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Refining the known extent of major onshore Quaternary glaciation in the UK — Types of evidence, nomenclature and uncertainty

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ABSTRACT

Repeated cycles of Quaternary glaciation have had a major impact on the morphology and shallow sub-surface properties of much of the UK landscape and continental shelf. Understanding the extent of glaciation involves understanding of our landscape history but is also critical to the broad range of applied users that interact with the shallow subsurface including engineers, hydrogeologists, planners and decision makers. Numerous interpretations of the onshore extent of the Anglian and Late Devensian glaciations have been published. However, many are not clearly evidenced or justified, being sometimes based on anecdotal evidence or supposition, with the levels of associated uncertainty not effectively communicated. As part of this work, the long-term record of Quaternary glaciation within the UK is reviewed and the types of geological and geomorphological information that can be employed to interpret their former extent are assessed. We also examine the range of factors that may influence the relative preservation of this evidence. As part of this assessment, we recommend abandoning the term 'glacial limit' (and other related synonyms) when interpreting the extent of glaciation within the geological record. Instead, we recommend using the term *limit of preserved evidence* which more accurately reflects the spatial context of such evidence. Finally, we present new onshore linework for the limit of preserved evidence of both the Anglian and Late Devensian glaciations, presenting how this linework was captured and the associated levels of uncertainty.

1. Introduction

Over the past 2.588 million years (the Quaternary Period) of Earth history, glaciers have been one of the most significant agents of landscape change across the UK landmass and continental shelf (Bowen et al., 1986; Sutherland and Gordon, 1993; Clark et al., 2004a; Sejrup et al., 2005; Stoker et al., 2011; Lee et al., 2018; Hall et al., 2019; Merritt et al., 2019; Goudie, 2020). Glaciers act to amplify and sculpt the topography, transferring sediment from upland areas into lowland and basinal sinks and variably eroding, deforming and concealing the underlying geology in the process. Over the past 40 years there have been significant advances in our understanding of the glacial history of the UK. This has been driven by: (1) improved accuracy and precision of geochronological techniques (Böse et al., 2012; Lowe and Walker, 2014; Clark et al., 2022); (2) the availability of high quality topographic imaging of formerly glaciated areas within both onshore and offshore environments (*e.g.*, Bradwell et al., 2008; Clark et al., 2004b, 2018, 2022; Livingstone et al., 2012); (3) improved accessibility of 2D and/or 3D seismic data in offshore areas (Eaton et al., 2020; Stewart and Lonergan, 2011; Praeg et al., 2015; Cotterill et al., 2017; Dove et al., 2017; Newton et al., 2024); and (4) enhanced understanding of subglacial/ice-marginal processes and glacial landsystems (Murray, 1997; Evans, 2003; Benn and Evans, 2014).

Current understanding now demonstrates that glaciers have been active components of the UK landscape throughout much of the Quaternary (Böse et al., 2012; Lee et al., 2012; Rea et al., 2018; Hall et al., 2019; Clark et al., 2022) with repeated expansions of ice onto the NW European continental margin (Stoker et al., 1994; Sejrup et al., 2005; Thierens et al., 2012; Bradwell et al., 2021) and adjacent areas of continental shelf including the North Sea Basin (Stewart and Lonergan, 2011; Dowdeswell and Ottesen, 2013; Rea et al., 2018; Kirkham et al., 2021). The onshore record of glaciation in the UK is more temporally constrained, restricted to the most recent (Younger Dryas Stadial) (Bickerdike et al., 2018a) and larger phases (*e.g.*, Anglian and Late Devensian) of glaciation (Bowen et al., 1986; Clark et al., 2004a, 2004b, 2022; Chiverrell and Thomas, 2010; Gibbard and Clark, 2011; Lee et al., 2011). Possible earlier and intervening phases of glaciation within the current onshore record are also indicated (*e.g.*, Davies et al., 2009; White et al., 2017; Evans et al., 2019b; Gibson et al., 2022; Gibson and Gibbard, 2024; Scourse, 2024) but the evidence is more discrete, subjective and sometimes open to several interpretations.

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The onshore extent of the Anglian and Late Devensian glaciations has attracted the curiosity of scientists for well over 100 years but there remains significant ongoing regional and/or local uncertainty. This reflects: (1) ambiguity of the interpreted evidence itself; (2) a lack of historical clarity relating to how an interpretation is justified; and (3) what the term 'glacial limit' means in practical terms. The interpreted extent of glaciation is often illustrated by lines shown within figures and maps, but the level of justification and uncertainty associated with that linework is often inconsistently or poorly communicated. This information is critical not only to underpin scientific rigour and informed debate but also because many of our current and future socio-economic needs interact with the Quaternary — specifically areas that have been previously glaciated. Glaciation drives a variable range of tectonic and sedimentary processes which introduce lithological and structural heterogeneity to the shallow sub-surface which can impact its properties and behaviour (*e.g.,* Le et al., 2014; McEvoy et al., 2016; de Freitas et al., 2017; Giles et al., 2017; Clarke, 2018; Moore et al., 2022). This can create a significant geological risk which in turn causes a socio-economic risk to applied users, for example, foundation conditions for buildings and infrastructure (*e.g.*, tunnelling, cuttings, cable routes, wind turbines); managing transport, energy and utility infrastructure; sustainable management of resources such as soils, water and mineral aggregates; and the management of geological hazards (*e.g.*, landslides, coastal erosion).

Within this paper we firstly review the evidence for glaciation within the UK, in particular highlighting glaciations where so-called 'glacial limits' have previously been proposed. Secondly, we assess the types of geological and geomorphological evidence that can be used to constrain the extent of Quaternary glaciations, factors that regulate their preservation within the geological record, and recommend refined nomenclature. Finally, we apply this approach and present newly constructed *limits of preserved evidence* for both the onshore Anglian and Late Devensian glaciations.

2. The UK glacial record

The significance of glaciers and glaciation in shaping the UK landscape was first recognised during the mid-nineteenth century (Agassiz, 1840; Buckland, 1840). Since then, an improved understanding of our long-term glacial history has progressively emerged, underpinned by an understanding of our onshore geological record and increasingly the record from the UK Continental Shelf (UKCS) (West, 1977; Bowen et al., 1986; Clark et al., 2004b; Gibbard and Clark, 2011; Lee et al., 2012). Allied to this have been significant improvements in geochronological methods and our understanding of glacial processes and landsystems (Evans, 2003; Böse et al., 2012; Clark et al., 2012, 2022; Benn and Evans, 2014). Within this section of the paper, we review current understanding of the glacial history of the UK (Fig. 1).

2.1. Early and early Middle Pleistocene glaciations

Over the course of the past 30 years, a growing body of evidence demonstrates that highland areas of northern and western Britain were extensively glaciated during the **Early and early Middle Pleistocene**, with repeated glacier expansion onto the adjacent continental shelf and margin. Evidence includes: (1) long-term records of glacigenic input onto debris fans along the NW European continental margin (Stoker et al., 1994; Sejrup et al., 2005); (2) ice rafted debris (IRD) records from deeper basinal areas (Bailey et al., 2012; Thierens et al., 2012); and (3) glacially-eroded sediment input into the Bay of Biscay from 1.2 Ma (Toucanne et al., 2009). Evidence for glaciation has been recognised extensively within the North Sea Basin within seismic data, including multiple generations of iceberg scour marks (Dowdeswell and Ottesen, 2013; Rea et al., 2018); subglacial tunnel valleys (Graham et al., 2007, 2011; Stewart and Lonergan, 2011; Stewart et al., 2013; Ottesen et al., 2020; Kirkham et al., 2021); and other landforms including moraines, megascale glacial lineations, crevasse-squeeze ridges, thrust structures and glacitectonic hill–hole pairs (Newton et al., 2024). Onshore, evidence for glaciation is more discrete and includes the presence of glacial erratics within river terrace sequences of the Ancestral Thames (Whiteman and Rose, 1992; Rose et al., 1999, 2010), glacially-sourced heavy mineral assemblages (Lee, 2009) and erratics (Larkin et al., 2011; Hoare, 2012) from northern Britain and Scandinavia within shallow marine deposits in eastern England. No attempts have been made to rigorously define the extent of these glaciations. An incursion of ice into northern East Anglia during Marine Isotope Stage (MIS 16) has also been proposed previously — the so-called 'Happisburgh Glaciation' (Lee et al., 2004; Hamblin et al., 2005; Rose, 2009). The status and timing of this glaciation remain unclear due to the: (1) absence of geochronological constraint; (2) problems resolving the Bytham terrace sequence which has been used to delineate this glaciation from the later Anglian Glaciation (Lewis, 1993; Westaway, 2009; Lee et al., 2004, 2020; Lewis et al., 2021); and (3) the presence of biostratigraphical and amino acid evidence which does not delineate this glaciation from the Anglian (Preece et al., 2009).

2.2. Late Middle Pleistocene glaciation: Anglian

The **Anglian (Elsterian) Glaciation** (Marine Isotope Stage (MIS) 12; 0.48–0.43 Ma) is the largest known and earliest glaciation to have affected the UK during the Quaternary for which there is widespread onshore geological evidence. The age of the Anglian glaciation is constrained by: (1) amino acid racemisation (AAR), uranium-series (U–Th) and Electron Spin Resonance dating of interglacial deposits that underlie and/or overlie Anglian glacial deposits in East Anglia (Rink et al., 1996; Rowe et al., 1999; Grün and Schwarz, 2000; Preece et al., 2007, 2009) and (2) optically stimulated luminescence (OSL) dating of Anglian-age river terrace deposits (Pawley et al., 2010) and glacial outwash deposits in north Norfolk that cap the glacial sequence (Pawley et al., 2008). The glaciation is widely understood to have initiated the development of modern drainage across parts of central, southern and eastern England (Gibbard, 1988; Bridgland, 2010) with meltwater making the initial incision through the Straits of Dover (Gibbard, 1988; Gupta et al., 2007). Offshore within the UK sector of the Southern North Sea, evidence for the Anglian is indicated by the presence of numerous deeply-incised and partially-infilled subglacial tunnel valleys (Cameron et al., 1987, 1992; Scourse et al., 1998; Mellett et al., 2020); however the offshore extent of this glaciation remains poorly constrained. Onshore, glacial deposits occur extensively across the English Midlands and East Anglia (Shotton, 1953; Bishop, 1958; Perrin et al., 1979; Rice, 1981; Hart and Boulton, 1991; Lunkka, 1994; Rose, 2009; Lee et al., 2017) and potentially as discrete outliers within the Malvern Hills (Richards, 1999), the Lower Severn Valley (Maddy et al., 1995) and Bristol (Gilbertson and Hawkins, 1978) although some of these latter localities have no independent age control and may not represent the full glacial extent. At its maximum known onshore extent, Anglian ice therefore reached the northern outskirts of London and southern East Anglia where it is relatively well constrained (Clayton, 1957; Perrin et al., 1979; Allen et al., 1991; Leszczynska et al., 2017). To the west of London however, extending across the South Midlands and into southwest England, the extent of the Anglian Glaciation remains poorly defined (Price, 2019; Scourse, 2019) (Fig. 2) where evidence appears to have been largely removed by slope and fluvial processes (Price, 2019). Further to the west in north Devon, glacial deposits at Fremington (Arber, 1964; Kidson and Wood, 1974) remain somewhat enigmatic with a range of different Middle and Late Pleistocene age interpretations (Rolfe, 2015; Scourse, 2024; Bennett et al., 2024). For the purpose of this study, it is assumed that the maximum likely age of these deposits is Anglian, and they are therefore included within the Anglian 'limit' presented below. However, we fully acknowledge that their absolute age may be younger. Various

