Lateglacial and early Holocene evolution of the Tyne Valley in response to climatic shifts and possible paraglacial landscape legacies

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Highlights

• Lateglacial to late Holocene fluvial response recorded from river terrace sequence.

• Fluvial landscape strongly conditioned by glacial legacy.

• Catchment-wide responses are non-linear and valley floors operated as reach-wide responses.

• River responded to climate and/or landscape perturbations at ~16, 11.9, 8.7, 4 ka.

Abstract

This paper presents new sedimentological, geomorphological, and optically stimulated luminescence (OSL) geochronological evidence for fluvial evolution of the mid- to lower River Tyne through the Lateglacial to late Holocene. These data reveal a series of fluvial terraces produced by cycles of aggradation and incision, conditioned by glacial inheritance, and driven by changing sediment availability and hydrological regime. The distribution and stratigraphy (where available) of nine river terrace and their associated sediments have been recorded. At two key sites the sediments have been dated using OSL measurements to constrain the fluvial geomorphology. Significant entrenchment of the fluvial system, followed by aggradation formed the earliest fluvial terrace (T1), which encompasses environments spanning the transition from deglaciation into Greenland Interstadial 1 (GI-1). Incision below T1 began towards the end of GI-1, with three terraces (T2 – T4) between the abandonment of T1 and the early Holocene (15.0–9.2 ka). Climatic shifts, limited vegetation cover/soil development, and peri−/paraglacial landscape instability conditioned the development of the early postglacial fluvial land system. Three further terraces (T5 – T7) developed during the mid- to Late Holocene (6.6–3.1 ka) and comprise most of the valley floor. Climatic instability, glacial inheritance, and widespread anthropogenic disturbances are reflected in greater hillslope-channel coupling during this period. The extent of later Holocene terraces (T8 – T9) is limited as the river became isolated from flanking hillslopes entrenched between existing river terraces. Fluvial landscape evolution in formerly glaciated catchments is strongly conditioned by the cold stage legacy that introduced excess sediment and landscape instability into the catchment. Subsequent catchment-wide responses are variable and non-linear, with valley floors operating in a series of reach-wide responses. There is a need for greater chronological control to constrain the Lateglacial and Holocene evolution in the Tyne catchment, but also to further our understanding of region-wide responses to external drivers and local dynamics.

1. Introduction

River terraces and their deposits are important archives of terrestrial environmental change and catchment sediment dynamics, as such they can reveal the response of fluvial systems to external forcing (e.g. climate and extreme events; base-level change; vegetation and land cover; and, anthropogenic activities) and internal fluvial dynamics. The degree of fluvial response to driving forces is often linked to landscape and river sensitivity (cf. Brunsden and Thornes, 1979; Fryirs, 2017), with sediment availability a major driver of geomorphic change. Changes in sediment flux can result in channel incision/aggradation, floodplain aggradation, and lateral channel migration. Additionally, local fluvial dynamics and discontinuities between and within reaches can mute or amplify the response to external drivers (Chiverrell et al., 2010; Philips, 2010). However, compared to other European river systems, the timescales and responses of British rivers, within the limits of the British-Irish Ice Sheet (BIIS; MIS 2), during the Lateglacial and early Holocene are poorly constrained, especially in contrast to lowland systems that lay beyond the BIIS (Collins et al., 2006; Gao et al., 2007; Lewin and Gibbard, 2010; Brown et al., 2013). Accurately dated fluvial landform sequences in the uplands and piedmont zones of systems within the MIS 2 ice sheet limit are rare in the UK for this period (Macklin and Lewin, 1993; Macklin et al., 2014), making it difficult to explore potential relationships between fluvial dynamics and forcing factors. Some important exceptions are available from northern Britain, however. There are dated sequences from both the eastern and western Pennine rivers such as the Wharfe (Howard et al., 2000a), Swale (Taylor et al., 2000) and Ure (Howard et al., 2000b; Bridgland et al., 2011), Hodder and Ribble (Chiverrell et al., 2009a; Foster et al., 2009) and, in Scotland the Kelvin, Feshie and Spey (Tipping et al., 2008; Ballantyne, 2019; Werritty, 2021).

Conceptual models of responses of fluvial systems through glacial-interglacial cycles in Northwest Europe indicate channel instability and channel pattern change, followed by aggradation and stability (Vandenberghe, 2008; Turner et al., 2013). In the UK, transitions from cold-to-warm have typically been associated with channel incision and erosion, coupled with shifts from a braided river system to a meandering river system (e.g. Maizels and Aitken, 1991; Bridgland, 2000; Chiverrell et al., 2009a; Macklin et al., 2013). Short-lived climatic oscillations (warm-to-cold), such as the Bølling-Allerød to Younger Dryas, have been recorded as catchment instability and aggradational episodes in lowland systems (Hill et al., 2008; Howard et al., 2011). The transition from the BIIS (MIS 2) glacial land-system to post-glacial fluvial system encompassed the climatic changes in the late glacial (GI-1 and GS-1) and the early Holocene climate events (Mayewski et al., 2004; Lowe et al., 2008; Lang et al., 2010; Shakun and Carlson, 2010; Thornalley et al., 2009; Rasmussen et al., 2014). The transition into the early Holocene in northern England was also accompanied by base-level changes, linked to lower than present sea levels (Bradley et al., 2011, Bradley et al., 2023; Shennan et al., 2012) and glacio-isostatic uplift (Bridgland et al., 2010; Bridgland and Westaway, 2014). The fluvial system changed from glacial to nival-fed (snowmelt) discharge regimes to temperate systems, and was marked by reductions in sediment availability reflecting both exhaustion (cf. Church and Ryder, 1972) and landscape stabilisation with vegetation and soil cover. Thus, a paraglacial landsystem conceptual model (cf. Ballantyne, 2005; Harrison et al., 2010) describes the post-glacial development of upland formerly glaciated catchments and describes the evolution of sediment regimes inside the last glacial maximum (LGM) limits. In this model the postglacial hillslope processes and fluvial systems of Britain are out of phase with major climatic shifts, thus the redistribution/availability of the sediment is important and may act as a lead or lag in fluvial development.

Northern England lies within the limits of MIS 2 ice and many river valleys, including the Tyne, are infilled with glacial, soliflucted, colluvial and fluvial deposits. Previous workers have investigated reaches in the Tyne basin during the mid and late Holocene period (e.g. Passmore and Macklin, 1994; Rumsby and Macklin, 1996), but these studies did not concentrate on the Lateglacial–Holocene transition. Here, we present evidence for fluvial development for a 22 km stretch of the piedmont middle Tyne valley. Our aims are: (i) to present the alluvial landform record; (ii) to identify the sequence of valley-floor development; (iii) to interpret the depositional environment from the sedimentary record; (iv) to establish a chronological framework using optically stimulated luminescence dating (OSL); (v) to explore the response of the fluvial system to climate change and other conditioning factors.

2. Study area

2.1. The Tyne Basin

The Tyne basin lies in the northeast of England (Fig. 1) and comprises a catchment area of 2936 km2. The Tyne basin (maximum elevation 893 m) comprises two main tributaries; the North Tyne rises on the Cheviot Hills near the Scottish border and the South Tyne forms on the North Pennines near the Cumbrian border. These tributaries combine near Hexham (Fig. 1) to form the River Tyne. The river Tyne is 118 km in length, and reaches the north sea at Tynemouth. Geologically, the basin is underlian by Carboniferous limestone, sandstone, siltstone and mudstone, along with Silurian greywackes and Devonian sandstones. Andesite outcrops in the Cheviot Hills, whilst Dolerite is found along the south Tyne. Structurally, the Alston block and Northumberland fault-trough bound the catchment (Scrutton, 1995; Johnson, 1997). Investigation focused on the mid-Tyne valley (w-e flowing section), extending as far upstream as the Allen confluence (South Tyne) and as far downstream as Broomhaugh (Tyne) (Fig. 1). The Tyne valley comprises wide valley floors (or basins), with occasional narrow sections (or gorges), and the present day river can be described as a wandering/meandering gravel-bed river.

