Was there a '4.2 kyr event' in Great Britain and Ireland? Evidence from the peatland record.

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Abstract

Palaeoenvironmental and archaeological data from several regions around the world show evidence of a multi-centennial climatic event occurring approximately 4200 cal yr BP (4.2 kyr). Whilst the climatic change and/or impact of the 4.2 kyr event is clear in certain regions, such as western Asia, evidence for the event has yet to be fully evaluated in northwest Europe. This study presents high-resolution, multi-proxy palaeoclimate records from sites in northern Ireland, ideally located for an objective examination of the nature of the event in Great Britain and Ireland within the broader context of mid-Holocene climate change c. 6.5 – 2.5 kyr. The peatlands of northwest Europe possess considerable potential for the examination of climatic change in the North Atlantic region, demonstrated by the range of palaeohydrological proxy data generated during this study (peat humification, plant macrofossil and testate amoebae analyses) supported by a high-resolution chronology (including comprehensive AMS ^{14}C and tephrochronology). The inter-site testate amoebae reconstructions appear coherent and were combined to produce a regional climatic record, in marked contrast to the plant macrofossil and peat humification records that appear climatically complacent. The testate amoebae reconstruction, however, provides no compelling evidence for a 4.2 kyr event signal and is consistent with previously reported studies from across northwest Europe, suggesting the origin and impact of this event is spatially complex.

Keywords: 4.2 kyr event; 2.8 kyr event; multi-proxy; peatlands; Great Britain and Ireland; testate amoebae; Hekla 4; abrupt and extreme climate change.

1. Introduction

In the context of current and projected future climate change, past abrupt climate events during the Holocene (the last 11.65 kyr; Walker et al., 2009) and their impact(s) on human populations are important foci for palaeoclimatic research (Alley et al., 2003; Broecker, 2006). Unlike early-Holocene events associated with deglaciation at the end of the last glacial period, mid- to late-Holocene events occurred under environmental boundary conditions similar to those of the present day and are therefore likely to provide better analogues for future change.

The '4.2 kyr event' has been identified globally as a period of abrupt climate change (Cullen et al., 2000; Bond et al., 2001; Thompson et al., 2002; Marchant and Hooghiemstra, 2004; Booth et al., 2005; Drysdale et al., 2006; Liu and Feng, 2012), initially associated with urban abandonment and societal collapse in Mesopotamia driven by a severe multi-centennial drought (Weiss et al., 1993). Subsequent work has since linked this event to societal disruption in other key centres of early civilisation (Weiss and Bradley, 2001; Stanley et al., 2003; Staubwasser and Weiss, 2006; Liu and Feng, 2012). In a comprehensive review of palaeoclimatic evidence for the 4.2 kyr event, Roland (2012) found a broad global pattern at this time characterised by pronounced dry conditions at lower latitudes, with more ambiguous but often cooler and/or wetter conditions at higher latitudes of the northern hemisphere and also in South America. Similar climatic anti-phasing has been observed in other palaeoclimate studies associated with the 4.2 kyr event (e.g. Marchant and Hooghiemstra, 2004; Booth et al., 2005) as well as in examinations of modern low-latitude drought episodes (e.g. Hoerling and Kumar, 2003). The origin of the 4.2 kyr event has been linked to ocean-atmospheric circulation changes in the North Atlantic (Bond et al., 2001; Booth et al., 2005; Roland, 2012) but its climatic impact remains poorly understood in comparison to similar events in the Holocene. Despite this, Walker et al. (2012) have recently identified the 4.2 kyr event as a suitable marker to subdivide the Holocene period into 'middle' and 'late' chronozones.

Proxy records developed from ombrotrophic raised bog systems are likely to possess a strong climate signal, owing to their reliance on a combination of precipitation and temperature (Charman, 2007; Charman et al., 2009; Booth, 2010; Amesbury et al., 2012). Their potential in Great Britain and Ireland for recording North Atlantic climatic change is well documented (Charman et al., 2006; Swindles et al., 2013). Progress in the discipline now allows for cross-proxy and cross-site validation of a range of quantitative and semi-quantitative proxy reconstructions (e.g. Blackford and Chambers, 1993; Barber et al., 1994; Charman et al., 2007) to identify and verify the presence of a regional climate signal (e.g. Charman et al., 1999; Chiverrell, 2001; Langdon et al., 2003; Blundell and Barber, 2005; Hughes et al., 2006). Such comparisons are aided by relatively high accumulation rates and the potential for developing highly-precise and accurate chronologies (e.g. ^{14}C and tephrochronology) associated with raised bogs.

Whilst other Holocene climatic deteriorations have been the subject of temporally-focussed, peat-based studies (e.g. Little Ice Age, Mauquoy et al., 2002, De Vleeschouwer et al., 2009; the c. 2.8 – 2.6 kyr event, van Geel et al., 1996, Plunkett, 2006, Chambers et al., 2007; Swindles et al., 2007a, Plunkett and Swindles, 2008; the c. 5.2 – 5.1 kyr event, Magny and Haas, 2004, Caseldine et al., 2005; the 8.2 kyr event, Hughes et al., 2006, Daley et al., 2009), equivalent studies on the 4.2 kyr event are remarkably limited in number. Where records from this period have been reported, data are frequently derived from single-proxy or single-site reconstructions with substantial differences in sampling and chronological resolution (e.g. Hughes et al., 2000; Barber et al., 2003; Barber, 2007; Mauquoy et al., 2008; Daley and Barber, 2012) (see Tab. 1, Fig. 10).

The peatlands of Great Britain and Ireland present an excellent opportunity to study the potential manifestation of the 4.2 kyr event in the region, potentially documenting the timing and nature of its palaeohydrological effects and likely drivers. To help determine the existence, impact and potential driver(s) of the 4.2 kyr in northwest Europe, we have investigated two highly-resolved peat sequences in northern Ireland, along the eastern seaboard of the North Atlantic. To place this event in the context of mid-Holocene climate change, we have undertaken high-resolution, multi-proxy palaeoclimate reconstructions supported by the development of robust chronologies to test whether a coherent 4.2 kyr event can be identified within the broader period of c. 6.5 – 2.5 kyr.

2. Regional setting

Ireland has a maritime climate dominated by prevailing westerly airflow and is sensitive to latitudinal variation of the Westerlies, the influence of the North Atlantic Oscillation (NAO) and thermohaline circulation (THC) and other ocean-atmospheric modes in the North Atlantic (McCabe and Clark, 1998; McDermott et al., 2001; Anderson et al., 2004; Turney et al., 2005, Swindles et al., 2010a). Ireland's climatic sensitivity, coupled with its large number of Holocene age peat sequences (Double, 1954; Smith and Goddard, 1991), well-developed regional tephrochronology (Pilcher et al., 1995a, 1996; Hall and Pilcher, 2002; Lowe et al., 2004) and archaeological record (Woodman, 1985) makes it an ideal location to study the 4.2 kyr event. Importantly, the Hekla 4 tephra horizon (4345 – 4229 cal yr BP; Pilcher et al., 1996), serving as an important temporal marker for the time period, is particularly abundant in the peatlands of northern Ireland.

The lower valleys of the Rivers Main and Bann form an extensive lowland area overlying Tertiary basalts between the Antrim Hills and Sperrin Mountains in northern Ireland. Two ombrotrophic raised bogs, approximately 22 km apart, were investigated here: Sluggan Moss, in County Antrim, and Fallahogy Bog, in County Derry (Fig. 1). Both sites were once part of large peatland complexes but have been affected by peat cutting in recent centuries. Owing to the mid-Holocene focus of this study, however, it is assumed that this activity has not affected the palaeohydrological record from either site during earlier millennia. Sluggan Moss and Fallahogy Bog were also the focus of the first modern palaeoecological studies in the region (Smith, 1958; Smith and Goddard, 1991) and have been employed together many times since (e.g. Pilcher and Hall, 1992; Hall et al., 1993, 1994; Pilcher et al., 1995b, 1996; Hall, 2000, 2003; O'Connell and Molloy, 2001; Swindles *et al*., 2013). Plant macrofossil data produced by this study, together with evidence from previous studies, confirms that both bogs became ombrotrophic over 1000 years before the proposed 4.2 kyr event.

Crucially, earlier work suggests that Ireland's peat archive possesses considerable potential for the examination of climatic variation in the North Atlantic region (Holmes, 1998; Plunkett, 1999, 2006; Barber et al., 2000; Turney et al., 2005; Swindles, 2006; Swindles et al., 2007a, b, 2010a; Amesbury, 2008; Blundell et al. 2008; Plunkett and Swindles, 2008; Langdon et al., 2012). Despite this, few published data extend beyond c. 4.5 kyr (e.g. Swindles et al., 2010a). It is clear, however, that the quality, location and chronological potential of these peatlands makes them an ideal 'testing ground' for ideas regarding the changing nature of North Atlantic climate-forcing mechanisms (Blundell et al., 2008).

3. Materials and methods

3.1 Field and Laboratory sampling

Cores were extracted using a wide-bore Russian ('D'-section) peat corer employing the parallel-borehole method. It has been shown that coring through lawn microforms maximises the potential of a sequence for recording past hydrological variation (Aaby, 1976; Barber et al., 1998; De Vleeschouwer et al., 2010), thus allaying concerns expressed about single-core studies (e.g. Blaauw and Mauquoy, 2012). Core sections were placed in labelled plastic guttering, wrapped in cling-film and/or sealable carbon-stable plastic bags, sealed using electric tape and later stored at a temperature of c. 4°C to minimise biological activity.

Sub-sampling procedure followed conventional methods (De Vleeschouwer et al., 2010) with contiguous (humification analysis) and non-contiguous (plant macrofossil and testate amoebae analysis) samples of 1 cm stratigraphic depth manually removed using a scalpel and spatula. Scissors were used where necessary to cut through root and other material. Sampling resolution for palaeoecological analyses (plant macrofossil and testate amoebae) was between 2 and 4 cm for both profiles. Sampling for tephra analysis followed standard techniques (Pilcher and Hall, 1992). Contiguous samples of 5 cm stratigraphic depth were initially analysed, with resolution increasing to 0.5 cm where a potential tephra horizon was identified.

3.2 Palaeoecological techniques

Preparation for testate amoebae analysis followed standard techniques (Hendon and Charman, 1997; Charman et al., 2000) with minor modifications, including a reduction in sample size from 2 to 1 cm^3 (Amesbury *et al*., 2011). Taxonomy followed Charman et al. (2000), except for the addition of *Centropyxis ecornis* (Booth, 2008) and the reclassification of *Archerella flavum* (Gomaa et al., 2013). At least 100 individual tests were counted for each level (Payne and Mitchell, 2009). Counts of as low as 50 may be sufficient in some circumstances (Payne and Mitchell, 2009) and may still be accepted for statistical analysis (Swindles et al., 2007b), but were avoided in all but a very small number of levels where testate concentration and/or preservation was exceptionally poor. Testate amoebae-derived water table reconstructions were produced using the pan-European ACCROTELM transfer function, based on weighted averaging tolerance-downweighted regression with inverse deshrinking (Charman et al., 2007). Sample-specific errors for the reconstruction were calculated using 1000 bootstrap cycles (Line et al., 1994). A 'local' transfer function is available for northern Ireland (Swindles et al., 2009) but it produces very similar reconstructions to those of more widely employed ACCROTELM model.

Preparation of plant macrofossil material and subsequent analysis followed standard protocols (Barber et al., 2003; Mauquoy et al., 2010), with sample size reduced from 4 to 2 cm^3. A range of type specimens and texts (Grosse-Brauckmann, 1972; Daniels and Eddy, 1990; Smith, 2004; Mauquoy and van Geel, 2006) aided identifications. Palaeoecological diagrams were produced using TILIA and TGView (Grimm, 1991, 2004). For ease of interpretation, it is common practice to transform multivariate plant macrofossil data into a univariate bog surface wetness (BSW) index, but debate continues as to which technique is most effective (e.g. Barber et al., 2003; Swindles et al., 2007b; Amesbury et al., 2012; Daley and Barber, 2012). Detrended Correspondence Analysis (DCA) is widely employed in the peat-based literature and is subsequently employed here to facilitate comparison with other records.

