Distal ash fall from the mid-Holocene eruption of Mount Hudson (H2) discovered in the Falkland Islands: new possibilities for Southern Hemisphere archive synchronisation

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Abstract

Cryptotephra deposits (microscopic volcanic ash) are important geochronological tools that can be used to synchronize records of past environmental change. Here we report a distal cryptotephra from a Holocene peat sequence (Canopus Hill) in the Falkland Islands, in the South Atlantic. Using geochemical analysis (major- and trace-element) of individual volcanic glass shards, we provide a robust correlation between this cryptotephra and the large mid-Holocene explosive eruption of Mt. Hudson in Patagonia, Chile (H2; ~3.9 ka cal BP). The occurrence of H2 as a cryptotephra in the Falkland Islands significantly increases the known distribution of this marker horizon to more than 1200 km from the volcano, a threefold increase of its previous known extent. A high-resolution radiocarbon chronology, based on terrestrial plant macrofossils, dates the H2 tephra to 4265 ± 65 cal yr BP, suggesting that the eruption may have occurred slightly earlier than previously reported. The refined age and new geochemical reference dataset will facilitate the identification of the H2 tephra in other distal locations. The high concentration of glass shards in our peat sequence indicates that the H2 tephra may extend well beyond the Falkland Islands and we recommend future studies search for its presence across the sub-Antarctic islands and Antarctic Peninsula as a potentially useful chronological marker.

Keywords: South America, cryptotephra, tephrochronology, Patagonia, Southern Volcanic Zone, Hudson, South Atlantic, Southern Ocean, Antarctic,

1. Introduction

Volcanic ash (tephra) dispersed from explosive volcanic eruptions has become a principal geochronological tool for correlating environmental records (e.g., Alloway et al., 2013; Lane et al., 2017). The near instantaneous deposition of tephra over large distances and its often-unique chemical signature allows tephra layers to provide time-parallel marker horizons (isochrones) (Turney and Lowe, 2001). Tephra isochrones can be used to synchronize records of past environmental change between sites and represent one of the most robust and versatile dating methods (Lowe 2011). The application of tephra isochrones has been extended to include microscopic ash deposits (cryptotephras) which have been found in distal areas thousands of kilometres from source volcanoes (e.g., Dugmore, 1989; Wastegård et al., 2000; Dunbar et al., 2017; Kearney et al., 2018; Smith et al., 2020).

Despite the value that tephrochronology offers as a powerful geochronological tool, the technique has been underutilized in many regions. One such area is the South Atlantic, a region that owing to the prevailing mid-latitude westerly airflow, is favourably positioned downwind from the major volcanic zones (AVZ and SVZ; Austral and Southern Volcanic Zones) of southern South America **(Fig. 1)**. Explosive volcanism is known to have occurred frequently at numerous volcanoes along these zones throughout the Holocene, including Mts. Burney, Aguilera and Reclus within the AVZ and Mt. Hudson in the SVZ (**Fig. 1a;** Stern, 2008; Fontijn et al., 2014). Tephras from these volcanic centres have previously been identified in lakes and peat bogs throughout southern Patagonia (Killian et al., 2003; Weller et al., 2015; Fontijn et al., 2016; Smith et al., 2019). Only a limited number of cryptotephra deposits originating from Patagonian explosive volcanism have previously been reported in peat bogs across the Southern Atlantic, including the Falkland Islands and South Georgia (Hall et al., 2001; Oppedal et al., 2018), with the most recently identified linked to eruptions at Mt. Burney (MB_1; 8.85-9.95 ka cal BP) and the Reclus Volcano (R_1; 14.76 ± 0.18 ka cal BP (Monteath et al., 2019; Stern et al., 2011).

Tephrochronology studies in this region offer potential for the alignment of proxy reconstructions investigating climate and environmental change, including Southern Hemisphere westerly wind flow (Kilian and Lamy, 2012; Moreno et al., 2014; Lamy et al., 2010). Unfortunately, few distal tephras (>100 km) have been described in this region and the precise ages and distribution of key marker horizons remain uncertain. Here we present the results of new tephrostratigraphic investigations of the Canopus Hill peat sequence in the

Falkland Islands **(Fig. 1b)**, with a focus on the provenance and significance of a mid-Holocene cryptotephra identified in the succession.

