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A revision of the British chronostratigraphy within the last glacial-interglacial cycle based on new evidence from Arclid, Cheshire UK

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ABSTRACT

Of the 24 Greenland interstadials in the Last Glacial-interglacial cycle (LGIC) only five are conventionally recognised in Britain. This paper aims to improve understanding of the LGIC in Britain from a site at Arclid, Cheshire. Sediments were characterised and luminescence used to establish a chronology. This found that the Chelford Sand Formation spans 77-47 ka with sand deposited initially by aeolian but later by fluvial transportation. Coleoptera and Diptera from the basal peat lens provided a reconstruction for a heather-rich heathland environment grazed by large herbivores, with summer temperatures between 13 and 18 °C, and winter temperatures between −14 and 1 °C. Flies included the earliest records of the blood-sucking horsefly *Haematopota pluvialis*, and the soldierfly *Chloromyia formosa.* The overlying Stockport Sand Formation was deposited fluvioglacially between 47-41 ka with the upper Stockport Till formed by the advance of the last British icesheet after ~33 ka. Stenothermic beetle analysis from Arclid indicate similarities with results from other British mid LGIC sites, some of which are at or beyond the limit of radiocarbon dating and may be of a similar age to Arclid. Basal organic sediments found at Arclid along with other reassigned sites are proposed as a new Arclid Interstadial. A revised British LGIC chronostratigraphy has the Wretton, Chelford and Brimpton Interstadials and the previously suggested but not widely recognised Cassington Interstadial. The Arclid Interstadial occurred after these, but prior to the Upton Warren Interstadial complex. This closes the previous gap in interstadials between the Brimpton Interstadial and the Upton Warren Interstadial complex within the British chronostratigraphy.

1. Introduction

Ice and ocean records of the last glacial-interglacial cycle (LGIC) show many interstadials superimposed on the longer-term cooling between Marine Isotope Stages 5d-2 (MIS; 124-11.7 ka; Fig. 1; NGRIP members, 2004; Lisiecki and Raymo, 2005; Rasmussen et al., 2014). The British Isles appears to have closely tracked North Atlantic climate during the LGIC as reflected in the changing extent of the British Irish Ice Sheet (BIIS; Fig. 1). There is evidence for glaciation during the Wolstonian (MIS 6) (Gibson et al., 2022; Gibbard et al., 2021; Fairburn and Bateman, 2021) and a temperate climate with widespread oak forests during the Ipswichian Interglacial (MIS 5e) (e.g., Hall et al., 2002; Gao and Boreham, 2011; Candy et al., 2016). Post-Ipswichian saw long-term cooling with BIIS expansion reaching its maximum extent at ~26 ka BP (Clark et al., 2022). Of the 24 Greenland interstadials (GI) in the LGIC only five are conventionally recognised in Britain (Mitchell et al., 1973; Bowen, 1999). Within the Early Devensian, the Wretton, Chelford (MIS 5c) and Brimpton (MIS 5a) interstadials are thought to represent major warm climate anomalies (Fig. 1; West et al., 1974; Bryant et al., 1983; Maddy et al., 1998; Rendell et al., 1991). During the Mid-Devensian, the Upton Warren Interstadial Complex occurred (Coope et al., 1961) with a variable warm climate, but which was cool enough at times for periglaciation to occur (Fig. 1; Bateman et al., 2014; Buckland et al., 2019). The most recent

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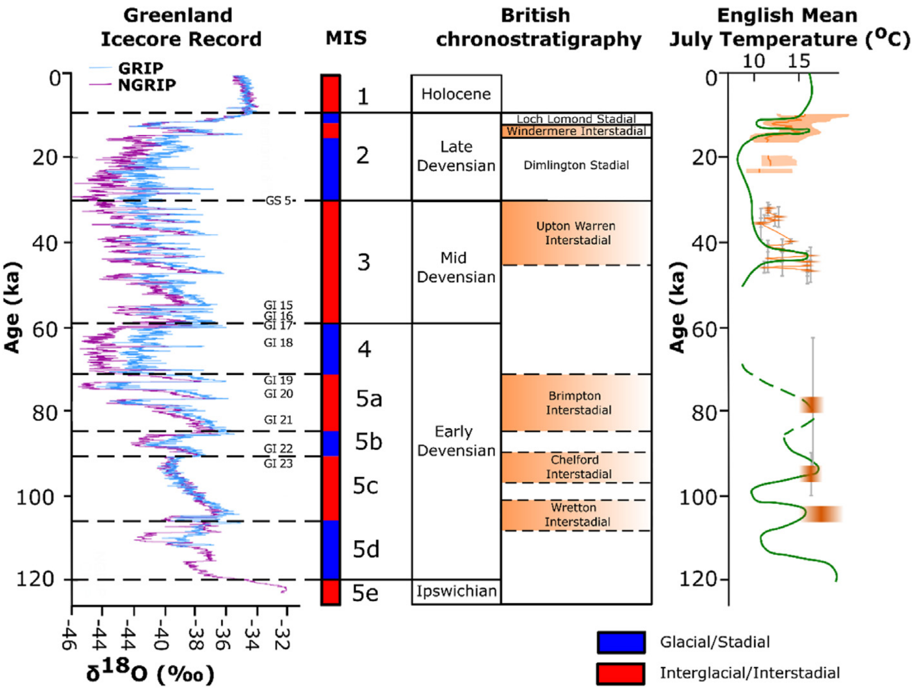

Fig. 1. The Greenland ice core record with 25 stadials and 24 interstadials (NGRIP members, 2004) and current chronostratigraphy of Britain with two conventionally recognised stadials and five interstadials. Note the lack of British interstadials between ~48 ka and 60 ka in comparison to the Greenland record. Dashed lines indicate uncertainty as to the exact timing and duration of some interstadials (See text for further details). Selected Greenland Stadials (GS) and Greenland Interstadials (GI) referred to in text have been annotated to the Greenland Ice core record based on the ages of Rasmussen et al. (2014). Also shown (green line) are July temperatures for England reconstructed from pollen and beetle evidence (Goudie and Migón, 2020) and English July temperatures for beetles only. The latter is based on radiocarbon dated beetle evidence from 21 MIS 1–2 sites (Atkinson et al., 1987) and 21 MIS 4 sites (Buckland et al., 2019) as well as beetle evidence from two luminescence dated interstadial sites (Maddy et al., 1998; Worsley et al., 1983) and 1 site correlated on the basis of biostratigraphy (West et al., 1974). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

interstadial, the Windermere Interstadial, occurred in the latter stages of the Late Devensian (Fig. 1).

Uncertainty regarding the timing and nature of British interstadials during the LGIC is due to the fragmentary preserved evidence. The absence of long and continuous sedimentary records in Britain like that found at La Grande Pile, France (de Beaulieu and Reille, 1992) is not surprising given multiple Late Pleistocene advances of the BIIS. High resolution records such as those found in Llangorse Lake, Brecons, Wales and Lake Flixton and Gransmoor, East Yorkshire, only extend back to when these areas were last deglaciated (Walker et al., 1993; Palmer et al., 2015, 2021). Additionally, sites which do detail British interstadials during this period are spatially disparate and often lack a robust chronology. Many sites rely on biostratigraphical correlation as their primary form of age control (e.g., Morgan, 1973a; Bryant et al., 1983; Holyoak, 1983; Worsley et al., 1983). Even where radiometric ages are available correlation remains difficult due to the limits of radiocarbon dating and contamination issues (Briant and Bateman, 2009; Buckland et al., 2019). Where sites do span the LGIC and have good chronological control sedimentation appears to have been episodic rather than continuous. For example, the Devensian stratotype site at Four Ashes has only limited sedimentation (the sediments representing the entire LGIC being only ~4.5 m thick) and has undergone periglacial disturbance (Shotton, 1977). Of note is the absence of reported terrestrial interstadials between the start of MIS 3 and the start of the Upton Warren Interstadial Complex, during which the Greenland ice core record shows at least three prominent interstadials (Fig. 1).

This paper aims to improve understanding of the LGIC in Britain and how it fits with events further afield by focussing on a site at Arclid, Cheshire. This site has thick sediments (>25m) containing organic deposits, which are thought to cover the LGIC (e.g., Worsley, 2008). It is difficult to correlate a spatially discrete terrestrial site such as Arclid to global marine records or ice core records. Whilst ice core records, like terrestrial records, are controlled by environmental factors, these are at the hemispheric scale and may not be synchronous with regional terrestrial records elsewhere (Gibbard and Hughes, 2021). In a similar vein, Marine Isotope Stage (MIS) records have different controls (global ice volume) so that without marker equivalent strata (i.e., isochroneity) correlations have to rely on assumed equivalence (ibid.). Following the recommendations of Gibbard and Hughes (2021), for this paper we initially independently establish the timing and climatic record of the terrestrial record at Arclid by sediment characterisation, luminescence dating, tephrochronology and fossil insect analysis of preserved organic material. Stenothermic species from Arclid were compared with other Early and Mid-Devensian sites, enabling Arclid with its luminescence chronology to be contextualised within known elements of the British chronostratigraphy of the LGIC, and revisions made to this chronostratigraphy. Finally, whilst acknowledging chronological uncertainties, potential leads/lags and different drivers, our chronostratigraphy is placed within those of Continental Europe and the MIS and Greenland ice core frameworks to aid further regional comparisons.

2. Site and samples

The Arclid site (Lat. 53°9′ 8″N, Long. 2° 19 43 W) is a quarry which lies north-east of Sandbach within the Cheshire Basin, a Permo-Triassic asymmetric half-graben (Fig. 2; Mikkelsen and

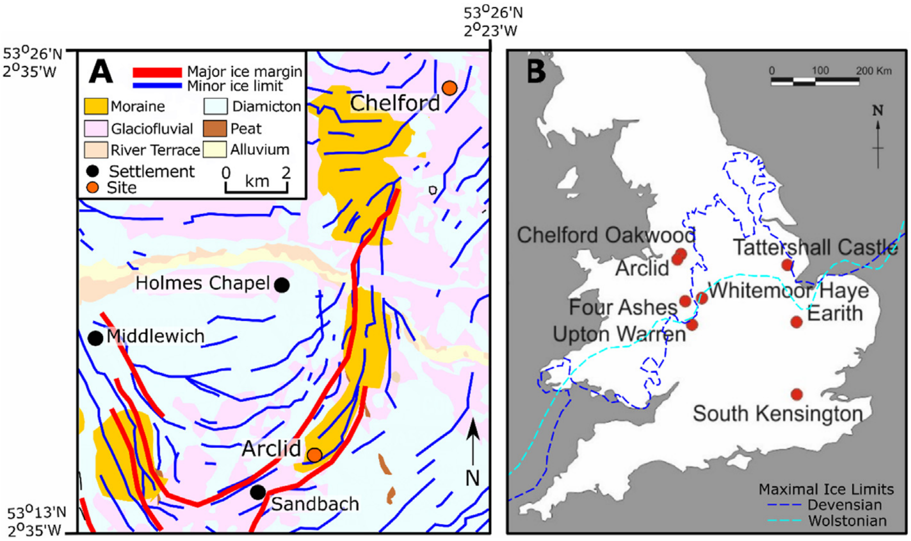

Fig. 2. Locality of Arclid quarry (A) along with mapped glacial geomorphology left by the Irish Sea Glacier of the last BIIS (Chiverrell et al., 2021), nearby Chelford interstadial site (Worsley et al., 1983) and superficial geology (Geological Map Data BGS © UKRI, 2022). Other Mid-Devensian sites mentioned in text (B) in relation to the Arclid site studied and BIIS maximal ice limits for England and Wales for both the Wolstonian and Devensian advances (after Scourse et al., 2021 and Gibbard and Clark, 2011).

Floodpage, 1997). Episodic rock dissolution of the Wilkesley Halite in the Mercian Mudstone Group during the Middle and Upper Pleistocene has led to collapse of the overlying sediments with subsidence extending to the surface to form depressions, which have filled with sediments and organic remains (Worsley, 2008). The quarry, owned by Bathgate Silica Sand Ltd, has been active since the 1960s extracting sand for commercial use.

