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First identification and characterization of Borrobol-type tephra in the Greenland ice cores: new deposits and improved age estimates

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ABSTRACT: Contiguous sampling of ice spanning key intervals of the deglaciation from the Greenland ice cores of NGRIP, GRIP and NEEM has revealed three new silicic cryptotephra deposits that are geochemically similar to the well-known Borrobol Tephra (BT). The BT is complex and confounded by the younger closely timed and compositionally similar Penifiler Tephra (PT). Two of the deposits found in the ice are in Greenland Interstadial 1e (GI-1e) and an older deposit is found in Greenland Stadial 2.1 (GS-2.1). Until now, the BT was confined to GI-1-equivalent lacustrine sequences in the British Isles, Sweden and Germany, and our discovery in Greenland ice extends its distribution and geochemical composition. However, the two cryptotephras that fall within GI-1e ice cannot be separated on the basis of geochemistry and are dated to 14358 ± 177 a b2k and 14252 ± 173 a b2k, just 106 ± 3 years apart. The older deposit is consistent with BT age estimates derived from Scottish sites, while the younger deposit overlaps with both BT and PT age estimates. We suggest that either the BT in Northern European terrestrial sequences represents an amalgamation of tephra from both of the GI-1e events identified in the ice-cores or that it relates to just one of the ice-core events. A firm correlation cannot be established at present due to their strong geochemical similarities. The older tephra horizon, found within all three ice-cores and dated to 17326 ± 319 a b2k, can be correlated to a known layer within marine sediment cores from the North Iceland Shelf (ca. 17179-16754 cal a BP). Despite showing similarities to the BT, this deposit can be distinguished on the basis of lower CaO and TiO2 and is a valuable new tie-point that could eventually be used in high-resolution marine records to compare the climate signals from the ocean and atmosphere.

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KEYWORDS: Borrobol; cryptotephra; Greenland ice cores; isochron; Penifiler.

Introduction

Tephrochronology has long been established as a tool that exploits ash deposits with unique geochemical fingerprints to precisely correlate a diverse range of palaeoarchives from widely separated localities (e.g. Lowe, 2011). Tephra deposits are preserved in a wide range of depositional environments including marine, ice and terrestrial records and thus have the potential to give rise to valuable time-synchronous horizons (e.g. Lane et al., 2013). Over the last few decades, the scope of this technique has changed considerably through the investigation of cryptotephra deposits that are invisible to the naked eye and can only be detected by employing microscopy techniques (e.g. Davies, 2015). Cryptotephra investigations in Greenland have highlighted the value of polar ice cores as volcanic ash repositories and the potential of bearing isochronous horizons for synchronizing the ice to other palaeoarchives (e.g. Grönvold et al., 1995; Mortensen et al., 2005; Davies et al., 2008, 2010; Abbott and Davies, 2012; Bourne et al., 2015, 2016).

Many Lateglacial tephra deposits identified in European terrestrial records, however, have not yet been identified in the ice. Here we target our searches to identify the Borrobol (BT) and Penifiler (PT) cryptotephras in the Greenland ice cores. Both are distinguishable from other Lateglacial cryptotephras by low FeO and TiO2 and high MnO content and are found exclusively in terrestrial deposits in the North Atlantic (NA) region. The BT and PT are close in age and composition and, as a result, present problems for correlation purposes (see Lind et al., 2016 for a summary of BT and PT findings in NA records). The BT was first identified in three Scottish palaeolakes, Borrobol Bog, Tynaspirit West and Whitrig Bog by Turney et al. (1997) in early Lateglacial Interstadial sediments (probably analogous to Greenland Interstadial 1e (GI-1e) in Greenland or Bølling in Scandinavia) and was subsequently thought to have been identified at Håssedal port and Skallhult in Sweden by Davies et al. (2003) (see Fig. 1 for site locations). However, with a new pollen stratigraphy and age estimates, Davies et al. (2004) showed that the horizon identified in Håssedal port is associated with Older Dryas sediments (probably analogous to the short-lived GI-1d cold event in Greenland). This discovery was inconsistent with the Scottish occurrences that were associated with older Lateglacial interstadial sediments (analogous to the warmer GI-1e) and prompted Davies et al. (2004) to propose that two tephras with identical geochemistry were deposited during GI-1. Further evidence to support this was presented by Pyne-O’Donnell (2007) and Pyne-O’Donnell et al. (2008) who revisited the Scottish palaeolakes investigated by Turney et al. (1997) and identified two closely spaced horizons with an identical composition to the BT. The
deposits were positioned in what were described by the authors as early- and mid-interstadial sediments (Fig. 2) and they recommended that the older deposit should be considered the BT, as defined by Turney et al. (1997), while the younger deposit was named the PT. Subsequent work by Matthews et al. (2011) outlined new radiocarbon age estimates for the BT and PT horizons based on their positions and, more importantly, chironomid-inferred temperature records (Bronk Ramsey et al. 2015) and are as follows: BT is 14 098 ± 47 (μ ± 1σ) or 14 190–14 003 cal BP (95%); IntCal13), and PT is 13 939 ± 66 (μ ± 1σ) or 14 063–13 808 cal a BP (95%; IntCal13). Both tephra deposits are close in age but a synthesis of age estimates, stratigraphic positions and, more importantly, chironomid-inferred temperature records led Brooks et al. (2016) to conclude that the BT was deposited during the latter stages of GI-1e. The PT, however, is thought to be associated with a colder interval, probably analogous to GI-1d. The chironomid-inferred temperature record from Whitrig Bog provides crucial evidence here as this is the only site, as yet, that fully captures the warming transition at the start of the Lateglacial interstadial (GI-1) and, as such, constrains the BT to the latter stages of GI-1e (Brooks and Birks, 2000; Brooks et al., 2016; Walker and Lowe, in press). At other Scottish sites a lag in the start of organic sedimentation has been proposed as an explanation for finding the BT at the base of Lateglacial sedimentary profiles and thus misinterpreted as equivalent to early GI-1e in previous studies (Walker and Lowe, in press).