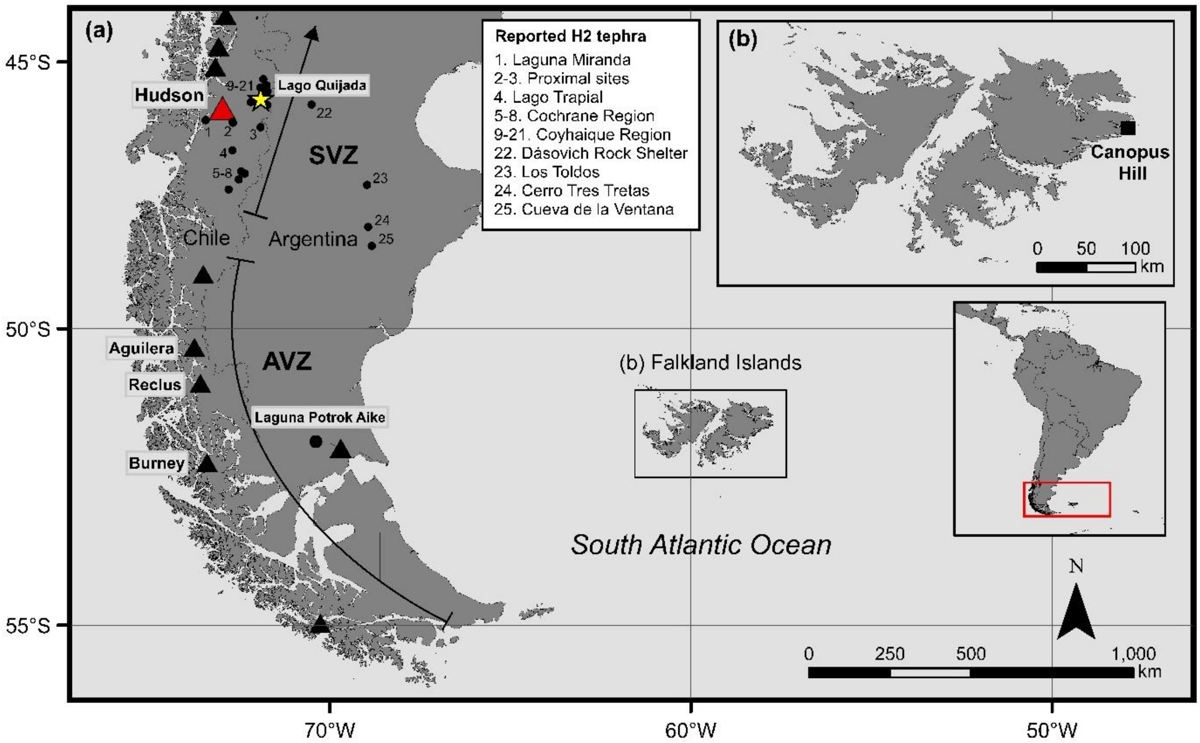

Figure 1. Patagonia in southern South America depicting (a) the volcanoes (triangles) known to have erupted during the Holocene (Global Volcanism Program 2020) from the Austral and Southern Volcanic Zones as defined by Stern (2004). (b) Location of the Falkland Islands and study site at Canopus Hill. Black dots represent locations where H2 tephra has been reported **(Table S1)**. (1) Haberle and Lumley, 1998; (2-3) Naranjo and Stern, 1998; (4) Fagel et al., 2017; (5-8) Stern et al., 2016; Fagel et al., 2017; (9-21) Weller et al., 2015; Markgraf et al., 2007; Weller et al., 2018; Elbert et al., 2013; Weller and Stern, 2018; (22) Stern et al., 2019; (23) Cardich, 1984-1985; (24) Paunero, 1993-1994; (25) Paunero, 2000.

2. Study Area and Methods

2.1 The Falkland Islands and the Canopus Hill sequence

The Falkland Islands are situated in the South Atlantic, 540 km east of the South American coast. The islands lie in the central latitudinal belt of the southern westerly winds (SWW) and have high monthly and annual windspeeds (6-9 ms^{-1}) (Upton and Shaw, 2002; Clark and Wilson, 1992). Peat bogs cover more than ~85% of the Falkland Islands and are ideal archives to trap and preserve volcanic ash (Otley et al., 2008). The combination of the prevailing airflow and abundance of peat makes the Falkland Islands ideally positioned to receive and preserve tephras from the major volcanic zones in South America **(Fig.1)**. Observations of modern volcanic eruptions suggest Patagonian ash fall has been deposited over the Falkland Islands, including ash from the 1991 Hudson eruption plume (Scasso et al., 1994; Kratzman et al., 2010).