The Arclid site is situated in an area dominated by till and glaciofluvial sands and gravels left as the Irish Sea Glacier of the BIIS retreated (Chiverrell et al., 2021, Fig. 2). Originally the stratigraphic sequence was described by Poole and Whiteman (1966) as a lower till overlain by sands and then an upper till. Worsley (2008) correlated the basal till with the Oakwood Formation and presumed it to be a subglacial till of the penultimate glaciation during the Wolstonian. Above the basal till is a very thick unit (up to 25 m in thickness) of high purity silica sands which have been attributed to the cold-climate Chelford Sands Formation (Worsley, 2008). Within the Chelford Sand Formation the Arclid site has several organic lenses referred to as the Arclid Member (Worsley, 2008, Fig. 4). The uppermost unit, a massive clay till, has been attributed to the Stockport Formation and is interpreted as a subglacial till deposited by the last BIIS (Fig. 3B–E and 3H). In places Holocene peat has infilled kettle holes within the upper part of the Stockport Formation till. Thus, the Arclid site provides thick sediments with the potential for a high-resolution record covering the entire LGIC. It also has the potential to define better interstadials within the LGIC and place them in a more secure chronological framework.

The quarry has expanded over the past 20 years and the site was visited multiple times between 2006 and 2019 to classify key lithologies and note sedimentary structures visible in wind etched faces of the quarry. Localities for sampling were chosen to ensure that each key lithology and interface was observed. Samples for luminescence dating and ICP-MS analysis were taken by hammering light-proof tubes into freshly exposed quarry faces (to prevent contamination from recently disturbed sediment). A total of 13 samples were collected along with *in-situ* dose rate measurements using a portable gamma spectrometer. For higher resolution sediment characterisation and portable OSL (pOSL) analysis, a series of 89 samples were taken every 0.25 m between the upper and lower tills (Fig. 3B). One of the three organic layers (a peat lens within sands a few metres above the lower till) was sampled as a continuous monolith for cryptotephra analysis and as a sequence of three 15 L samples (S1 - uppermost, S2 – middle, S3 - lowermost) for insect analysis (Fig. 4D).

3. Materials and methods

3.1. Stratigraphy and sediment characterisation

Bathgate Silica Sand Ltd gave access to 66 previously extracted borehole logs (mostly extending down to the underlying clay-rich till), that were amalgamated and examined as discrete stratigraphic units. Interpolated surfaces representing the depth of key contacts were then produced using kriging in ArcMap Spatial Analyst toolbox (Version 10.4.1). Where the stratigraphy was complex (for example, where the borehole did not extend to sample the basal till), borehole logs were excluded from the process to prevent skewing of the interpolated surface by false values. From this a composite log was produced.

Sediment characterisation used particle size analysis and geochemistry. The former was carried out with a Horiba LA-950 laser diffraction particle size distribution analyser using the 89 samples spanning the upper to basal tills. Each sample was saturated in 0.1% sodium hexametaphosphate to ensure the measurement of a representative particle size distribution. Mean particle size, sorting, skew and kurtosis for each sample were calculated using the output distributions following Folk and Ward (1957). Selected samples representing all stratigraphic units, were sent to SGS Canada Inc. for 56 element ICP-MS analysis. From these data the thorium-chromium-zirconium (Th–Cr–Zr) and thorium-cobalt-hafnium (Th–Co-Hf) ratios were computed to indicate changes in sediment source (Taylor and McLennan, 1985; Effoudou-Priso et al., 2014).

3.2. Chronology

Given that site antiquity was thought to be beyond the reliable limit of radiocarbon, a range of luminescence dating methods were employed to maximise establishment of a reliable chronology. Samples were dated using both quartz OSL and feldspar Infrared

Fig. 3. Sedimentary units and bedding structures observed within the Arclid Quarry. (A) View of quarry workings at Arclid as of 2019. (B) Chelford Sands extending down to Oakwood Formation till (bottom right). (C) Stockport Formation till with Holocene peat filled kettle hole above and upper part of Chelford Sands below. (D) Close-up of interface between Stockport Formation till and luminescence samples (Shfd18098-99) in it and Chelford Sand with gamma spectrometer denoted luminescence sample Shfd18097. (E) Cross-cutting bedding within Chelford Sands with position of luminescence sample Shfd18147. (F) Syngenetic ice wedge cast within Chelford Sands. (G) Cross-section of channel fill in Chelford Sands. (H) Close up of the Oakwood Formation till at base of exposed stratigraphy.

Stimulated luminescence (IRSL) with the latter conducted both at 50 °C ($IRSL_{50}$) and by a post $IRSL_{50}$ IRSL measurement at 225 °C ($pIRIR_{225}$). Each method has advantages and disadvantages (e.g., Mahan and DeWitt, 2019). Quartz is quick to bleach when exposed to sunlight and does not fade but elsewhere in the Cheshire basin it has been shown to have a low sensitivity to dose (Chiverrell et al., 2021). The $IRSL_{50}$ signal is prone to fading but relatively quick to reset whereas the $pIRIR_{225}$ signal may not be impacted by fading but is slower to reset. Samples were prepared as per Bateman and Catt (1996; for further details on methods employed see supplementary data). Dose rates were calculated using a combination of the ICP-MS results (beta dose), field gamma spectrometer data (gamma dose) and a calculated cosmic ray contribution (Bateman et al., 2015a; Prescott and Hutton, 1994). Dose rates were corrected for a palaeo-moisture contents based on those adopted for luminescence dating in the nation-wide BRITICE project (Evans et al., 2021). Palaeomoistures of 10–15% were applied to the upper till samples which are above the water table and unsaturated or only saturated for a limited part of their burial time, 23% was applied to samples from the sands which are currently free draining but probably saturated for considerable periods of their burial and 27% was applied to samples just above/below the peat lenses which would have been fully saturated for almost their entire burial. A large uncertainty of 5% was applied to all palaeomoisture values recognising these may have varied through time.

Quartz OSL was measured at the multi-grain level using a single aliquot regenerative (SAR) protocol to determine equivalent dose (D_e) with a preheat temperature of 180 °C based on a preheat dose recovery plateau test (Murray and Wintle, 2000, 2003; See supplementary data for further details). Feldspars were measured at the single grain level using a SAR protocol as per Rhodes (2015) and with an IRSL measurement at 50 °C ($IRSL_{50}$) and a post $IRSL_{50}$ IRSL measurement at 225 °C ($pIRIR_{225}$; see supplementary data for further details). With luminescence dating, selecting the correct burial age D_e value can be challenging. The approach used in this study was two-fold. Firstly, it adapted the statistical models applied to sample D_e data to reflect the bleachability of the mineral/signal measured and the relative susceptibility of the data to fading. Secondly, it included a Bayesian type approach using expectation of increasing age with depth and site stratigraphy as a priori factors to revise the D_e analysis and/or reject ages. Full details are given in supplementary data but in summary, where samples had low

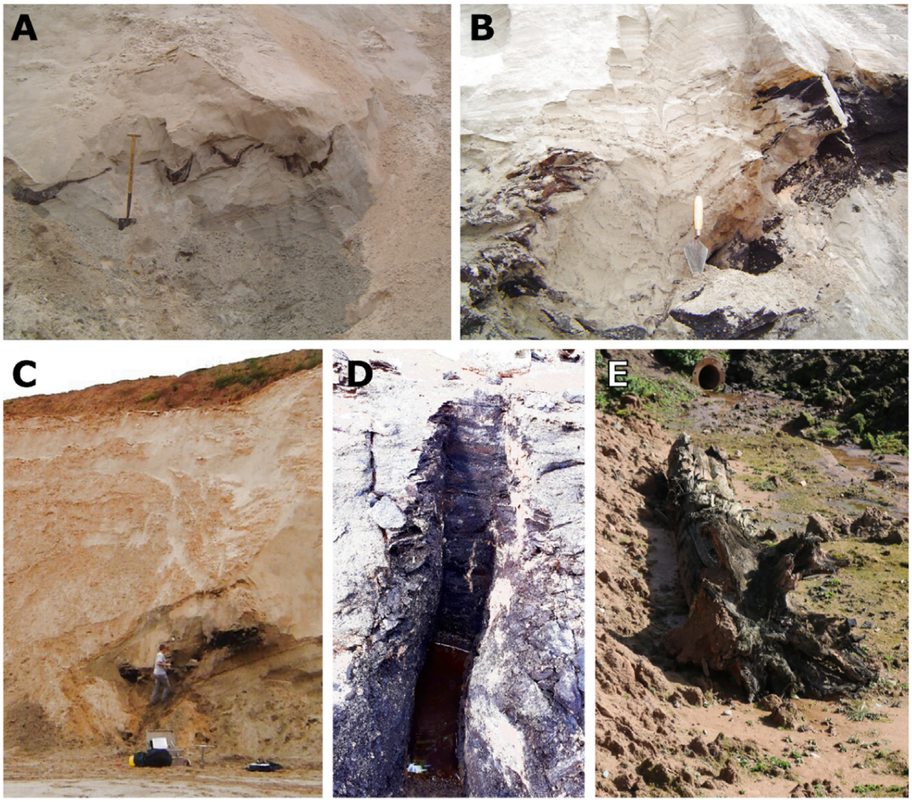

Fig. 4. Various beds of the Arclid Member found within the Chelford Sands. (A) Thin contorted upper peat. (B) Thermal erosion gully through upper peat with ice wedge cast in gully. (C) Middle peat found stratigraphically higher than the basal peat. (D) Basal peat sampled for insect remains and tephra. (E) Not in situ preserved whole trees found during quarrying.

overdispersion (OD) values (<25%) and the D_e distribution was not skewed, the D_e value for age calculation was obtained using the central age model (CAM; Galbraith et al., 1999). Otherwise, D_e analysis used the minimum age model (MAM; Galbraith et al., 1999) for OSL and $pIRIR_{225}$ or finite mixture model (FMM; Galbraith and Green, 1990) for $IRSL_{50}$ measurements. Once ages had been calculated, the whole age dataset was further screened to check ages were stratigraphically reasonable to guide final age selection between the three chronological approaches.

In addition to the full luminescence ages, portable optically stimulated luminescence (pOSL) measurements were made for 89 samples spanning the lower to upper till units to establish whether sediment accumulation between luminescence ages was gradually accretionary or rapid but episodic (as per Bateman et al., 2015b). Samples were prepared for pOSL analysis by removal of light-exposed tube ends and drying at 30 °C for 48 h. All pOSL measurements were made using a SUERC portable OSL (pOSL) reader (Sanderson and Murphy, 2010) following the procedure set out in Bateman et al. (2015b), making both infrared (pIRSL) and blue light (pOSL) measurements. Down-section pOSL measurements were corrected for any variability in pIRSL (assumed to be from feldspars) and for dose-rates based on those calculated for the quartz OSL ages for the different identified units.

3.3. Cryptotephra

Investigations for volcanic ash layers in the British Isles terrestrial archive remain rare for pre-late glacial times (e.g., >18 ka BP) though recent work in Middle Pleistocene interglacial sequences has demonstrated that preserved tephra from this period exists (e.g., Brough et al., 2010) and that terrestrial-marine tephra-based correlations are possible (Candy et al., 2021). The potential for success, even in short lived sedimentation accumulation events, has also been demonstrated by Brough et al. (2010). In contrast, many tephra layers, of probable Icelandic origin, have been identified in marine cores from around the UK and extending into the Norwegian Sea for the time range of interest in this study (e.g., Abbot et al., 2011; Davies et al., 2014; Abbot et al., 2018). To assess whether any direct terrestrial-marine tephrocorrelation was possible, the basal peat sequence (Figs. 4D and 5) was sampled contiguously in 3 cm 'scans' samples: 3 (L) x 1.5 (W) x 1.5 (D) cm from 0 to 105 cm. The peat samples were ashed in furnace at 550 °C for 2 h to remove organic content before being wet sieved, the particle fraction between 25 and 125 μm was then mounted onto slides using Canada balsam as the mounting medium and visually assessed using a high-powered binocular transmitted light microscope with cross polarising filters at x10 and x40 magnification objectives. Not including a heavy liquid density separation step (e.g., Blockley et al., 2005) meant that all volcanic glass geochemistry types could be looked for, including basaltic shards and other higher FeO tephra shards.