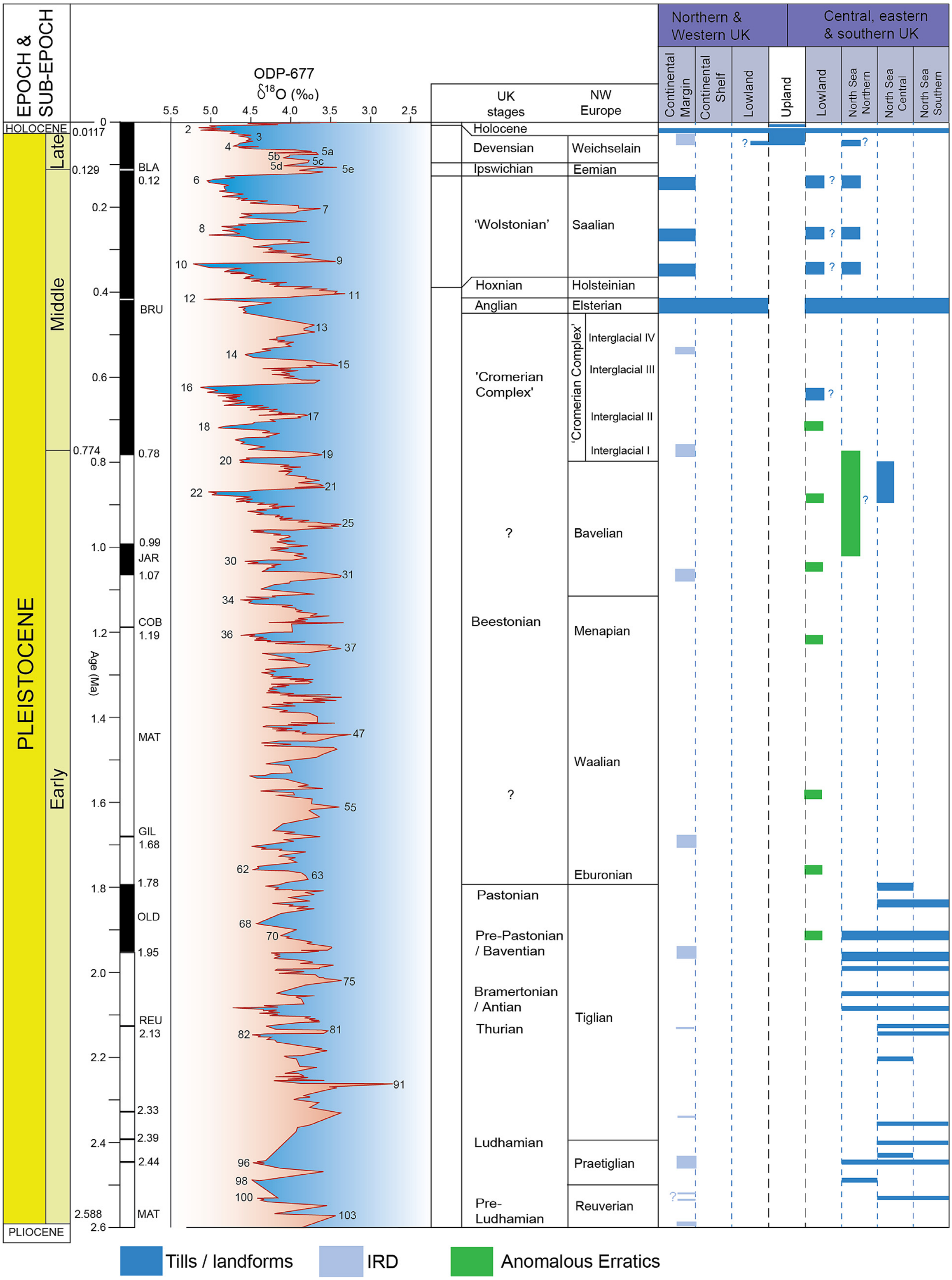

Fig. 1. The Quaternary timescale showing the marine isotope record (based on Lisiecki and Raymo, 2005) and projected temperate (pink) and cold (blue) stage intervals. Superimposed upon this timescale is evidence for the long-term glacial history of the UK utilising direct (*e.g.*, tills, landforms) and indirect (*e.g.*, IRD, erratics) on the onshore and offshore records. Data from: Sejrup et al. (2005); Graham et al. (2011), Stewart and Lonergan (2011), Lee et al. (2012), Thierens et al. (2012), Rea et al. (2018) and Scourse (2024). Note that there is considerable uncertainty on the timing on many of the older events.

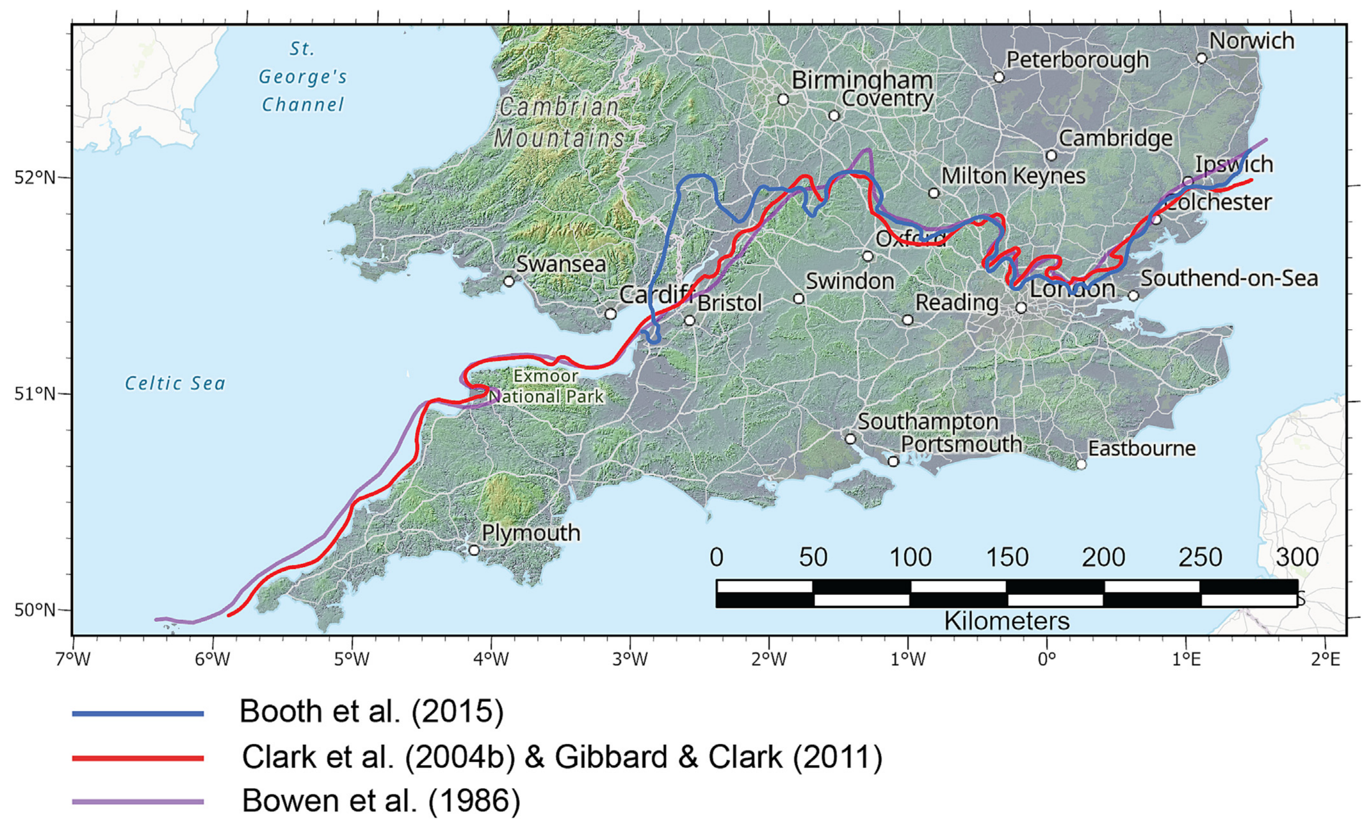

Fig. 2. Historical interpretations of the Anglian *glacial limit*. The eastern sectors of all three lines are in general agreement with local differences in interpretation likely reflecting subtle differences in interpretation, the scale of interpretation and linework compilation methods. Within the Lower Severn Valley and extending west, there are fundamental differences in interpretation between several of the studies. For example, three of the studies interpret the Anglian limit as extending along the northern flanks of Somerset, Devon and Cornwall, with one indicating that ice reached the Isles of Scilly. Derived in part from DTM of Great Britain at 5 m resolution © Bluesky International Limited. Esri "World Topographic Map". Jan 4, 2024. Esri Sources: Esri, Ordnance Survey.

historical interpretations have also inferred the widespread presence of Anglian ice abutting the southern flanks of the Bristol Channel, extending along the coast of north Devon and Cornwall. With the exception of possible evidence from Fremington outlined above — which is caveated by the caution indicated, there is no widespread evidence to support "… the notion of an Anglian Glaciation off the northern coast of southwest England, an *idée fixe* of the Quaternary community for several decades…" (Scourse, 2019, p. 6).

2.3. Late Middle Pleistocene glaciation: other

Much debate, both historic and present day, has focussed on the possibility of additional post-Anglian Middle Pleistocene glaciations. During the post-Anglian **late Middle Pleistocene** (MISs 10–6), discussion has centred on the occurrence of a so-called 'Wolstonian' glaciation within the English Midlands and East Anglia (West and Donner, 1956; Straw, 1979, 1983; Shotton, 1983; Rose, 1987; Lewis, 1993; Hamblin et al., 2005; Gibbard et al., 2012, 2021; Bridgland et al., 2015; White et al., 2017; Langford, 2018; Rose et al., 2021; Gibson et al., 2022). Hitherto, resolving this issue has proven highly challenging. This reflects the often fragmented and indirect (*e.g.,* drainage reorganisation) nature of the evidence; the potential for alternate interpretations; apparent conflicts with other types of evidence; the general lack of unambiguous indicators of glaciation; and the availability of reliable absolute age control. Currently, there is growing speculation indicating the presence of at least one additional lowland glaciation in central and eastern England during MIS 10 (Rose et al., 2021), MIS 8 (White et al., 2010, 2017; Bridgland et al., 2015), MIS 6 (Gibbard et al., 1992, 2018; Evans et al., 2019b; Gibson et al., 2022) or both MISs 8 and 6 (Langford, 2018). Offshore the picture remains uncertain. MIS 8 and 6 glacial deposits have been recognised within the Dutch sector of the Southern North Sea (*e.g.,* Laban and van der Meer, 2011; Cartelle et al., 2021). However, whilst the presence of MIS 6 ice has been indicated within the British sector of the Southern North Sea (*e.g.,* Clark et al., 2018; Gibson and Gibbard, 2024), no tills of MIS 6 (or MIS 8 or MIS 10) have yet been identified (Cameron et al., 1992; Lee et al., 2012) (Fig. 3).

2.4. Late Pleistocene: Early Devensian glaciation

The presence of a glaciation during the **Early Devensian** (MISs 5d–4) prior to the Late Devensian (MIS 2) has also stimulated significant debate (Mitchell et al., 1973; Bowen et al., 1986; McCabe, 1987; Gibbard et al., 2022; Scourse, 2024). Key elements of the discussion have focussed on the application and significance of different geochronological methods (Bowen et al., 2002; McCarroll, 2002; Hall et al., 2003) and the pre-MIS 2 timing of the initial inception of the Last British–Irish Ice Sheet especially in Scotland (Hall et al., 2003; Merritt et al., 2017). Provenanced IRD from the European continental margin provides compelling evidence for the existence of marine-terminating glaciers within Britain during either part (Scourse et al., 2009; Fabian et al., 2023; Toucanne et al., 2023) or all (Hibbert et al., 2010) of the last cold stage (MISs 5d–2). Offshore cores from the Goban Spur and the Bay of Biscay indicate the presence of marine terminating ice in western UK/Ireland during MIS 4 (Fabian et al., 2023; Toucanne et al., 2023) although the overall extent of ice was likely limited (Scourse, 2024). Additional evidence for Early Devensian glaciation in the UK includes cosmogenic exposure ages from exposed bedrock surfaces in North Wales (Hughes et al., 2022), Lundy (Rolfe et al., 2012; Carr et al., 2017), and glacial outwash deposits in Cheshire (Rex et al., 2023) and Scotland (Duller et al., 1995; Bradwell et al., 2021).

