 km east of southern South America in the South Atlantic Ocean (Figure 1). The islands are affected by the Falklands (Malvinas) Current, a branch of the Antarctic Circumpolar Current that brings cool (7°C), nutrient-rich waters east through the Drake Passage, and northward toward the Falklands (Upton & Shaw, 2002). The main body of the current flows around the shelf break, east of the Falkland Islands, whereas a more minor branch flows northward over the continental shelf of South America. The geology of the Falkland Islands is comprised of mid- to late-Paleozoic deltaic sandstones, quartzites, and mudstones (Aldiss & Edwards, 1999). Mesozoic dolerite dykes intrude the sedimentary units, but no volcanic deposits or visible tephra beds have been reported from the islands (Aldiss & Edwards, 1999; Stone, 2013). Cryptotephra deposits (nonvisible volcanic ash) are common in many peatlands, however, and re-worked volcanic ash forms a large component of the regional dust flux mostly sourced from Patagonia (Monteath et al., 2019, 2022).

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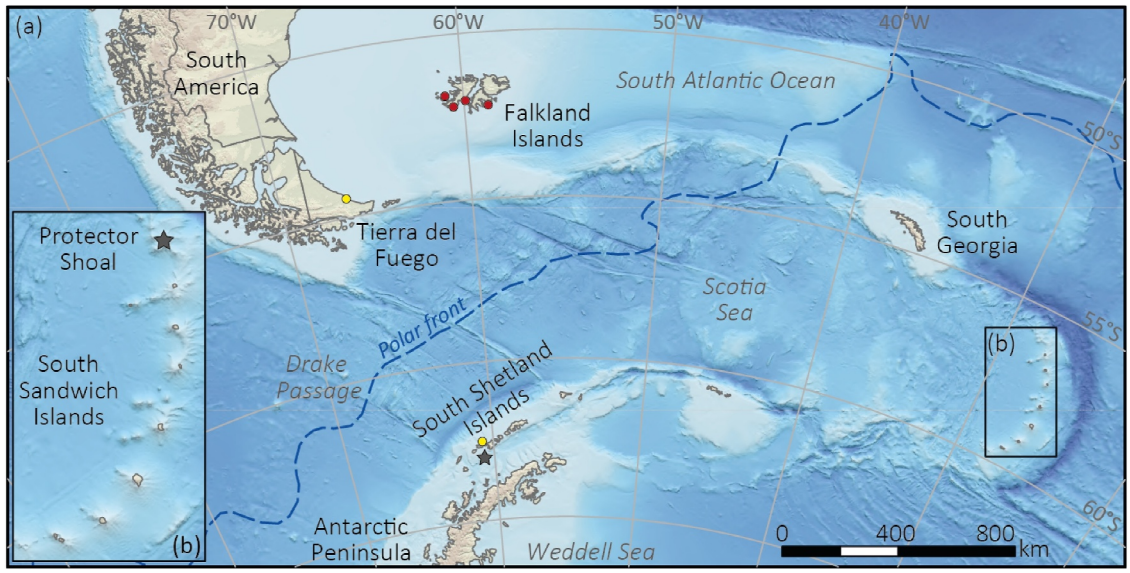

Figure 1. (a) The position of the Falkland Islands and South Sandwich Islands. The Falkland Islands shorelines where pumice clasts have been collected are shown as red dots. From west-to-east these include Weddell Island, Cape Meredith, Carcass Bay, and Bleaker Island. The collection points of Risso et al. (2002) are shown as yellow dots. Deception Island is shown as a gray star. (b) The position of Protector Shoal seamount in the South Sandwich Islands.

Pumice clasts have been noted on Falkland Islands beaches for some time. Assistant Surgeon William Kent collected a specimen of black, highly vesicular '*scoriae*' on a beach near Cape Meredith, West Falkland during the surveying voyage of HMS Beagle in the 1830s. The specimen was subsequently incorporated into Charles Darwin's 'Beagle' collection (specimen n. 1891), however, has never been studied in detail, and its provenance remains unresolved (Stone, 2013). Younger blocks of pale gray pumice are common on many Falkland Islands shorelines (Aldiss & Edwards, 1999) and are well known to the islanders; "*It arrived in the early* 60s…. *and was found on nearly every beach on the Falklands. Often as great boulders that you could lift above your head*" (Lewis Clifton pers coms, 2024). When peat cutting was more prevalent, pieces of pumice were collected and used to clean peat burning stoves (Phyl Rendell pers coms, 2024). Today, well-rounded pumice clasts up to 30 cm in length (long-axis) can be found at high-tide marks amongst other light debris (e.g., seaweed, driftwood and plastics; Figure S2 in Supporting Information S1).

