

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

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- 1 Lateglacial and early Holocene evolution of the Tyne Valley in response to climatic
- 2 shifts and possible paraglacial landscape legacies.
- 3
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11

12 Abstract

13 This paper presents new sedimentological, geomorphological, and optically stimulated

14 Iuminescence (OSL) geochronological evidence for fluvial evolution of the mid- to lower River

15 Tyne through the Lateglacial to late Holocene. These data reveal a series of fluvial terraces

16 produced by cycles of aggradation and incision, conditioned by glacial inheritance and driven by

17 changing sediment availability and hydrological regime. The distribution and stratigraphy (where

- 18 available) of nine river terrace and their associated sediments have been recorded. At two key
- 19 sites the sediments have been dated using OSL measurements to constrain the fluvial
- 20 geomorphology. Significant entrenchment of the fluvial system, followed by aggradation formed
- 21 the earliest fluvial terrace (T1), which encompasses environments spanning the transition from

22 deglaciation into Greenland Interstadial 1 (GI-1). Incision below T1 began towards the end of GI-

23 1, with three terraces (T2 – T4) between the abandonment of T1 and the early Holocene (15.0 –

- 24 9.2 ka). Climatic shifts, limited vegetation cover/soil development, and peri-/paraglacial landscape
- 25 instability conditioned the development of the early postglacial fluvial landsystem. Three further
- terraces (T5 T7) developed during the mid- to Late Holocene (6.6 3.1 ka), and comprise most
- 27 of the valley floor. Climatic instability, glacial inheritance, and widespread anthropogenic

28 disturbances are reflected in greater hillslope-channel coupling during this period. The extent of 29 later Holocene terraces (T8 – T9) is limited as the river became isolated from flanking hillslopes 30 entrenched between existing river terraces. Fluvial landscape evolution in formerly glaciated 31 catchments is strongly conditioned by the cold stage legacy that introduced excess sediment and 32 landscape instability into the catchment. Subsequent catchment-wide responses are variable and 33 non-linear, with valley floors operating in a series of reach-wide responses. There is a need for 34 greater chronological control to constrain the Lateglacial and Holocene evolution in the Tyne 35 catchment, but also to further our understanding of region-wide responses to external drivers and 36 local dynamics.

37

Abbreviations: BIIS, British-Irish Ice Steam; BSW, Bog Surface Wetness; CAM, Central Age
Model; DEM, Digital Elevation Model; GI, Greenland Interstadial; GI, Greenland Stadial; LGM,
Last Glacial Maximum; LiDAR, Light Detection and Ranging; MAM, Minimum Age Model; MIS,
Marine Isotope Stage; NSL, North Sea Lobe; OD, Ordnance Datum; OSL, Optically Stimulated
Luminescence; SAR, Single aliquot regeneration; TGIS, Tyne Gap Ice Stream; YDS, Younger
Drvas Stadial.

44

45 Keywords: Lateglacial; Fluvial development; Glacial legacy; Climatic shifts; Tyne valley
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48 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

56 channel migration. Additionally, local fluvial dynamics and discontinuities between and within 57 reaches can mute or amplify the response to external drivers (Chiverrell et al., 2010; Philips, 58 2010). However, compared to other European river systems, the timescales and responses of 59 British rivers, within the limits of the British-Irish Ice Sheet (BIIS; MIS 2), during the Lateglacial 60 and early Holocene are poorly constrained, especially in contrast to lowland systems that lay 61 beyond the BIIS (Collins et al., 2006; Gao et al., 2007; Lewin and Gibbard, 2010; Brown et al., 62 2013). Accurately dated fluvial landform sequences in the uplands and piedmont zones of 63 systems within the MIS 2 ice sheet limit are rare in the UK for this period (Macklin and Lewin, 64 1993; Macklin et al., 2014), making it difficult to explore potential relationships between fluvial 65 dynamics and forcing factors. Some important exceptions are available from northern Britain, 66 however. There are dated sequences from both the eastern and western Pennine rivers such as 67 the Wharfe (Howard et al., 2000a), Swale (Taylor et al., 2000) and Ure (Howard et al., 2000b; 68 Bridgland et al., 2011), Hodder and Ribble (Chiverrell et al., 2009a; Foster et al., 2009) and, in 69 Scotland the Kelvin, Feshie and Spey (Tipping et al., 2008; Ballantyne, 2019; Werritty, 2021).

70

71 Conceptual models of responses of fluvial systems through glacial-interglacial cycles in Northwest 72 Europe indicate channel instability and channel pattern change, followed by aggradation and 73 stability (Vandenberghe, 2008; Kaiser et al., 2012). In the UK, transitions from cold-to-warm have 74 typically been associated with channel incision and erosion, coupled with shifts from a braided 75 river system to a meandering river system (e.g. Maizels, 1982; Bridgland, 2000; Chiverrell et al., 76 2009a; Macklin et al., 2013). Short-lived climatic oscillations (warm-to-cold), such as the Bølling-77 Allerød to Younger Dryas, have been recorded as catchment instability and aggradational 78 episodes in lowland systems (Hill et al., 2008; Howard et al., 2011). The transition from the BIIS 79 (MIS 2) glacial land-system to post-glacial fluvial system encompassed the climatic changes in 80 the late glacial (GI-1 and GS-1) and the early Holocene climate events (Mayewski et al., 2004; 81 Lowe et al., 2008; Lang et al., 2010; Shakun and Carlson, 2010; Thornalley et al., 2009; 82 Rasmussen et al., 2014). The transition into the early Holocene in northern England was also 83 accompanied by base-level changes, linked to lower than present sea levels (Bradley et al., 2011;

84 Shennan et al., 2012) and glacio-isostatic uplift (Bridgland et al., 2010; Bridgland and Westaway, 85 2014). The fluvial system changed from glacial to nival-fed (snowmelt) discharge regimes to 86 temperate systems, and was marked by reductions in sediment availability reflecting both 87 exhaustion (cf. Church and Ryder, 1972) and landscape stabilisation with vegetation and soil 88 cover. Thus, a paraglacial landsystem conceptual model (cf. Ballantyne, 2005; Harrison et al., 89 2010) describes the post-glacial development of upland formerly glaciated catchments and 90 describes the evolution of sediment regimes inside the last glacial maximum (LGM) limits. In this 91 model the postglacial hillslope processes and fluvial systems of Britain are out of phase with 92 major climatic shifts, thus the redistribution/availability of the sediment is important and may act 93 as a lead or lag in fluvial development.