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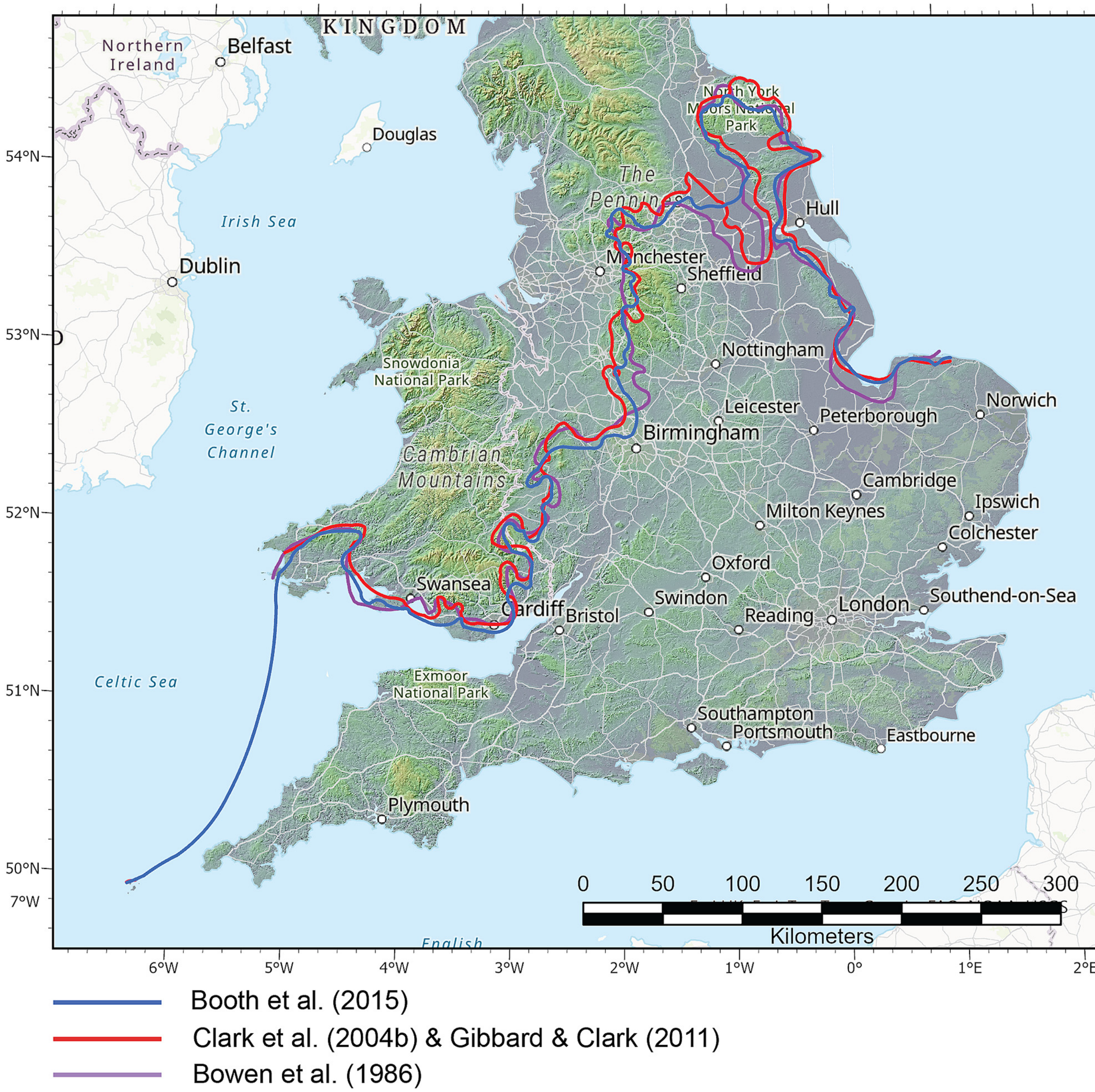

Fig. 3. Historical interpretations of the Late Devensian *glacial limit* within the UK. There is a consensus within the historical linework of the broad geometric extent of the Late Devensian glaciation. However, there is notable divergence in southwest England, with Booth et al. (2015) acknowledging other published research in that glaciation of the Isles of Scilly occurred during the Late Devensian and not the Anglian as previously considered (see also Fig. 2). Locally, there are spatial differences (up to km scale) in the positioning of the linework reflecting likely differences in interpretation and the method and resolution of data capture. Derived in part from DTM of Great Britain at 5 m resolution © Bluesky International Limited. Esri "World Topographic Map". Jan 4, 2024. Esri Sources: Esri, Ordnance Survey.

2.5. Late Pleistocene: Late Devensian glaciation

During the Late Pleistocene, the UK was glaciated by an additional major glaciation for which there is abundant preserved evidence — the **Late Devensian/Weichselian** (MIS 2 *c.*, 30–16 ka). Evidence for this glaciation is reflected by the extensive range of glacial sediments and relatively fresh landforms that have been mapped onshore across much of northern and central England, and offshore within the Irish and North Sea basins and around the continental margin (*e.g.*, Clark et al., 2004a, 2018; Evans et al., 2009; Livingstone et al., 2010, 2012; Hughes et al., 2014; Dove et al., 2017; Chiverrell et al., 2021). The onshore extent of the Late Devensian glaciation is relatively well established because of the better-preserved (compared to the Anglian) archive of sediments and landforms, although issues persist locally where the field evidence is ambiguous. Within the Vale of York, the Escrick Moraine is widely interpreted as the southern-most limit of Late Devensian ice (Ford et al., 2008), however others have speculated that ice may have extended southwards into South Yorkshire and Lincolnshire based on the presence of possible glacial outwash deposits (Gaunt, 1994; Friend et al., 2016). However, without clear evidence for grounded ice (*e.g.*, a mapped subglacial till, glacitectonic features) the Escrick Moraine is utilised here as the southern-most known extension of Vale of York ice.

Much of the recent research on the Late Devensian has, under the auspices of the BRITICE2 project, focussed on better constraining the chronology of ice sheet development and patterns of ice-marginal advance and retreat. This body of research has demonstrated the diachronous behaviour of different sectors of the ice sheet, reflecting both climatic and internal glaciological controls on ice sheet behaviour (Roberts et al., 2018; Benetti et al., 2021; Evans et al., 2021b; Scourse et al., 2021; Clark et al., 2022). Significantly improved understanding of the offshore extent of this glaciation has also resulted from the BRITICE2 programme (Clark et al., 2022).

2.6. Younger Dryas glaciation

A considerable body of research has also focussed on a third and most recent phase of glaciation, corresponding to the short-lived **Younger Dryas** (Greenland Stadial 1/GS-1; *c.*, 12.9–11.7 ka) event (Rasmussen et al., 2006), often referred to as the Loch Lomond Stadial in the UK. During the Younger Dryas, the temporary switching-off of thermohaline circulation in the North Atlantic (caused by the collapse of the Laurentide Ice Sheet in North America) led to a rapid drop in temperatures across northern Europe and the UK. This initiated the rapid growth of localised ice caps and/or expansion of small valley glaciers across many highland parts of northern and western UK (Hughes, 2009; Golledge, 2010; Bendle and Glasser, 2012; McDougall, 2013; Boston et al., 2015; Bickerdike et al., 2018a,b). The importance of the Younger Dryas event is that it was a short-lived sub-Milankovitch scale glacial event, demonstrating the susceptibility of the UK landscape to glacier inception. The extent of the Younger Dryas has not been assessed within this study as modern interpretations have been published elsewhere (Bickerdike et al., 2018a).

3. Key evidence and terminology for defining the onshore extent of glaciation

3.1. Context

The term 'glacial limit' and other similar descriptive nomenclature have been widely used by geologists to communicate the maximum interpreted extent of major periods of glaciation during the Quaternary and are historically represented on published figures and maps by means of a line. Within a modern glacial environment, this interpretation can often be undertaken either directly (*i.e.,* observed) or captured using historical aerial photography or satellite data. However, within geological examples, the placement of a 'glacial limit' is always a subjective interpretation utilising, where preserved, geological and/or geomorphological information and varying degrees of conjecture in areas where information is limited or absent. This raises an obvious need for scientific transparency and the requirement to justify how an interpretation has been constructed. Relevant information being: (1) what evidence has been used; (2) what uncertainties are linked to this evidence; (3) where and what conjecture has been used; (4) the underpinning assumptions of this conjecture; and (5) alternative interpretations. Without this transparency, informed debate becomes restricted, and this can lead to concepts becoming accepted as facts without effective scientific rigour or scrutiny. Within this section of the paper, the types of geological and geomorphological evidence used to interpret an onshore 'glacial limit' are considered, key scientific assumptions are evaluated, and use of the term 'glacial limit' is critically examined.

3.2. Diagnostic evidence of an onshore glacial limit

3.2.1. Extent of subglacial till

The mapped spatial extent of subglacial tills has been widely used in the UK Quaternary to help interpret the onshore extent of the Anglian and Late Devensian glaciations. Although not explicitly acknowledged within published interpretations, the use of subglacial till extent implies two underpinning assumptions. Firstly, that a grounded glacier advance will always produce a subglacial traction till; and secondly, that the outer extent of a till sheet corresponds to the maximum glacier extent. Recent developments in the understanding of subglacial processes demonstrate that whilst subglacial traction tills provide excellent evidence for the presence of grounded ice, tills are not produced ubiquitously across the entire subglacial bed including within ice-marginal areas (Benn and Evans, 2014).

Thermal regime plays an important role in regulating till development beneath glaciers. In crude terms, glacier thermal regime can be subdivided between three members: *cold-based glaciers* that characterised many upland areas of the UK during the Quaternary, *warm-based* that occupied more lowland and basinal settings and intermediate *polythermal glaciers* where the thermal regime varies spatially — for example, cold-based around the snout, glacier margins/sides and surface and warm-based in the thicker accumulation areas (Hambrey and Glasser, 2012).

Historically, it has been argued that subglacial traction tills are not widely produced beneath cold-based glaciers as much of the forward motion of a glacier is driven by internal deformation within the glacier itself, with little or no basal sliding and/or subglacial deformation (Shreve, 1984). This view has evolved in recent years, with the recognition that abrasion (*i.e.,* sediment generation), sediment accretion and glacitectonic deformation can take place beneath cold-based ice (Waller, 2001; Lloyd Davies et al., 2009). Sub-marginal and ice-marginal zones of cold-based ice can also be notable zones of till development, through the stacking of debris by regular cycles of regelation entrainment (Knight, 1997) and by glaciers advancing, over-riding and incorporating frontal debris (Hiemstra et al., 2007; Lloyd Davies et al., 2009). Warm-based (or temperate) glaciers, by contrast, are generally regarded as being more efficient at generating subglacial tills through enhanced basal sliding, subglacial deformation or a combination of both. The ability of warm-based glaciers to produce subglacial till reflects: (1) the availability of porewater at or adjacent to the ice–bed interface; (2) the transmission of strain through the base of the glacier into the subglacial bed; and (3) the availability of materials that can be entrained into the subglacial bed (van der Meer et al., 2003; Larsen et al., 2004; Piotrowski et al., 2004; Evans et al., 2006; Lee and Phillips, 2013; Phillips et al., 2018). Porewater availability is the principal control as it regulates the amount of ice–bed coupling and in turn the amount of strain transmitted into the subglacial bed. With low–moderate porewater availability basal sliding will occur, but strain will also be transmitted down into the subglacial bed entraining materials that ultimately will accrete as subglacial till. However, if the porewater pressures are high — for example due to an excess of meltwater and/or the presence of an impermeable or poorly-drained substrate, ice–bed decoupling may occur with minimal strain transmitted into the underlying subglacial bed. This can lead to transient phases of fast ice flow where the resultant till may either be thin, discontinuous or with glacier motion preserved as a melange of deformed parent material (a glacitectonite) (Iverson, 2010; Minchew and Meyer, 2020; Narloch et al., 2020). In such a scenario, a mappable till sheet may not actually be produced during a major ice advance (Lee, 2018; Fig. 4).

