Fluvial Geomorphology of Great Britain

Edited by

K.J. Gregory
Goldsmiths College, University of London, UK

Sections co-ordinated by A. Werritty, J. Lewin, A.M. Harvey, M.G. Macklin and K.J. Gregory

GCR Editor: J.M. Hooke

JOINT NATURE CONSERVATION COMMITTEE

CHAPMAN & HALL
London · Weinheim · New York · Tokyo · Melbourne · Madras

Chapter 5

Fluvial geomorphology of north-east England

M.G. Macklin

HOLOCENE FLUVIAL DEVELOPMENT IN NORTH-EAST ENGLAND

Introduction

The principal river systems of north-east England are the Tyne, the Wear and Tees, and the Cheviot rivers in the northern part of the region (Coquet, Aln, Till) that flow eastwards to the North Sea (Figure 5.1). The sites described in this chapter, with the exception of two upland streams in the Yorkshire Dales (Shaw Beck) and Cheviot Hills (Harthope Burn), however, all lie within the watershed of the River Tyne and its major tributaries. This uneven distribution of sites reflects, primarily, the considerable amount of fluvial geomorphological research that has been undertaken in the Tyne basin, but also the lack of similar investigations in the Tees and Wear river systems, which, despite their size and propensity to flooding, have been little researched. Nevertheless, the Tyne basin does contain a diverse range of physiographic and geological terrains with contemporary and Holocene channel forms, and alluvial deposits, representative of north-east England in particular, and northern England as a whole.

North-east England was ice-covered during the Last Glacial Maximum, at around 18 000 BP, and glacial erosion and sedimentation from this and earlier glaciations have strongly influenced Holocene river development in the region. In response to declining sediment supply after deglaciation, and glacio-isostatic adjustments, upland (e.g. Aspinall *et al.*, 1986) and piedmont (Passmore *et al.*, 1993) reaches of many rivers in the region have entrenched their valley floors in postglacial times, forming well-developed flights of river terraces. In some upland catchments, most notably in the Cheviot Hills, partial refilling of valley floors has occurred more recently, following major deforestation in the prehistoric and early historical periods (Macklin *et al.*, 1991; Tipping, 1992). In contrast, the vertical tendency of channels in the lower Tyne, Wear and Tees valleys during the Holocene has been one of episodic, progressive alluviation. This was in response, principally, to rapid sea-level rise in the early Holocene and anthropogenically induced accelerated catchment erosion in more recent times (Passmore *et al.*, 1992).

The Tyne catchment (drainage area 2927 km^2, basin relief 893 m) is developed predominantly on Carboniferous sandstone, limestone and shale, with igneous outcrops in the headwaters of the North Tyne and along the lower part of the South Tyne valley. The geology of the North Tyne catchment compared with the South Tyne catchments (the principal tributaries of the River Tyne), however, differs in detail; the South Tyne and its tributaries (Black Burn, Nent, West and East Allen) drain the Northern Pennine orefield, which was once the most productive lead and zinc mining area in Britain (Dunham, 1990). Fine-grained sediment from the South Tyne basin has a distinctive geochemical signature that can be recognized in Holocene alluvium downstream in the Tyne valley. Investigations of the dispersal of 19th and early 20th centuries mining waste in the region's rivers have been especially valuable in this context, enabling long-term (Macklin *et al.*, 1992c; Macklin *et al.*, 1994a; Passmore and Macklin, 1994) and large-scale (Macklin and Dowsett, 1989; Macklin, 1992) fine sediment transport processes and storage patterns to be studied.

As in many other base-metal mining areas in Britain (Lewin and Macklin, 1987; Macklin, 1996), historical mining activity significantly increased sediment delivery to rivers in the Tyne catchment, and resulted in widespread contamination of the South Tyne and Allen systems, and much of the Tyne River, downstream as far as Newcastle (Macklin, 1992). The input of coarse material took place mainly in the 17th and 18th centuries primarily through a primitive, but very effective form of hydraulic mining called 'hushing'. Headwater streams in the mining areas of upper Tynedale, Weardale and Teesdale were most affected, with hushing causing localized river aggradation and channel planform change. The impact of the more easily dispersed finer metal-rich wastes was more widespread. Being phytotoxic, high levels of lead, zinc and cadmium in this material severely impaired vegetation growth (Richards *et al.*, 1989; Macklin and Smith, 1990), reducing bank stability and colonization rates of gravel bars, promoting river instability and braiding (Macklin, 1986; Macklin and Lewin, 1989; Passmore *et al.*, 1993).

Present river channels in the Tyne basin are inset either within Pleistocene glacial and glaciofluvial deposits, Holocene alluvium or bedrock. Holocene river sediments range from coarse gravels in the Northern Pennine uplands (Macklin *et al.*, 1992b) and piedmont (Passmore *et al.*, 1993), deposited by laterally and vertically active near-braided channels, to sandy and silty alluvium in the lower (Macklin *et al.*, 1992a) parts of the basin, characterized by vertical accretion and relatively low rates

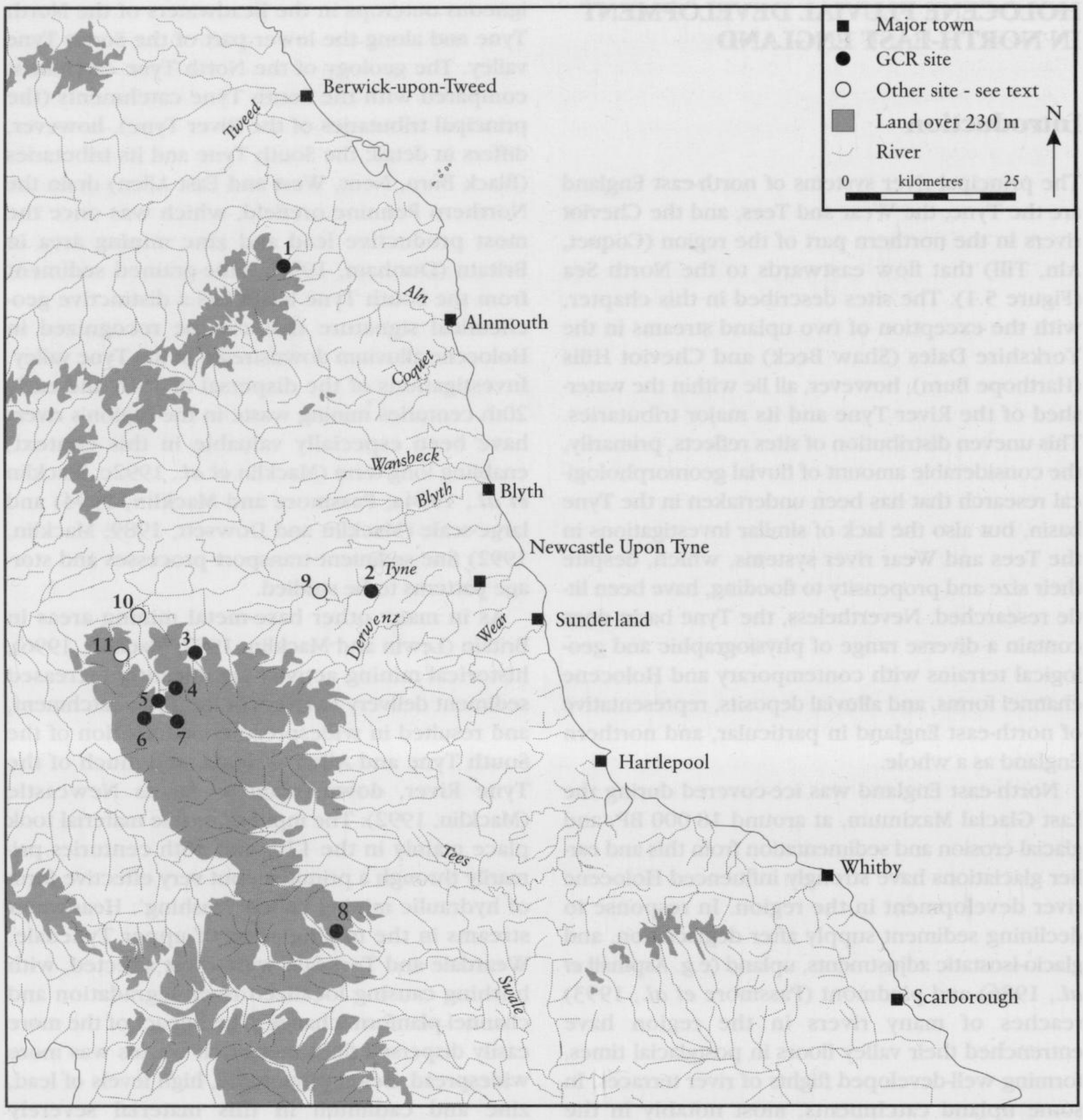


Figure 5.1 The major river systems and relief of north-east England. GCR Sites: 1 Harthope Burn; 2 Low Prudhoe; 3 Blackett Bridge; 4 Blagill; 5 The Islands, (Alston Shingles); 6 Black Burn; 7 Garrigill; 8 Shaw Beck. Other sites descibed in the text: 9 Farnley Haughs; 10 Lambley; 11 Thinhope Burn.

of channel migration. Local differences in valley slope, degree and nature of channel confinement and the calibre of bed and bank sediment have, however, engendered considerable diversity in both Holocene sedimentation styles in the Tyne basin and present-day river channel patterns and bar development. To represent the spatial and temporal variability of river development in the Tyne basin fully, a suite of sites has been selected in order to include, as far as possible, the full range of fluvial environments and histories found in the catchment. The majority of sites are located in the upper part of the South Tyne basin within (Black Burn, Garrigill, The Islands, Blagill, Thinhope Burn and Blackett Bridge), and fringing (Lambley), the Northern Pennine Hills (Figure 5.1). This is because contemporary river processes are particularly active in this area, and also Holocene river sediments and, especially, landforms (e.g. river terraces and palaeochannels) tend to be well-preserved.

Although river channels are less active, and barforms are more poorly developed, at Farnley Haughs and Low Prudhoe downstream in the Tyne valley, the importance of these sites lies in their longer and more complete Holocene fluvial sedimentary records.

Research in the Tyne basin over the past decade has combined contemporary fluvial process studies (e.g. Sear, 1992; Sohag, 1994) with the evaluation of river response to longer-term environmental change (e.g. Rumsby, 1991; Passmore, 1994), and three broad themes have emerged from these investigations: (1) river channel, floodplain and drainage basin response to natural (principally climate) and anthropogenically induced (deforestation, changes in farming practice and metal mining) environmental change (Macklin and Lewin, 1989; Macklin *et al.*, 1992a; Macklin *et al.*, in press; Passmore *et al.*, 1993; Rumsby and Macklin, 1994); (2) identifying and dating flood units in Holocene alluvial sequences and assessing the role of large floods in valley floor development (Macklin *et al.*, 1992b,c; Newson, 1989); and (3) fine sediment provenance studies, notably the use of heavy metals as stratigraphic markers and sediment source indicators (Macklin and Dowsett, 1989; Macklin *et al.*, 1994a; Passmore and Macklin, 1994). The sites included in this review have been judiciously chosen to illustrate one or more of these research themes and to embrace some representative landforms.

BLACK BURN, CUMBRIA (NY 685415)

Highlights

Black Burn demonstrates channel pattern and sedimentation style changes associated with the downstream movement of a sediment wave, generated by historical mining activity. At this locality, late Holocene river terraces with excellent examples of braided stream palaeochannel traces are also found.