Humification analysis procedures were adapted from the standard colorimetric technique (Blackford and Chambers, 1993), with sample size reduced from 0.2 to 0.1 g. Percentage light transmission data are presented as detrended residuals, following linear regression of the raw data, to remove the down-core tendency towards a higher degree of humification (e.g. Blackford and Chambers, 1995; Langdon et al., 2003; Blundell and Barber, 2005; Borgmark and Wastegård, 2008).

3.3 Chronological techniques

AMS ^{14}C dating of *in situ*, above ground plant remains and tephrochronology was used to construct age-depth models for both sites. Tephra horizons were identified in the peat cores using standard ashing and light microscopy techniques (Pilcher and Hall, 1992; Pilcher et al., 1995a; Hall and Pilcher, 2002; Swindles et al., 2010b) and the isolation of tephra shards followed the acid digestion method (Persson, 1971; Dugmore, 1989; Hall and Pilcher; 2002). Geochemical analysis of tephra shards using electron probe microanalysis (EPMA) was carried out using the Cameca SX100 electron probe microanalyser at the School of Geosciences, Edinburgh University. Analytical conditions were set in order to eliminate sodium migration while maintaining an acceptable level of precision. An accelerating voltage of 15 kV and beam currents of 0.5 nA (Na, Al), 2 nA (Mg, Si, K, Ca, Fe) and 60 nA (P, Ti, Mn) were used with a beam diameter of 3 μm, and 2 nA (Na, Mg, Al, Si, K, Ca, Fe) and 60 nA (P, Ti, Mn) with a diameter of 5 μm (Hayward, 2011). Geochemical results were corrected automatically for atomic number effects, including back-scattering, fluorescence and absorption using a PAP correction programme (Pouchou and Pichoir, 1984). Geochemical results were compared with other relevant datasets (Newton et al., 2007; http://www.tephrabase.org).

Whilst it has been suggested data with oxide totals of less than 95% should be omitted from analyses (Hunt and Hill, 1993), totals exceeding this are not always consistently obtainable, owing frequently to the primary magmatic and/or post-depositional hydration of shards (Pearce et al. 2008) and lower minimum oxide totals (e.g. ≥93%, Eiríksson et al., 2000, Bergman et al., 2004) have been imposed. Given the strong intra-population uniformity of the geochemical data in this study, oxide totals of ≥94% were deemed appropriate. Of the 35 shards analysed from Fallahogy Bog, 24 were accepted for analysis; from Sluggan Moss, 47 shards were analysed with 40 accepted.

Calibration of ^{14}C ages was undertaken using the IntCal09 calibration curve (Reimer et al., 2009) and CALIB v. 6.1.0 (Stuiver et al., 2005). Median point estimates were calculated within the CALIB programme and weighted averages of the date range distribution (2σ) were taken as the midpoint of the range that accounted for the greatest proportion of relative probability (Telford et al., 2004). Full, calibrated probability distributions were used in the construction of age-depth models (Telford et al., 2006; Michczyński, 2007).

4. Results

4.1 Chronology

The rhyolitic Hekla 4 tephra horizon (4345 – 4229 cal yr BP; Pilcher et al., 1996) was identified in both profiles, following comparison of shard geochemistry data between geochemically and/or chronologically similar eruptions (i.e. Hekla 3, Hekla S-Kebister) (Fig. 2). Analysis of shard distribution at 0.5 cm resolution revealed clear and discrete horizons with c. 80% of shards stratigraphically located within 1 cm in both instances. This tephrochronological pinning-point facilitates precise correlation of the proxy climate records, just prior to the hypothesised onset of the 4.2 kyr event and can be incorporated in age-depth models for each profile.

Smaller concentrations of shards found elsewhere in the sequences during the initial ashing process (Fig. 2) were also investigated at higher resolution but no distinct horizons could be identified. Other tephra horizons, occurring during across the period encompassed by this study, have been identified in northern Irish peatland sites. Of note are the BMR-190, GB4-150 and OMH-185 (or 'Microlite') horizons, which are frequently found in close stratigraphic proximity to one another, centring on a period c. 2.6 – 2.7 kyr (Plunkett et al., 2004). The Microlite horizon has been detected in another core taken from Sluggan Moss (Plunkett, 2006) but was not found here. The potential for inter- and intra-site variability in tephra shard deposition is great (e.g. Dugmore and Newton, 1992; Langdon and Barber, 2004), however, and the Microlite horizons have been shown to possess lower shard concentrations and more complex stratigraphic distributions than, for example, the Hekla 4 horizon in this study (Swindles et al., 2010a). Combined, these factors could account for the absence of the Microlite tephra from the sequences in this study.

4.1.1 Age-depth model development

Age-depth models were constructed in *Clam* (Blaauw, 2010), which addresses many of the criticisms of 'classical' age-depth models (e.g. Bennett, 1994; Telford et al., 2004, 2006; Parnell et al., 2011) and is suggested as an alternative where the use of Bayesian approaches are unlikely to add further chronological constraint (Blaauw, 2010).

Table 2 presents details of the ^{14}C and tephrochronological information from both sites from which age-depth models were constructed. Initial exploratory age-depth modelling of the Sluggan Moss sequence revealed ^{14}C date SM204 to be a statistical outlier and it was omitted from further models. No outliers were identified from the Fallahogy Bog sequence. Default settings included a 2σ confidence level (95.4%); 1000 (bootstrap/Monte Carlo) iterations per model, removing those that found age-depth reversals; and calendar age point estimates for depths were based on weighted averages of all age-depth curves. At both sites, small amounts of extrapolation (i.e. 95 – 96 cm and 333 – 350 cm at Sluggan Moss; 195 – 198 cm and 448 – 450 cm at Fallahogy Bog) provided age estimates for all sections of the sequence subjected to palaeoecological analyses.

At both sites, a number of age-depth models were developed and considered. Blaauw (2010) recommends that the use of smooth age-depth models in sequences that accumulated within a stable environment are likely to have experienced fewer hiatus and/or dramatic accumulation changes. As a result, smooth spline models (Fig. 3) were accepted ahead of linear interpolation models, as they do not assume abrupt changes in accumulation rate at the dated depths (Bennett, 1994) for which there was no evidence in either the litho- or biostratigraphies. Polynomial regressions of varying orders were attempted, but performed poorly at both sites with higher order models producing too many age reversals. Conversely, lower order polynomials, which ran successfully were deemed too rigid to accurately model the data (Bennett and Fuller, 2002).

Based on these smooth spline models, accumulation rates fluctuate between c. 14 and 25 years cm^{-1}, with an average of 17 years cm^{-1} at Sluggan Moss, and c. 4 and 20 years cm^{-1}, with an average of 11 years/cm^{-1} at Fallahogy Bog, consistent with previous accumulation rate estimates at both sites (e.g. Plunkett, 2006, 2009; Amesbury, 2008).

4.2 Palaeoecological results

4.2.1 Plant macrofossils

Plant macrofossil data are summarised in Figures 4 and 5. Both profiles are dominated by *Sphagnum austinii*, with periodic incursions of other *Sphagnum* species of the *Acutifolia* and *Cuspidata* sections. DCA of the plant macrofossil data produced eigenvalues of 0.6145 at Sluggan Moss and 0.4738 at Fallahogy Bog, therefore approaching or exceeding the desired value of >0.5 (ter Braak, 1995). The slightly poorer score at Fallahogy Bog could be explained by the exceptional dominance of *S. austinii*, with *S.* s. *Acutifolia* achieving concentrations over 20% just three times within the studied sequence. The absence of *S.* s. *Cuspidata*, together with an increased abundance of unidentified organic matter (UOM) compared with levels seen at Sluggan Moss, indicates that Fallahogy Bog was historically the drier site. Nevertheless, at both sites species were distributed along the first axes in such a way as to indicate the presence of a latent BSW gradient within the data, as species indicative of drier (e.g. *Calluna vulgaris*, *Erica tetralix*, *Trichophorum cespitosum*) and wetter (e.g. *S.* s. *Cuspidata*, *Eriophorum angustifolium*) conditions were positioned at either end of the axes. Distribution of species scores at both sites approached 5 standard deviations along this first axis, suggesting a lack of overlap between species of different hydrological preferences, further strengthening subsequent interpretation (Daley and Barber, 2012)

4.2.2 Humification

Contiguous detrended percentage light transmission data are shown alongside plant macrofossil data in Figures 4 and 5. At Sluggan Moss, three notable shifts towards higher transmission values and lower degrees of humification, potentially indicative of wetter and/or cooler climatic conditions, occur (to the nearest 50 years) c. 5.5 – 5.2, 4.05 – 3.85 and 2.75 – 2.55 kyr. At Fallahogy Bog the data exhibit greater variability with periods of higher transmission values less defined, but a number of shifts characterised by prolonged (>10 cm) trends towards higher transmission values begin at c. 5.65, 5.05, 4.55, 4.35, 4.2 and 3.55 kyr.

4.2.3 Testate amoebae

Summaries of the fossil testate amoebae data are shown in Figures 6 and 7. Fallahogy Bog appears to be a generally drier site, with species indicative of moderate to dry conditions (e.g. *Assulina muscorum*, *Difflugia pristis*-type and *Trigonopyxis arcula*-type) broadly more prevalent than at Sluggan Moss. The records at both sites are characterised by the interchange between two dominant species, *Archerella flavum* and *Difflugia pulex*. Although relatively underrepresented in surface samples compared with other species, *D. pulex* occupies a relatively dry position in the current pan-European transfer function (Charman et al., 2007), whereas *A. flavum* is generally considered indicative of wetter bog surface conditions.

DCA of the datasets, to identify any latent environmental gradients influencing the data (cf. Woodland et al., 1998; Chiverrell, 2001), performed well with species distributed across the respective first axes clearly demonstrating a water table gradient, as wet indicator taxa (e.g. *A. flavum* and *Amphitrema wrightianum*) and dry indicator taxa (e.g. *Trigonopyxis arcula* and *Hyalosphenia subflava*) were located toward either end of the axes. The relatively poor eigenvalues at Sluggan Moss (0.2819) and at Fallahogy Bog (0.2369) could be explained by the relative abundance and covariance of the two dominant species. Subsequently, the data were submitted to the pan-European ACCROTELM transfer function (Charman et al., 2007). Sample-specific errors were calculated using 1000 bootstrap cycles (Birks et al., 1990; Line et al., 1994).

5. Discussion

5.1 Establishing a regional palaeoclimate record

Peat-based palaeoclimate data from Great Britain and Ireland rarely extend back far enough to provide sufficient context to satisfactorily evaluate any potential manifestation of a 4.2 kyr event, often focusing on the last c. 4.5 kyr (e.g. Charman et al., 2006; Swindles et al. 2010a). Where longer records exist, they tend to lack the sampling and chronological resolution necessary to examine the timing and nature of mid-Holocene climatic events, and are often based on single palaeoecological proxy reconstructions (e.g. plant macrofossils: Hughes et al., 2000; Barber et al., 2003; testate amoebae: Mauquoy et al., 2008).

Inconsistencies between peat-based proxies from the same sequence are well documented (e.g. Charman et al., 1999; Chiverrell, 2001; Mauquoy et al., 2002; Blundell and Barber, 2005 Hughes et al., 2006). Subsequently, the importance of multi-proxy, multi-site studies for the cross-validation of proxy reconstructions and the establishment of a more robust regional climate signal is increasingly recognised. If an allogenic climatic signal is present in palaeoecological data it would be reasonable to expect high-resolution datasets with robust chronological control, such as those presented in this study, to exhibit a degree of coherence between profiles in a similar vicinity, on a proxy-by-proxy basis (cf. Mauquoy and Barber, 1999).

5.1.1 Plant macrofossils

At both sites, DCA axis one scores are heavily influenced by variations in the dominant *Sphagnum* species. This is especially clear at Sluggan Moss, where alternations between *S*. s. *Acutifolia*, *S*. s. *Cuspidata* and the dominant *S*. *austinii* are abrupt. As the drier of the two sites, Fallahogy Bog's axis one score is largely driven by interchanges between *S*. *austinii* and UOM values. Modern examples of *S*. *austinii* have been shown to be capable of growing in relatively xeric conditions (Mauquoy and van Geel, 2006), whilst the species' ability to grow under wetter bog surface conditions within the fossil record has also been demonstrated (Casparie, 1972; van Geel, 1978; Barber, 1981). Owing to the relatively broad tolerance of *S*. *austinii* to water-table depth changes, records dominated by the species can exhibit climatic insensitivity, demonstrating complacency towards small-scale changes of either short duration or low magnitude (cf. Blundell and Barber, 2005; Hughes et al., 2006). Barber et al. (1994) found plant macrofossil records to be at their most climatically sensitive when populated by a range of *Sphagnum* species, rather than a single eurytopic taxa.