The occurrence of two separate eruptions with similar ages and identical geochemical compositions means there is a danger of miscorrelation, especially for sites that only preserve a single tephra deposit (e.g., records such as Håsseldalaport and Skallahlut; Davies et al., 2003, 2004). For finding the BT at the base of Lateglacial sedimentary profiles and thus misinterpreted as equivalent to early GI-1e in previous studies (Walker and Lowe, in press). The occurrence of two separate eruptions with similar ages and identical geochemical compositions means there is a danger of miscorrelation, especially for sites that only preserve a single tephra deposit (e.g., records such as Håsseldalaport and Skallahlut; Davies et al., 2003, 2004). Current thinking suggests a correlation between the Swedish deposits and the PT based on pollen evidence and stratigraphic position, but this cannot be proven given the overlap between BT and PT age estimates (Bronk Ramsey et al., 2015). Furthermore, new trace element comparisons of the BT, extracted from a new core from the Borrobol site and presumably the PT from these Swedish sites found that the deposits were indistinguishable from each other (Lind et al., 2016).

To complicate matters, individual deposits in marine cores HM107-05 (382–379 cm), MD99-2275 (3679 cm) and MD99-2271 (806–808 cm) from the North Iceland shelf have been discovered by Eiríkur et al. (2000), Søndergaard (2005) and Gudmundsdóttir et al. (2011, 2012), respectively. All cores have been correlated to each other by Gudmundsdóttir et al. (2012) using magnetic susceptibility and isotope profiles and the tephra deposits found were originally correlated to the BT...
Indeed, the Borrobol-type tephra (i.e. a similar stratigraphically located below Bølling or GI-1-equivalent tephras) are in fact associated with glacial sediments, context. References for all sites containing these horizons are given in Fig. 1.

2013 and the best available AMS14C age estimate is benthic foraminifera. Similarly, a Borrobol-type tephra was based on geochemical similarities (i.e. Haflidason et al., 2001; Gudmundsdottir et al., 1997), deposits with a similar composition to the BT have been identified in 28 locations around the NA spanning the early and late Holocene, GI-1d, GI-1e and GS-2.1 (Fig. 1).

The sampling strategy adopted to search for Borrobol-type tephra deposits in NEEM, NGRIP and GRIP ice cores, presented against depth and δ18O profiles for the interval between GI-1 and GS-2.1 (GRIP: Johnsen et al., 1997; NGRIP: NGRIP Members, 2004; NEEM: Buizert et al., 2014). For each core, the depth intervals sampled are shaded in grey. Horizontal blue bars highlight tephra layers found in each core and proposed tie-points between cores are shown. The stratigraphic position of three known Borrobol-type deposits (North Iceland Shelf, BT, PT) found in terrestrial and marine sediments (e.g. Gudmundsdottir et al., 2011, 2012; Matthews et al., 2011; Brooks et al., 2016) is shown for context. References for all sites containing these horizons are given in Fig. 1.

Based on geochemical similarities (i.e. Haflidason et al., 2000; Gudmundsdottir et al., 2011, 2012), however, all tephra deposits are in fact associated with glacial sediments, stratigraphically located below Bølling or GI-1-equivalent material. Indeed, the Borrobol-type tephra (i.e. a similar composition to BT) in HM107-05 has an age range of 16.490–16.120 cal a BP (±1σ), based on calibrated (CALIB 3.0) accelerated mass spectrometry (AMS) 14C dating of benthic foraminifera. Similarly, a Borrobol-type tephra was found in another core, MD99-2272 (1697 cm), by Jarvis (2013) and the best available AMS 14C age estimate is 17.179–16.754 cal a BP (±1σ), derived from mollusc shell material located 4.5 cm above the tephra layer (calibrated using OxCal 4.1 and the Marine04 curve). Stratigraphic and chronological evidence therefore indicates that the marine layers were deposited in GS-2.1-equivalent glacial sediments and this discrepancy between terrestrial and marine-based radiocarbon age estimates was first noted by Lowe (2001). Both Jarvis (2013) and Eiríksson et al. (2004) applied a standard reservoir correction of 400 years to their 14C dates, yet Eiríksson et al. (2004) noted that the temporal variability in reservoir ages around the North Iceland Shelf exceeds the variability expected from marine model calculations, and may explain offsets between their marine age estimates and between the Icelandic shelf and NGRIP ice-core age estimates.

Since the first identification of the BT by Turney et al. (1997), deposits with a similar composition to the BT have been identified in 28 locations around the NA spanning the early and late Holocene, GI-1d, GI-1e and GS-2.1 (Fig. 1). Here we undertake a comprehensive search of the high-resolution Greenland ice cores in an attempt to pinpoint the stratigraphic position of the BT, PT and the GS-2.1 tephra. We also refine the signature of the deposits by major and trace element analysis, particularly to explore whether the latter can aid in discriminating between the different tephras.