3.2.2. Landform evidence — terrestrial terminal moraines

Terminal moraines are morainic ridges that accreted at a terrestrial glacier margin and mark the maximum extent of a glacier advance. These differ from recessional moraines that are found up-ice of the terminal moraine and record temporary episodes of ice-marginal advance and/or stillstand during an overall longer-term pattern of glacier retreat. Terminal moraines form through a range of processes and four main types of moraine have been defined (Table 1) as well as a range of composite moraines which exhibit elements of two or more groups (Evans et al., 2019a).

Proglacial Glacitectonic Landforms incorporate morainic ridges where >25 % of the landform is composed of pre-existing and/or syn-tectonic materials (Table 1). Pre-existing materials may include reworked Quaternary deposits and commonly bedrock. They are formed by the proglacial glacitectonic displacement and thrust-accretion of material by glacier-induced stresses. Ice-marginal landforms within this group include hill–pole pairs, composite ridges and thrust-block moraines, cupola hills, mega blocks and rafts (Bluemle and Clayton, 1984; Aber et al., 1989; Aber and Ber, 2007; Phillips et al., 2017; Evans et al., 2021a). Examples of these features in the UK and Ireland include morainic landforms at Kilcummin Head, County Mayo (Vaughan et al., 2024), Lake of Menteith in Scotland (Evans and Wilson, 2006) and the steep-sided

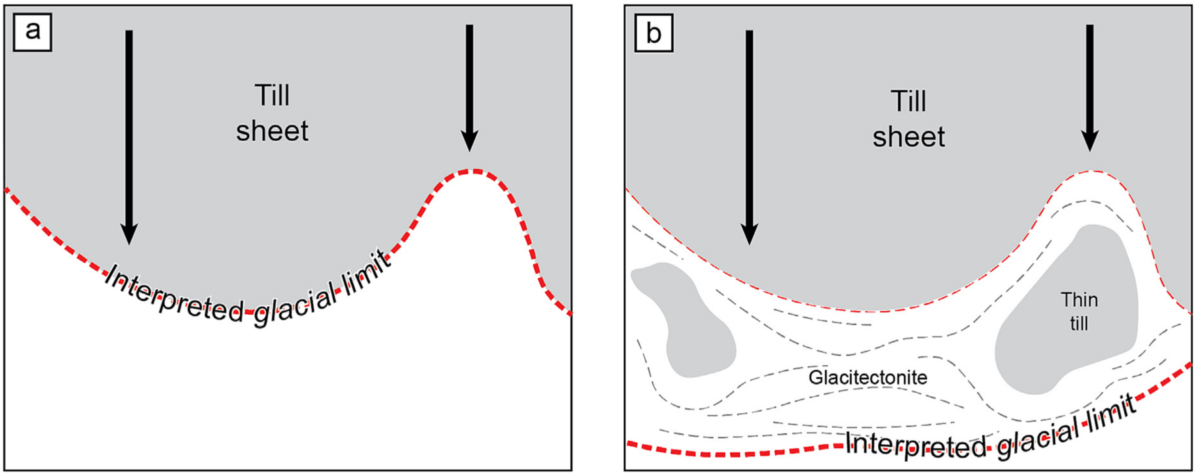

Fig. 4. Plan-view schematic diagrams showing the apparent and actual *glacial limit* using the edge of a till sheet. (a) Historical interpretation of the edge of a till sheet as a glacial limit. (b) Recent developments in the understanding of subglacial deformable beds show that not all ice advances produce tills and/or only thin and discontinuous tills. In such instances an interpreted glacial limit which utilises the edge of the till sheet to define the maximum glacier extent can represent a significant under-interpretation of true glacier extent.

conical hills along the north Norfolk coast (Lee et al., 2013; Phillips and Lee, 2013).

Push and squeeze moraines typically form at the sub-marginal to marginal position at the snout of the glacier (Table 1). Push and squeeze related processes and landforms represent end member processes with both likely to occur in close association (Evans and Hiemstra, 2005; Chandler et al., 2016). *Pushing* corresponds to the lateral bulldozing of ice-marginal materials at the snout of an advancing glacier. During major ice-marginal advances, materials are often overridden by the snout of the glacier and incorporated into the subglacial bed. *Pushing* therefore becomes more relevant during the winter when the snout is often frozen to its bed (slab freeze-on; Krüger, 1996), and where glaciers are undergoing progressive retreat, often leading to the development of a stepped sequence of recessional push moraines (Evans and Twigg, 2002). The morphology of push moraines can vary between arcuate-undulating-irregular planforms reflecting the geometry of the ice margin and the glacier's behaviour (Sharp, 1984; Evans and Twigg, 2002). *Squeezing* occurs during periods of ablation and corresponds to the loading of often water-saturated sediments by the glacier, and the squeezing of materials *via* cavities, basal crevasses and other similar means. Benn and Evans (2014) describe *squeeze moraines* as typically being steep to vertically sided, making them susceptible to subaerial modification (a function of gravity and elevated porewater content) or being deformed by subsequent pushing. Their long-term preservation potential within the geomorphological record is likely to be limited. Examples of push–squeeze moraines described in the UK and Ireland occur in northwest Wales (Thomas and Chiverrell, 2007), Lincolnshire and Yorkshire (Evans and Thomson, 2010; Evans et al., 2019b, 2024), the Cromer Ridge in north Norfolk (Hart, 1990; Lee et al., 2013), offshore along the continental margin (Bradwell et al., 2008; Peters et al., 2016) and within the North Sea (Dove et al., 2017).

Table 1
Types of ice-marginal moraine that are present within the geomorphological record (after Benn and Evans, 2014). Note that these four landform groups are often not distinctive, and many examples are composite features that display elements of several groups.

Term	Definition
Proglacial Glacitectonic Landforms	Morainic ridges where >25 % of the moraine is comprised of pre- or syntectonic materials including bedrock that have displaced proglacially by glacier-induced stresses. Morainic landforms can include features called hill–hole pairs, composite ridges and thrust-block moraines, cupola hills, glacitectonic mega-blocks, and rafts.
Push and squeeze moraines	Ice-marginal moraine ridges produced by lateral pushing and vertical loading (squeezing). 'Push' and 'squeeze' processes represent end members, and many landforms are formed by a variable combination of both.
Dump moraines including latero-frontal dump moraines	Formed by the dumping of supraglacial material at the glacier snout by mass flows, falls or water-driven transport.
Latero-frontal fans and ramps	Relatively low-angle ice-contact fans composed of diamicton, mixed diamicton and sorted sediments or entirely sorted sediments.

Dump moraines and larger *latero-frontal dump moraines* form through the accumulation of supraglacial debris at a stationary ice front *via* rock falls, minor mass-flow and water-driven transport (Table 1; Benn and Evans, 2014). The size of dump moraines reflects the amount of debris accumulation and how long the ice front was stationary (Owen and Derbyshire, 1989; Lukas, 2003; Evans et al., 2010, 2018) plus their sensitivity to modification by other processes during subsequent ice-marginal readvances (Lukas, 2005). Examples of dump moraines in the UK have been reported from the Scottish Highlands (Lukas, 2005; Benn and Lukas, 2006; Phillips and Kearsey, 2020; Phillips and Merritt, 2024).

Latero-frontal fans and ramps form through the coalescence of debris flow and glaciofluvial sediments at stationary ice fronts (Table 1). These landforms tend to form lower-angle features than dump moraines due to the lower gradient of the ice front and dominance of mass-flow rather than rock fall processes (Owen and Derbyshire, 1989; Krzyszkowski and Zieliński, 2002; Evans et al., 2010). Typically, they are composed of diamictic sediments, inter-mixed diamictic and sorted sediments, or fining-upward sequences of stratified gravels to sands and silts (Krzyszkowski and Zieliński, 2002). As with conventional dump moraines these types of ice-contact fans are often attributed to overall patterns of ice-marginal recession albeit with localised push (Lukas, 2005). Examples of latero-frontal fans have been interpreted in northwest Scotland (Benn and Lukas, 2006) and the Scottish Highlands (Lukas, 2003).

Collectively, terminal moraines can be excellent indicators of the maximum extent of a glacier. However, terminal moraines do not form everywhere along an ice margin reflecting temporal and spatial variations in ice-marginal dynamics, material availability, ice–bed traction and ground conditions. Care needs to be taken to understand the true glaciological context of morainic landforms and specifically whether they are terminal or minor recessional moraines (Chandler et al., 2019). Rigour is also needed in the primary interpretation of terminal moraines especially in more degraded (*i.e.*, older) terrains where remote landform evidence is being used to constrain an interpretation. For example, moraine-like ridges could potentially be confused with underlying bedrock and/or bedrock structures, or low interfluve ridges that separate river valleys.

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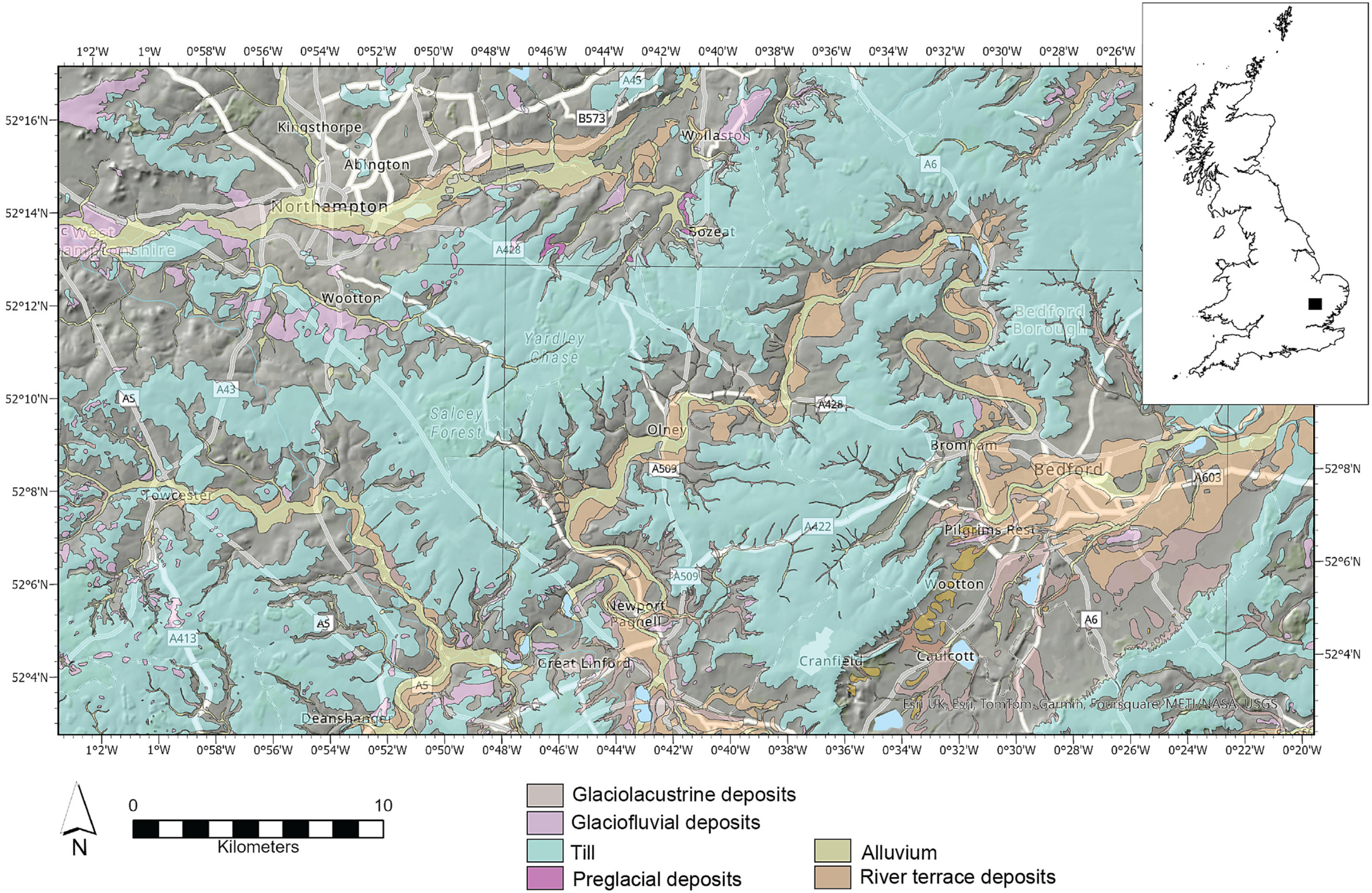

Fig. 5. Quaternary geological map (BGS Geology 50) showing the distribution of the heavily dissected Anglian aged till sheet around Bedford and Northampton draped over a hillshade. The till sheet (blue) has been incised by postglacial drainage (Great Ouse) with the modern floodplains indicated by the mapped alluvium (yellow) and the amount of valley incision indicated by river terrace deposits (orange) that flank the valley sides. Bedrock is indicated by the grey background. Derived in part from DTM of Great Britain at 5 m resolution © Bluesky International Limited. Sources: Esri "World Topographic Map". Jan 4, 2024. Esri Sources: Esri, Ordnance Survey.