Figure 8A plots normalised plant macrofossil DCA axis one data from both sites against one another on a common age axis. Despite their topographic and environmental similarity and relative proximity to one another (c. 22 km), little coherence can be seen between the records, including between c. 4.25 – 3.75 kyr. This suggests that any climate signal present in these data is weak during this period, most likely owing to climatic complacency caused by the dominance of *S*. *austinii* at both sites, and so should not be used to examine the timing and nature of the 4.2 kyr event.

5.1.2 Humification

Although the efficacy of humification analysis for producing records of past changes in BSW has recently been called into question, owing to potentially differential decay rates in the various peat-forming plant species (Yeloff and Mauquoy, 2006), the role of secondary decomposition during short-lived dry periods (Borgmark and Schoning, 2006) and issues associated with the humic acid extraction itself (Caseldine et al., 2005), the technique remains a relatively quick and simple way to produce high-resolution, contiguous datasets, which, when incorporated as part of a comprehensive palaeohydrological multi-proxy study, can aid palaeoclimatic reconstruction.

Variability in humification values at both sites follows distinctive patterns that correspond strongly to shifts in plant macrofossil data. These patterns can be seen by comparing the plant macrofossil DCA axis one scores with percentage light transmission values in Figures 4 and 5. Relationships can be statistically validated by calculation of Pearson product moment correlation coefficient (PPMCC) between all humification values and plant macrofossil DCA axis one scores, revealing moderately strong correlations at both Sluggan Moss (PPMCC = -0.602, $p < .05$) and Fallahogy Bog (PPMCC = -0.441, $p < .05$).

Differential decay rates between peat-forming species can result in the reflection of botanical changes, alongside or in place of any direct climatic signal, in humification records (Yeloff and Mauquoy, 2006). The strength of the visual and statistical relationships suggests the presence of a 'species signal' within the humification data at both sites. Hughes et al. (2012) developed a method of adjusting humification data, based on the *k*-values of the species present, in an effort to remove this 'species signal'. However, they found the technique to be most effective over long (>8000 years) timescales where abrupt changes between *Sphagnum*- and sedge-dominated peats occurred, rather than shorter sequences in which *Sphagnum* generally dominates. The technique was subsequently not applied here.

As the likely climatic complacency of the plant macrofossil data from both sites has already been demonstrated, corresponding humification data, strongly affected by botanical composition, are unlikely to present a coherent regional climate signal. By plotting records on a common age axis, it becomes clear that only limited regional coherence exists (Fig. 8B), with little or no coherence during the period c. 4.25 – 3.75 kyr period, implying that the data do not yield a consistent climatic signal during this period and so should not be used to examine the timing and nature of the 4.2 kyr event.

5.1.3 Testate amoebae

Once errors associated with ^{14}C dating are taken into consideration, the two water table reconstructions exhibit a good degree of coherence (Fig. 8C) suggestive of a common climatic driver. As well as intra-site consistency in the broad patterns of peaks and troughs in inferred water table depth, two key periods of documented mid- to late-Holocene climatic change appear to register in both profiles. Firstly, the period c. 5.5 – 5.15 kyr is characterised at both sites by a broad climatic downturn, with a persistence of higher water tables, consistent with other records from Europe (e.g. Magny and Haas, 2004; Caseldine et al., 2005). Furthermore, considerable agreement is demonstrated as water table conditions indicate the presence of a regional drought period, consistent with Swindles et al. (2010a), before descending into the well-documented '2.8 kyr event' (e.g. van Geel et al., 1996; Barber et al., 2004; Plunkett, 2006; Swindles et al., 2007a).

Comparison of transfer function reconstructions with instrumental climate data from the recent past has shown testate amoebae to be reliable in reconstructing even relatively low amplitude water table changes (Charman et al., 2004). This degree of sensitivity must be enabled, at least in part, by the rapid response time of testate amoebae to environmental change (Buttler et al., 1996; Amesbury et al., 2012), likely to be facilitated by rapid reproduction rates exhibited by the organisms (McCarthy et al., 1995, Charman, 2001). These characteristics are encouraging to those wishing to reconstruct periods of change, which are abrupt and/or subtle in nature. Indeed, Blundell and Barber (2005) found that in some circumstances, testate amoebae reconstructions are more consistent than the other BSW reconstruction techniques, which, as observed here, can exhibit complacency.

5.1.4 Tuning and stacking

Since only the testate amoebae data expressed consistent regional coherence, they have been combined to produce a regional, mid-Holocene palaeoclimate reconstruction following the methods of Charman et al. (2006) and Blundell et al. (2008) in Great Britain and Swindles et al. (2010a) in Ireland. After conversion to normalised values, key points of change, based on peaks and troughs, were identified in each record, with an average age calculated for each 'match point' based on the original age-depth models. An adjusted age-depth model was produced based on linear interpolation, in preference to polynomial and regression models (cf. Telford et al., 2004), between these match points. The revised chronology also included the Hekla 4 tephra isochron as an independent time-parallel marker horizon (cf. Langdon and Barber, 2004).

Charman et al. (2006) stated that whilst this process cannot guarantee that the revised chronology is any nearer to the true age-depth relationship, it is important that the age estimates are consistent with the original age-depth model for any of the incorporated records. Subsequently, the revised chronology was plotted alongside each original chronology, to ensure that it fell within the initial age estimates (at 2σ error).

The potential for subjectivity in the tuning process has, however, been criticised (Blaauw, 2012). Swindles et al. (2012a) emphasised the importance of presenting alternative tuning scenarios, based on plausible combinations of match points. Therefore, a number of a number of plausible combinations were considered, with the set chosen (Fig. 9, i – x) representing the most parsimonious scenario, in that they required the least chronological migration from the existing age-depth models.

The composite record was produced by merging data from each record using a 100-year moving average, retaining long-term climate signals, whilst reducing chronological and ecological uncertainties specific to each site's record (Charman et al., 2006; Blundell et al., 2008). As the studied sequence is temporally shorter at Fallahogy Bog, values from Sluggan Moss were taken as being representative of the region for the periods at either end of the combined record. The result is a regional palaeoclimate curve spanning approximately 4000 years, between c. 6.5 – 2.5 kyr (Fig. 9C) which, whilst bearing in mind the potential for chronological and reconstructive error (Swindles et al., 2012a), is presented as a regional palaeoclimatic curve, overcoming problems that beset the correlation of such records and providing a more reliable basis for comparisons with other regional records than single-proxy, single-site records alone (cf. Charman et al., 2006).

5.2 A 4.2 kyr event in Great Britain and Ireland?

During the period c. 4.25 – 3.75 kyr some moderate increases in water table depth can be seen in the stacked testate amoebae records from Sluggan Moss and Fallahogy Bog (Fig. 10A), but these are not distinguishable from variability elsewhere in the studied sequence and therefore present no compelling evidence to support previous assertions that this was a marked period of prevailing wet conditions in Great Britain and Ireland (e.g. Hughes et al., 2000; Barber et al., 2003; Barber, 2007; Mauquoy et al., 2008; Daley and Barber, 2012).

Other stacked testate amoebae data from northern Ireland (Fig. 10B; Swindles et al., 2010a) and northern Britain (Fig. 10C; Charman et al., 2006) lack sufficient temporal resolution toward the beginning of the c. 4.25 – 3.75 kyr period and do not persist back beyond c. 4.5 kyr, making contextualisation of a potential 4.2 kyr event difficult. Together with a fourth lower-resolution, stacked but untuned palaeoecological (i.e. plant macrofossil and testate amoebae data) record from Scotland (Fig. 10D; Langdon and Barber, 2005), these records display some broad correlation, but agreement during the c. 4.25 – 3.75 kyr period is negligible.

Figure 10 (E – J) presents a number of peat-based palaeoecological records from Great Britain and Ireland, in an effort to establish regional coherence. Four of these records (Walton Moss, Fig. 10E, Hughes et al., 2000; Butterburn Flow, Fig. 10F, Mauquoy et al., 2008; Abbeyknockmoy Bog, Fig. 10H; Barber et al., 2003; Bolton Fell Moss, Fig. 10I, Barber et al., 2003) demonstrate some form of shift to wetter conditions during the c. 4.25 – 3.75 kyr period, but coherence in terms of timing, duration and signal structure is relatively poor.

The above records exhibit rather more complex variability than the high-resolution stacked records (Figs. 10A – C) supporting an assertion that climate is not the sole driver of these records. Indeed three records (Fig. 10E, H and I) are based on plant macrofossil data alone, which this study along with others (e.g. Blundell and Barber, 2005; Hughes et al., 2006) has demonstrated a potential for periodic climatic complacency, a feature most obviously demonstrated during this period by the record from Mongan and Abbeyknockmoy Bogs, central Ireland (Fig. 10G, Barber et al., 2003).

Sampling strategy and chronological control also varies greatly between these records. For example, analytical resolution of the testate amoebae record at Butterburn Flow is extremely varied, and whilst dating resolution is relatively good at Bolton Fell Moss during the c. 7.0 – 2.0 kyr period presented here, the ^{14}C ages were obtained from bulk samples, which included material from up to 8 vertical cm; a relatively imprecise practice abandoned in the wake of the small samples sizes required and stratigraphic precision afforded by AMS ^{14}C dating. Similarly, linear regression age depth models were employed at Abbeyknockmoy and Mongan Bogs and Bolton Fell Moss, which are unlikely to present a realistic model of peat accumulation, especially given the dramatic alternations between *Sphagnum* and monocotyledonous material within the sequences.

A second, multi-proxy record from Walton Moss (Fig. 10J, Daley and Barber, 2012) demonstrates a shift toward wetter conditions c. 4.2 kyr. However, shifts of similar relative magnitude occur elsewhere in the record and comparison of these data with other records from the region again reveals considerable disagreement with key regional trends. For example, the period after c. 3.0 kyr is characterised by a notable drying trend in this Walton Moss core, whereas the majority of other records from region exhibit a clear, if complex, shift towards wetter conditions, perhaps questioning the record's legitimacy as an archive solely of climatic change.

Broad regional comparisons of these and a number of other similar bog records have been undertaken in an attempt to identify periods of climatic change in northwest Europe (e.g. Hughes et al., 2000; Barber et al., 2003, 2004; Barber, 2007). However, in light of the various issues outlined here, it could be suggested that in some instances, such as the 4.2 kyr event, it is very difficult to reconcile inconsistencies in chronological and analytical resolution, especially when hypothesised proxy climate records from those sites have not been cross-validated with equivalent records in the immediate vicinity. In comparison, the regional palaeoclimate record developed by this study was the result of comprehensive inter- and intra-site cross-validation of proxy records of robust chronology, from climatically sensitive sites in a region heavily influenced by North Atlantic ocean-atmosphere circulation systems, changes in which are proposed as influential factors of the 4.2 kyr event. From this record, alongside comparisons with other regional peat-based records, no regionally coherent, prolonged phase of notably wetter and/or colder prevailing climatic conditions associated with the 4.2 kyr event in Great Britain and Ireland could be identified.

The lack of a coherent 4.2 kyr event in Great Britain and Ireland implies that the dominant forcing mechanisms of the period of change may not lie in the North Atlantic, or at least that any atmospheric-oceanic circulation changes in the region may not have been severe enough to register in the peatland archive. The manifestation of the event at lower latitudes, most often as a period of drier conditions, is far more convincing (Roland, 2012) and therefore further work, possibly by simulating the specific event using general circulation models, is required to shed further light on the event's likely causes.

5.3 Other mid-Holocene climatic events

The fact that the '2.8 kyr event' complex is so clearly visible in this study's stacked testate amoebae record further emphasises its legitimacy as a regional palaeoclimate record. Figure 10 highlights this period across all previously discussed records showing that, within the errors associated with ^{14}C dating, a period of considerable climatic change can be seen in the majority of profiles between c. 3.25 – 2.6 kyr, characterised by an overall downward shift towards wetter conditions, preceded by a notably drier period.

