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Late Middle Pleistocene Wolstonian Stage (MIS 6) glaciation in lowland Britain and its North Sea regional equivalents – a review

SEBASTIAN M. GIBSON AND PHILIP L. GIBBARD

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Two major glaciations have been identified on land in England during the Middle Pleistocene. The earliest occurred during the Anglian Stage (= Elsterian, *c*. Marine Isotope Stage, MIS 12), evidence for which is best developed in lowland Britain, as well as offshore in the southern North Sea and Irish Sea basins. The second took place during the late Middle Pleistocene, with the most compelling evidence found in the West Midlands, intermediate between the Hoxnian (= Holsteinian; broadly MIS 11) and Ipswichian (= Eemian; broadly MIS 5e) interglacial stages during the Late Wolstonian Substage. Until recently this younger glacial episode was less clearly represented in the Pleistocene record and, as a result, had been little studied and weakly defined. Interpreted as the Moreton Stadial glaciation during the Late Wolstonian Substage (= Late Saalian Substage/Drenthe Stadial, *c*. MIS 6), it was originally recognized in the English Midlands, subsequently being identified in Yorkshire, Lincolnshire and northern East Anglia, and potentially further SW as far as the Bristol Channel. Mapping, in particular by members of the British Geological Survey, however, resulted in the Wolstonian Stage glacial deposits being thought to pre-date the stage. This was particularly so in East Anglia where there was considerable controversy concerning the number and relationships of glacial sequences, during the 1970–1980s. Yet to the west of East Anglia there remained unequivocal evidence for glaciation during the stage, particularly in Fenland and the eastern English Midlands. Recent radiometric dating across lowland Britain on glacial sediments long thought to belong to a glaciation event in the Wolstonian Stage have now placed a geochronological control on the established regional stratigraphy and confirmed that glaciation occurred in two phases between 199 and 147 ka during the Late Wolstonian Substage. The glacial events of the British Middle Pleistocene can clearly be correlated with the European continent.

Sebastian M. Gibson (smg64@cam.ac.uk), Cambridge Quaternary, University of Cambridge, Cambridge CB2 3EN, UK; Philip L. Gibbard, Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, UK; *received 19th April 2024, accepted 19th July 2024.*

Glaciation during the Pleistocene is known to have occurred throughout most of Britain, north of a line linking London to Bristol. However, the varied geology, tectonic setting, relief, glacial/periglacial regimes and fluvial rejuvenation have resulted in great variation in the preserved evidence (Hughes *et al*. 2022). In lowland western and eastern Britain, where depositional sequences predominate, glacial landforms are relatively subdued, although sediments and associated features indicating glacial expansion and retreat of at least three and potentially more glaciation episodes (during the Anglian, Wolstonian and Devensian Stages) are well established (e.g. Clark *et al*. 2004). Earlier glaciation is known from the central North Sea basin but evidence of these events has so far not been found on land (Rea *et al*. 2018; Gibbard *et al*. 2022).

Within the British Isles the Anglian (= Elsterian) glaciation has been believed to be the most extensive event. In stark contrast to that is the evidence across the near European continent where the penultimate glaciation is the most extensive glaciation across the Northern Hemisphere within the last 500 ka. Globally, its maximum extent is constrained by the marine isotope stratigraphy to *c*. 140 ka, during Marine Isotope Stage (MIS) 6b (Stirling *et al*. 1998; Margari *et al*. 2014; Head & Gibbard 2015) (Fig. 1). It is important to note that the terrestrial environment responds differently to the oceans. Across the European continent and lowland Britain the terrestrial penultimate glacial maximum (tPGM) occurs some *c*. 20–40 ka earlier, where an increase in precipitation allows for the increase in highland glacial ice. This glacial maximum is considered to be represented by the Drenthe Stadial (*c*. 164-154 ka/MIS 6c) and equivalents during the Saalian Stage (Fig. 1) (Ehlers & Gibbard 2004; Busschers *et al*. 2008; Gibbard *et al*. 2009; Lüthgens *et al*. 2010, 2011; Ehlers *et al*. 2011b, 2016; Bickel *et al*. 2015; Head & Gibbard 2015; Rades *et al*. 2018). In lowland Britain, the equivalent Wolstonian Stage (equivalent to MIS 11b–6e) has traditionally been considered to represent the tPGM between the termination of the Hoxnian (= Holsteinian) interglacial Stage (West 1956; Ashton *et al*. 2008) and the initiation of the Ipswichian (= Eemian) interglacial Stage (Fig. 1) (cf. Shotton 1953, 1976, 1983; Shotton & West 1969; Mitchell *et al*. 1973; Phillips 1974; Shotton *et al*. 1977; Gibbard & Turner 1988; Litt & Turner 1993). The 260 ka time interval is divided into three chronostratigraphic substages: Early-, Middle- and Late-Wolstonian Substages (Fig. 1), with various authors identifying different glacial events as the tPGM (Gibbard *et al*. 2009; Head & Gibbard 2015; Gibson *et al*. 2022). The sequence of glaciogenic deposits at Wolston in Warwickshire (Fig. 2) forms the stratotype locality of a major glacial event during the Wolstonian (= Saalian)

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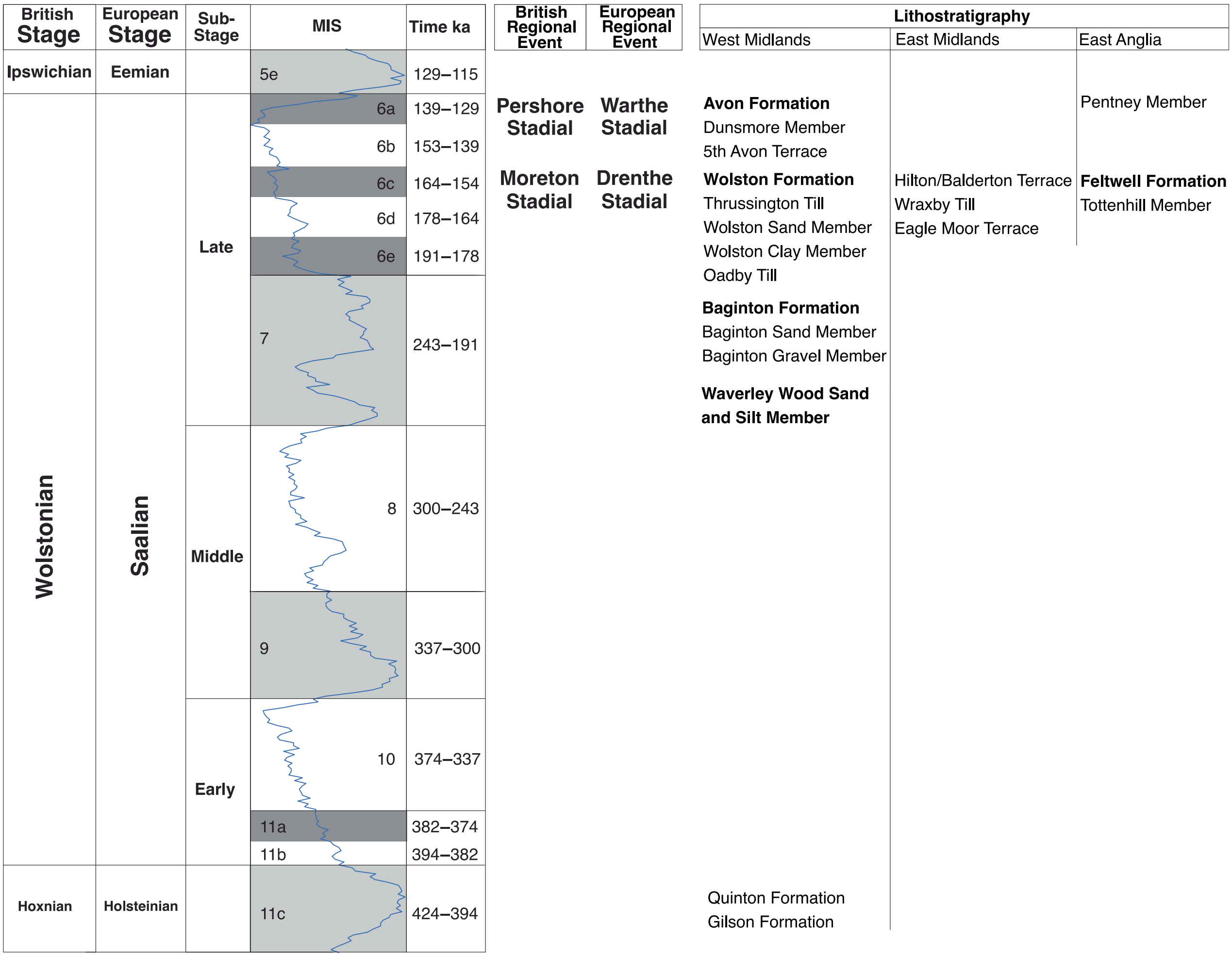


Fig. 1. Chronostratigraphical and lithostratigraphical divisions, regional Middle Pleistocene stages and corresponding events in lowland Britain, compared with the marine isotope stage (MIS) chronology (modified from Gibson *et al.* 2022).

Stage, as represented by the Wolstonian Glacigenic Formation (Wolston Formation) (Fig. 1) (Bridge *et al.* 1998). However, the sequence lacks definitive interglacial sediments, with the basal Baginton Sand and Gravel Formation (Baginton Formation; Fig. 1; Bridge *et al.* 1998) overlying discreet channels interdigitated with interglacial deposits of Cromerian age at Waverley Wood (Shotton *et al.* 1993). Previously the Wolston Formation and Baginton Formation have been observed by some to have been deposited glacial activity during the preceding Anglian (= Elsterian) Stage (*c.* MIS 12) (Fig. 2) (Rose 1987, 1994; Lee *et al.* 2004). At Waverley Wood, Warwickshire (Fig. 2) these basal Baginton Formation sediments overlie a channel cut into the Triassic Mercia Mudstone bedrock. Fossiliferous assemblages recovered from the channel (Waverley Wood Sand and Silt; Fig. 1) were originally attributed to the Cromerian Stage but now are regarded as the stratotype of the Middle Wolstonian Substage temperate event which has been equated to the latter part of *c.* MIS 7 (Gibbard & West 2020). Recent work has demonstrated that the Baginton Formation sediments were deposited within a river, the Proto-Soar, and occurred during the Early to Middle Wolstonian Substages in the period up to and immediately before the glaciation.