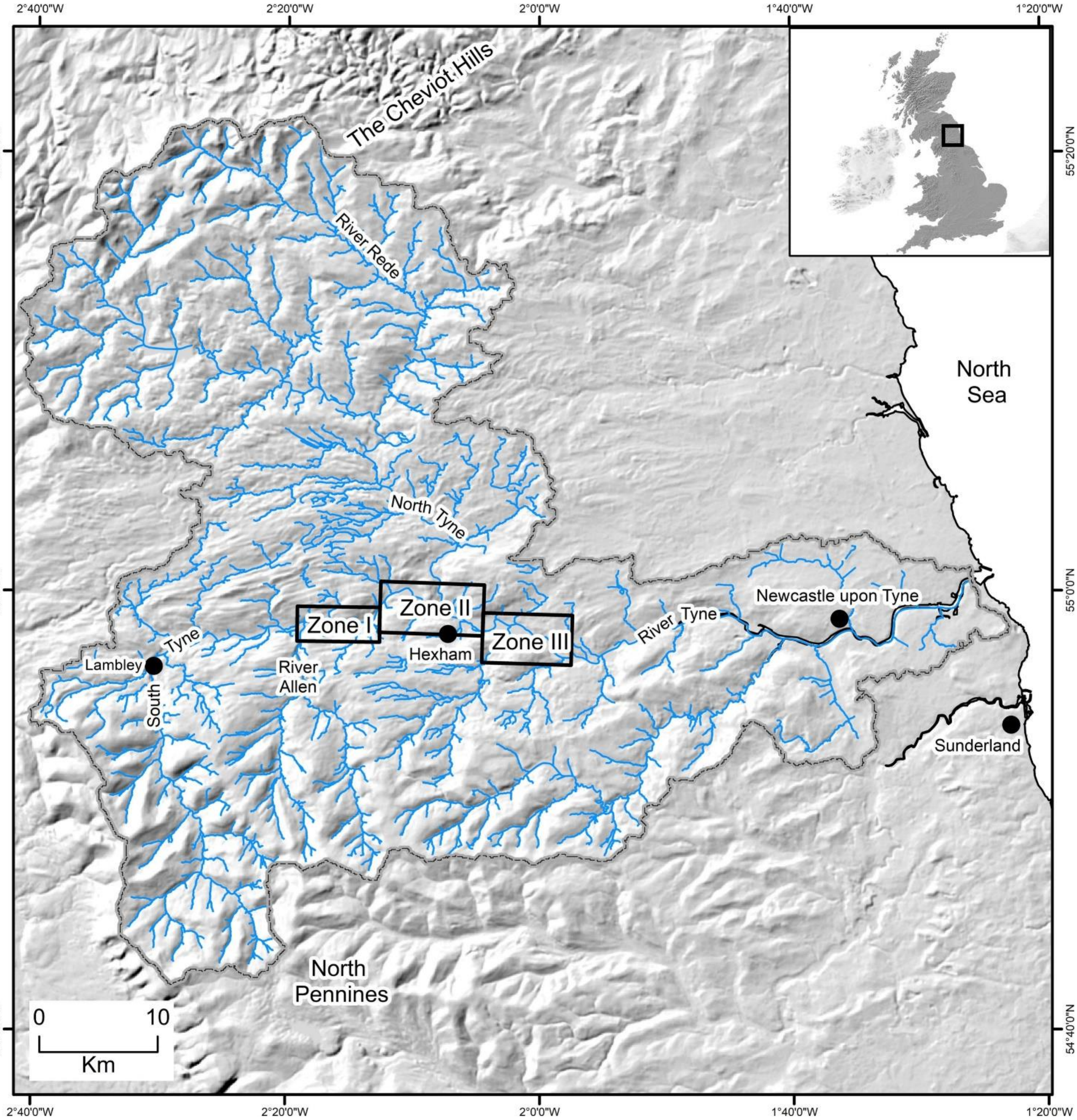

Fig. 1. Extent of the Tyne catchment, with key rivers and places named. Overlain on a shaded relief SRTM DEM (Pope, 2017). The key locations in the mid-Tyne valley have been divided into three zones (I, II and III) and are demarcated by the black rectangles.

During the last glaciation northern England and the Tyne valley were overridden by British-Irish Ice Sheet (BIIS) (Hughes et al., 2016). Regionally, the ice was around 0.8 km thick at the LGM. A west-east flowing ice stream (Tyne Gap Ice Stream; TGIS) extended along the Tyne valley (Smith, 1994; Mills and Holliday, 1998; Livingstone et al., 2012, Livingstone et al., 2015) and an ice lobe extended north–south down the North Sea coast (North Sea Lobe; NSL). Constrained by Bayesian statistical analysis of radiocarbon and cosmogenic ages, retreat of the TGIS had begun by 18.5–18.3 ka (Livingstone et al., 2012, Livingstone et al., 2015; Evans et al., 2021; Clark et al., 2022), creating accommodation space in the mid and lower Tyne valley as it decoupled from the NSL impounding waters in the Tyne lowlands. In the Tyne valley an extensive pro-glacial drainage system developed feeding water and sediments towards a large ice-dammed lake (Glacial Lake Wear) (Smith, 1994; Davies et al., 2009; Yorke et al., 2012; Teasdale, 2013). The NSL had retreated completely from the east coast by 17–16.5 ka (Roberts et al., 2018; Evans et al., 2021), with ice retreating to the upland dispersal centres (Lake District) by 17 ka (Davies et al., 2019). Following deglaciation, regional sea levels were low, lying at −30 m Ordnance Datum (OD) at 12 ka BP (Bradley et al., 2011). Buried peats within estuarine sediments found in the lower Tyne constrain early Holocene marine inundation to 8.5 ka cal. BP (Horton et al., 1999a, Horton et al., 1999b). Glacio-isostatic uplift across Northumberland has declined since deglaciation, with a present-day uplift rate of 0.2–0.8 mm a−1 south to north respectively (Bradley et al., 2011; Shennan et al., 2012; Bradley et al., 2023). Base-level change for regional river systems, driven by both eustatic and glacio-isostatic factors, may have influenced fluvial dynamics during the Lateglacial and early Holocene period.

This study focuses on three reaches. Zone I is a lowland reach set within ice-disintegration topography, where narrow valley floor fluvial terraces are preserved on inner meander banks between the Allen confluence and a knick-point gorge (Newbrough) upstream of Fourstones. Zone II is a gently meandering reach that straddles the confluence of North and South Tyne, with terraces preserved on both sides of the valley floor flanked by subglacial features between Fourstones and Acomb. Zone III is a major alluvial basin (Corbridge) between Hexham and Broomhaugh (Fig. 1), with extensive valley floor fluvial terraces present set below extensive glacial outwash deposits.

3. Materials and methods

3.1. Geomorphological mapping

Mapping of the valley floor features drew on interpretation of Light Detection and Ranging (LiDAR) digital elevation model (DEM), supplied by the Environment Agency's Geomatics Group. The LiDAR DEM had a spatial resolution of 1 m2, with a vertical accuracy of ~0.15 m. Mapping was undertaking using the interpretative tools within ArcGIS. Extensive flat areas and linear depressions reflect and were digitised as river terrace fragments and palaeochannels respectively. Identification was possible through manipulation of the DEM to produce hill-shaded surfaces, narrow elevation range shaded DEMs and interval contours. Field mapped data were used to ‘ground-validate’ the terrace fragments and palaeochannels interpreted from the LiDAR DEM at scales of 1: 10,000.

3.2. Sedimentological investigations

The sediments underlying the mapped terraces were recorded from river-bank exposures and using closely spaced sediment profiles interpreted from the British Geological Survey (BGS) online database of borehole logs. Sediment analysis followed a lithofacies approach (Miall, 1988) and sediments were recorded on the basis of grain size, bed contact and bedding, sorting and texture, sedimentary structures, colour, and sediment body geometry (Jones et al., 1999). Clast form and provenance was established by clast (>0.05 m) lithological analysis (Bridgland, 1986). Established fluvial form-process models (Miall, 1996) underpin interpretations of lithofacies and helped interpretation of the generalised vertical succession.

3.3. Optically stimulated luminescence dating

In the absence of in situ organic material for radiocarbon dating, to develop a chronology for the terrace sequence we used Optically Stimulated Luminescence (OSL) dating to target sands within terraces 1, 4, 5 and 7. Suitable lithofacies that had the greatest potential to have been exposed to light prior to deposition (cf. Thrasher et al., 2009) were targeted for OSL dating, e.g. overbank and bar-top sands. Samples were collected (in daylight) by hammering opaque plastic tubes (300 × 50 mm) into cleaned faces. Bulk materials collected within 30 cm of the OSL sample provide materials for measurement of moisture content and γ dose rate in the laboratory. Sand-sized quartz (180-255 µm or 90-125 µm) mineral grains were extracted from the sediment samples using standard preparation techniques. These included wet sieving, removal of organic matter using H2O2 (10 %), HCl (10 %) treatment to remove carbonates, HF (48 %) treatment for 60 min followed by an additional etching in H2SiF6 acid for two weeks to dissolve remaining feldspathic components as well as heavy mineral separation using sodium polytungstate (2.63 g cm−3). All the samples were measured as medium sized (4 mm diameter) multigrain aliquots mounted on aluminium discs inside an automated Risø TL/DA15 luminescence reader (Bøtter-Jensen, 1997; Bøtter-Jensen et al., 2000) using a SAR post-IR blue OSL measurement protocol (Murray and Wintle, 2000; Banerjee et al., 2001; Wintle and Murray, 2006). Due to the fluvial nature of the sediments and in order to avoid overestimating the true depositional age of the sediments as a result of incomplete bleaching of the OSL signal (Murray et al., 1995, Wallinga, 2002), the De estimates were calculated using a Minimum Age Model (Galbraith et al., 1999) within the ‘R' statistical programming language (Kreutzer et al., 2012). Dose rate calculations are based on the concentrations of radioactive elements (potassium, thorium, uranium and rubidium) within the sediment. These were derived from elemental analysis performed by Actlabs (Canada) using induced coupled plasma mass spectroscopy / atomic emission spectroscopy (ICP-MS/AES) and a fusion sample preparation technique. The final OSL age estimates include an additional 2 % systematic error to account for uncertainties in source calibration. Dose rate and age calculations were obtained using DRAC version1.2 developed by Durcan et al. (2015). These are based on Aitken (1985) and incorporated updated grain size attenuation factors of Brennan et al. (1991) and Guérin et al. (2012), etch depth attenuation factors of Bell (1979), dose rate conversion factors of Guérin et al. (2011) and an absorption coefficient for the water content. The contribution of cosmic radiation to the total dose rate was calculated as a function of latitude, altitude, burial depth and average over-burden density based on data by Prescott and Hutton (1994). The OSL age estimates (presented as ka: Table 1) include an additional 2 % systematic error to account for uncertainties in source calibration.