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3.3. Preservation of geological and landform evidence

The presence of tills, terminal moraines and other more subtle lines of geological and geomorphological evidence is critical evidence for interpreting so-called 'glacial limits'. However, their practical use within palaeo-studies also reflects their preservation within the geological and landform records. The preservation potential for tills and morainic landforms is generally low and decreases progressively over time.

Several studies have examined the degradation of till sheets and glacial landform assemblages within recently deglaciated landscapes. These studies have shown that higher rates of surface lowering are initially focussed on steeper terranes (Rose, 1991; Putkonen et al., 2008); but that all glacial sediments and landforms will undergo significant long-term degradation leading to a progressive topographic smoothing (Putkonen and O'Neal, 2006). This typically reflects the often poorly-consolidated nature of the glacial sediments and landforms, the presence of unequilibrated slopes, free water availability (*e.g.*, seasonal melt) and the activity of neotectonic, periglacial and paraglacial landscape processes (Ballantyne, 2002; Evans, 2003, 2017; Giles et al., 2017; Murton and Ballantyne, 2017; Finlayson, 2020; Murton, 2021; Smith et al., 2021; Ballantyne and Murton, 2023). Till sheet and landform degradation can however be temporarily buffered, and mechanisms include: (1) rapid consolidation (over-consolidation) of a till by drying and/or loading/unloading either by the glacier snout or ice-marginal thrust stacking; (2) the presence of buried ice within landforms (Tonkin et al., 2016; Midgley et al., 2018) although upon melting this can cause rapid landscape change and inversion (Everest and Bradwell, 2003); (3) the abundance of relatively free-draining open-framework sediments (Oliva and Ruiz-Fernández, 2015); (4) high aridity areas with an absence of vertical mixing (*e.g.*, frost heave) (Morgan et al., 2011); and (5) removal of ice by sublimation from glacier forelands by sublimation.

The longer-term transition to interglacial/interstadial conditions also drives significant changes in landscape dynamics as part of the ongoing paraglacial adjustment of the landscape, this in turn impacting the stability of glacial sediments and landforms (Ballantyne, 2019). Periglacial processes, including the development of patterned ground and solifluction, typically become restricted to more upland areas. Mass movement processes also transition from the development of large rock slope failures (in areas with susceptible bedrock and steep slopes) to translational slides, debris flows and hillwash on slopes mantled by talus and/or superficial deposits. The overall role of fluvial systems within postglacial landscape denudation is complex reflecting local and regional scale relationships between topographic gradient, flow regime, sediment supply and substrate strength. Fluvial dissection is widely believed to be enhanced during glacial–interglacial transitions due to high seasonal peak river discharges (Bridgland, 2010) and during interglacial stages by extreme flood events (Macklin et al., 2013). Periods of intense rainfall during interglacials can also be significant drivers of landscape denudation, triggering landslides on metastable slopes that have been previously oversteepened by glacial erosion (Moon et al., 2011) although this can be buffered to a degree by vegetation cover. In the UK, widespread fluvial dissection has impacted the extent and preservation of evidence from the Late Devensian and especially Anglian glaciations (Fig. 5).

Time is also a critical factor in landscape preservation because it dictates the duration that landscape smoothing can operate over. This is well-illustrated in the UK where relict Middle Pleistocene landscapes in central and eastern England have been subjected to multiple cycles of temperate and periglacial weathering and landscape degradation including (potentially) multiple phases of glaciation. Accordingly, there are far fewer recorded examples of Middle Pleistocene ice-marginal landforms in the UK compared to those from the Late Devensian or Younger Dryas. Over such geological timescales neotectonics also play a significant role in degrading relict glacial landscapes, driving long-term crustal uplift and subsidence, and critically fluvial dissection (Maddy et al., 2001; Bridgland et al., 2015; White et al., 2017). Widespread evidence for long-term dissection is indicated by the bevelled featheredge of many UK till sheets, fluvial incision and river terrace development that occurs down through/beneath the base of the till.

Relative topographic position also plays an important role in regulating the preservation potential of glacial deposits and landforms. Unlike other parts of continental Europe, there are no major sedimentary basins onshore within the UK that lie within the known extent of Quaternary glaciation (*cf.*, Bovey Basin in Devon). Instead, most of the UK landmass can be described as interbasinal being situated beyond the margins of major sedimentary basins that typically (but not exclusively) occur around our continental shelf and margins. The long-term preservation potential of glacial deposits and landforms is therefore low over geological time scales (*i.e.,* hundreds of thousands to millions of years). This is because sediment accommodation space within the interbasinal landscape is limited and slope, fluvial and other earth surface processes (*e.g.*, weathering, periglacial, glacial and paraglacial) are variably acting to remobilise interbasinal materials basinwards. Preservation rates tend to be greater in lower elevation and lower gradient topographic settings (*e.g.*, lowland areas, valley bottoms in upland areas) due to the lower magnitude of gravitational processes. By contrast, the preservation potential on slopes within upland areas is very low due to the propensity of active slope processes that can rapidly rework, modify and erode pre-existing sediments and landforms as well as the potential for reglaciation. Preservation potential on the summits of upland areas is also likely to be relatively low because, whilst gravitational slope processes may be more limited, the elevated relief makes sediments and landforms more susceptible to physical processes such as freeze–thaw and deflation by wind. Basins, by contrast, are long-term sediment sinks with ongoing cycles of sediment burial acting to preserve glacial deposits and landforms (*e.g.,* the North Sea Basin). Even in areas of net marine erosion and scouring, the winnowing of finer sediments can leave a residual cobble/boulder lag which can armour the underlying substrate and increase preservation. The significance of relative topographic position is demonstrated by the long-term record of glaciation within the UK, the offshore record preserving a much more detailed recent and longer-term record of glaciation than onshore sequences. This is especially evident within the North Sea Basin where sequences of Quaternary sediments up to 1 km thick have been recorded in the Central Graben (Ottesen et al., 2018). Critically, 2D and 3D seismic data demonstrate that significant superpositional

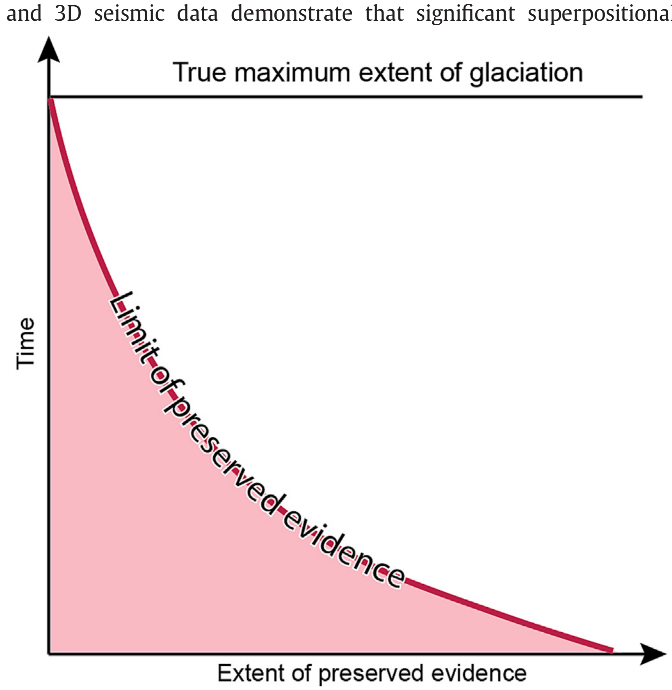

Fig. 6. Theoretical representation demonstrating the temporal relationship between the actual extent of a glacier and the limit of preserved evidence. Erosion/modification rates will initially be faster, but will slow as the feature reaches a dynamic equilibrium with the boundary conditions that operate within a given landscape.

preservation of evidence for glaciation occurs across the basin, reflecting repeated cycles of glaciation, submarine sediment burial and enhanced preservation (Graham et al., 2007; Stewart and Lonergan, 2011; Stewart et al., 2013; Rea et al., 2018; Newton et al., 2024). Onshore, by contrast, limited accommodation space within the interbasinal landscape means that evidence for glaciation is frequently removed during subsequent phases of glaciation (Bowen et al., 1986; Clark et al., 2004b; Gibbard and Clark, 2011; Gibbard et al., 2022).

3.4. Nomenclature

As discussed above, the extent of tills and terminal moraines are key types of evidence that can provide important information relating to former glacier extent. The presence and absence of both features are partly a function of glacier dynamics but also of short- to long-term preservation. However, preservation potential, especially onshore in the UK, is generally low, reflecting the limited accommodation space within the landscape coupled with the variable activity of slope, fluvial, periglacial and paraglacial processes which act to progressively smooth the landscape over time. A so-called 'glacial limit' interpreted using these common types of data should therefore be viewed as a *limit of preserved evidence* rather than a demonstration of the maximum extent of glaciation *per se*. This means that the *true maximum extent of glaciation* will likely occur down-ice of this *limit of preserved evidence* and that the distance between the two will increase with time (Fig. 6).

4. Refining the limit of preserved evidence for Quaternary glaciation

4.1. Methodology

Within the previous section of the paper, we assessed the primary types of geological and landform information that can be used to interpret the extent of onshore glaciation within the UK — with till sheets and terminal moraines being the key lines of evidence. Both types of evidence are well-developed within the onshore geological and geomorphological record, but this information needs to be interpreted with care as there are both glaciological and preservation issues that can generate uncertainty within any interpretation. In short, the key findings are that an interpreted *glacial limit* represents the *limit of preserved evidence* rather than a demonstration of maximum glacial extent.

To build new linework to refine the onshore limit of preserved evidence for the Anglian and Late Devensian glaciations, a range of digital datasets were utilised by this study (Table 2). The key underpinning dataset was the British Geological Survey (BGS) Geology 50k (Superficial deposits) digital dataset, which shows the UK distribution of mapped superficial geology polygons within published BGS 1:50,000 geological maps. The digital dataset was queried to highlight superficial deposits that had been mapped as till, diamicton or equivalent lithostratigraphically named units. Ice-marginal landforms such as terminal moraines have not historically been captured consistently on published geological maps; however, some mapped features occur within the published BGS Geology 50k dataset (*e.g.*, Escrick Moraine Member) and were utilised in this study. Terminal moraines reported elsewhere within published literature and other datasets (*e.g.*, BRITICE) were also used to build an interpretation. Much of this data is presented at a lower spatial resolution than the BGS Geology 50k dataset, nevertheless it could be used to constrain new interpretations where appropriate.