Recent re-evaluation of the glacial sequence in the West Midlands and Fenland regions, including optically stimulated luminescence (OSL), post-infra-red stimulated luminescence (pIRSL) and terrestrial cosmogenic exposure (TCN ^{36}Cl) dating of the glaciofluvial deposits, has demonstrated that the tPGM glacial advance in lowland Britain occurred during the Late Wolstonian Substage. The numerical dating of this glacial maximum indicates that the regional tPGM occurred some 20 ka before the Drenthe Stadial, during the Moreton Stadial (~180 ka, *c.* MIS 6c) Late Wolstonian Substage (Gibson 2018; Gibson *et al.* 2022), negating claims that this glaciation took place during the older, *c.* MIS 8 (i.e. Middle Wolstonian Substage; White *et al.* 2017; Straw 2023, 2024). Recent studies (Gibson 2018; Gibson *et al.* 2022) have assigned

Fig. 2. Map of locations and major cities in lowland Britain. The insert map summarizes previously published limits of glaciation during the Anglian, Wolstonian and Devensian stages in the southern British Isles (Ehlers & Gibbard 2004).

much of the West Midland's glacial sediments to the Late Wolstonian Substage (Fig. 3A–C), with a distinct lack of evidence for earlier extensive Anglian Stage glaciation in the west of lowland Britain, constrained to an advance across the Upper Severn Valley (destroying the West Midlands Ancient Thames headwaters) and constrained by re-calibrated TCN ^{36}Cl dates at Churchill, where an erratic boulder derived from north Wales is dated to 423±50 ka (Gibson 2018).

The maximum extent of the glaciation during the Late Wolstonian Substage can be traced from north of Moreton-in-Marsh in Warwickshire to north of Cambridge in eastern England and thence beneath the North Sea where it met and became confluent with the Drenthe Stadial ice lobe in the Dutch North Sea region (Fig. 3C). Additionally, the ice limit can be traced further to the west and south west where it crossed the Bristol Channel, terminating against the north coast of the South West Peninsula.

This paper summarizes the current state of knowledge on the late Middle Pleistocene glacial sediments across lowland Britain. It discusses, region by region, the known cold-climate glacial and river sediments and where possible provides an independent biostratigraphic boundary. All known geochronology (including OSL, pIRSL, TCN ^{36}Cl and U-series dating techniques) is reviewed in terms of its stratigraphic relationship to Wolstonian Stage sequences. The localities mentioned within the paper are shown in Figs 2, 3.

Late Middle Pleistocene glaciation

West Midlands

Following the classic work of Shotton (1953), the glacial sequence of the West Midlands in the area around Coventry, Rugby and Leamington Spa (Fig. 2) was considered to represent what was termed the 'Wolstonian Glaciation'. This name was also selected for the predominantly cold-climate interval or stage as a chronostratigraphical division in the Middle Pleistocene by Mitchell *et al.* (1973). The Wolstonian (= Saalian) Stage is broadly equivalent to MIS 11b–6a (Fig. 1). The sequence comprises a series of fluvial, glacial and glaciolacustrine sediments identified over a large area in the west and central Midlands (Bishop 1958; Rice 1968, 1981; Rice & Douglas 1991; Sumbler 2001; Gibson *et al.* 2022), evidenced by the Baginton Formation and Wolston Formation. Of these, diamictons and associated meltwater sediments provide the evidence for an extensive glaciation of the region as far south as the Cotswold Hills at Moreton-in-Marsh in Gloucestershire (Fig. 2).

The glacial sediments of the West Midlands region overlie deposits of a pre-existing river system, the Proto-Soar, represented by the Baginton Formation (Fig. 4B). These deposits are characteristically composed of quartz-rich and quartzite-rich 'Bunter Pebble' sediment derived from underlying Triassic bedrock. In contrast to normal long-lived fluvial systems in the region, this south

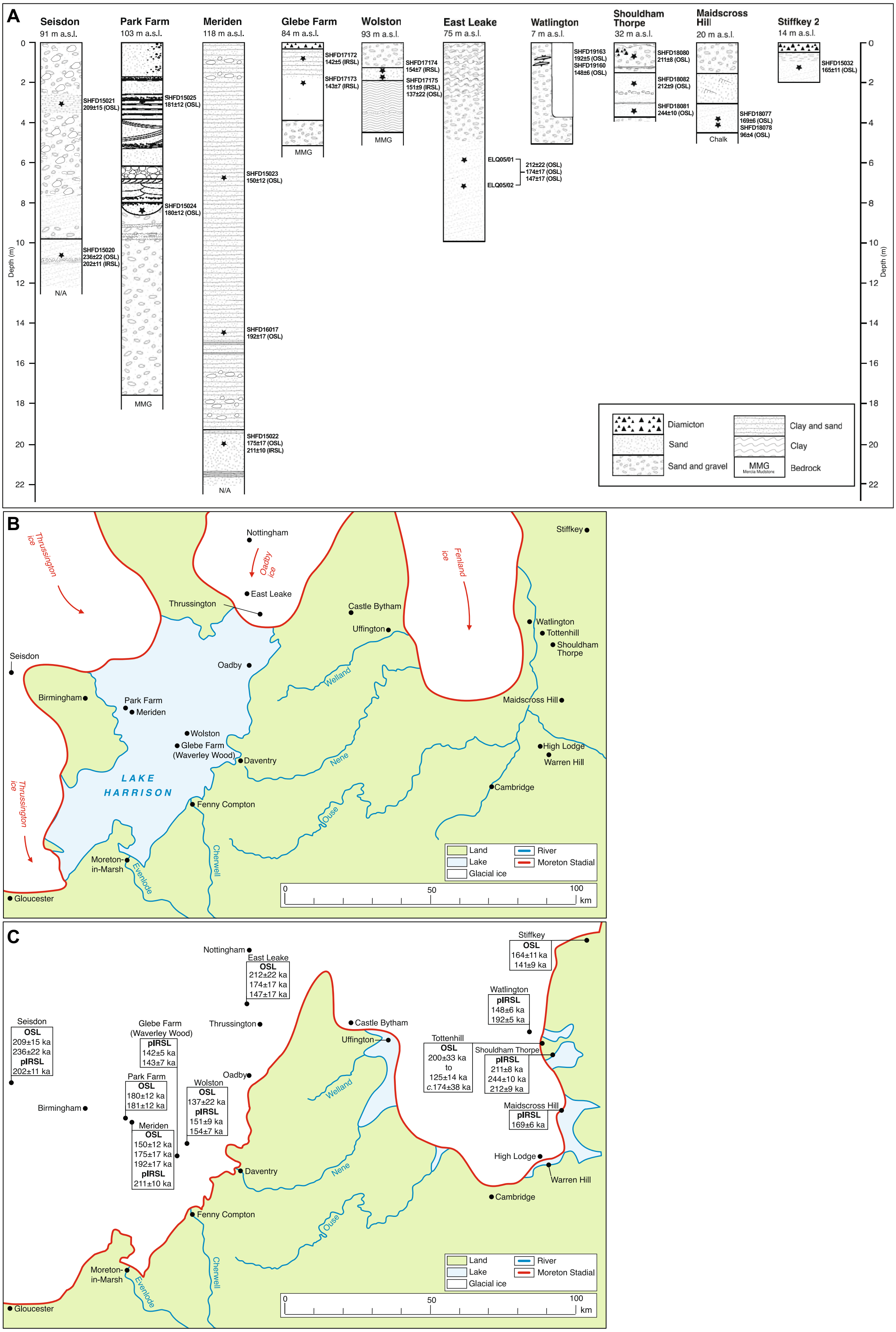

A
Seisdon
91 m a.s.l.
Park Farm
103 m a.s.l.
Meriden
118 m a.s.l.
Glebe Farm
84 m a.s.l.
Wolston
93 m a.s.l.
East Leake
75 m a.s.l.
Watlington
7 m a.s.l.
Shouldham Thorpe
32 m a.s.l.
Maidscross Hill
20 m a.s.l.
Stiffkey 2
14 m a.s.l.
Depth (m)
0
2
4
6
8
10
12
14
16
18
20
22
SHFD15021 209±15 (OSL)
SHFD15020 236±22 (OSL) 202±11 (IRSL)
N/A
SHFD15025 181±12 (OSL)
SHFD15024 180±12 (OSL)
MMG
SHFD15023 150±12 (OSL)
SHFD16017 192±17 (OSL)
SHFD15022 175±17 (OSL) 211±10 (IRSL)
N/A
SHFD17172 142±5 (IRSL)
SHFD17173 143±7 (IRSL)
MMG
SHFD17174 154±7 (IRSL)
SHFD17175 151±9 (IRSL) 137±22 (OSL)
MMG
ELQ05/01
ELQ05/02
212±22 (OSL)
174±17 (OSL)
147±17 (OSL)
SHFD19163 192±5 (OSL)
SHFD19160 148±6 (OSL)
SHFD18080 211±8 (OSL)
SHFD18082 212±9 (OSL)
SHFD18081 244±10 (OSL)
SHFD18077 169±6 (OSL)
SHFD18078 96±4 (OSL)
Chalk
SHFD15032 165±11 (OSL)
Diamicton
Sand
Sand and gravel
Clay and sand
Clay
MMG
Mercia Mudstone
Bedrock
B
Nottingham
Oadby ice
East Leake
Thrussington ice
Thrussington
Castle Bytham
Fenland ice
Stiffkey
Watlington
Tottenhill
Shouldham Thorpe
Uffington
Seisdon
Oadby
Welland
Maidscross Hill
Birmingham
Park Farm
Meriden
Wolston
Glebe Farm (Waverley Wood)
Daventry
Nene
High Lodge
Warren Hill
LAKE HARRISON
Cambridge
Thrussington ice
Fenny Compton
Ouse
Moreton-in-Marsh
Evenlode
Cherwell
Gloucester
Land
Lake
Glacial ice
River
Moreton Stadial
0
50
100
km
C
Nottingham
East Leake
OSL
212±22 ka
174±17 ka
147±17 ka
Stiffkey
OSL
164±11 ka
141±9 ka
Watlington
pIRSL
148±6 ka
192±5 ka
Seisdon
OSL
209±15 ka
236±22 ka
pIRSL
202±11 ka
Glebe Farm (Waverley Wood)
pIRSL
142±5 ka
143±7 ka
Thrussington
Castle Bytham
Uffington
Tottenhill
OSL
200±33 ka
to
125±14 ka
c.174±38 ka
Shouldham Thorpe
pIRSL
211±8 ka
244±10 ka
212±9 ka
Park Farm
OSL
180±12 ka
181±12 ka
Wolston
OSL
137±22 ka
pIRSL
151±9 ka
154±7 ka
Oadby
Welland
Birmingham
Meriden
OSL
150±12 ka
175±17 ka
192±17 ka
pIRSL
211±10 ka
Maidscross Hill
pIRSL
169±6 ka
High Lodge
Warren Hill
Daventry
Nene
Cambridge
Fenny Compton
Ouse
Cherwell
Moreton-in-Marsh
Evenlode
Gloucester
Land
Lake
Glacial ice
River
Moreton Stadial
0
50
100
km

