

The presence of Holocene cryptotephra in Wales and southern England

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ABSTRACT: There have been few detailed studies into the tephrostratigraphy of southern Britain. We report the tephrostratigraphy of two sites, one in southern England (Rough Tor, Cornwall) and one in Wales (Cors Fochno, west Wales). Our study extends the known southernmost reach of Icelandic cryptotephra in northern Europe. Given the large distance between sites in southern England and eruptive sources (e.g. Iceland 1500–1700 km distant), most of the cryptotephra layers consist of sparse numbers of shards, even by the standards of distal tephrostratigraphy (as low as 3 shards cm⁻¹), each layer spanning only 1 or 2 cm in depth. We identify multiple cryptotephra layers in both sites, extending the known distribution of several tephra layers including the MOR-T4 tephra (~AD 1000) most probably of Icelandic origin, and the AD 860 B tephra correlated to an eruption of Mount Churchill, Alaska. The two sites record contrasting tephrostratigraphies, illustrating the need for the inclusion of multiple sites in the construction of a regional tephrostratigraphic framework. The tephra layers we describe may provide important isochrons for the dating and correlation of palaeoenvironmental sequences in the south of Britain. 2017 The Authors. Journal of Quaternary Science Published by John Wiley & Sons Ltd.

KEYWORDS: chronology; peatlands; tephra; volcanic ash.

Introduction

Cryptotephra layers form chronological markers for the dating and correlation of palaeoenvironmental records (Davies, 2015). In addition, tephra layers provide important information about the spatiotemporal nature of volcanic ash clouds affecting Europe during the Holocene (Swindles *et al.*, 2011, 2013). Most cryptotephra layers identified at sites in northern Europe are of Icelandic origin (Swindles *et al.*, 2011). However, the identification of tephra shards with a geochemistry suggesting an origin in the Azores and Alaska (Jensen *et al.*, 2014; Reilly and Mitchell, 2015) indicates that tephra can reach northern Europe from volcanic regions located to the south of the continent.

Cryptotephra layers have been identified across northern Britain (cf. Lawson *et al.*, 2012). However, only two tephrostratigraphies exist from southern Britain, both from Exmoor ((Matthews, 2008; Fyfe *et al.*, 2014): Fig. 1). Cryptotephra shards have been reported in cores from peatlands in Wales (Buckley and Walker, 2002; Hall and Pilcher, 2002), but until now the lack of geochemical data has prevented the identification of their source eruptions, as well as the use of tephra layers as chronological markers. Examining the tephrostratigraphy of sites in southern England would extend the southernmost limit of tephrostratigraphy in the UK and may lead to the identification of new cryptotephra layers from source regions to the south.

We describe the tephrostratigraphies from two sites in the south of Great Britain to: (i) bring the south of Britain into line with other regions of northern Europe (where tephra layers already offer a valuable and robust set of dating isochrons);

(ii) examine the southernmost boundary of Holocene ash dispersal over northern Europe.

Methods

Study sites

Cors Fochno, Wales

Cors Fochno (Borth Bog) is a raised bog in Ceredigion, West Wales (52.50°N, 4.01°W) (Fig. 1). Peat at Cors Fochno has accumulated to a depth of ~6.9 m (basal age 6910–7170 cal a BP) (Hughes and Schulz, 2001). The centre of the peatland is still accumulating peat and the site has been the subject of palaeoecological research into the past vegetation dynamics of the bog (Schulz, 2004; Hughes *et al.*, 2007).

Rough Tor, Bodmin, England

Bodmin Moor is an area of moorland in the south of England. Rough Tor South is a topogenous valley mire located to the north-west of Bodmin Moor (50.59°N, 4.63°W). The mire has accumulated up to a depth of ~3 m around a spring and has been subject to several previous stratigraphic and palaeoecological studies (Gearey and Charman, 1996; Gearey *et al.*, 2000; Hopla and Gearey, 2009).

Tephrostratigraphy

Peat from both sites was sampled following the parallel hole method, with a 50-cm-long Russian-type corer (barrel diameter of 5 cm) (Jowsey, 1966; De Vleeschouwer *et al.*, 2011). Cores were subsampled into contiguous 5-cm samples, ashed at 550 °C and treated with 10% HCl (Hall and Pilcher, 2002). Samples were mounted onto slides using Histomount agent