Location	Lab code	Depth (m)	W∗ (%)	Cosmic dose rate (Gy/ka)	Total dose rate (Gy/ka)	Aliquots accepted (measured)	Equivalent dose+(Gy)	Over-dispersion (%)	Age estimate++ (ka)
Fourstones	X2730	0.70	18	0.19 ± 0.02	1.91 ± 0.02	16 (18)	21.09 ± 2.04	17.10	10.77 ± 1.13
	X2731	5.50	18	0.11 ± 0.01	0.90 ± 0.06	14 (18)	57.67 ± 10.89	35.70	61.98 ± 11.98
	X2732	2.00	18	0.16 ± 0.01	0.98 ± 0.06	17 (18)	18.54 ± 3.29	53.60	18.51 ± 3.36
	X2733	0.90	18	0.19 ± 0.02	1.22 ± 0.08	17 (17)	4.03 ± 0.66	41.70	3.24 ± 0.54
	X2832	3.00	24	0.14 ± 0.01	2.56 ± 0.17	11 (12)	57.18 ± 7.78	22.80	21.13 ± 2.99
Farnley Haugh	X2734	2.00	12	0.16 ± 0.01	2.45 ± 0.01	17 (17)	28.80 ± 2.96	20.40	12.96 ± 1.44

Table 1. Summary of new optically stimulated luminescence (OSL) estimated ages and associated information for five samples from Fourstones (south Tyne) and one sample from Farnley Haugh (Tyne). The table includes the total number of aliquots measured with OSL that passed the acceptance criteria and the overdispersion of the resulting dose distribution. Measurements were made on dried, homogenized and powdered material by ICP-MS/AES with an assigned systematic uncertainty of ±5 %. Dry beta dose rates calculated from these activities were adjusted for the field water content and dose rate and age calculations were obtained using DRAC ver1.2 (Durcan et al., 2015). ∗ The recorded moisture contents (values in brackets) are not considered to be representative of the mean water content of the sediment during the burial period as a result of recent (<20 years) bank migration and/or quarrying activity. The dose rate calculations are based on more realistic saturation estimates with an associated error of ±5 %. + OSL measurements were made with an automated TL/DA-15 Risø luminescence reader (Bøtter-Jensen, 1997; Bøtter-Jensen et al., 2000) and conducted on 180–250 µm or 90-125 µm diameter quartz grains mounted as multigrain aliquots (n = 12–17). The equivalent dose (De) was obtained using a single-aliquot regeneration (SAR) measurement protocol (Murray and Wintle, 2000; Wintle and Murray, 2006) and was based on a minimum age model after Galbraith et al. (1999). ++ The age datum refers to AD 2007 when the samples were measured and the luminescence

dates. The total uncertainty (1σ), calculated as the quadratic sum of the random and systematic errors, includes all measurement uncertainties as well as a relative error of 2 % to account for possible bias in the calibration of the laboratory beta source.

4. Results

4.1. Fluvial geomorphology

Across the three zones (Fig. 1) of the mid-Tyne valley, the geomorphology and longitudinal height-range relationships reveal nine fluvial terraces that lie between 20 and 2 m above present river level (T1 – T9; highest to lowest) and the modern floodplain (Fig. 2, Fig. 3). T1, broadly 20 m above the modern river, comprises fragmented surfaces that lie along the valley margins of the South Tyne system. However, within zone III the surfaces are laterally extensive (Fig. 2c) and show some continuity with extensive glaci-fluvial/−lacustrine desposits (Yorke, 2008) in terms of extent, however, they are inset ∼10 m below the glacigenic surfaces. T2 lies at 15 m above modern river level and is restricted to isolated fragments located towards the outer margins of the valley, with greater lateral extent in the South Tyne upstream of Newbrough Gorge (zone I). It is present most extensively around the confluence of the North and South Tyne (zone II), and forms a component of an alluvial fan at Dilston (Fig. 2c). T3, 14 m above modern river level, is laterally extensive in zone I along the South Tyne above Newbrough Gorge (Fig. 2a), and restricted to isolated fragments in zones II-III downstream of Newbrough Gorge, and in the area around the town of Corbridge, hereafter referred to as the Corbridge Basin (Fig. 2b). This upper group of terraces lack any surface palaeochannel topography and are altitudinally separated by 8 m from the lower terraces T5 – T9. Their elevated, fragmentary and valley margin nature reflects that they are terrace remnants preserved in less active sectors of the former floodplain, with removal from the main channel belt during subsequent fluvial erosion and basal incision that generated terraces T4 – T9.

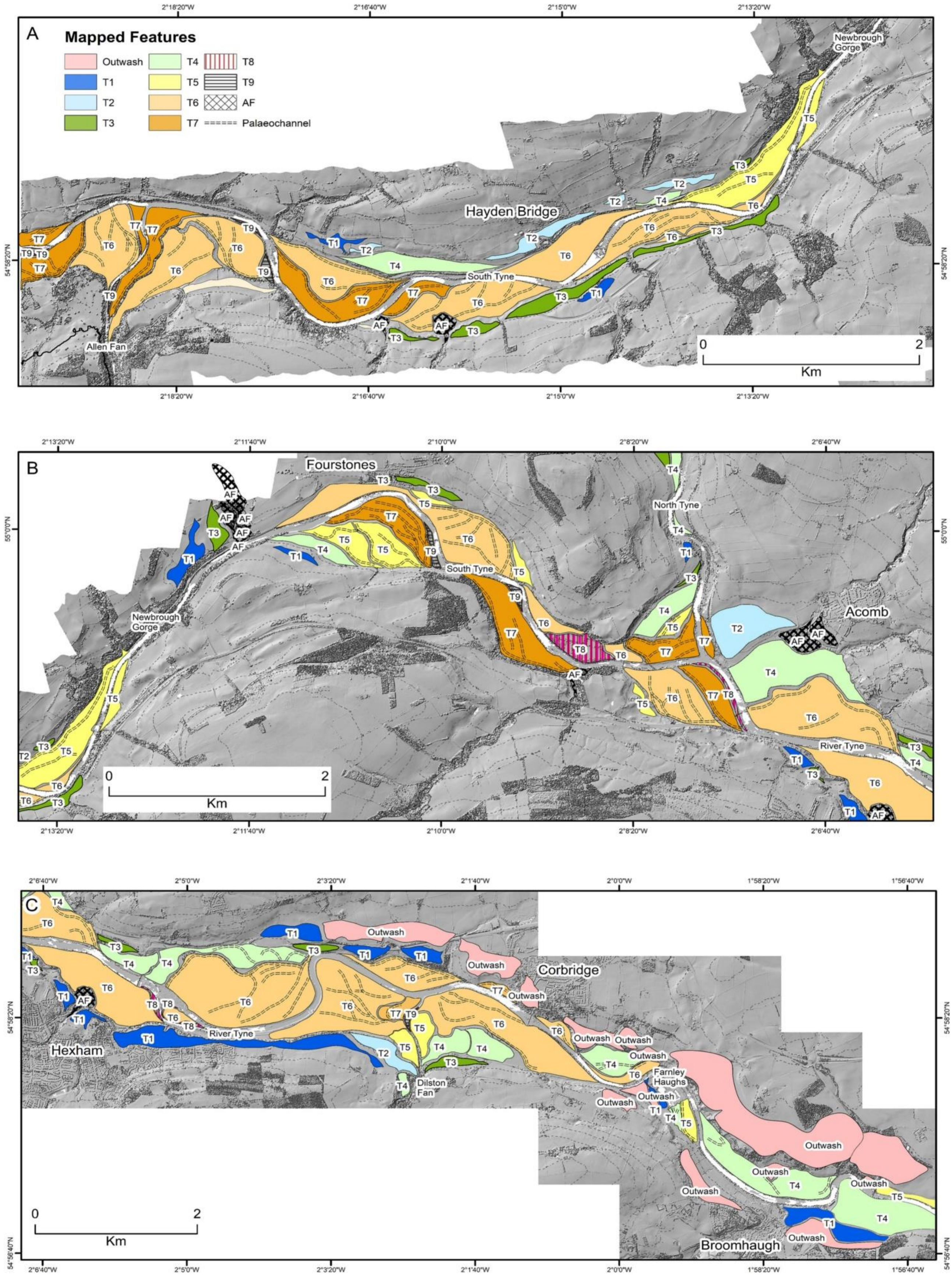

Fig. 2. Geomorphic map of the mid-Tyne valley, showing river terraces, palaeochannels (demarcated by double hashed lines) and alluvial fans, overlain on 1 m resolution LiDAR data and displayed as hillshade layers (© Environment Agency copyright (2023). All rights reserved). Key sites and localities are shown; (A) zone I, (B) zone II, and (C) zone III.