**Methodology**

**Ice-core sampling**

Three Greenland ice-cores (NGRIP, GRIP and NEEM) were used to search for the BT, PT and the older Borrobol-type tephras between GS-2.1 and GI-1. The timing of Greenland interstadials (GI) and stadials (GS) and ages presented in this study have been defined by Greenland Ice Core Chronology 2005 (GICC05) (Andersen et al., 2006; Rasmussen et al., 2006, 2014; Seierstad et al., 2014) and GICC05modelext-NEEM-1 (Rasmussen et al., 2013). The GICC05 multi-core (NGRIP, DYE-3, GRIP) timescale was constructed by counting annual layers back from 2000 AD (b2k) using multiple parameters (e.g. δ18O, calcium ions) and uncertainty is based on a maximum counting error (MCE) of ambiguous layers, equivalent to 2σ, where cumulative errors increase with depth (Andersen et al., 2006; Rasmussen et al., 2006). NGRIP and GRIP ice samples were selected to encompass mid-GI-1e through to early GI-1c ice (Fig. 2) to maximize the chances of isolating the BT and PT. The GI-1 sampling strategy for NEEM was based on coarse-resolution screening of meltwater samples (1.1 m) derived directly from the continuous flow analysis (CFA) system (Bigler et al., 2011) for the entire interstadial and high-resolution sampling was informed by the age estimates of Matthews et al. (2011) and GICC05modelext-NEEM-1, which encompassed mid- to late GI-1e and the complete GI-1d (Fig. 2). To trace the older GS-2.1-equivalent Borrobol-type tephra, coarse-resolution CFA samples from NEEM were screened and used to inform a higher-resolution
sampling strategy for NEEM, NGRIP and GRIP (Fig. 2). All ice sampling was contiguous to maximize cryptotephra extraction. Ice cores are cut into sections of 55-cm length in the field, and a 2-cm³ section of ice was cut from the outer edge of each 55-cm section and further subsampled at a resolution of 15–20 cm. Individual samples were melted and centrifuged in tubes for 5 min at 2500 r.p.m. and at the end of this process any particulate matter, including tephra, remained concentrated at the bottom of the tubes. Supernatant water was discarded, leaving 2–3 mL of sample that was evaporated onto a frosted glass microscope slide and covered in epoxy resin for optical assessment, using high-magnification light microscopy. Slides containing tephra were selected for electron probe micro-analysis (EPMA).

Geochronology

Stratigraphic position and age of cryptotephras were used in the age model of each core as described by Hayward (2012). At NEEM and NGRIP, new high-precision age models were developed for the GI-1e, GI-1d and GS-2.1 events (Table 2). At NEEM, a GICC05 age has been assigned to the GRIP-2-1 deposit 1524.80 m as it can be correlated to the NGRIP deposit at 1665.60 m. At NGRIP, a GI-1e age has been assigned to the GS-2.1 deposit 1582.75 m. The NEEM core was cut into sections of 55-cm length in the field and sampled with a 2-cm³ section of ice. Individual samples were melted and centrifuged in tubes for 5 min at 2500 r.p.m. and at the end of this process any particulate matter, including tephra, remained concentrated at the bottom of the tubes. Supernatant water was discarded, leaving 2–3 mL of sample that was evaporated onto a frosted glass microscope slide and covered in epoxy resin for optical assessment, using high-magnification light microscopy. Slides containing tephra were selected for electron probe micro-analysis (EPMA).

Tephra in GI-1e ice: stratigraphic position and geochronology

Two individual cryptotephras were identified within the GI-1d cold event in three ice cores no colourless glass shards consistent with the BT/PT rhyolite were identified within these sampling windows (Fig. 2), some of which were by Seierstad et al. (2014) for the timescale transfer of GICC05 to GRIP; however, this work focuses only on the Borrobol-type horizons and the full tephratigraphy will be reported elsewhere.

Table 1. Summary information for Borrobol-type tephra deposits from GI-1e and GS-2.1 including the ice-core depth interval (metres) within which each deposit was found and a Greenland Ice Core Chronology 2005 (GICC05) age (using the lower ice depth age). Age uncertainty is based on ‘uncertain annual layers’ and for N uncertain layers the error = N × 0.5 years, and the accumulated error is obtained by summing these layers and is called the maximum counting error (MCE), equivalent to 2σ (Andersen et al., 2006; Rasmussen et al., 2006). For NEEM, a GICC05 age has been assigned to the GS-2.1 deposit 1524.80 m as it can be correlated to the NGRIP deposit at 1665.60 m. Geochronological, shard concentrations and average shard size are provided. The rock type classification is based on Le Maitre (2002). EPMA conditions were optimized for analysis of small cryptotephra grains (<20 μm diameter) and samples in this study were analysed with either a 5- or 3-μm beam diameter using the operating conditions outlined in Hayward (2012).