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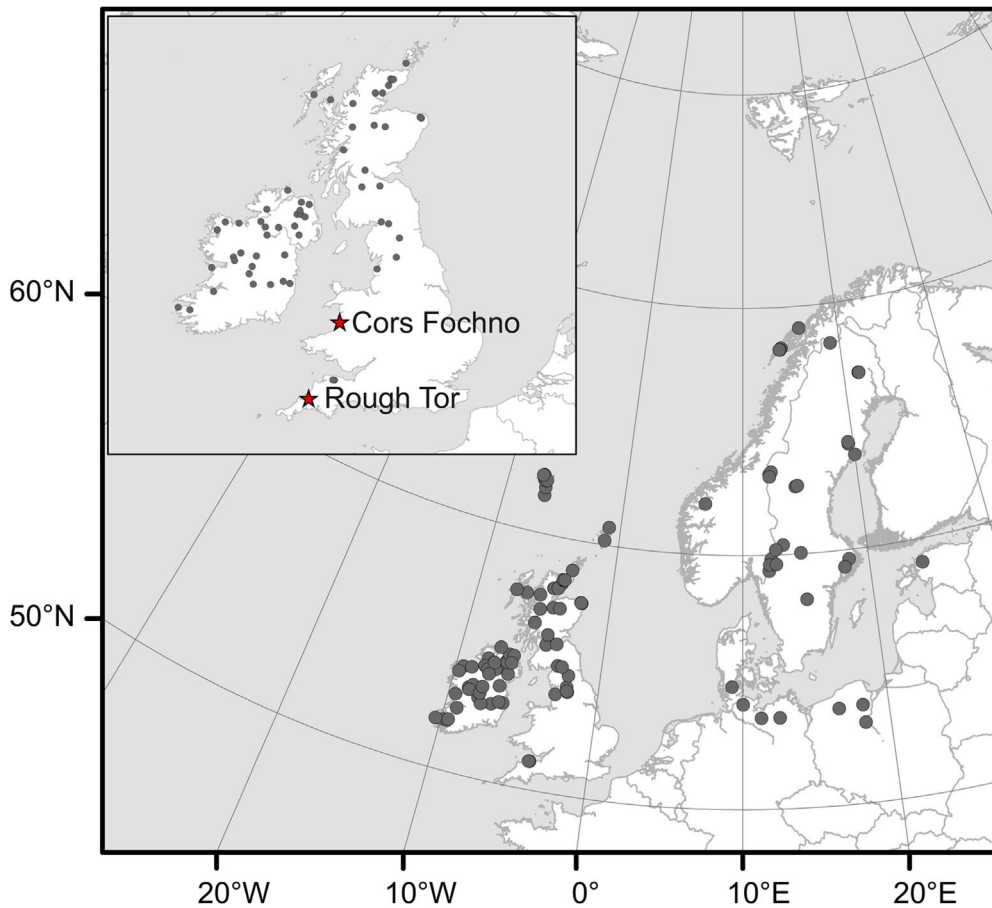


Figure 1. Sites in northern Europe which contain at least one published Holocene tephra layer (circles). Inset: existing tephra sites in Ireland and the United Kingdom (grey dots) and new sites examined in this study (stars).

and examined under 200–400 \times magnification. Where tephra shards were identified, cores were sampled at 1-cm intervals. Samples from the Rough Tor core required sieving at 10 μm in an ultrasonic bath to remove detrital material.

The tephra layers identified at both Rough Tor and Cors Fochno were extracted for geochemical analysis using the acid digestion method (Dugmore and Newton, 1992). Samples were treated with hot concentrated HNO_3 and H_2SO_4 acids, diluted with water and sieved at 10 μm . The coarse fraction was rinsed thoroughly with deionized water before mounting. Blockley *et al.* (2005) raised concerns about changes to cryptotephra shard geochemistry caused by prolonged exposure to acid or alkali conditions. However, recent work indicates that the geochemistry of glass shards of rhyolitic and intermediate composition is not significantly altered by acid extraction processes, such as those used in this study, which exclude alkali steps (Roland *et al.*, 2015; Watson *et al.*, 2016).

An additional density separation stage was required on Rough Tor samples due to the presence of mineral grains and samples were floated at 2.5 g cm^{-3} (Turney, 1998; Blockley *et al.*, 2005). All samples were mounted into blocks and polished to a 0.25- μm finish (Hall and Hayward, 2014). Geochemical analysis was conducted on the Cameca SX100 EPMA housed at the University of Edinburgh. All analyses were conducted using wavelength dispersive spectroscopy (WDS), with a beam diameter of 5 μm , 15 kV and beam currents of 2 nA (Na, Mg, Al, Si, K, Ca, Fe) and 80 nA (P, Ti, Mn) (Hayward, 2012). Secondary glass standards [basalt (BCR-2G) and rhyolite (Lipari)], were analysed before and after unknown tephra samples. Raw data are presented in Supplementary File S1.