Introduction

Black Burn (catchment area 64 km^2), one of the principal headwater tributaries of the River South Tyne, is a steep, boulder-bedded upland stream that drains in a northeasterly direction from Cross Fell, which at 893 m is the highest peak in the Northern Pennines. In a 1 km long reach immediately upstream of the disused Rodderup Fell mine, the progressive downstream transfer of coarse sediment introduced into the channel by hydraulic mining (hushing) can be documented over the past 200 years or so. This is still continuing at the present-day with aggradation of coarse bed sediment and braiding in the lower part of the study reach. River landforms and sediments associated with valley floor aggradation and incision, linked to the down-valley movement of a sediment mega-form (*sensu* Church and Jones, 1982) or slug (*sensu* Nicholas *et al.*, 1995) are especially well-developed.

Description

The reach lies immediately above the disused Rodderup Fell lead mine (NY 699427), 5 km south-east of Alston (Figure 5.1). The river at this point flows through an alluvial basin (the largest in the Black Burn catchment), 850 m long and up to 250 m wide, bordered by steep, convex till-covered valley-side slopes. At the head of the basin, on the east bank of the river, a number of prominent gully-like erosion scars produced by hydraulic mining for metal ores, run down the hillside and debouch on to the valley floor. At the mouths of some of these, cones of coarse mining debris still remain, although considerable volumes of hushed sediment have been eroded, transported downstream and incorporated into the historical floodplain. Along with Hudeshope Beck (NY945293) in upper Teesdale, this is one of the few sites in the Northern Pennines at which upstream input of coarse mining debris generated by hushing can be clearly linked to downstream channel and floodplain sedimentation.

Three alluvial terraces are evident on the valley floor (Figure 5.2). The highest two terrace units (4 m and 3 m above the present river bed) are vegetated, formed of coarse gravels overlain by a thin veneer (0.2 – 0.4 m) of silts and sands. Both terraces have a series of well-developed palaeochannels preserved on their surfaces (Figure 5.3). Wood excavated from the fill of one of these palaeochannels in the 4 m terrace has been ^{14}C dated to *c.* 366 cal AD, while a tree trunk recovered from the base of the 3 m terrace gave a date of *c.* 420 cal AD. These dates indicate large-scale valley floor incision and aggradation, of the order of 3 m, which occurred in Black Burn towards the end of the Roman occupation. The lower terrace (2 m above the present river bed) is composed of

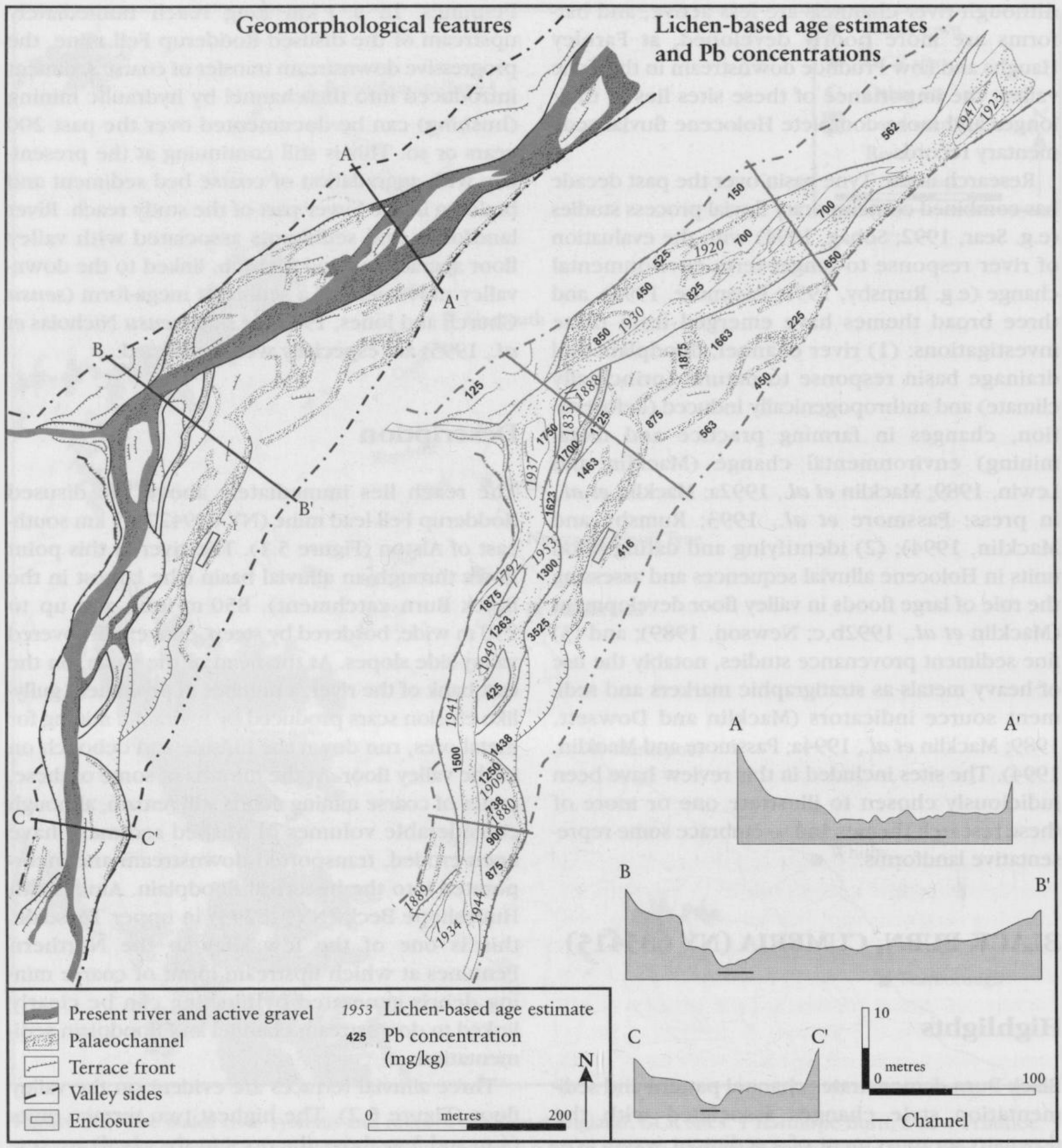


Figure 5.2 Black Burn: geomorphological features and dated sedimentary units, with cross-sectional profiles.

boulder- to cobble-sized sediment (with little or no plant cover), the surfaces of which are covered by lichens, the most prominent of which are *Rhizocarpon* sp. and *Huilia tuberculosa.* On this terrace upstream of the confluence of Black Burn and Rowgill Burn (NY 684417) there are a series of exceptionally well-preserved meander cutoffs (Figure 5.4). Historical maps (Figure 5.5) show that these were part of the active channel up to the end of the 19th century until being cut off some time between 1900 and 1957. On the north-west side of the valley floor, downstream of Rowgill Burn, are found a number of inactive mid-channel bars that were part of the active channel until 1957. Side channels adjacent to these bars have been choked and plugged by boulder-sized sediment deposited during a major flood, that resulted in the natural straightening of the channel.

Figure 5.3 Black Burn, looking downstream in a northeasterly direction, showing well-developed palaeochannels on low river terrace surfaces. (Photo: M.G. Macklin.)

Figure 5.4 Black Burn, looking upstream in a southerly direction, showing prominent meander cutoffs dated to between 1900 and 1957. (Photo: M.G. Macklin.)

Interpretation

Historical maps (Figure 5.5) and lichenometric dating show that the 2 m terrace marks the limit of channel reworking of the valley floor since the mid-18th century. Analysis of metal concentrations in these sediments shows generally higher concentrations than those of the 3 and 4 m terraces, although metal levels in the former unit are comparatively high, especially at sites closest to the margin of the

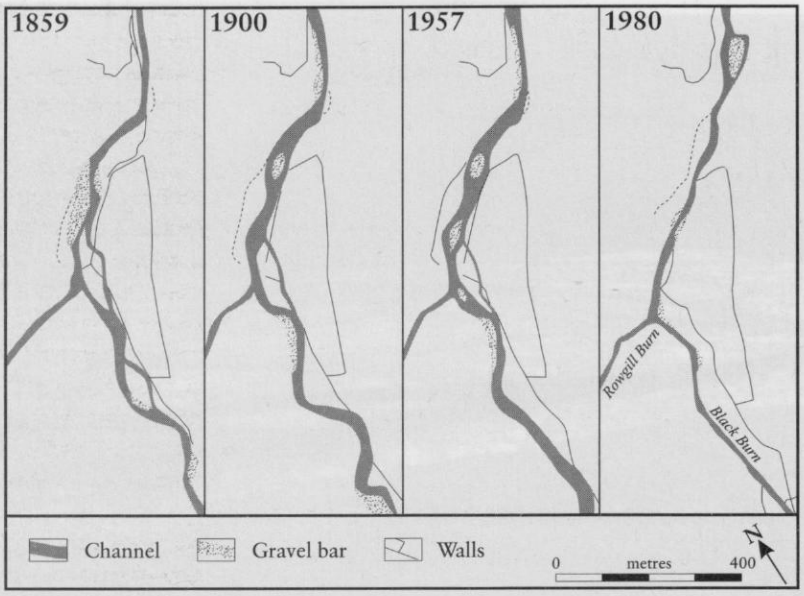


Figure 5.5 Channel change at Black Burn, 1859–1980.

valley floor reworked since the middle of the 19th century. It is likely, therefore, that floods during and since this period have partly inundated earlier terraces, depositing metalliferous sediment. Although mining in the Black Burn catchment dates back at least to the 1780s, it is equally likely that metal contamination of this older fill may have been associated with a pre-18th century phase of mining.

Black Burn is presently a steep (0.023 m m^{-1}) boulder- and cobble-bedded stream which is capable of transporting bedload material the intermediate axes of which exceed 70 cm. Above Rowgill Burn the river is laterally confined by alluvial terraces (described above) and is currently incising through bedrock with a prominent knickpoint 50 m upstream of cross-section C (Figure 5.2). Height relations between current bedload sedimentation levels and coarse-grained alluvium deposited between the middle 19th to early 20th centuries changes in a systematic fashion down the study reach. At cross-section C the present channel is 1.9 m below late 19th century alluvial sediments, and at cross-section B 1.6 m, while at cross-section A the river bed is less than 0.4 m below alluvium deposited in the early part of the 20th century. Below cross-section A the present channel is aggrading, with coarse bed material burying the late 19th and early 20th century floodplain.

River landforms and deposits in Black Burn are of particular regional interest by virtue of it being the most upland river system in north-east England the late Holocene and recent development for which have been documented. Moreover, the study reach presently constitutes the most extensive and currently active boulder-bedded stream in the Tyne basin, with good examples of mid-channel bars and boulder berms formed by historical floods, as well as high- and low-sinuosity palaeochannels. In this respect, Black Burn is similar to steep gradient boulder- and cobble-bedded upland streams described by Harvey *et al.* (1979) in the Bowland Fells and by Milne (1982) in the Cheviot Hills. Although changes in the availability of coarse sediment over Holocene and historical times can be studied in a general way in both of these areas, at Black Burn it is possible to identify historical metal mining as the principal source, and primary cause, of increased sediment supply to the valley floor in recent times. Down-valley coarse sediment transfer rates can also be determined, as well as associated patterns of sediment storage and channel change. By quantifying the volume of hushed sediment introduced into the reach and comparing this with amounts of hushed material currently stored on the valley floor, it should be possible also to calculate a sediment budget for the study reach over the past 200 years, and perhaps longer.

Conclusion

Black Burn displays alluvial landforms and deposits associated with the down-valley movement of a sediment waveform associated with the episodic input of coarse mining waste. It is one of the few sites in the Northern Pennines at which upstream input of coarse sediment produced by hushing for metal ores can be clearly linked to downstream historic floodplain sedimentation. The study site also constitutes the most extensive, laterally mobile, low-sinuosity boulder bedded river reach in the Tyne basin.