A 'double-dip' pattern can be clearly seen in all of the higher-resolution stacked records from northern Ireland (this study; Swindles et al., 2010a) and northern Great Britain (Charman et al., 2006) (Fig. 10A – C). Disparity in the timing of these changes may be accounted for by the error margins of their ^{14}C chronologies and the comparatively small number of records used in the northern Irish studies, compared to Great Britain.

The initial shift to drier conditions c. 3.25 kyr is particularly prominent in the testate amoebae records from Sluggan Moss (Fig. 6) and Fallahogy Bog (Fig. 7), representing the largest magnitude shift in either record and possessing such a degree of chronological coherence between sequences that it can be confidently attributed to a significant climatic change.

Swindles et al. (2010a) found evidence for a number of widespread summer 'drought' phases in two late-Holocene peat records from northern Ireland, the earliest of which was dated to c. 1150 – 800 BC (i.e. c. 3.1 – 2.75 kyr). As is the case in the WTD reconstructions presented in this study, the drought phases identified by Swindles et al. (2010a) were followed immediately by significant shifts back towards wetter conditions. The similarity in this pattern, coupled with the potential for minor chronological offset between the tuned and stacked records produced here and by Swindles et al. (2010a), leads to the conclusion that the events are the same, with the reasonable assumption made that chronological error can account for the slight disparity in timing. Subsequently, this temporal correlation indicates the presence of a significant climatic change around this time, and further confirms the climatic nature of the regional signal produced by the testate amoebae data.

The succeeding wet shift, commencing c. 3.1 kyr, persists until c. 2.6 kyr, but is punctuated by a short-lived dry period centring c. 2.8 kyr. When likely chronological discrepancies are taken into consideration, this pattern is consistent with many BSW records from Great Britain (e.g. Walton Moss, Hughes et al., 2000, Fig. 10E; Butterburn Flow, Mauquoy et al., 2008, Fig. 10F) and central Ireland (e.g. Abbeyknockmoy, Barber et al. 2003, Fig. 10H; Mongan Bog, Barber et al., 2003; Fig. 10G), as well as stacked records from northern Great Britain (Fig. 10C, Charman et al., 2006) and Scotland (Fig. 10D, Langdon and Barber, 2005), despite the latter's lower resolution. If the potential chronological issues regarding the Swindles et al. (2010a) stacked record, outlined above, are extended through this period, then good agreement also exists here. At many of these sites, the wet phase persists until c. 2.3 kyr. In the stacked record presented here (representing only Sluggan Moss data at this age), however, water tables appear to return to levels comparable with the sequence mean c. 2.6 kyr, although, these levels are still significantly below the preceding dry period.

Further comparison with palaeoclimatic records from the North Atlantic region demonstrates that the c. 3.25 – 2.3 kyr period is characterised by significant climatic variation, appearing broadly concurrent with IRD event 2 (Bond et al., 2001). Sea surface temperatures in the North Atlantic (Sejrup et al., 2011) and GISP2 Na concentrations, a proxy for the latitudinal extent of the polar vortex (O'Brien et al., 1995), rise and fall in a fashion very similar to the pattern witnessed in this study's stacked palaeoecological record during the period. Records of estimated temperature from Greenland also display a decline at this time (Alley, 2000).

Overall, this collective body of evidence further reinforces previous assertions, that this period was one of major climatic change in both hemispheres, often hypothesised to have had considerable societal repercussions and characterised by a decline to wetter and/or colder conditions just after c. 3.0 kyr in northwest Europe (e.g. van Geel et al., 1996, 2004; Chambers et al., 2007; Tipping et al., 2008).

Many studies have attributed these changes to fluctuations in solar activity, dominated by a reduction c. 2.8 – 2.71 kyr (e.g. van Geel et al., 1996, 1998; Speranza et al., 2002; Blaauw et al., 2004a; Mauquoy et al., 2004b). However, in Ireland, it has been suggested that whilst records exhibit evidence for a similar response to this solar forcing, this manifestation is delayed by approximately 100 years (Swindles et al., 2007a; Plunkett and Swindles, 2008). It has been suggested that this is perhaps the result of the island's proximity to the ocean, with peatlands responding to solar-mediated changes in ocean circulation patterns (Mauquoy et al., 2008). Plunkett (2006) has also discussed the possibility of a non-uniform response to solar forcing, but still the precise nature of the impact of solar forcing on peat-based palaeoclimate records remains uncertain. Whilst the chronologies presented in this study can be considered robust, it would still be difficult to assess whether variation in solar activity had any bearing on the palaeoecological changes seen here, on the basis of these data. The complex period of change characterised by an initial shift to drier conditions c. 3.25 kyr does, however, appear to precede any major changes in solar activity.

6. Conclusions

Evidence for the '4.2 kyr event' has been reported globally and is strongest, but not limited to, the lower latitudes (Roland, 2012). The broad spatial scale, severity of its effects in some regions and apparent manifestation in the archaeological record (Weiss and Bradley, 2001; Staubwasser and Weiss, 2006) highlight the period as one of great palaeoclimatic importance and societal interest. The 4.2 kyr event was most likely caused by a complex set of interactions within the global ocean-atmosphere circulation system.

Although some previous peat-based data have suggested a period of climatic change in Great Britain and Ireland at this time, this study found no compelling evidence support this, despite using methods and site selection criteria specifically designed with this purpose in mind. The high-resolution, multi-proxy palaeoecological records from the North of Ireland provided the best opportunity to examine this event, in terms of the potential for climatic sensitivity and chronological constraint, in northwest Europe. It is possible that homeostatic water table responses masked the effects of climatic forcing during the 4.2 kyr event at one or both of the peatlands employed in this study (cf. Swindles et al., 2012b), but the lack of coherence between these and other regional BSW/WTD reconstructions at this time suggests that this was not the case (Fig. 10). As a result it is argued that the manifestation of the 4.2 kyr event in Great Britain and Ireland is unclear and of questionable significance, and its use as a new Middle-Late Holocene boundary (Walker et al., 2012) may not be justified in the northwest European region. Furthermore, these findings emphasise that caution must be exercised when correlating changes in the archaeological record to 'events' in climatic record. Changes in both the climatic and archaeological archives are frequently time-transgressive and/or of spatially variable manifestation. As a result, climatic change, whilst providing important context for cultural changes, can rarely be identified as a determining factor (Coombes and Barber, 2005; Brown 2008) and these relationships are often far more complex (Tainter, 1988; Amesbury et al., 2008; Brown et al., 2011). The findings of this study support the suggestion that simple correlations between climatic events and hypothesised societal responses are likely to be problematic.

The effects of non-climatic and/or allogenic forcing factors on BSW/WTD reconstructions (Swindles et al., 2012b) were minimised in this study through careful site selection and intra-site proxy record comparison. However, certain palaeoecological proxy records (e.g. plant macrofossil and humification) still exhibit signs of climatic complacency. This suggests that the construction of composite BSW curves and the identification of wet shifts based upon multi-proxy climate curves should never be attempted without confirming first that each record used represents a robust regional climatic signal. This can be achieved through the inter-site comparison of proxy reconstructions.

As a result of the climatic complacency of proxy records in certain instances, a multi-proxy, multi-site approach to the examination of Holocene climatic change and the events within that variability is essential. In this study, this approach enabled climatically insensitive records from both sites to be identified and excluded from further analyses. This study also found that by fully exploring the potential of both ^{14}C and tephrochronological dating techniques, inter-site comparisons can be far more robust and should be practiced to the greatest extent possible.

Currently there is a disparity between the reality and the potential of long-core peat-based multi-proxy palaeoclimate studies in Ireland as the majority of records do not extend beyond 4.5 kyr. Owing to the region's proximity to the climatically-important North Atlantic, the potential palaeoclimatic contribution of the region is great and further research may yield important developments in our understanding of mid and early-Holocene climate change in the region, especially if recent developments in the reconstruction of atmospheric circulation changes based on geochemical and mineralogical data (e.g. Daley et al., 2010; De Jong et al., 2006; De Vleeschouwer et al., 2009) are extended here.

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Figure 1. Map showing the location of study sites: a) Sluggan Moss, County Antrim (54°45’56N, 6°17’37”W, 42m asl) b) Fallahogy Bog, County Derry (54°54’42N, 6°33’40”W, 43m a.s.l.). Map adapted, with permission, from Walker et al. (2012).

Figure 2. Stratigraphic distribution and geochemical comparison of tephra shards found at Sluggan Moss (black-lined distribution) and Fallahogy Bog (grey-lined distribution), with comparisons of geochemical data derived from electron probe microanalysis with that of Hekla 4 (dark grey distribution, both diagrams), Hekla-S/Kebister (light grey distribution, upper diagram) and Hekla 3 (light grey distribution, lower diagram) type material obtained from Tephrabase (Newton et al., 2007). Black bar charts indicate shard distribution at 5cm ashing resolution. Black line histograms show shard distribution at an increased 0.5cm ashing resolution of samples indicated by the black dotted lines. Appendix A (Supplementary Information) contains details of the geochemical data displayed here.

Figure 3. Age-depth models for Sluggan Moss and Fallahogy Bog, based on smooth spline models between AMS ^{14}C dates (blue) and the Hekla 4 tephra horizon (turquoise). The ^{14}C dates are presented as calibrated years before present with 2σ ranges. Calendar age point ‘best’ estimates for depths are presented (black line) based on weighted average of all age-depth curves produced during 1000 bootstrap/Monte Carlo iterations (grey distributions). The Sluggan Moss model possesses an estimated uncertainty range of 54 – 126 years with an average uncertainty of 80 years, whereas the Fallahogy Bog model has a range of 54 – 251 years with an average of 105 years.

Figure 4. Summary palaeoecological diagram showing selected plant macrofossil and humification data from Sluggan Moss. Plant macrofossil data are displayed as percentages; percentage light transmission and plant macrofossil DCA axis one scores have been normalised for comparison with other palaeoecological proxies; increasing bog surface wetness conditions are indicated by shifts to the left in these curves. The stratigraphic position of the Hekla 4 tephra horizon is shown by the light grey band (H4).

Figure 5. Summary palaeoecological diagram showing selected plant macrofossil and humification data from Fallahogy Bog. Plant macrofossil data are displayed as percentages; percentage light transmission and plant macrofossil DCA axis one scores have been normalised for comparison with other palaeoecological proxies; increasing bog surface wetness conditions are indicated by shifts to the left in these curves. The stratigraphic position of the Hekla 4 tephra horizon is shown by the light grey band (H4).

Figure 6. Summary palaeoecological diagram showing selected testate amoebae data from Sluggan Moss displayed as percentages; Inferred WTD reconstructions based on the ACCROTELM pan-European transfer function (black curve) with errors derived from bootstrapping (grey curves). The stratigraphic position of the Hekla 4 tephra horizon is shown by the light grey band (H4).

Figure 7. Summary palaeoecological diagram showing selected testate amoebae data from Fallahogy Bog displayed as percentages; Inferred WTD reconstructions based on the ACCROTELM pan-European transfer function (black curve) with errors derived from bootstrapping (grey curves). The stratigraphic position of the Hekla 4 tephra horizon is shown by the light grey band (H4).

Figure 8. Comparison of data for: A) plant macrofossil DCA palaeoecological data, B) humification and C) testate amoebae-based reconstructed water table at Sluggan Moss (black) and Fallahogy Bog (grey), plotted against a common age axis. Downward trends indicate shifts towards wetter bog surface conditions, with drier bog surface conditions indicated by upward trends. The shaded c. 3.75 – 4.25 kyr section represents the period within which the ‘4.2 kyr event’ might be expected to occur. All data are normalised to aid comparison.

Figure 9. Normalised testate amoebae-inferred water table depth reconstructions from: A) Sluggan Moss and B) Fallahogy Bog, detailing the match points (i – x) and Hekla 4 tephra horizon used to tune the chronologies; C) regional composite water table record for northern Ireland, based on Sluggan Moss and Fallahogy Bog.