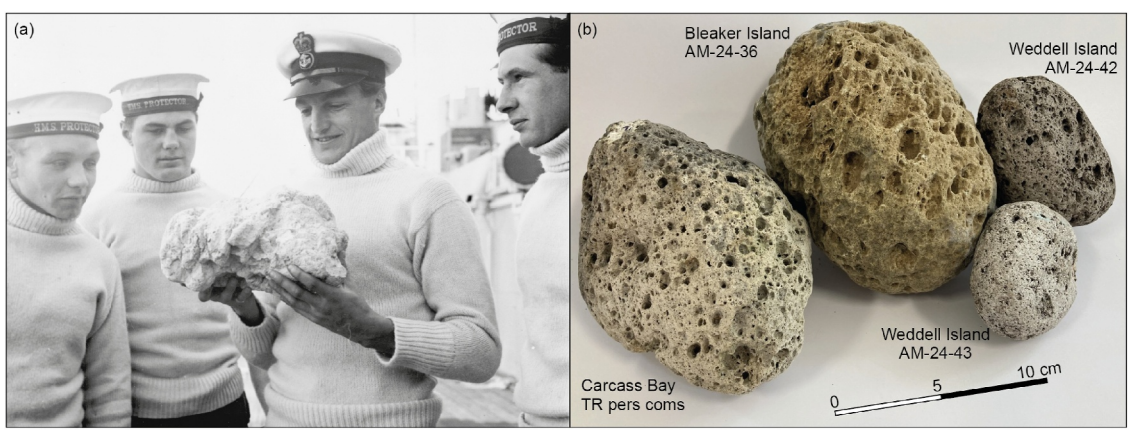

Figure 2. (a) Crew of the HMS Protector inspecting a large pumice clast (~40 cm in diameter) from the 1962 Protector Shoal raft. © Crown copyright Imperial War Museum. (b) The analyzed pumice clasts collected from Falkland Islands shorelines.

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2. Materials and Methods

We collected pumice clasts from Falkland Islands shorelines at Carcass Bay (−51.97, −59.91) in March 2023 and from Bleaker Island (−52.21, −58.85) and Weddell Island (−51.78, −60.86) in February 2024 (Figures 1 and 2b; Table S1 in Supporting Information S2). Subsamples from these were ground and sieved for geochemical analyses. Aliquots for electron probe microanalysis (EPMA) were wet sieved at 200 and 60 μm, whereas aliquots for laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) were wet sieved at 200 and 80 μm. The sieved material was then subjected to heavy liquid density separation at 2.45 g/cm^3 to extract volcanic glass (Turney, 1998). Material from this extraction was mounted in epoxy resin, within acrylic stubs, for EPMA and LA-ICP-MS. In the case of the Carcass Bay pumice, subsamples were taken from either end of the clast and analyzed with EPMA separately. We also prepared and analyzed reference samples from Protector Shoal seamount using the same methods. Sample BM.1963,360 (Natural History Museum London specimen) was collected from the 1962 raft by HMS Protector (hereafter called Protector Shoal raft). Samples DR.162.23, DR.162.22, and DR.162.9 were dredged from immediately southeast of the Protector Shoal seamount summit during the 1997 British Antarctic Survey Cruise of RRS James Clark Ross (JR18; hereafter called Protector Shoal dredge). These dredged samples were previously analyzed by Leat et al. (2007) and categorized as Type A pumice (DR.162.22 and DR.162.9) and Type B pumice (DR.162.23) based on their chemical compositions. The complete EPMA and LA-ICP-MS data set and associated standard measurements are reported in Supporting Information S2 (Tables S2, S3).

2.1. Electron Probe Microanalysis (EPMA)

We analyzed the major-minor element composition of volcanic glass extracted from pumice subsamples using EPMA with wavelength dispersive spectrometry, on a JEOL 8900 Superprobe, at the University of Alberta. A suite of 10 elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, Cl) were measured using a 15 keV accelerating voltage, 6 nA beam current, and 5 μm beam diameter. Analyses were run with time-dependent intensity corrections applied to Na to compensate for the narrow beam (<10 μm) diameter (e.g., Jensen et al., 2021). During these analyses, we ran two secondary standards of known compositions alongside the pumice samples to check for instrumental drift and analytical accuracy and precision; (a) Lipari rhyolitic obsidian ID3506 and (b) Old Crow tephra (Kuehn et al., 2011). The major-minor element compositions of the pumice samples are presented as normalized weight percent (wt%) oxides in comparative diagrams.

2.2. Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS)

We analyzed the trace element chemical composition of pumice subsamples from AM-24-42, AM-24-43 (Weddell Island) and BM.1963,360 (Protector Shoal raft) using an Agilent 8900 triple quadrupole ICP-MS (ICP QQQ) coupled to a Resonetics 193 nm ArF excimer laser-ablation at the Department of Earth Sciences, Royal Holloway, University of London. We used a 15 μm beam size with a repetition rate of 5 Hz. A count time of 40 s on the sample and 40 s of the gas blank was used to allow the subtraction of the background signal. Analyses from each pumice clast were bracketed by the NIST612 glass, which was used as a calibration standard. LA-ICP-MS data reduction was performed within Microsoft Excel following the protocols outlined by Tomlinson et al. (2010). Accuracies of LA-ICP-MS analyses of the MPI-DING reference glasses, ATHO-G and StHs6/80-G, were typically ≤5% for most elements measured (Jochum et al., 2006).

2.3. Oceanographic Modeling

2.3.1. Ocean and Wave Model

To quantitively identify the likely transport pathways for the 1962 Protector Shoal pumice raft, we used particle tracking experiments. For these experiments, we obtained daily ocean surface currents from cycle one of the 0.1° global ocean-sea ice model ACCESS-OM2-01 (Kiss et al., 2020). This simulation was driven by version 1.4.0 of the interannually varying JRA55-do forcing from 1958 to 2018 (Tsujino et al., 2018) and was initialized with temperature and salinity from World Ocean Atlas 2013 version 2 (Kiss et al., 2020; Levitus et al., 2014). The nominal 0.1° horizontal resolution resolves mesoscale eddies across the Antarctic Circumpolar Current region (Hallberg, 2013) but does not resolve the Southern Ocean submesoscale field. Since the pumice clasts we simulate are buoyant and float at the ocean surface, we used surface-only currents from the top 1.1 m of the ocean model to advect the particles. We combined the surface currents from ACCESS-OM2-01 with Stokes drift velocities from

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WAVEWATCH III (Rascle & Ardhuin, 2013) at 0.5°, as previous research has shown that these wave-induced velocities are important for modeling connectivity in the Southern Ocean (Fraser et al., 2018).