94

95 Northern England lies within the limits of MIS 2 ice and many river valleys, including the Tyne, are 96 infilled with glacial, soliflucted, colluvial and fluvial deposits. Previous workers have investigated 97 reaches in the Tyne basin during the mid and late Holocene period (e.g. Passmore and Macklin, 98 1994; Rumsby and Macklin, 1996), but these studies did not concentrate on the Lateglacial-99 Holocene transition. Here, we present evidence for fluvial development for a 22 km stretch of the 100 piedmont middle Tyne valley. Our aims are: (i) to present the alluvial landform record; (ii) to 101 identify the sequence of valley-floor development; (iii) to interpret the depositional environment 102 from the sedimentary record; (iv) to establish a chronological framework using optically stimulated 103 luminescence dating (OSL); (v) to explore the response of the fluvial system to climate change 104 and other conditioning factors.

105 **2. Study area**

106 2.1. The Tyne Basin

The Tyne basin lies in the northeast of England (Fig. 1) and comprises a catchment area of 2,936
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.

112 Geologically, the basin is underlian by Carboniferous limestone, sandstone, siltstone and 113 mudstone, along with Silurian greywackes and Devonian sandstones. Andesite outcrops in the 114 Cheviot Hills, whilst Dolerite is found along the south Tyne. Structurally, the Alston block and 115 Northumberland fault-trough bound the catchment (Scrutton, 1995; Johnson, 1997). Investigation 116 focused on the mid-Tyne valley (w-e flowing section), extending as far upstream as the Allen 117 confluence (South Tyne) and as far downstream as Broomhaugh (Tyne) (Fig. 1). The Tyne valley 118 comprises wide valley floors (or basins), with occasional narrow sections (or gorges), and the 119 present day river can be described as a wandering/meandering gravel-bed river.

120

121 During the last glaciation northern England and the Tyne valley were overridden by British-Irish 122 Ice Sheet (BIIS) (Hughes et al., 2016). Regionally, the ice was around 0.8 km thick at the LGM. A 123 west-east flowing ice stream (Tyne Gap Ice Stream; TGIS) extended along the Tyne valley 124 (Smith, 1994; Mills and Holliday, 1998; Livingstone et al., 2012, 2015) and an ice lobe extended 125 north–south down the North Sea coast (North Sea Lobe; NSL). Constrained by Bayesian 126 statistical analysis of radiocarbon and cosmogenic ages, retreat of the TGIS had begun by 18.5-127 18.3 ka (Livingstone et al., 2012, 2015; Evans et al., 2021; Clark et al., 2022), creating 128 accommodation space in the mid and lower Tyne valley as it decoupled from the NSL impounding 129 waters in the Tyne lowlands. In the Tyne valley an extensive pro-glacial drainage system 130 developed feeding water and sediments towards a large ice-dammed lake (Glacial Lake Wear) 131 (Smith, 1994; Davies et al., 2009; Yorke et al., 2012; Teasdale, 2013). The NSL had retreated 132 completely from the east coast by 17–16.5 ka (Roberts et al., 2018; Evans et al., 2021), with ice 133 retreating to the upland dispersal centres (Lake District) by 17 ka (Davies et al., 2019). Following 134 deglaciation, regional sea levels were low, lying at -30 m Ordnance Datum (OD) at 12 ka BP 135 (Bradley et al., 2011). Buried peats within estuarine sediments found in the lower Tyne constrain 136 early Holocene marine inundation to 8.5 ka cal. BP (Horton et al., 1999a.b). Glacio-isostatic uplift 137 across Northumberland has declined since deglaciation, with a present-day uplift rate of 0.2-0.8 138 mm a⁻¹ south to north respectively (Bradley et al., 2011; Shennan et al., 2012; Bradley et al.,

139 2023). Base-level change for regional river systems, driven by both eustatic and glacio-isostatic

140 factors, may have influenced fluvial dynamics during the Lateglacial and early Holocene period.

141

142 This study focuses on three reaches. Zone I is a lowland reach set within ice-disintegration 143 topography, where narrow valley floor fluvial terraces are preserved on inner meander banks 144 between the Allen confluence and a knick-point gorge (Newbrough) upstream of Fourstones. 145 Zone II is a gently meandering reach that straddles the confluence of North and South Tyne, with 146 terraces preserved on both sides of the valley floor flanked by subglacial features between 147 Fourstones and Acomb. Zone III is a major alluvial basin (Corbridge) between Hexham and 148 Broomhaugh (Fig. 1), with extensive valley floor fluvial terraces present set below extensive 149 glacial outwash deposits.