Spheroidal carbonaceous particles

Spheroidal carbonaceous particles (SCPs), a marker produced by the burning of fossil fuels, first appear in records during the Industrial Revolution (19th century) and gradually increase in abundance before reaching a peak in concentration in samples dating to ca. 1970 in the UK (Rose and Harlock, 1998). Glass slides from both sites were examined for the presence of SCPs during the processing of initial tephra scans of slides under the microscope.

Tephra assignments

Initial assessment involved a visual comparison of the glass shard chemistry of the tephra layers identified in this study with the chemistry of tephra from known eruptions using co-variation plots of major elements. Similarity coefficients (SCs) can also be used to evaluate the degree of similarity between the glass shard composition of tephra from two samples (Hunt *et al.*, 1995). SCs were calculated following Borchartd *et al.* (1972). The data were normalized and the mean glass chemistry for tephra layers identified in this study was compared with that of eruptions which are known to have deposited tephra in other sites across the north of England and Ireland (Table S1). Oxides comprising <1.0% were excluded from the calculation as these analyses are inherently less precise (Hunt *et al.*, 1995; Davies *et al.*, 2005). SC values vary between 0 and 1 with a result approaching 1 indicative of a high degree of similarity, and a value exceeding 0.95 is usually accepted as an indicator of a good correlation (Begét *et al.*, 1992). Similarity coefficients based on mean values for a tephra layer can be biased by outliers. However, the identification of outliers is subjective and in order to retain

information on the heterogeneity of the tephra layers we include all the analyses in the mean values. Cluster analysis was conducted using R version 3.1.0 (Package Pvcust: Suzuki and Shimodaira, 2006) on normalized data values. Bootstrap resampling was applied to identify clusters exceeding the 95% confidence interval.

Results and discussion

Cors Fochno, Wales

The 7.2-m core from Cors Fochno contained five cryptotephra layers, all found in the top 1.3 m of peat. Given the low shard concentrations in the cryptotephra layers identified, the number of successful geochemical analyses was low for some layers. Traces of tephra (one or two shards) were present below 1.3 m but were not viable for geochemical analysis.

The uppermost two cryptotephra layers CF-1 (13–15 cm) and CF-2 (23–24 cm) contain glass shards with a dacitic–andesitic chemistry. Only a small number of successful geochemical

analyses were obtained on glass shards from these tephras ($n=5$ and $n=4$, respectively) and a degree of heterogeneity was identified. Such heterogeneity may indicate that these shards are from different eruptions. However, the geochemistry of glass produced by a single eruption can be heterogeneous due to changes in the magma composition as the eruption progresses. Such heterogeneity is a characteristic of magma produced during some eruptions of Hekla. Three of the glass shards from both CF-1 and CF-2 have geochemistry similar to that of glass produced during the eruptions of Hekla 1947, 1845 and 1510 (Fig. 2). Given the highly similar geochemistry of these Hekla tephras (Dugmore *et al.*, 1996; Rea *et al.*, 2012; Watson *et al.*, 2015), an independent dating method, SCPs, was used to aid identification.

SCPs were detected in large numbers in samples containing the CF-1 tephra, whereas only a small number of SCPs were present in samples containing the CF-2 tephra. The presence of SCPs alongside glass shards from both the CF-1 and the CF-2 tephra layers suggests that these tephras were deposited after the industrial revolution and therefore cannot correlate