2.3.2. Lagrangian Particle Tracking

We released virtual particles, representing pumice clasts, in the nine closest model grid cells to Protector Shoal seamount. Daily ocean surface velocities and hindcast Stokes drift estimates are not available for 1962. Instead, we chose to release particles in 2003 because the following four years are relatively neutral with respect to the major climate modes of variability (Stewart et al., 2020). In this way, the resulting trajectories can be interpreted as providing an average estimate of dispersal pathways. We released 90,000 particles (10,000 per grid cell) every day from the 5th of March 2003 to the 16th of March 2003 (inclusive), totaling just over one million particles for the simulation. The chosen release period in March is based on observations by HMS Protector on the 14th of March 1962 and records of seismic activity that suggest an eruption date of the 5th of March 1962 (Gass et al., 1963). Virtual particles were advected offline and forward-in-time for 4 years using version 2.3 of OceanParcels (Delandmeter and van Sebille, 2019). We assume the pumice clasts are sufficiently small that they do not extend far above the surface and so are not strongly impacted by windage in a region with high amplitude swells and wave heights such as the Southern Ocean. The potential impact of windage is explored with a sensitivity experiment described in Supporting Information S1. As we are interested in the pathways of pumice clasts that reach the Falkland Islands, we neglect sinking and particles are transported with surface currents for the duration of their trajectories. We also neglect the influence of sea ice on pumice clast trajectories. For our simulations, this is a good assumption because almost all the simulated pumice clasts that reach the Falkland Islands remain north of the sea ice edge for their entire tracking period. We did not add any horizontal diffusion to our simulations to replicate the sub grid scale motion that is not resolved by the flow fields. However, thousands of particles were released per grid cell, thus capturing variations in the flow field associated with small changes in the initial starting positions of the particles. Model caveats and the potential implications of model assumptions are detailed further in Supporting Information S1 (Text S1). Particle positions were saved to file every 2 days during the simulation. Particles that reached a 6° longitude by 3.5° latitude target box encompassing the Falkland Islands were considered successful transport events from which associated transport pathways and arrival dates were calculated. The same methods were used to establish the transport pathways between Protector Shoal seamount and Australia, New Zealand, and the Southern Ocean, south of Macquarie Island, where pumice rafts were observed by HMNZS Piikai following the eruption (Coombs & Landis, 1966; Sutherland, 1965). We also conducted sensitivity experiments to explore the influence of temporal variability in the underlying ocean flows as outlined in Supporting Information S1 (Text S2).

3. Results and Discussion

3.1. Pumice Provenance

Major-minor elements from Falkland Islands pumices closely overlap and show that the clasts are derived from the same island arc tholeiite volcanic source (Figures 3a and 3b). The high SiO_2 (76.8–78.8 wt%), low K_2O (0.7–0.9 wt%) geochemical signature plots along-trend with lavas from the South Sandwich Islands and is very different from other Southern Ocean and Antarctic volcanoes (Figure 3c) as well as Fueguino (Cook), the most southerly (and only coastal) volcano in the South American Austral Volcanic Zone, which produces calc-alkaline andesites (Corbella & Lara, 2008). The major-minor element compositions of the clasts are also unlike tephra produced in the 1967, 1969, and 1970 eruptions of Deception Island (Smellie, 2002), which are characterized by basaltic trachyandesite/trachyandesite compositions (Pedrazzi et al., 2018) and have previously been hypothesized as a source of pumice in the Falkland Islands (Aldiss & Edwards, 1999). Therefore, the Falkland Islands pumice clasts can be confidently linked with Protector Shoal seamount, the only known source of rhyolitic material amongst the South Sandwich Islands volcanic arc (Figure S4 in Supporting Information S1; Pearce et al., 1995; Leat et al., 2007).

Reference material from the 1962 Protector Shoal raft (BM.1963,360) also has the distinctive high SiO_2 (76.0–79.0 wt%) and low K_2O (0.6–1.0 wt%) values of the low-K tholeiitic fractionation trend of South Sandwich Islands lavas (Leat et al., 2007). Although, values for several elements span a wider range than the Falkland Islands pumice analyzed here (e.g., SiO_2 and FeO_T), the close compositional affinity between the clasts is obvious. Trace element analyses from the BM.1963,360 raft sample and two Weddell Island pumice