Topographic datasets including the NEXTMap Digital Terrain Model (DTM) including hillshade and slope model derivatives, plus the OS 1:25,000 scale colour raster were employed to help interpret landforms (*e.g.*, moraines) as well as constraining the edges of mapped till sheets where geological mapping coverage was limited.

BGS also holds over 1 million digital borehole and site investigation records from across the UK with individual records ranging in age from the 1860s through to the 2020s exhibiting varying levels of quality, descriptive detail and spatial accuracy (*e.g.*, x–y location, unit thickness). These boreholes and the separate BGS Borehole Geology (BOGE) database were used to test and refine the mapped occurrence of till and related deposits. BOGE includes geological interpretations of borehole and site investigation records, thus a filter was run on the database to extract records that contained interpreted units of till and diamicton. Note that not all held borehole records have corresponding borehole interpretations, and most interpreted boreholes coincide with areas where various BGS geological studies (*e.g.*, 3D geological models, linear route assessments, site investigations) have been commissioned over the past 30 years. The location of the filtered boreholes was then plotted to identify outlier boreholes that contain interpreted till and/or diamicton that occur beyond the previously accepted till extent and/or 'glacial limit'. The original borehole logs for all outlier records were checked manually to validate the interpretations. Whilst most outlier records were valid, till had been misinterpreted within a small proportion of borehole records. These erroneous interpretations occur along parts of the historical glacial limits where sands and gravels have been mixed with weathered mudstones (*e.g.*, Paleogene strata) and now form discontinuous veneers or ribbons of slope deposits (*e.g.*, head or colluvium) rather than till.

Digitisation of new linework was undertaken using the standard GIS software (ArcGIS Pro) at a scale of between 1:10,000 and 1:20,000 depending on the resolution of the constraining data. A subtle GIS smoothing function was applied to the linework to enhance its cartographic presentation. Segments of reconstructed linework were assigned to one of three constraint classes to capture how the linework was interpreted and highlight the relative levels of uncertainty — *mapping constrained*, *borehole constrained* and *conjectural*. For *mapping constrained* and *borehole constrained* sectors of linework interpreted from published geological mapping/geomorphology or borehole information, the linework was drawn around the outer edge of a narrow buffer (typically 50 m) to encompass the projected feather-edge of the till. For mapped or reported terminal moraines, the linework was reconstructed along the basal concave slope break on the inferred up-ice side of the landform using the DTM to represent the minimum extent of ice. *Conjectural* lines were used where there was no evidence available, but the linework could be constrained between two reliable control points using, for example, a topographic feature, constant elevation, or glaciological rules (*i.e.*, lobate margins will form in mudstone-dominated areas). *Conjectural* linework is subjective and accordingly carries a

Table 2
Table showing the main datasets used in the interpretation of new linework, how the datasets were used and their accessibility.

Dataset	Practical use	Accessibility
BGS Geology 50k Superficial	Superficial geology linework used to constrain the mapped presence of 'till' or other units of interest.	Open Access *via* BGS GeoIndex.
BGS Borehole Geology database	Interpretations of boreholes and other site investigation reports used to constrain the spatial presence of 'till'.	Corporate dataset but all borehole logs are Open Access and available by the BGS GeoIndex portal.
NEXTMap Britain DTM	Digital Terrain Model (DTM) used as a topographic base, tiled at 50 m horizontal resolution.	Used under licence from Intermap Technologies.
OS 1:25,000 Scale Colour Raster	OS topographic base.	Used under licence from the Ordnance Survey.
BGS Buried Valleys	Used to further constrain subglacial environments.	Open Access *via* BGS GeoIndex or BGS Datasets.
BRITICE	Specific landform layers utilised to constrain ice-marginal locations.	https://www.sheffield.ac.uk/geography/research/projects/britice

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higher level of uncertainty. Whilst *conjectural* linework can be used with caution, there were notable instances where there was no constraining information to interpret the glacial limit, and in these cases no interpretation was attempted.

4.2. Reconstructed limit of preserved evidence for glaciation

The *limit of preserved evidence* for the onshore extent of both the Anglian and Late Devensian glaciations is shown in Figure 7. Further description and more detailed regional summaries that communicate the relative uncertainty of the reconstructed linework are provided below.

4.2.1. Anglian glaciation

The *limit of preserved evidence* for the Anglian Glaciation shows a general agreement with the historical linework but contains much greater local-scale detail (Fig. 8). The eastern sector, located to the north and east of London, generally follows the mapped extent of the Anglian till sheet (Clayton, 1957; Gibbard, 1977; Allen et al., 1991; Price, 2019), although its preserved extent has been refined based on geological mapping and borehole information. Around Colchester, for example, the *limit of preserved evidence* has been extended eastwards by approximately 6.5 km reflecting the occurrence of till within boreholes to the east and south of Colchester (Fig. 9a). Significant areas of linework between Chelmsford and Colchester are conjectural, reflecting widespread postglacial fluvial incision of the Paleogene bedrock and removal of the till (Clayton, 1957). Linework has also been modified around Maldon reflecting new understanding of the Danbury–Tiptree Ridge (Fig. 9a). During the Anglian Glaciation, the ridge acted to constrain the morphology of the ice margin enabling the nucleation of a marginal-ridge complex, with localised breaching enabling small lobes of ice to extend southeastwards beyond the confines of the landform (Leszczynska et al., 2018). The preservation and form of this morainic ridge are intriguing given its age and the widespread regional erosion of the till and underlying bedrock. Much like the Cromer Ridge moraine in north Norfolk (Lee

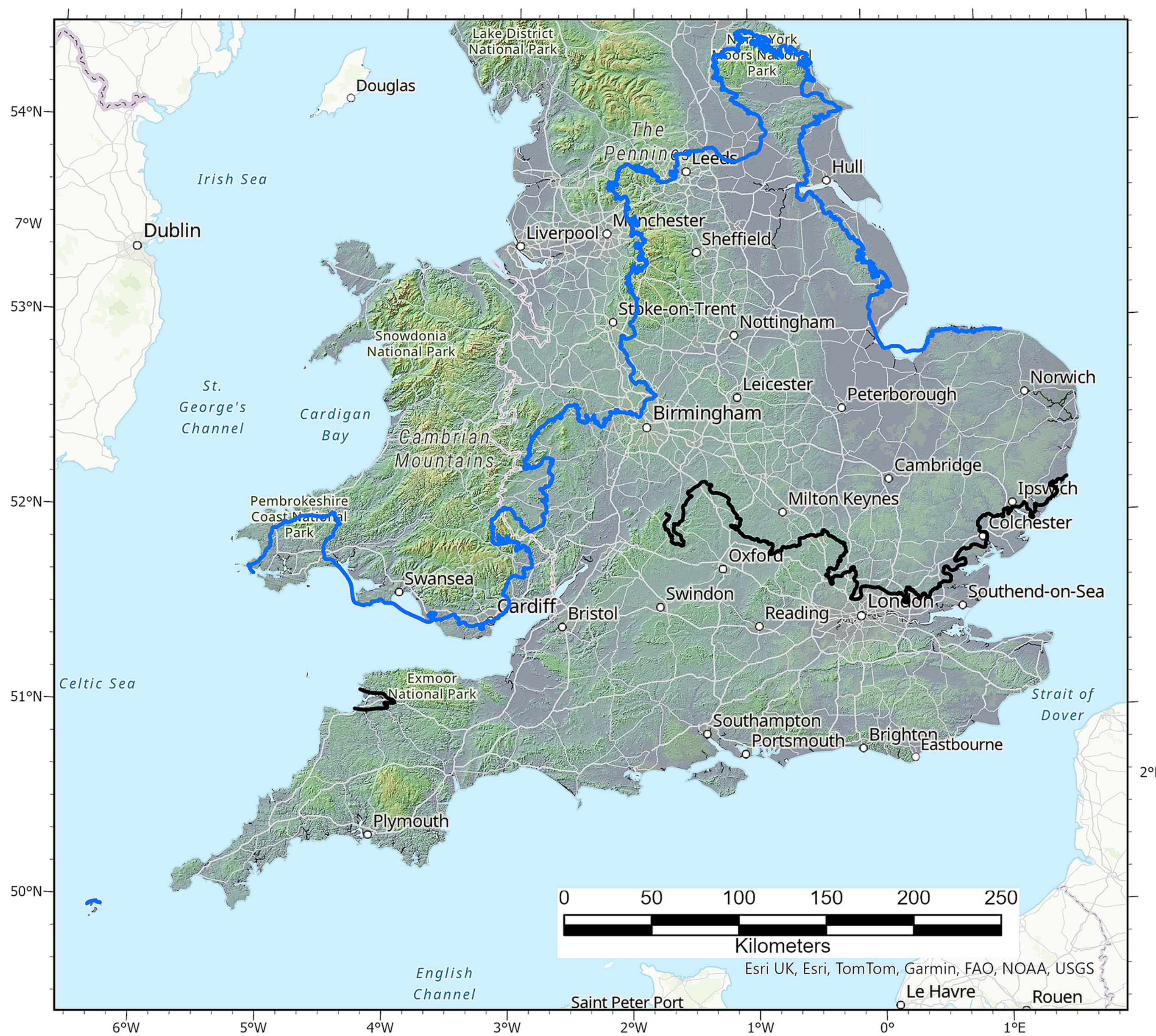

Fig. 7. Reconstructed *limits of preserved evidence* for both the Anglian (black line) and Late Devensian (blue line) glaciations. No differentiation is made here for uncertainty of the linework and readers are referred to Figures 8–11 for further information. Derived in part from DTM of Great Britain at 5 m resolution © Bluesky International Limited. Esri "World Topographic Map". Jan 4, 2024. Esri Sources: Esri, Ordnance Survey.

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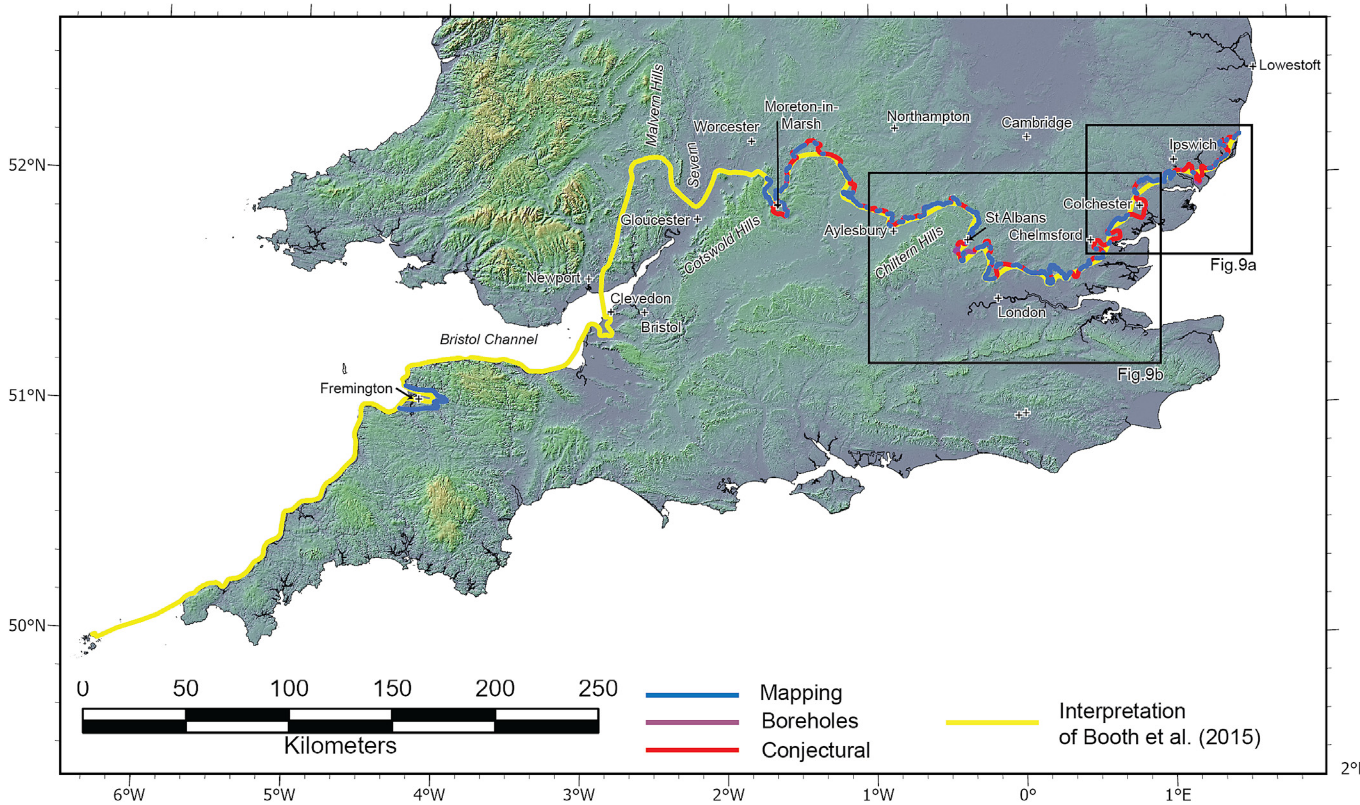

Fig. 8. The *limit of preserved evidence* for the Anglian Glaciation onshore in southern UK showing the distribution of underpinning evidence for different segments of linework. The Anglian glacial limit of Booth et al. (2015) is also indicated for comparison. Locations of Figure 9a and b are indicated by the black boxes. Derived in part from DTM of Great Britain at 5 m resolution © Bluesky International Limited.

et al., 2013), the relative preservation of the landform is likely linked to its glacitectonic accretion on a pre-existing bedrock high.