3.4. Insect analysis

The three basal peat samples (S1–S3) were processed for insect remains. Although the standard sample size for insect analysis is 5 L, a larger sample size of 15 L was necessary, in order to obtain sufficient results. The compacted sediment proved difficult to disaggregate requiring soaking for several days before washing out over a 300 μm mesh sieve; a few large, irregular pieces of wood (up to 200 mm) were removed at this stage. Liquid paraffin was worked into the disaggregated material retained on the sieve before cold

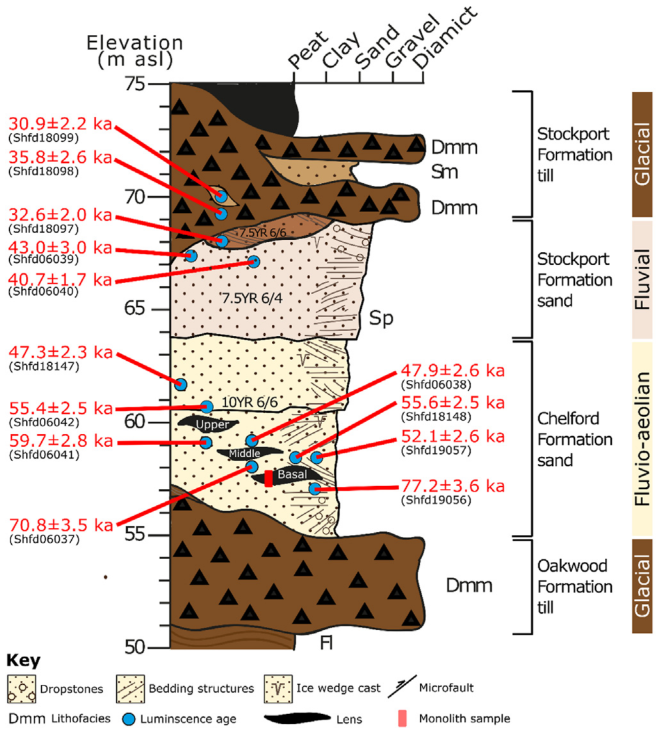

Fig. 5. Composite log for Arclid, showing a summary of the lithologies and relationships observed in the borehole logs and during fieldwork. Peat monolith and OSL sampling locations are shown as well as final luminescence ages.

water was added allowing floating off of insect cuticle (Coope and Osborne, 1968). Each subsample was floated three times but still produced limited faunas of Coleoptera, although remarkable numbers of Diptera. Sorting was with a low power binocular microscope and material was identified to the lowest taxonomic level where possible by comparisons with modern reference material. Ecological and Mutual Climatic Change (MCR) diagrams were compiled using the BUGScep database (Buckland and Buckland, 2006). Additional insect data, including relevant dates, from similar Devensian sites with a stratigraphic and chronological framework were collated and MCR diagrams produced for comparison with Arclid. Further comparisons of Mid-Devensian assemblages concentrated on stenothermic Coleoptera and utilised detrended correspondence analysis (DCA), and Vegan package 2.5–7 in R (Oksanen et al., 2020).

4. Results and interpretations

4.1. Stratigraphy and sediment characterisation

The basal till was massive and comprised a consolidated, poorly sorted and positively skewed clay (Dmm; mean diameter 36 μm, mean sorting = 1.63, mean skewness = −0.52) with range of larger sediment sizes and occasional large cobbles (Figs. 3H, 5 and 6). Where observed, the unit had been distorted by large scale post-depositional deformation and organic clasts were prevalent towards the surface. Based on these observations, the till was interpreted as a till of glaciogenic origin and assigned to the Oakwood Formation till (Worsley, 2015; British Geological Survey, 2019a). Borehole data showed the elevation of this basal till deepened to the north of the site and thinned centrally. The basal till is interpreted as having infilled a palaeovalley or zone of enhanced halite subsidence (Fig. 6).

Overall, the overlying sands were moderately well sorted, unskewed (mean sorting = 0.59, mean skewness = -0.06), dominated by round and sub-round grains and exhibited low angle planar cross bedding and horizontal bedding structures (Sp; Fig. 3B, E, 5 and 7). Ice wedge structures (Fig. 3F) and infilled channels (Fig. 3G) were observed in places. Most of the sand was medium in grain size (mean diameter 265 μm) and light brown to brownish yellow (7.5 YR 6/4-10 YR 6/6) in colour (Munsell Color, 2000). Reddish yellow (7.5 YR 6/6) sand was observed in places directly below the upper till. Gleying and iron staining was common around the organic lenses and above the basal till. Detailed particle size analysis revealed three significant changes within the sands not observed in the field (Fig. 7). The lowest 7.5 m of sand was very consistent with a mean diameter of 208 μm (Fig. 7). Above this there was 5.5 m of coarser (mean diameter of 303 μm) but uniform sand (Fig. 7). In contrast the upper 8 m of sand had a series of coarse, poorly sorted and negatively skewed events in which, as shown by d10 and d90 values, both fine and very coarse sand were deposited (Fig. 7). It is interpreted that the lower 13.0 m belongs to the Chelford Sand Formation fluvio-aeolian sands (Simpson and West, 1958; British Geological Survey, 2019b). The sub-division within it is interpreted as indicating a shift in the balance between aeolian dominant (lowest 7.5 m) and fluvial dominant (upper 5.5 m). The upper 8 m is interpreted as belong to the Stockport Formation sands showing an increase in overall fluvial activity with sudden periods of energetic flow depositing coarser and less well sorted sediment. Both the Stockport and Chelford Sand Formations have broadly consistent elemental compositions regardless of stratigraphic position (Fig. 8) with no evidence of differences within or between the two units. Thus, whilst they were deposited under different environmental regimes, they were likely to have originated from the same source region (cf. Harrison, 1968). The Chelford and Stockport Formation sands appear thickest where accommodation space was greatest in the basal till depressions, based on the borehole data (Fig. 6).

Detrital eutrophic limnic mud/gyttja and peat accumulations have been preserved at various elevations within the lower part of the Chelford Sand Formation (Figs. 4 and 5). Based on the borehole data, peats and those logged as peat rich sands were localised and appear to have been preserved only in palaeo-topographic depressions within the basal till (Fig. 6). The basal peat accumulation, around 1–2 m above the basal till, consisted of a pair of lenses separated by 0.5 m of sand (Fig. 4D). Both comprised largely of compact, amorphous peat which was fibrous and felted with numerous irregular bedding planes, reddish-brown (5 YR 6/8) in colour. Approximately 1–2 m further up the stratigraphy a 0.7 m thick peat lens (referred to as middle peat) was observed which was also dominated by monocotyledon vegetation (Fig. 4C). The uppermost peat lens had a dense, amorphous peat 0.9 m in thickness, separated from a thin upper peat lens by 0.7 m of sand. At this locality, periglacial ice wedge casts were observed, and the peat layer was distorted (possibly by frost mound formation; Fig. 4A and B). Whilst the stratigraphic context of the basal peat does bear a close resemblance to the Farm Wood Member at Chelford (Worsley et al., 1983; Rendell et al., 1991), the absence of in situ tree (Norway spruce; Holyoak, 1983) as found at Chelford rule this correlation out. Therefore, all peat lenses are ascribed to the Arclid Member as defined by Worsley (2008). The presence of large trunks (Fig. 4E) and well-preserved conifer cones noted during quarrying but not seen in situ, and these may indicate that some lenses equivalent to the Farm Wood Member may have occurred elsewhere in the pit but have since been destroyed.

The Stockport Sand Formation was overlain by a massive, reddish grey consolidated upper till (Dmm) dominated by clay (Fig. 3C and D, 5 and 6). The till was poorly sorted (mean = 2.22) with a

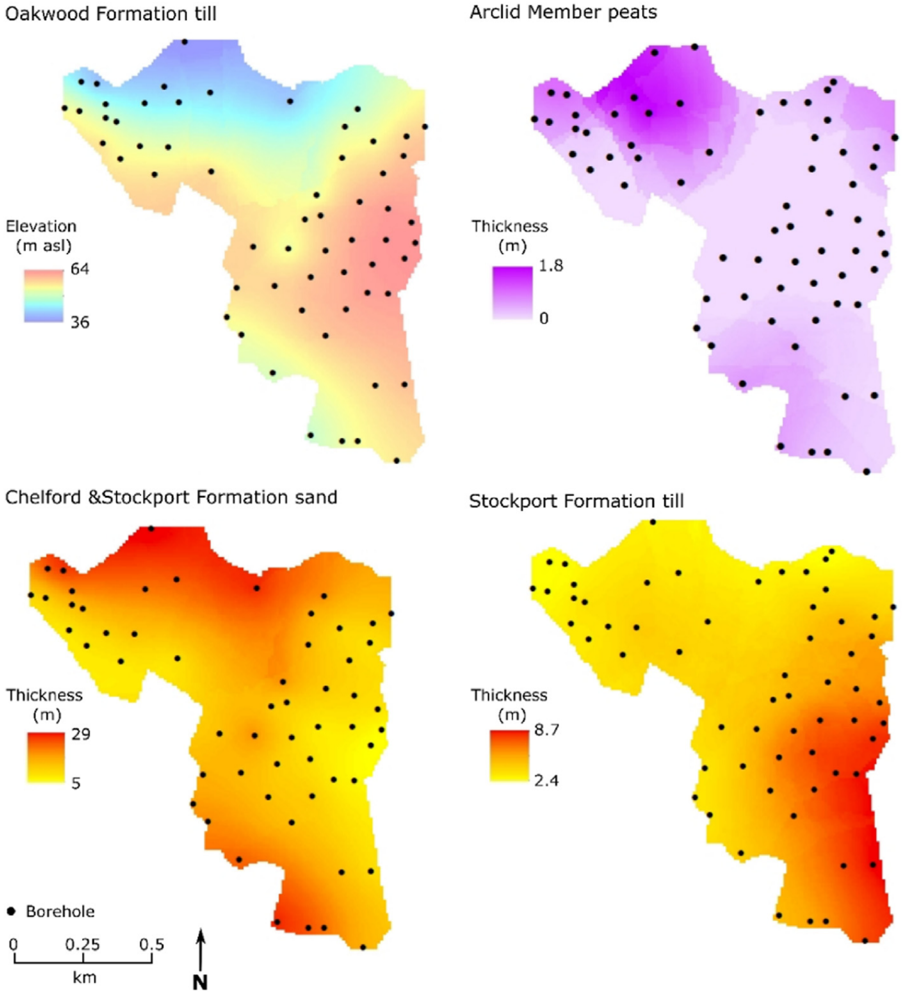

Fig. 6. Site-wide interpolation from borehole data of surfaces of the basal Oakwood Formation till and thicknesses of the Arclid Member, Chelford Sand Formation and Stockport Formation till.

mean diameter size of 17 μm (Fig. 7) and greater quantities of large clasts relative to the Oakwood Formation till. In places the till contained brown sand lenses (10 YR 4/3y) up to ~0.3 m in thickness (Fig. 3D). The till-sand contact contained reverse microfaults taken to indicate sub-glacial shearing and small scale glaciotectonic activity (Vaughan et al., 2014; Girad et al., 2015). The deposit was assigned to the Stockport Till Formation (Worsley, 1991; British Geological Survey, 2019c). Unlike all other units examined, the borehole data shows that the Stockport Formation till at the surface did not follow a pattern of thickening to the north in a palaeovalley or subsidence depression. Instead till thickened to the east, probably associated with the mapped moraine, which represents a still stand position of the Irish Sea Glacier (Figs. 2A and 6). The ICP-MS analysis demonstrate the Stockport Formation till is geochemically distinct from the underlying Stockport and Chelford Sand Formation (Fig. 8). This till was thought to have been deposited by the Irish Sea Glacier of the BIIS and so its provenance is likely to have been from ice transported sediments from the Irish Sea Basin, Lake District and the west of Scotland.

4.2. Luminescence chronology

The new luminescence ages produced are shown in Fig. 5 and Table 1 (further details are provided in Supplementary Data). The lower sand exhibited lower OD values and unimodal D_e distributions indicating they were deposited in an environment where sediments were bleached more completely prior to burial. The upper sand samples generally displayed a prominent low D_e peak and are somewhat skewed indicative of some incomplete bleaching. The till samples showed a wide range of D_e values and high OD (>25%), indicating poor bleaching and mixing of sediments of different ages during transportation (Fuchs and Owen, 2008).