Fig. 3. Known Late Wolstonian Substage sites with dates on the timing of glaciation in lowland Britain. A. Composite multiple logs of UK sites with luminescence dating indicating glaciation during the Late Wolstonian Substage (Seisdon, Park Farm, Meriden, Glebe Farm (Waverley Wood), Wolston, East Leake, Watlington, Shouldham Thorpe, Maidscross Hill and Stiffkey) with luminescence ages (in ka) indicated by stars. Elevations (metres above sea level; m a.s.l.) refer to the top of the section. Modified from Bridgland *et al.* (2014), Gibbard *et al.* (2021) and Gibson *et al.* (2022). B. A palaeogeographical reconstruction of the initial advance of glacial ice during the Wolstonian Stage and the formation of Lake Harrison. The reconstruction is modified from Gibbard *et al.* (2018) and Gibson *et al.* (2022). C. A palaeogeographical reconstruction of the Wolstonian Stage terrestrial glacial maximum during the Moreton Stadial in lowland Britain. The terrestrial penultimate glacial maximum (tPGM) is modified from Gibbard *et al.* (2018) and Gibson *et al.* (2022).

west–north east aligned system was apparently relatively short-lived since it lacks a terrace-like system. The deposits infilled a natural rock head depression (Crofts 1982) within the Proto-Soar palaeovalley following the Hoxnian (= Holsteinian) interglacial Stage and overridden by glacial ice during Wolstonian Stage (Figs 3C, 4C) (Shotton 1953, 1983; Gibson *et al.* 2022). The Proto-Soar flowed north-north-eastward from a catchment on Bredon Hill, Evesham capturing waters from the termination of the West Midlands ancient Thames immediately following the Anglian Stage glaciation (Shotton 1953; Gibson 2018) (Fig. 4B).

The reinterpretation of these basal cold-climate sediments as the headwaters of a pre-Anglian 'Bytham River', aligned towards East Anglia across the Fenland, found favour for some years. The implication was that the overlying Wolston Formation sediments were re-assigned as an eastward extension of a glacial ice lobe during the Anglian Stage (e.g. Rose 1987, 1994; Lee *et al.* 2004). However, reinvestigation of the sequence (Gibbard *et al.* 2009, 2013) has demonstrated that the Bytham River did not exist in the form suggested by authors such as Lee *et al.* (2004) and therefore Shotton's interpretation has been re-established (Fig. 4A, B) (Gibson *et al.* 2022), with the Baginton and Wolston Formation deposited during the latter part of the Wolstonian Stage.

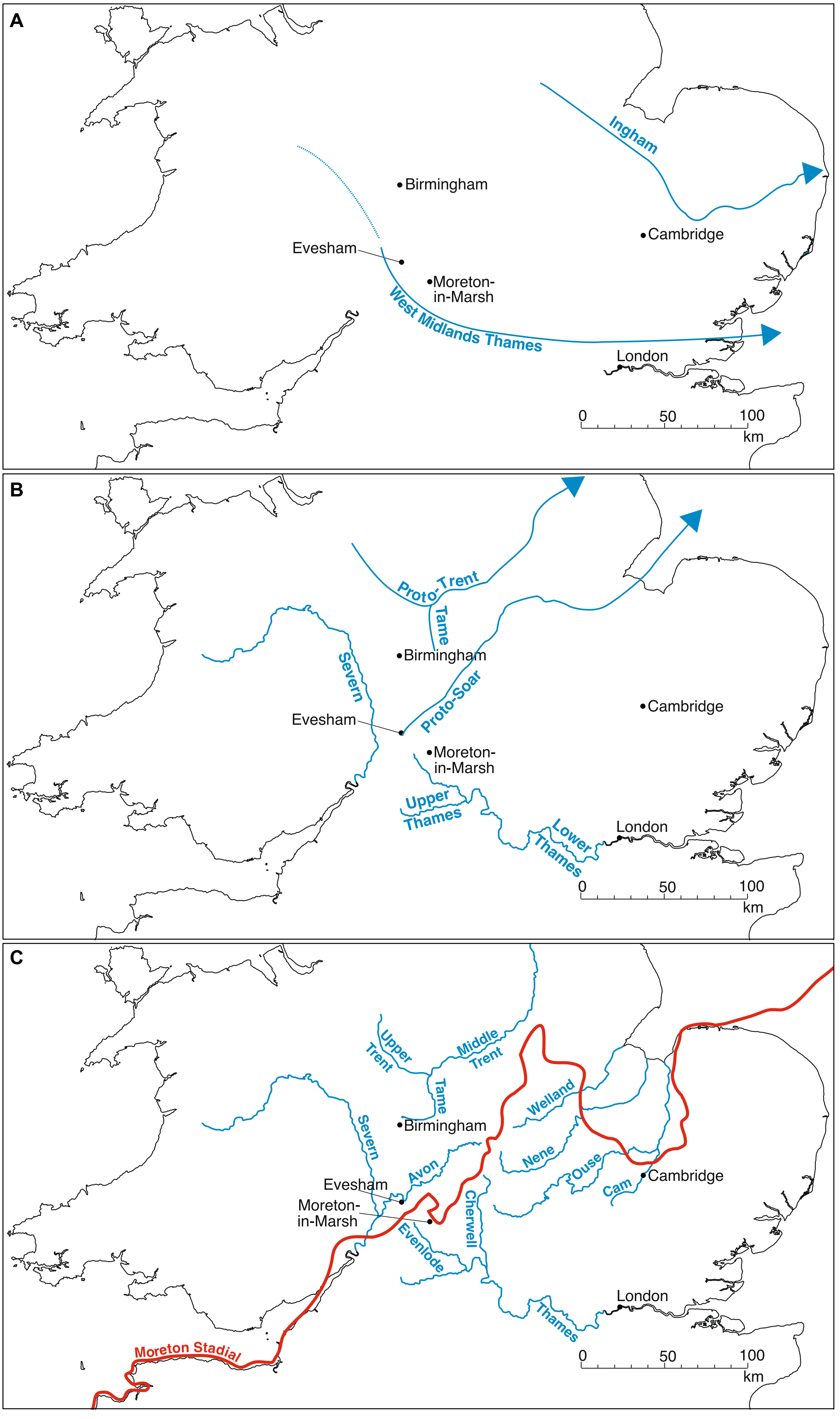
As defined by Shotton (1953) and developed since by Rice (1968, 1981), Shotton (1983) and Gibson *et al.* (2022), the West Midlands Wolston Formation, which overlies the Baginton Formation (Fig. 1), consists of two regionally identified till units, the Thrussington and Oadby members. The tills are interdigitated by glacial sand and gravels below (Baginton Member), between (Wolston Sand Member) and above (Dunsmore Member) (Fig. 1). The Thrussington Till (Fig. 1) is reddish brown and mainly Triassic derived, with rare erratic boulders of volcanic origin (volcanic tuffs, ignimbrites and quartz latites) derived from north Wales (with rhyolites more likely to derive from the Snowdon area) (Fig. 3B). The till overlies the Baginton Member, from the proceeding Proto-Soar river and is generally 3–5 m thick. The Oadby Till (Fig. 1), however, contains chalk, flint and Jurassic limestone clasts in a grey matrix derived mainly from Liassic clays. It represents the tPGM in Moreton-in-Marsh, against the Jurassic Escarpment (Fig. 3B, C) (Bishop 1958).

The Thrussington Till (Figs 1, 3B) deposited a series of glacial erratics found east of Birmingham from north Wales (Fig. 2). A series of exposure dates confirming the initial ice advance across the region during the late part of the Wolstonian Stage has been reported by Phillips *et al.* (1994) and Gibson *et al.* (2022). These erratics are part of a spread of boulders found across most of the West Midlands. Shotton (1932) speculated that Monzonite erratics around Coventry (Fig. 2) were brought in from south of Leicester by a significant glacial ice advance, possibly as ice-rafted debris within a glacial lake, that also deposited the Wolston Formation.

During the intervening time between the advance of the Thrussington Till ice and the Oadby Till ice, a large ice-dammed Lake Harrison was formed between the ice margins and the Jurassic escapement to the south between Moreton-in-Marsh and Daventry (Figs 2, 3B). Up to 25 m of laminated clays and silts accumulated, with counts of lacustrine varves covering at least 9600 years (Shotton 1976).

The Oadby Till was then deposited over much of the Midlands (Figs 1, 3B) as far north as Nottingham and Derby and as far west as Stratford-upon-Avon. To the south, Lake Harrison reformed and deposited the upper part of the Wolston Clay Member (Figs 1, 3B). The tPGM is represented by an advance of the Oadby Till (and its equivalent Moreton Till) southwards to Moreton-in-Marsh and Fenny Compton (Fig. 3C), where flint presumed to originate from its associated outwash was incorporated into the Wolvercote Terrace gravels of the Upper Thames Valley (Bishop 1958; Gibbard 1985). This has been correlated with terraces of the Middle Thames as young as the Taplow Terrace gravels (Gibbard 1985; Gibson *et al.* 2022), while Sumbler (1995, 2001) argued that the Oadby Till at Moreton-in-Marsh might relate to *c.* MIS 10, with earlier observations from Tomlinson (1929) and Bishop (1958) originating the aggradation of glaciofluvial Oadby Till outwash deposits into the Cherwell and Evenlode valleys to the main glaciation in the Wolstonian Stage.