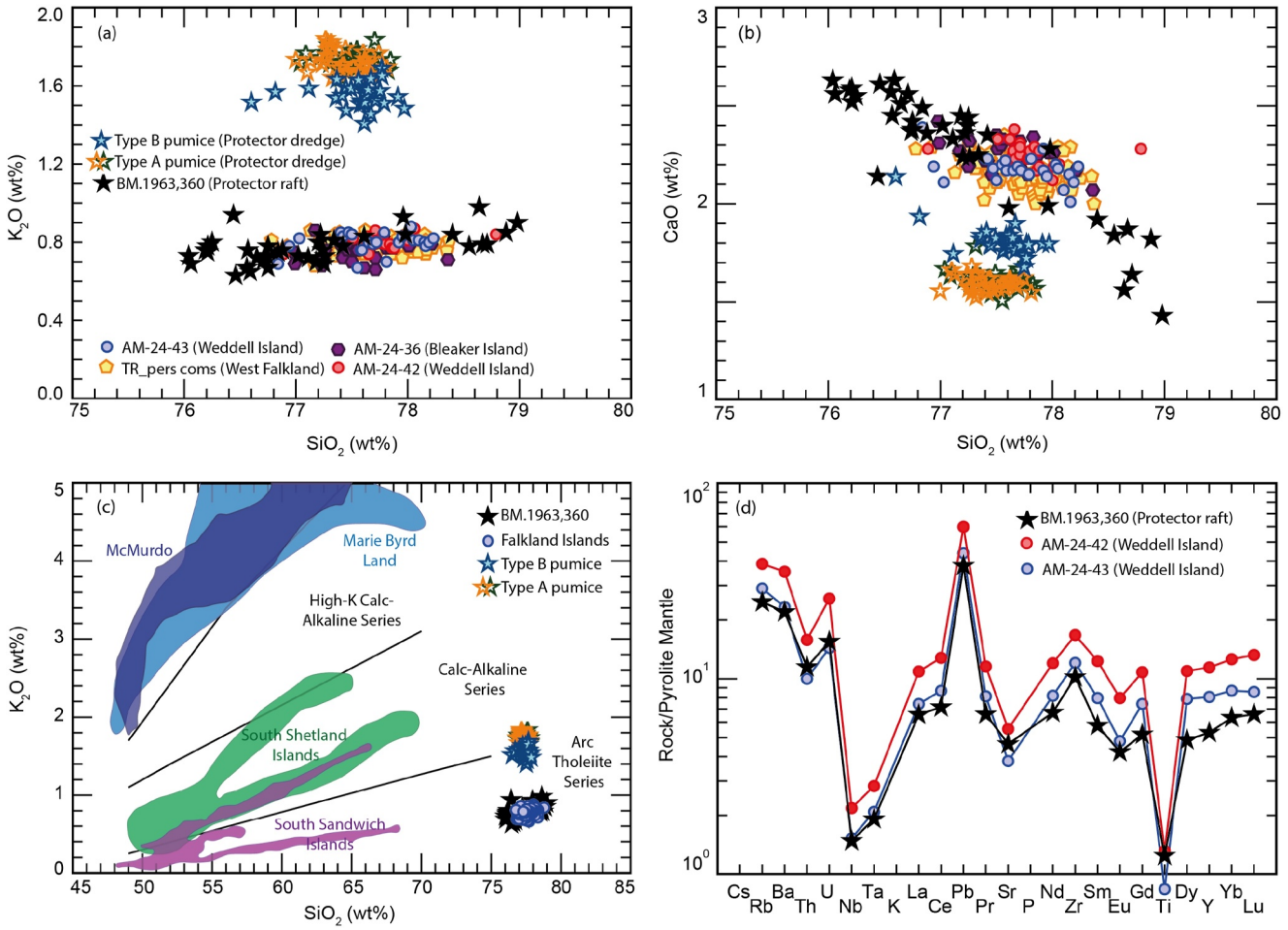

Figure 3. (a,b) Major element EPMA data from Falkland Island pumice clasts and reference samples; BM.1963,360, Type A pumice (DR.162.22 and DR.162.9), and Type B pumice (DR.162.23; Leat et al., 2007. (c) Major element EPMA geochemical fields from Antarctic and Southern Ocean volcanoes after Narcisi et al. (2005). Chemical classification and nomenclature for K_2O v SiO_2 after Peccerillo and Taylor (1976). (d) Trace element LA-ICP-MS data from Protector Shoal seamount sample BM.1963,360 and Falkland Islands pumice.

clasts are also broadly similar (although somewhat enriched overall in the Falkland Islands pumices) supporting the correlation (Figure 3d). The elemental differences between the Falkland Islands pumices and Protector Shoal raft (BM.1963,360) may reflect differing crystallinity/texture maturity of the sampled pumices as certain microtextural features and processes will allow some clasts to float, whereas others sink (Mitchell et al., 2021). Therefore, pumices collected from a recently erupted, coherent raft may not have exactly the same chemistry and texture as those that remained afloat for several years.

As pumice clasts arrived on Falkland Islands beaches shortly after the 1962 eruption of Protector Shoal seamount and have distinctive major-minor-trace element compositions that can be confidently linked with the South Sandwich Islands, we consider it very likely that the Falkland Islands pumices were produced during the 1962 eruption on Protector Shoal seamount. The observed distribution, modeled transport pathways, and timing of arrival are all consistent with this hypothesis.