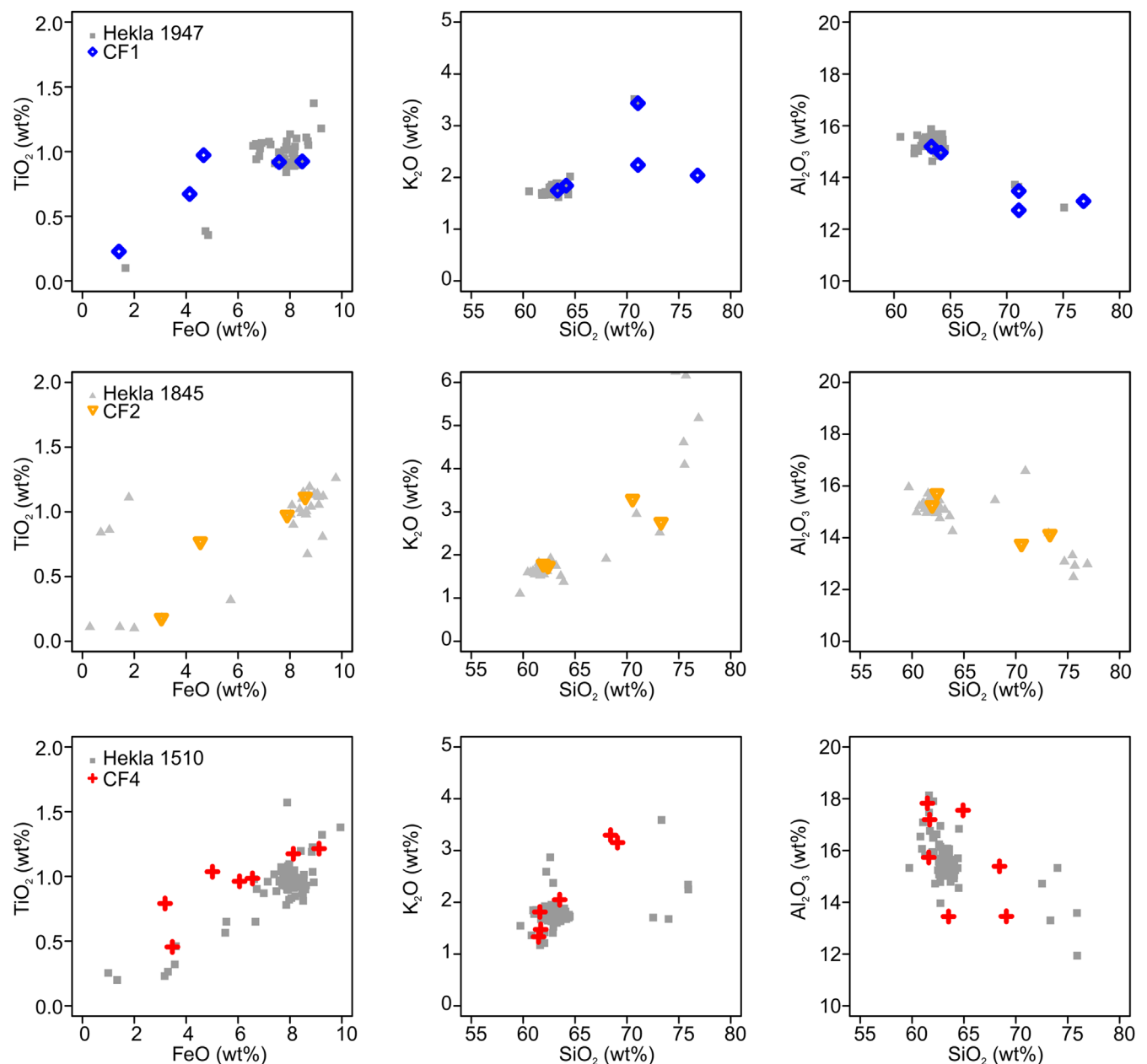


Figure 2. Major element bi-plots showing glass chemistry from the CF-1, CF-2 and CF-4 tephra layers detected at Cors Fochno, Wales, contrasted with the glass chemistry of known tephras based on type data from Dugmore *et al.* (1995), Pilcher *et al.* (1996, 2005), Larsen *et al.* (1999), Hall and Pilcher (2002), Wastegård (2002), Swindles (2006) and Watson *et al.* (2015).

with the Hekla 1510 eruption on stratigraphic grounds (Swindles and Roe, 2006; Swindles *et al.*, 2015). Given the available stratigraphic constraints and geochemical information, we assign CF-1 and CF-2 to the eruptions of Hekla in 1947 and 1845, respectively. Due to the small number of successful geochemical analyses which were obtained on each sample our assignments are tentative. However, existing records indicate that tephra from these eruptions was transported in the direction of Wales. Glass shards from both the Hekla 1947 and 1845 eruptions have been identified at sites in Ireland (Rea, 2011; Watson *et al.*, 2015). The Hekla 1947 tephra has also been identified in Scotland (Housley *et al.*, 2010). Our tentative correlation may represent the first record of these cryptotephra layers in Wales, and the first of the Hekla 1845 cryptotephra outside of Ireland and the Faroe Islands (Wastegård, 2002).