GARRIGILL, RIVER SOUTH TYNE, CUMBRIA (NY 739421)

Highlights

Garrigill is an important locality in the upper South Tyne basin for Late Pleistocene and Holocene river terraces and palaeochannel sequences. It also is a site at which Holocene river incision through bedrock can be demonstrated.

Introduction

The valley floor of the South Tyne at Garrigill displays some of the best preserved flights of Holocene and Pleistocene river terraces in the Tyne basin (Aspinall *et al.*, 1986). On the surface of terraces believed to be of Holocene age are a series of exceptionally well defined palaeobars and high-sinuosity palaeochannels.

Description

Immediately downstream of the village of Garrigill (NY 740420), the River South Tyne flows within an alluvial basin (350 m wide and 600 m long), in which six unpaired terraces have been identified above the present floodplain (Figures 5.1 and 5.6). On the surface of terraces on the north bank of the river are preserved a number of high-sinuosity palaeochannels infilled with between 1 and 1.5 m of organic rich, fine sands and silts. At the northern end of the basin, river bank sections in the oldest of these terraces (just over 4 m above the present river-bed level) show 1 m of sandy cobble-gravels resting directly on bedrock, overlain by 0.75 m of laminated silts and sands. Sections in higher terraces on the south bank of the river reveal poorly sorted, cobble- and boulder-sized sediments that are typical of Pleistocene glaciofluvial deposits in the region. Judging from their high heavy metal concentrations (Pb 1000 - 1400 $mgkg^{-1}$), deposition of fine sediments that form part of the lowest north bank terrace (2 - 3 m above the bed of the present River South Tyne), was contemporaneous with upstream metal mining. At present, the precise date for this period of mining is unknown. Garrigill does, however, lie downstream of some of the oldest mines in the Northern Pennine orefield, which were known in the 12th century as the 'silver mines of Carlisle'. There is also circumstantial evidence for lead extraction nearby during the Roman occupation (Raistrick and Jennings, 1965).

At the north-west end of the study reach, the modern river is confined by Quaternary terraces and bedrock which have restricted recent lateral movement of the channel. Below the footbridge (Figure 5.6) the valley floor widens and the channel has moved 70 m in the past 130 years, depositing a sequence of coarse-grained lateral accretion sediments. These deposits span the heyday of metal mining in the catchment (*c.* 1840 - 80) and contain high concentrations of heavy metals (Pb 1600 - 1750 $mgkg^{-1}$). Investigations of the chemical and physical characteristics of alluvial soils developed on the three north bank terraces were carried out in an attempt to clarify their ages (Aspinall *et al.*, 1986). This showed very little variation in the degree of pedogenic modification of hydrous iron oxides, which suggests that there is no great difference in age between these alluvial units.

Interpretation

The importance of Garrigill lies in the recognition of two episodes of Holocene alluviation and valley floor entrenchment that pre-date historical metal mining in the South Tyne basin. This is somewhat unusual in the upper reaches of the South Tyne basin, where high rates of lateral channel movement during the Holocene have usually resulted in the erosion and removal of older alluvial units. Pollen analysis and ^{14}C dating of palaeochannel fills could in the future establish the ages of these alluvial units. Holocene river terraces at the site can be compared with similar Holocene alluvial sequences in Mid-Wales (Macklin and Lewin, 1986), the Bowland Fells (Harvey and Renwick, 1987) and the Cairngorms (Robertson-Rintoul, 1986a). Although Holocene river incision is chiefly through bedrock, it has been more pronounced at Garrigill.

Conclusion

Holocene alluvial and Pleistocene glaciofluvial terraces are well developed at Garrigill. Well defined

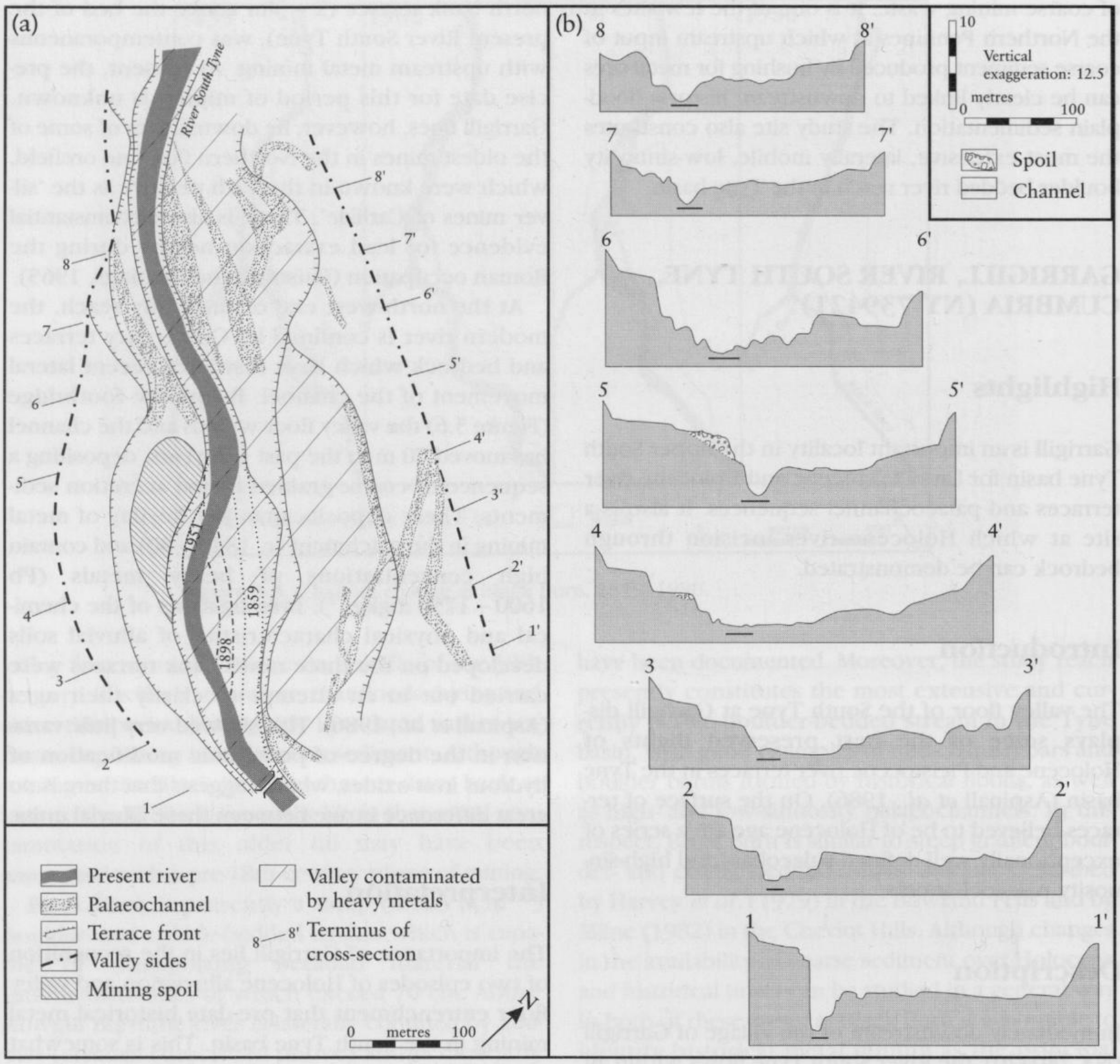


Figure 5.6 Garrigill, River South Tyne: (a) alluvial landforms, palaeochannels and sediment units and (b) cross-sections of the valley floor. (After Aspinall *et al.*, 1986.)

high-sinuosity palaeochannel traces are preserved on Holocene age river terraces at this site, and investigation of their sediment infill may in future help to clarify the Holocene alluvial history of the upper South Tyne basin.

RIVER NENT, BLAGILL, CUMBRIA (NY 745466)

Highlights

This site in the Nent valley (one of the most intensely mined parts of the Northern Pennines) provides a rare combination of cartographic, geomorphological and trace metal evidence that can be used to interpret the sequence and causes of historical river metamorphosis.

Introduction

The River Nent at Blagill was the first site in England at which metal mining and flood-related channel and floodplain metamorphosis were demonstrated (Macklin, 1986). It also provided the impetus for subsequent examinations of the impact of historical flooding and metal mining in other

Figure 5.7 Blagill, River Nent, looking upstream in a southwesterly direction, showing an abandoned braided channel system dating from *c.* 1896–1950 which is currently being entrenched by the present river. (Photo: M.G. Macklin.)

river systems of the Northern Pennines (Macklin and Aspinall, 1986; Macklin and Lewin, 1989; Macklin *et al.*, 1994a; Rumsby and Macklin, 1994). Channel and floodplain sedimentation patterns can be documented in considerable detail at this site over a 200 year period, which constitutes the longest record of historic river channel change in northern England.

Description

The site is located 2.5 km east of Alston, Cumbria (Figure 5.1), along a 925 m reach of the River Nent between Foreshield Bridge (NY 748467) and an unnamed bridge just south of Blagill (NY 740469). Evidence of recent channel metamorphosis initially drew attention to this site, at which a number of poorly vegetated, elongate gravel bars, typical of those found within a multi-channel braided river system, are currently being incised by a single-thread channel of much lower sinuosity (Figure 5.7). Three valley floor river landform elements were identified in the reach (Figure 5.8). The first of these, located on the north-eastern side of the Nent valley, is a low alluvial terrace 1.5 – 3.0 m above the present river bed. Serial cartographic and photographic sources have shown that this terrace lay beyond that part of the valley floor reworked by the channel since 1775. During this period, judging from the fine-grained nature of its deposits, it had received sediment only when floodwaters had overtopped the river bank. Trace metal analyses of laminated silts and silty sands which make up this unit revealed high metal concentrations throughout the sequence (Figure 5.9), indicating that it had been deposited during a period of large-scale mining (in the Nent valley, this dates from 1680). High zinc concentrations in the upper 0.5 m of this alluvial unit mark the advent of zinc mining in the Nent catchment, which began shortly after 1880 (Dunham, 1990). Lead production peaked shortly before this (1840 – 80) and maximum lead concentrations are recorded in sediments immediately below those with highest zinc levels.

The second major historical alluvial unit at Blagill is an abandoned braided channel system, up to 1.5 m above the present river bed (Figure 5.8), which historical maps and aerial photographs show to have been active from the middle of the 19th century until the late 1940s.