To investigate the presence of distal cryptotephra, a 1.6 m peat sequence was extracted with a D-section corer from an exposed Ericaceous–grass peatland on Canopus Hill (-51.691° S, 57.785 ° W) outside Port Stanley. Previous research at this site recognised the input of exotic pollen and charcoal derived from South America (Turney et al., 2016), as well as a multi-proxy reconstruction of atmospheric circulation changes (Thomas et al., 2018).

2.2 Tephrostratigraphy

The Canopus Hill peat sequence contained no visible tephra layers. The sequence was sampled contiguously every 4 cm. Peat from each interval was ashed at 550°C using an adopted method to concentrate any present cryptotephra (Dugmore, 1989; Pilcher and Hall, 1992). The mineral component was sieved (90 to 25 μm), centrifuged and mounted onto glass slides with Canada balsam. Glass shards were counted using a light microscope. The concentration of volcanic ash shards was determined as shard number per gram of dry sediment. This process was repeated at 1cm intervals where high concentrations of glass shards were detected to determine the exact depth of the cryptotephra peak. The depth interval displaying a peak in volcanic glass shards was then re-sampled and subjected to density separation techniques to isolate the shards (as described in Blockley et al., 2005). The glass shards were then picked using a micromanipulator and bedded into an epoxy resin stub for geochemical characterization.

2.3 Grain-specific major and trace element analysis of tephra

The major element volcanic glass composition of the tephra was determined using a wavelength-dispersive JEOL JXA-8200 electron microprobe at the School of Archaeology, University of Oxford. Full analytical conditions are reported in **Text S1**. All glass data presented has been normalised to 100 wt% for comparative purposes. Error bars on plots represent reproducibility, calculated as a 2x standard deviation of replicate analysis of MPI-DING StHs6/80-G reference glass (Jochum et al., 2006). The full glass dataset of the Canopus Hill cryptotephra and the secondary standard (MPI-DING reference glasses) data are reported in the **Supplementary Dataset.** Trace element analysis of volcanic glass shards from the Canopus Hill cryptotephra, and the Hudson 2 reference ash deposit from Lago Quijada, Chile (see Smith et al., 2019 for details) were performed using an Agilent 8900 triple quadrupole ICP-MS (ICP QQQ) coupled to a Resonetics 193nm ArF excimer laser-ablation in the Department of Earth Sciences, Royal Holloway, University of London. The full analytical conditions are reported in **Text S1**. Full trace element glass datasets for the Canopus Hill cryptotephra and a Hudson 2 reference sample from Lago Quijada are provided in the **Supplementary Dataset**, along with the MPI-DING glass analyses (StHs6/80-G and ATHO-G).

2.4 Chronology

Radiocarbon ages for the Canopus Hill peat sequence have previously been published by Thomas et al., (2018). These dates were derived using terrestrial plant macrofossils (fruits and leaves) and were given an acid–base–acid (ABA) pre-treatment. Samples were pretreated, combusted and graphitised in the University of Waikato AMS laboratory, and the $^{14}C/^{12}C$ measurements were performed at the University of California at Irvine (UCI) on a NEC compact (1.5SDH) AMS system. The ^{14}C measurements were supplemented by ^{137}Cs measurements near the top of the profile to detect the onset of nuclear tests in the mid- 20th century. An additional macrofossil sample (graminoid fragments) was extracted for ^{14}C dating from the sequence at 134 cm, to help constrain the existing age-depth model. The macrofossil was pre-treated, graphitised and measured on an Ionplus MICADAS at the University of New South Wales Chronos ^{14}Carbon-Cycle Facility (Turney et al., in press). The additional ^{14}C date was added to the Bayesian age depth model and re-calibrated using SHCal20 (Hogg et al., 2020) and Bomb13SH1-2 (Hua et al, 2013). All radiocarbon ages for Canopus Hill are provided in **Table S2**.

3. Results and discussion

3.1 Tephrostratigraphy

Volcanic glass was found in varying abundances throughout the Canopus Hill sequence. Most shards were clear and appeared light pink, but a smaller proportion were darker. A distinct peak in volcanic glass occurred within the 136-140 cm and 140-144 cm intervals of the peat sequence **(Fig. 2a; Fig S1)**. These intervals contained very high concentrations (>40,000 shards per gram) of clear/light pink volcanic glass shards. Further examination at 1 cm resolution indicated the peak in glass shards occurred between 139-140 cm **(Fig 2b.)**. The morphology of the shards at 139 cm were predominantly formed of clear, platy and cuspate shards. The age depth model for the Canopus Hill sequence, indicates the age of this cryptotephra deposit is 4265 ± 65 cal yrs BP **(Fig 3)**, based off the midpoint of the cryptotephra at 139.5 cm.