<table>
<thead>
<tr>
<th>Core</th>
<th>Depth (top) (m)</th>
<th>Depth (bottom) (m)</th>
<th>Max. age (a b2k) and MCE</th>
<th>Composition</th>
<th>Grain count</th>
<th>Grain size: long axis (μm)</th>
<th>EPMA beam size (μm)</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGRIP</td>
<td>1582.55</td>
<td>1582.75</td>
<td>14 252 ± 173</td>
<td>Rhyolite</td>
<td>86</td>
<td>30.5</td>
<td>3</td>
<td>GI-1e</td>
</tr>
<tr>
<td>GRIP</td>
<td>1727.55</td>
<td>1727.75</td>
<td>14 252 ± 173</td>
<td>Rhyolite</td>
<td>102</td>
<td>33.1</td>
<td>5</td>
<td>GI-1e</td>
</tr>
<tr>
<td>GRIP</td>
<td>1733.80</td>
<td>1734.00</td>
<td>14 358 ± 177</td>
<td>Rhyolite</td>
<td>93</td>
<td>34.3</td>
<td>3</td>
<td>GI-1e</td>
</tr>
<tr>
<td>NGRIP</td>
<td>1665.40</td>
<td>1665.60</td>
<td>17 326 ± 319</td>
<td>Rhyolite</td>
<td>&gt;2000</td>
<td>47.4</td>
<td>5</td>
<td>GS-2.1</td>
</tr>
<tr>
<td>GRIP</td>
<td>1818.15</td>
<td>1818.30</td>
<td>17 326 ± 319</td>
<td>Rhyolite</td>
<td>431</td>
<td>49.4</td>
<td>5</td>
<td>GS-2.1</td>
</tr>
<tr>
<td>NEEM</td>
<td>1524.60</td>
<td>1524.80</td>
<td>17 326 ± 319</td>
<td>Rhyolite</td>
<td>124</td>
<td>36.8</td>
<td>5</td>
<td>GS-2.1</td>
</tr>
</tbody>
</table>

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Table 2. Mean major and trace element values for each tephra deposit with associated standard deviations (1 or 2σ). Major elements were obtained by EPMA of individual grains and mean anhydrous (norm) values are expressed as weight% of sample, together with average values of raw (hydrous) totals. The ice-core sample depth and the number of analyses (n) are given for each deposit. All analyses were performed at the Tephra Analysis Unit (TAU), University of Edinburgh, using a Cameca SX100 electron microprobe. Trace element data are expressed in parts per million. All samples were analysed by LA-ICP-MS at the University of Aberystwyth with a 10-μm beam spot size using a Coherent Geolas ArF 193-nm Eximer laser ablation unit coupled to a Thermo Finnigan Element 2 high-resolution sector mass spectrometer. The USGS reference glass BCR2-G was analysed as an unknown under the same operating conditions at the same time. Analytical precision is typically between ±5% and 10% and accuracy is typically around ±5%, when compared with the published concentrations for BCR2-G.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Depth (m)</th>
<th>Mean (n=6)</th>
<th>2σ (n=7)</th>
<th>Mean (n=8)</th>
<th>2σ (n=25)</th>
<th>Mean (n=12)</th>
<th>2σ (n=8)</th>
<th>Mean (n=8)</th>
<th>2σ (n=8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGRIP</td>
<td>1582.75 m</td>
<td>SiO2 76.37 0.94</td>
<td>76.48 0.80</td>
<td>76.42 1.18</td>
<td>75.94 0.55</td>
<td>75.83 0.77</td>
<td>75.91 0.29</td>
<td>75.85 2.17</td>
<td></td>
</tr>
<tr>
<td>GRIP</td>
<td>1727.75 m</td>
<td>TiO2 0.12 0.02</td>
<td>0.11 0.04</td>
<td>0.12 0.02</td>
<td>0.15 0.01</td>
<td>0.15 0.03</td>
<td>0.16 0.02</td>
<td>0.15 0.03</td>
<td></td>
</tr>
<tr>
<td>GRIP</td>
<td>1734 m</td>
<td>Al₂O₃ 12.89 0.75</td>
<td>12.61 0.50</td>
<td>12.64 1.14</td>
<td>12.91 0.43</td>
<td>12.89 0.33</td>
<td>12.96 0.42</td>
<td>13.12 1.47</td>
<td></td>
</tr>
<tr>
<td>GRIP</td>
<td>1665.60 m</td>
<td>FeO 1.52 0.26</td>
<td>1.46 0.76</td>
<td>1.47 0.31</td>
<td>1.59 0.21</td>
<td>1.60 0.34</td>
<td>1.58 0.18</td>
<td>1.52 0.34</td>
<td></td>
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<tr>
<td>GRIP</td>
<td>1818.30 m</td>
<td>MgO 0.04 0.02</td>
<td>0.04 0.02</td>
<td>0.04 0.03</td>
<td>0.04 0.01</td>
<td>0.04 0.01</td>
<td>0.04 0.01</td>
<td>0.04 0.01</td>
<td></td>
</tr>
<tr>
<td>GRIP</td>
<td>1524.80 m</td>
<td>MnO 0.07 0.05</td>
<td>0.09 0.07</td>
<td>0.07 0.04</td>
<td>0.11 0.03</td>
<td>0.11 0.05</td>
<td>0.12 0.05</td>
<td>0.11 0.06</td>
<td></td>
</tr>
<tr>
<td>GRIP</td>
<td>808 cm</td>
<td>CaO 0.80 0.13</td>
<td>0.82 0.13</td>
<td>0.84 0.08</td>
<td>0.95 0.10</td>
<td>0.95 0.13</td>
<td>1.00 0.06</td>
<td>1.04 0.64</td>
<td></td>
</tr>
<tr>
<td>GRIP</td>
<td>1582.75 m</td>
<td>Na₂O 4.08 0.23</td>
<td>4.16 0.32</td>
<td>4.16 0.39</td>
<td>4.27 0.20</td>
<td>4.28 0.40</td>
<td>4.22 0.30</td>
<td>4.36 0.65</td>
<td></td>
</tr>
<tr>
<td>GRIP</td>
<td>1727.75 m</td>
<td>K₂O 3.90 0.19</td>
<td>3.95 0.22</td>
<td>3.95 0.15</td>
<td>3.91 0.17</td>
<td>3.92 0.22</td>
<td>4.01 0.15</td>
<td>3.79 0.47</td>
<td></td>
</tr>
<tr>
<td>GRIP</td>
<td>1734 m</td>
<td>P₂O₅ 0.01 0.01</td>
<td>0.01 0.02</td>
<td>0.01 0.01</td>
<td>0.02 0.01</td>
<td>0.02 0.01</td>
<td>0.02 0.01</td>
<td>0.02 0.01</td>
<td></td>
</tr>
<tr>
<td>GRIP</td>
<td>1665.60 m</td>
<td>Rb 0.19 0.17</td>
<td>0.26 0.21</td>
<td>0.24 0.52</td>
<td>0.17 0.15</td>
<td>0.22 0.27</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>
| GRIP    | 1818.30 m| Sr 216 JOURNAL OF QUATERNARY SCIENCE