The present-day channel and floodplain (post *c.* 1950) form the third valley floor element. They are incised and inset within mining-age alluvium, with contemporary stream flow confined to a single-thread channel located towards the centre of the valley floor. The contemporary channel has low width : depth ratios except where erosion has

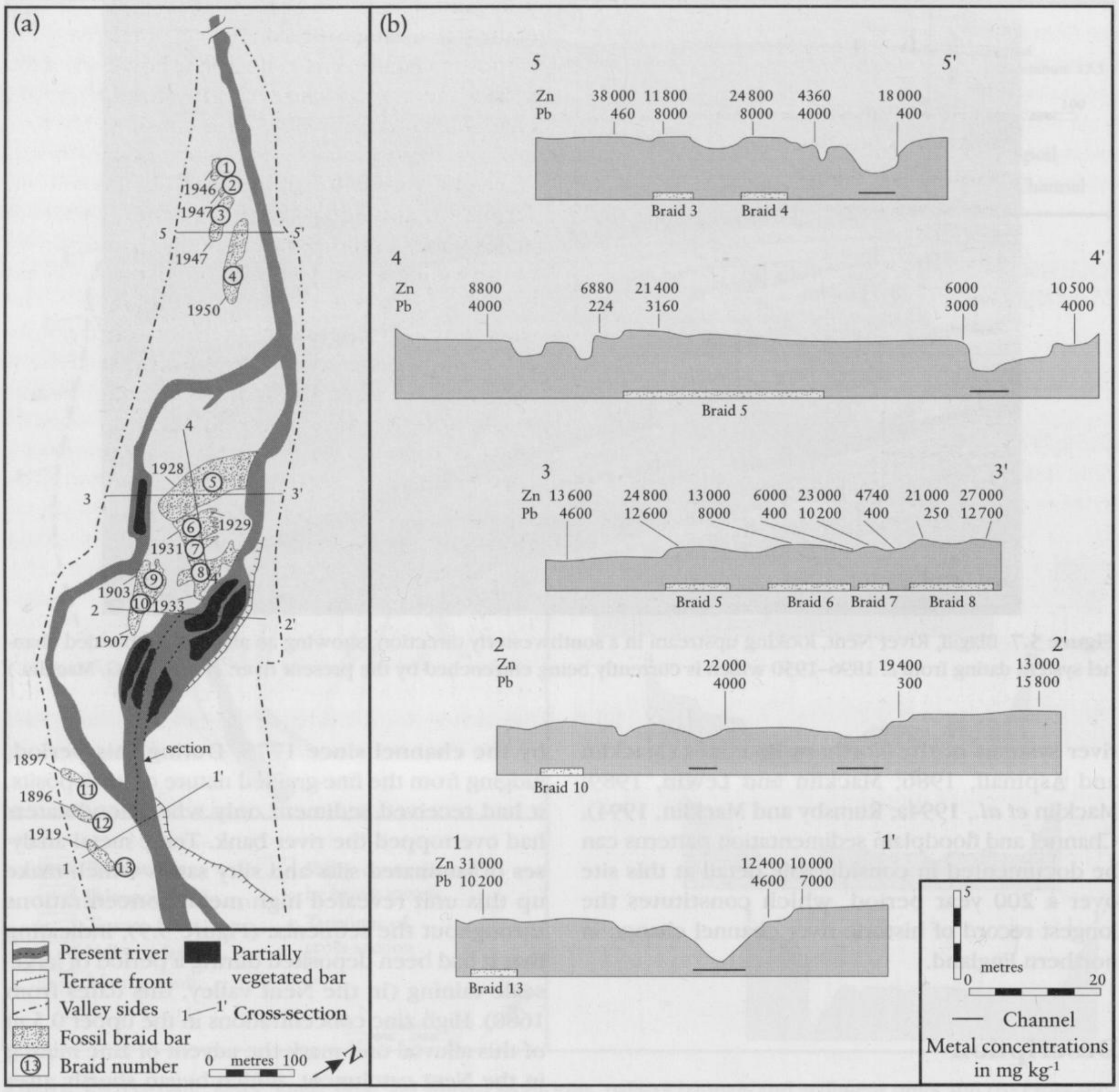


Figure 5.8 Nent valley at Blagill: (a) alluvial landforms, sediment units and metal concentrations in the historical floodplain and earlier alluvial sediments; (b) cross-sections. (After Macklin, 1986).

removed older alluvium and coarse sedimentation occurs in the form of small point-bar complexes or lobate bars. Channel avulsion during a major flood in August 1986 breached the valley floor adjacent to palaeo-braid bar 10 (Figure 5.8) and resulted in the abandonment of a channel on the south side of the site downstream of cross-section 3 (Figure 5.8).

Interpretation

An excellent range of large-scale topographic maps and aerial photographs, spanning the period 1775 – 1984, enables changes in channel position and river planform at the site to be documented in more detail over the past 200 years (Figure 5.10). In addition, lichen-based age estimates of poorly vegetated gravel units allow channel bar development and abandonment to be examined between *c.* 1896 and 1950. Braiding began initially in the most upstream part of the study reach (Figure 5.10), followed between 1896 and 1950 by an intermittent downstream movement of coarse gravel in the form of a jerky sediment wave (Figures 5.8 and 5.10).

Maps show the River Nent at Blagill over a 60

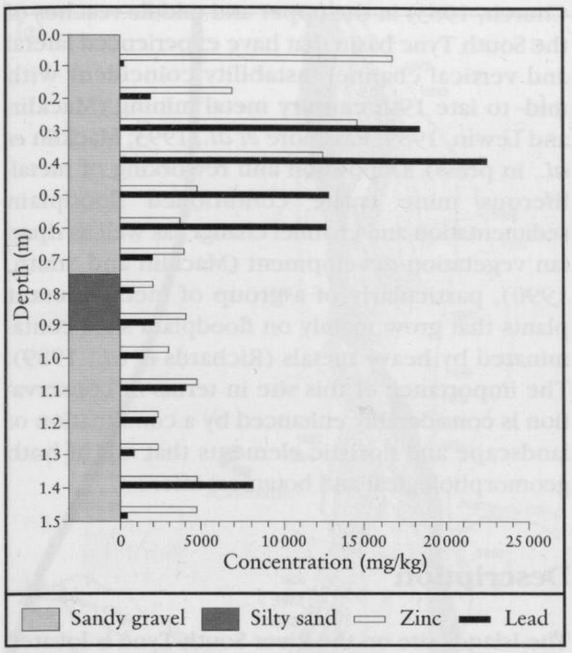


Figure 5.9 An up-section plot of metal concentrations in the low alluvial terrace at Blagill. The location of the section is shown in Figure 5.8. (After Macklin, 1986.)

year period between 1775 and after 1840, as a laterally stable, single-thread channel of relatively low sinuosity (Figure 5.10). By 1861, however, a dramatic metamorphosis of the floodplain and channel had taken place, with considerable bank erosion, deposition of gravel and a change from a single- to a multi-thread channel. The initial transformation appears to have followed a series of major floods in the 1840s, although metal mining, by providing a ready source of coarse sediment, both indirectly prepared the site for metamorphosis and also perpetuated the transformation by continuing to supply waste of bedload calibre to the river system. Furthermore, severe metal contamination of the valley floor significantly retarded post-flood floodplain stabilization by preventing vegetation from recolonizing alluvial surfaces. Post-mining (after World War Two) floodplain re-adjustment has involved rationalization and simplification of the channel system into a single rather sinuous channel, as the river has incised through its alluvial valley floor. Since 1948 significant departures from this adjustment to reduced rates of sediment supply have occurred only during major floods, when old channels have been temporarily re-occupied.

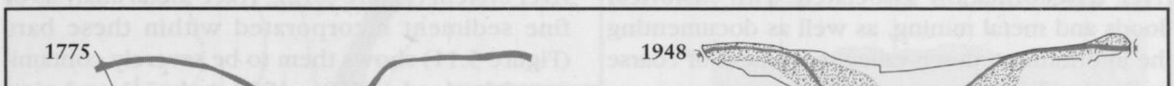


Figure 5.10 Channel change at Blagill, River Nent, 1775 - 1984. (After Macklin, 1986.)

Investigation of the recent alluvial history of the River Nent at Blagill can be considered to be exemplary in its use of field mapping, serial historical maps and aerial photographs, lichenometry and trace metal analysis for elucidating the role of floods and metal mining in channel and floodplain metamorphosis. It is one of only a handful of sites in England and Wales, outside the South Tyne basin, where historical channel and floodplain transformation has been documented. In addition, it is the only site in Britain (with the exception of Black Burn, Cumbria) at which it has been possible to date and map the down-valley passage of a sediment wave. Finally, it demonstrates the value of trace metals as stratigraphic markers within sequences of fluvial sediments in a region in which the development and history of metal mining is known in some detail.

Conclusion

The River Nent at Blagill has the longest (1775 - 1984) and the most detailed map and aerial photograph based record of channel change in northern England. Cartographic and photographic sources, together with field mapping, lichenometry and trace metal analysis, have been used to date river transformation associated with historical floods and metal mining, as well as documenting the intermittent, down-valley movement of coarse bedload sediment.

THE ISLANDS (ALSTON SHINGLES), RIVER SOUTH TYNE, CUMBRIA (NY 716441 – NY 716454)

Highlights

This is an important locality for the study of river channel planform change and terrace formation associated with mining activity and a series of major flood events in the 19th century. In addition, late 19th to early 20th century age river terraces, severely polluted by heavy metals, provide a habitat for rare metallophyte plants.

Introduction

The Islands (Alston Shingles) is one of a series of historical alluvial sedimentation zones (*sensu* Church, 1983) in the upper and middle reaches of the South Tyne basin that have experienced lateral and vertical channel instability coincident with mid- to late 19th century metal mining (Macklin and Lewin, 1989; Passmore *et al.*, 1993; Macklin *et al.*, in press). Deposition and reworking of metalliferous mine waste conditioned floodplain sedimentation and channel change, as well as riparian vegetation development (Macklin and Smith, 1990), particularly of a group of metal-tolerant plants that grow mainly on floodplain sites contaminated by heavy metals (Richards *et al.*, 1989). The importance of this site in terms of conservation is considerably enhanced by a combination of landscape and floristic elements that are of both geomorphological and botanical interest.

Description

The Islands site on the River South Tyne is located 1 km south of Alston. It is a relatively large alluvial basin (1.3 km long and between 150 and 250 m wide), in which most of the valley floor dates from the mid-19th century. Preserved on the valley floor adjacent to Scalebank farm (Figures 5.1 and 5.11) are a series of gravel bar forms typical of those found in a multi-channel, braided river system (Figure 5.12). Trace metal analysis of fine sediment incorporated within these bars (Figure 5.11) shows them to be severely contaminated by lead (3750 - 4500 $mgkg^{-1}$) and zinc (6750 - 36 350 $mgkg^{-1}$). However, they do provide the habitat for uncommon metallophyte plant communities that include species such as *Thlaspi alpestre* and *Minuartia verna* (Richards *et al.*, 1989). The source of these metals is a large number of disused lead mines in the upper South Tyne and Black Burn catchments. Lichenometric-based age estimates of these bars show them to date from 1872 - 1907 (Figure 5.11), with no metallophyte plants recorded on older or younger deposits at the site (Macklin and Smith, 1990).

Serial historical maps and aerial photographs over the period 1860 - 1975 show a complicated pattern of channel change (Figure 5.13). In the middle 19th century the River South Tyne at the Islands reach was a single-thread channel of comparatively low sinuosity, with side, point and mid-channel bars. By 1898, however, this was replaced by a multi-channel river that divided around large (200 - 300 m in length), lozenge-shaped bar complexes. The western channel, into which Brown Ghyll presently drains (Figure 5.13;