A third tephra layer, CF-3 (31–34 cm), contains glass shards with a pink tinge. The age of this collection of shards is bounded by its stratigraphic position between CF-2 (Hekla 1845, 23 cm) and CF-5 (MOR-T4, 115–118 cm, ca. AD 1000). Cluster analysis indicates that the glass shards in CF-3 show two chemical compositions ($p < 0.05$) (Fig. S1). The nine geochemical analyses on glass shards from CF-3-G1 are characterized by slightly higher SiO₂ content and a lower wt % of FeO and MgO than the four analyses on CF-3-G2. Both CF-3-G1 and CF-3-G2 show a low degree of similarity with tephtras previously identified in sites towards the south of Europe (SCs <0.85 and 0.80, respectively). Bi-plots of major elements indicate geochemical similarity to the QUB 384 tephra population groups 3 and 4 (ca. AD 1650–1750) (Fig. 3). These tephtras were previously identified, also apparent as one single tephra layer, containing shards with a pink/brown tinge in Norway (Pilcher *et al.*, 2005). Therefore, we tentatively suggest that CF-3 (G1-G2) represents the second discovery of the QUB 384 group 3 (=CF-3-G2) and 4 (=CF-3-G1) tephtras (the other being in the Lofoten Islands: Pilcher *et al.*, 2005), greatly extending the known fallout region of these tephtras. The source of the QUB 384 tephtras remains unidentified. However, there is a degree of geochemical similarity between shards of the QUB 384 group 3 (=CF-3-G2) tephtra and the SILK tephtras produced by the Katla volcano, Iceland (Larsen *et al.*, 2001). Although there have been no silicic eruptions of Katla since ~1600 BP, we do not discount Katla as a source because small amounts of silicic tephtra have been produced during more recent major basaltic eruptions of Katla (Larsen *et al.*, 2001; Wastegård and Davies, 2009).

We were able to obtain only seven successful geochemical analyses on glass shards from the CF-4 tephtra layer (95–97 cm). These analyses indicate a wide range of geochemistries. We could not identify a geochemical match between the geochemistry of glass shards from CF-4 and the geochemistry of any cryptotephtra layers identified in northern Europe which are younger than CF-5 (MOR-T4 ~AD 1000, see below). Some of the analyses (shards 4–7) suggest a geochemical match to a Hekla tephtra, perhaps Hekla 1510 on stratigraphic grounds (SC = 0.87), which has previously been identified at sites in the south of England (Matthews, 2008; Fyfe *et al.*, 2014). Shard 3 contains a lower concentration of CaO than glasses previously identified as Hekla 1510 tephtra and displays more similarity to the composition of glass shards from the MOR-T2 tephtra tentatively correlated to the Azores. The age of the MOR-T2 tephtra is estimated to be ca. AD 1400 (Chambers *et al.*, 2004) so it is not inconceivable that this tephtra might be identified alongside shards from the Hekla 1510 tephtra. However, only one shard of this composition was analysed and the total for this shard is <98% (although over 95%), perhaps indicating an

unsatisfactory analysis. Although a number of the shards analysed in the CF-4 tephtra layer indicate geochemical similarity to the Hekla 1510 tephtra, equally, CF-4 may represent a new tephtra layer rather than a mixture of reworked shards. Further investigation is needed to distinguish between these two possibilities.

Only the oldest of the tephtra layers at Cors Fochno could be correlated with a known source eruption with a similarity coefficient ≥ 0.95 (File S1). On the basis of major element bi-plots and SC, CF-5 (115–118 cm) is correlated to the MOR-T4 tephtra previously identified in Ireland (Chambers *et al.*, 2004; Watson *et al.*, 2016) (Fig. 3) (SC = 0.95). The discovery of the MOR-T4 tephtra at Cors Fochno is the first identification of this tephtra outside of Ireland. The source eruption for the MOR-T4 tephtra is unknown but the tephtra is thought to be of Icelandic origin (Chambers *et al.*, 2004).

Figure 4 indicates an age–depth model generated from the assignments and tentative assignments of the tephtras above (excluding CF-4). The accumulation rate varies between 5 and 16 a cm⁻¹, very similar to the accumulation rate calculated based on ¹⁴C dating of the top ~150 cm of peat at Cors Fochno (7–16 a cm⁻¹: Schulz (2004)) and in other undisturbed Welsh peatlands (~5–15 a cm⁻¹) (Hughes and Schulz, 2001; Hughes and Dumayne-Peaty, 2002; Hughes *et al.*, 2007), adding further support to our tephtra correlations.