The lithological similarity of the Oadby Till to the Lowestoft Formation Till of East Anglia, despite acknowledging that multiple tills can be formed by ice that traversed the same bedrock during different glacial stadials, led to suggestions that it was deposited by a westward extension of the same Anglian ice sheet (Perrin *et al.* 1979). As a result, the Wolston Formation, which is


A
Ingham
Birmingham
Cambridge
Evesham
Moreton-
in-Marsh
West Midlands Thames
London
0 50 100
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B
Proto-Trent
Tame
Birmingham
Severn
Evesham
Proto-Soar
Cambridge
Moreton-
in-Marsh
Upper
Thames
Lower
Thames
London
0 50 100
km
C
Upper
Trent
Middle
Trent
Tame
Welland
Birmingham
Severn
Nene
Avon
Ouse
Evesham
Cambridge
Cam
Moreton-
in-Marsh
Cherwell
Evenlode
London
Thames
Moreton Stadial
0 50 100
km

Fig. 4. Changing drainage systems of major rivers in lowland Britain during the Middle Pleistocene. A. The pre-Anglian, modified from Clark *et al.* (2004) and Gibbard *et al.* (2013). B. The Late Wolstonian Substage, modified from Gibson (2018). The West Midlands are dominated by the proto-Soar river network flowing north-eastwards (Shotton 1953). C. The post-Moreton Stadial/Late Wolstonian Substage. The Avon, Cherwell, Nene and Welland river courses are notably controlled by terrestrial penultimate glacial maximum (tPGM) limits. Modified from Gibson (2018) and Gibson *et al.* (2022).

over- and underlain by glacial material (Rice 1968, 1981; Shotton 1976; Shotton *et al.* 1977), was of Anglian age (Perrin *et al.* 1979; Rose 1987). This observation misled geologists for two decades in the 1980–1990s, leading to the opinion that glaciation in the Wolstonian made little significant impact on lowland eastern England, south of Yorkshire.

Contrary opinions were held by other authors (e.g. Shotton 1983; Gibbard & Turner 1988; Ehlers 1990), who pointed out the apparent disparity with the near European continent, where Scandinavian and Baltic glaciation is very extensive during the Saalian Drenthe Stadial (*c.* MIS 6c) and less so during the Warthe Stadial (*c.* MIS 6a). As Gibbard *et al.* (1992) concluded, it would have been surprising if lowland Britain had not been subjected to significant contemporaneous glaciation, as correctly demonstrated by Shotton (1953).

Crucially, work by Rose (1987, 1994) and Lee *et al.* (2004) overlooked key biostratigraphical evidence from interglacial deposits at Quinton (Figs 1, 2) that are overlain by glacial sediments, equivalent to the Wolston Formation (Horton 1974; Gibson *et al.* 2023). The fossil assemblages represent full temperate conditions during the Hoxnian interglacial Stage. More recently, Hoxnian-age temperate deposits at Gilson (Figs 1, 2) are overlain by glaciofluvial sediments equivalent to the Wolston Formation sequence. Gibson *et al.* (2023) made the critical observation that the Late Wolstonian Substage sand and gravel deposited during the Moreton Stadial now has a recognized basal interglacial deposit dated to the Hoxnian Stage at Gilson, making an alternative correlation to the Anglian Stage impossible.

Compelling evidence for glaciation during the tPGM Moreton Stadial (*c.* MIS 6c) across the West Midlands was presented by Gibson *et al.* (2022). The contemporaneous advances of the Thrussington and Oadby ice into the region as far as the Cotswold Hills (Fig. 3B, C) was supported by multiple geochronological dating on glacial erratics and glaciofluvial quartz and feldspars, which constrained the timing of the Moreton Stadial to the Late Wolstonian Substage (*c.* MIS 6) (Fig. 3A, C). The previous assumption that the Anglian glaciation was the most widespread glaciation in the British Isles has now been rejected in favour of the correlation of the Moreton Stadial glacial event to that of the Drenthe Stadial across the European continent (Gibson *et al.* 2022). In the time following, the continental Europe record holds evidence for a second glacial advance during the Warthe Stadial (*c.* MIS 6a). Across lowland Britain, evidence for this stadial is represented by the establishment of the first river terraces of all modern rivers within Late Wolstonian Substage tPGM limits. Gibson (2018) tentatively calls this event the Pershore Stadial, based on the inclusion of Oadby Till deposits in the 5th Terrace of the Avon river at Pershore (Figs 1, 2). If standing, the Warthe Stadial in the British Isles is a time of cold-climate periglacial conditions and fluvial aggradation, with glaciation potentially restricted to the higher land areas.

The Late Wolstonian Substage tPGM glaciation has had a profound impact on the modern drainage systems across lowland Britain (Fig. 4C). Glacial sediments intimately relate to fluvial sediments of the major Pleistocene river systems in lowland Britain with repeated glacial ice advances disrupting the drainage and re-alignment of rivers around the glacial advance. The river catchments of the Avon, Tame, Severn, Trent, Cherwell, Evenlode, Thames, Soar, Nene and Welland (Fig. 2) and their tributaries equate to the maximum extent of the Moreton Stadial ice (Fig. 4C) (Gibson 2018). Within the tPGM limits, the postglaciation Avon river flows south-westwards, whereas the river Nene, beyond the glacial limits, flows north east, and to the same theme, the Evenlode and Cherwell rivers have re-captured their headwaters from the tPGM limits. Such re- organization of the rivers had not been seen since the Anglian glaciation across lowland Britain (Rose 1987; Lee *et al.* 2004; Gibbard *et al.* 2013).

East Midlands

Geologists, and particularly Straw (1983, 1991, 2023, 2024), have been claiming that, owing to the perceived lack of glaciation during the Late Wolstonian Substage in lowland Britain (cf. above), deposits across the East Midlands (and South Yorkshire) are of an older glacial event during the Middle Wolstonian (= Saalian) Substage (*c.* MIS 8) which saw the deposition of the Wraxby Till and its associated glacially derived fluvial terrace deposits of the Eagle Moor Sands and Gravels, and the Balderton Gravel (Fig. 1) (Straw 1963, 1983, 2005; Brandon & Sumbler 1991; White *et al.* 2007; Bridgland *et al.* 2014). Gibson *et al.* (2022) negated this concept by correlating the East Midlands as part of wider tPGM during the Moreton (= Drenthe) Stadial across all of lowland Britain (Fig. 3).

The Eagle Moor Terrace is contemporaneous with the Wraxby Till, as glaciofluvial outwash contains numerous Wraxby (and Oadby) Till clasts, with the Balderton Terrace that was laid down between two full interglacial events (Bridgland *et al.* 2014). The Balderton Terrace is correlated by Brandon & Sumbler (1991) to the Hilton Terrace (Fig. 1) in the main River Trent. The remains of *Palaeoloxodon antiquus* and *Stephanorhinus hemitoechus* found in the Balderton Gravel indicate a pre-Ipswichian (= Eemian) age for the deposit (Stuart 1982; Bridgland *et al*. 2014). The mammal assemblages within the Balderton Terrace place the deposit firmly within the Late Wolstonian Substage (*c*. MIS 6) (Brandon & Sumbler 1991; Bridgland *et al*. 2014). Furthermore, the Hykeham palaeosol (Brandon & Sumbler 1999), occurs at the top of the Balderton Terrace at Hykeham and is attributed to the Ipswichian interglacial Stage (*c*. MIS 5e). It is clear these terraces formed immediately after the tPGM, post-dating the wider lowland glaciation of Britain, and before the subsequent Ipswichian interglacial Stage.

White *et al*. (2017) suggested that the Wraxby Till ice in the East Midlands is evidence for *c*. MIS 8 glaciation in lowland Britain, rather than *c*. MIS 6, despite strong evidence across the wider European continent for major lowland glaciation during *c*. MIS 6 (Ehlers & Gibbard 2004; Ehlers *et al*. 2011a, 2016). White *et al*. (2017) based their interpretation of a *c*. MIS 8 glaciation on the apparent occurrence of ice during *c*. MIS 8 in the southern North Sea Basin (Beets *et al*. 2005). Although the *c*. MIS 8 ice in the East Midlands has been equated to the Oadby Till ice in the West Midlands by White *et al*. (2017), deposits associated with glaciation in the West Midlands have been dated by OSL, pIRSL and TCN ^{36}Cl to *c*. MIS 6 in Meriden, Park Farm, Frankley Hill, Clent Hill and Seisdon (Phillips *et al*. 1994; Gibson *et al*. 2022) (Fig. 3A).

The modern River Trent is a product of north eastern glacial ice advancing through the Humber gap (White *et al*. 2007; Bridgland *et al*. 2014). Yet with Moreton Stadial glacial ice infilling the Trent Valley during the Late Wolstonian Substage, the Trent system is younger than previously thought (Fig. 4C). Without the Humber gap, a river took middle Trent Valley waters out through the Lincoln Gap (Clayton 1953; White *et al*. 2007).

The basal fluvial sands and gravels at Nechells (Kelly 1964) and Gilson (Fig. 2) (Gibson *et al*. 2023), deposited in the Proto-Tame Valley, aligned to the east-east-north, are possibly the missing evidence for a 'Proto-Trent' in the West Midlands with the system draining north west into the Irish Sea before the Anglian (= Elsterian) glaciation (Gibson 2018). Conceivably, the current Trent (upper, middle and lower sectors) represents the merger of different river catchments around the re-organization of lowland glaciation across the West Midlands, East Midlands and Lincolnshire.