overlap with rhyolitic products of Icelandic origin (Fig. 3B). The exception, however, is the eastern rift zone central volcano Bórðarhra that has a similar composition (although the reference data are based on just three analyses of whole rock samples). Little is known about this volcano, located beneath the Vatnajökull ice cap, but three nunataks were analysed by X-ray fluorescence (XRF) by Jónasson (2007) and the limited data are used for comparison in Fig. 3B.

Both GRIP GI-1e deposits geochemically match the NGRIP deposit, and their chronological positions were assessed by Seierstad et al. (2014) as part of a wider study to identify tie-points between cores for transfer of the GICC05 chronology to the GRIP record. The two youngest deposits, NGRIP 1582.75 m and GRIP 1727.75 m, were matched and thus share the common age of 14 252 ± 173 a b2k and also occupy a stratigraphic position approximately 200 years before the start of GI-1d. GRIP 1734 m is 106 ± 3 years older (14 358 ± 177 a b2k) and is found in the middle of the GI-1e warm event, immediately before a gradual downturn trend in surface air temperature according to the δ18O record (Fig. 2) (NGRIP Members, 2004).

Single-shards were analysed by LA-ICP-MS (Table 2) and when average rare earth element (REE) profiles are displayed together with the individual grain analyses, there is general similarity between all layers from GI-1e (Fig. 3D). The REE profiles appear typical of Icelandic rhyolitic products.
Figure 3. (A) Normalized glass analyses from three GI-1e and three GS-2.1 ice core deposits, plotted against rock type, which is assigned on the total alkali vs. silica content (TAS) (Le Bas et al., 1986). Data are normalized to an anhydrous basis (i.e. 100% total oxides) following the recommendation of Pearce et al. (2014). (B) Compositional envelopes for identifying tephra provenance of Icelandic silicic tephra layers using major elements. The diagram is adapted from Meara (2012) with data for Eyjafjallajökull and Snæfellsjökull volcanic systems sourced from Larsen et al. (1999) and Jonasson (2007). The low and high alkali boundary is based on Jonasson (2007). (C) Comparison of the GI-1e and GS-2.1 ice core deposits relative to the compositional envelope for the BT and PT are constructed using data from Turney et al. (1997), Pyne-O’Donnell (2007), Pyne-O’Donnell et al. (2008), Matthews et al. (2011) and Lind et al. (2016). This comparison highlights the difference in CaO and TiO₂ in the GS-2.1 ice-core tephras. Error bars represent two standard deviations (2σ) of replicate analyses of the Lipari obsidian secondary standard; grey bars correspond to GI-1e samples and blue to GS-2.1 samples. (D and E) Chondrite-normalized REE profiles for individual grains from GI-1e and GS-2.1 deposits respectively. The chondrite composition is from McDonough and Sun (1995) and thick blue bars represent end member characterizations of Icelandic rhyolites, reported in Oskarsson et al. (1982).
based on a comparison with end-member characterizations of Icelandic rhyolites from Öskarsson et al. (1982) (Fig. 3D). This includes high absolute concentrations of Sr, Zr and Ba, light REE (LREE) enrichment (La to Nd >100 times the chondritic value) with a profile that slopes steeply down to the pronounced negative anomaly of Eu, indicating feldspar fractionation. The steep profile of these incompatible LREEs gives way to a flat profile that characterizes the abundance of middle REEs (MREEs) and heavy REEs (HREEs) between Gd and Lu. The range of concentrations and element ratios, e.g. Ce/Yb (Fig. 4) are the same for sample pairs GRIP 1734.75 m and NGRIP 1582.75 m, and also GRIP 1734 m, although not identical in terms of REE, with the NGRIP sample looking to be more evolved than GRIP 1727.75 m, based on higher REE abundance. It must be emphasized that only a small number of analyses were possible on the Greenland ice-core samples (Table 2) and these may only represent part of the eruption’s compositional range, with the possibility that further analyses could extend the fields of data. When coupled with the analytical noise for analyses performed at 10 µm, close to the limit of the LA-ICP-MS method, it should be noted that the data will be influenced by larger uncertainties that do not typically hamper analyses of larger particles. Statistical analysis of 15 trace elements from deposits NGRIP 1582.75 m and GRIP 1727.75 m (that form the younger Gl-1e horizon) produces a $D^2_{\text{critical}}$ value of 3.506, which is below the critical value of 30.58 at the 99% confidence level and demonstrates that the geochemical composition is not significantly different.