Between Chelmsford and Brentwood, the *limit of preserved evidence* is well constrained by geological mapping and borehole data albeit with the interpreted evidence indicating a more crenulate margin to the till sheet than previously indicated (Fig. 9b). Refinement of the linework between Brentwood and St Albans (Fig. 9b) supports the previously-held interpretation of the existence of several prominent ice lobes (Gibbard, 1977). Further to the west, between St Albans and Leighton Buzzard, the mapped extent of till helps to refine the preserved limit of evidence to up to 5 km inside of the previous linework (Fig. 9b). Around Moreton-in-Marsh, Gloucestershire, Anglian aged glacial deposits form an isolated outlier resting on Jurassic bedrock and extend northwards as a discontinuous body into the South and West Midlands (Shotton, 1953; Bishop, 1958; Sumbler, 1983, 2001). The geometry of these deposits suggests that they have been heavily eroded and therefore their proximity to the ice margin remains unclear.

To the west of the Cotswold Hills, heavily dissected bodies of till and other glacial deposits have been recorded along the western flanks of the Malvern Hills (Richards, 1999), within the lower Severn Valley (Maddy et al., 1995) and Clevedon near Bristol (Gilbertson and Hawkins, 1978). But their proximity to any postulated extent of Anglian ice remains unclear and no attempt is made to reconstruct the limit of preserved evidence through this area (Fig. 8). The Anglian limit is also tentatively reconstructed locally around the mapped extent of till at Fremington, north Devon. As previously stated, an Anglian age is the likely maximum age of the unit and for that reason is included within this interpretation.

4.2.2. Late Devensian Glaciation

The revised *limit of preserved evidence* for the Late Devensian Glaciation is in good agreement with other published interpretations with local refinement (Fig. 10). In the eastern sector, the occurrence of Late Devensian glacial deposits in north and northwest Norfolk corresponds to the southern-most known expansion of the North Sea Lobe of the Last British Irish Ice Sheet (Evans et al., 2019b, 2021b). The *limit of preserved evidence* is demonstrated by the mapped extent of till (Holkham Till) and localised terminal moraines (Pawley et al., 2006; Moorlock et al., 2008; Evans et al., 2019b), with local refinements based on borehole information joined by conjectural linework. Within The Wash, only occasional boreholes contain Holkham Till, so the interpreted linework is largely conjectural. The nature of subglacial bed conditions — dominated by low-permeability Jurassic mudstones, suggests that fast ice flow conditions may have developed, with ice potentially extending southwards through The Wash and into the Fen Basin. However, no boreholes containing Holkham Till have yet been identified within the Fen Basin. Through Lincolnshire and Holderness, till has been mapped discontinuously along the east-facing dip slope of the chalk escarpment and the edge of this till body is interpreted as the *limit of preserved evidence*. Locally, the western edge of the till sheet is dissected by several mis-fit or dry valleys demonstrating significant chalk mass-wastage within the Lincolnshire and Yorkshire Wolds following deglaciation (Fig. 11a).

On the northern flanks of Flamborough Head, the *limit of preserved evidence* is constrained largely by mapped till (Fig. 11a), with ribbons of discontinuous recessional moraine ridges occur up-ice (north) of the mapped till (Evans et al., 2017, 2024). The *limit of preserved evidence* is extended conjecturally into the Vale of Pickering and is pinned locally by the Wykeham Moraine (terminal moraine; (Fig. 11a)) (Evans et al., 2017; Fairburn, 2019; Eddey et al., 2022). Extending around the Cleveland Hills between Scarborough and Thirsk, the limit is partly constrained by the mapped extent of till including local refinements from occasional boreholes (Fig. 11a). The geometry of the till sheet includes discontinuous bodies of till extending upslope into several of

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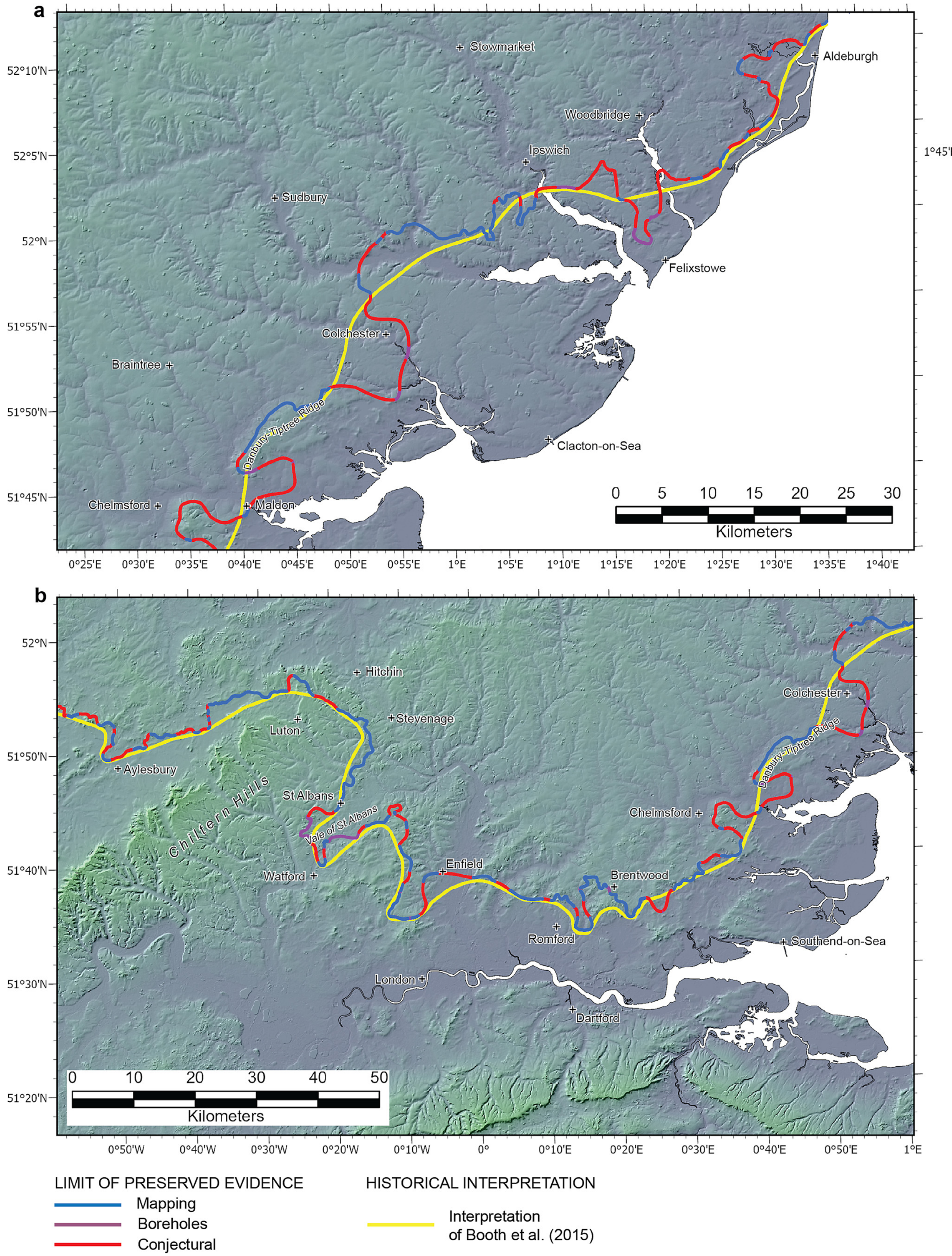

Fig. 9. Local detail of the *limit of preserved evidence* for the Anglian Glaciation for the area around Colchester (a) and further southwest to the north of London (b). The historical interpretation of the glacial limit of Booth et al. (2015) is shown for comparison. See Figure 7 for the location of the two figures. Derived in part from DTM of Great Britain at 5 m resolution © Bluesky International Limited.

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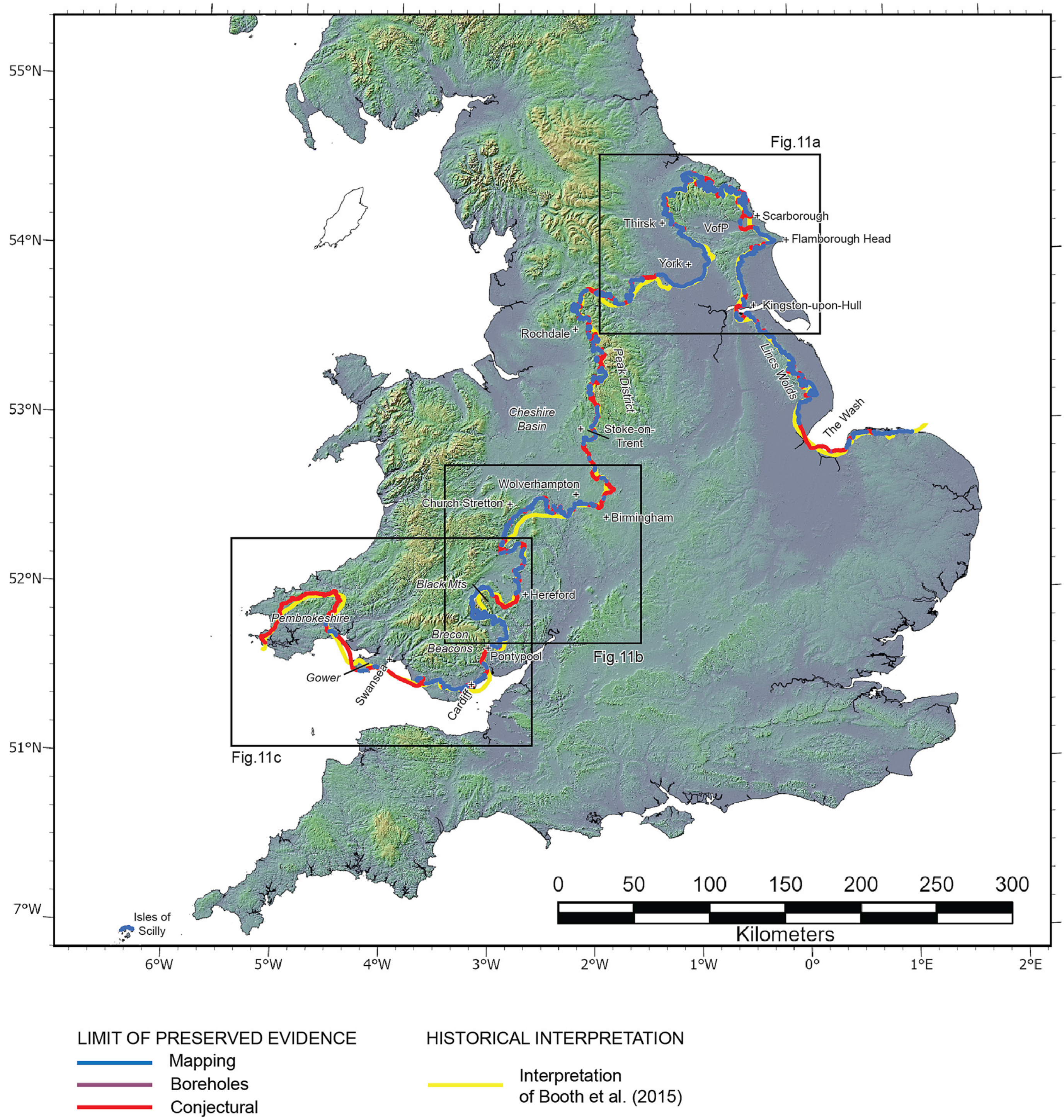