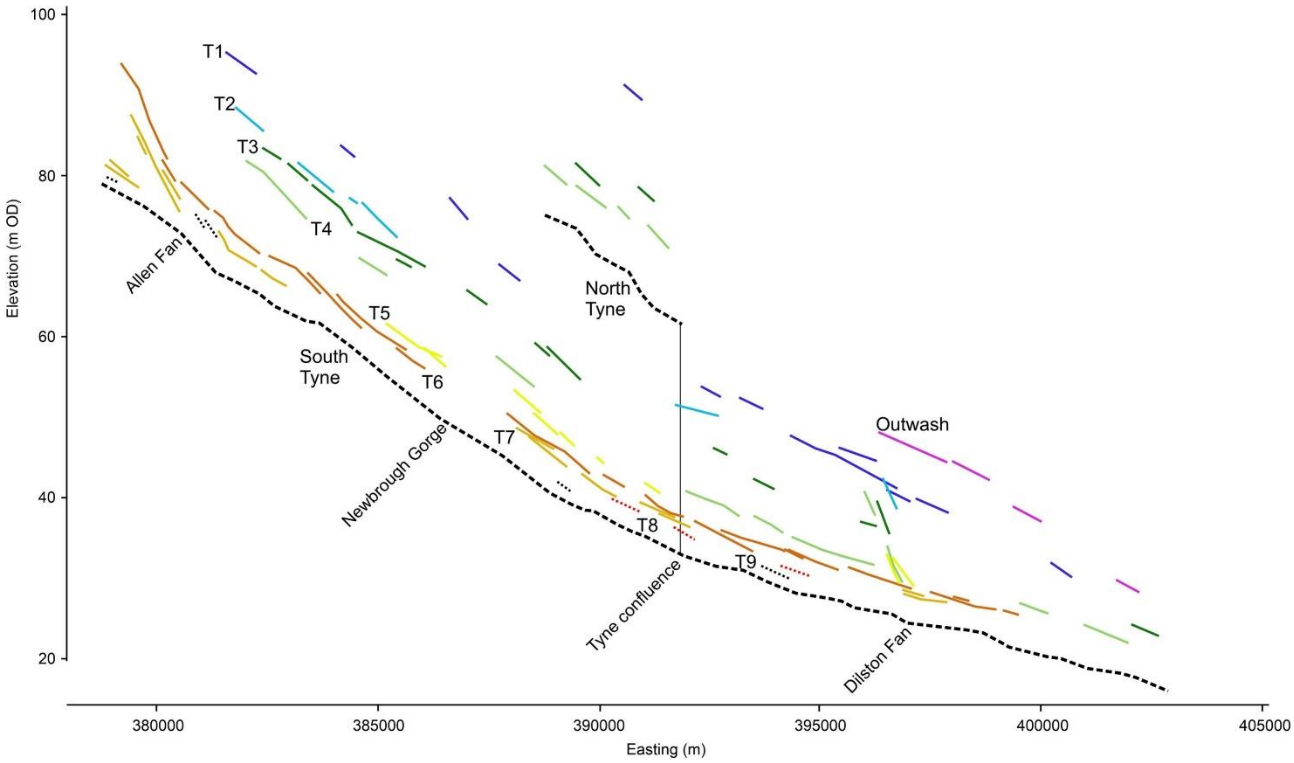

Fig. 3. LiDAR (© Environment Agency copyright (2023). All rights reserved) derived height range diagram for the Rivers South Tyne, North Tyne and Tyne in metres above UK Ordnance Datum (OD). Contemporary river long profiles are indicated by the dashed black lines. Differentiated river terraces are labelled T1 to T9 respectively and colour coded as follows: T1 dark blue; T2 light blue; T3 dark green; T4 light green; T5 yellow; T6 orange; T7 dark orange; T8 dashed pink; T9 dotted black lines respectively. Outwash represents the glacigenic terrace sequences (pink line).

T4, at 9 m above current river level, occurs throughout zones I to III, but is most extensive in zone III, the Corbridge Basin. The terrace long profile shows a reduction in gradient downstream from 0.05 to 0.01, and lies closer in elevation to the present river downstream (9 to 6 m above river level). Several sinuous (sinuosity index 1.3) palaeochannels are visible on T4 (zone III), indicating a meandering system and suggesting some lateral stability of channel systems. T5 lies 6 m above the base of the modern river and has limited presence throughout the study area. T5 grades into the Newbrough Gorge. Numerous surficial palaeochannels are evident on this terrace, and their planform sinuosity is almost straight (sinuosity index <1.05). The channels show evidence of progressive lateral change through avulsion and chute cutoffs. T6 lies 5 m above the bed of the present river and is present in all zones, I – III. T6 extensively occupies the meander bend within zone III. Surficial palaeochannels are ubiquitous on this terrace, and whilst sinuosity is straight to low (sinuosity index <1.05–1.03), in zones II – III channel planforms indicate bar progradation and downstream translation of the meander bend. Migration within these palaeochannels is similar to the development of the present-day meanders. T7 is only present in zones I – II, lies 4 m above the modern river and is sculpted with extensive palaeochannels. Their morphology reflects a low-sinuosity (sinuosity index 1.06–1.30) planform, with lateral valley-floor channel migration through avulsion and chute cut-offs.

T8 and T9 are the least extensive terraces recorded in the main Tyne valley. T8 lies 3 m above the base of the modern river, and is present in zone II immediately upstream and downstream of the Tyne confluence. T9 lies 2 m above the present river, occurs as discrete deposits along the inner banks of the meanders in zone I (Allen Fan), and in zone III associated with the Dilston Fan (zone III). Both T8 and T9 reflect the most recent depositional activity of the river.

The South Tyne valley-floor (zones I–II), through to the confluence, is dominated by T6 and T7, bounded by the higher T1 to T4. T6 and T7 form a significant sediment depocenter (sensu Chiverrell et al., 2010) in the South Tyne accounting for >90 % of the valley floor. Zone III continues to be dominated by T6, accounting for >80 % of the valley floor and represents another significant depocentre. Zone II forms a division, separating the higher T5 of the South Tyne system from the lower T6 and T7 of the River Tyne. The narrow Newbrough Gorge, South Tyne, with its lack of valley floor provides a natural break in the terrace sequence.

Alluvial fans have formed at the mouths of a number of small tributaries but two significant fans are found at confluences of the River Allen (zone I) and Devil's Water (Dilston Fan, zone III). The Allen Fan terrace sequence comprises T6 and T7 and is coherent with the terraces in the South Tyne, and suggests a younger development of this fan. The Dilston Fan terrace sequence comprises an older sequence of terraces, with T1 to T5 present, with T5 grading into the valley-floor sequence. The Dilston Fan represents a long history of formation that corresponds with the Lateglacial and Holocene fluvial development of the Tyne fluvial terraces.

4.2. Sediments and geochronology

Exposure of the fluvial succession adjacent to the modern channel is restricted to cut-bank exposures at Fourstones (Zone II) and Farnley Haugh (Zone III) which reveal detail on the stratigraphy of T1, 4, 5 and 7. Borehole logs (from the BGS archive) provided additional sub-surface stratigraphy for T1, 6 and 7.

4.2.1. The A69 (Zone II) and A68 (Zone III) borehole series

Borehole logs from the construction of the A69 (near Hexham) and A68 roads (near Broomhaugh) show the sediment stratigraphy (Fig. 4a,b) extending to bedrock revealing a significant infill of basal sediments in the Tyne valley (Fig. 5a,b). The profile indicates incision into bedrock to ∼10 m OD and the undulations in the bedrock surface reflect a former channel position. This channel is offset from the current day river, and has a channel base falling from 0 m OD below zone II to −30 m OD near the estuary (Cumming, 1971, Cumming, 1977). The incision of the bedrock valley probably reflects some glacial deepening by ice draining the Tyne Gap and North Tyne Valley, and/or earlier fluvial incision under lower eustatic sea levels (Cox, 1983; Mills and Holliday, 1998). The channel forms a palaeovalley to the north of the present-day river. The valley sediment fill comprises basal over-consolidated diamicts ∼5 m thick. Moving downstream the palaeovalley (Fig. 6) the glacial diamicton thickens towards the valley centre (∼15 m thick), and is overlain by pro-glacial sands and sandy gravels of varying from 10 to >15 m in thickness (Fig. 5, Fig. 6). This sequence records the presence of ice in the region, and the subsequent ice retreat with the development of the pro-glacial drainage system (Yorke et al., 2012; Livingstone et al., 2012). The basal sediments represent >20 m of aggradation and were likely deposited between 30 and 15 ka BP (Livingstone et al., 2015). The upper bounding surface of these glacigenic sediments forms a base to the overlying post-glacial fluvial succession.

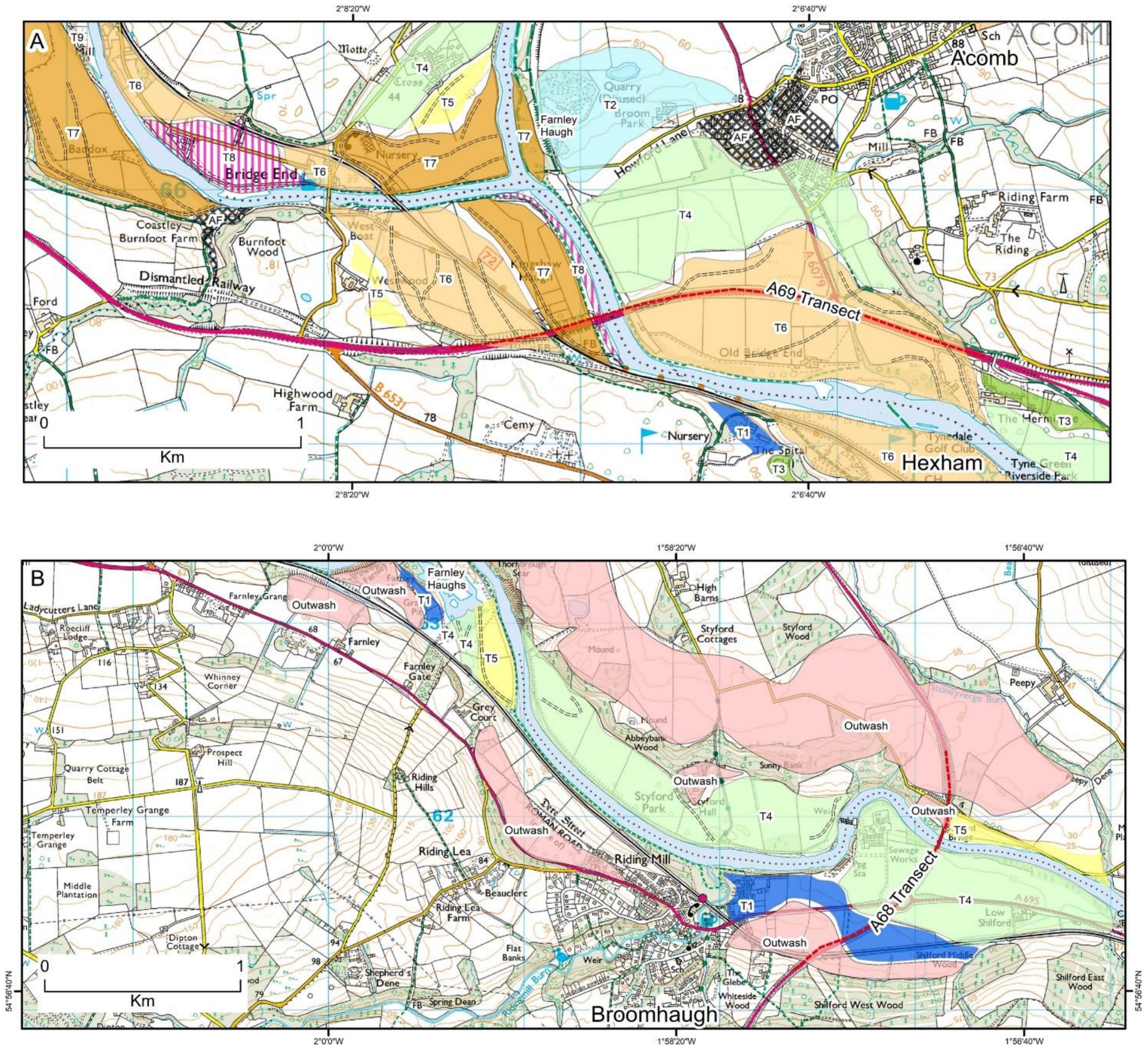

Fig. 4. Location of (A) the A69 (road) and (B) the A68 (road) borehole transects, overlain on an Ordnance Survey 1: 25000 Scale Colour Raster (© Crown copyright and database rights 2023 Ordnance Survey). Showing mapped river terraces, palaeochannels and alluvial fans. AF, alluvial fan, T1–8, differentiated river terraces, refer to legend in Fig. 2.