East Anglia

In the past, there has been controversy over the extent of post-Hoxnian/pre-Ipswichian Stage glaciation in eastern England following the work of Bristow & Cox (1973). More recently, following reappraisals of the glacial evidence in northern East Anglia, Rose and colleagues (cf. Clark *et al*. 2004) proposed that additional glaciations might have occurred during the Early/Middle Wolstonian (= Saalian) Substages (*c*. MIS 8–10). The evidence for the age of this glaciation was based almost exclusively on the geochronometry of overlying or underlying non-glacial deposits and long-distance correlation with river sediments in the West and East Midlands. Evidence considered critical to this interpretation was derived from U-series determinations from the Nar Valley, near Kings Lynn in Norfolk, where sediment overlying Lowestoft Formation till at Tottenhill yielded an *c*. MIS 9 age (Rowe *et al*. 1997), a date that is close to the maximum that can be resolved using the U-series method. Rose (in Clark *et al*. 2004), following Scourse *et al*. (1999), took this to imply that the till was deposited during *c*. MIS 10. However, nowhere else in lowland Britain is a diamicton of this age known, and since this single determination conflicts with both the litho- and biostratigraphy at this site (cf. Ventris 1985, 1986, 1996), as well as the regional stratigraphy (Gibbard *et al*. 1992; Clark *et al*. 2004), its validity remains questionable.

The presence of glacial-margin delta-like fan sediments of unequivocal post-Anglian (= Elsterian)/pre-Devensian (= Weichselian) Stage age at Tottenhill on the East Anglian north eastern Fenland Basin margin (Fig. 2) confirmed this view (Gibbard *et al*. 2009). The dating of this Tottenhill Member (Feltwell Formation) (Fig. 3A), in north west Norfolk, is demonstrated by the fact that the Tottenhill Member gravels (Fig. 1) directly overlie both Anglian-age Lowestoft Formation glacial and the Hoxnian-age marine Nar Valley interglacial Member deposits (Ventris 1986, 1996). Later incision of the Tottenhill sediments left them at an elevation above the adjacent Fenland Basin and the Nar Valley fluvial Pentney Member. The latter includes organic sediments interstratified within the gravels that have been correlated with the first half of the Ipswichian (= Eemian) interglacial Stage on the basis of their contained pollen assemblages. A palaeosol is also developed on the surface of the Tottenhill sediments, which shows only one phase of temperate weathering considered to have formed in the Ipswichian Stage after the deposition of the gravels (Lewis & Rose 1991). The Tottenhill gravels thus pre-date the stage, demonstrating that they must be of Late Wolstonian Substage age (*sensu* Mitchell *et al*. 1973; Gibbard & Turner 1988), as Ventris himself concluded.

The advance of the Tottenhill ice lobe into the East Anglian Fenland Basin (Fig. 3B, C) reached the eastern marginal area and was possibly halted by the rising ground of the Chalk hills to the east and south (Gibbard *et al*. 2019). Here a group of landforms and their underlying deposits represent a series of glaciofluvial delta-fan and related sediments deposited as ice-marginal deltas in a lake at the maximum ice-marginal position (the 'Skertchly Line'). This evidence confirms historical descriptions of a glaciation of the Fenland, and demonstrates that reinterpretations of the sediments as of fluvial rather than of glacial meltwater origin (e.g. Lee *et al*. 2004), at sites including Warren Hill, High Lodge, Brandon, Lakenheath, Feltwell and Shouldham Thorpe (Figs 2, 3C), are incorrect.

This glaciation during the Late Wolstonian Substage (*c*. MIS 6c; see below), although originally recognized in the West Midlands, was subsequently identified in Yorkshire, northern East Anglia and the Welsh Borderlands. In many places, however, Wolstonian Stage glacial deposits were subsequently thought by some to pre-date the stage. For example, in the south Midlands, Sumbler (1983) questioned the basis for the relative age of the Wolston Formation sequence, pointing to an apparent continuity with the Anglian deposits further to the east, and therefore concluding that the West Midlands sequence should also be assigned to the Anglian Stage. This conclusion was also supported by Rose (1988). However, now that the latter has been rejected, and glaciation of Moreton Stadial has been identified in eastern England (Tottenhill ice lobe), it is no longer doubted that the Wolston Formation is indeed of Late Wolstonian Substage age (*sensu stricto*, i.e. *c*. MIS 6), as Shotton concluded (e.g. Gibson *et al*. 2022).

The recognition of the eastern Fenland ice margin extends the Tottenhill glacial limit south and south west and indicates that, at its maximum extent, the ice lobe occupied the entire Fenland Basin (Figs 3C, 5). Independent confirmation of this interpretation derives from the numerical dates and a possible western limit recognized by Langford (2018) west of Peterborough, Cambridgeshire and north of Uffington, Lincolnshire. A potential more northerly equivalent in Lincolnshire is the Welton Till, described from the Welton-le-Wold area by Straw (1991, 2005, 2023, 2024), which in both its stratigraphical position and lithology closely compares with red-brown eastern Fenland diamicton. However, Straw (2000, 2005, 2023, 2024) continues to favour an older age for the glaciation, which he equated to *c*. MIS 8 (i.e. Middle Wolstonian Substage) rather than *c*. MIS 6, on the basis of landscape relationships in his area, although he previously noted that it ‘could fall into any of the “MIS” Stages 6, 8 or 10’ (Straw 2005: p. 34). A similar conclusion was reached by White *et al*. (2010) in the East Midlands, although in both cases the dating of these sequences is equivocal, especially in the light of recent numerical age determinations (cf. Gibbard *et al*. 2021; Gibson *et al*. 2022). Therefore, while it remains possible that these observations might represent a different event to that seen in East Anglia or in the Midlands, further work has repeatedly failed to demonstrate an older glacial event within the Wolstonian Stage in the region. Rather, the Early to Middle Wolstonian interval seems to have predominantly been a lengthy period of periglacial conditions, punctuated by two temperate events (Fig. 1).

Despite these divergent views, on balance the evidence indicates that during the Late Wolstonian Substage, a substantial ice-lobe advanced down the eastern side of Britain, on each side of the Lincolnshire Wolds ridge, filling the Fenland Basin, where it dammed a series of westward-flowing streams to form shallow glacial lakes that coalesced culminating in an extensive proglacial lake in immediate contact with the ice front (Fig. 3C).

Western Britain

In the South Western Peninsula and South Wales, glaciation occurred during the Middle and Late Pleistocene. Despite some discussion, arising from the limited evidence available, glacial ice extended as far south as the Bristol Channel reaching coastal Somerset and north Devon, most likely during the Late Wolstonian (= Saalian) Substage interval.

The glaciation of the Bristol Channel area was first recognized by Maw (1864), who identified glacial deposits in the Barnstaple area (Fig. 2) and later by Strahan & Cantrill (1904). Mitchell (1968) agreed with the concept of an ice sheet pushing up the Bristol Channel and also supported the idea of ice filling the southern part of the Irish Sea as far as the Isles of Scilly. The latter is now well established for the Late Devensian (= Weichselian) (e.g. Scourse 1991; Scourse & Furze 2001; Chiverrell *et al*. 2013). However, the situation in the Bristol Channel area is less clear. A significant and important contribution to the debate on the Quaternary history of the Bristol Channel has been presented by John (1968, 2008), who argues that the Bristol Channel was glaciated from the west in the Devensian Stage but from the north during the late Middle Pleistocene. Bowen (1994) also recognized that the Bristol Channel had been glaciated, arguing that glaciation of the Bristol Channel must date from the Middle Pleistocene. It was further suggested by Bowen (1994) that easterly glacial deposits, found in the Bristol area, might equate to the older Cromerian (= Donian) Stage (*c*. MIS 16). This is contrasted by earlier workers who equated the glaciation of the Bristol Channel to the much later Late Wolstonian Substage (*c*. MIS 6) based on the relation to the overlying Ipswichian Stage age raised beach and associated sand deposits (John 1968, 2008; Gilbertson 1974; Gilbertson & Hawkins 1978; Kidson & Heyworth 1978; Dowsett *et al*. 2018; Bennett *et al*. 2024), although this has been hesitatingly revised on the basis of amino-acid racemization (Bowen *et al*. 1985). The glacial deposits around the Barnstable area have previously been ascribed to the Anglian (= Elsterian) Stage (*c*. MIS 12), despite there being no independent evidence to support the interpretation of Croot *et al*. (1996). It is more likely that the deposits on the land around Barnstable correlate with the oldest glaciation of the Bristol Channel, i.e. Late Wolstonian Substage (potentially during the Moreton

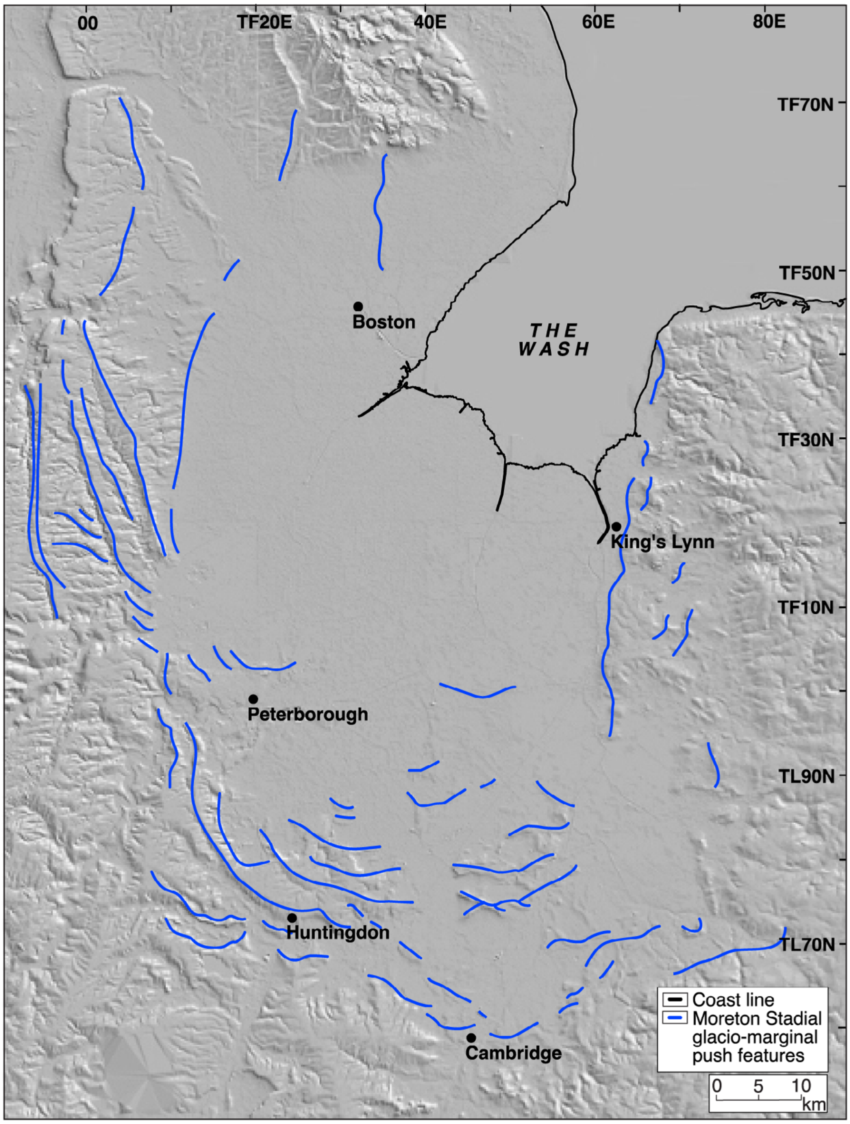

Fig. 5. Glaciotectonic push moraines marking the limits of the Late Wolstonian Substage ice lobe in the Fenland. Reproduced from Gibbard *et al.* (2018).