Figure 10. Comparison of this study's stacked water table record with peat-based palaeoecological studies from Great Britain and Ireland. All normalised and plotted against standard units. Leftward trends indicate shifts towards wetter bog surface conditions, with drier bog surface conditions indicated by rightward trends. A) Northern Irish stacked (2 records) testate amoebae-inferred WTD reconstruction (this study); B) Northern Irish stacked (2 records) testate amoebae-inferred WTD reconstruction (Swindles et al., 2010a); C) Northern British stacked (12 records) testate amoebae-inferred WTD reconstruction (Charman et al., 2006); D) Scottish stacked (7 records) multi-proxy palaeohydrological reconstruction (Langdon and Barber, 2005); E) Walton Moss, northern England, plant macrofossil DCA BSW reconstruction (Hughes et al., 2000); F) Butterburn Flow, northern England, testate amoebae-inferred WTD reconstruction (Mauquoy et al., 2008); G) Mongan Bog, central Ireland, plant macrofossil DHI BSW reconstruction (Barber et al., 2003); H) Abbeyknockmoy Bog, central Ireland, plant macrofossil DHI BSW reconstruction (Barber et al., 2003); I) Bolton Fell Moss, northern England, plant macrofossil DHI BSW reconstruction (Barber et al., 2003); J) Walton Moss, northern England, plant macrofossil DHI BSW reconstruction (grey), testate amoebae-inferred WTD reconstruction (black solid) and humification (black dashed). N.B. Records G), H) and I) were digitised from hard copies as original data were unavailable (Barber, pers. comm.). Dark grey shading shows, for reference, the period c. 4.25 – 3.75 kyr. Light grey bands refer to periods c. 5.5 – 5.0 and c. 3.2 – 2.3 kyr.

Table 1

Study	Site(s)	Proxy (stats)	Proposed nature of change	Proposed age of change; Chronological control (2.5 – 6.5 kyr)
Hughes et al. (2000)	Walton Moss, northern England	Plant macrofossils (DCA)	Major wet event	4.41 – 3.99 kyr; 2 radiometric ^{14}C dates of bulked material from 8 cm stratigraphic depth, no tephrochronology.
Barber et al. (2003)	Abbeyknockmoy Bog, central Ireland	Plant macrofossils (DCA)	Major change to wetter/cooler conditions	4.4 kyr; 7 radiometric ^{14}C dates of bulked material from 2 cm stratigraphic depth, no tephrochronology.
	Bolton Fell Moss, northern England	Plant macrofossils (DCA)	Major change to wetter/cooler conditions	4.4 kyr; 10 radiometric ^{14}C dates of bulked material from 3 – 8 cm stratigraphic depth, no tephrochronology.
Barber (2007)	Review of studies (1976 – 2005) from a number of sites across Ireland and northern Great Britain, as well as elsewhere in NW Europe	Plant macrofossils (DCA), testate amoebae (TF), humification (%T)	Changes to cooler/wetter conditions	Range from 4.62 to 3.99 kyr; high variability in chronological strategy between studies, tephrochronology limited to one study
Mauquoy et al. (2008)	Butterburn Flow, northern England	Testate amoebae (TF); plant macrofossils	Moderate wet shift	c. 4.15 kyr; 14 AMS ^{14}C dates, no tephrochronology.
Daley and Barber (2012)	Walton Moss, northern England	Testate amoebae (TF), plant macrofossils (DCA/NMDS/DHI), humification (%T)	Rapid shift to wetter conditions	c. 4.2 kyr; 14 AMS ^{14}C dates, no tephrochronology.

Table 1. Existing evidence used to support the presence of a 4.2 kyr event in Great Britain and Ireland (Detrended Correspondence Analysis – DCA; Non-metric Multidimensional Scaling – NMDS; Dupont Hydroclimatic Index – DHI; Transfer Function – TF; Percentage Light Transmission - %T; all AMS ^{14}C dates were from 1 cm stratigraphic depth).

Table 2

Site	Sample code	^{14}C Lab. code	Depth (cm)	Material	^{14}C age (BP)	$\delta^{13}C$ (‰)	Calibrated age (2σ; cal yr BP)	
							Age range	*WA mid-point*
Sluggan Moss	SM96	UBA-19064	96 – 97	*Sphagnum* stems and leaves	2281 ± 27	-26	2163 – 2349	2326
	SM148	SUERC-33593	148 – 149	*Sphagnum* stems and leaves	2912 ± 36	-26.3	2952 – 3207	3059
	SM168	SUERC-33594	168 – 169	*Sphagnum* stems and leaves	3246 ± 35	-23.4	3391 – 3559	3475
	SM188	BETA-284116	188 – 189	*Sphagnum* stems and leaves	3450 ± 40	-25.3	3616 – 3834	3725
	SM204	UBA-19708	204 – 205	*Sphagnum* stems and leaves	3990 ± 35	-32.3	4319 – 4568	4470
	Hekla 4	-	*222*	-	-	-	*4229 – 4345*	-
	SM238	UBA-19709	238 – 239	*Sphagnum* stems and leaves	4184 ± 35	-29.4	4585 – 4839	4690
	SM254	SUERC-33595	254 – 255	*Sphagnum* stems and leaves	4379 ± 36	-22.7	4858 – 5042	4950
	SM270	SUERC-33596	270 – 271	*Sphagnum* stems and leaves	4744 ± 38	-24.9	5326 – 5587	5517
	SM282	BETA-284117	282 – 283	*Sphagnum* stems and leaves	4870 ± 40	-25.4	5483 – 5709	5621
	SM296	SUERC-33598	296 – 297	*Sphagnum* stems and leaves	5058 ± 35	-27.3	5726 – 5906	5816
	SM333	UBA-19065	333 – 334	*Calluna vulgaris* wood	5617 ± 31	-26.3	6311 – 6465	6382
Fallahogy Bog	FAL198	UBA-19066	198 – 199	*Calluna vulgaris* wood	2806 ± 24	-22.1	2849 – 2965	2907
	FAL244	SUERC-13660*	244 – 245	*Sphagnum* stems and leaves	3343 ± 37	-28.5	3475 – 3685	3559
	FAL261	SUERC-12999*	261 – 262	*Calluna vulgaris* wood	3467 ± 35	-29.7	3640 – 3834	3737
	FAL274	SUERC-13000*	274 – 275	*Sphagnum* stems and leaves	3545 ± 35	-27.4	3716 – 3958	3821
	FAL300	UBA-19607	300 – 301	*Sphagnum* stems and leaves	3835 ± 25	-24.2	4150 – 4406	4225
	Hekla 4	-	*323*	-	-	-	*4229 – 4345*	-
	FAL348	UBA-19068	348 – 349	*Sphagnum* stems and leaves	4059 ± 29	-23.8	4435 – 4787	4529
	FAL376	UBA-19710	376 – 377	*Sphagnum* stems and leaves	4192 ± 35	-28.9	4588 – 4842	4690
	FAL400	UBA-19069	400 – 401	*Sphagnum* stems and leaves	4609 ± 26	-21.8	5296 – 5448	5416
	FAL448	UBA-19070	448 – 449	*Sphagnum* stems and leaves	4901 ± 26	-26.7	5589 – 5661	5625

Table 2. Details of AMS ^{14}C age and tephra horizon information used to construct age-depth models at Sluggan Moss and Fallahogy Bog. * ^{14}C ages previously published in Amesbury et al. (2012).