In terms of final chronology, the Chelford Sand Formation range in age from 47.3 ± 2.3 ka to 77.2 ± 3.6 ka. The sand beneath the Arclid Member peat layers is older, spanning from 77.2 ± 3.6 ka to 70.8 ± 3.5 ka, compared to the sand above the peat layers, which spans 52.9 ± 1.3 ka (a combined age of sands just above peat layers using OxCal 4.4; e.g., Bronk Ramsey and Lee, 2013) to 47.3 ± 2.3 ka. The peat units of the Arclid Member were not directly sampled but ages bracket the basal peat to between 70.8 ± 3.5 ka (Shfd06037) and 53.9 ± 1.8 ka (combining Shfd19057 and Shfd18148 ages). The middle peat lens was bracketed by ages between 53.9 ± 1.8 ka and 47.9 ± 2.6 ka (Shfd06038) and the upper peat was bracketed by ages between 59.7 ± 2.8 ka and 55.4 ± 2.5 ka (Shfd06041 and Shfd06042). The Stockport Formation sands range from 47.3 ± 2.3 ka (the uppermost age for the Chelford Sand Formation) to 41.3 ± 1.5 ka (a combined age of Shfd06039 and Shfd06040). The Stockport Formation till gave ages of between 35.8 ± 2.6 ka and 30.9 ± 2.2 ka (32.8 ± 1.3 ka when combined). The apparent 8.5 ka hiatus between the Stockport Formation till and underlying sand

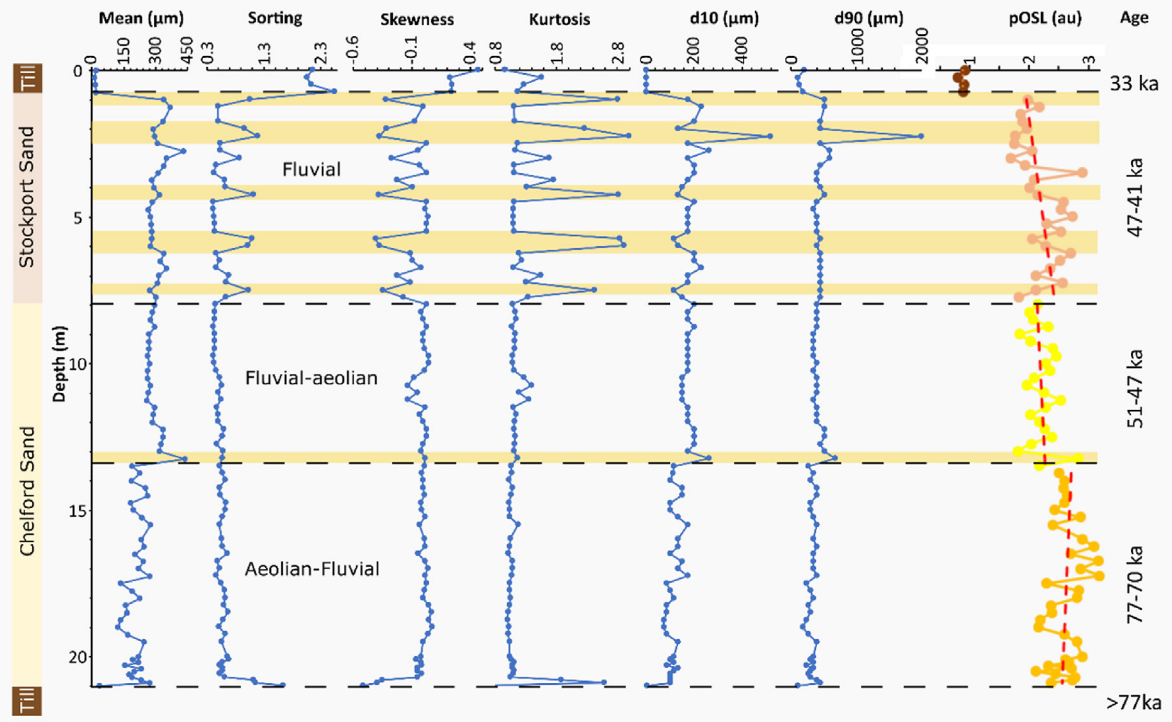

Fig. 7. Particle size analysis of 89 samples collected through the entire stratigraphic sequence and identified subdivisions made (yellow bars represent 'flood' events picked out by short-lived coarsening and poorer sorting). Also shown is the pOSL data with the luminescence chronology adjusted based on the trends shown within it (see text for details). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

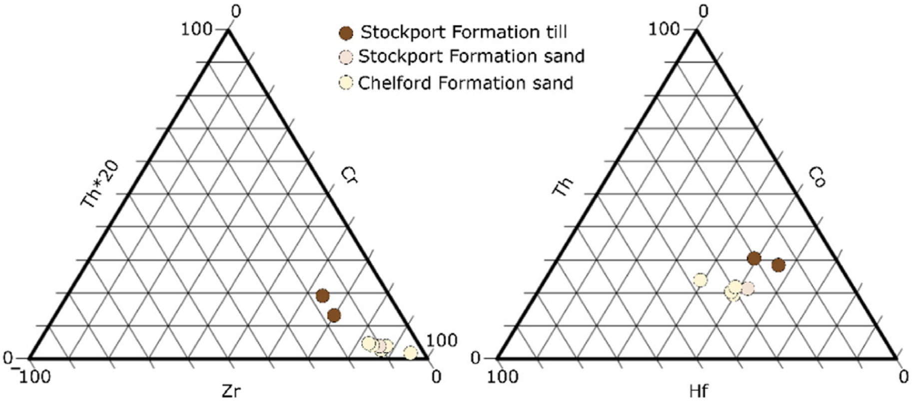

Fig. 8. Ternary plots showing the Th–Cr–Zr and Th–Co-Hf ratios Arclid samples from various stratigraphic positions derived from ICP-MS measurements.

Table 1
Luminescence data and methods used for final chronology. Measurement (SA = single aliquot, SG = single grain, OSL = Optically Stimulated luminescence, pIRIR = post Infrared Stimulated Luminescence). Full details provided in Supplementary Data.

Stratigraphic Position	Sample Code	Depth (m)	Water (%)	Luminescence Type	Total Dose Rate (Gy Ka^{-1})	D_e (Gy)	A g e (Ka)
Stockport Formation till	Shfd18099	1.3	15 ± 5	Feldspar, SG, $pIRIR_{225}$	3.18 ± 0.12	98.2 ± 5.9	30.9 ± 2.2
Stockport Formation till	Shfd18098	1.6	15 ± 5	Feldspar, SG, $IRSL_{50}$	3.55 ± 0.14	127 ± 7.5	35.8 ± 2.6
Stockport Formation till	Shfd18097	2.1	10 ± 5	Feldspar, SG, $IRSL_{50}$	2.01 ± 0.07	65.7 ± 3.3	32.6 ± 2.0
Stockport Formation sands	Shfd06039	10.4	23 ± 5	Feldspar, SG, $IRSL_{50}$	1.57 ± 0.06	67.2 ± 4.0	43.0 ± 3.0
Stockport Formation sands	Shfd06040	11.5	23 ± 5	Feldspar, SG, $pIRIR_{225}$	1.56 ± 0.06	63.5 ± 1.1	40.7 ± 1.7
Top Chelford Sands Formation	Shfd18147	19.5	23 ± 5	Feldspar, SG, $pIRIR_{225}$	1.71 ± 0.07	80.9 ± 2.6	47.3 ± 2.3
Sand above Upper Peat	Shfd06042	23.0	27 ± 5	Feldspar, SG, $pIRIR_{225}$	1.67 ± 0.07	92.7 ± 1.8	55.4 ± 2.5
Sand below Upper Peat	Shfd06041	25.3	27 ± 5	Feldspar, SG, $pIRIR_{225}$	1.67 ± 0.07	99.6 ± 2.4	59.7 ± 2.8
Sand above Middle Peat	Shfd06038	25.0	27 ± 5	Feldspar, SG, $pIRIR_{225}$	1.77 ± 0.07	84.8 ± 3.1	47.9 ± 2.6
Sand above Middle Peat	Shfd18148	23.5	27 ± 5	Feldspar, SG, $pIRIR_{225}$	1.74 ± 0.07	96.8 ± 1.9	55.6 ± 2.5
Sand below Middle Peat	Shfd06037	27.2	27 ± 5	Feldspar, SG, $pIRIR_{225}$	1.87 ± 0.07	133.6 ± 3.8	70.8 ± 3.5
Sand above Basal Peat	Shfd19057	22.5	27 ± 5	Feldspar, SG, $pIRIR_{225}$	1.87 ± 0.07	82.5 ± 2.2	52.1 ± 2.6
Sand below Basal Peat	Shfd19056	23.5	27 ± 5	Feldspar, SG, $pIRIR_{225}$	1.48 ± 0.06	114.5 ± 2.7	77.2 ± 3.6

units fits with the sharp erosional unit boundary and the till not conforming to pre-existing topography as shown by the borehole data (Fig. 7). Given the high D_e overdispersion, multi-modal D_e distributions and depositional context, it seems likely that these samples were only partially bleached by the time of burial. Whilst extraction of the D_e for final age calculation used FMM to try to mitigate the partial bleaching, some age over-estimation may persist.

pOSL data, by virtue of being derived from quick measurements of chemically unprepared material, are always variable but the different units do show some key differences (Fig. 7). The basal part of the Chelford Sand Formation shows a pOSL signal slightly higher than the preceding unit hinting at a small temporal gap in sand deposition associated with the peat lenses but shows no increase in signal with depth indicating rapid accretion over a brief period of time. The uppermost Chelford Sand Formation shows a slight pOSL increase with depth but is constrained by only one luminescence age (Shfd18147). To establish its duration, the change with depth of pOSL signal was calculated using a linear fit and this was scaled using the luminescence age. This enabled the pOSL signal at unit boundaries to be converted to age. This found that the 5.5 m of sand of this unit accumulated in ~3.3 ka between 47.3 and 50.6 ka (Fig. 7). The Stockport Formation sands shows an appreciable increase in pOSL signal with depth. With similar linear modelling the pOSL data predict the age of the base of this unit to be 50.5 ± 1.8 ka which is within errors of the uppermost age of the underlying Chelford Sand Formation. This units therefore appears to have gradually aggraded over the course of ~8 ka with no hiatus between it and the underlying Chelford Sand Formation. There is a large jump in pOSL signal between the Stockport Formation sand and the overlying Stockport Formation till indicating a temporal hiatus between these two units consistent with both the borehole data and the luminescence ages. The pOSL data shows a no discernible difference within the Stockport Formation till samples indicating, as the luminescence ages did, rapid deposition.

4.3. Cryptotephra

Despite the detailed sampling approach and level of analysis adopted, no tephra shards were detected from within the basal peat. As far as we are aware, this is the first UK cryptotephra investigation in a terrestrial sequence during this time period. The lack of cryptotephra found within the period 54 to 71 ka does not allow tie points to be made between the terrestrial and oceanic tephrostratigraphic record. Given the good organic and inorganic preservation at Arclid and accumulation of peat under low energy conditions, it seems likely this lack of cryptotephra is due to an absence of volcanic tephra deposition during this time period though more studies on similar ages terrestrial sequences across Northern England would be needed to confirm this pattern more widely.