By contrast, the compositions of the dredge samples from Protector Shoal are substantially different (Figures 3a and 3b) with clear elemental offsets from the rafted pumice (e.g., K_2O, CaO). Although a provenance from Protector Shoal is unequivocal (the samples were dredged from the Protector Shoal seafloor), they are clearly derived from an eruption that was different and probably geographically separate from the one responsible for the 1962 raft and Falkland Islands shoreline pumices. There are also compositional differences between the dredge material, as demonstrated by Leat et al. (2007), and up to three discrete magmas are indicated (corresponding to pumice A, pumice B, and lava-like samples; Figure 3, S4). This is perhaps unsurprising as dredge DR.162 was

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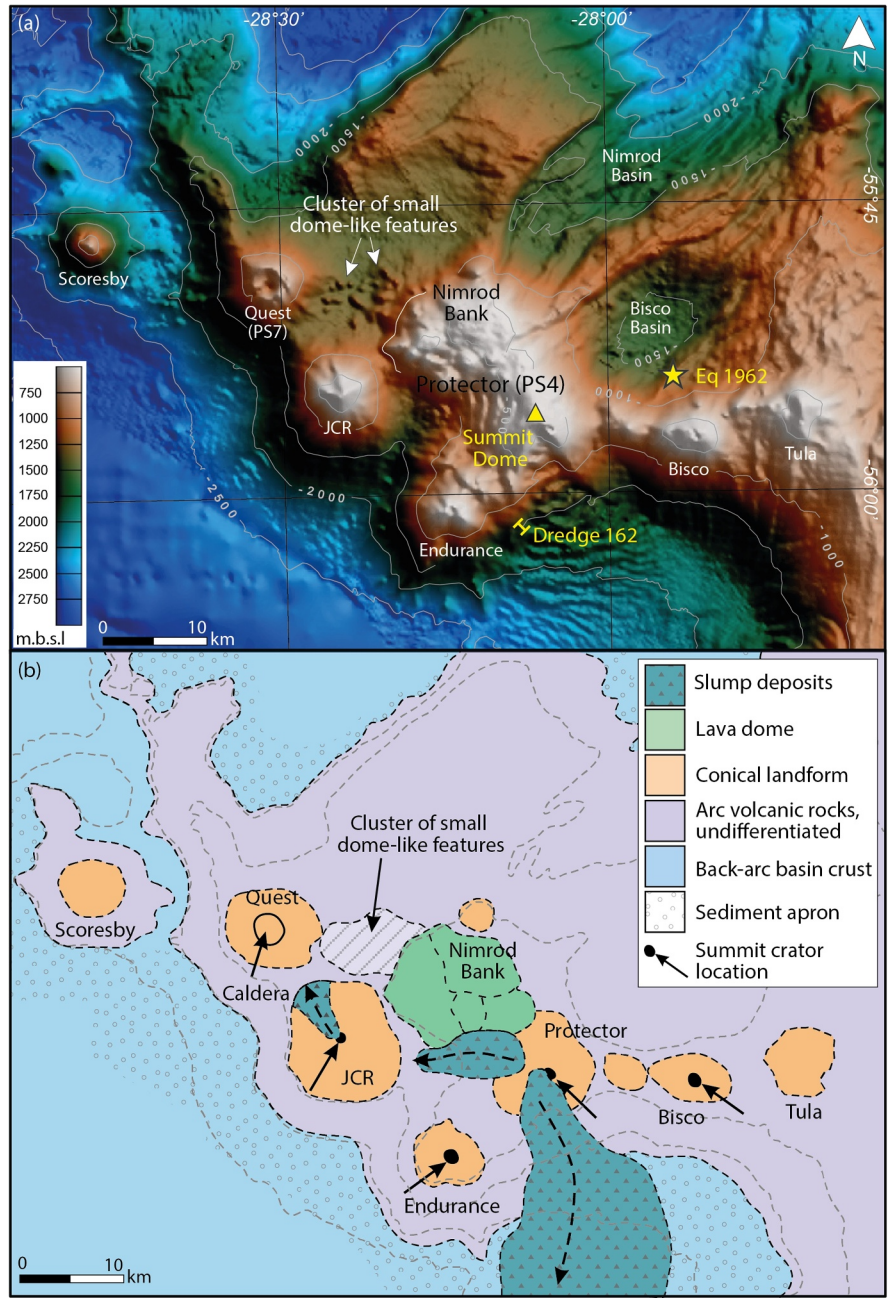

Figure 4. (a) Bathymetric map of Protector Shoal seamount showing the locations of the 14 March 1962 earthquake (Eq 1962; Gass et al., 1963; Leat et al., 2007) and Dredge DR.162 that was undertaken during the 1997 British Antarctic Survey Cruise of RRS James Clark Ross (Leat et al., 2007). (b) Geological sketch map of Protector Shoal seamount and surrounding area. Underlying bathymetric data taken from Leat et al. (2014).

taken from the margin of a major slump structure (Figure 4), where mass movements may have mixed pumice fragments from several previous eruptions. The precise age of these eruptions is unknown, but Leat et al. (2013) argued that the dredged samples must be <10,000 years old based on the absence of glacial dropstones. Given that these pumices were dredged from the present-day sea floor, a young age is likely, possibly in the order of centuries.