Stadial of Gibson *et al.* 2022). However, in the outer Bristol Channel area, Rolfe *et al.* (2012, 2014) found that glaciated granite surfaces on Lundy island date to the Middle Devensian Substage (*c.* MIS 3), indicating that they became ice free at that time. The ice limit of the outer Bristol Channel has been identified in Barnstaple Bay and east of Lundy, as evidenced by the offshore record (Gibbard *et al.* 2017; Rolfe *et al.* 2019).

Evidence on the evolution of the Bristol Channel has been revealed through various offshore investigations, including the synthesis of the publicly available borehole and bathymetric data. Based on these data, Gibbard *et al.* (2017, 2020) interpreted the later Pleistocene evolution of the Bristol Channel from Lundy and Swansea Bay in the west to the Severn Estuary and surrounding land areas, including the palaeo-Severn catchment. Here, the former river course is incised through glacial sediments on the Bristol Channel floor with at least three stages of glaciation being recorded, with the oldest basal sediments being correlated to a glaciation older than the Early Devensian (*c.* MIS 4–3). On the southern coast of the Bristol Channel the evidence for glaciation is limited, although valleys appear to be truncated or aligned parallel to the coast, such as at Lynton (Fig. 2). Similar channels are found along the coast as far as Ilfracombe to the west and Minehead to the east. Some of these are consistent with ice-marginal meltwater channels when the Bristol Channel was filled with ice, an argument also made by Stephens (1966, 1970, 1974) and most recently by Gibbard *et al.* (2017).

The earliest account of the glacial deposits in South Western Peninsula was by Maw (1864), and more recent investigators have included Mitchell (1960), Stephens (1966, 1970, 1974), Wood (1974), Croot *et al.* (1996) and John (2020). Published descriptions of the deposits vary, based upon anecdotal evidence. The previously named Fremington Till (now Fremington Clay) forms a continuous clay body that extends for 4 km between Fremington and Lake in north Devonshire (Fig. 2), with small, isolated till bodies to the north and west of the main mass. In the Fremington area, glacial clays, resting on the basal gravels, include four or five distinct units. The predominantly fine-grained deposits with pseudo-laminated structure, contain scattered erratics and have been interpreted as representing accumulation in a glacially dammed lake (Taylor 1956; Wood 1974). Shell fragments, together with a derived foraminifera, typical Irish Sea types, imply derivation from the sea floor. The Hele gravels, capping the Hele–Bickington ridge, were also considered to be glaciofluvial deposits (Stephens 1970; Kidson & Wood 1974), and are likely to have been deposited by streams emanating from the same ice sheet that deposited the till. Although the glacial deposits in the Fremington–Hele area have a limited distribution, their importance in the Quaternary of the South Western Peninsula is substantial, with this being the only accepted evidence of direct glacial deposition in the Peninsula. The glacial evidence of the region indicates glacial transport of Irish Sea sediments, this indicating that the till and associated glaciofluvial gravels were deposited near the limit of the Irish Sea lobe of an ice sheet of Wolstonian or possibly Devensian age, most likely the former (Campbell & Croot 1998; John 2020; Bennett *et al.* 2024).

Problems remain in the detailed interpretation of these deposits, however, particularly the depositional environments of the different units (cf. Scourse & Furze 2001; Rolfe *et al.* 2012; Rolfe 2015; Scourse 2024). A re-examination by Croot *et al.* (1996), concluded that the bulk of the Fremington Clay Member is probably glaciolacustrine in origin and has been overridden by glacier ice, although they favoured glacial deposition during the Anglian Stage (*c.* MIS 12). Preliminary attempts at numerical dating of the deposits have yielded equivocal results. Amino-acid racemization analysis of the raised beach deposits at Saunton and Croyde (Fig. 2) has estimated deposition during the Middle Wolstonian Substage (*c.* MIS 8–7), which implies that associated Fremington deposits are of Anglian age (Bowen *et al.* 1985). These ages, however, have been used by outdated analytical methods and should be regarded as preliminary (McCarroll 2002). The OSL ages from the raised beaches have subsequently indicated deposition during the Early Devensian (see below). The implication of these preliminary geochronological attempts on the glacial sediments of the South Western Peninsula is that glacial sediments underlying the pre-Devensian Stage raised beaches must be of Late Wolstonian Substage or (unlikely) of earlier glaciation.

Fig. 6. Large far-travelled boulders occur both in the till and exposed in coastal localities, mainly on old shore platforms. The largest and most accessible coastal erratic boulder is a block of pink granite at Saunton, NW of Braunton on the north Devon coast. Rolfe (2015) has dated the overlying sands to 130–90 ka (photograph P.L. Gibbard 2019).

Associated with the glacial deposits are the so-called giant erratic blocks which are found principally on the southern shore of the Bristol Channel. These large, far-travelled boulders occur both in the till and exposed in coastal locations, resting on rock shore platforms, where they are overlain by raised beach deposits attributed to the Ipswichian (= Eemian) interglacial Stage (*c.* MIS 5e) sea-level high (Fig. 6) (Taylor 1956; Madgett & Inglis 1987). The largest pink granite erratic examples can be seen at Saunton (Figs 2, 6). Here littoral sands directly overlying the boulder have been dated to 130–90 ka by Rolfe (2015), and additionally by Croot *et al.* (1996), who dated the sands to the Ipswichian interglacial Stage. This provides substantial geochronological control on the timing of glaciation in the Bristol Channel, within the Late Wolstonian Substage (*c.* MIS 6).

These erratics (containing porphyry, dolerite and spilite) were certainly transported by an ice sheet sourced in western Scotland. The most likely explanation for the occurrence of these erratic boulders is that they were ice rafted, reflecting their widespread distribution on the shoreline platforms of both the Bristol Channel and English Channel coasts. In south Devon, erratics have been recorded eastwards to Prawle Point, but they also occur as far east as Sussex (Kellaway *et al.* 1975) and on the French coast. However, apart from the blocks in the till inland, in north Devon an isolated block of epidiorite occurs at ~80 m a.s.l. on Baggy Point promontory (Madgett & Madgett 1974). While this implies potential emplacement by an ice sheet, it is important to consider the role of the tectonic upland of the region early in the Pleistocene (cf. Gibbard 1988; Antoine 1990). Equally, the impact of possible isostatic rebound, initiated by ice-sheet retreat from South Wales, could explain the occurrence of elevated raised beach platforms in the southern Bristol Channel area. Scourse (2024) has suggested that a number of the giant erratics around the coast could be related to the high relative sea levels during the Early Devensian when ice was present in the southern Irish Sea and east of Lundy (see above). It is possible therefore that both modes of transport have been involved in the South West (Bennett *et al*. 2024). While some erratics have possibly been deposited by Devensian ice, Bennett *et al*. (2024) suggest that at least some of the giant erratics on the Bristol Channel coast were deposited during glaciation in the Late Wolstonian Substage. Needless to say, there is little evidence to demonstrate whether all the inland glacial deposits and the erratics on the South-Western Peninsula represent a single or multiple glacial events (cf. Scourse 2024).

Miscellaneous glacial deposits

In many other parts of the country poorly dated glacial deposits of restricted lateral extent have also been attributed to a glaciation intermediate between the Ipswichian (= Eemian/*c*. MIS 5e) and Hoxnian (= Holsteinian/*c*. MIS 11) interglacial Stages, but only because they seem to be either older than Ipswichian or younger than Hoxnian, and are lithologically distinct from extensive local Anglian (= Elsterian) and Devensian (= Weichselian) glacial deposits. They are particularly identified where they occur outside the accepted Devensian ice limit. Examples include (i) the Bridlington Member or Basement Till of East Yorkshire which is lithologically similar the Welton Member in Lincolnshire (cf. above) and Warren House Gill on the coast of County Durham (the Warren House Formation), (ii) the Oakwood Formation at Chelford, Cheshire, (iii) the Ridgacre Formation overlying the Hoxnian Quinton lacustrine deposits at Quinton, Birmingham, (iv) the reddish brown till-like Fremington Member of Barnstaple Bay, north Devon (cf. above), (v) the Pilkenzane Formation of Lancashire, (vi) the Thornsgill Formation of Thornsgill (Lake District), (vii) the Balby Formation at Balby and Brayton Barff in the Vale of York and (viii) the Bakewell Formation at Shining Bank Quarry, in north Derbyshire (Gibbard & Clark 2011). The discovery of thick till deposits on the eastern margin of the Peak District at the last-mentioned locality (Aitkenhead *et al*. 1985; Burek 1991; Gibbard & Clark 2011) implies that the ice lobes moved southwards marginal to and on both sides of the Southern Pennine upland chain during this glaciation (Burek 1991), comparable with the pattern seen in the younger Late Devensian glaciation. To the south of the Peak District in the Wolstonian (= Saalian) Stage, the chalk-rich Oadby Till ice lobe and the Irish Sea ice met in the East Midlands and produced interdigitating deposits of the two tills (e.g. Huncote, Leicestershire; Lewis 1989).