Rough Tor, Bodmin, England

We identified two tephtra layers in the Rough Tor South core at depths of 30–31 cm (BD 30) and 36–37 cm (BD 36). Both tephtra layers contained <20 shards cm⁻³. The major element glass chemistry of shards from BD 30 reveals a high degree of geochemical similarity with the White River Ash (Eastern Lobe: WRAe) of Alaskan origin, recently correlated to the AD 860 B tephtra (SC, AD–860 B = 0.94) (Jensen *et al.*, 2014) (Fig. 5). BD 36 shows geochemical similarity (SC = 0.94) to the AD 860 A tephtra, which has previously been identified at Exmoor (Fyfe *et al.*, 2014). However, there are differences between the geochemistry of shards from BD 36 and AD 860 A on some elements (e.g. BD 36 has lower TiO₂, average 0.15 vs. 0.20 AD 860 A samples). The analyses of the TiO₂ standard during the BD 36 runs indicate that TiO₂ was well calibrated. These differences may be attributed to calibration error in existing AD 860 A analyses and/or the small number of type data points for the AD 860 A tephtra. However, they are significant enough to make any assignment tentative. The identification of the AD 860 tephtras at only 30 cm depth would necessitate a very low rate of peat accumulation over the past ~1000 years. Instead, we hypothesize that the top of the core at Rough Tor South was lost due to anthropogenic disturbance. Many areas of peat on Bodmin Moor have been subject to peat cutting, artificial drainage and tin mining (Gearey *et al.*, 2000). Furthermore, despite sampling to the depth of the peat–mineral soil interface, the 1.4-m core recovered in this study was shorter than the 2.8-m cores retrieved by Gearey *et al.* (2000) and Hopla and Gearey (2009); and no SCPs were identified in the uppermost samples. Given that there have been no large eruptions of Mount Churchill (source for WRAe) since ~AD 860 it is unlikely that the BD 30 tephtra could be from a more recent eruption. Therefore, we tentatively assign the tephtras we identified to the AD 860 A (BD 36) and AD 860 B (BD 30) events. The BD 30 tephtra at Rough Tor South represents the first identification of the AD 860 B tephtra in the south of England.