Figure 1

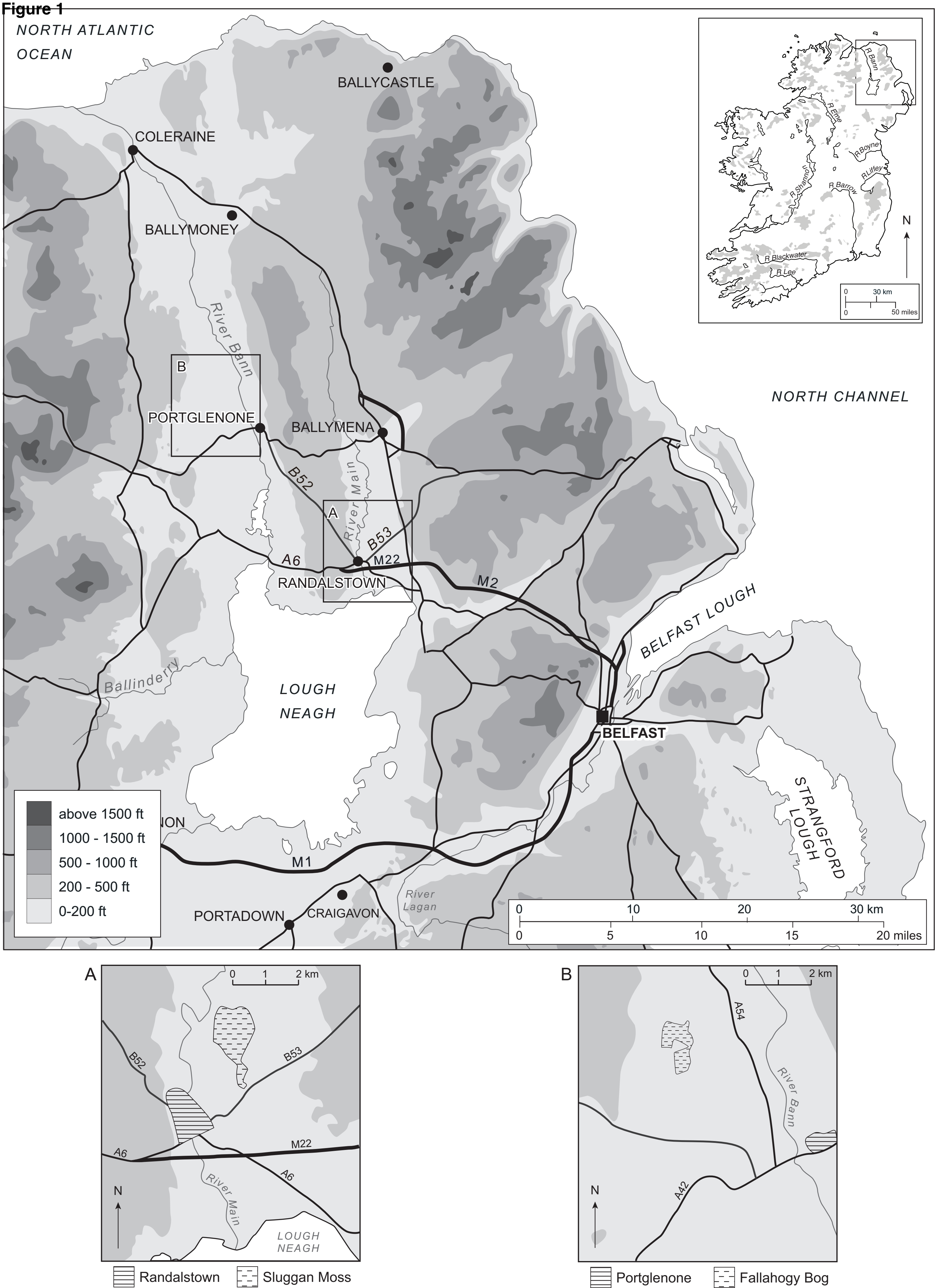
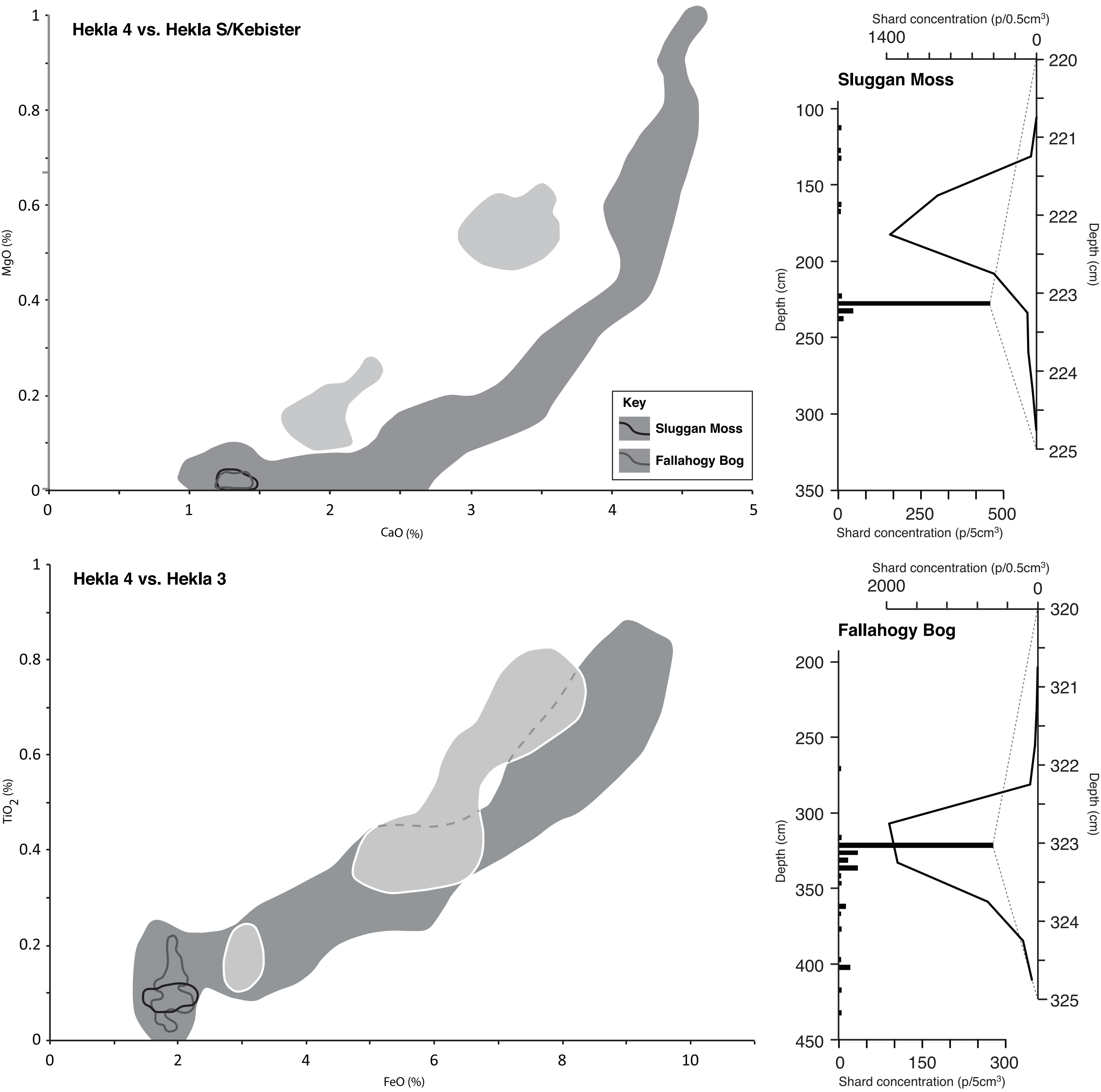
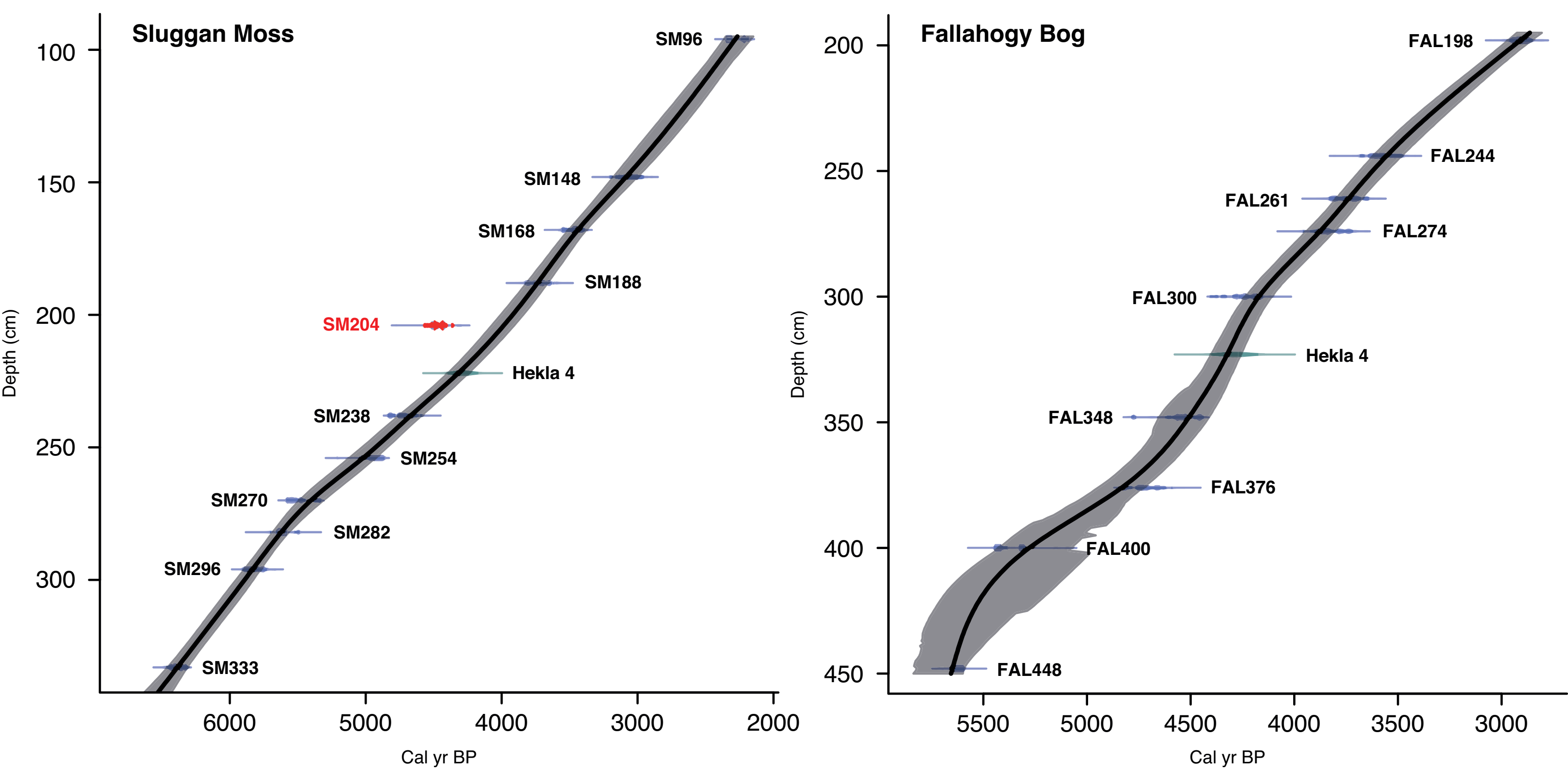

NORTH ATLANTIC OCEAN
BALLYCASTLE
COLERAINE
BALLYMONEY
River Bann
B
PORTGLENONE
BALLYMENA
B52
River Main
A
B53
A6
M22
RANDALSTOWN
M2
NORTH CHANNEL
BELFAST LOUGH
Ballinderry
LOUGH NEAGH
BELFAST
STRANGFORD LOUGH
M1
PORTADOWN
CRAIGAVON
River Lagan
above 1500 ft
1000 - 1500 ft
500 - 1000 ft
200 - 500 ft
0-200 ft
0 10 20 30 km
0 5 10 15 20 miles
R Bann
R Erne
R Boyne
R Liffey
R Shannon
R Barrow
R Blackwater
R Lee
N
0 30 km
0 50 miles
A
0 1 2 km
B52
B53
A6
M22
River Main
LOUGH NEAGH
Randalstown
Sluggan Moss
B
A54
River Bann
A42
Portglenone
Fallahogy Bog

Figure 2



Hekla 4 vs. Hekla S/Kebister
MgO (%)
CaO (%)
0
0.2
0.4
0.6
0.8
1
1
2
3
4
5
Key
Sluggan Moss
Fallahogy Bog
Shard concentration (p/0.5cm3)
1400
0
Sluggan Moss
Depth (cm)
Shard concentration (p/5cm3)
100
150
200
250
300
350
250
500
220
221
222
223
224
225
Hekla 4 vs. Hekla 3
TiO2 (%)
FeO (%)
6
8
10
2000
Fallahogy Bog
400
450
300
320
321
322
323
324
325

Figure 3



Sluggan Moss
SM96
SM148
SM168
SM188
SM204
Hekla 4
SM238
SM254
SM270
SM282
SM296
SM333
Depth (cm)
100
150
200
250
300
6000
5000
4000
3000
2000
Cal yr BP
Fallahogy Bog
FAL198
FAL244
FAL261
FAL274
FAL300
Hekla 4
FAL348
FAL376
FAL400
FAL448
Depth (cm)
200
250
300
350
400
450
5500
5000
4500
4000
3500
3000
Cal yr BP

Figure 4

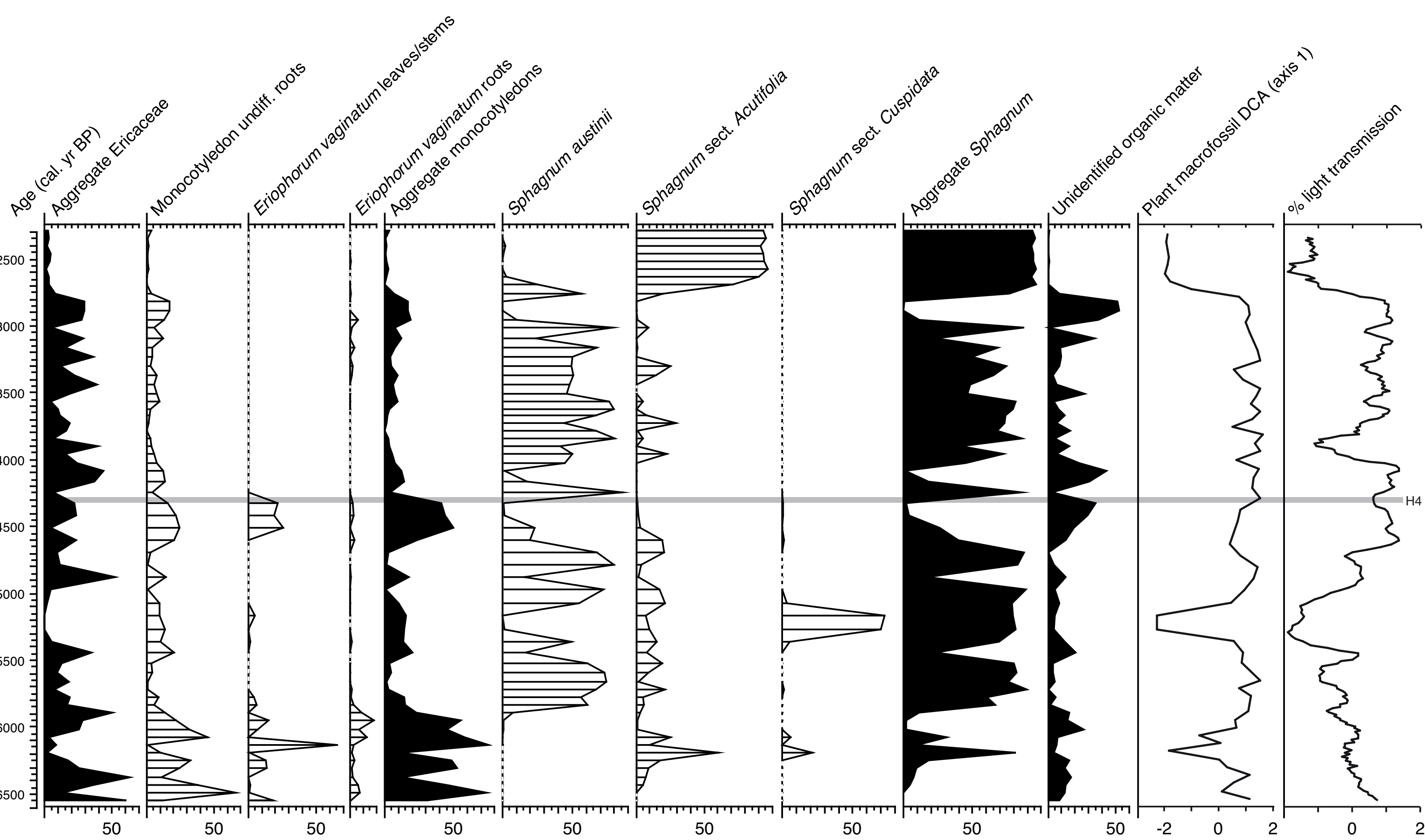

Age (cal. yr BP)
Aggregate Ericaceae
Monocotyledon undiff. roots
Eriophorum vaginatum leaves/stems
Eriophorum vaginatum roots
Aggregate monocotyledons
Sphagnum austinii
Sphagnum sect. Acutifolia
Sphagnum sect. Cuspidata
Aggregate Sphagnum
Unidentified organic matter
Plant macrofossil DCA (axis 1)
% light transmission
H4
2500
3000
3500
4000
4500
5000
5500
6000
6500
50
-2
0
2