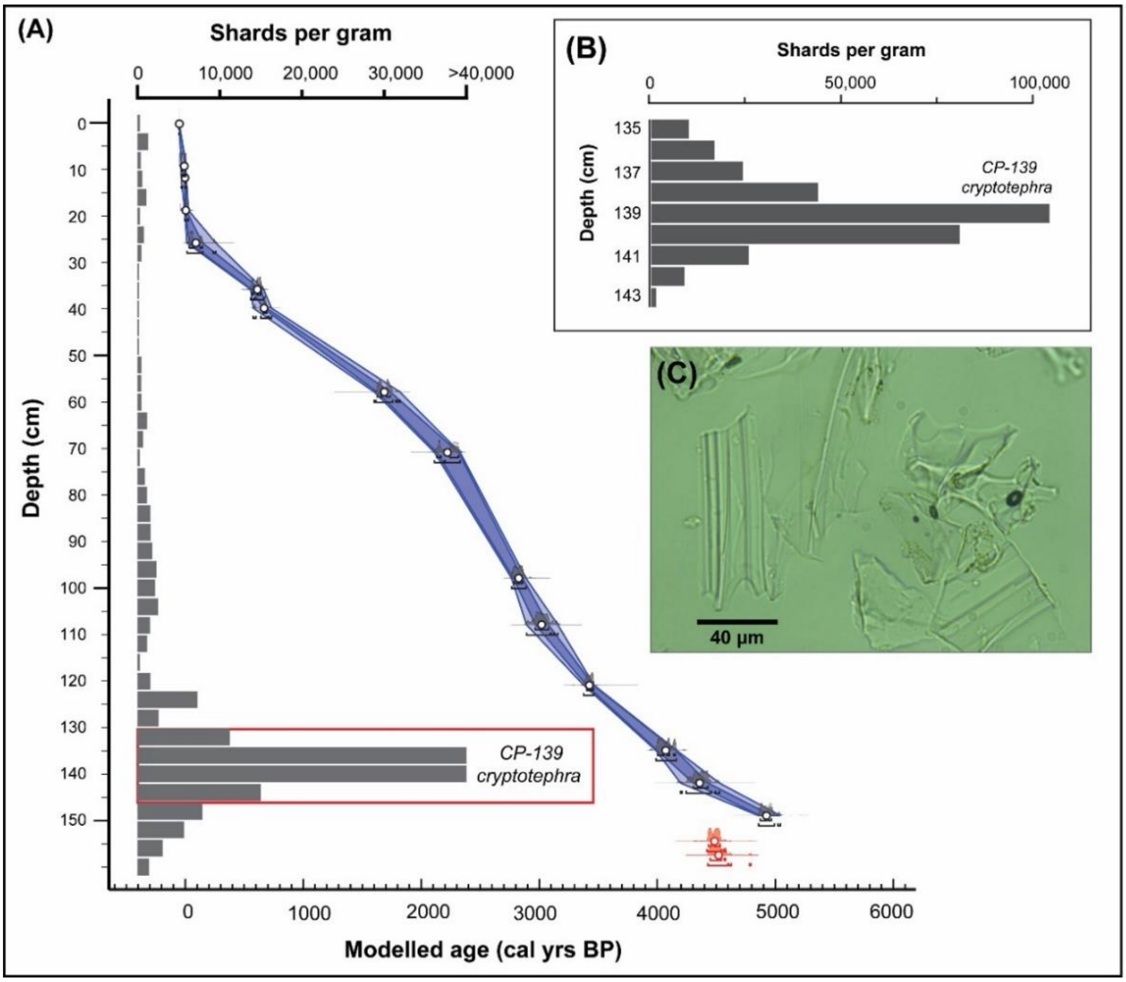

Figure 2. Tephrostratigraphy of the Canopus Hill sequence. (A) Glass shard concentrations of samples spanning 4 cm intervals from 0-164 cm and the updated age depth model for the Canopus Hill peat sequence (Thomas et al., 2018). The P_sequence and "outlier analysis" options were used to develop the age depth model in OxCal 4.4 (Bronk Ramsey, 2008; Bronk Ramey, 2009; Bronk Ramsey and Lee, 2013; Bronk Ramsey, 2017). (B) The glass shard concentrations between 135-143 cm at 1 cm intervals. (C) Image of volcanic shards from the CP-139 cryptotephra (light microscope, 20x magnification).