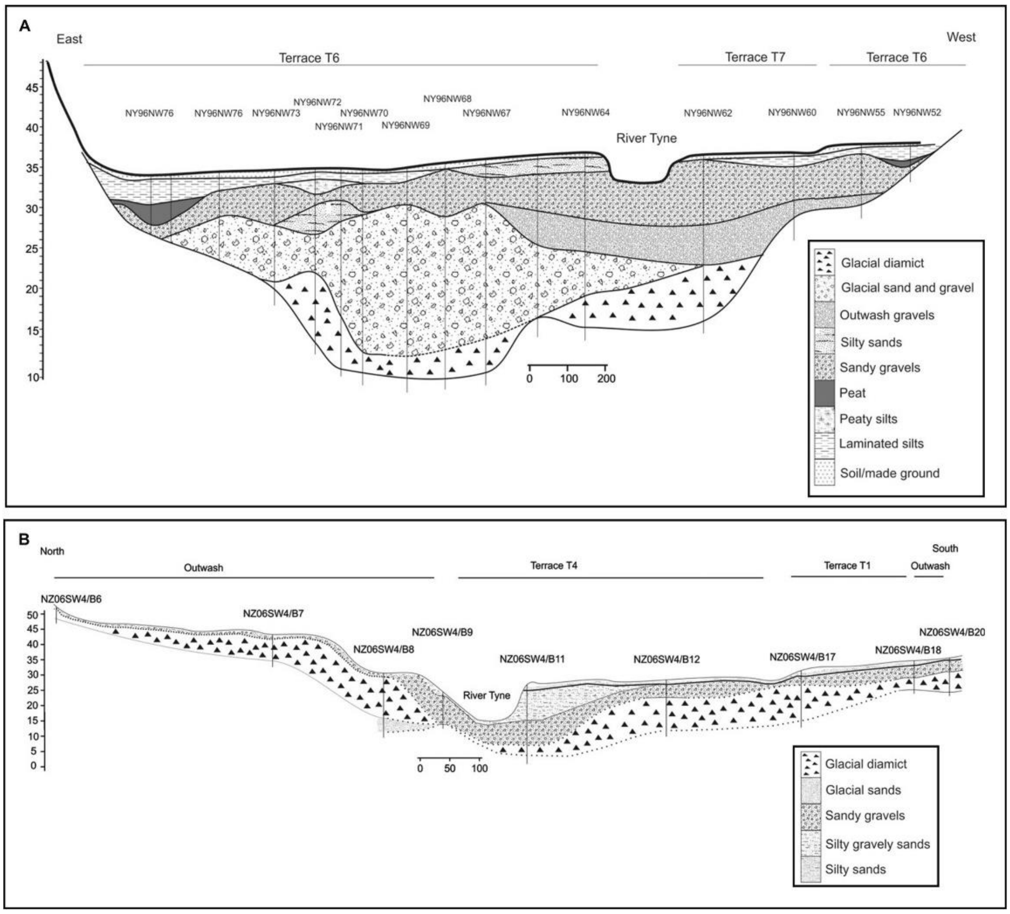

Fig. 5. Detailed stratigraphic and lithofacies assemblages derived from borehole data within zones II and III. (A) the A69 (road) transect, and (B) the A68 (road) transect. Valley-floor transect locations are shown in Fig. 4. Based upon GeoIndex (onshore) Borehole records, with the permission of the British Geological Survey. Individual borehole records demarcated by codes beginning with NY and NZ, with locations indicated by vertical black lines.

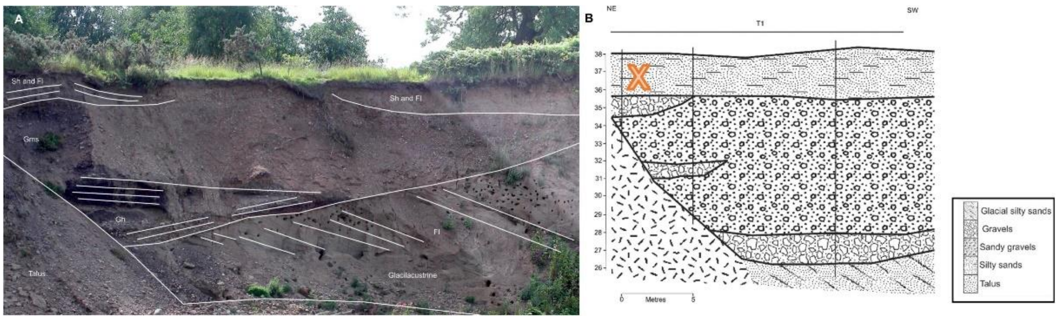

Fig. 6. Farnley Haugh. (A) T1 alluvium exposed in the cut-bank on the true right-hand side of the valley. (B) Detailed stratigraphic and lithofacies assemblage based upon interpolation of field-gathered vertical profile logs (locations indicated by vertical black lines). The 'X' indicates the sampling location for optically stimulated luminescence dating; lab code X2734. Estimated ages and age ranges are compiled in Table 1.

The A68 borehole series crosses the valley-floor, revealing the composition of T1 and T4 (Figs. 4b, 5b). T4 shows incision to a diamict surface, and subsequent aggradation of ∼6 m of sandy gravels, overlain by ∼10 m of silty, gravelly sands and capped by 1–2 m of silty sands. The sedimentary sequence and palaeochannels visible on the surface of T4 suggest a meandering fluvial system. The A69 borehole series crosses both T6 and T7 (Figs. 4a, 5a) recording for T6 a basal post-glacial unit of ∼7 m thick sandy gravels, with occasional silty sands. Towards the outer margins of the valley within T6 there are three discrete units cut into the sandy gravels. These units comprise a channel fill of <2 m laminated peat and peaty silt, and the whole sequence is buried by 4 m of laminated silts. Well-developed meanders and scroll-bar forms on T6 downstream of Newbrough Gorge (zone II) identify lateral migration of the channel reflecting increased sediment mobility and stream power. Meandering and migration of scroll-bars has led to development of ‘peaty’ back-channel swamp environments with channel migration (Hooke, 2003, Hooke, 2004; van de Lageweg et al., 2014). For T7, ~7 m of sandy gravels overlie the diamict, capped by ~1 m of laminated silty sands. Both the T6 and T7 sequences suggest a transition from a high-energy channel to a low-energy system. The sandy gravels reflect bedload deposition within the main channel, with the silty sands indicative of overbank deposition. The silty sands of T7 exposed at Fourstones and were targeted for OSL dating (X2733) to constrain the meandering and scroll-bar progradation associated with T6 – T7.

4.2.2. Exposures at Farnley Haughs

Near Farnley Haughs (zone III) a 20 m long erosion scar (Fig. 6a) exposes the sediments comprising T1. Thinly laminated, very fine basal sands are interpreted as subaqueous glacio-fluvial sediments (Yorke et al., 2012). High elevation valley-side glacial outwash terraces reflect a proglacial drainage system entering Glacial Lake Wear, dammed by the NSL to the east (Smith, 1994; Yorke et al., 2012; Davies et al., 2019). This unit is overlain unconformably by ~4 m of fluvial sediments comprising rounded cobbles, forming a concave channel lag deposit at the base of the post-glacial sequence. Above the channel lag are rounded, clast- to matrix-supported gravels (predominantly Carboniferous sandstones and greywacke, and igneous clasts inc. Shap granite originating from the Lake District), which reflect vertical accretion as longitudinal bars, with initial aggradation in low water from tractional processes and small-scale structures superimposed on the larger bedforms during waning flow (Miall, 1996; Bridge, 2009; Rice et al., 2009). The longitudinal bars are intercalated with coarse sandy gravel, pebbly sands and silty sands, which indicates fluctuating flows (Smith et al., 2009; Rice and Church, 2010) (Fig. 6b). Laminated fine sands (2 m thickness), indicative of overbank deposition, cap the sequence and are typical of floodplains adjacent to shallow, wandering gravel-bed river (Miall, 1996). The upper sands were sampled for OSL dating (X2734; Fig. 6b) to constrain late-stage aggradation of T1 and provide a younger than constraint on the incision to T2.

4.2.3. Exposures at Fourstones

T4 and T5 were examined through a cut-bank section that exposes 0.5 km of sediments, opposite the town of Fourstones (zone II) (Fig. 7a). For T4, the section reveals a basal till (which forms the stream bed), overlain by ~4 m of well-rounded, weakly horizontal-stratified to structureless cobble- and boulder-rich gravels (a-axis up to 120 cm) that are indurated with iron-manganese coatings and imbrication is well developed. Clasts within T4 are predominantly volcanic and igneous in origin (81 %), with fewer Carboniferous sandstones, limestones and mudstones (19 %). This matches the clast lithologies recorded within the till (predominantly Lake District volcanic and igneous clasts – dolerite, quartzite and granite, with subordinate amounts of Carboniferous sedimentary clasts), indicating that the river reworked earlier sequences. A chute channel truncates the gravel at the downstream end of T4, and is infilled with cross-stratified to massive cobble- and pebble-sized sandy gravel, indicative of high relief bar edges, overlain by laminated sands. Chronological control for T4 was obtained from the laminated sands (X2730) (Fig. 7b). The stratified gravels represent bedload, with sorting, imbrication and iron-coatings all indicate transport and deposition in shallow water/fluctuating water levels. The presence of large boulders, structureless gravels, chute channel and bar deposits in the upper 2 m suggests higher-magnitude flows (Desloges and Church, 1987; Smith, 1990; Brierley and Hickin, 1991). The sequence is interpreted as a wandering gravel-bed system (Miall, 1996), with periods of lateral channel instability during extreme flow events (Wooldridge and Hickin, 2005).