The Bridlington Member is the most likely candidate for a Wolstonian (*c*. MIS 6) till in northern England (Catt *et al*. 2006). This unit underlies the Ipswichian interglacial Stage (*c*. MIS 5e) raised beach at Sewerby near Bridlington on the Yorkshire coast (Catt & Penny 1966), and at Speeton in Filey Bay overlies the estuarine Raincliff Formation (Speeton Shell Bed), which contains estuarine shells dated to *c*. MIS 7 by the amino-acid technique (Wilson 1991). However, it is possible that both the Raincliff Formation and the Bridlington Member at Speeton were glacially rafted to their present position by glaciation in the Late Devensian (Catt *et al*. 2006; cf. below).

Numerical dating of late Middle Pleistocene glacial sediments in the British Isles

West Midlands

The West Midlands provides a crucial geochronological control on the regional lithostratigraphy, as well as addressing outstanding questions against glaciation during the Wolstonian (= Saalian) Stage, which have remained in the literature. Work by Gibson *et al*. (2022) constrained the region's chronology by applying 11 OSL and pIRSL ages to the glacial, glaciofluvial and fluvial sands of key Wolstonian age sequences (Fig. 3A). However, pIRSL dating suffers from age underestimates arising from their slower resetting in a glacial environment (Gibson *et al*. 2022). Novel methodologies were applied to allow for a combination of dates to be produced by OSL and pIRSL at 50 and 225 °C to best understand the age of the sample within its lithostratigraphy. It is noteworthy that Gibson *et al*. (2022) reported dates from Glebe Farm (formerly Waverley Wood) and Wolston, both with sequences part of the Wolston Formation (Fig. 3A). At Glebe Farm (Fig. 2), samples from cross-bedded and massive glacial sand from the Baginton Member, which is believed to have been deposited in an ancient river Bytham by Rose (1987), resulted in a combined age (combined using OxCal v. 4.4.3; Bronk 2009) of 143±4 ka. At Wolston (Fig. 2), sampling from the Wolston Sand Member gave a combined age of 150±3.3 ka (Fig. 3A). The consistency of these two ages, both of which are taken within close proximity of the same geological Formation, indicate true burial ages for the Wolston Formation during the Moreton Stadial of the Late Wolstonian Substage. When combining all 11 ages, the resultant luminescence data set from the West Midlands were combined and analysed by OxCal to indicate two key depositional stages across the region. The first phase corresponds to the advance of the Thrussington ice from the north west at 199±5 ka and the later main phase of glaciofluvial deposition occurred during the Moreton Stadial at no earlier than 147±2.5 ka (Fig. 3C) (Gibson *et al*. 2022).

East Midlands

Schwenninger *et al*. (2014) reported luminescence dates from sand and gravel deposits in the River Trent Valley.

Initially Schwenninger *et al*. (2014) stated that these dates were partially beached and can be treated as minimum ages for the deposition of the sediments sampled. Bridgland *et al*. (2014) reported that this was too harshly judged since it was believed that sites such as East Leake (Fig. 2) must be of Anglian age and thus the dates did not fit the expected age of the sediments. It is unclear whether complications around partial bleaching have been dealt with in any meaningful way, and the equivalent dose (De) for the ages are calculated from a very small sample (eight to 10 values). Nevertheless, even with uncertainties around palaeomoisture contents, the luminescence ages reported can be applied successfully to the dating of River Trent deposits (Schwenninger *et al*. 2014). Bridgland *et al*. (2014) used luminescence dating from East Leake, Loughborough (Fig. 3A), to correlate deposits there to an equivalent outwash gravel deposit derived from the Oadby Till ice, formed during the deposition of the downstream Eagle Moor Terrace of the River Trent. This critical sequence is highly relevant because the luminescence ages from the site studied by Schwenninger *et al*. (2014) place deposition to *c*. 178±19 ka (with weighted means of 212±22, 174±17 and 147±17 ka) (Fig. 3A, C) as an ice-proximal deposit of the Oadby Till ice across the modern Trent Valley. Silts within the Southrey Terrace, at the Tattershall (Thorpe) Quarry, formed in a cool climate much like the silts reported in the Balderton Terrace gravels (Bridgland *et al*. 2014). The gravels have been dated to *c*. 123±12 ka by Schwenninger *et al*. (2014). This provides a clear restraint on the postglacial deposition of the Eagle Moor and Balderton Terraces within the Trent catchment and are directly correlated, through the Hilton Terrace (Fig. 1) to the Dunsmore Gravel and 5th Avon/Pershore Terrace (Fig. 1) across in the West Midlands (Clayton 1953; Posnansky 1960; Tomlinson 1961).

East Anglia

The West Midlands Pleistocene deposits have been correlated with those found in East Anglia. Six OSL ages from Shouldham Thorpe and Watlington in Norfolk and Maidscross Hill in Suffolk between 212±9 and 169±6 ka (Fig. 3A) have been reported by Gibbard *et al*. (2021) as representing ice-marginal delta and alluvial fan deposits within the Fenland Basin as ice advance during the Moreton Stadial. In addition, a further seven OSL ages from the Tottenhill sand and gravel have yielded ages between 200±33 and 125±14 ka with a mean of *c*. 174±38 ka, constraining the maximum advance of the Fenland ice lobe to the Late Wolstonian (= Saalian) Substage (Gibbard *et al*. 2013, 2018; Griffiths & Martin 2017; S.M. Pawley pers. comm. 2017). This observation is supported in luminescence dating by Langford (2018) at Kings Dyke, south east of Peterborough, where glaciofluvial sand and gravel, deposited by the advance of the Wraxby Till ice (and its equivalents) into the Welland and Nene catchments, has been dated to the Moreton Stadial, at 158±14 ka (Langford 2018). Along the north Norfolk coast at Stiffkey (Figs 2, 3A, C), two luminescence ages within an ice-proximal depositional environment formed from outwash sands and part of the Britons Lane Sand and Gravel Member have returned ages of 164±11 and 141±9 ka (Evans *et al*. 2019).

The glaciation proposed for *c*. MIS 8 by White *et al*. (2017) is, beyond reasonable doubt, the *c*. MIS 6, Moreton Stadial across lowland Britain and on the European continent (Winsemann *et al*. 2007; Gibson *et al*. 2022). The growing number of luminescence ages (Fig. 3A, C), currently reported from Seisdon in the west to Stiffkey in the east, supports the tPGM extent of the glacier during the Moreton Stadial in all regions. The increasing lithostratigraphical and chronostratigraphical evidence across all regions of lowland Britain strongly suggests the presence of glaciation during the Late Wolstonian Substage's Moreton Stadial (i.e *c*. MIS 6) in the British Isles, the deposits of which overlie Hoxnian (= Holsteinian) deposits in the West Midlands at Quinton, Nechells and Gilson. The latter is of importance as there has been a direct correlation of the Gilson sand and gravel overlying the organic beds to the Late Wolstonian Substage Wolston Formation by Gibson *et al*. (2023) and Anglian (= Elsterian) (Lowestoft Formation) glacial deposits in East Anglia (they themselves dated by Pawley *et al*. (2004, 2008) to the Anglian Stage on the ice-marginal Cromer Ridge, in north Norfolk).

Correlation across the North Sea

Shotton (1953) stated that 'the Pleistocene deposits of the area around Wolston are more than of local significance, suggesting that the Oadby glacier advance during the Wolstonian Stage is the same age as the Drenthian (Drenthe Stadial) in the Netherlands and the Saale (Saalian Stage) in Germany'. This statement is reinforced by multiple lines of evidence from recent research, as noted herein.

Offshore a glacial limit based on the extent of tunnel-valleys and a ridge-like push-morainic structure has been identified north of East Anglia (the Norfolk High) and continuing eastwards towards the centre line and beyond to join the Netherlands' Drenthe Stadial tPGM by Moreau *et al*. (2009) and Moreau (2010). This strongly defined feature can be differentiated from the Anglian (= Elsterian) Stage limit on the basis of detailed seismic analyses. The identification of this limit confirms that the tPGM identified in the Fenland region by Gibbard *et al*. (1992, 2009) is indeed a continuation of that of the same age as the Drenthe Haarlem–Utrecht–Nijmegen–Düsseldorf Ice-Push Ridge Complex limit in the Netherlands and Germany (Busschers *et al*. 2008), as previously noted by Gibbard *et al*. (2018) (Fig. 7).

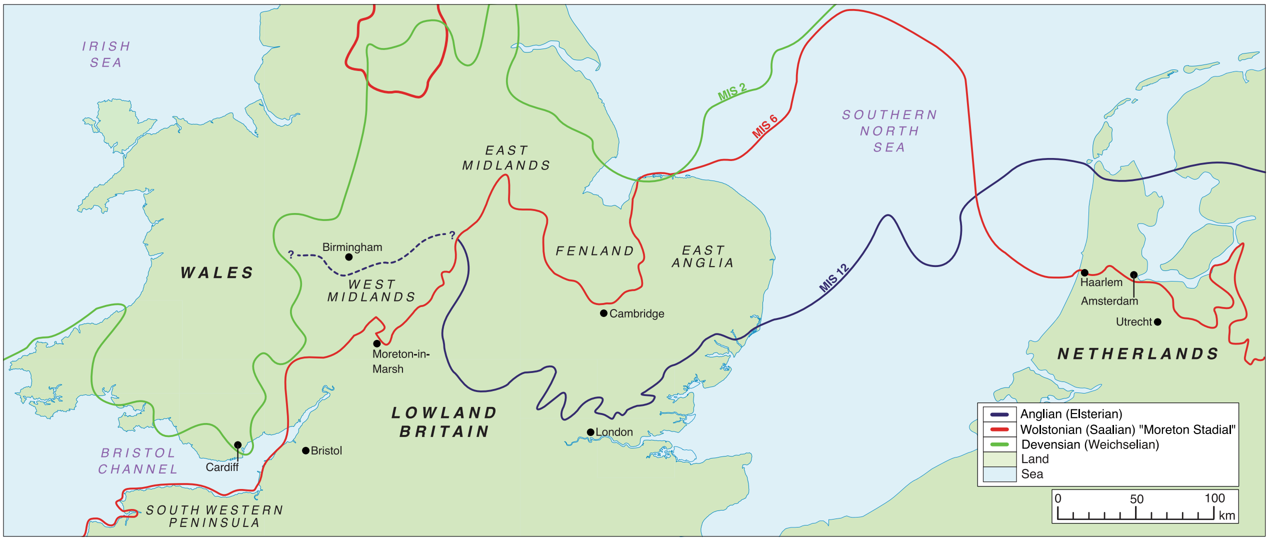

Fig. 7. The Morton Stadial/terrestrial penultimate glacial maximum (tPGM) of the Late (= Saalian) Wolstonian Substage ice limits across the British Isles, North Sea and the Netherlands. The Moreton Stadial limit is adapted from Gibson *et al.* (2022) and Cartelle *et al.* (2021) and is the most significant glaciation within the British Isles in the last 450 000 years. The Anglian (= Elsterian) Stage glacial limits are well established in the eastern British Isles, yet little evidence supports significant glaciation in the west (Gibson 2018; Gibson *et al.* 2022). The Devensian glacial limit follows that identified by Clark *et al.* (2018).