Figure 5

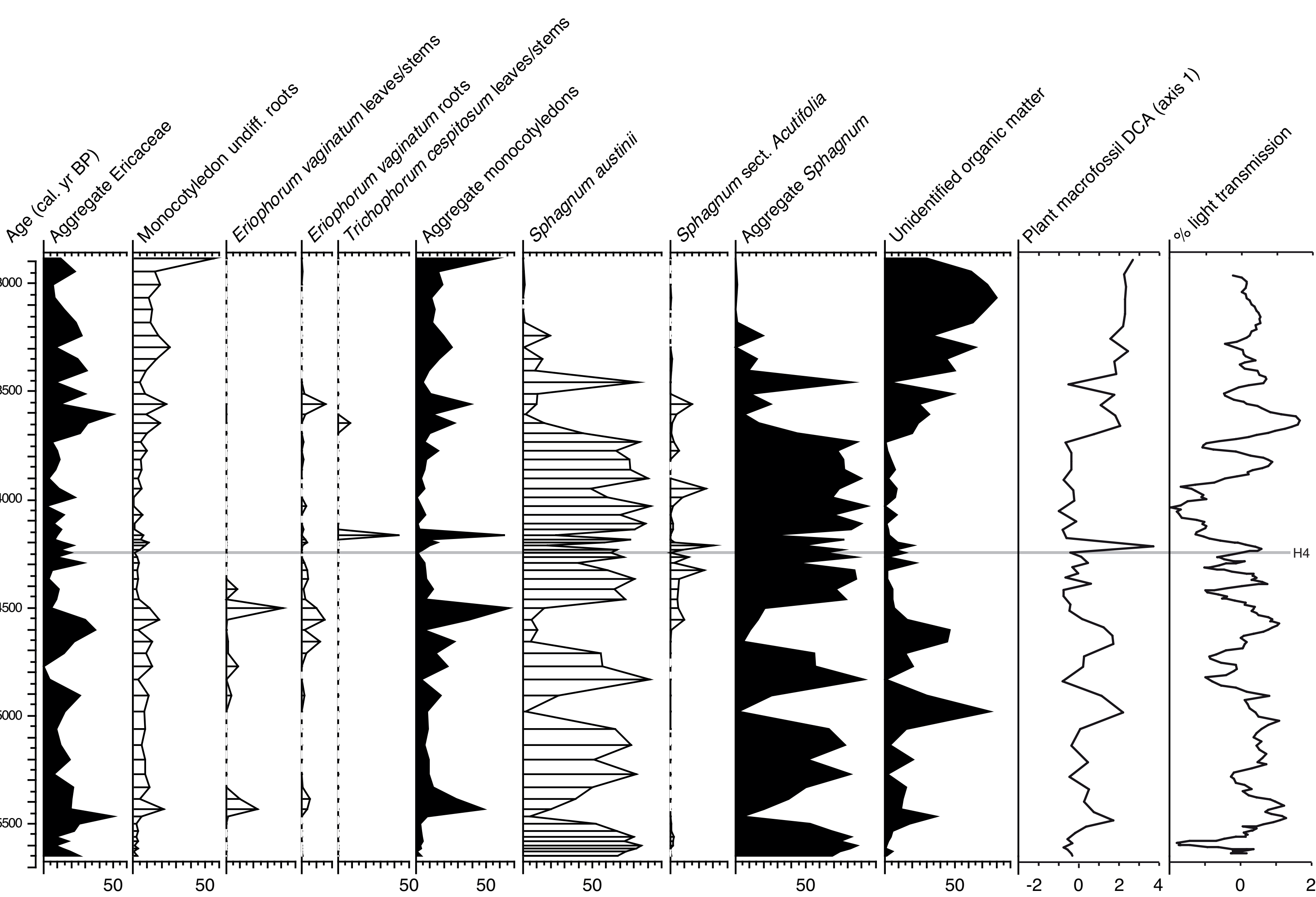
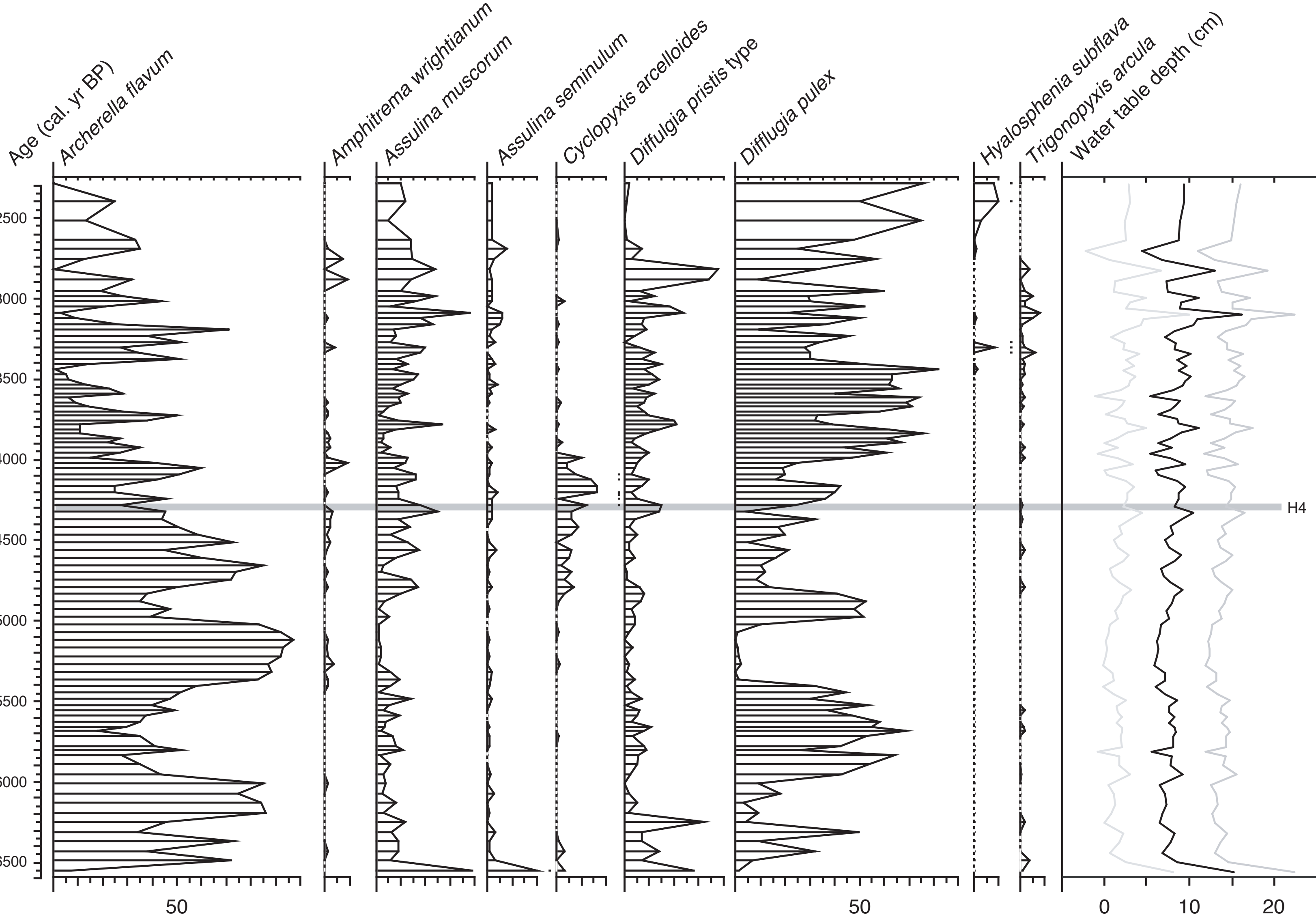
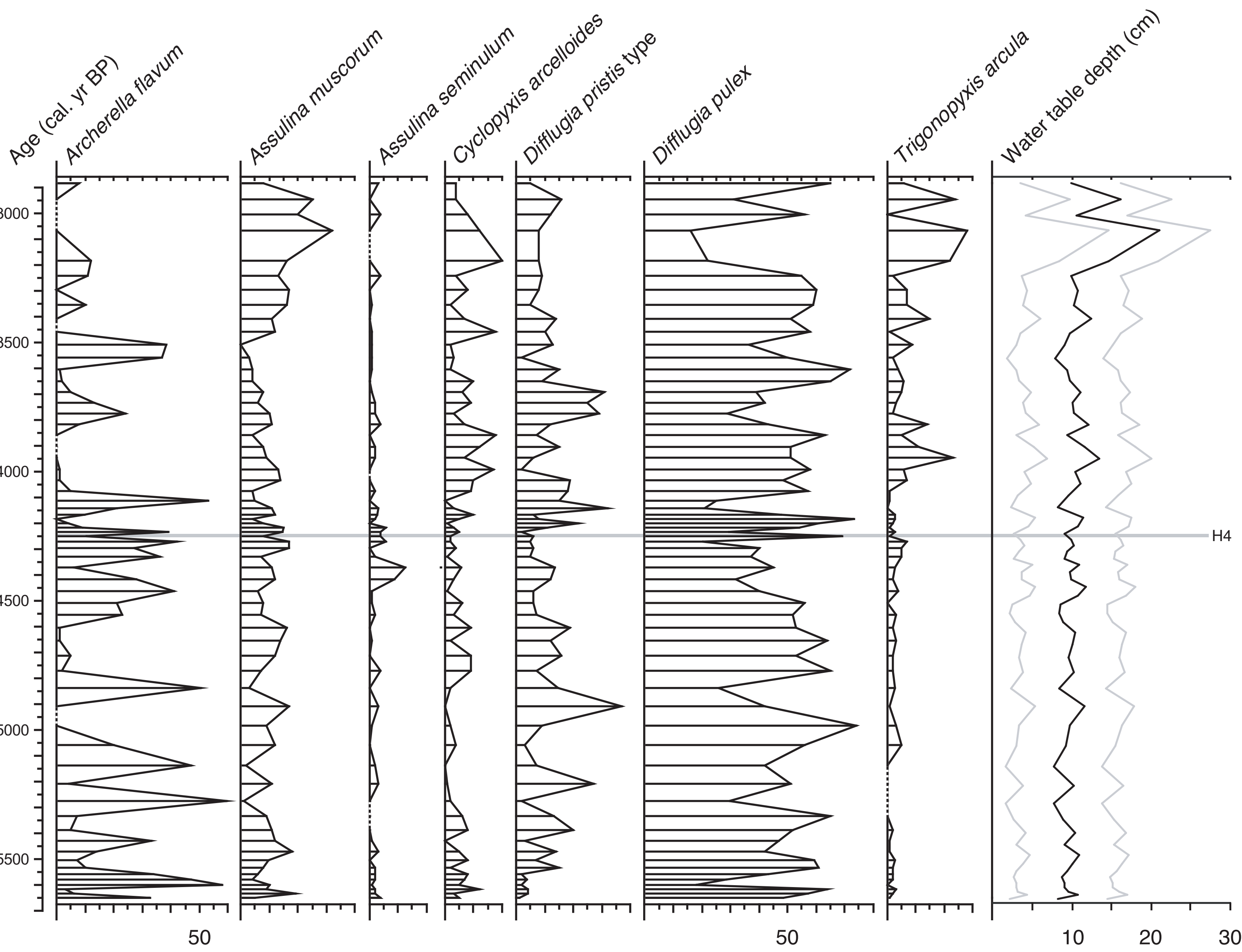

Age (cal. yr BP)
Aggregate Ericaceae
Monocotyledon undiff. roots
Eriophorum vaginatum leaves/stems
Eriophorum vaginatum roots
Trichophorum cespitosum leaves/stems
Aggregate monocotyledons
Sphagnum austinii
Sphagnum sect. Acutifolia
Aggregate Sphagnum
Unidentified organic matter
Plant macrofossil DCA (axis 1)
% light transmission
3000
3500
4000
4500
5000
5500
H4
50
50
50
50
50
50
50
-2
0
2
4
0
2

Figure 6



Age (cal. yr BP)
Archerella flavum
Amphitrema wrightianum
Assulina muscorum
Assulina seminulum
Cyclopyxis arcelloides
Diffulgia pristis type
Diffulgia pulex
Hyalosphenia subflava
Trigonopyxis arcula
Water table depth (cm)
2500
3000
3500
4000
4500
5000
5500
6000
6500
50
50
0
10
20
H4