150 **3. Materials and methods**

151 3.1. Geomorphological mapping

152 Mapping of the valley floor features drew on interpretation of Light Detection and Ranging 153 (LiDAR) digital elevation model (DEM), supplied by the Environment Agency's Geomatics Group. 154 The LiDAR DEM had a spatial resolution of 1 m^2 , with a vertical accuracy of ~0.15 m. Mapping 155 was undertaking using the interpretative tools within ArcGIS. Extensive flat areas and linear 156 depressions reflect and were digitised as river terrace fragments and palaeochannels 157 respectively. Identification was possible through manipulation of the DEM to produce hill-shaded 158 surfaces, narrow elevation range shaded DEMs and interval contours. Field mapped data were 159 used to 'ground-validate' the terrace fragments and palaeochannels interpreted from the LiDAR 160 DEM at scales of 1: 10,000.

161 3.2. Sedimentological investigations

162 The sediments underlying the mapped terraces were recorded from river-bank exposures and

163 using closely spaced sediment profiles interpreted from the British Geological Survey (BGS)

164 online database of borehole logs. Sediment analysis followed a lithofacies approach (Miall, 1988)

165 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.

170 3.3. Optically Stimulated Luminescence dating

171 In the absence of *in situ* organic material for radiocarbon dating, to develop a chronology for the 172 terrace sequence we used Optically Stimulated Luminescence (OSL) dating to target sands within 173 terraces 1, 4, 5 and 7. Suitable lithofacies that had the greatest potential to have been exposed to 174 light prior to deposition (cf. Thrasher et al., 2009) were targeted for OSL dating, e.g. overbank and 175 bar-top sands. Samples were collected (in daylight) by hammering opaque plastic tubes (300 x 50 176 mm) into cleaned faces. Bulk materials collected within 30 cm of the OSL sample provide 177 materials for measurement of moisture content and y dose rate in the laboratory. Sand-sized 178 quartz (180-255µm or 90-125µm) mineral grains were extracted from the sediment samples using 179 standard preparation techniques. These included wet sieving, removal of organic matter using 180 H₂O₂ (10%), HCI (10%) treatment to remove carbonates, HF (48%) treatment for 60 minutes 181 followed by an additional etching in H_2SiF_6 acid for two weeks to dissolve remaining feldspathic 182 components as well as heavy mineral separation using sodium polytungstate (2.63g cm⁻³). All the 183 samples were measured as medium sized (4mm diameter) multigrain aliguots mounted on 184 aluminium discs inside an automated Risø TL/DA15 luminescence reader (Bøtter-Jensen 1997, 185 2000) using a SAR post-IR blue OSL measurement protocol (Murray and Wintle, 2000; Banerjee 186 et al., 2001; Wintle and Murray, 2006). Due to the fluvial nature of the sediments and in order to 187 avoid overestimating the true depositional age of the sediments as a result of incomplete 188 bleaching of the OSL signal (Murray et al. 1995, Wallinga 2002), the De estimates were calculated 189 using a Minimum Age Model (Galbraith et al. 1999) within the 'R' statistical programming 190 language (Kreutzer et al. 2012). Dose rate calculations are based on the concentrations of 191 radioactive elements (potassium, thorium, uranium and rubidium) within the sediment. These 192 were derived from elemental analysis performed by Actlabs (Canada) using induced coupled 193 plasma mass spectroscopy / atomic emission spectroscopy (ICP-MS/AES) and a fusion sample

194 preparation technique. The final OSL age estimates include an additional 2% systematic error to 195 account for uncertainties in source calibration. Dose rate and age calculations were obtained 196 using DRAC version1.2 developed by Durcan et al. (2015). These are based on Aitken (1985) 197 and incorporated updated grain size attenuation factors of Brennan et al. (1991) and Guerin et al. 198 (2012), etch depth attenuation factors of Bell (1979), dose rate conversion factors of Guerin et al. 199 (2011) and an absorption coefficient for the water content. The contribution of cosmic radiation to 200 the total dose rate was calculated as a function of latitude, altitude, burial depth and average 201 over-burden density based on data by Prescott and Hutton (1994). The OSL age estimates 202 (presented as ka: Table 1) include an additional 2% systematic error to account for uncertainties 203 in source calibration.

4. Results

205 4.1. Fluvial geomorphology

206 Across the three zones (Fig. 1) of the mid-Tyne valley, the geomorphology and longitudinal 207 height-range relationships reveal nine fluvial terraces that lie between 20 and 2 m above present 208 river level (T1 – T9; highest to lowest) and the modern floodplain (Fig. 2 and Fig. 3). T1, broadly 209 20 m above the modern river, comprises fragmented surfaces that lie along the valley margins of 210 the South Tyne system. However, within zone III the surfaces are laterally extensive (Fig. 2c) and 211 show some continuity with extensive glaci-fluvial/-lacustrine desposits (Yorke, 2008) in terms of 212 extent, however, they are inset ~10m below the glacigenic surfaces. T2 lies at 15 m above 213 modern river level and is restricted to isolated fragments located towards the outer margins of the 214 valley, with greater lateral extent in the South Tyne upstream of Newbrough Gorge (zone I). It is 215 present most extensively around the confluence of the North and South Tyne (zone II), and forms 216 a component of an alluvial fan at Dilston (Fig. 2c). T3, 14 m above modern river level, is laterally 217 extensive in zone I along the South Tyne above Newbrough Gorge (Fig. 2a), and restricted to 218 isolated fragments in zones II-III downstream of Newbrough Gorge, and in the area around the 219 town of Corbridge, hereafter referred to as the Corbridge Basin (Fig. 2b). This upper group of 220 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.