4.4. Insect analysis

4.4.1. Coleoptera

The beetle faunas from all three subsamples (S1, S2, S3) from the basal peat are sufficiently similar to be considered as a whole (Table 2). The assemblage is consistent with an origin from an acid Mor humus beneath heather (Fig. 9). The larvae of the small Weevil (*Micrelus ericae)* develop in the seeds of ling (*Calluna vulgaris*), and *Erica tetralix* (Rheinheimer and Hassler, 2010) and the other weevil, (*Otiorhynchus nodosus)*, is polyphagous on low herbage (Böcher, 1988). At present, the latter is almost ubiquitous in the Arctic extending down to Scotland, Northern England, upland Wales and Northern Ireland (Morris, 1997). The most frequent carabid found, *Pterostichus diligens*, prefers an acid peaty substrate, occurring amongst the litter of rush and purple moor-grass (Boyce, 2004). Its distribution extends northwards to the low arctic (Lindroth, 1986). The carabids *Cymindis vaporariorum* and *Patrobus septentrionis* are predators in damp grassland and heathland and are probable components of a damp *Calluna* heath fauna found presently largely in uplands of the British Isles as far south as the Pennines (Luff, 1998; Marsh, 2009). The few unidentified fragments of water beetle, Dytiscidae, and absence of obligate aquatic beetles suggests that any pools were ephemeral. The rove beetle assemblage is typical of low arctic, boreo-montane localities, occurring in plant litter beneath low vegetation. The most frequent rove beetle, *Acidota cruentata*, is recorded from a wide range of ground surface habitats, from woodland to peat moss (Marsh, 2016). It has an extensive British fossil record including at Lateglacial (e.g., Gransmoor; Walker et al., 1993) and Holocene sites (e.g., Star Carr; Taylor and Allison, 2018) but this is the first Mid-Devensian record from Britain. One species, *Pycnoglypta lurida*, a species group as a result of recent work (Shavrin, 2016), appears no longer to be found in the British Isles. Typical of Lateglacial assemblages, it survived at least into the Early Holocene on the Middle Trent (Greenwood, unpubl.) and is widespread, if rare across Europe, occurring in both upland and lowland situations (e.g., Hansen, 1951; Palm, 1948). *Olophrum consimile* is another species of plant debris, occurring in leaf litter of willow and alder, as well as in wet moss and sedge clumps (Campbell, 1983). Whilst Marsh (2016) notes two old records from the Scarborough district, all other British finds of *O. consimile* are from the Scottish Highlands (Hyman, 1994) with only two recent records (Boyce, 2022).

Whilst most deposits sampled for fossil insects inevitably produce large numbers of unidentifiable sclerites, it is unusual to recover an elytron with an evidently diagnostic pattern and microsculpture which cannot be matched with modern reference material from somewhere in the Palaearctic. Fig. 10A shows the proximal half of a carabid right elytron. The scutellary stria, basal pore and overall form of the basal margin suggest a species of the genus *Stenolophus*; two dorsal punctures are also evident. Whilst the structural colour patterns in this genus may vary, none of the described European species shows the dark band in the third and fourth interstice moving to the second and third before coalescing at the suture. Although it is possible that the fossil is a colour variant of *S. teutonus* (Schrank), identification will have to await the recovery of more complete individuals. Overall, the assemblages indicate the absence of any significant woodland in the immediate vicinity.

4.4.2. Diptera

The Holocene record of a number of synanthropic fly species, largely based upon material recovered from archaeological contexts (Panagiotakopulu, 2004), is fairly extensive (e.g., the house fly, *Musca domestica* (Panagiotakopulu and Buckland, 2018) and the haematophagous stable fly, *Stomoxys calcitrans* (Hakbijl, 1989; Smith, 2011)). However, the longer Quaternary record of Diptera (true flies), is poor, not only because of preservation but also as a result of limited and incomplete description of the pupal stage of many species.

The Diptera from the basal sample (S3) are markedly different from the assemblage from the uppermost sample (S1; Table 1). Diptera remains from S3 consist almost entirely of puparia of agromyzids, of which only a few are unemerged (Fig. 10C). Whilst the immature stages of pest species, including some Agromyzidae, are often well described, many remain to be determined (Skidmore, 1996, 111) and the puparia from S3 could only be tentatively identified to the generic level as *Liriomyza* sp., most of which are leaf miners, occurring on a wide range of plants. The consistent

Table 2
Insect remains recovered from the three basal peat samples (S1-3) from Arclid. S3 is the bottom sample and S1 the top sample. The numbers represent MNIs (Minimum Numbers of Individuals).

Order	Family	Taxon	S1	S2	S3
Coleoptera	Carabidae	*Patrobus septentrionis* Dej.		1	
		Patrobus sp.			1
		Pterostichus diligens (Sturm)	5	5	3
		P. nigrita (Payk.)/*rhaeticus* Heer		1	
		Agonum sp.	1		
		Stenolophus cf. *teutonus* (Schrank)	1		
		Cymindis vaporariorum (L.)		1	1
	Dytiscidae	Dytiscidae indet.	1	1	1
	Staphylinidae	*Pycnoglypta lurida* (Gyll.)	2	1	
		Olophrum fuscum (Grav.)	1		
		O. consimile (Gyll.)	1		
		Acidota cruentata Mann.	2	7	3
		Stenus sp.	1	5	
		Medon sp.	1		
		Lathrobium (s.l.) sp.			1
		Leptacinus pusillus (Steph.)	2		
		Xantholinus linearis (Ol.)			1
		Gabrius sp.	5	2	
		Quedius/Philonthus sp.	1		
		Aleocharinae indet.	2	6	
	Pselaphidae	*Bryaxis* sp.	1		
	Elateridae	Elateridae indet.		1	1
	Curculionidae	Curculionidae indet.	1		
		Otiorhynchus nodosus (Müll.)	1	1	1
		Micrelus ericae (Gyll.)	4	1	4
Diptera		Diptera indet. (adult)	35		1
	Tabanidae	*Haematopota pluvialis* (L.)	15		
	Stratiomyidae	*Chloromyia formosa* (Scop.)	5	11	
	Agromyzidae	*Liriomyza* sp.		40	664
	Muscidae	Muscidae indet.	4		
	Calliphoridae	Calliphora sp.	4	1	
		Calliphoridae indet.	6		1
Trichoptera		Limnephilidae indet.	1	3	1
Homoptera		Homoptera indet.		3	
Hymenoptera	Formicidae	*Myrmica* sp.	3		
		Formica sp.		8	

nature of the assemblage suggests that a single event is recorded, and since *Liriomyza* tend to lay up to a few hundreds of eggs per female (cf. Leibee, 1984), infestation of pest proportions can take place over one or a few seasons.

The forty *Liriomyza* sp. Puparia in the middle sample (S2) reflect the environment in the basal sample, whilst the well preserved imagines of the soldierfly (*Chloromyia formosa)* relate to that of the upper sample (S3). Tentatively identified on wing venation, the recovery of the greater part of individuals of *C. formosa*, which included much of an antenna, allowed the use of other confirmatory characters (Fig. 10B; cf. Stubbs and Drake, 2014, 309). Most sources (e.g., *idem*; Lawrence, 1953; Skidmore, 1991) note that the larvae are found in cow dung (Lee and Wall, 2006) and the adults may be found on flowers and foliage in sunny situations, sometimes occurring in swarms (Dobson, 1997; Lawrence, 1988). Although the species may occasionally breed in vegetable debris rotted to the same condition, the Arclid basal peat material is probably indicative of the proximity of the dung of large vertebrates and this inference is reinforced by the fauna from the upper sample. The Arclid specimens constitute the earliest Quaternary record of soldierflies.

The uppermost sample (S1) has remarkable preservation. The most frequent dipterous wings in the sample have the characteristic venation of a tabanid, a family which includes horse-flies and clegs. The fossil record of the Tabanidae (horseflies) preserved in amber, extends back to the early Cretaceous and modern genera occur in the Miocene (Grimaldi and Engel, 2005, 523), but there is only one Quaternary record, an adult of *Chrysops*/*Haematopota* sp. from the 10th century AD on Orkney in Scotland (Skidmore and Panagiotakopulu, in press). The Arclid insect faunas provide the first Quaternary evidence for *Haematopota pluvialis,* which is now largely associated with domestic ruminants as an ectoparasite (Dörge et al., 2020) and an important vector of a variety of diseases (Baldacchino et al., 2014). Preservation shows the diagnostic light grey mottled surface and the short appendicular recurrent vein of R4 of *Haematopota pluvialis* (Fig. 12, Stubbs and Drake, 2014, 373). The Arclid assemblage is unusual in the predominance of males with a ratio of 3:1 males suggesting the preservation of a tabanid mating swarm (Thomson, 1986). *H. pluvialis* is widespread in northern Europe (Fig. 12C) and has high tolerance for cold temperatures and a preference for grassland and scrubland avoiding sparse vegetation (Dörge et al., 2020*)*. *H. pluvialis*, other tabanids and *Chrysops*, have been observed active in a temperature range from 14° to 23 °C (Ganeva, 2022). Two other Diptera were identified; the muscid *Muscina* sp. breeds in warm accumulations of plant debris such as manure (Hogsette and Farkas, 2000) and may have been attracted to significant accumulations of herbivore dung, perhaps around an adjacent waterhole, whilst *Calliphora* sp, the blue bottles or flesh flies, develop in carrion (Erzinçlioğlu, 1996; Smith, 1986). Despite the absence of bones from the deposit therefore, the adult fly fauna (Fig. 11, Table 2, Supplementary Data Table 1) would indicate the proximity of large vertebrates, as a blood source, and for dung and carrion.

4.4.3. *Mutual Climatic Range and comparison to other Mid-Devensian site in British Isles*

Current climate in Cheshire around Arclid has average maximum temperatures of ~13–22 °C during the summer and minimum temperatures of approximately 1–8 °C during winter

(Prior, 2010). MCR reconstruction of the Arclid fossil insect data from the basal peat suggest summer maximal temperatures between 13 °C and 18 °C, broadly similar to modern ones (Fig. 13). Winter temperature minima probably lay between −14 and 1 °C (S1, S2) indicating colder conditions than modern day winters. Several of the stenothermic species from Arclid, e.g., *C. vaporariorum*, *L. pusillus*, *P. septentrionis* and *O. consimile* are primarily upland species, while *P. lurida* and *A. cruentata* are also found in upland localities. The reconstructed climate for low level Arclid (~70m msl) could be comparable to present climatic conditions in upland (>400 m msl) localities in the British Isles.

The OSL dates (48 ± 3 to 71 ± 3 ka) for the three Arclid peat lenses overlap with the final phase of the Upton Warren Interstadial (*sensu* Coope et al., 1961, de Vries, 1958) and other British Mid-Devensian sites. A comparison of insect data with results from British sites, within the dating framework of Arclid, was undertaken in order to understand if there are temperature and faunal similarities between them. To this end, dates associated with insect work were collated (Supplementary Data Table 2). MCR results with chronological overlap to the latest Arclid date, i.e., Upton Warren, Four Ashes (Morgan, 1973b), Tattershall Castle 1 and Tattershall Castle 2 (Girling, 1980; Holyoak and Preece, 1985), Earith (Coope, 2000), Whitemoor Haye (Schreve et al., 2013) and South Kensington, Ismaili Centre (Coope et al., 1997) were compared with results from Arclid (Fig. 13). MCR data for all chronological phases were produced as opposed to selected dated samples, in order to consider climate data from stenothermic species for the relevant sites without the constraint of particular dates. Samples which contained beetle faunas with three or more stenothermic species were considered as part of this comparison to avoid including unreliable results.

Assemblages from Whitemore Haye, Tattershall Castle 1 (lower silts), Samples E4, E5 and E9 from Earith, Sample E2 from South Kensington, Ismaili Centre, various samples from Four Ashes and most from Upton Warren produced MCR results that are different from Arclid. Five samples from Four Ashes (S4, S9, S12, S15, S34), a single sample from Earith (E7) and Upton Warren (A5), all seven samples from Tattershall 2 (the upper silts), and three samples (C2, S2 and S4) from South Kensington provided similar MCR results to the three samples from Arclid both in terms of Tmax (mean temperatures of the warmest month of the year) and Tmin (mean temperatures of the coldest month; Fig. 13). One hundred and fifty six (156) stenothermic species from these samples were therefore listed in order to understand whether there was any similarity in terms of taxa in periods with broadly similar winter and summer temperatures (Supplementary data Table 4). DCA results indicated similarities between all samples from Arclid and Four Ashes (Fig. 14, Supplementary Data Table 4), in particular S4 and S12 (dated 43.2–48.1 and 41–42.4 cal ka respectively; Morgan, 1973b, Supplementary Data Table 2). These share several stenothermic species and insect faunas indicating similar boreo-alpine environments. E7 from Earith, dated to 42.7–48.7 cal ka, was also similar to Arclid.