Fig. 10. The *limit for preserved evidence* onshore for the Late Devensian glaciation showing the distribution of underpinning evidence for different segments of linework. The locations of three inset maps (Fig. 11) showing detail of the interpretation are also indicated. Derived in part from DTM of Great Britain at 5 m resolution © Bluesky International Limited.

the deeply incised valleys. Further to the south, the mapped extent of till associated with the Vale of York ice lobe coincides with the Escrick Moraine (Fig. 11a; Ford et al., 2008). Extending along the southern and western edge of the Pennines and Peak District towards Stoke-on-Trent, the *limit of preserved evidence* is constrained by the mapped extent of till and conjecturally based upon elevation where till is absent. The discontinuous nature of the mapped till sheet in this sector indicates that substantial erosion of the lower slopes of the Pennines and Peak District has occurred following deglaciation.

Passing south and southwestwards across Shropshire, the West Midlands and Welsh Borders, the Late Devensian till sheet was accreted by Irish Sea ice that extended through the Cheshire Basin and glaciers emanating from upland ice dispersal centres in neighbouring Wales (Fig. 10; Boulton and Worsley, 1965; Thomas, 1989; Worsley, 2005; Parkes et al., 2009; Chiverrell et al., 2021). Northward retreat of the ice margin from its maximum led to the development of a complex pattern of moraine belts, glacial lake basins and outwash fans (Chiverrell et al., 2021). The *limit of preserved evidence* is indicated primarily by the mapped extent of till that can be traced discontinuously between

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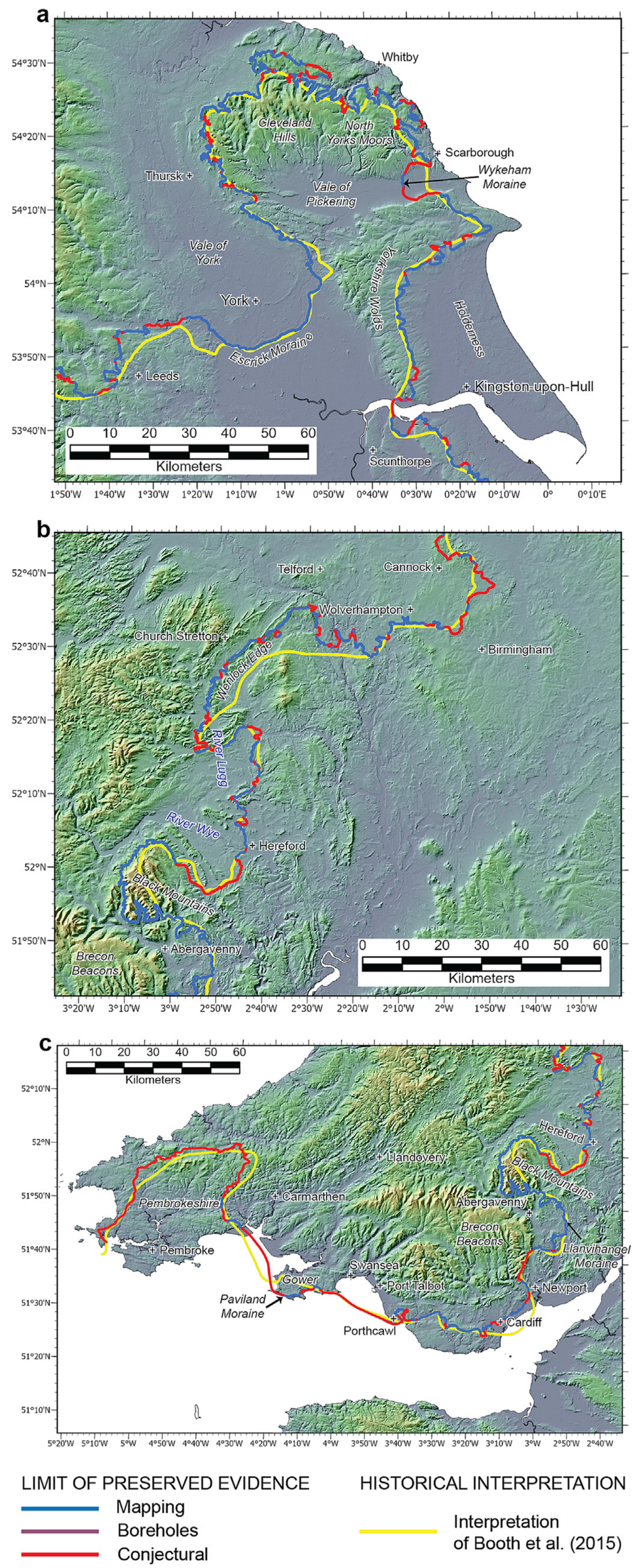

Fig. 11. Detailed maps of local areas of the limit of preserved evidence for the Late Devensian with local points of interest: (a) Eastern Sector – Yorkshire; (b) West Midlands and the Welsh Borders; (c) Welsh Borders and South Wales. Derived in part from DTM of Great Britain at 5 m resolution © Bluesky International Limited.

Cannock and Hereford (Fig. 11b; Eastwood et al., 1925; Morgan, 1973; Old et al., 1991; Powell et al., 2000). The till has been heavily dissected by glaciofluvial/fluvial erosion where the *limit of preserved evidence* is largely conjectural. To the northwest of Birmingham, the till limit is typically well constrained by geological mapping and refined locally by borehole data. Extending south-westward, the mapped extent of the till is confined to the north and west of several major bedrock escarpments, including Wenlock Edge. Localised ice breaching of Wenlock Edge is indicated by small lobes of mapped till that extend down and beyond the eastern slopes of the ridge (Fig. 11b).

Between Wenlock Edge and Hereford, ice emanating from Wales extended into a broad lowland area containing the mid parts of the Wye and Lugg catchments with the *limit of preserved evidence* constrained mainly by the mapped extent of till. To the south of Hereford, the interpreted extent of the preserved evidence is conjectural: inferred by linking the elevation of the till sheet adjacent to Hereford with that around the northern and western margins of the Black Mountains. Ice emanating from the Brecon Beacons *via* the Usk Valley accreted a mapped body of till that drapes the valley flanks and splays to form a broad lobe that extends eastwards beyond Abergavenny and Pontypool (Lewis and Thomas, 2005; Thomas and Humpage, 2005; Carr, 2020). Locally, the *limit of preserved evidence* is constrained by terminal moraines, such as the Llanvihangel Moraine situated to the north of Abergavenny (Fig. 11c). In South Wales, west of Cardiff, the mapped extent of till largely forms the limit of the preserved evidence of the Late Devensian, refined locally by boreholes, with small sections of conjectural linework where till has been eroded by modern drainage (*e.g.*, adjacent to the Taff and Ebbw valleys). Swansea and Port Talbot are also underlain by thick sequences of glacial till, with overdeepened meltwater tunnel valleys occurring beneath the rivers Neath and Tawe (Wright, 1991). Ice likely extended into the present offshore area of Swansea Bay (Gibbard et al., 2017); however, recent geological mapping has indicated that possible terminal moraines may in fact potentially be bedrock (Carboniferous) ridges (Rhian Kendall, personal communication, 2023).

To the southwest of Swansea in The Gower, evidence for grounded Late Devensian ice and the *limit of preserved evidence* is more conjectural but pinned by localised bodies of mapped till and the Paviland Moraine (Fig. 11c; Hiemstra et al., 2009; Shakesby et al., 2018). It should be noted that the age of the Paviland Moraine has historically courted controversy with its age being alternatively interpreted as being Middle Pleistocene (Bowen, 2005). Further west in Pembrokeshire, mapped Late Devensian tills are highly discontinuous which has driven multiple historical interpretations of known ice extent (Campbell and Bowen, 1989). New linework created as part of this study is highly conjectural but follows the general southern margin of the dissected till sheet (Fig. 11c) and is in general accordance with other regional interpretations (Glasser et al., 2018). The southern-most known onshore *limit of preserved evidence* for Late Devensian ice extent is constrained by mapped bodies of till and terminal moraines that occur on several of the northern islands within the Isles of Scilly (Fig. 10; Mitchell and Orme, 1967; Scourse, 1991; Hiemstra et al., 2006). These observations are linked (offshore) between the islands by conjectural linework. Recent research has demonstrated that the tills and landforms within southwest Wales and the Isles of Scilly correspond to the southward expansion of the Irish Sea Ice Stream which, at its maximum, reached the edge of the continental shelf within the Celtic Sea (Praeg et al., 2015; Smedley et al., 2017; Glasser et al., 2018; Scourse et al., 2021). No attempt has here been made to interpret the offshore extent of evidence between mainland UK and the Isles of Scilly.

5. Conclusions

- The current understanding of the long-term glacial history of the UK during the Quaternary is reviewed within this paper. Significant developments have been made during the past decade with widespread demonstration that our UK Continental Shelf has been repeatedly glaciated throughout the Quaternary by ice emanating from highland dispersal centres.

- The types of geological and landform evidence that can be used to interpret the extent of Quaternary glaciations are also reviewed. The primary evidence historically utilised in reconstructing the extent of major glaciations includes the edges of major till sheets and terminal moraines. However, the presence and/or absence of this evidence can reflect a range of primary (*e.g.*, genetic) and secondary (*e.g.*, preservation) processes that operate within the landscape.
- Preservation is an often-overlooked aspect of reconstructing the extent of former periods of glaciation, with progressive topographic smoothing driven by glacial and postglacial (*e.g.*, periglacial, paraglacial, fluvial, slope, marine) processes. The impact of these processes magnifies over time reflecting long-term landscape degradation under different climatic regimes. The position of the evidence within the landscape is also a critical preservation factor with typically much greater preservation potential in basinal as opposed to interbasinal areas. This reflects higher sedimentation rates within basinal areas which act to bury and preserve pre-existing sediments and landforms, compared to interbasinal areas where gravity-driven landscape processes (*e.g.*, slopes and rivers) are actively reworking and recycling landscape materials. Within the UK Quaternary context, our spatial record of glaciations reflects this process with enhanced long-term preservation on the UK Continental Shelf and more limited, fragmentary preservation onshore.
- An assessment of the historically-used terminology recommends abandoning usage of the term 'glacial limit' except in modern environments where its position can be accurately interpreted (*e.g.*, by direct observation, remote sensing). For geological analogues, it is recommended that the term *limit of preserved evidence* is adopted, with the acknowledgement that, over time, the distance between the *limit of preserved evidence* and the glacial limit will increase.
- The *limit of preserved evidence* for both the onshore Anglian and Late Devensian glaciations is presented. Linework is classified according to how the position is constrained (*e.g.*, by mapping, boreholes, conjectural) enabling users to understand how the interpretation has been justified and the associated levels of uncertainty.

CRediT authorship contribution statement

Jonathan R. Lee: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sam Roberson:** Writing – review & editing, Investigation, Data curation.

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.

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