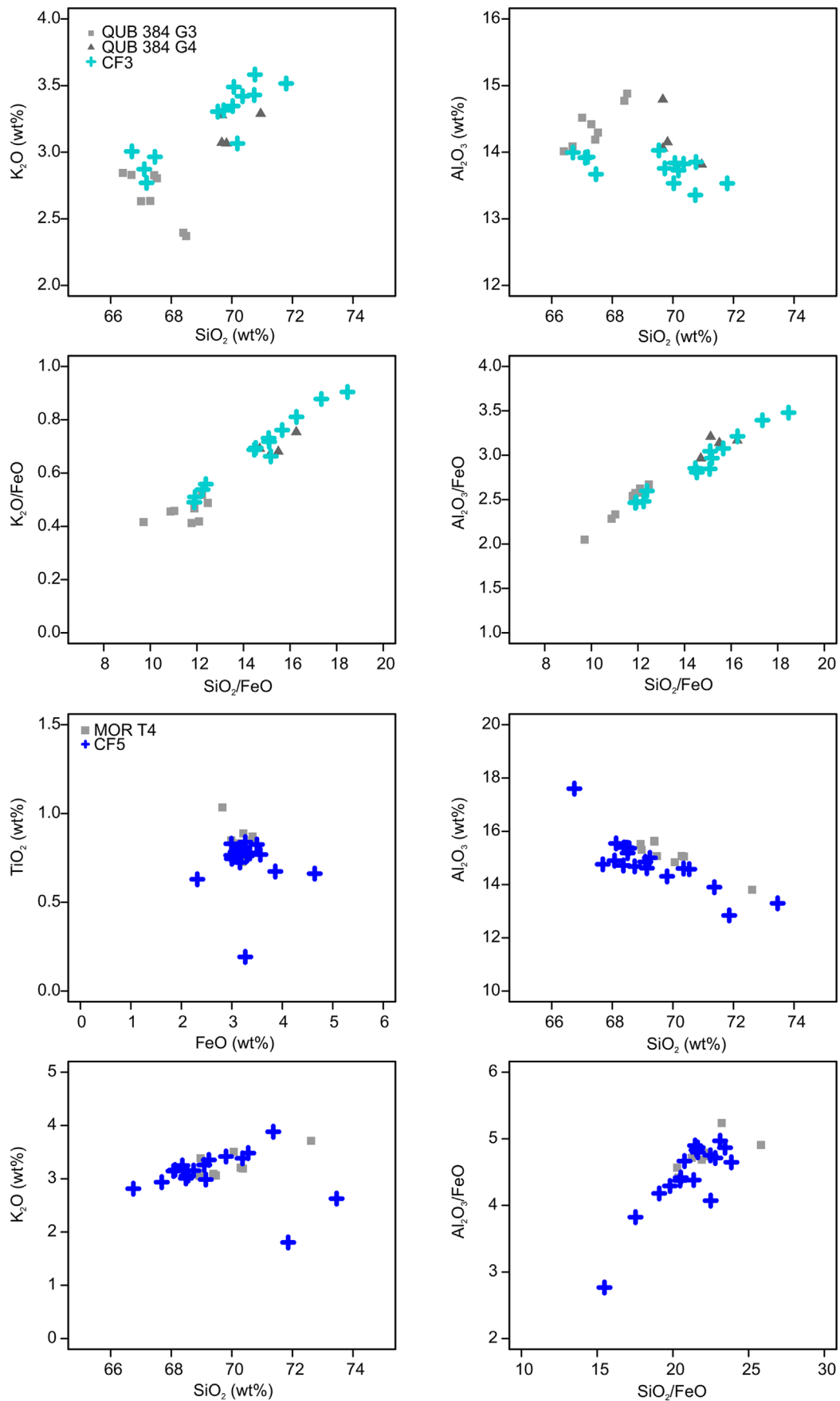


Figure 3. Major element bi-plots showing glass chemistry from the CF-3 and CF-5 tephra layers detected at Cors Fochno, Wales. CF-3 shows similarity to the QUB 384 G3 and G4 tephras identified by Pilcher *et al.* (2005). However, there is an offset which might conceivably be caused by slight differences in probe calibration. Although secondary standards were used by Pilcher *et al.* (2005), no standard data are published preventing the comparisons of calibrations. Here we plot the ratios of elements; assuming the ratios of elements to one another remain similar despite calibration differences, these plots can provide an alternative means for assessing the similarity between two tephras (cf. Mackay *et al.*, 2016). A similar although smaller offset is apparent between the MOR-T4 tephra and CF-5 tephra layer.

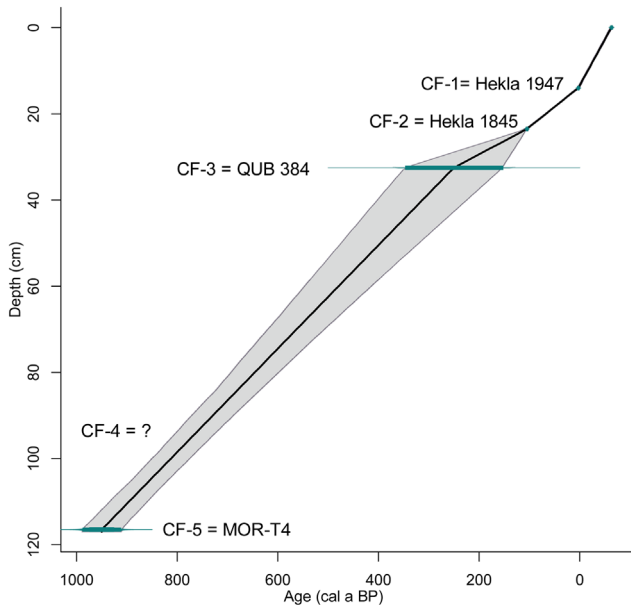


Figure 4. Age–depth model based on linear interpolation between the ages/age ranges of tephra layers CF-1, CF-2, CF-3 and CF-5. Plotted in CLAM v.2.2. The stratigraphic position of CF-4 is illustrated, but was not included in the calculation of the age–depth model.

The tephrostratigraphy of southern Britain and Wales

The identification of five cryptotephra layers at Cors Fochno and two at Rough Tor indicates that volcanic ash has fallen out over southern England and Wales on multiple occasions during the Holocene. All the cryptotephra layers identified (excluding CF-4) have been previously identified at sites in

northern Europe. However, in many instances their identification in Wales and southern England expands the southerly limit of their distributions. Most of the tephra layers identified in this study have been at least tentatively correlated to eruptions of Icelandic volcanoes, the exception being the AD 860 B tephra identified at Rough Tor, which would appear to have had an origin in Alaska. We did not identify any tephra layers with a major element geochemistry suggesting a source eruption in the Azores, typically characterized by tephra of trachytic chemistry, despite the southerly location of our sites in comparison with sites previously examined for tephra in the UK.