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3.2. Nature of Volcanic Eruptions on Protector Shoal

No eruptions have been observed on Protector Shoal and the nature of volcanism, whether effusive or explosive, is unknown. The 1962 pumice raft was produced during the only recorded eruption on the seamount and was implicitly assumed to be explosive in early studies (Gass et al., 1963). Recent swath bathymetry shows the surface of Protector Shoal seamount is dotted with dome-like and conical submarine features (Figure 4) interpreted as primary volcanic landforms (lava domes and small stratovolcanoes; Leat et al., 2010). The conical features are broadly circular in plan and have basal diameters of ∼5–7 km with relatively smooth upper slopes. The cones were previously thought to be too large for domes (Leat et al., 2010). Although generally true, some subaqueous domes, particularly if stacked (composite), can have similar diameters (up to 10 km; Stewart & McPhie, 2006; McIntosh et al., 2025). However, within the resolution limits of the swath image, many of the cone features have small summit craters ∼600–900 m in diameter (Figure 4) consistent with an explosive origin. By contrast, much of the shallow summit area, including Nimrod bank and Summit Dome, has a prominent rough surface, which contrasts with the smooth-surfaced conical landforms. Subaqueous domes are characterized by a distinctive uneven surface due to alternating massive and brecciated lithofacies, which gives them a high roughness (Carey et al., 2018; DeRita et al., 2001; Stewart & McPhie, 2006). It is therefore likely that the summit area of Protector Shoal seamount includes several large overlapping domes with basal diameters of ∼3–6 km (Figure 4).

Possible clues to the nature of eruptions on Protector Shoal seamount are also provided by the 1962 raft and dredged pumices. They include large clasts, up to 1.5 m across, formed of finely vesicular, pale-colored pumice (including tube pumice) and darker gray more coarsely vesicular examples; the two pumice types are sometimes interlayered and hence coeval (Gass et al., 1963). Pumices in dredge DR.162 (Leat et al., 2007) include a specimen with prominent relatively well-formed planar cooling fractures, giving it a well-formed prismatic shape *c*. 10 cm in diameter similar to columnar joints in water-quenched lavas (Figure S5 in Supporting Information S1). Gray lava-like clasts are also present in the DR.162 collection but are poorly vesicular (∼30%; Leat et al., 2007). Large pumices are also a conspicuous feature of the pumice blocks that were washed up on the beaches in the Falkland Islands (Lewis Clifton pers coms, 2024). Large pumices in subaqueous neptunian and effusive eruptions of silicic lavas and lava domes are highly vesicular, characterized by angular polygonal shapes caused by disintegration along cooling fractures, and they may have breadcrust textures, features not dissimilar to the large pumice block shown in Figure 2a (Stewart & McPhie, 2004; Allen et al., 2010; von Lichtan et al., 2016; Carey et al., 2018; Manga, Fauria, et al., 2018,Manga, Mitchell, et al., 2018; McIntosh et al., 2025).

It was surmised by HMS Protector (Gass et al., 1963) that the 1962 eruption probably took place on March 5th, coinciding (in timing but not in position; Gass et al., 1963; Leat et al., 2007) with a weak earthquake recorded at Protector Shoal (Figure 4). The shallow depths (to ∼30 m; Gass et al., 1963) and thus low water pressures above the summits of many of the sea floor features would have facilitated explosive eruptions probably Plinian or phreatoplinian (phreatomagmatic) in nature (e.g., Houghton et al., 2003) and consistent with the presence of summit craters of many of the conical edifices (Figure 4). Eruptions at those sites would result in a substantial subaerial eruption column that would probably have reached well above the tropopause, which is low in the South Polar region (>15 km; cf. Yoshida et al., 2022). Such a prominent column would have been visible from a long distance (>400 km). HMS Protector was within ∼200–250 km from Protector Shoal prior to and following March 5th during her transit to the southern South Sandwich Islands from South Georgia and an eruption column should have been visible. However, the region is frequently cloudy, which could have obscured the view, and the eruption (and plume) duration may have been short (e.g., less than a day perhaps only a few hours; Yeo et al., 2024). Given the large size of the pumice raft (∼0.6 km^3 of erupted pumice; Gass et al., 1963), there would conceivably have been substantial ash and lapilli fall on islands downwind of the eruption (e.g., Zavodovski and Visokoi, just 35–70 km distant from Protector Shoal, respectively), but none was seen although the islands were observed free of cloud and from a close distance (1–3 km). It is unclear whether shallow-subaqueous felsic eruptions with a substantial subaerial component create abundant large pumices, although falling into seawater might help preserve large clasts intact compared with subaerial settings, and such eruptions can generate pumice rafts (e.g., Houghton et al., 2003; Stewart & McPhie, 2004; Yeo et al., 2024). However, large pumices are a common, distinctive, and relatively widely dispersed feature associated with subaqueous felsic domes and nonexplosive (or weakly explosive) effusive eruptions of neptunian type (Stewart & McPhie, 2004; Allen & McPhie, 2009; von Lichtan et al., 2016; Carey et al., 2018; Manga, Fauria, et al., 2018,Manga, Mitchell, et al., 2018; McIntosh et al., 2025). It has also been suggested that highly vesicular giant pumice is diagnostic of subaqueous dome and low-intensity neptunian eruptions over a wide range of water depths (Allen et al., 2010;