Comparison of the coalescent ice lobes within the North Sea region shows a remarkable parallelism of events and indeed glacial marginal ice-lobal style during this glaciation, in particular, the recognition of a major glacial advance during the Drenthe Stadial during which the glacier reached a maximum stillstand position in the Central Netherlands (Laban & van der Meer 2004; Busschers *et al.* 2007, 2008). It is remarkable that the ice-sheet limit in the Netherlands reaches virtually the same latitude as the Moreton Stadial ice lobe, identified in eastern England (Fig. 7). The OSL dating of the marginal sediments associated with this ice position in the Netherlands indicates a mean date for the glaciation maximum at *c.* 174–150 ka (i.e. during *c.* MIS 6) (Gibbard *et al.* 2009, 2018; Griffiths & Martin 2017; S.M. Pawley pers. comm. 2017).

The question of ice extent during the Late Saalian (= Wolstonian) Substage (Warthe Stadial) (Woldstedt 1927; Ehlers *et al.* 2016) (= Pershore Stadial in Britain: Gibson 2018; Gibson *et al.* 2022) remains open. Nowhere in lowland Britain has evidence for glaciation been reliably demonstrated representing this and the latest Saalian advance(s) seen in north Germany and Poland. Therefore, it appears that in lowland Britain at least this period intervening between the Morton (= Drenthe) Stadial and the Ipswichian (= Eemian) Stage was predominantly a period of severe periglacial (i.e. non-glacial) climates (cf. Gibbard *et al.* 2019). It is likely that the mountains of northern and western Britain did indeed carry glaciation during this time, although in the absence of supporting evidence, apart from possibly in the Peak District where two phases of Wolstonian Stage glacial advance were postulated by Waters & Johnson (1958), little can be said about this event. In comparison with the ice extent on the near European continent (e.g. Ehlers 1990) it is possible that glaciation of Britain at this time was similar in extent to that during the Late Devensian (= Weichselian) event. Instead, the interval was principally characterized by fluvial incision and the deposition of terrace deposits in river valleys (e.g. Gibbard *et al.* 2018; Gibson *et al.* 2022). The occurrence of this *c.* 20 ka long periglacial interval (Gibson *et al.* 2022) might explain the absence of kettle-like depressions in lowland Britain in which subsequent last-interglacial deposits might have accumulated.

It has been recognized that the most extensive glaciations in lowland Britain occurred in the Anglian, the Late Wolstonian Substage (Moreton–Drenthe Stadial) and the Devensian Stage (i.e. *c.* MIS 12, 6 and 4–2 respectively). As discussed above, the Warthe Stadial is not observed as a glacial event in lowland Britain, but as an interval of cold-climate river aggradation during the Pershore Stadial. Evidence from the Bay of Biscay sequence offshore of the mouth of the English Channel (Toucanne *et al.* 2009), based on 'Fleuve Manche' (Channel River) discharges, indicates that glaciation occurred in each event and that these palaeodischarges were directly controlled by the European ice sheets' behaviour during glacial stages *c.* MIS 12, 10, 8 and 6, and indeed 4–2. However, 'Fleuve Manche' activity during the *c.* MIS 10 (Early Wolstonian/Saalian Substage) and *c.* MIS 8 (Middle Wolstonian/Saalian Substage) glaciations was significantly less than during *c.* MIS 6 and *c.* MIS 2, implying that European ice sheets during the tPGM and last glacial periods were more extensive in comparison with the two previous glaciations. This led

Hughes *et al*. (2020) to allude to these more restricted glaciations as 'missing glaciations' in the stratigraphical record. Potentially therefore the ice was markedly more limited in extent both in lowland Britain and in the near European continent during *c*. MIS 10 and 8 (cf. Hughes *et al*. 2020, 2022). It also implies that the Scandinavian and British ice masses were almost certainly not confluent across the North Sea basin during these phases (Toucanne *et al*. 2008, 2009).

Conclusions

The two major glaciations have been identified in lowland Britain on land and neighbouring submerged areas of the North and Irish Sea basins during the Middle Pleistocene, the earliest of which occurred during the Anglian (= Elsterian) Stage (*c*. MIS 12). The second occurred during the late Middle Pleistocene, intermediate between the Hoxnian (= Holsteinian) (*c*. MIS 11) and Ipswichian (= Eemian) (*c*. MIS 5e) interglacial Stages during the Late Wolstonian (= Saalian) Substage (Fig. 7). The younger, although less well represented in the Pleistocene, has now been recognized as a significant event in the development of the lowland British landscape evolution. Two major stadials are recognized within the Late Wolstonian Substage (*c*. MIS 6), the first of which is termed the Moreton Stadial glaciation. This was first recognized in the West Midlands, but has subsequently been identified in eastern England, and further south west as far as the Bristol Channel. Despite geological mapping and incorrectly correlated interglacial sequences, which resulted in the Wolstonian Stage glacial deposits being thought to pre-date the stage, unequivocal evidence for glaciation during the stage is known, particularly in the Fenland and the eastern English Midlands. Correlation to equivalent Drenthe Stadial events on the near European continent reinforces the view that this glaciation was a significant, widespread event.

Previous opinions that glaciation occurred during the Middle Wolstonian Substage (*c*. MIS 8) in eastern England are now unequivocally falsified, thanks to systematic, co-ordinated litho-, bio- and chronostratigraphical investigations across the region and beyond the limits of known Anglian Stage glaciation extents in the west. Authors such as Gibbard *et al*. (2018, 2021) and Gibson *et al*. (2022, 2023) have demonstrated beyond doubt that glaciation occurred in the Late Wolstonian Substage Moreton Stadial. This is supported by significant geochronological dating and independent biostratigraphy from sites including Quinton (Horton 1974), Waverley Wood (Gibbard & West 2020) and Gilson (Gibson *et al*. 2023) in the West Midlands.

Glaciation in lowland Britain appears to have occurred some 20 ka before the main Drenthe Stadial event across the neighbouring European continent. The Moreton Stadial and Drenthe Stadial tPGMs have been correlated across the North Sea (Fig. 7), placing the British ice sheet in synergy with the most extensive glacial event within the Northern Hemisphere during the Middle to Late Pleistocene.

Major re-advance of glacial ice following the tPGM, as observed during the Warthe Stadial event across continental north west Europe, is not seen in lowland Britain, with glacial advance potentially constrained to the higher lands of Wales, the Lake District and Scotland. The near 20 ka cold-climate stadial in lowland Britain was instead a time of extensive severe periglacial and fluvial activity which saw river terrace sequences established during the interval between the Moreton Stadial and before the Ipswichian Stage that have tentatively been termed the Pershore Stadial in the British Isles by Gibson (2018) and Gibson *et al*. (2022).

The nature of the glaciation during the Late Wolstonian Substage, compared with that during the preceding Anglian Stage, implies a different set of immediately pre-existing ground conditions. For example, the Anglian glaciation deposits characteristically comprise thick sheets of till. The former suggests that an abundant supply of weathered regolith material was available for recycling during the Anglian ice advance. Likewise, the occurrence of deeply eroded and infilled tunnel valleys implies that large volumes of meltwater were drained from the ice sheet in these substantial channel systems during this phase. In contrast, the Late Wolstonian Substage ice lobes appear generally to have deposited notably thinner till sheets, potentially suggesting a more limited regolith stock than that in the preceding glaciation (the first to have advanced into lowland Britain). This, combined with the recessional landforms that characteristically occur as ice-push marginal landform complexes, like those in the Fenland, beneath the adjacent North Sea and in the central Netherlands marginal zones, again contrasts with a lack of such features apparently formed during the Anglian deglaciation phase(s). Furthermore, the apparent absence of tunnel valleys on land, at least in lowland marginal areas, suggests that meltwater discharge during the Moreton Stadial glaciation, rather than being restricted to and focused on substantial tunnel valley networks, was generally through widely distributed subglacial meltwater channels.

Major drainage diversions followed each of the major Middle Pleistocene glaciations. That following the Late Wolstonian Substage event resulted in the significant destruction of the Midlands Proto-Soar system (Baginton Formation) and the drainage of the substantial proglacial Lake Harrison meltwater into the Upper Thames catchment where it merged into the Wolvercote Terrace gravels. Similar reroutings included the courses of several Midlands river networks (Fig. 4C). Moreover, the confluence of the eastern English ice lobe with that from the eastern North Sea area dammed the drainage systems from both eastern England and the nearby

European continent to form a major North Sea proglacial lake that itself drained through the Dover Strait into the 'Fleuve Manche' (Channel River) network.

As regards recent continuing research, this is focused on establishing rigorous geochronological control on the timing of cold-stage deposition across lowland Britain. It has demonstrated that sediments, long associated with glacial events, relate to the Wolstonian Stage. This is based on the application of new methods and innovative techniques that combine both OSL and pIRSL over a series of different heat treatments. Understanding the behaviour of such datable material, from depositional route to its ability to yield a reliable age, would be a useful direction for future research.

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