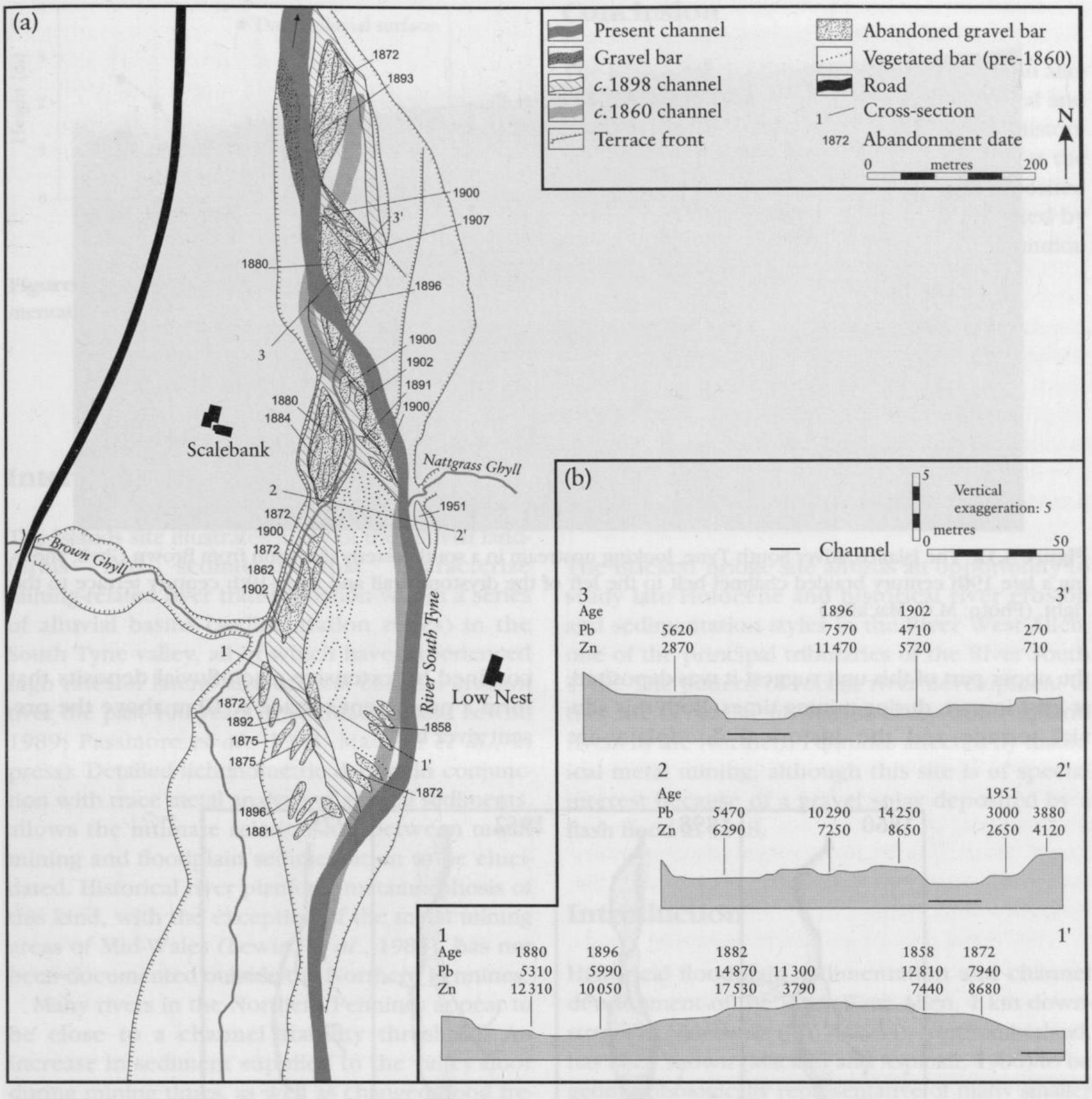


Figure 5.11 The Islands, River South Tyne: (a) alluvial landforms and palaeochannels and metal concentrations in historical and earlier alluvial units; (b) cross-sections and lead and zinc concentrations.

first shown on the 1898 map), appears to have been formed by an avulsion across the floodplain some time between 1862 and 1874 (lichenometric age estimates).

Channel transformation occurred during a period of valley floor incision (Figure 5.14) that had begun some time before the mid-19th century. The height of bed material sedimentation decreased rapidly in the late 19th century, to a level approaching that of the present channel. Since the turn of the century, construction of bank protection structures in the upstream part of the reach, and further bed incision, have prevented the western anabranch from being re-occupied (Figure 5.11). The present channel is similar in form to that of 1860, but has significantly less active gravel and is of lower sinuosity.

Coarse-grained alluvium deposited in the 19th and early 20th centuries is inset into two older valley fills. The youngest lies between 3 and 4.5 m above the present river bed level, and comparatively high lead concentrations in sediments within

Figure 5.12 The Islands, River South Tyne, looking upstream in a southeasterly direction from Brown Ghyll, showing a late 19th century braided channel belt to the left of the drystone wall and a pre-19th century terrace to the right. (Photo: M.G. Macklin.)

the upper part of this unit suggest it was deposited, at least in part, during mining times. Both this alluvial terrace and the historical floodplain are confined by extensive glaciofluvial deposits that form a prominent terrace *c.* 10 m above the present river bed.

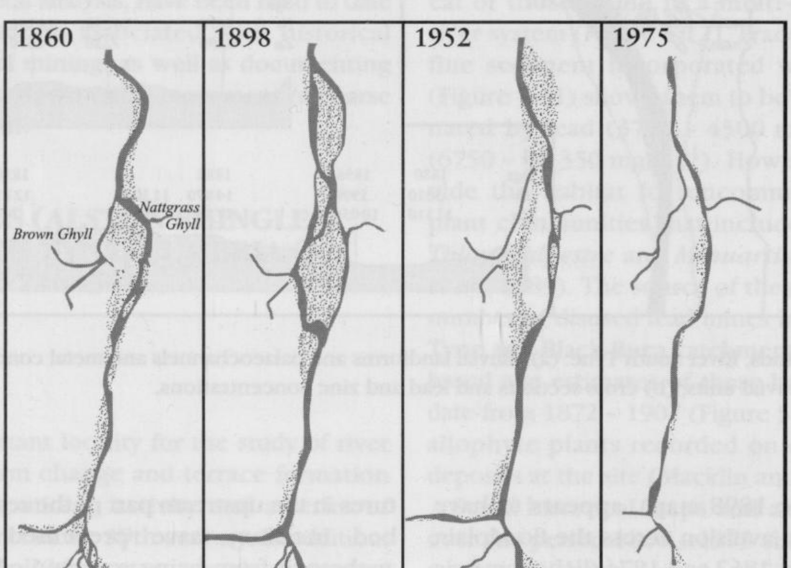


Figure 5.13 Channel change at the Islands, River South Tyne, 1860–1975. (After Macklin and Lewin, 1989.)

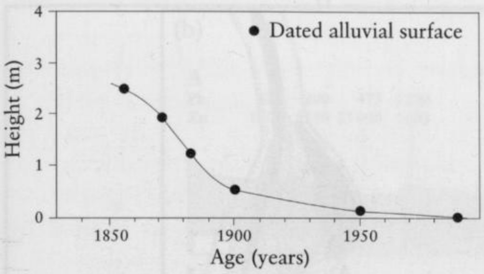


Figure 5.14 Changes in the height of bed material sedimentation at the Islands, 1858–1987.

Interpretation

The Islands site illustrates many of the alluvial landforms and sediments that characterize mining-related river transformation within a series of alluvial basins (sedimentation zones) in the South Tyne valley, all of which have experienced high rates of lateral and vertical channel erosion over the past 100 years or so (Macklin and Lewin, 1989; Passmore *et al.*, 1993; Macklin *et al.*, in press). Detailed lichenometric dating, in conjunction with trace metal analysis of alluvial sediments, allows the intimate relationship between metal mining and floodplain sedimentation to be elucidated. Historical river planform metamorphosis of this kind, with the exception of the metal mining areas of Mid-Wales (Lewin, *et al.*, 1983), has not been documented outside the Northern Pennines.

Many rivers in the Northern Pennines appear to be close to a channel stability threshold. An increase in sediment supplied to the valley floor during mining times, as well as changed flood frequency and magnitude in the latter part of the 19th century (Macklin and Lewin 1989; Rumsby and Macklin, 1994), together induced river metamorphosis. Following the closure of mines shortly before World War Two, the South Tyne and most of its tributaries affected by historical mining (Black Burn and Rivers Nent, West and East Allen) have incised through mining age alluvium which now forms a terrace 1.5–2.5 m above the present channel, on the surface of which braided palaeochannel traces are common. This comparatively brief but well documented episode of mining-related alluviation in the Northern Pennines, well illustrated by the Islands reach of the River South Tyne, may provide a useful analogue for terrace formation processes in other coarse-grained fluvial systems.

Conclusion

The Islands reach of the River South Tyne is an alluvial basin that experienced accelerated lateral and vertical channel instability associated with historical metal mining and altered flood regimes at the end of the 19th century. Alluvial gravels deposited during this period are severely contaminated by heavy metals, but provide a habitat for uncommon metallophyte plants.

BLACKETT BRIDGE, RIVER WEST ALLEN, NORTHUMBERLAND (NY 780540)

Highlights

The Blackett Bridge site affords an opportunity to study late Holocene and historical river erosion and sedimentation styles in the River West Allen, one of the principal tributaries of the River South Tyne. The pattern of recent river development at this site is similar to that of many other upland rivers in the Northern Pennines affected by historical metal mining, although this site is of special interest because of a gravel splay deposited by a flash flood in 1848.

Introduction

Historical floodplain sedimentation and channel development of the River West Allen, 1 km downstream of Ninebanks (NY 782533), Northumberland, has been shown (Macklin and Aspinall, 1986) to be geomorphologically representative of many smaller river valleys (e.g. East Allen, Devil's Water and the Derwent) that drain the north and north-east parts of the Northern Pennines. All valleys in this part of the Northern Pennines are underlain by Namurian rocks of Carboniferous age, and were considerably modified during Pleistocene glaciations and grossly polluted by historical metal mining. Recent river deposits and Quaternary alluvial landforms at this site therefore serve as a useful benchmark for future studies of valley floor development in the region.

Description

The extent to which valley floors in the Northern Pennines have been reworked by recent lateral channel migration appears to depend on whether channels are located in a basin, where postglacial incision has removed earlier Pleistocene deposits and contemporary rates of channel migration are generally high, or in steeper gradient rock or drift-bound reach where lateral channel movement is restricted. In this respect the River West Allen, along a 1150 m reach centred on Blackett Bridge (NY 781540), is morphologically typical (Figure 5.15(a)). The locality includes two alluvial basins, each approximately 400 m in length and up to 200 m wide which, over the period of topographic documentation (1859 to the present), have been characterized by comparatively high rates of both lateral and vertical channel movement. These sedimentation zones are separated by a short (200 m), narrow (70 m) reach where the channel is confined by Pleistocene glacial deposits.

Above the level of the historical floodplain, three terraces are evident; the highest (T1, 20 m above the bed of the present river) is of Pleistocene age and comprises glaciofluvial gravels overlying till. There are two younger Holocene river terraces; the oldest (T2) lies 3 m above the present river bed and comprises 2.5 m of horizontally bedded sandy gravels overlain by 0.5 m of silty sands. A tree trunk recovered from the base of the gravel member has been ^{14}C dated to *c.* 410 cal AD and shows, similarly to many other sites (e.g. Black Burn) in the upper South Tyne basin, a major phase of valley floor gravel aggradation during, or shortly after, the Roman period (Macklin *et al.*, 1992a; Passmore et al., 1993). The second and lower Holocene terrace (T3) lies 2 m above the present river level and is composed of laminated silts and sands. Trace metal analysis of these sediments shows the whole unit to be highly contaminated with lead (2100 – 9200 mgkg^{-1}; Figure 5.15). Although today T3 lies above the level of major floods, it clearly was a site of active overbank sedimentation sometime during the period of large-scale lead mining in the West Allen valley, that took place between 1694 and 1880.