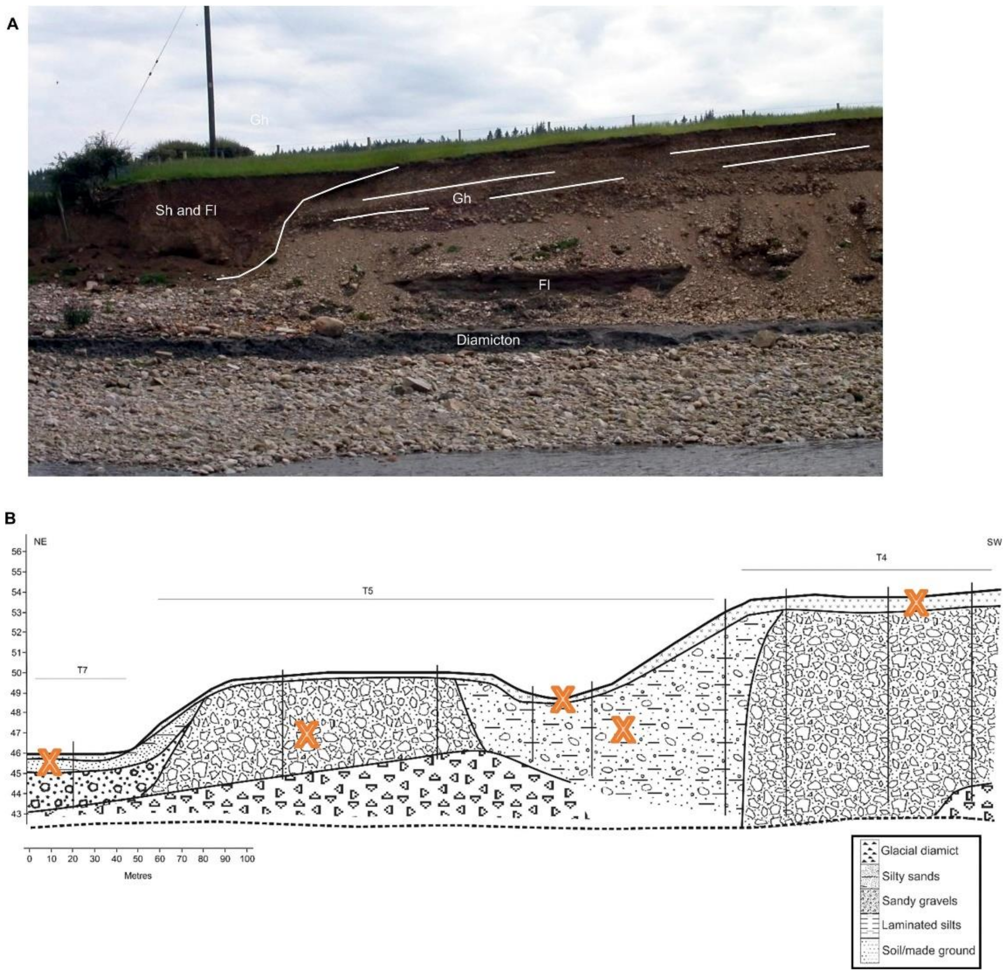

Fig. 7. Fourstones. (A) T5 and T7 alluvium exposed on the true right-hand side of the valley. (B) Detailed stratigraphic and lithofacies assesemblages based upon interpolation of field-gathered vertical profile logs (locations indicated by vertical black lines). The 'X' indicates the sampling locations for Optically Stimulated Luminescence dating; lab. Codes X2733 (T7), X2832, X2732, X2731 (T5), and X2730 (T4). Estimated ages and age ranges are compiled in Table 1.

For T5, the sequence displayed extensive exposure of the basal lodgement till (∼2 m). The fluvial sediments of T5 appear to reflect a large remnant palaeochannel, channel bed deposits and occasional infilled chute channels. The palaeochannel sediments form the boundary between T4 and 5, comprising ∼4 m of laminated to massive sands, overlain by a silty sandy clay, with intercalated sandy gravel layers (Fig. 7b). The sands were sampled for OSL dating (X2731; X2732). The basal sands probably formed under upper flow regime conditions (Smith, 1990; Tucker, 2011), with the overlying sandy clays and intercalated gravels suggesting slower flows with occasional fluctuations in stream competence (Miall, 1996; Bridge, 2009). The sands grade (downstream) into a sequence of horizontally bedded gravel, with intercalated sands (∼6 m thick), capped by laminated sands (∼1 m thick). The gravels comprised 47 % volcanic and igneous clasts, with 52 % Carboniferous sandstones and mudstones, and sub-ordinate amounts of coal. The gravel geometry suggests development of longitudinal bars in shallow water, (Whiting et al., 1988; Miall, 1996). Periods of lateral instability and high-energy flows are indicated by the multi-storey layers of inversely graded clast- to matrix-supported cobble- and pebble-sized gravel, and thinly laminated sands, cut into the sands. Within the gravels, chute channels are infilled with laminated silty clays and suggest channel migration and abandonment, with deposition under slack water conditions (Smith, 1990; Miall, 1996). The silty clays provided an opportunity for OSL dating T5 (X2832). The sequence represents the main channel belt, with deposition towards the outer margins of the valley floor, and is typical of a wandering gravel bed system (Miall, 1996).

4.3. Geochronology and fluvial sequence

The new geochronological control obtained for T1, 4, 5 and 7 of the Tyne sequence, alongside two existing 14C ages of 5900 ± 70 cal. BP (BETA-37060) for T5 (tree trunk in basal gravels) at Farnley Haughs (Passmore and Macklin, 1994) and 3030 ± 60 cal. BP (BETA-45549) for T7 (wood fragments within a basal channel incised into till) at Lambley (Fig. 1, ∼13 km upstream of the Allen confluence; Passmore and Macklin, 2000) provide a basis for exploring the landform sequence. We discounted Passmore and Macklin's (1994) OSL age of 2.45 ± 3.5 ka obtained from T5 (upper sequence channel fill sandy silts) at Farnley Haughs on the basis that it was obtained 30 years ago. Significant improvements in techniques and instrumentation in the last 20 years have occurred and it was not until post-1999 that OSL dating protocols became more reliable (Wintle, 2008; Mahan et al., 2023). We have employed an approach, using OxCal (Ramsey, 2001), that facilitates statistical testing of these theoretical models of the likely relative order of events in the Tyne geomorphology (Chiverrell et al., 2009b). Bayesian assessment using OxCal of these relative order models (Bronk Ramsey, 2008) helps with identification (Fig. 8) of anomalous ages that are nonconformable and/or out of sequence (Buck et al., 1996; Chiverrell et al., 2009b). The objective with the dating was to constrain the timing of switches between river terrace levels, but these are rarely dated directly, typically sitting as erosion episodes between landforms and derived ages. The Bayesian models were coded in OxCal v4.4.4 Bronk Ramsey (2021) and using the INTCAL20 atmospheric data from Reimer et al. (2020) as a Sequence model. The Prior models in Bayesian nomenclature are structured as a series of Phases, which are unordered groups of events/parameters that contain age information e.g. the differing individual river terraces. Boundaries, in the OxCal nomenclature, use the relationships between dated individual samples or Phases to generate estimated age probability ranges for undated events (e.g., T1 to T4 Boundary in Fig. 7). The Tyne model (Fig. 8) has an overall agreement index of 90 % exceeding the >60 % threshold advocated by Bronk Ramsey (2009). This level of agreement was achieved by handling three OSL ages as 100 % outliers as detailed below.

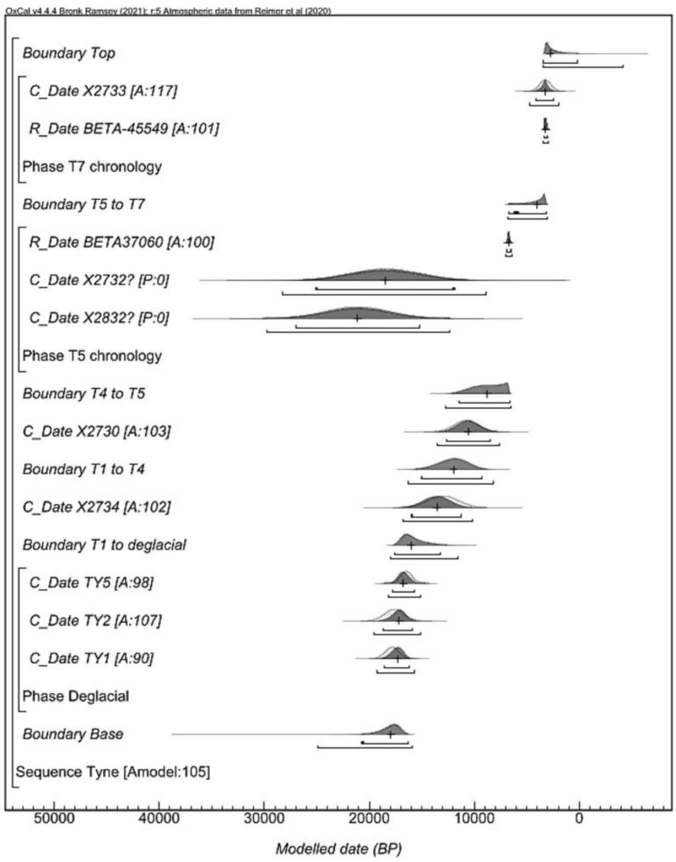

Fig. 8. Bayesian model of the dating of the Tyne terrace sequence, based on the new optically stimulated luminescence (OSL) ages obtained by this study, alongside a published 14C age (BETA-37060; Passmore and Macklin, 1994) and published cosmogenic ages (from boulder for deglaciation of the Tyne Gap Ice Stream (TGIS; Livingstone et al., 2015). The model structure shown used OxCal brackets (left) and key words define the relative order of events (Bronk Ramsey, 2009). Modelled age in ka BP on the x-axis. Each distribution (light grey) represents the relative probability of each

age estimate with posterior density estimate (solid) generated by the modelling. Outliers are indicated by '?' and their probability (P) of being an outlier denoted by low values <5 (95 % confidence); X2730 not shown as the date is beyond the modelled scale. Model agreement indices (A) for each age shows their fit to model, with >60 % the advocated threshold by Bronk Ramsey (2009).