225

226 T4, at 9 m above current river level, occurs throughout zones I to III, but is most extensive in zone 227 III, the Corbridge Basin. The terrace long profile shows a reduction in gradient downstream from 228 0.05 to 0.01, and lies closer in elevation to the present river downstream (9 to 6 m above river 229 level). Several sinuous (sinuosity index 1.3) palaeochannels are visible on T4 (zone III), indicating 230 a meandering system and suggesting some lateral stability of channel systems. T5 lies 6 m above 231 the base of the modern river and has limited presence throughout the study area. T5 grades into 232 the Newbrough Gorge. Numerous surficial palaeochannels are evident on this terrace, and their 233 planform sinuosity is almost straight (sinuosity index <1.05). The channels show evidence of 234 progressive lateral change through avulsion and chute cutoffs. T6 lies 5 m above the bed of the 235 present river and is present in all zones, I – III. T6 extensively occupies the meander bend within 236 zone III. Surficial palaeochannels are ubiquitous on this terrace, and whilst sinuosity is straight to 237 low (sinuosity index <1.05–1.03), in zones II – III channel planforms indicate bar progradation and 238 downstream translation of the meander bend. Migration within these palaeochannels is similar to 239 the development of the present-day meanders. T7 is only present in zones I - II, lies 4 m above 240 the modern river and is sculpted with extensive palaeochannels. Their morphology reflects a low-241 sinuosity (sinuosity index 1.06–1.30) planform, with lateral valley-floor channel migration through 242 avulsion and chute cut-offs.

243

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.

257

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 valleyfloor sequence. The Dilston Fan represents a long history of formation that corresponds with the Lateglacial and Holocene fluvial development of the Tyne fluvial terraces.

265 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 subsurface stratigraphy for T1, 6 and 7.

270

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

275 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

277 m OD near the estuary (Cumming, 1971, 1977). The incision of the bedrock valley probably 278 reflects some glacial deepening by ice draining the Tyne Gap and North Tyne Valley, and/or 279 earlier fluvial incision under lower eustatic sea levels (Cox, 1983; Mills and Holliday, 1998). The 280 channel forms a palaeovalley to the north of the present-day river. The valley sediment fill 281 comprises basal over-consolidated diamicts ~5 m thick. Moving downstream the palaeovalley 282 (Fig. 6) the glacial diamicton thickens towards the valley centre (~15 m thick), and is overlain by 283 pro-glacial sands and sandy gravels of varying from 10 to >15 m in thickness (Fig. 5, 6). This 284 sequence records the presence of ice in the region, and the subsequent ice retreat with the 285 development of the pro-glacial drainage system (Yorke et al., 2012; Livingstone et al., 2012). The 286 basal sediments represent >20 m of aggradation and were likely deposited between 30 and 15 ka 287 BP (Livingstone et al., 2015). The upper bounding surface of these glacigenic sediments forms a 288 base to the overlying post-glacial fluvial succession.

289

290 The A68 borehole series crosses the valley-floor, revealing the composition of T1 and T4 (Fig. 4b, 291 5b). T4 shows incision to a diamict surface, and subsequent aggradation of ~6 m of sandy 292 gravels, overlain by ~10 m of silty, gravelly sands and capped by 1-2 m of silty sands. The 293 sedimentary sequence and palaeochannels visible on the surface of T4 suggest a meandering 294 fluvial system. The A69 borehole series crosses both T6 and T7 (Fig. 4a, 5a) recording for T6 a 295 basal post-glacial unit of ~7 m thick sandy gravels, with occasional silty sands. Towards the outer 296 margins of the valley within T6 there are three discrete units cut into the sandy gravels. These 297 units comprise a channel fill of <2 m laminated peat and peaty silt, and the whole sequence is 298 buried by 4 m of laminated silts. Well-developed meanders and scroll-bar forms on T6 299 downstream of Newbrough Gorge (zone II) identify lateral migration of the channel reflecting 300 increased sediment mobility and stream power. Meandering and migration of scroll-bars has led 301 to development of 'peaty' back-channel swamp environments with channel migration (Hooke, 302 2003, 2004; van de Lageweg et al., 2014). For T7, ~7 m of sandy gravels overlie the diamict, 303 capped by ~1 m of laminated silty sands. Both the T6 and T7 sequences suggest a transition 304 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.

308

309 4.2.2. Exposures at Farnley Haughs

310 Near Farnley Haughs (zone III) a 20 m long erosion scar (Fig. 6a) exposes the sediments 311 comprising T1. Thinly laminated, very fine basal sands are interpreted as subaqueous glacio-312 fluvial sediments (Yorke et al., 2012). High elevation valley-side glacial outwash terraces reflect a 313 proglacial drainage system entering Glacial Lake Wear, dammed by the NSL to the east (Smith, 314 1994; Yorke et al., 2012; Davies et al., 2019). This unit is overlain unconformably by ~4 m of 315 fluvial sediments comprising rounded cobbles, forming a concave channel lag deposit at the base 316 of the post-glacial sequence. Above the channel lag are rounded, clast- to matrix-supported 317 gravels (predominantly Carboniferous sandstones and greywacke, and igneous clasts inc. Shap 318 granite originating from the Lake District), which reflect vertical accretion as longitudinal bars, with 319 initial aggradation in low water from tractional processes and small-scale structures 320 superimposed on the larger bedforms during waning flow (Miall, 1996; Bridge, 2009; Rice et al., 321 2009). The longitudinal bars are intercalated with coarse sandy gravel, pebbly sands and silty 322 sands, which indicates fluctuating flows (Smith et al., 2009; Rice and Church, 2010) (Fig. 6b). 323 Laminated fine sands (2 m thickness), indicative of overbank deposition, cap the sequence and 324 are typical of floodplains adjacent to shallow, wandering gravel-bed river (Miall, 1996). The upper 325 sands were sampled for OSL dating (X2734; Fig. 6b) to constrain late-stage aggradation of T1 326 and provide a younger than constraint on the incision to T2.