Since the end of the 19th century there has been a general reduction in floodplain width, particularly in the northern alluvial basin, and also a progressive decrease in the area of active gravel and total channel sinuosity (Figure 5.16). Downstream at Blackett Bridge incision of the river bed, following a major flood in October 1900, has resulted in the preservation of an extensive area of coarse-grained alluvium that dates from the turn of the century (Figure 5.17). This includes, on the west side of the valley (opposite Whamlands Farm, Figure 5.16), an

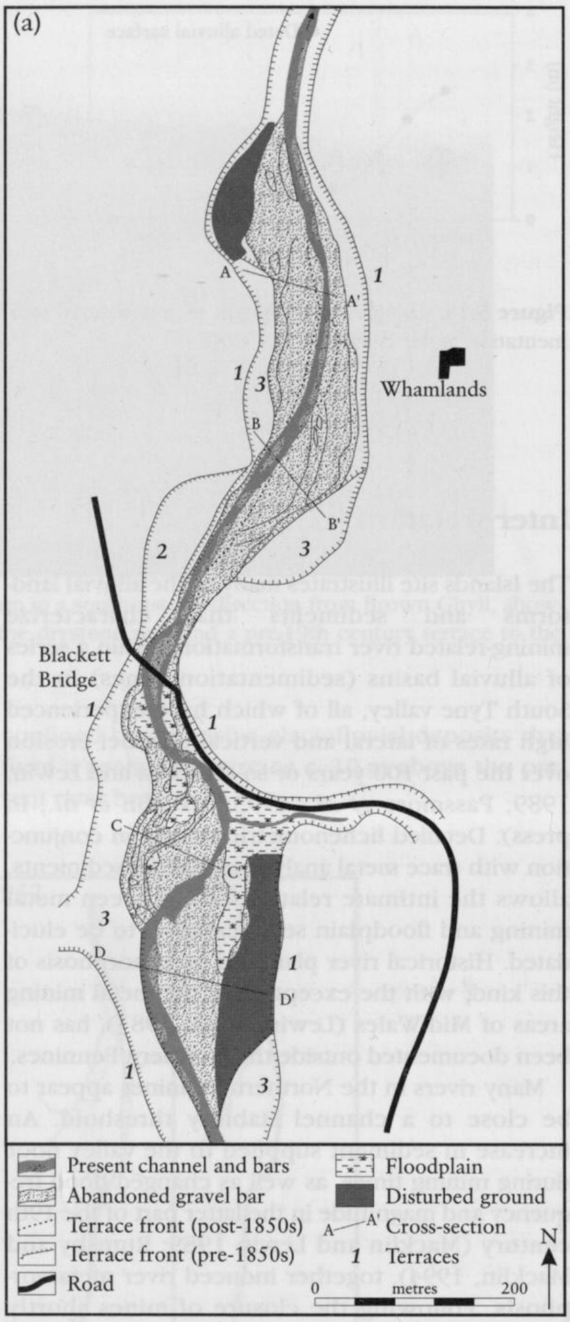


Figure 5.15 (a) Blackett Bridge, River West Allen. Floodplain and valley floor morphology, cross profiles and metal concentrations for alluvial units. (After Macklin and Aspinall, 1986.)

elongate gravel splay, convex in cross-section (Figure 5.15(a); cross-section A), believed, on the basis of lichen-based age estimates, to have been deposited during a flash flood in 1848. All 19th century alluvial gravels are heavily contaminated by

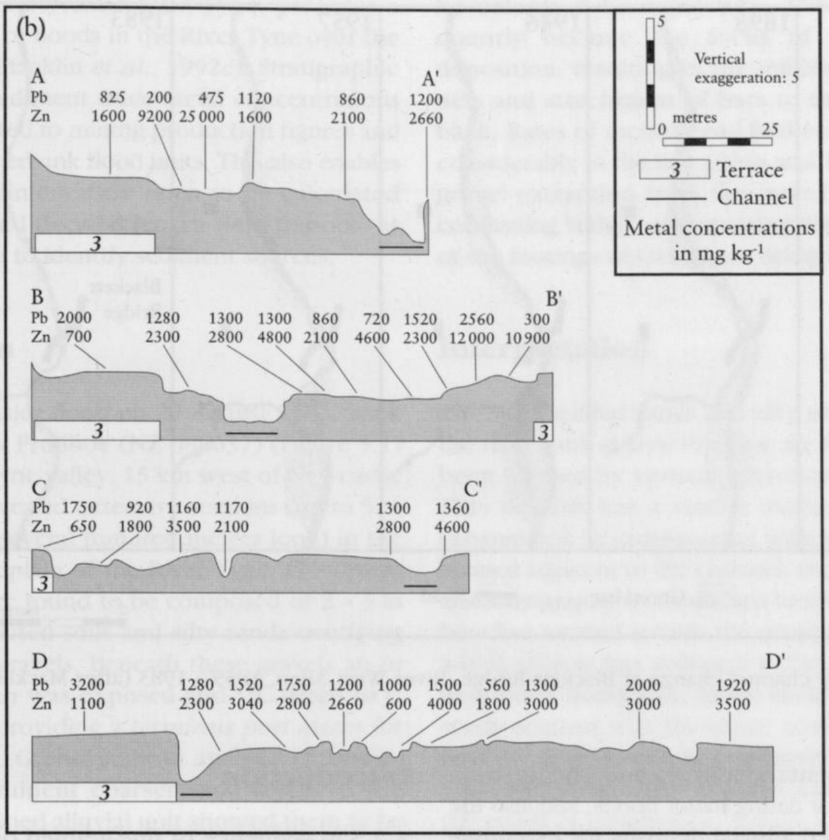


Figure 5.15 (b) Blackett Bridge, River West Allen. Cross-sections. (After Macklin and Aspinall, 1986.)

fine-grained metal ore waste released by upstream lead and zinc mining. These gravels do, however, provide a habitat for metallophyte plants.

Interpretation

Blackett Bridge in the West Allen valley, along with Lambley in the middle South Tyne valley (Passmore *et al.*, 1993; Macklin *et al.*, in press), is one of only a handful of sites in the Northern Pennines at which river dynamics in contiguous alluvial basins, one currently active and one recently stabilized, can be compared. It provides an excellent example of 'space for time' substitution, which gives a useful insight to the processes controlling alluvial basin development in the region. The site is also of some botanical importance, in that the Rivers West Allen and Nent are the only major tributaries of the South Tyne where metallophyte plants have been recorded growing on historical alluvium.

Conclusion

Investigation of the alluvial valley floor in the West Allen valley at Blackett Bridge shows how channel development and deposition have been conditioned by the configuration of earlier postglacial and Pleistocene valley fills. Two contiguous alluvial basins at the site, one currently active and the other recently stabilized, illustrate both contemporary and late Holocene river sedimentation and erosion processes that appear to be typical of many Northern Pennine rivers.

RIVER TYNE AT LOW PRUDHOE, NORTHUMBERLAND (NZ 088637)

Highlights

Exposures of floodplain sediments at Low Prudhoe provide a record of flooding in the lower Tyne valley over the past 100 years. This site illustrates the

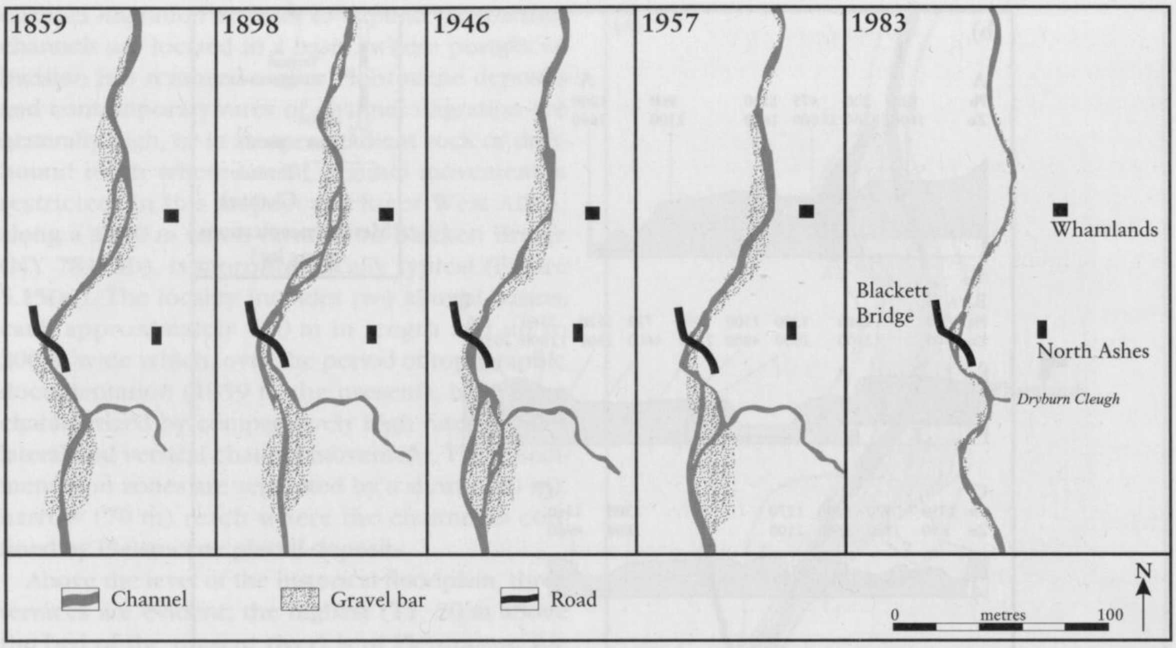


Figure 5.16 River channel change at Blackett Bridge, River West Allen, 1859 – 1983 (after Macklin and Aspinall, 1986.)

value of documentary sources and chemostratigraphic studies for dating major floods, and also the use of fine-grained alluvial deposits for extending the flood series.

Introduction

A 2.5 m sequence of fine-grained overbank sediments at Low Prudhoe in the lower Tyne valley,

Figure 5.17 Blackett Bridge, River West Allen, looking downstream in a northerly direction, showing a late Roman age terrace on the left of the present channel and a 19th century terrace on the right. (Photo: M.G. Macklin.)

1 km west of Newcastle-upon-Tyne, provides a unique record of floods in the River Tyne over the past century (Macklin *et al.*, 1992c). Stratigraphic variations in sediment trace metal concentrations have been related to mining production figures and used to date overbank flood units. This also enables floodplain sedimentation rates to be calculated over annual and decadal length time periods, as well as helping to identify sediment sources.

Description

Following a major flood on 26 August 1986, bank erosion at Low Prudhoe (NZ 088637) (Figure 5.1) in the lower Tyne valley, 15 km west of Newcastle upon Tyne, revealed extensive sections (up to 5 m in height and several hundred metres long) in the historical floodplain of the River Tyne. Floodplain sediments were found to be composed of 2 – 3 m of finely laminated soils and silty sands overlying 2 m of sandy gravels. Beneath these gravels an *in situ* tree stump was exposed and ^{14}C dated to *c.* 1460 cal AD, providing a *terminus post quem* for the sequence. Granulometric analysis (Rumsby, 1991) of prominent coarser sand layers in the upper fine-grained alluvial unit showed them to be similar to sands deposited overbank on the Tyne floodplain during the August 1986 flood (Macklin and Dowsett, 1989), suggesting that sediments at this site could provide a valuable record of recent major floods in the lower Tyne valley. Although unusually good exposure of alluvium at Low Prudhoe initially prompted sedimentological and stratigraphic-based studies of recent floods in the lower Tyne valley, flood stones on the Rectory steps at Ovingham (Figure 5.18), marking the heights of the great floods of 1771 (the largest on record) and 1815, together with good archive records (newspapers, local books and journals and meteorological publications) of major floods in the Tyne catchment since 1699 (Rumsby, 1991; Archer, 1992), make Low Prudhoe an excellent site at which to compare documentary and sedimentary flood records.

Over the past 130 years or so, the thalweg of the Tyne at Low Prudhoe has moved very little (Figure 5.18(a)), but since the early 1950s its channel has narrowed appreciably, most notably in a 500 m reach downstream of Ovingham Bridge, within which the study section is located. Channel narrowing has been primarily the result of incision which elevated former lateral gravel bars above the level of the low-flow channel and enabled them to be colonized by vegetation. These sites subsequently became the focus of fine sediment deposition, resulting in the infilling of side channels and attachment of bars to the former river bank. Rates of incision and bed erosion increased considerably in the late 1950s and 1960s following gravel extraction from the river bed, and is still continuing today, necessitating regular upgrading of the footings of Ovingham Bridge.