Conclusions

We report the tephrostratigraphy of two sites in the south of Britain, Cors Fochno, Wales, and Rough Tor, on Bodmin moor, Cornwall. The identification of tephra layers in both sites indicates that rather than reflecting the margins of cryptotephra distribution, the gaps in tephra records from the south of Britain are more likely to reflect a lack of research in these regions. The concentrations of shards in many of the cryptotephra layers we detect are low, probably due to the large distance between our sites and the dominant source of the cryptotephra layers we identify (Iceland 1500–1700 km distant). Despite low shard concentrations, five cryptotephra layers at Cors Fochno were viable for geochemical analysis, four of which can be at least tentatively correlated to tephra layers already identified in the UK and Ireland. All the tephra layers at Cors Fochno have a major element geochemistry consistent with an Icelandic origin. Only two tephra layers were identified at Bodmin moor, where the more recent part of the record has probably been truncated due to human activity. The tephra layers we report provide a framework for dating

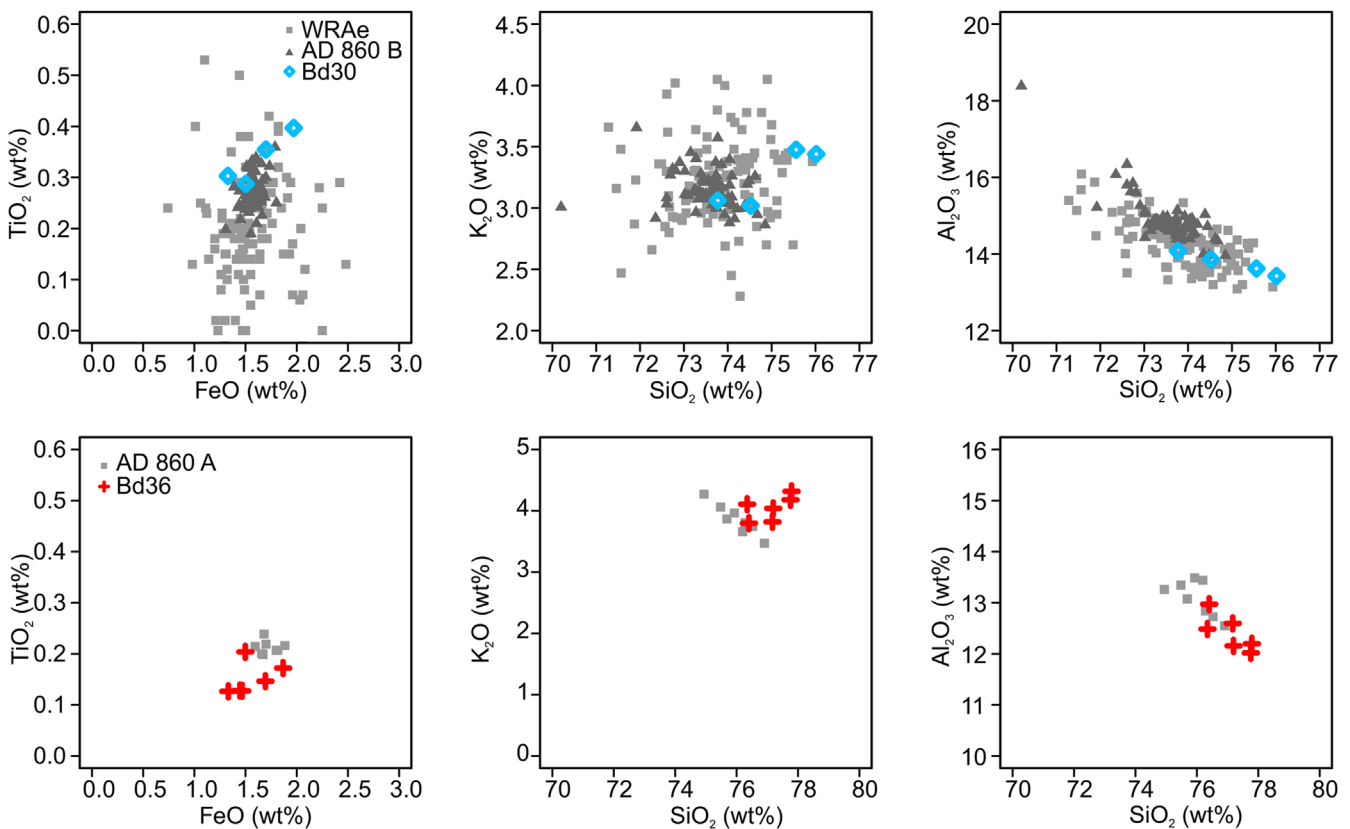


Figure 5. Geochemical bi-plots of major elements of glass from the two tephra layers detected at Bodmin moor (Rough Tor South) plotted against the glass chemistry of known tephra based on type data from Pilcher *et al.* (1995), Hall and Pilcher (2002), Swindles (2006) and Jensen *et al.* (2014).

and correlating palaeoenvironmental records from the south of England and Wales.

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Abbreviations. SC, similarity coefficient; SCP, spheroidal carbonaceous particle; WDS, wavelength dispersive spectroscopy; WRAe, White River Ash (Eastern Lobe).

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