327

328 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

333 coatings and imbrication is well developed. Clasts within T4 are predominantly volcanic and 334 igneous in origin (81%), with fewer Carboniferous sandstones, limestones and mudstones (19%). 335 This matches the clast lithologies recorded within the till (predominantly Lake District volcanic and 336 igneous clasts – dolerite, quartzite and granite, with subordinate amounts of Carboniferous 337 sedimentary clasts), indicating that the river reworked earlier sequences. A chute channel 338 truncates the gravel at the downstream end of T4, and is infilled with cross-stratified to massive 339 cobble- and pebble-sized sandy gravel, indicative of high relief bar edges, overlain by laminated 340 sands. Chronological control for T4 was obtained from the laminated sands (X2730) (Fig. 7b). 341 The stratified gravels represent bedload, with sorting, imbrication and iron-coatings all indicate 342 transport and deposition in shallow water/fluctuating water levels. The presence of large boulders, 343 structureless gravels, chute channel and bar deposits in the upper 2 m suggests higher-344 magnitude flows (Desloges and Church 1987; Smith, 1990; Brierley and Hickin, 1991). The 345 sequence is interpreted as a wandering gravel-bed system (Miall, 1996), with periods of lateral 346 channel instability during extreme flow events (Wooldridge and Hicken, 2005).

347

348 For T5, the sequence displayed extensive exposure of the basal lodgement till (~ 2 m). The fluvial 349 sediments of T5 appear to reflect a large remnant palaeochannel, channel bed deposits and 350 occasional infilled chute channels. The palaeochannel sediments form the boundary between T4 351 and 5, comprising ~4 m of laminated to massive sands, overlain by a silty sandy clay, with 352 intercalated sandy gravel layers (Fig. 7b). The sands were sampled for OSL dating (X2731; 353 X2732). The basal sands probably formed under upper flow regime conditions (Smith, 1990; 354 Tucker, 2011), with the overlying sandy clays and intercalated gravels suggesting slower flows 355 with occasional fluctuations in stream competence (Miall, 1996; Bridge, 2009). The sands grade 356 (downstream) into a sequence of horizontally bedded gravel, with intercalated sands (~6 m thick), 357 capped by laminated sands (~1 m thick). The gravels comprised 47% volcanic and igneous 358 clasts, with 52% Carboniferous sandstones and mudstones, and sub-ordinate amounts of coal. 359 The gravel geometry suggests development of longitudinal bars in shallow water, (Whiting et al., 360 1988; Miall, 1996). Periods of lateral instability and high-energy flows are indicated by the multistorey 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).

367

368 4.3. Geochronology and fluvial sequence

369 The new geochronological control obtained for T1, 4, 5 and 7 of the Type sequence, alongside 370 two existing 14 C ages of 5900 ± 70 cal. BP (BETA-37060) for T5 (tree trunk in basal gravels) at 371 Farnley Haughs (Passmore and Macklin, 1994) and 3030 ± 60 cal. BP (BETA-45549) for T7 (wood 372 fragments within a basal channel incised into till) at Lambley (Fig. 1, ~13km upstream of the Allen 373 confluence: Passmore and Macklin, 2000) provide a basis for exploring the landform sequence. 374 We discounted Passmore and Macklin's (1994) OSL age of 2.45 ± 3.5 ka obtained from T5 375 (upper sequence channel fill sandy silts) at Farnley Haughs on the basis that it was obtained 30 376 years ago. Significant improvements in techniques and instrumentation in the last 20 years have 377 occurred and it was not until post-1999 that OSL dating protocols became more reliable (Wintle, 378 2008; Mahan et al., 2022). We have employed an approach, using OxCal (Bronk Ramsey, 2001), 379 that facilitates statistical testing of these theoretical models of the likely relative order of events in 380 the Tyne geomorphology (Chiverrell et al., 2009b). Bayesian assessment using OxCal of these 381 relative order models (Bronk Ramsey, 2008) helps with identification (Fig. 8) of anomalous ages 382 that are nonconformable and/or out of sequence (Buck et al., 1996; Chiverrell et al., 2009b). The 383 objective with the dating was to constrain the timing of switches between river terrace levels, but 384 these are rarely dated directly, typically sitting as erosion episodes between landforms and 385 derived ages. The Bayesian models were coded in OxCal v4.4.4 Bronk Ramsey (2021) and using 386 the INTCAL20 atmospheric data from Reimer et al. (2020) as a Sequence model. The Prior 387 models in Bayesian nomenclature are structured as a series of Phases, which are unordered 388 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.

394

395 OSL ages obtained from overbank sands at Fourstones (zone II) and Farnley (zone III) (Table 1) 396 alongside the published ¹⁴C age (tree trunk within basal gravels of our T4; Passmore and Macklin, 397 1994) help to establish an outline geochronological framework for the Tyne terraces. The 398 uppermost alluvial sediments of T1 (Farnley) provided an OSL age (X2734) of 12.9 ± 1 ka (Fig. 399 9a). T2 and T3 remained undated, but the top of the T4 (Fourstones) sequence yielded an OSL 400 age (X2730) of 10.7 ± 1.1 ka (Fig. 9b). Samples from T5 (X2731; X2732; X2832) returned OSL 401 ages suggestive of poor resetting of the OSL signal and were regarded on that basis as too old. 402 The uppermost sediments of T7 (Fourstones) yielded an OSL age (X2733) of 3.2 ± 0.5 ka (Fig. 403 9c). Though not dated here historic map data suggest that T8 and T9 relate to the last 300 years. 404 The OSL ages obtained suggest the major terraces developed during the Lateglacial to mid-405 Holocene period. The Bayesian modelling has calculated modelled age probability distributions 406 for the evolution of the Tyne terraces, constraining the T1 / Deglacial transition to 16.0 ± 2.1 ka, 407 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. 408

409 **5. Discussion**

410 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 Halliday, 1998; Yorke, 2008; Livingston 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.