5. Discussion

5.1. The palaeoenvironmental history of Arclid

The age of the basal Oakwood Formation till remains unresolved at Arclid although the new data shows it is more than 77 ka (Fig. 5). Expansion of a post-Ipswichian Interglacial but pre-Late-Devensian BIIS as proposed by Hibbert et al. (2010) and Gibbard et al. (2018) could account for the Oakwood Formation till at Arclid and explain the lack of preserved in situ Ipswichian Interglacial material. However, the existence of such an icesheet is disputed (Evans et al., 2018d) and at Arclid some Ipswichian Interglacial pollen was recovered from a *Mammuthus primigenius* tooth found on the floor of the quarry (Worsley, 1992). In addition, quarrying down to the top of the Oakwood Formation Till has recovered macro remains of trees (Fig. 4E), sadly not seen in situ, but which have been tentatively identified to include oak. Both hint at Ipswichian Interglacial deposits which have been eroded away leaving only a sporadic lag deposit. At the nearby Chelford site (11 km to the north) silts and gravels forming the Lapwing Bed were found under the Oakwood Formation till with an MCR indicating minimum temperatures of −27 to −10 °C and maximum temperatures of 9–11 °C (S57B, Supplementary Data Table 3; Worsley et al., 1983). A pre-Ipswichian amino acid age from the Lapwing Bed was obtained from this unit (Bowen, 1992). Therefore, whilst a larger temporal hiatus between the Oakwood Formation till and the dated sands above cannot be ruled out, the Oakwood Formation till is most likely to be Wolstonian in age, due to its composition and recent evidence that the BIIS extended as far south as the Midlands and Eastern England during this time (Gibson et al., 2022; Gibbard et al., 2018, 2021, Fig. 1B).

Arclid provides no evidence for an expansion of the BIIS in the Mid-Devensian as proposed elsewhere in the UK (Carr et al., 2006; Hibbert et al., 2010; Straw, 2016; Gibbard et al., 2017). Instead, the preserved sediments indicate near continuous sediment deposition from after ~77 ka to 41 ka (Figs. 1 and 5). The thickness of the Chelford Sand Formation relative to the elevation of the basal till suggests that the accrual of sand occurred preferentially in a palaeo-valley. This valley may have been over-deepened through the Mid- and Upper-Pleistocene by sub-surface halite dissolution and subsidence (Worsley, 2008). The discontinuous nature of this subsidence may be related to episodic release of fresh water down to the upper surface of the rock salt during post glacial permafrost aggradation. The general absence of organic material, presence of windblown material and aggrading fluvial sequences with ice wedge casts is interpreted as indicating formation within an open cold periglacial environment with braided river flow driven by spring snow melting and aeolian deflation in the summer months. The switch between more aeolian dominated sediments to more fluvial dominated sediments may indicate a transition from initial drier conditions to wetter conditions. The Chelford Sand Formation as recorded at the Chelford site has similar sediment characteristics and bedding structures and is thought to have formed from the accumulation of ephemeral lags and cut-off channels of varying amplitude on an aggrading sandur plain (Worsley et al., 1983).

The spatially distinct peats (Arclid Member) are interpreted to have formed as localised wetlands within a palaeovalley rather than indicating climatically induced low river flows. Whilst peat accumulation punctuated the deposition of the Chelford Sand Formation, intercalated sand in the upper part of the basal peat and in places within the upper peat unit are testament to some continued sand transportation, i.e., water flow. The luminescence ages of sands bracketing the peat lenses disprove the assignment of the Arclid Member to the Ipswichian Interglacial (cf. Worsley, 1992) instead placing it within the Mid-Devensian. The samples studied for insects from the basal peat lens of the Arclid Member represent a brief period of time, perhaps a few decades or hundreds of years maximum, since they produced similar faunas and almost identical climatic reconstructions (see Fig. 10, Table 2, Supplementary Data Table 3). The beetle faunas suggest an increase in wetness towards the top of the sequence, from S3 to S1. It also indicates an open landscape with sedges and grasses and a degree of shading, which would have been provided by mature heather and other shrubby vegetation rather than trees, equivalent to high altitude environmental and climatic conditions (see Fig. 9). This environment is similar to reconstructions from the much more abundant and much colder assemblages from the Oakwood pit at Chelford, where

Worsley et al. (1983) also argue for a *Calluna* dominated heath away from the wetland, although the characteristic weevil *Micrelus ericae* is absent. The dipterous assemblages also show differences from S3 to S1. The basal sample (S3) contains evidence for phytophagous flies and grasses, whilst in S2 and S1 coprophagous flies and swarms of blood-sucking flies occur, which in upland localities would be in flight on warmer days, primarily in July and August. They provide evidence for dung, both from taxa living in dung and those feeding on faecal matter. The Arclid faunas present strong evidence for herbivores in a treeless landscape. Preliminary insect research undertaken from the upper peat, where a lack of preservation led to limited faunal recover, produced similar results indicating heathland environments (Barnes, 2015). Since insect data for pools and wet environments preclude dry conditions as the driver for the lack of trees, it is probable that grazing by large herbivores, mammoth, woolly rhinoceros, bison, reindeer and/or horse could provide an alternative explanation (cf. Coope et al., 1961). More recently, Vera (2000) has flagged the role herbivores may play in suppressing woodland development. However, in northwest Europe during the Mid-Devensian, it remains doubtful whether grazing pressures could produce open, treeless environments. Instead, the short, precipitate nature of the warm interludes might have precluded tree immigration and woodland establishment (Coope, 2002).

The Stockport Formation sands indicate a change in depositional environment from fluvio-aeolian to fluvial with increasing carrying capacity indicated by the larger and less well sorted grain sizes. Ice wedge casts suggest that periglacial conditions prevailed although punctuated deposits of coarse sediment may indicate some flow variability. The 8.5 ka temporal hiatus between the Stockport Formation sands and till, shown in the luminescence chronology and pOSL data, is consistent with significant erosion of pre-existing sediments by the last BIIS as it overran the site. Elsewhere at Chelford, a major unconformity has been reported between the Stockport Formation till and underlying sands with syngenetic wedge casts infilled with till penetrating down into the sands (Ballantyne and Harris, 1994). The distribution and thickness of the resultant Stockport Formation till, based on borehole data, ignores pre-existing topography, instead thickening to the east as part of the regional moraine configuration (Fig. 1). At Chelford, the Stockport Formation is up to 6 m thick with sediments that have clearly been recycled from the underlying Chelford Sands (Worsley, 2015). Geochemical data presented here did not find such recycling at Arclid indicating that most of the till material had been transported from further afield by the Irish Sea Glacier of the BIIS. The Stockport Formation till, with a combined age of 33 ± 1.3 ka, falls within GS 5 at the Mid to Late-Devensian transition. Chiverrell et al. (2021) suggested the BIIS did not reach south Lancashire (to the north of Arclid) until after 30 ± 1.2 ka but their age model is not well constrained for ice build-up being based on early radiocarbon ages from Four Ashes (discussed below) and loess deposits from upland Yorkshire Dales (Telfer et al., 2009). The new luminescence ages directly date the glacial deposits themselves and suggest a slightly earlier build-up of the BIIS in NW England. However, this might not be the case as basal ice is likely to have cannibalised older unbleached material and so these ages may be slight over-estimates.

5.2. Mid-Devensian interstadials in the British Isles

Abrupt and short-lived change from stadial to interstadial climatic conditions coupled with the considerable time lag for the establishment of widespread trees (cf. Huntley, 1993) were probably the key drivers for vegetation change within Mid-Devensian interstadials. Research into insects and environmental gradients and their importance in understanding and predicting climate change (e.g., Andrew and Hughes, 2004; Hodkinson, 2005; Fielding et al., 1999; Whittaker and Tribe, 1996) is important in relation to the stenothermic Coleoptera from Arclid. The question is whether each rapid climatic episode would have led to unique environmental conditions and therefore distinct assemblages, or whether similar climatic conditions across multiple interstadials could have shaped identical natural assemblages. With insects, the sheer number of taxa and their ability to migrate fast at the start of a warm interval, in theory, could have led to unique assemblages during each interstadial, although taphonomy might limit our ability to understand the full story.

To place the Arclid Member into the wider terrestrial British chronostratigraphy, it was compared to the nearby Chelford site (Fig. 1). The MCR reconstruction from coleopteran assemblages found in the Chelford Farm Wood Member (reanalysis of Coope, 1959) indicates maximum summer temperatures from 16° to 18 °C and minimum winter temperatures from −9° to −5 °C (Sample S1; Supplementary Data Table 3). The Chelford Farm Wood member also contained well preserved remains (in some cases whole tree stumps in life position) of birch, pine and spruce. These, as well as pollen and Coleoptera, indicate a boreal forest with heathland prone to both flooding and fire (Coope, 1959; Simpson and West, 1958; Green, 1991). The palaeoclimate and palaeoenvironment of Arclid is therefore distinctly different from the Chelford site and therefore despite its proximity, cannot be of Chelford Interstadial age. Chelford has previously been equated to MIS 5c (GI 22/23; Holyoak, 1983; Ballantyne and Harris, 1994). A uranium-thorium date of 86 ± 26 ka (Heijnis and van der Plicht, 1992) tentatively supports this but has large uncertainties, as do old bracketing thermoluminescence ages of 99 ± 12 ka and 74 ± 8 ka (Rendell et al., 1991). Early experimental OSL ages of 71 ± 17 and 64 ± 10 ka bracketing an unspecified organic layer at Chelford (Rhodes, 1990; Smith et al., 1990) are slightly younger.

Elsewhere, at Brimpton, two interstadial organic units were reported, one of which was assigned to the Chelford Interstadial and one defined as the Brimpton Interstadial (Bryant et al., 1983, Worsley and Collins, 1995); insect faunas from the Brimpton interstadial are yet to be studied (Bryant et al., *ibid*). Again, distinct from Arclid, Brimpton is dominated by *Betula* and *Pinus* and has been correlated with the more extensive warm interstadial of MIS 5a). The Mid-Devensian site that is most similar to Arclid in terms of context is that examined by Maddy et al. (1998) at Cassington, Oxfordshire. Here a low energy meandering fluvial system transitioned to a high energy braided channel system with a corresponding change from temperate to colder climatic conditions. Pollen of the interstadial phase indicated an open boreal forest. Maddy et al. (1998) argued for a separate Cassington Interstadial after the Brimpton Interstadial and the OSL ages of 84 ± 19 to 73 ± 15 ka would place this site at around the MIS 4/5 boundary.

Correlation of the above interstadials with the more complete LGIC sequences from the adjacent continent remains tentative. The pine-spruce dominated peat from the Chelford Interstadial is usually equated on palynological and plant macrofossil grounds with the Brørup or Amersfoort/St Germain I Interstadial (e.g., Jones and Keen, 1993, Fig. 9.9). Based on Helmens' (2014) review of north European Last Interglacial Glacial sequences these fall within MIS 5c, and are matched to GI 23 (Wohlfarth, 2013). The Brimpton and Cassington Interstadials could be the equivalent to the succeeding Odderade/St Germain II and Oerel/Ognon I Interstadials (Wohlfarth, 2013) at the MIS 5/4 transition around GI 19 to GI 21.

With its more open heath and younger ages, Arclid would appear to be distinctive from and post-date the Chelford, Brimpton and Cassington Interstadials. The comparison of MCR results from British Mid-Devensian sites with chronological overlap with the Arclid Member indicated that samples from Four Ashes, Tattershall

Table 3
Revised Early to Mid-Devensian British Chronostratigraphy with reconstructed palaeoclimatic information where available. Greenland Interstadials are taken from Rasmussen et al. (2014) as are the ages, which are therefore independent of any chronology at specific sites. Both MIS and GI stages are provided as a broad framework whilst acknowledging that environmental drivers for the British terrestrial record may be different and may have had different lead and lags. The European Chronostratigraphy is drawn from long-terrestrial records found in Northern Germany, The Netherlands and France (see text for details).