OSL ages obtained from overbank sands at Fourstones (zone II) and Farnley (zone III) (Table 1) alongside the published 14C age (tree trunk within basal gravels of our T4; Passmore and Macklin, 1994) help to establish an outline geochronological framework for the Tyne terraces. The uppermost alluvial sediments of T1 (Farnley) provided an OSL age (X2734) of 12.9 ± 1 ka (Fig. 9a). T2 and T3 remained undated, but the top of the T4 (Fourstones) sequence yielded an OSL age (X2730) of 10.7 ± 1.1 ka (Fig. 9b). Samples from T5 (X2731; X2732; X2832) returned OSL ages suggestive of poor resetting of the OSL signal and were regarded on that basis as too old. The uppermost sediments of T7 (Fourstones) yielded an OSL age (X2733) of 3.2 ± 0.5 ka (Fig. 9c). Though not dated here historic map data suggest that T8 and T9 relate to the last 300 years. The OSL ages obtained suggest the major terraces developed during the Lateglacial to mid-Holocene period. The Bayesian modelling has calculated modelled age probability distributions for the evolution of the Tyne terraces, constraining the T1 / Deglacial transition to 16.0 ± 2.1 ka, the progression from T1 to T4 to 11.9 ± 2.7 ka, T4 to T5 to 8.7 ± 2.3 ka, and T5 to T7 4.0 ± 1.8 ka.

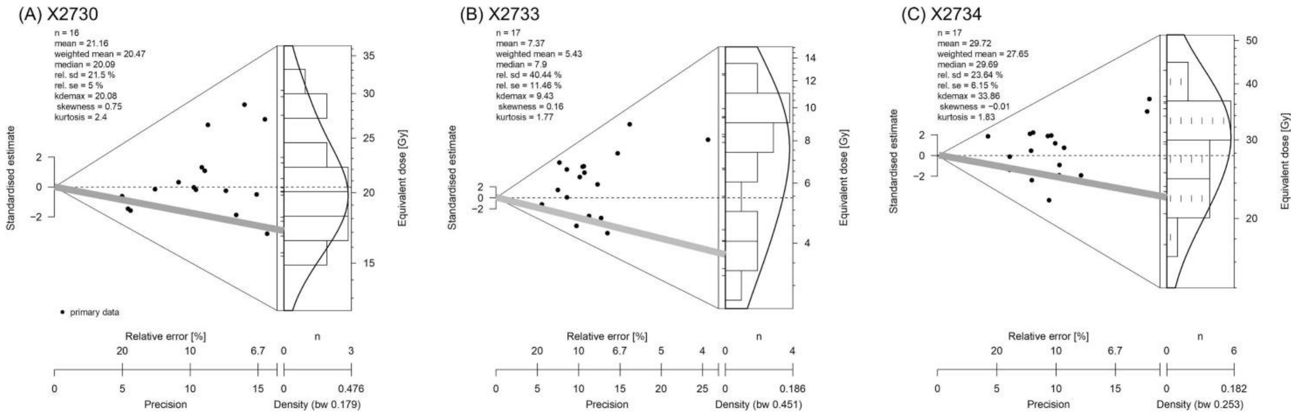

Fig. 9. Abanico plots of the individual aliquot equivalent does (De) values determined for optically stimulated luminescence dating. Plots shown are for samples taken at (A) Fourstones X2730 (T4) and (B) Fourstones X2733 (T7), and at (C) Farnley Haugh X2734 (T1). The plots comprise two parts (i) a bivariate plot, showing standardised estimates of De values in relation to precision (x-axis), and (ii) a univariate plot, showing the age frequency distribution of De values but this does not give any indication of precision. Both plots are linked by the z-axis of the De values. Data points (or primary data) are indicated by the black dots. Age estimates for the samples shown were determined using the MAM De; the black line across the plots represents the MAM De value for that sample. The abanico plots enable assessment of the data precision and the characteristics of the age distribution; samples with a greater range of De values on the x-axis have a larger scatter in the De distribution. Samples that are well bleached before burial typically have more symmetrical De distributions.

5. Discussion

5.1. Late MIS 2 to GI-1

In northern Britain, landscape development with deglaciation responded to the progressive retreat of the TGIS, with regional ice retreat models indicating that the Tyne valley deglaciated before 16.4–15.7 ka during a regional collapse of ice dispersal centres. As changes to ice drainage routeways developed with deglaciation more local topographical control of ice became dominant (Hughes et al., 2014; Livingstone et al., 2015; Davies et al., 2019). An extensive proglacial drainage network developed in the Tyne draining towards Glacial Lake Wear (Yorke et al., 2012), which formed between 17.0 and 16.5 ka as the NSL extended across the lowlands impounding glacial meltwaters (Smith, 1994; Bateman et al., 2011; Davies et al., 2019). Ice marginal glaciofluvial and glaciolacustrine sediments aggraded against the retreating and decaying Tyne Gap Ice Stream, forming a series of valley side outwash terraces (Peel, 1941; Mills and Holliday, 1998; Yorke, 2008; Livingstone et al., 2015). The highest outwash deposits lie at between 30 and 40 m above the base of the present river, and likely aggraded during the period 16.0 ± 2.1 ka.

The earliest of the Tyne fluvial terraces (T1) are inset 10 m below the lowest outwash surface. An OSL age (X2734) obtained from the overbank sands of T1 dates indicates fluvial aggradation up to 12.9 ± 1 ka and implies the river was active during the Interstadial (GI-1). T1 comprises coarse gravels, intercalated with sandy layers and capped by fine silty sands, typical of channel and bar features and material deposited from overbank flows. The fluvial system is considered to be meandering, with episodic flooding events and intermittent fluvial-lacustrine conditions (Gibbard and Lewin, 2002), possibly developing during the earliest phase (GI-1e/d) before the landscape stabilised and vegetation cover (i.e. Betula, Juniperus) became established (Innes et al., 2021). The upper part of the unit represents repeated overbank deposition and suggests the channel had already begun to incise or laterally migrate during the latter stages of the Interstadial, with this area of active channel replaced by floodplain aggradation (Vandenberghe, 2015).

5.2. GS-1 to early Holocene

Between the onset of GS-1 and the early Holocene, the OSL ages obtained from T1 and T4 (12.9 ± 1 ka and 10.7 ± 1 ka) imply cycles of fluvial incision and aggradation characterised the transitional phase of the Lateglacial period. The event boundary creates a timeframe of 13.3 to 10.4 ka for the development of this upper group of terraces. Cooling at the transition between GI-1a and GS-1 signified a return to cold stage conditions (Bakke et al., 2009). The partially wooded conditions established during GI-1 were impacted by the periglacial conditions, with open woodland and shrub-heath replaced by sedge-tundra open herbaceous vegetation (Innes, 1999; Innes et al., 2021).

The absence of accessible sediments prevents an interpretation of T2 and T3, however, T2 represents incision and aggradation after 12.9 ka. If we assume they are cut and fill rather than erosional terraces (Lewin and Macklin, 2003 suggest renewed aggradation during GI-1) then their development can be linked to hydrological and landscape change during GI-1. We infer that geomorphic activity was strongly conditioned by periglacial slope processes and paraglacial adjustment during GI-1 (Chiverrell et al., 2007; Passmore and Waddington, 2009; Ballantyne, 2019; Harrison et al., 2021), driven by nival flow and spring flood runoff, creating a sediment-dominated fluvial system. T4 returned an OSL age of 10.7 ± 1 ka (X2730; obtained from the upper sands) implying aggradation during the earliest Holocene and that incision or channel abandonment had probably already occurred as overbank sedimentation had begun. If we assume that sediment exhaustion has not occurred by the early Holocene, and with shifts to cooler, wetter conditions at 11.2, 11.4 and 10.8 ka cal. BP (Barber et al., 2003; Mayewski et al., 2004; Lang et al., 2010; Vincent et al., 2011) recorded in terrestrial, lacustrine and bog surface wetness (BSW) records, it is easy to envisage a situation where paraglacial adjustment remained dominant (Ballantyne, 2005, Ballantyne, 2019) and a sediment-dominated fluvial system persisted. The presence of this higher group of terraces (T1-T4) and the Dilston fan (Zone I) suggests the period was dynamic and unstable and that cycles of incision and aggradation during the GS-1 continued into early Holocene period. Comparable responses are evident from the landform sequences of river systems in north Northumberland, the Southern Uplands, central Scotland and the Highlands (Tipping et al., 2008; Passmore and Waddington, 2009; Ballantyne, 2019; Werritty, 2021).