423

424 The earliest of the Tyne fluvial terraces (T1) are inset 10 m below the lowest outwash surface. An 425 OSL age (X2734) obtained from the overbank sands of T1 dates indicates fluvial aggradation up 426 to 12.9 ± 1 ka and implies the river was active during the Interstadial (GI-1). T1 comprises coarse 427 gravels, intercalated with sandy layers and capped by fine silty sands, typical of channel and bar 428 features and material deposited from overbank flows. The fluvial system is considered to be 429 meandering, with episodic flooding events and intermittent fluvial-lacustrine conditions (Gibbard 430 and Lewin, 2002), possibly developing during the earliest phase (GI-1e/d) before the landscape 431 stabilised and vegetation cover (i.e. Betula, Juniperus) became established (Innes et al., 2021). 432 The upper part of the unit represents repeated overbank deposition and suggests the channel 433 had already begun to incise or laterally migrate during the latter stages of the Interstadial, with 434 this area of active channel replaced by floodplain aggradation (Vandenberghe, 2015).

435

436 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 \pm 1 ka and 10.7 \pm 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).

445

446 The absence of accessible sediments prevents an interpretation of T2 and T3, however, T2 447 represents incision and aggradation after 12.9 ka. If we assume they are cut and fill rather than 448 erosional terraces (Lewin and Macklin, 2003 suggest renewed aggradation during GI-1) then their 449 development can be linked to hydrological and landscape change during GI-1. We infer that 450 geomorphic activity was strongly conditioned by periglacial slope processes and paraglacial 451 adjustment during GI-1 (Chiverrell et al., 2007; Passmore and Waddington, 2009; Ballantyne, 452 2019; Harrison et al., 2021), driven by nival flow and spring flood runoff, creating a sediment-453 dominated fluvial system. T4 returned an OSL age of 10.7 ± 1 ka (X2730; obtained from the 454 upper sands) implying aggradation during the earliest Holocene and that incision or channel 455 abandonment had probably already occurred as overbank sedimentation had begun. If we 456 assume that sediment exhaustion has not occurred by the early Holocene, and with shifts to 457 cooler, wetter conditions at 11.2, 11.4 and 10.8 ka cal. BP (Barber et al., 2003; Mayewski et al., 458 2004; Lang et al., 2010; Vincent et al., 2011) recorded in terrestrial, lacustrine and bog surface 459 wetness (BSW) records, it is easy to envisage a situation where paraglacial adjustment remained 460 dominant (Ballantyne, 2005; 2019) and a sediment-dominated fluvial system persisted. The 461 presence of this higher group of terraces (T1-T4) and the Dilston fan (Zone I) suggests the period 462 was dynamic and unstable and that cycles of incision and aggradation during the GS-1 continued 463 into early Holocene period. Comparable responses are evident from the landform sequences of 464 river systems in north Northumberland, the Southern Uplands, central Scotland and the Highlands 465 (Tipping et al., 2008; Passmore and Waddington, 2009, Ballantyne, 2019; Werritty, 2021).

466 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

471 and were most likely the result of poor resetting of the OSL signal. Thus, development of T4 and 472 T5 is constrained to the period 8.7 ± 2.3 ka (probability-based time frame). Both T4 and T5 have 473 low sinuosity to straight palaeochannels evident on their surfaces, and the sediments comprise 474 lithofacies assemblages of crudely bedded, imbricated coarse sandy gravels, overlain by a 475 veneer of silty sands. Channel fills within the sequence comprise poorly bedded sands, silty 476 sands and silts, with occasional lenses of coarse boulders and inversely graded sands, thought to 477 represent flooding events. The sediments of T4 and T5 are interpreted as channel bed and bar 478 deposits, channel fills and overbank sedimentation. T4 sequences suggest low aggradation rates 479 and laterally stable channels during the early Holocene, whereas T5 comprises some vertically 480 stacked sequences suggesting periods of instability as we moved towards the mid-Holocene. The 481 early to mid-Holocene landscape was one of increasing stability and soil development, with 482 regional vegetation records indicating that open grasslands and shrubs were replaced by 483 postglacial woodlands (Juniperus, Betula and Corylus) (Innes, 1999; Vincent et al., 2011; Ghilardi 484 and O'Connell, 2013; Innes et al., 2021). Anthropogenic disturbances have been recorded in 485 North Tyne pollen sequences (Moores, 1998) as early as 8.5 ka BP (late Mesolithic), which when 486 combined with recorded cooler and wetter conditions at 8.6-8.2 and 7.8-7.4 ka cal. BP (Barber et 487 al., 2003; Lang et al., 2010; Vincent et al., 2011) may explain the flooding deposits and lateral 488 instability recorded as we move towards the mid-Holocene.

489 5.4. Mid to Late Holocene

490 The mid- to Late Holocene fluvial development is reflected in the lower group of terraces, T5 to 491 T7. An OSL age of 3.2 ± 0.5 ka (X2733) was obtained from overbank sands of T7, and 492 development of T5 – T7 has been constrained to 4.0 ± 1.8 ka (probability-based time frame). T6 493 and T7 dominate zones II and III, however, only T6 is present in zone I and inset below the higher 494 terrace group (T1-T4) and the outwash terraces. Palaeochannels on the surface of T6 indicate 495 low to moderately sinuous channels suggesting development of a wandering-gravel bed system, 496 however, there are several migratory meander bends, evidenced by scroll-bars, indicating 497 channel instability. The sediments of T6 and T7 comprise basal sandy gravels that pass into silty 498 sands and laminated silts. Significant peat-infilled channels and silty peats dominate the upper