3.2 Geochemical characterization and origin of the CP-139 cryptotephra

The CP-139 cryptotephra has a relatively heterogeneous volcanic glass composition that straddles the trachydacite-rhyolite boundary (67.3-70.6 wt.% SiO_2; 8.9-9.7 wt.% Na_2O+K_2O; **Fig. 3a**). These volcanic glasses also display a High-K calc-alkaline affinity (HKCA; 3.2-3.6 wt.% K_2O). Using increasing SiO_2 as a fractionation index, the CP-139 glasses display a clear decrease in TiO_2, FeOt, MgO and CaO contents, whilst the K_2O content increases.

Incompatible trace element contents of the CP-139 glasses reveal minor heterogeneity (e.g., 458-534 ppm Zr; 40-46 ppm Y; 891-946 ppm Ba) and show Light Rare Earth Element (LREE) enrichment relative to the Heavy Rare Earth Elements (HREE) ($La/Yb = 9.6 \pm 4.7$ [2.s.d]).

The SiO_2 content of the CP-139 glass shards is relatively low compared to those of known widespread tephra units from large magnitude eruptions within the AVZ, for instance activity at Mt. Burney, Reclus and Aguilera **(Fig. 3).** Furthermore, widespread tephras from Mt. Burney and Reclus consist of glass compositions with a calc-alkaline affinity (CA; Smith et al., 2019) inconsistent with the source of the CP-139 tephra. Further north in the SVZ of the Andes, a number of volcanoes active during the Holocene have erupted HKCA deposits, including Quatrupillian, Sollipuli and Lanín (Fontijn et al., 2016). However, chronological inconsistency combined with a clear offset to higher Na_2O content in the CP-139 glass shards, relative to the products of these volcanoes at overlapping SiO_2 content, clearly preclude any potential correlations.

The CP-139 glass shards are indistinguishable at a major element level from the HKCA products of Hudson volcano in the SVZ, and specifically the mid-Holocene Hudson-2 (H2) that was chemically characterised in Smith et al., (2019). Near-source (55 km NE) H2 major element glass data reported in Smith et al., (2019) was generated from ash layers preserved in Lago Quijada and Lago Espejo that were identified by Weller et al., (2015). To test the strength of our major element correlation, we compared trace elements concentrations from CP-139 glass shards to new grain-specific data produced here for the H2 tephra at Lago Quijada. Trace element concentrations observed in CP-139 are consistent with the H2 tephra at Lago Quijada (**Fig. 4**) and can be clearly distinguished from the less enriched incompatible trace element contents (e.g., Th, Y, Zr) of widespread tephra units erupted within the AVZ (De Carlo et al., 2018).