Geochemical and chronological comparison to other North Atlantic Borrobol-type deposits in Gl-1e

The two ice-core tephra horizons fall within the BT/PT compositional envelope (Fig. 3C) and these may only represent part of the eruption’s
Table 3. Graphical comparisons between major and trace element datasets were supported by two statistical tests; the similarity coefficient (ISC) of Borchardt et al. (1972) and statistical distance ($D^2$) method of Perkins et al. (1995, 1998). This table presents SC and $D^2$ values for major elements (normalized to 100%), and $D^2$ values for trace elements (T). Five major elements (with >1 wt%) were used for SC calculations, based on the method from Hunt et al. (1995), where values >0.95 suggest products are from the same magmatic source. $D^2$ is from Perkins et al. (1995, 1998) and seven major elements were used in the comparisons (with >0.01 wt%). The value for testing the statistical distance values at the 99% confidence interval is 18.48 (seven degrees of freedom). For calculating $D^2$, 15 trace elements were used, following recommendations by Pearce et al. (2008). The value for testing $D^2$ at the 99% confidence interval is 30.58 (15 degrees of freedom).

Major and trace element similarity: CI-1e Borrobol-type

<table>
<thead>
<tr>
<th>Deposit</th>
<th>BT: BO521</th>
<th>PT: BO486</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRIP 1727.75 and NGRIP 1582.75 m</td>
<td>SC 0.966</td>
<td>SC 0.974</td>
</tr>
<tr>
<td></td>
<td>$D^2$ 3.036</td>
<td>$D^2$ 4.527</td>
</tr>
<tr>
<td></td>
<td>$D^2$ 10.078 (T)</td>
<td>$D^2$ 5.137 (T)</td>
</tr>
<tr>
<td>GRIP 1734.00 m</td>
<td>SC 0.974</td>
<td>SC 0.987</td>
</tr>
<tr>
<td></td>
<td>$D^2$ 1.614</td>
<td>$D^2$ 1.131</td>
</tr>
<tr>
<td>NEEM 1524.80 m</td>
<td>SC 0.986</td>
<td>SC 0.957</td>
</tr>
<tr>
<td></td>
<td>$D^2$ 2.022</td>
<td>$D^2$ 3.479</td>
</tr>
</tbody>
</table>

Major element similarity: GS-2.1 Borrobol-type

<table>
<thead>
<tr>
<th>Deposit</th>
<th>MD99-2271</th>
<th>MD99-2272</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGRIP 1665.60 m</td>
<td>SC 0.990</td>
<td>SC 0.951</td>
</tr>
<tr>
<td></td>
<td>$D^2$ 0.836</td>
<td>$D^2$ 4.225</td>
</tr>
<tr>
<td>GRIP 1818.30 m</td>
<td>SC 0.990</td>
<td>SC 0.952</td>
</tr>
<tr>
<td></td>
<td>$D^2$ 0.725</td>
<td>$D^2$ 3.865</td>
</tr>
<tr>
<td>NEEM 1524.80 m</td>
<td>SC 0.986</td>
<td>SC 0.957</td>
</tr>
<tr>
<td></td>
<td>$D^2$ 2.022</td>
<td>$D^2$ 3.479</td>
</tr>
</tbody>
</table>

matches are with the new data-sets (BT: BO521 and PT: BO486) from the original Borrobol site published in Lind et al. (2016) (Fig. 4A–C). Older data have a consistently lower Na$_2$O content, typically ~0.65 wt% less than the ice-core results. The offset is probably due to sodium loss in older analyses and the similarities between our data and the Lind et al. (2016) analyses could be because they were both analysed with improved conditions and EPMA modification, described by Hayward (2012). There is consistent major element overlap between the ice-core data and BO521 and BO486 and all exhibit the trend of evolution by fractionation of feldspar (Fig. 4B), which is typical for Icelandic rhyolites (SiO$_2$ increases as CaO and Al$_2$O$_3$ decrease). Lind et al. (2016) have assumed BT and PT ages from Bronk Ramsey et al. (2015), so with respect to the ice-core age estimates, the older ice deposit GRIP 1734.3 (14 308 ± 177 a BP) is consistent only with the BT (14 190–14 003 cal a BP). Statistical investigation of the dataset shows compositional similarity between these two layers, with SC and $D^2$ values of 0.974 and 1.614, respectively (Table 3). The younger Greenland deposit (NGRIP 1582.75 m/GRIP 1727.75 m; 14 202 ± 173 a BP) overlaps on age with both the BT and the PT (14 063–13 939 cal a BP) with SC and $D^2$ values of 0.966 and 3.036 and 0.974 and 4.527, respectively (Table 3).