British Chronostratigraphy				Age (ka)	GI	MIS	European Chronostratigraphy
Interstadial	Site	Summer Temp (°C)	Winter Temp (°C)				
Wretton		15 to 20	0 to −8	90–104	22/23	5c	Brørup/Amersfoort and St Germain I
Chelford	Farm Wood Quarry	16 to 18[a]	−9 to −5[a]	90–104	22/23	5c	
				88–90			
Brimpton	Brimpton	~15[b]	~-8[b]	78–86	21	5a	Odderade and St Germain II
Cassington	Cassington	17 to 18	−4 to 4	74–76	20/19	4	Oerel and Ognon I
				69–72			
Arclid	Arclid, Earith, Four Ashes, Tattershall	13 to 18[c]	−14 to 1[c]	57–59	16	3	Glinde and Ognon II or Moershoofd-Pile/Goulotte

[a] For more information on MCR see Supplementary data Table 3.
[b] Temperatures estimated based on pollen (not directly comparable to MCR from Coleoptera).
[c] Based on samples S1 and S2 (see Supplementary Data Table 3).

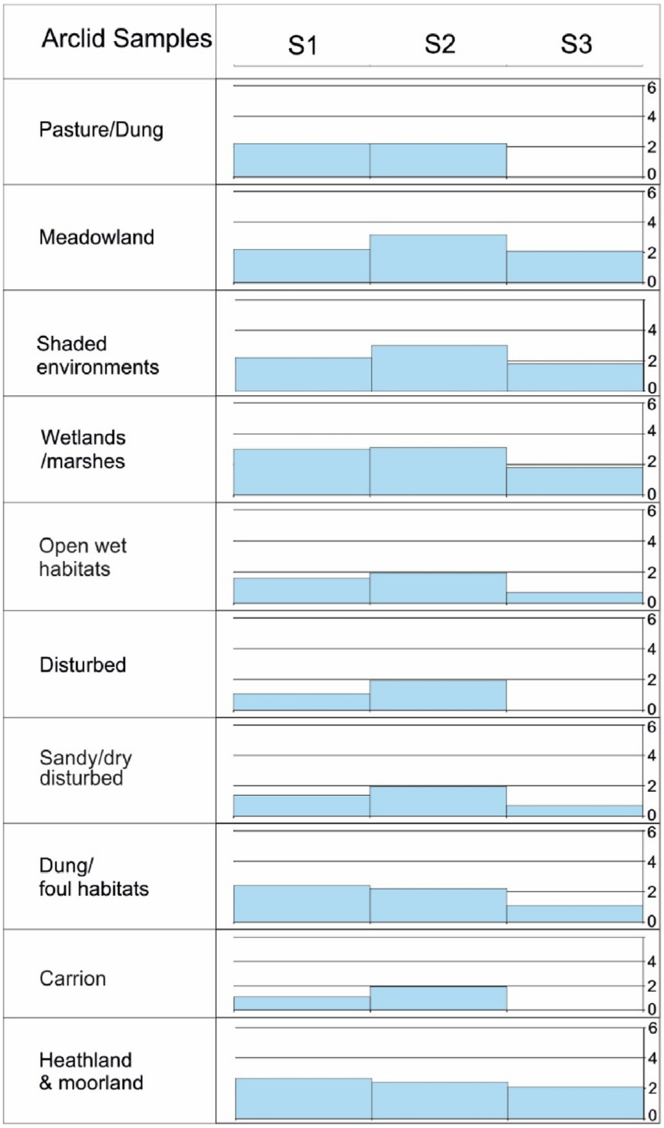

Fig. 9. Ecological diagram for the Coleoptera from Arclid, based on MNIs (Minimum Numbers of Individuals) redrawn from BUGScep (Buckland and Buckland, 2006). For full information on the beetle faunas see Table 2.

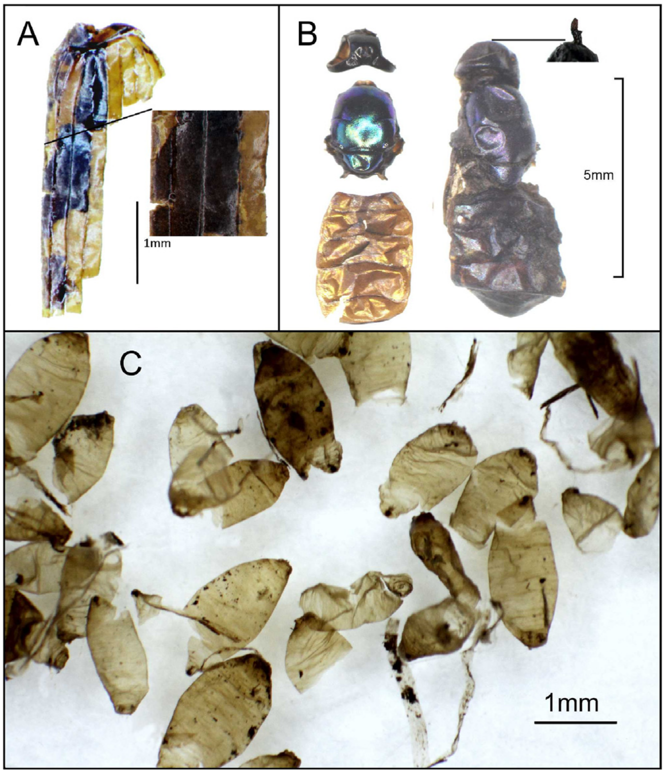

Fig. 10. Insect remains from the basal peat at Arclid. (A) Carabid elytron of *Stenolophus* cf. *teutonus* (Schrank), the inset showing detail of the microsculpture and structural colours. (B) male (left) and female (right) of *Chloromyia formosa* (Scop.), the inset showing the characteristic antenna. (C) Puparia of *Liriomyza* sp. from sample S3. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Castle 2 (upper silts), and one sample from Earith, S7, were similar to Arclid. In particular, comparisons based on stenothermic beetles, showed similarities with samples from Four Ashes and E7 from Earith indicating either very similar interstadial conditions, or the same interstadial. Previously it has been argued that Upton Warren, the key site which lends its name to the interstadial but which is poorly dated, and other Mid-Devensian sites with early radiocarbon dates could in reality be older (e.g., Bowen et al., 1989; Maddy et al., 1995; Buckland et al., 2019) due to them being at or

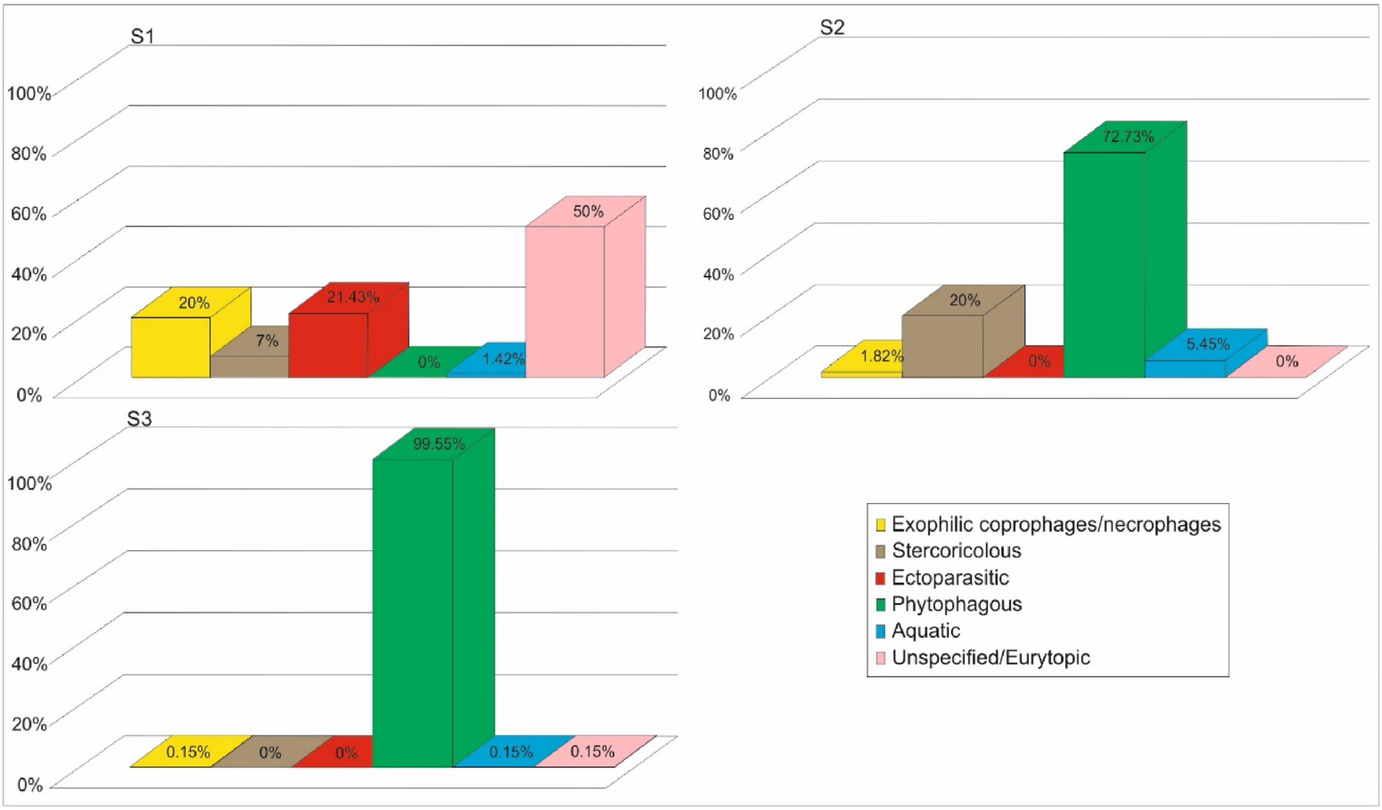

Fig. 11. Ecological categories for Diptera and Trichoptera from the basal peat at Arclid. For additional information see Supplementary Data Table 1.

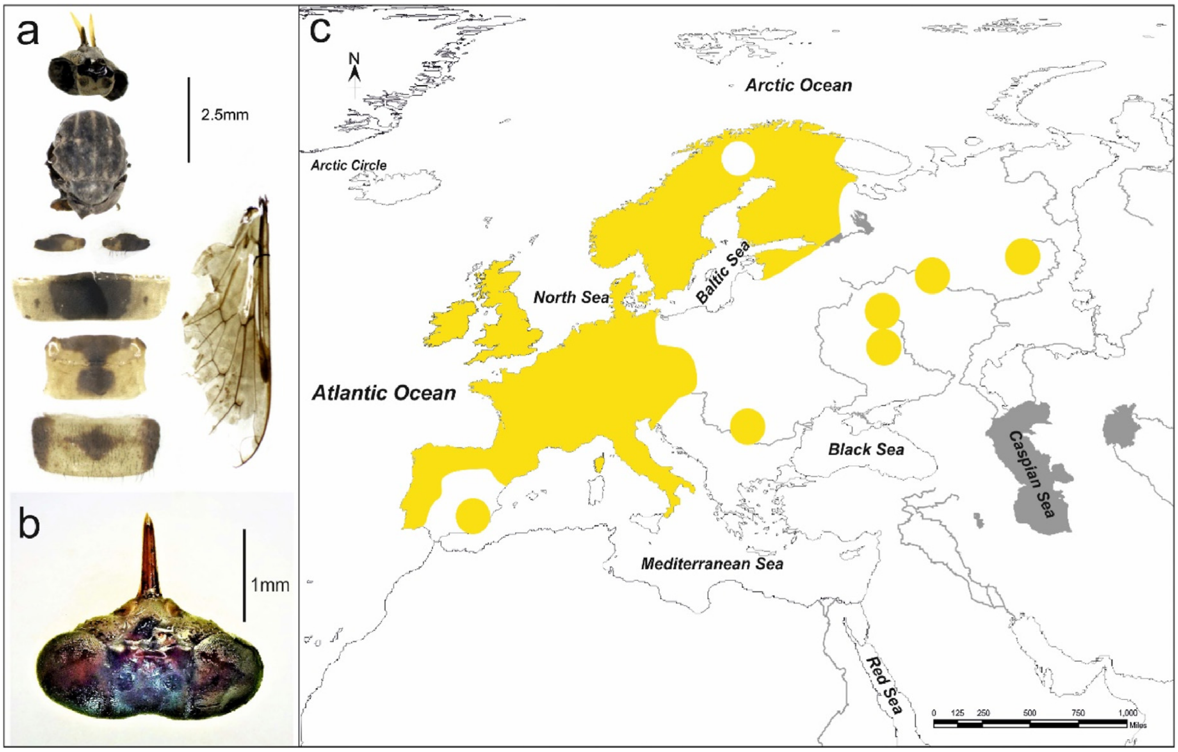

Fig. 12. *Haematopota pluvialis* (L.) from Arclid, S1 (A) Head, thorax, halteres, abdominal segments and wing with the characteristic venation and spots visible. (B) Head of a female *H. pluvialis* with compound dichoptic eyes with a distinctive pattern. (C) Modern distribution of *H. pluvialis* redrawn from GBIF (GBIF.org, April 14, 2020).