Figure 7



Age (cal. yr BP)
Archerella flavum
Assulina muscorum
Assulina seminulum
Cyclopyxis arcelloides
Difflugia pristis type
Difflugia pulex
Trigonopyxis arcula
Water table depth (cm)
3000
3500
4000
4500
5000
5500
H4
50
50
10
20
30

Figure 8

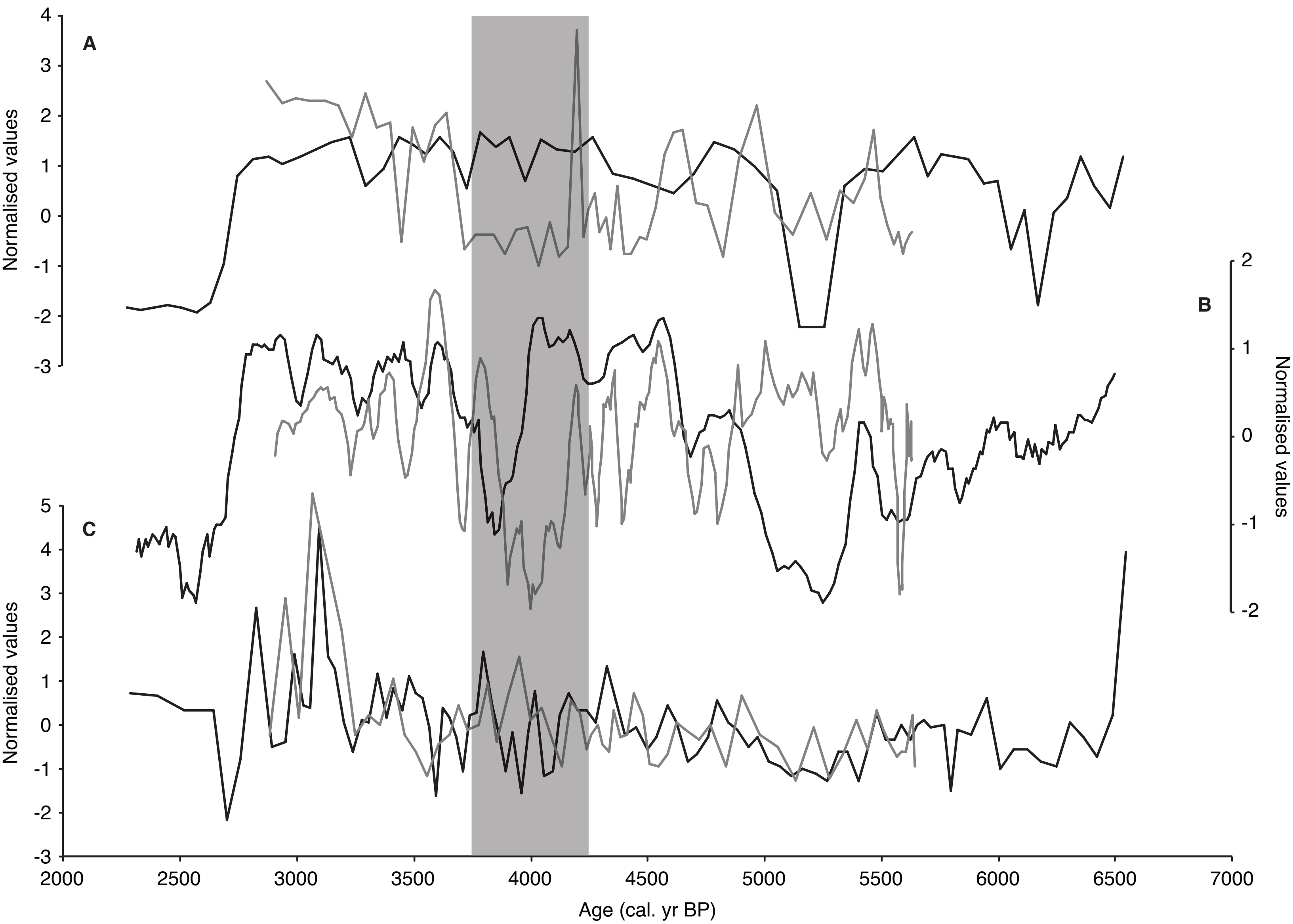
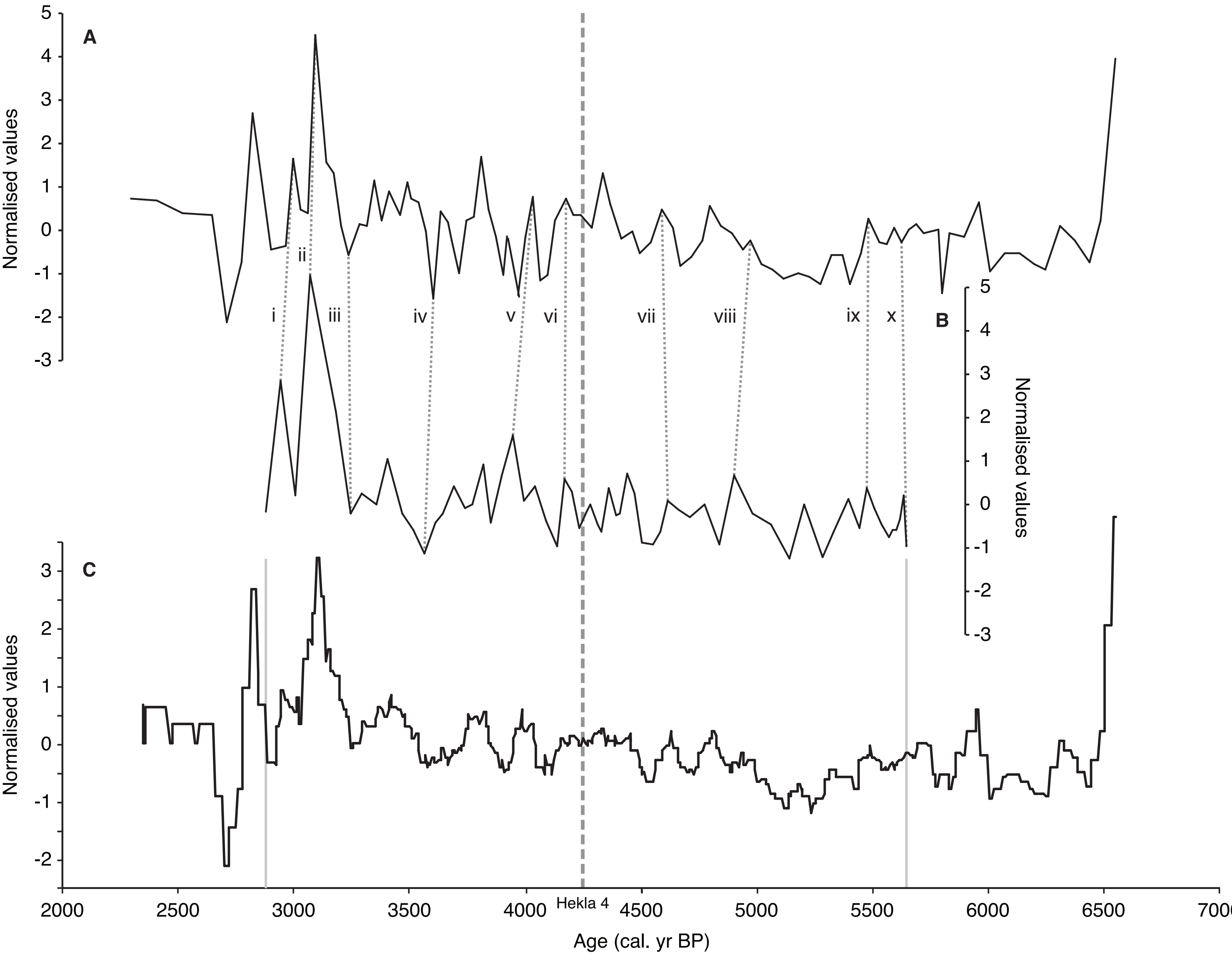
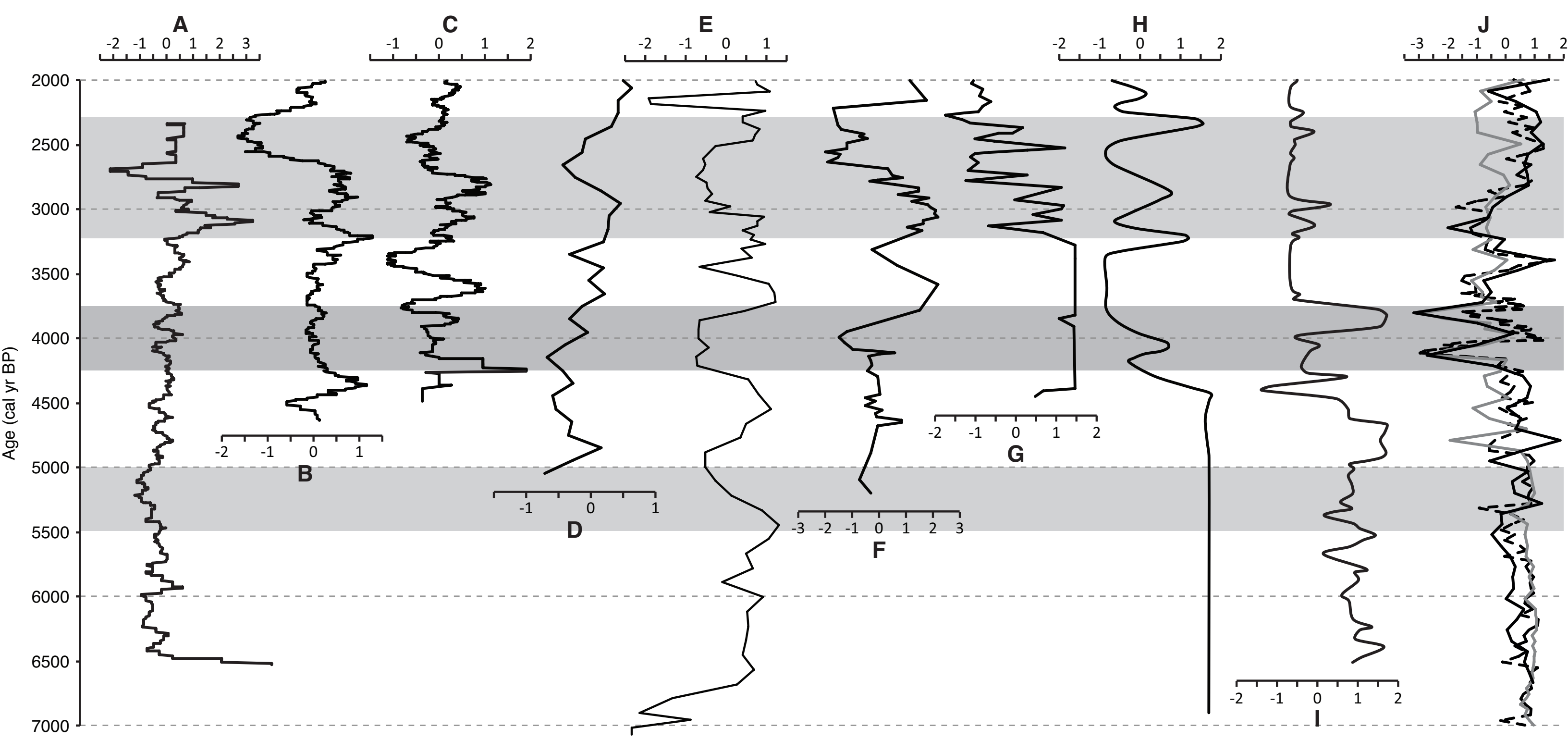

A
B
C
Normalised values
Normalised values
Normalised values
4
3
2
1
0
-1
-2
-3
5
4
3
2
1
0
-1
-2
-3
2
1
0
-1
-2
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
Age (cal. yr BP)

Figure 9



A
B
C
Normalised values
Normalised values
Normalised values
i
ii
iii
iv
v
vi
vii
viii
ix
x
Hekla 4
Age (cal. yr BP)
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000

Figure 10


A
B
C
D
E
F
G
H
I
J
Age (cal yr BP)
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000

Supplementary Data

Click here to download Supplementary Data: Roland - 4.2 kyr event - Supplementary information.docx