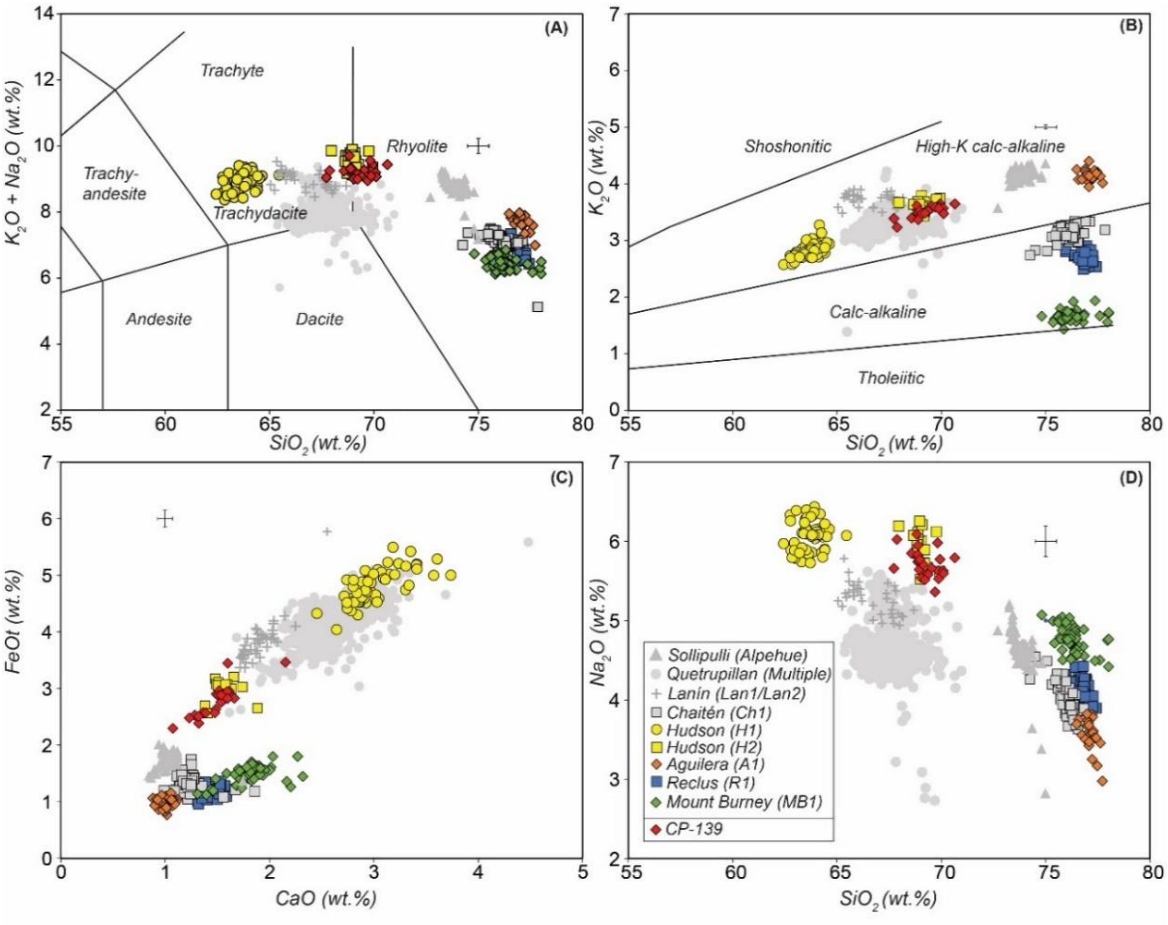

Figure 3. Major element biplots comparing major elements of individual glass shards of CP-139 cryptotephra and widespread Holocene-Late Glacial tephra units originating from the volcanoes of the AVZ (Mt. Burney [MB1], Reclus [R1] and Aguilera [A1]) and the SVZ, (Hudson-1 [H1] and Hudson-2 [H2]) (data from Smith et al., 2019). Also shown are glass compositions of HKCA tephra layers from volcanoes located further north in the Southern Volcanic Zone including Chaitén, Lanín, Quetrupillan and Sollipulli (Fontijn et al., 2016). (A) Total alkali vs. Silica diagram follows Le Bas et al., (1986) and (B) SiO_2 vs K_2O classification diagram following Percerillo and Taylor (1976). Glass data presented has been normalized to 100 wt%, and error bars represent 2 standard deviations of repeat analyses of the StHs6/80-G secondary standard.