499 lithofacies assemblages. These suggest laterally migrating channels, and backwater zones are 500 indicated by the burial of peat-filled channels and slough channels infilled with inverted 501 stratigraphy towards the outer margins of T6. During this period, climatic instability is reflected in 502 increased bog surface wetness (BSW) records at 6.2, 5.7, 5.4, 5.4, 4.4-4.0 ka cal. BP (Hughes at al., 2000; Barber et al., 2003; Charman et al., 2006). Additionally, regional vegetation records 503 504 (Moores, 1998; Moores et al., 1999) indicate early anthropogenic disturbances in the North Tyne 505 catchment, with significant human activity from the late Mesolithic through to the Neolithic (cf. 506 Tolan-Smith, 1996; Waddington and Passmore, 2009). The landscape became largely tree-less, 507 with cultivated pollen taxa and anthropogenic indicator species dominating, especially during the 508 late Bronze Age to Romano-British period. It is easy to envisage periods of widespread fluvial 509 activity driven by increased incidence of flooding, extreme events and channel abandonment in a 510 landscape that was primed (sensitised) by human disturbances and with a paraglacial legacy 511 (Ballantyne, 2005; 2019) providing plentiful erodible sediments. The extent of T6 and T7 (Zones I-512 III), including the Allen fan (Zone III) reflect major fluvial activity within the catchment, with 513 significant valley floor reworking and probable reincorporation of earlier fluvial deposits but it did 514 not incise into its Lateglacial valley infill (Figs. 5 & 6).

515

516 Passmore and Macklin (2000) present a radiocarbon date of 3.2 ka cal. BP (BETA-45549) for (our) 517 T7, obtained from the South Tyne at Lambley (Fig. 1), however, Passmore and Macklin (1994) 518 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 519 (our) T5, obtained from the Tyne at Farnley Haughs (though discounted for the Bayesian model 520 due to reliability of OSL ages obtained using earlier dating protocols) that raises questions about 521 our chronology. However, there is very little altitudinal separation between T5 and T7 (only 2m), 522 and the terrace long profile (Fig. 3) shows that the surfaces lie closer in elevation downstream 523 and may reflect lateral variability evidenced by the switch to scroll-bars on the surface of T6. 524 rather that significant incision. In addition, sediment deposition at Farnley Haughs occurs in a 525 pinch-point in the valley, potentially allowing higher aggradation at this site compared to the open 526 valley floor setting in the South Tyne at Lambley and Fourstones. Whilst significant

527 improvements in dating protocols (both radiocarbon and OSL) have occurred in the last 30 years 528 (Wintle, 2008; Mahan et al., 2022), we could be seeing a situation of pass-the-parcel sediment 529 movement through depocentres (sensu Chiverrell et al., 2010) and a well-ordered younging 530 progression downstream is not present. Using an example from the last 200 years, Passmore and 531 Macklin (2000) have shown that in response to 18th Century metal mining-induced sedimentation 532 and Little Ice Age (LIA) climatic instability the Tyne propagated sediment slugs (cf. Nicholas et al., 533 1995) through its system. The widespread lateral instability in the uplands was subsequently 534 transmitted downstream in a time-transgressive manner.

535

536 The last 3 ka has seen periods of increased instability recorded in river systems throughout 537 northern England (Foster et al., 2009; Chiverrell et al., 2010; Macklin et al., 2014). The results 538 here suggest that there is limited later Holocene activity in the central reaches of the Tyne Valley. 539 Although T8 and T9 are undated, they must be younger than 3.2 ± 0.5 ka based on the OSL age 540 obtained from T7 (X2734). They constitute the least well-developed terraces in the sequence due 541 to their limited extent along the central reaches. Comparable to those recorded in the South Tyne 542 at Lambley (Passmore and Macklin, 2000), they most likely developed during the recent historic 543 period. Early clearance of the Tyne catchment likely explains regional (northern England) 544 variations in fluvial response during this period, driven by the relationship between land-use 545 changes, climatic shifts and flooding episodes. Whilst incision (down to bedrock) is recorded in 546 the tributaries of the South Tyne during last 1.2 ka (Macklin et al., 1992), it appears that there is a 547 disconnect between the uplands (hillslope) and channel after the large depocentres (T6 - T7)548 developed, and subsequent periods of instability were reflected in lateral channel migration and 549 reach instability, but not in further cut and fill episodes in the central reaches.

550

551 Naturally, the uplands with their connectivity to hillslopes and their fragility in terms of land cover 552 would be more sensitive to external forcing. The response to such forcing is evident in the 553 channel floor activity and incision seen in the upper reaches of the South and North Tyne rivers 554 and their tributaries (Macklin et al., 1992; Moores et al., 1999; Passmore and Macklin, 2000;

555 Macklin and Rumsby, 2007). The fluvial response in the uplands (South Tyne tributaries) has 556 been much more dynamic and sensitive to climatic instabilities and anthropogenic activity 557 (Macklin et al., 1992; Rumsby and Macklin, 1996) during the last 1 ka than that in the central 558 zones in the Tyne Valley corridor, which have been relatively stable since the onset of the later 559 Holocene period. This indicates that major sub-sections of the catchment are not synchronous. 560 Therefore, the upper catchment can be assumed to be more sensitive to change, and that 561 connectivity between the hillslope and the catchment is weaker in the piedmont zone. This 562 suggests that catchment-wide response is diachronous, and it is apparent that the system is 563 operating in discrete, reach-wide responses, such that correlating terraces throughout the whole 564 system is not always possible.

565 **6. Conclusion**

566 This study aimed to reconstruct the alluvial record of the Tyne valley following deglaciation.

567 Through a combination of geomorphological mapping and sedimentological investigations,

568 combined with new OSL ages obtained from fluvial sands, we have been able to present a valley

569 floor history that spans the period following retreat of the TGIS up to the recent historic period.