All ice-core samples have lower REEs when compared to BO521 (Fig. 4D) although the range of REE patterns (Fig. 4D), trace element concentrations (Fig. 4E–H) and ratios are similar (e.g. Ce/Yb in Fig. 4I), which strongly suggests a cogenetic relationship between the layers. Trace elements could not be derived from BO486 (Lind et al., 2016). BO521 is slightly more compositionally evolved than the ice-core samples which have higher CaO and Sr (e.g. Fig. 4F) and a regression line through these analyses (r~0.35) shows Sr decreasing with CaO, consistent with a possible genetic link between them by feldspar extraction. Additionally, almost all the other incompatible elements (e.g. U, Nb, Ta, the REE, and Rb and Ba which behave incompatibly or neutrally in rhyolites) increase from the ice-core layers to BO521. This suggests the relationship between these samples is related to an eruption from a compositionally zoned or stratified magma chamber, with the more evolved upper part of the magma body producing the BO521 deposit, and later erupted (less evolved) magma from deeper in the magma body travelling to Greenland to be deposited as GRIP 1727.75 m/NGRIP 1582.75 m or GRIP 1734 m. Deposits from the younger ice-core layer GRIP 1727.75 m/NGRIP 1582.75 m overlap with BO521 in terms of their Sr and Y concentrations (albeit at the less evolved end of the BO521 composition) (Fig. 4G). In contrast, Y is visibly higher in some of the shards from the older ice-core deposit GRIP 1734 m and BO521 are not the same, and were produced by different eruptions (Fig. 4G). However, these observations are based on a small number of analyses, and additional analyses are required to explore this further.

Tephra in GS-2.1 ice: stratigraphic position and geochemical composition

Three new deposits were identified within GS-2.1 ice in the following samples: NEEM 1524.80 m, NGRIP 1665.60 m and GRIP 1818.30 m (Table 1) and contain high concentrations of colourless glass shards. The ages of the deposits are consistent between cores and the NGRIP 1665.60 m/GRIP 1818.30 m match-point is included within an NGRIP/GRIP timescale synchronization performed by Sieiestad et al. (2014). While the GICC05 age for this GS-2.1 deposit is 17 326 ± 319 a b2k (17 276 ± 319 a BP), the age according to the first NEEM timescale is 17 386 ± 173 a b2k (GICC05modelext-NEEM-1). However, this new deposit sits along a trend line (Fig. 5) when plotted together with the depths of NEEM/NGRIP
ECM match-points (from Rasmussen et al., 2013), supporting the correlation, and providing a new match-point to amend GICC05modelext-NEEM-1 in a future version of this timescale.

All deposits have an identical rhyolite major element composition (Table 2, Fig. 3A,B) and are almost identical in composition to the GI-1e ice-core deposits. It is apparent, however, that there are consistent differences in the CaO and TiO₂ values that distinguish between the GS-2.1 and GI-1e deposits (Fig. 3C). Statistical analyses of major elements support a correlation between the NGRIP, GRIP and NEEM deposits with SC values ranging between 0.988 and 0.995 and D² values ranging between 0.240 and 1.100, strongly suggesting a compositional/genetic link between the deposits.

The average REE profiles of the GS-2.1 deposits fall within boundaries of typical Icelandic rhyolitic products and are very similar with a particularly good agreement between the incompatible LREE and MREE profiles, including a pronounced negative Eu anomaly (Fig. 3E). There is more variability between individual analyses of HREEs because of the low concentrations of these elements, which are close to detection limits at the analysis crater diameter used here, but this is smoothed out in the averages. Statistical comparison of the GS-2.1 trace element data of NGRIP 1665.60 m and GRIP 1818.30 m produces a low SC value of 1.401, and this further supports the correlation. It was not possible to obtain reliable trace element data from the NEEM sample because of the small sample size and low signal.

Geochemical and chronological comparison to other North Atlantic Borrobol-type deposits in GS-2.1

The GS-2.1 ice-core horizon has potential counterparts in the marine realm, with four similar Borrobol-type deposits found in glacial (GS-2.1 equivalent) sediments. The best (reservoir-corrected) age estimate for this marine isochron is 17 179–16 754 cal a BP (Jarvis, 2013) and is comparable to the ice-core age of 17 276±319 a BP. Furthermore, major element comparisons between the ice-core deposits and MD99-2271 (newly acquired data for this study, Table 2), MD99-2272 and MD99-2275 (Table S1) shows good agreement between the datasets (Fig. 6). This relationship is supported by statistical analyses, particularly with MD99-2271, which has an SC of 0.99 and a D² of 2.07 and can be interpreted as a volcanic event match as well as a provenance match. SC and D² values of 0.95 and 4.32, respectively, also support a common volcanic source between the ice-core deposits and MD99-2272 (Table 3), although there is an observed Na₂O offset that probably reflects sodium loss during EPMIA (Fig. 6A). A similar offset is observed in data from MD99-2275 grains, which otherwise compares well to the ice-core data (Fig. 6B,C). However, with just three analyses from this deposit and low oxide totals, statistical comparison could not be performed with confidence.