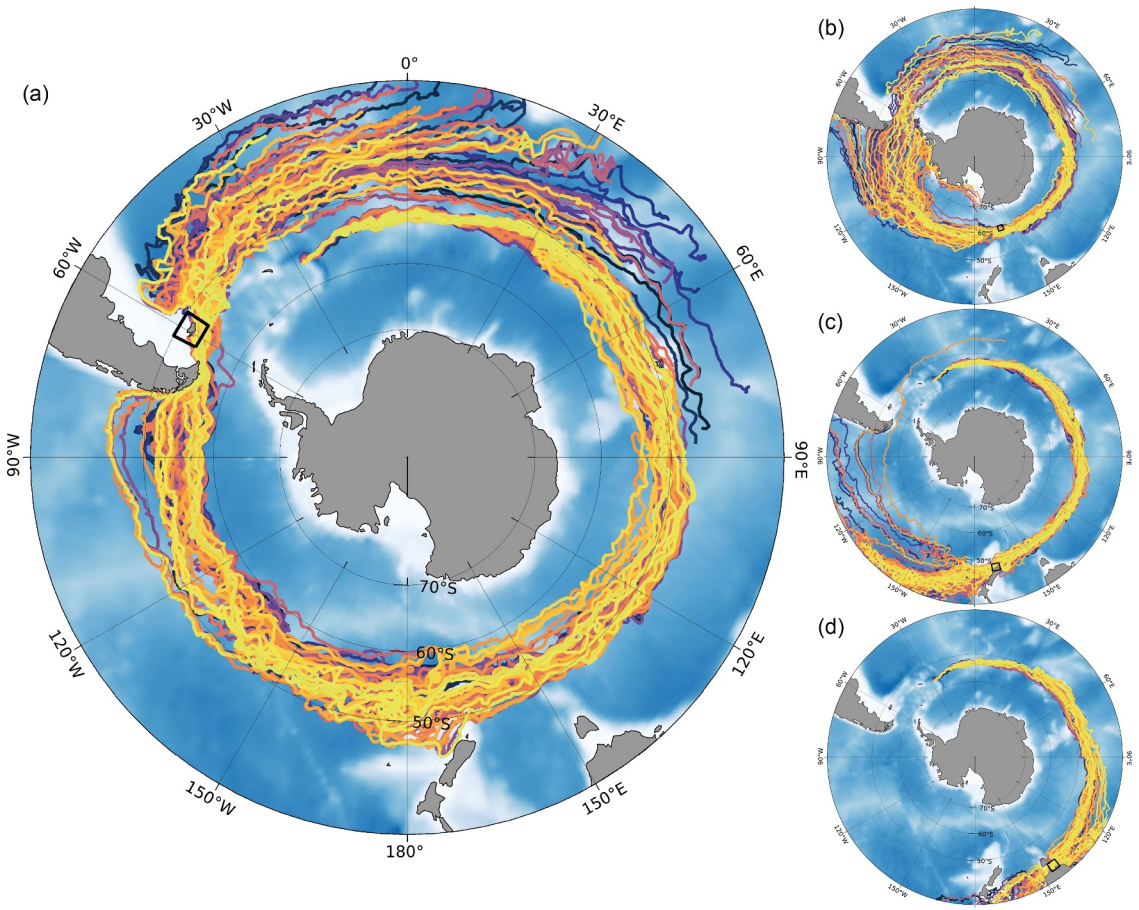

Figure 5. Modeled transport paths of pumice clasts from Protector Shoal seamount that reach (a) the Falkland Islands, (b) the 24th January 1964 observation point of HMNZS Piikai south of Macquarie Island in the Southern Ocean, (c) New Zealand, (d) Tasmania, Australia. Colored lines represent individual trajectories and background shading is bathymetry.

Allen & McPhie, 2009). For effusive submarine rhyolite eruptions, there is also commonly a close association with poorly vesicular clasts (Stewart & McPhie, 2004) as seen in the dredge DR.162 specimens.

We therefore suggest that, on an a priori basis, eruptions on the summit of Protector Shoal have probably included explosive events, of Plinian—phreatoplinian type with tall subaerial columns sourced from the shallow submerged summits of at least some of the numerous conical edifices. They were probably associated with pumice rafts with or without some large pumices. Highly vesiculated rhyolite magma was also erupted on the sea floor as submarine lava domes or perhaps during low-intensity neptunian eruptions. The quenched pumiceous surfaces of subaqueous domes fracture into prismatic columns, at least in part, and hot clasts rapidly become detached due to their buoyancy. Most rise to the surface, floating away as a pumice raft, whereas others become waterlogged and sink to the sea floor. The denser gray clasts may be fragments of less vesicular massive lava from underneath the pumiceous surface of a dome that were also quench fragmented but too dense to float and accumulated closer to source. During neptunian eruptions, pumiceous fragments also float to the surface of the sea to create prominent pumice rafts (Stewart & McPhie, 2004; Allen & McPhie, 2009; Manga et al., 2018a, 2018b). Therefore, at least three modes of subaqueous eruption have probably occurred on the summit of Protector Shoal: highly explosive (Plinian/phreatoplinian), dome-forming, and (possibly) neptunian. Protector Shoal is therefore likely to be volcanically quite diverse. The conspicuous presence of large pumices in the raft, dredged, and beach samples tends to favor an origin associated with dome-forming or neptunian eruptions particularly for the dredged samples, but the locations of the source vents remain uncertain. The geochemical evidence suggests that the products of at least three eruptions have been sampled in this study (Section 3.1) all of recent age.

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Table 1
Modeled Pumice Arrival Dates and Observed Pumice Arrival at Locations Within the Southern Ocean

Location	Model range	Model mean	Observation
Falkland Islands	27th June 1964–6th December 1965	12th March 1965	"Early 60s" (Lewis Clifton pers coms, 2024)
Southern Ocean	10th August 1963–16th February 1964	28th October 1963	24th January 1964 (HMNZS Piikai)
New Zealand	11th October 1963–13th July 1965	12th January 1964	January 1964 (Coombs & Landis, 1966)
Tasmania	25th September 1963–23rd September 1964	15th February 1964	Late December 1963–early January 1964 (Sutherland, 1965)

Note. Note that the 5–16th of March 2003 release date used in the oceanographic modeling has been commuted to 5–16th of March 1962 for comparison.