570

571 The Tyne valley terrace sequence reveals significant alluvial response following deglaciation, 572 resulting in a pattern of incision and valley refilling and leading to the presence of nine alluvial 573 terraces lying between 20 and 2 m (T1 – T9) above present river level. New OSL ages obtained 574 from T1 (12.9 \pm 1 ka), T4 (10.7 \pm 1 ka) and T7 (3.2 \pm 0.5 ka), alongside probability-based modelling 575 bracket terrace development to four phases (i) deglacial phase: 16.0 ± 2.1 ka; proglacial outwash 576 terraces, (ii) Lateglacial phase: 11.9 ± 3.1 ka; high level alluvial terraces T1-T4, (iii) early to mid-577 Holocene phase: 8.7 ± 2.3 ka; alluvial terraces T4-T5, and (iv) mid- to late Holocene phase: 4.0 ± 578 1.8 ka; low level extensive alluvial terraces T5-T7. The later Holocene to recent historic period is 579 reflected by the presence of T8 and T9.

580

581 Development of T1 to T4 was in response to climatic shifts (GI-1, GS-1, and early Holocene

582 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.

587

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 cannibalisation of earlier terraces, with recent historic activity (T8 and T9) confined to within these dominant terraces (T6 – T7).

595

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 wanderinggravel bed system that persists today.

601

602 This research highlights the importance of catchment-wide investigations and the need for 603 rigorous dating controls. The Tyne valley terrace sequence reflects the importance of complex 604 responses within the fluvial system, and demonstrates that localised responses can temper and 605 impact the broader responses to external climatic drivers. The results are broadly similar to 606 models of fluvial response in other upland UK (Chiverrell et al., 2010) and northern European 607 systems (Vandenderge 2008, 2015) but highlights that the valley floor has been operating in a 608 series of discrete reach-wide responses, and thus, correlation of terraces throughout the whole 609 system is not always possible.

610

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Figure 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.

- 1054
- 1055 Figure 2. Geomorphic map of the mid-Tyne valley, showing river terraces, palaeochannels
- 1056 (demarcated by double hashed lines) and alluvial fans, overlain on 1 m resolution LiDAR data and
- 1057 displayed as hillshade layers (© Environment Agency copyright (2023). All rights reserved). Key
- 1058 sites and localities are shown; (A) zone I, (B) zone II, and (C) zone III.



Figure 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).

- 1069 Figure 4. Location of (A) the A69 (road) and (B) the A68 (road) borehole transects, overlain on an
- 1070 Ordnance Survey 1: 25 000 Scale Colour Raster (© Crown copyright and database rights 2023
- 1071 Ordnance Survey). Showing mapped river terraces, palaeochannels and alluvial fans. AF, alluvial
- 1072 fan, T1-8, differentiated river terraces, refer to legend in figure 2.



1073

Figure 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

1078 beginning with NY and NZ, with locations indicated by vertical black lines.



1079

Figure 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 fieldgathered 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.

- 1087 Figure 7. Fourstones. (A) T5 and T7 alluvium exposed on the true right-hand side of the valley.
- 1088 (B) Detailed stratigraphic and lithofacies assesemblages based upon interpolation of field-
- 1089 gathered vertical profile logs (locations indicated by vertical black lines). The 'X' indicates the
- 1090 sampling locations for Optically Stimulated Luminescence dating; lab. codes X2733 (T7), X2832,
- 1091 X2732, X2731 (T5), and X2730 (T4). Estimated ages and age ranges are compiled in Table 1.



1095 Figure 8. Bayesian model of the dating of the Tyne terrace sequence, based on the new optically 1096 stimulated luminescence (OSL) ages obtained by this study, alongside a published ¹⁴C age 1097 (BETA-37060; Passmore and Macklin, 1994) and published cosmogenic ages (from boulder for 1098 deglaciation of the Tyne Gap Ice Stream (TGIS; Livingstone et al., 2015). The model structure 1099 shown used OxCal brackets (left) and key words define the relative order of events (Bronk 1100 Ramsey, 2009). Modelled age in ka BP on the x-axis. Each distribution (light grey) represents the 1101 relative probability of each age estimate with posterior density estimate (solid) generated by the 1102 modelling. Outliers are indicated by '?' and their probability (P) of being an outlier denoted by low 1103 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
- 1105 by Bronk Ramsey (2009).





1107

1108 Figure 9. Abanico plots of the individual aliquot equivalent does (D_e) values determined for optically stimulated luminescence dating. Plots shown are 1109 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 D_e values in relation to precision (*x*-axis), and (ii) a univariate plot, showing the age frequency 1110 1111 distribution of D_e values but this does not give any indication of precision. Both plots are linked by the z-axis of the D_e values. Data points (or primary 1112 data) are indicated by the black dots. Age estimates for the samples shown were determined using the MAM D_e; the black line across the plots 1113 represents the MAM D_e value for that sample. The abanico plots enable assessment of the data precision and the characteristics of the age 1114 distribution; samples with a greater range of D_e values on the x-axis have a larger scatter in the D_e distribution. Samples that are well bleached before 1115 burial typically have more symmetrical De distributions.

1116 **Table 1.** Summary of new optically stimulated luminescence (OSL) estimated ages and associated information for five samples from

- 1117 Fourstones (south Tyne) and one sample from Farnley Haugh (Tyne). The table includes the total number of aliquots measured with OSL that
- 1118 passed the acceptance criteria and the overdispersion of the resulting dose distribution. Measurements were made on dried, homogenized and
- 1119 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).

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

- 1122
- ^{*} 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 (<20years) bank migration and/or quarrying activity. The dose rate calculations are based on
- 1125 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 180–250µm or 90-125µm 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
- 1129 on a minimum age model after Galbraith et al. (1999).

- 1131 ⁺⁺ 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
- 1133 account for possible bias in the calibration of the laboratory beta source.