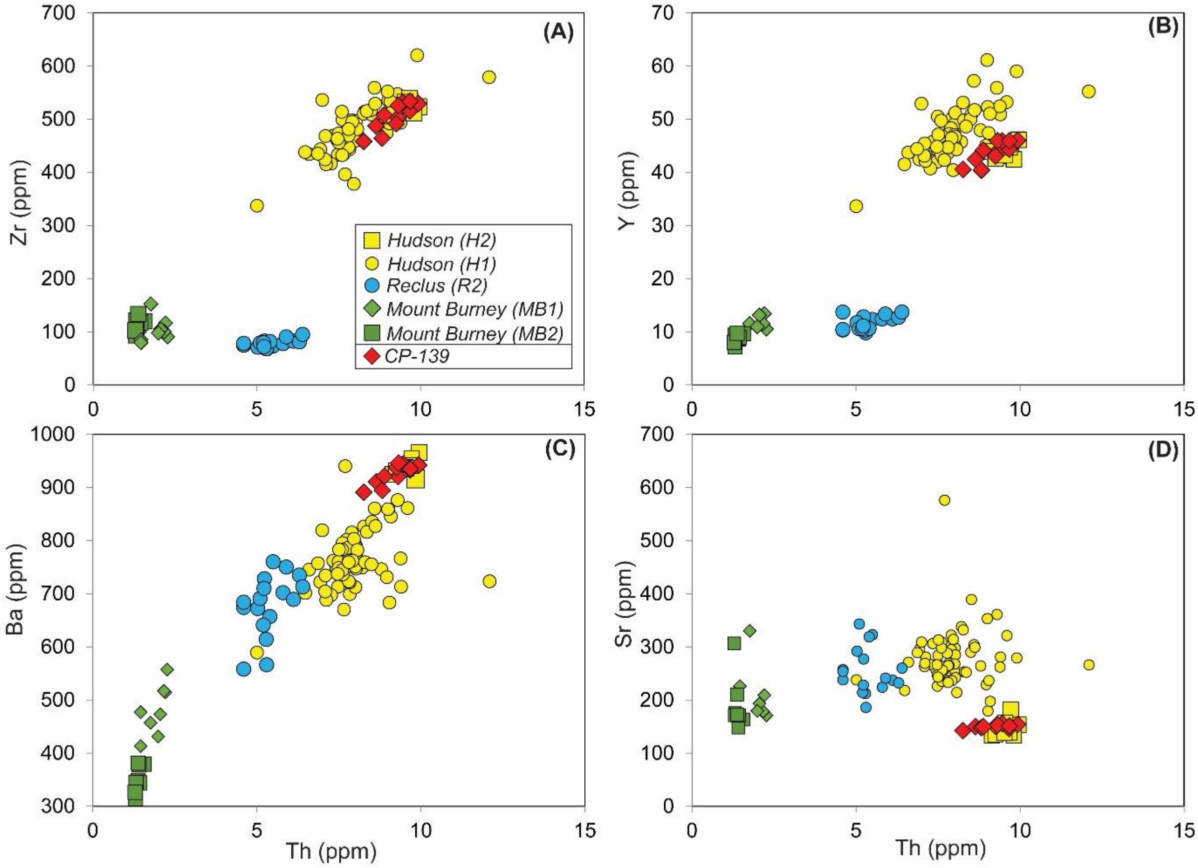

Figure 4. Trace element biplots showing the concentrations of individual glass shards from the CP-139 cryptotephra (Falkland Islands), the mid-Holocene Hudson-2 (H2; Lago Quijada). Also shown are the trace element concentrations of the Hudson-1 (H1), Mt. Burney-1 (MB1), Mt. Burney-2 (MB2), and Reclus-2 (R2) tephra deposits, which relate to the Del Carlo et al., (2018) EO-2L, EO-2D, EO-1b and LA-IB samples. 2 x standard deviation error bars associated with repeat analyses of the StHs6/80-G secondary standard run alongside the CP-139 and H2 samples are typically smaller than the data symbols.

3.3 Implications

3.3.1 Distribution of the H2 tephra

The occurrence of H2 as a cryptotephra in the Falkland Islands (1280 km SE of Mount Hudson) significantly extends the previously known distribution of this marker horizon (Fig 1). The first detailed report of H2 deposits by Naranjo and Stern (1998) showed an easterly dispersal with thicknesses that ranged from 40 cm at 55 km from the volcano, to <5 cm at 90 km from Mt. Hudson. H2 is widespread (>10 cm-thick) near the city of Coyhaique (80 km NE; sites 9-21 in Fig. 1) and has been reported 140 km to the SSE near Cochrane (<2 cm-thick; sites 5-8 in Fig. 1). H2 tephra has also been reported (>5 cm thick layers) at several distant sites, including the Los Toldos, Cerro Tres Tetas and Cueva de la Ventana archaeological sites 350 to 430 km SE (sites 23-25 in Fig. 1).

3.3.2 Dispersal and spatial extent of the H2 tephra

The occurrence of H2 ash in the Falkland Islands also indicates that the widespread distribution of H2 ash by high altitude winds may have been in a more SE direction than previously reported. According to Naranjo and Stern (1998), the dispersal axis of tephra fall from the H2 eruption, inferred from near-source deposits, was predominantly in an easterly direction (N85°E). Distal transport of volcanic ash towards the Falkland Islands (SE) may therefore seem inconsistent with this dispersal axis. However, distal transport to the SE is also supported by the reported H2 occurrences in the localities of Los Toldos, Cerro Tres Tetas and Cueva de la Ventana (Fig. 1). These sites are also directly in line with the SE distribution of the Hudson 1991 tephra (Scasso et al., 1994). H2 deposits at these sites are > 5cm, which is similar to or greater than the thickness of the 1991 tephra that fell at these localities, according to the isopachs drawn by Scasso et al., (1994). This and the occurrence of H2 ash in the Falklands suggests that distal distribution of H2 tephra to the SE was as great, if not greater than during the 1991 eruption.