Discussion

Three cryptopha deposits with a Borrobol-type composition have been identified for the first time in Greenland ice spanning GS-2.1 (one horizon) and GI-1e (two horizons), but Borrobol-type deposits were absent from GI-1d ice. For the two compositionally identical events, ca. 106 years apart in GI-1e ice, the correlation issues that plague the BT remain. Without any diagnostic geochemical features, pinpointing a correlation to either the BT or the PT in terrestrial sequences is limited. Our new trace element data show some tentative and subtle differences but require further exploration to robustly assess their use for discrimination purposes. Furthermore, while the older ice-core deposit (GRIP 1734 m; 14 308±177 a BP) is consistent only with the calibrated age range of the BT, the younger deposit (GRIP 1727.75 m/NGRIP 1582.75 m; 14 202±173 a BP) overlaps with the age ranges of both the BT and the PT layers. Although a firm correlation is precluded, we discuss various possibilities below that will require testing in future work.

One possibility is that the GI-1e deposits in the ice represent two closely spaced eruptions that have become ‘fused’ into one BT deposit in some terrestrial records. Indeed, Pyne-O’Donnell et al. (2008) previously alluded to this after observing diffuse BT shard distributions over 10 cm within the cores from Borrobol Bog (green bars, Fig. 7), Loch an t’Suidhe and Tanera Mor (Roberts et al., 1998). A dispersed shard concentration profile is not observed at all sites, however, and a distinct single peak spanning just a few centimetres is observed at Abernethy Forest (Fig. 7) (Matthews et al., 2011). The best age estimate of 14 190–14 003 cal a BP for the BT is derived from the latter site by Bronk Ramsey et al. (2015) and this age range agrees well with the youngest deposit found in the Greenland ice, but also shows some overlap with the upper age range of the older deposit. This is consistent with our
The tephra identified in GS-2.1 is simpler in terms of its wider application as an ice-marine tie-point. This is the oldest known deposit with a Borrobol-type composition, but we demonstrate that it can be separated from the BT and PT on the basis of CaO vs. TiO₂ content (Fig. 3C). This compositional difference will be valuable in poorly resolved marine or terrestrial sediments and should circumvent any potential miscorrelations with BT or PT deposits. Found in all three ice cores with high shard concentrations and dated to 17326 ± 319 a b2k (Table 1; Fig. 2), this tephra has huge potential as a time-synchronous marker horizon for an interval that often poses dating challenges. For the ice, GS-2.1 has few match points between ice cores, and this new tephra horizon adds a reliable tie-point to synchronize cores and to facilitate GICC05 timescale transfer from NGRIP to NEEM (Fig. 5) (e.g. Rasmussen et al., 2013). For marine records, this common tephra deposit provides a new fix-point for synchronizing with the two GI-1e tephra couplets as a diffuse unit (e.g. Borrobol Bog), whereas other sites (e.g. Abernethy Forest) may only preserve one of these ice-core deposits (Fig. 7). The ability to temporally resolve closely spaced volcanic events is a strength afforded to high-resolution ice cores and, in this context, creates a need to investigate terrestrial samples in ultra-fine resolution, to explore the finer anatomy of the BT and PT in terrestrial records. This, however, may not be possible due to the relatively lower resolution of terrestrial records. Nevertheless, based on our current data sets, we can suggest that any BT deposit found in Lateglacial terrestrial records should be synchronized to both ice-core deposits spanning a 106-year interval. This proposed correlation is consistent with the Scottish chironomids-inferred temperature record from Abernethy Forest shown to highlight the relative positions of the BT and PT (Brooks et al., 2012) with ages from Bronk Ramsey et al. (2015). The solid green line represents a scenario where the PT is absent in the Greenland ice and the two GI-1e ice deposits have been fused into a single diffuse layer in the terrestrial record, potentially shown in the wide Borrobol Bog shard profile. The dashed green line represents another possible scenario...
name for this deposit — GS-2.1-RHY — based on its position in the Greenland stratigraphic framework and its geochemical composition.

Conclusions

Adopting a contiguous ice-core sampling approach has provided further insight into the complexity of the Borrolool Tephra. Two cryptotephra deposits detected in GI-1e, and probably equate to the BT found in terrestrial records but a firm correlation is precluded given the indistinguishable composition and closely timed deposition of the BT and PT. In this study trace element compositions show possible but tentative signs that may prove fruitful for future discrimination purposes. If these deposits are to be used as valuable marker deposits, further work is urgently required in this area. As yet there are no trace element analyses from terrestrial records that contain both the PT and the BT, and this is essential if differences are to be observed between these deposits. Re-analysis of BT and PT major element signatures with improved microprobe operating conditions may also prove beneficial to tease out any subtle differences that may be obscured by analytical noise. Furthermore, ultra-high-resolution sampling of Scottish Lateglacial sequences together with high-precision chronologies may prove beneficial to unpick the diffuse tephra profiles associated with the BT. Lastly, the GS-2.1-RHY horizon identified in three ice cores illustrates the value of marine-ice tie-points in an interval plagued by dating uncertainties and highlights its potential to assess marine reservoir offsets for the North Iceland Shelf.

Supporting information

Supporting information relating to this article can be accessed via the publisher’s website.

Table S1. Major oxide concentrations and secondary standards.
Table S2. Trace element data.

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Abbreviations. AMS, accelerated mass spectrometry; CFA, continuous flow analysis; EPMA, electron probe micro-analysis; GI, Greenland Interstadial; LA-ICP-MS, laser ablation inductively-coupled plasma mass spectrometry; MCE, maximum counting error; NA, North Atlantic; REE, rare earth element; SC, similarity coefficient; TA, total alkali; TAU, tephra analysis unit; WD, wavelength dispersive; WDS, wavelength dispersive spectrometry; XRF, X-ray fluorescence.

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