5.3. Early to mid-Holocene

Early to mid-Holocene fluvial development is reflected in a single incision and aggradation cycle, leading to the development of T4 and T5. The incision of T4 occurred after 10.7 ± 1 ka (X2730). Although OSL ages were obtained for T5 (X2731, X2732, X2832) the model identified these as outliers and were disregarded. The rationale for this was that the obtained OSL ages were too old and were most likely the result of poor resetting of the OSL signal. Thus, development of T4 and T5 is constrained to the period 8.7 ± 2.3 ka (probability-based time frame). Both T4 and T5 have low sinuosity to straight palaeochannels evident on their surfaces, and the sediments comprise lithofacies assemblages of crudely bedded, imbricated coarse sandy gravels, overlain by a veneer of silty sands. Channel fills within the sequence comprise poorly bedded sands, silty sands and silts, with occasional lenses of coarse boulders and inversely graded sands, thought to represent flooding events. The sediments of T4 and T5 are interpreted as channel bed and bar deposits, channel fills and overbank sedimentation. T4 sequences suggest low aggradation rates and laterally stable channels during the early Holocene, whereas T5 comprises some vertically stacked sequences suggesting periods of instability as we moved towards the mid-Holocene. The early to mid-Holocene landscape was one of increasing stability and soil development, with regional vegetation records indicating that open grasslands and shrubs were replaced by postglacial woodlands (Juniperus, Betula and Corylus) (Innes, 1999; Vincent et al., 2011; Ghilardi and O'Connell, 2013; Innes et al., 2021). Anthropogenic disturbances have been recorded in North Tyne pollen sequences (Moores, 1998) as early as 8.5 ka BP (late Mesolithic), which when combined with recorded cooler and wetter conditions at 8.6–8.2 and 7.8–7.4 ka cal. BP (Barber et al., 2003; Lang et al., 2010; Vincent et al., 2011) may explain the flooding deposits and lateral instability recorded as we move towards the mid-Holocene.

5.4. Mid to late Holocene

The mid- to Late Holocene fluvial development is reflected in the lower group of terraces, T5 to T7. An OSL age of 3.2 ± 0.5 ka (X2733) was obtained from overbank sands of T7, and development of T5 – T7 has been constrained to 4.0 ± 1.8 ka (probability-based time frame). T6 and T7 dominate zones II and III, however, only T6 is present in zone I and inset below the higher terrace group (T1-T4) and the outwash terraces. Palaeochannels on the surface of T6 indicate low to moderately sinuous channels suggesting development of a wandering-gravel bed system, however, there are several migratory meander bends, evidenced by scroll-bars, indicating channel instability. The sediments of T6 and T7 comprise basal sandy gravels that pass into silty sands and laminated silts. Significant peat-infilled channels and silty peats dominate the upper lithofacies assemblages. These suggest laterally migrating channels, and backwater zones are indicated by the burial of peat-filled channels and slough channels infilled with inverted stratigraphy towards the outer margins of T6. During this period, climatic instability is reflected in increased bog surface wetness (BSW) records at 6.2, 5.7, 5.4, 5.4, 4.4–4.0 ka cal. BP (Hughes et al., 2000; Barber et al., 2003; Charman et al., 2006). Additionally, regional vegetation records (Moores, 1998; Moores et al., 1999) indicate early anthropogenic disturbances in the North Tyne catchment, with significant human activity from the late Mesolithic through to the Neolithic (cf. Tolan-Smith, 1996; Passmore and Waddington, 2009). The landscape became largely tree-less, with cultivated pollen taxa and anthropogenic indicator species dominating, especially during the late Bronze Age to Romano-British period. It is easy to envisage periods of widespread fluvial activity driven by increased incidence of flooding, extreme events and channel abandonment in a landscape that was primed (sensitised) by human disturbances and with a paraglacial legacy (Ballantyne, 2005, Ballantyne, 2019) providing plentiful erodible sediments. The extent of T6 and T7 (Zones I-III), including the Allen fan (Zone III) reflect major fluvial activity within the catchment, with significant valley floor reworking and probable reincorporation of earlier fluvial deposits but it did not incise into its Lateglacial valley infill (Fig. 5, Fig. 6).

Passmore and Macklin (2000) present a radiocarbon date of 3.2 ka cal. BP (BETA-45549) for (our) T7, obtained from the South Tyne at Lambley (Fig. 1), however, Passmore and Macklin (1994) also present a radiocarbon date of 5.7 ka cal. BP for (our) T4 and an OSL age of 2.45 ± 3.5 ka for (our) T5, obtained from the Tyne at Farnley Haughs (though discounted for the Bayesian model due to reliability of OSL ages obtained using earlier dating protocols) that raises questions about our chronology. However, there is very little altitudinal separation between T5 and T7 (only 2 m), and the terrace long profile (Fig. 3) shows that the surfaces lie closer in elevation downstream and may reflect lateral variability evidenced by the switch to scroll-bars on the surface of T6, rather that significant incision. In addition, sediment deposition at Farnley Haughs occurs in a pinch-point in the valley, potentially allowing higher aggradation at this site compared to the open valley floor setting in the South Tyne at Lambley and Fourstones. Whilst significant improvements in dating protocols (both radiocarbon and OSL) have occurred in the last 30 years (Wintle, 2008; Mahan et al., 2023), we could be seeing a situation of pass-the-parcel sediment movement through depocentres (sensu Chiverrell et al., 2010) and a well-ordered younging progression downstream is not present. Using an example from the last 200 years, Passmore and Macklin (2000) have shown that in response to 18th Century metal mining-induced sedimentation and Little Ice Age (LIA) climatic instability the Tyne propagated sediment slugs (cf. Nicholas et al., 1995) through its system. The widespread lateral instability in the uplands was subsequently transmitted downstream in a time-transgressive manner.

The last 3 ka has seen periods of increased instability recorded in river systems throughout northern England (Foster et al., 2009; Chiverrell et al., 2010; Macklin et al., 2014). The results here suggest that there is limited later Holocene activity in the central reaches of the Tyne Valley. Although T8 and T9 are undated, they must be younger than 3.2 ± 0.5 ka based on the OSL age obtained from T7 (X2734). They constitute the least well-developed terraces in the sequence due to their limited extent along the central reaches. Comparable to those recorded in the South Tyne at Lambley (Passmore and Macklin, 2000), they most likely developed during the recent historic period. Early clearance of the Tyne catchment likely explains regional (northern England) variations in fluvial response during this period, driven by the relationship between land-use changes, climatic shifts and flooding episodes. Whilst incision (down to bedrock) is recorded in the tributaries of the South Tyne during last 1.2 ka (Macklin et al., 1992), it appears that there is a disconnect between the uplands (hillslope) and channel after the large depocentres (T6 – T7) developed, and subsequent periods of instability were reflected in lateral channel migration and reach instability, but not in further cut and fill episodes in the central reaches.

Naturally, the uplands with their connectivity to hillslopes and their fragility in terms of land cover would be more sensitive to external forcing. The response to such forcing is evident in the channel floor activity and incision seen in the upper reaches of the South and North Tyne rivers and their tributaries (Macklin et al., 1992; Moores et al., 1999; Passmore and Macklin, 2000; Macklin and Rumsby, 2007). The fluvial response in the uplands (South Tyne tributaries) has been much more dynamic and sensitive to climatic instabilities and anthropogenic activity (Macklin et al., 1992; Rumsby and Macklin, 1996) during the last 1 ka than that in the central zones in the Tyne Valley corridor, which have been relatively stable since the onset of the later Holocene period. This indicates that major sub-sections of the catchment are not synchronous. Therefore, the upper catchment can be assumed to be more sensitive to change, and that connectivity between the hillslope and the catchment is weaker in the piedmont zone. This suggests that catchment-wide response is diachronous, and it is apparent that the system is operating in discrete, reach-wide responses, such that correlating terraces throughout the whole system is not always possible.

6. Conclusion

This study aimed to reconstruct the alluvial record of the Tyne valley following deglaciation. Through a combination of geomorphological mapping and sedimentological investigations, combined with new OSL ages obtained from fluvial sands, we have been able to present a valley floor history that spans the period following retreat of the TGIS up to the recent historic period. The Tyne valley terrace sequence reveals significant alluvial response following deglaciation, resulting in a pattern of incision and valley refilling and leading to the presence of nine alluvial terraces lying between 20 and 2 m (T1 – T9) above present river level. New OSL ages obtained from T1 (12.9 ± 1 ka), T4 (10.7 ± 1 ka) and T7 (3.2 ± 0.5 ka), alongside probability-based modelling bracket terrace development to four phases (i) deglacial phase: 16.0 ± 2.1 ka; proglacial outwash terraces, (ii) Lateglacial phase: 11.9 ± 3.1 ka; high level alluvial terraces T1-T4, (iii) early to mid-Holocene phase: 8.7 ± 2.3 ka; alluvial terraces T4-T5, and (iv) mid- to late Holocene phase: 4.0 ± 1.8 ka; low level extensive alluvial terraces T5-T7. The later Holocene to recent historic period is reflected by the presence of T8 and T9.

Development of T1 to T4 was in response to climatic shifts (GI-1, GS-1, and early Holocene events), associated landscape instability and the legacy of glacial inheritance during GS-1 and early Holocene. This is in contrast with previous studies that suggested there was little/no activity during the early Holocene. However, we suggest this was, in part, due to a lack of dated sequences and the lack of high-resolution digital terrain (LiDAR) data to facilitate better identification. Significant fluvial activity is recorded during the mid- to late Holocene, with T6 and T7 representing a major period of landscape instability and reorganisation. These laterally extensive terraces comprise most of the valley floor sequence, and reflect a period of upland landscape stripping and redistribution driven by increased precipitation due to climatic instability, major anthropogenic disturbances, and a ready supply of easily erodible glacigenic sediments. Subsequent fluvial activity suggests reworking of earlier terraces, with recent historic activity (T8 and T9) confined to within these dominant terraces (T6 – T7).

The sedimentary sequence underlying the terraces indicates that incision following deglaciation did not incised through the glacial infill (in the mid-Tyne valley) and there is a clear boundary between those sediments and the Holocene fill. The sediments underlying the terraces reflect transition from a meandering system during the early postglacial phase to a dominant wandering-gravel bed system that persists today. This research highlights the importance of catchment-wide investigations and the need for rigorous dating controls. The Tyne valley terrace sequence reflects the importance of complex responses within the fluvial system, and demonstrates that localised responses can temper and impact the broader responses to external climatic drivers. The results are broadly similar to models of fluvial response in other upland UK (Chiverrell et al., 2010) and northern European systems (Vandenberghe, 2008, Vandenberghe, 2015) but highlights that the valley floor has been operating in a series of discrete reach-wide responses, and thus, correlation of terraces throughout the whole system is not always possible.

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