Dispersal mechanisms and synoptic wind conditions similar to those observed during the 1991 Hudson eruption may also help explain the delivery of H2 ash fall to the Falkland Islands. Satellite observations and simulations of phase II of the 1991 eruption indicate the ash plume was initially directed to the south before moving to the east and settling into a fixed SE direction (Kratzmann et al., 2010; Constantine et al., 2000). At its peak, the plume was elongated (1500 km SE) and reached a width of 370 km over the Falkland Islands (Scasso et al., 1994). High velocity westerly winds in the jet stream resulted in a relatively confined plume and long-range distal transport of ash (Scasso et al., 1994). Similar mechanisms observed during the 1991 eruption may account for both an easterly dispersal axis near the source and long-range distal southern transport of fine H2 ash over the Falkland Islands. Given the high concentrations of glass shards, H2 tephra is likely to be present throughout South Eastern Patagonia and may even extend to the Southern Ocean and the fringes of Antarctica as a cryptotephra.

3.3.3 Age of the H2 eruption

According to our age-depth model, the H2 tephra is slightly older (4265 ± 65 cal BP) than previously reported age estimates (Naranjo and Stern, 1998). Our age depth model derived from terrestrial plant macrofossils likely provides a more accurate age for the H2 eruption. Dating short-lived terrestrial plant remains ensures that the assimilated atmospheric CO_2 is near-contemporaneous with the terrestrial environment, reflecting time of deposition (Lowe and Walker, 1997; Turney et al., 2000). In addition, a site location with minimal opportunities for redeposition such as a local topographic peak (e.g. Canopus Hill) provides an important basis of a robust chronology (Thomas et al., 2019).

In contrast, bulk sediment, that forms the majority of previous dating, may incorporate root material or downward vertical migration of microfossils by water movement/flow, both of which would result in a younger radiocarbon age determination. The commonly cited age of the H2 eruption (3600 BP; ~3.9 ka cal BP) was derived from ^{14}C ages of organic soil, sediment and bulk peat bracketing the tephra (Naranjo and Stern, 1998; Weller et al., 2018). Other age-estimates of the H2 eruption have been extrapolated from lake sediment cores using bulk radiometric dates and the total organic fraction of bulk sediment samples (e.g. Haberle and Lumley, 1998; Elbert et al., 2013).

Given this older age of 4265 ± 65 cal BP, the H2 tephra may provide a key marker horizon for the Middle–Late Holocene Boundary (4.2 ka BP; Walker et al., 2012), an important climatostratigraphic boundary for which there are limited absolute time markers across the Southern Hemisphere. In South America, it marks the end of a period of widespread aridity that resulted in population decline and/or collapse (Riris and Arroyo-Kalin, 2019). The H2 cryptotephra may therefore provide an important isochron for terrestrial and marine studies across Patagonia and Tierra del Fuego during a period of significant palaeoclimatic and prehistoric societal change across this region.

4. Conclusion

The identification of a distal trachydacite-rhyolitic cryptotephra (CP-139) from the H2 eruption in the Falkland Islands greatly increases the previously known distribution of this key marker horizon. The high concentration of glass shards in our peat sequence suggests that the tephra may be more widespread than presently understood and may serve as an important isochron for the South Atlantic Ocean and also possibly Antarctica. Our reference dataset of major and trace element glass composition can be used to identify the H2 tephra in other distal locations and is an important contribution in the development of a regional framework for the tephrostratigraphy of Patagonia. Finally, this research sets a precedent for further work into identifying South American cryptotephra in the sedimentary records of the Falkland Islands.

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Supporting Information

Figure S1. Light microscope image of volcanic tephra shards from Canopus Hill (136-140 cm). Scale bar = 50 μm

Table S1. Summary of previously reported H2 tephra.

Table S2. The chronological framework for the Canopus Hill peat sequence updated from Thomas et al., (2018). Radiocarbon and modelled calibrated age ranges for the Canopus Hill peat sequence.

Text S1. Major and trace element analysis of volcanic glass.

Supplementary Data

Glass compositional data, including means and two standard deviations, for both sample and secondary glass standard measurements.

DOI will be created for the supplementary data upon submission

Declaration of competing interests

The authors declare no competing interests.

Author contributions

P. Panaretos: Conceptualization, Investigation, Data collection and Analysis, Writing – original draft.

P. G. Albert: Conceptualization, data analysis, methodology, Writing - review & editing

Z. A. Thomas: Conceptualization, Supervision, Data analysis, Writing – review & editing

C. S.M. Turney: Conceptualization, Methodology, Supervision, Writing – review & editing

G. Jones: Data collection and analysis, Writing – review & editing

C. R. Stern: Data collection , resources, Writing - review & editing

A. N. Williams: Data collection, Writing - review & editing

V. C. Smith: Data collection, Writing - review & editing

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C. J. Manning: Data collection, Writing - review & editing

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