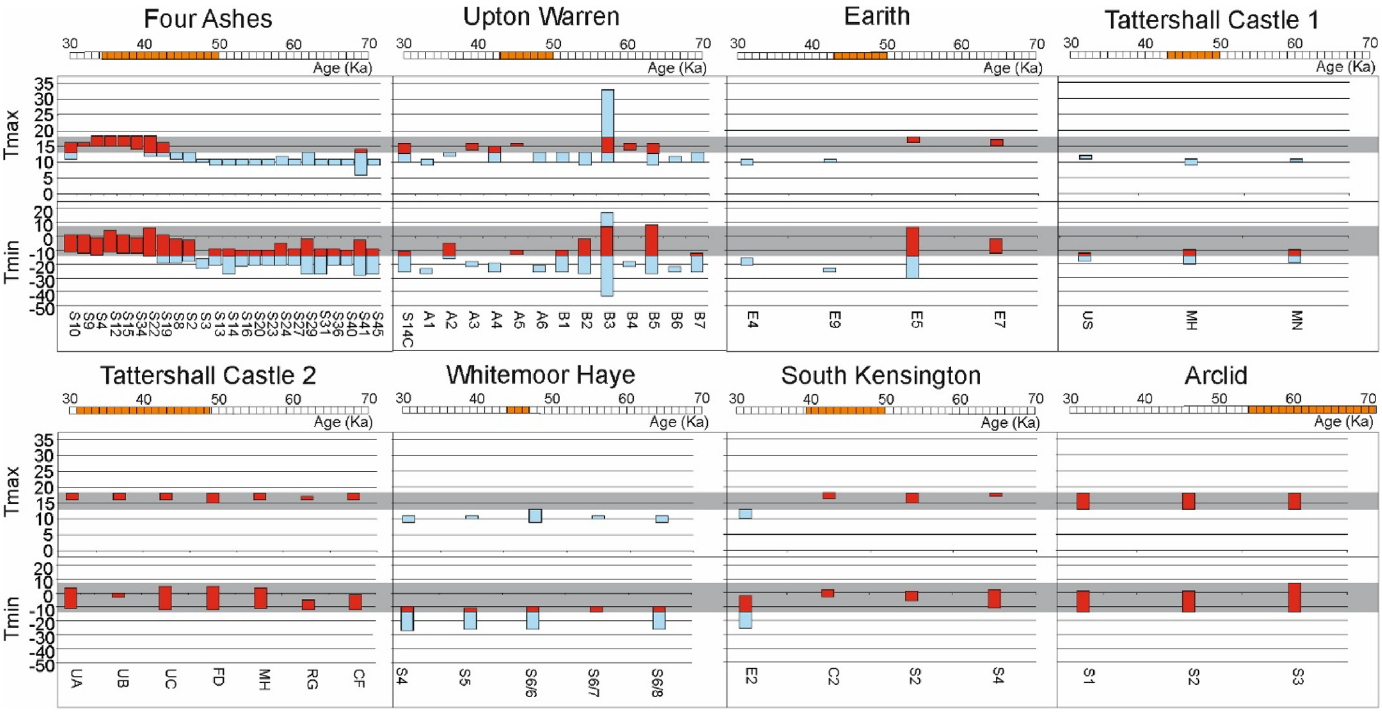

Fig. 13. Comparison of MCR diagrams, redrawn from BUGScep (Buckland and Buckland, 2006), of Mid-Devensian sites in the British Isles which overlap chronologically with Arclid, indicating similar summer maximum temperatures (Tmax) and winter minimum temperatures in degrees Celsius (Tmin). The samples from each site used for MCR are listed on the horizontal axis. Grey bar indicates similarities with Arclid temperatures, with samples falling within the same Tmax and Tmin indicated in red and falling outside this in blue (for further information see Supplementary Data Tables 2 and 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

possibly beyond the limits of conventional radiocarbon dating and therefore potentially unreliable (Briant and Bateman, 2009). Until now this has been impossible to prove, but with the new luminescence based-chronology for Arclid and similarity of MCR analysis shown above, interstadial deposits at Tattershall (upper silts) and perhaps some organic units at Four Ashes and Earith along with the basal peat at Arclid may be better assigned together as a separate interstadial; here proposed as the Arclid Interstadial. Assuming the Arclid Interstadial reflected an environmental response significant enough to also be recorded in the Greenland ice core record without appreciable leads or lags, the OSL bracketing ages of ~71-54 ka from Arclid itself could place it in any Greenland Interstadial (GI) between GI 19-2 and GI 15 (Rasmussen et al., 2014, Fig. 1). Of these GI 19 is only partially within the age range and GI 18, GI 17 and GI 15 are of insufficient duration for the climate over Britain to have warmed sufficiently to become cool temperate as indicated by the insect evidence (Rasmussen et al., 2014, Fig. 1). GI 16, which follows on quickly from GI 17 and spans ~2 ka from ~57 to 59 ka, would appear the most likely GI equivalent for the Arclid basal peat. If correct the proposed Arclid Interstadial may be the British equivalent to the continental European Glinde/Ognon II Interstadials. Alternatively, it could be equivalent to the early part of the Moershoofd-Pile/Goulotte interstadial complex the base of which was radiocarbon dated to ca. 50–60 cal ka BP (Guiter et al., 2003).

A revised British chronostratigraphy would retain the Wretton, Chelford and Brimpton Interstadials in the Early Devensian and add the Cassington Interstadial by accepting this as a separate interstadial (Table 3). The early Mid-Devensian, based on evidence from Arclid, some of Four Ashes and Earith as well as Tattershall Castle (upper silts), is proposed as the Arclid Interstadial (Table 3) which was followed by the Upton Warren Interglacial Complex (Fig. 1).

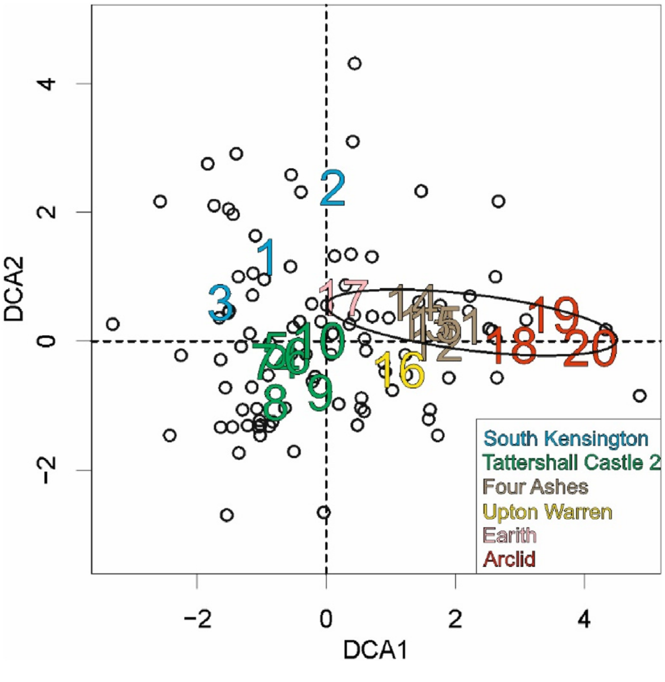

Fig. 14. Comparison of the presence of stenothermic Coleoptera (open circles) from Mid- Devensian sites from the British Isles using detrended correspondence analysis (DCA). Samples from Arclid are colour coded in red, from Earith in pink, from Upton Warren in yellow, from Four Ashes in brown, from Tattershall Castle 2 (upper silts) in green and from South Kensington in blue. Samples from Arclid are more similar to Four Ashes and the selected sample from Earith, E7 (circled area). For full information on the stenothermic species from the relevant sites and samples used and their numbering for the DCA see this paper and Supplementary Data Table 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Based on this, the British chronostratigraphy would no longer have a large temporal gap between the Brimpton Interstadial and the Upton Warren Interstadial complex. The Greenland ice-core record shows interstadials between 60-30 ka were much shorter with a mean duration ~1.4 ka compared to ~3.0 ka between 110-60 ka and ~2.1 ka between 30-13 ka (Fig. 1; based on data from Rasmussen et al., 2014). Interstadials between 60-30 ka were also more frequent with on average ~5 interstadials per 10 ka compared to ~2.6 per 10 ka between 110-60 ka and ~3.3 per 10 ka between 30-12 ka (Fig. 1; based on data from Rasmussen et al., 2014). Assuming this increased frequency and reduced duration of interstadials also occurred in Britain, this combined with dating uncertainties (especially where the dating relies upon bulk sediment radiocarbon ages made when the technique was in its infancy) may explain why many previously reported Mid-Devensian sites cannot be confidently attributed to individual interstadials. Arclid, where the fossil insect evidence from the organic remains can be placed into a well dated and clear stratigraphy, offers a model to apply to other sites in future.

6. Conclusions

The production of a chronostratigraphic framework at Arclid Quarry for the last glacial-interglacial cycle has improved understanding of past environmental shifts in this region. Arclid is the only site beyond the limit of radiocarbon dating where palaeoecological and palaeoclimatic information from the insects, Coleoptera and Diptera, can be directly associated with detailed stratigraphic results and well dated samples. The following conclusions can be made.

- The basal unit is interpreted as the glaciogenic Oakwood Formation Till, deposited by a BIIS in excess of ~77 ka ago and likely during the penultimate glacial period (Wolstonian).
- The Chelford Sand Formation spans 77 to 47 ka and was deposited on an intermittently vegetated braided floodplain initially under periglacial conditions dominated by aeolian transportation with fluvial inputs but later by fluvial transportation with aeolian reworking.
- The Arclid Member comprises three spatially distinct peat lenses from which coleopteran results indicate environments similar to present day high altitude open heathlands and dipterous results provide evidence for large herbivores.
- The Arclid assemblage include the earliest records of the blood-sucking fly *Haematopota pluvialis*, and the soldierfly *Chloromyia formosa.*
- Mutual Climatic Range reconstructions based on beetle data from the basal peat indicate summer temperatures between 13 °C and 18 °C, and winter temperatures between −14 °C and 1 °C.
- The Stockport Sand Formation was deposited fluvioglacially and included several major ‘flood’ events between 47-41 ka.
- The upper till is interpreted as the glaciogenic Stockport Till formed by the advance of the BIIS. The site was ice-covered after ~33 ka or soon after.
- Stenothermic beetle analysis from the Arclid Member indicate similarities with results from other Mid-Devensian sites in the British Isles, suggesting that the latter are at the limit of radiocarbon dating and may be of a similar age to the basal peat at Arclid.
- A revised British chronostratigraphy would place the Wretton, Chelford, Brimpton and Cassington Interstadials in the Early Devensian.
- Basal organic sediments found at Arclid along with other reassigned sites are proposed as a Mid-Devensian interglacial; the Arclid Interstadial. This closes the previous gap in the British interstadial record between the Brimpton Interstadial and the Upton Warren Interstadial Complex.

Authors contribution

All the authors participated to the discussion of the results and the interpretations. Bateman M.D. led writing of the paper with contributions from all authors. Fieldwork and sediment characterisation: C. Rex, M.D. Bateman, S.J. Livingstone and L. Eddy. Luminescence analysis: C. Rex and M.D. Bateman. Insect identification and interpretation: P.C. Buckland and E. Panagiotakopulu. Insect comparative analysis: E. Panagiotakopulu. Tephrochonology: M. Hardiman.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2022.107882.

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