Interpretation

The well-bedded sands and silty sands exposed in the river bank at Low Prudhoe are believed to have been formed by vertical accretion (Figure 5.19). This deposit has a similar surface morphology (asymmetric in cross-section with its highest point located adjacent to the channel; see Figure 5.18(b)) and stratigraphy to shrub- and herb-covered alluvial benches located *within* the present Tyne channel which accrete fine sediment to the level of the contemporary floodplain. Initial sedimentation at the study section was therefore under sub-bankfull flow conditions, with fine sediment deposition confined within the channel banks. Later sediments, as the result of progressive vertical accretion, would tend to be deposited under flow conditions close to bankfull and also by overbank floods. Thus a considerable proportion of fine-grained alluvium at Low Prudhoe is believed to represent the vertical component of within-channel sedimentation, and is of a somewhat different origin from overbank fines (usually of silt and clay size and deposited some distance from the channel) more frequently described on British floodplains (e.g. Lambert and Walling, 1987).

Flood events in fine-grained alluvial deposits at Low Prudhoe are represented by layers of generally flat-bedded sands and silty sands (Figure 5.20), which on the basis of grain size can be assigned to one of three sedimentary categories; medium–fine sand, fine–very fine sand or silty fine sand. Following Knox (1987), textural discontinuities formed by layers of medium–fine (type 1 flood unit) and fine–very fine sand (type 2 flood unit) which reverse the overall fining upward sequence are interpreted as the deposits of large floods. Finer-grained silty sands (type 3 flood unit) are believed to represent lower magnitude floods or sediment deposited on the falling stage of a large flood event. Twenty-five large flood events would appear to be represented in the alluvial profile at Low Prudhoe, and these have been dated by relating sediment

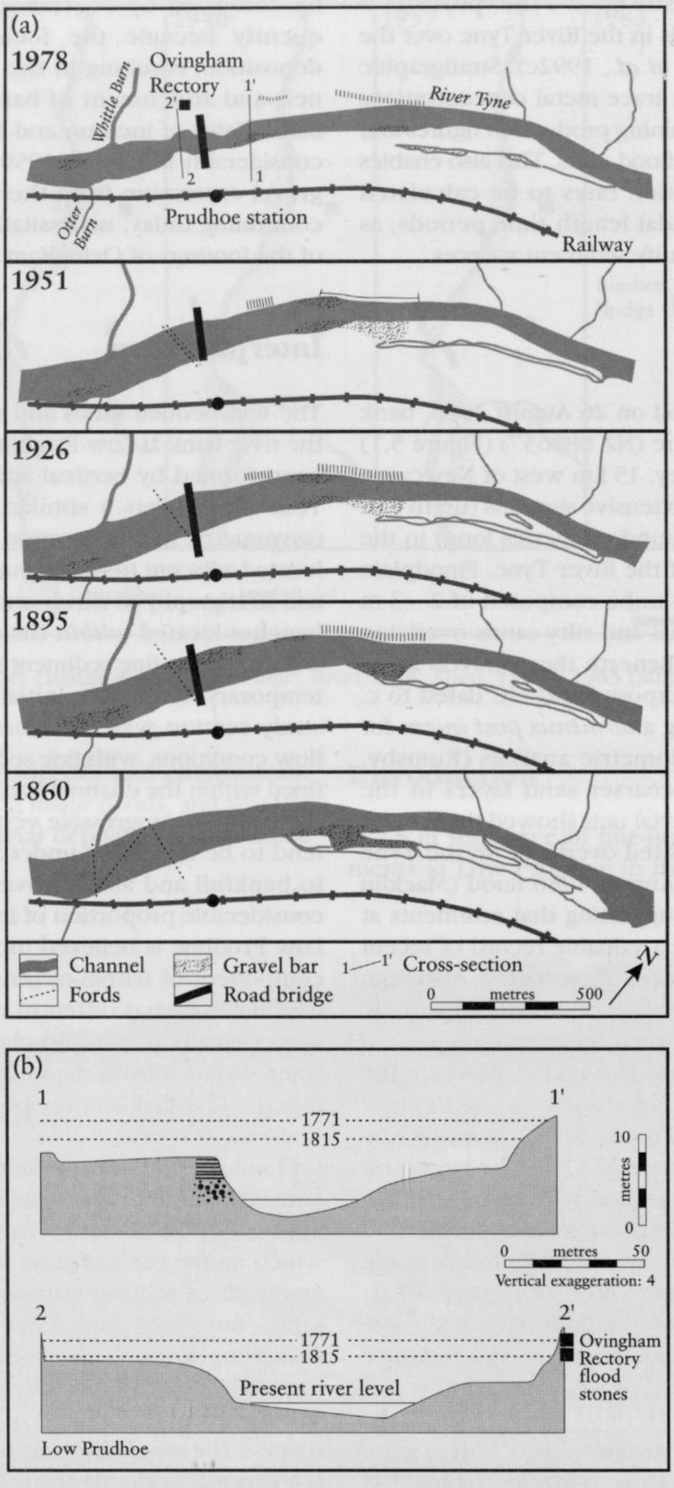


Figure 5.18 (a) Maps showing channel change at Low Prudhoe between 1860 and 1978, and the location of the sections. (b) Valley floor and channel cross-sections upstream and downstream of Ovingham bridge: the relative heights of the 1771 and 1815 floods are indicated. (After Macklin *et al.*, 1992c.)

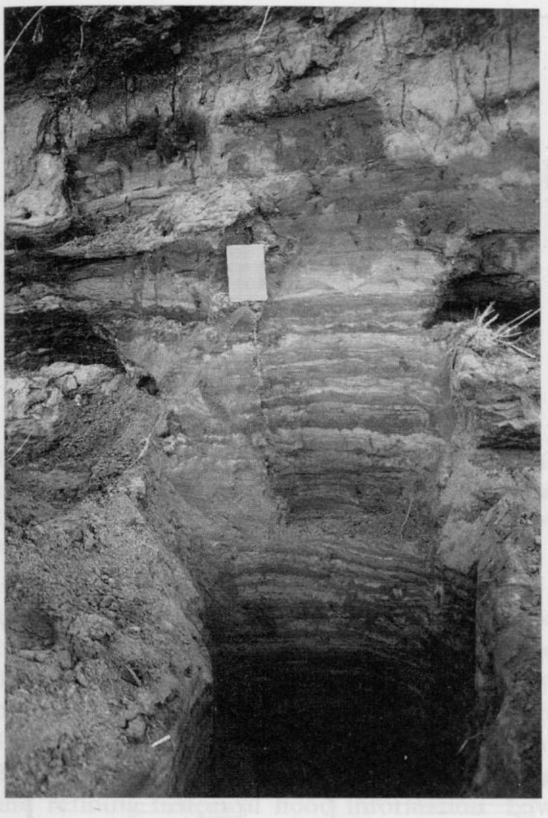


Figure 5.19 Low Prudhoe, River Tyne: a section of the late 19th and early 20th century fine-grained alluvium. Lighter layers are sand units representing major flood events. Scale: 0.2 m. (Photo: M.G. Macklin.)

trace metal concentrations to lead and zinc production in the Northern Pennine orefield (Macklin *et al.*, 1992c).

As has been shown in mining-age alluvium elsewhere in the Tyne basin (Macklin and Lewin, 1989; Macklin *et al.*, 1994a), especially high zinc levels mark the peak of zinc extraction in the Allendale and Alston Moor orefields between 1897 and 1915. At Low Prudhoe this is evident in sediments between 196 and 118 cm in the section. Above 118 cm zinc concentrations decline, corresponding with the demise of zinc mining in the region after 1915. Comparatively low lead levels (<1000 mgkg^{-1}) between 118 and 90 cm indicate that sedimentation at Low Prudhoe post-dates the main phase of lead production in the Tyne basin, which ended in 1880, confirming age estimates provided by sediment zinc concentrations. Above 90 cm, lead concentrations rise in response to the revival of lead mining in the 1920s and 1930s. Peaks in lead production in 1927, 1933 and 1937 are reflected by increased lead concentrations in flood sediments and decreased zinc : lead ratios at 56, 28 and 24 cm. Trace metal dating of fine-grained alluvial sediments at Low Prudhoe therefore indicates that the major part of the sequence was deposited over a comparatively short period of time (*c.* 50 years) between 1890 and 1937.

On the basis of dating control provided by sediment heavy metal analyses, and in the knowledge that archive sources tend to record larger spatially extensive floods (Archer, 1992), flood units evident in the Low Prudhoe section were assigned as far as possible to documented floods since 1890 in the Tyne valley. However, not all flood units could be related to recorded flood events, and in these cases chemostratigraphic dating control provided general bounded time limits. In Figure 5.21 floods documented in the Tyne basin between 1890 and 1989 are plotted with the sedimentary flood record (where present) over the same period. The documentary flood record of the River Tyne between 1890 and 1949 shows an increase in flood frequency between 1890 - 1909 and 1920 - 1939 with relatively few floods in the decades 1910 - 19 and 1940 - 49. Flooding over this period (1890 - 1949) follows changing hydrometeorological conditions in north-east England, with increases in flood frequency corresponding with rainfall maxima recorded in the region during the late 19th century and again between 1920 and 1939 (Harris, 1985).

Most flood units deposited before 1900 appear to have resulted from sub-bankfull flows, many of which would not have been reported by local commentators or newspapers. The similar number of floods between 1900 and 1929 evident in both the stratigraphic and documented flood record, however, suggests that type 1 and 2 flood units were deposited during overbank events that inundated both the depositional bench at Low Prudhoe and the Tyne valley floor. Since 1930 an increase in the relative height of this surface above the river bed (resulting initially from sediment accretion and later by channel incision) has effected a 'censoring' of the alluvial stratigraphic record to reflect progressively less frequent and larger floods. Today, continuing river bed incision has enlarged the Tyne channel at Low Prudhoe to a size that can accommodate floodwaters in all but the very largest floods.

The disparity between the stratigraphic and documentary flood records at Low Prudhoe over the past 100 years probably reflects the latter's bias towards recording large overbank floods. Archive sources will therefore inevitably under represent