3.3. Pumice Transport Pathways

Lagrangian particle tracking experiments indicate the 1962 Protector Shoal raft circumnavigated Antarctica via the Antarctic Circumpolar Current, a journey of ~20,000 km (Figure 5). Comparison between model outputs and historical observations in Australia, New Zealand, and the Southern Ocean suggest that our global ocean-sea ice model is accurately estimating transport times (Table 1); in each case, the observation timing falls within the modeled range. Transport to the Falkland Islands likely took around 3 years (Table 1), although there is a degree of uncertainty in our modeled transport times due to choice of model parameterization and temporal variability in the underlying ocean flows (Table S1 in Supporting Information S2). For example, if windage is included in the model simulations, particles follow more southerly trajectories and transport times to the Falkland Islands are reduced. The role of windage in pumice clast advection depends on the extent to which the clast extends above the sea surface and hence its buoyancy. The latter likely varies over the course of the trajectory as the level of waterlogging increases, hence the role of windage likely reduces over time. Sensitivity experiments show that temporal variability in the underlying ocean flows impacts both the numbers of particles reaching the locations of historical observations and the transport times. However, despite these differences, particles consistently reach the Falkland Islands from Protector Shoal seamount in all simulations, suggesting a persistent long-distance connection (Table S2 in Supporting Information S2, Figure 5 and Figure S3 in Supporting Information S1). Such long-lived pumice rafts have not yet been directly observed (i.e., by remote tracking) as coherent rafts quickly break up and individual clasts are not visible to even the highest resolution satellites. However, pumice clasts from the eruptions of Volcán Barcena (1952) and Fukutoku-Oka-no-Ba volcano (2021) remained afloat for over a year (Ishimura & Hiramine, 2025; Richards, 1958) and long-lived floating particles can be replicated in laboratory experiments. For example, Mitchell et al. (2021) described clasts that remained floating for more than 5 years likely because of isolated gasses (Fauria et al., 2017; Takeuchi et al., 2024).

Our finding confirms the hypothesis of Risso et al. (2002) and indicates that material from the 1962 eruption of Protector Shoal seamount traveled further than any remotely tracked pumice raft or even any explosively erupted terrestrial tephra (Ponomareva et al., 2015). The results highlight the potential for pumice rafting to disperse non-native, potentially invasive, marine organisms throughout the Southern Ocean (e.g., bivalves, molluscs, gastropods, sponges, bryozoans, and echinoderms; Bryan et al., 2012). Kelp rafts and other floating debris provide similar opportunities for dispersal and can transport organisms across several oceanographic barriers (Dawson et al., 2024; Fraser et al., 2018). Biological debris may represent a less substantial threat to native species than pumice rafts, however, as they have limited lifespans, typically sinking within six-to-eight weeks (Graiff et al., 2016). Pumice rafts provide rare high-magnitude rafting opportunities for marine taxa simply because of the sheer volume and number of clasts that may be produced during an eruption—every one of which represents a possible raft (although note that there is a wide range of sinking timescales—from minutes to years). For example, Bryan et al. (2012) estimated the number of pumice clasts produced during the Volcanic Explosivity Index 2–3 (0.16 km^3 magma) 2012 Home Reef eruption to have been $>2.5 \times 10^{12}$. Although the extreme climates of sub-Antarctic islands and Antarctic coastlines have protected high levels of species endemism, a warming climate may leave these areas vulnerable to colonization by future rafted organisms (Duffy et al., 2017). While it is difficult to mitigate for volcanic events, any pumice rafting event should be closely monitored in areas of high species endemism such as Antarctica.

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4. Conclusions

Major-minor-trace element analyses show that rhyolitic pumice clasts collected from Falkland Islands shorelines were derived from the 1962 eruption on Protector Shoal seamount in the South Sandwich Islands. Dredged pumice samples from Protector Shoal seafloor have different elemental compositions and represent products of previous eruptions. A priori assessment suggests at least three discrete styles of submarine eruptions have taken place on Protector Shoal seamount: Plinian—phreatoplinian from the shallow summits of smooth-flanked conical landforms; lava domes represented by rough-surfaced oblate landforms and possibly neptunian. The Protector Shoal seamount is therefore more volcanically diverse than previously thought. Oceanographic particle tracking experiments are consistent with historical observations and indicate the 1962 Protector Shoal raft circumnavigated Antarctica via the Antarctic Circumpolar Current, a journey of ~20,000 km that took approximately three years. Our quantitative modeling results confirm that Risso et al. (2002) were correct in their assessment that pumice clasts collected from shorelines on either side of the Drake Passage were derived from Protector Shoal seamount, and that they had reached these locations via the Antarctic Circumpolar Current. Together, these findings show that pumice rafts can disperse potentially invasive marine organisms throughout the Southern Ocean.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The complete EMPA and LA-ICP-MS data set, including secondary standards, is available in Supporting Information S1. The ocean model output used for the particle tracking experiments is available from the COSIMA data collection; https://doi.org/10.25914/608097cb3433f (experiment '01deg_jra55v140_iaf'). Stokes drift velocities estimated by WAVEWATCH III are available from https://ftp.ifremer.fr/ifremer/ww3/HINDCAST/GLOBAL/. The trajectory data for all particle tracking experiments, including the sensitivity tests, are available on Zenodo (https://zenodo.org/records/17613163).

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