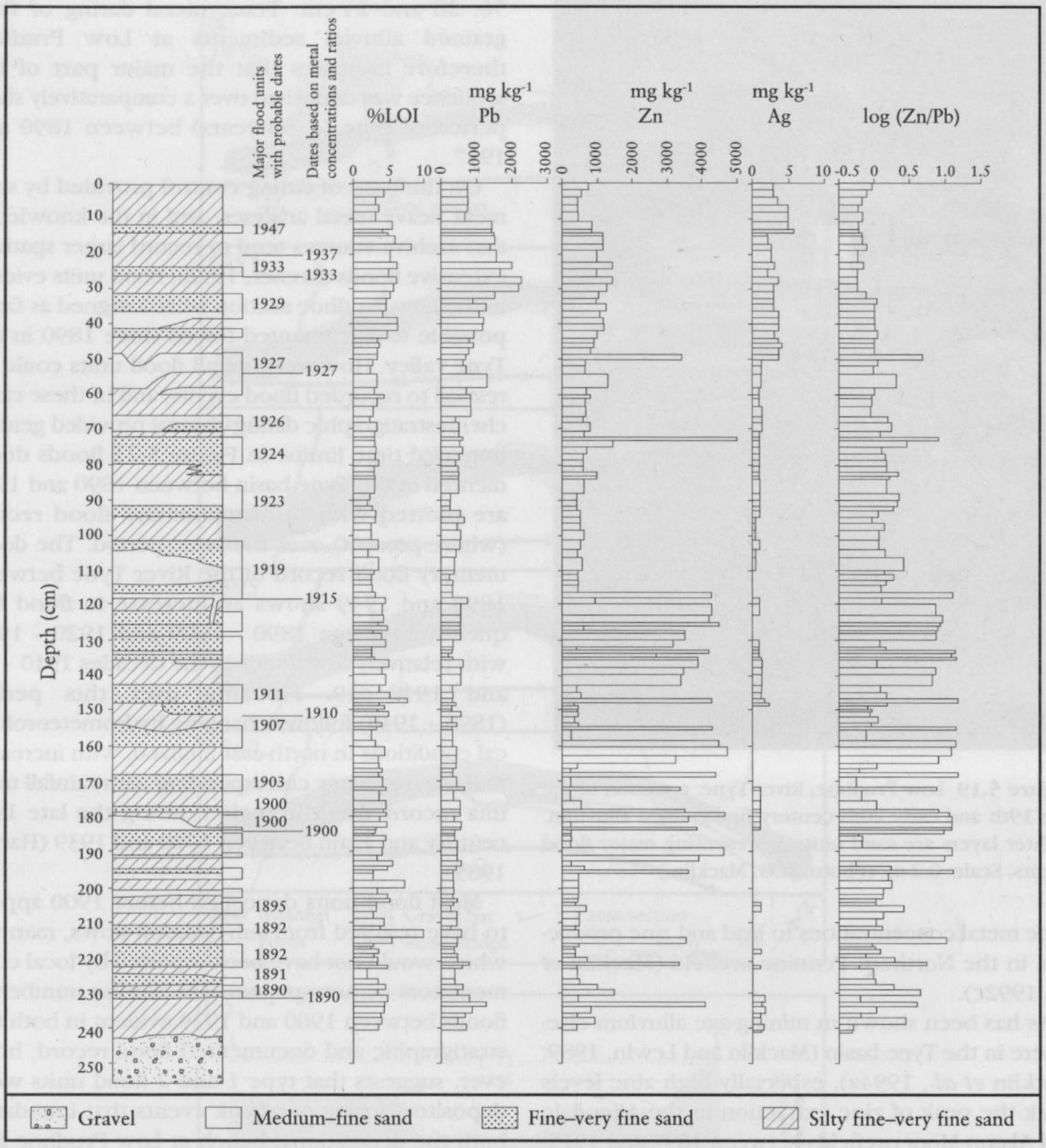


Figure 5.20 Metal concentrations and organic matter content in vertically accreted alluvium at Low Prudhoe, showing major flood units with their probable dates. (After Macklin *et al.*, 1992c.)

the actual number of flood events recorded in the stratigraphic record when a depositional surface is of low elevation and subject to inundation by low-magnitude floods. Deposition of fine-grained flood sediment within the Tyne channel (which in this particular study forms the basis of the palaeoflood record), although reflecting in a systematic way changes in flood flow magnitude and frequency (controlled primarily by climate), has also been strongly influenced by variations in sediment supply (associated with upstream bank erosion rates and input of mining waste) and entrenchment of the channel over the period of investigation. It is therefore imperative that sediment availability and the vertical tendency of a channel reach are evaluated, and quantified, before stratigraphic evidence at a site is used to extend the flood series in a river basin.

Studies of floodplain development at the Low Prudhoe site in the lower Tyne valley represent one of the most detailed investigations of longer-term vertical accretion yet undertaken in a major British river. From a methodological viewpoint it confirms the utility of trace metals for dating fine-

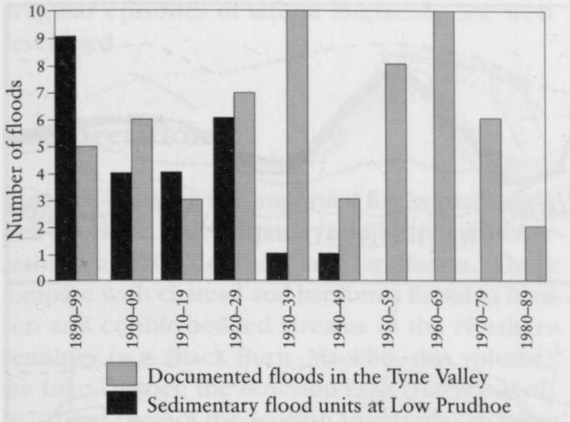


Figure 5.21 A comparison of floods documented in the lower Tyne valley and the sedimentary flood record at Low Prudhoe between 1890 and 1989. (After Macklin *et al.*, 1992c.)

grained alluvial sequences in large mineralized catchments. The identification of systematic differences between sedimentary and documentary-based estimates of flood frequency in the lower Tyne highlights the important contribution that fluvial geomorphologists can make to developing and refining historical flood information. Low Prudhoe is also of special significance with respect to the historical flood record of the Tyne, for it is one of only five sites in the catchment at which levels of major floods (marked by flood stones) in the past 200 years or so have been recorded (Archer, 1992). Comparison of documented floods in the lower Tyne valley with the sedimentary sequence at Low Prudhoe, however, demonstrates the inherent partiality of both types of historical flood record. Nevertheless, in combination, these records reveal a non-stationarity in the flood series which has been attributed, primarily, to recent climate change (Rumsby and Macklin, 1994).

Conclusion

Historical documentation of floods, together with sedimentological and trace metal analysis of fine-grained flood sediments, have been used to construct a flood record for the River Tyne over the past 100 years. Changes of trace metal concentrations in vertically accreted alluvium have been related to lead- and zinc-ore production in the Tyne basin and used to date flood events. Significant differences between documentary- and sedimentary-based estimates of the frequency of inundation emerge, but are shown to be the result of bias in archive sources towards recording large overbank events and the censoring of the alluvial stratigraphic record, as the result of variations in sediment supply and channel entrenchment, to reflect progressively less frequent and larger floods. Climate change, however, appears to be the underlying control of non-stationarity in the incidence of major floods in recent times.

HARTHOPE BURN, NORTHUMBERLAND (NT 961230)

Highlights

Harthope Burn is an upland stream in the Cheviot Hills, where dramatic flood-related river-channel change has been elucidated using cartographic evidence and lichenometric analysis.

Introduction

The upper Harthope valley was the first site in north-east England (and indeed is still the only river system in the Cheviot Hills) where historical planform change in a cobble/boulder-bedded upland river channel has been documented using Ordnance Survey maps, aerial photographs and lichenometry (Milne, 1982). Harthope valley is an important site for an assemblage of recent coarse-grained flood deposits and associated channel forms.

Description

The site, investigated by Milne (1982), is a 750 m long reach of Harthope Burn (NT 961230), a low-sinuosity, steep (0.01 m m^{-1}) boulder- and cobble-bedded stream (catchment area 14.8 km^2) in the Cheviot Hills (Figure 5.1). The historical floodplain (up to 100 m wide) is entrenched and inset within two low terraces (comprising coarse alluvial gravels) 4.4 and 2.5 m above the present stream bed (Figure 5.22). Valley sides are steep and mantled with soliflucted till. River-related landforms on the floodplain include arcuate depressions marking former channels and prominent relict mid-channel bars composed of cobbles and boulders.

Since 1897, historical map evidence shows a

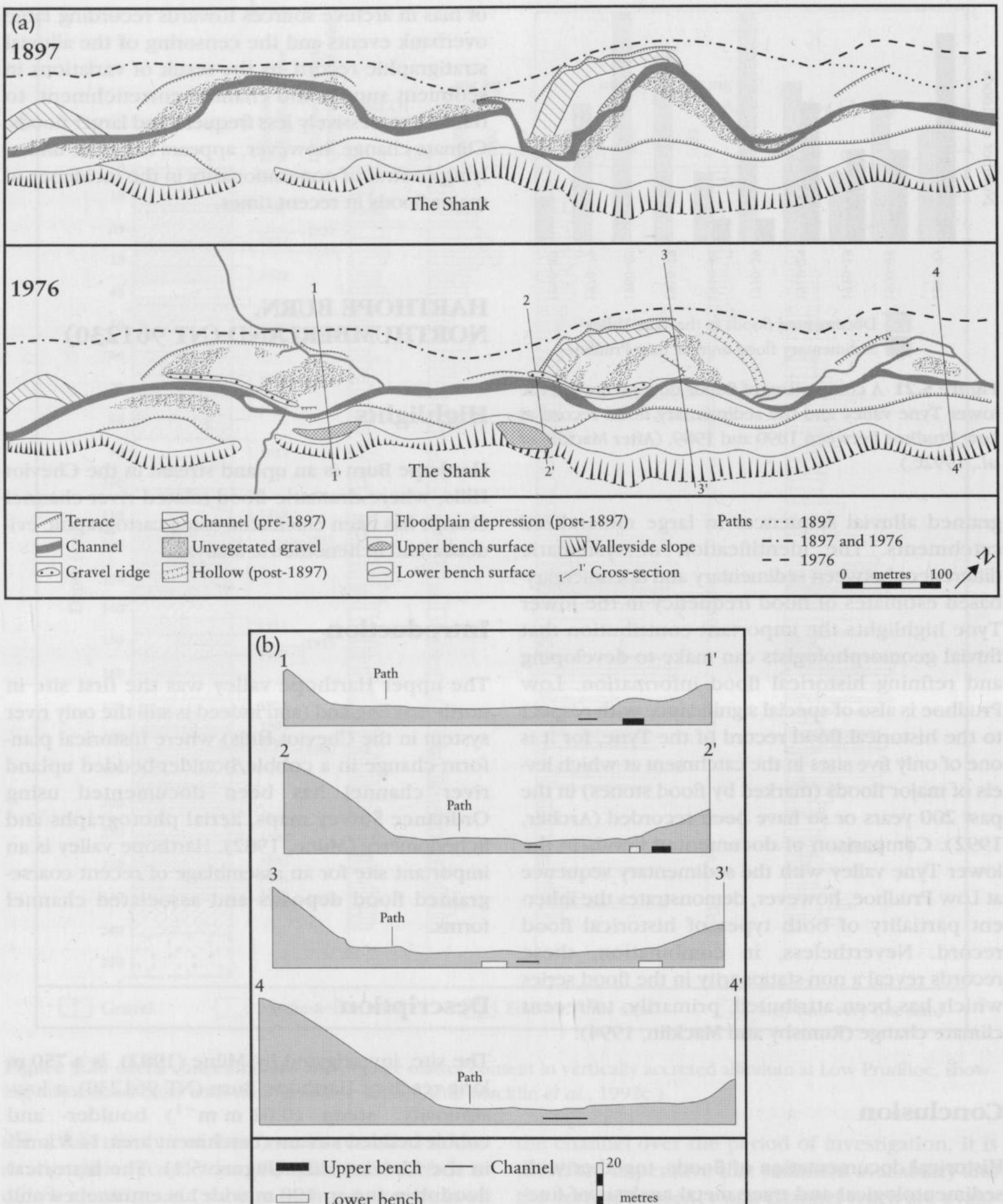


Figure 5.22 The Harthope study reach: (a) the channel position in 1897 and 1976, and (b) the present valleyside and floodplain features. (After Milne, 1982).

reduction in both reach sinuosity (a result of a series of low-sinuosity chute cutoffs during a major flood dated by lichenometry to the early 1930s) and mean channel width (Figure 5.22). In recent decades there has been an increased tendency towards braiding of the channel. Mid-channel bars, chutes and sloughs, typical bed and channel forms of an active gravel-bed channel experiencing irregular episodes of lateral migration, are well-developed.

Interpretation

Harthope Burn is a site important for its particularly well-developed contemporary and historical coarse-grained alluvial deposits and landforms. These compare with channel and bar forms found in boulder- and cobble-bedded streams in the Northern Pennines (e.g. Black Burn, Macklin, this volume), the Lake District, the Bowland Fells (Harvey *et al.*, 1979) and parts of the Scottish Highlands (McEwen and Werritty, 1988). Alluvial terraces of probable Holocene age are also found in the reach. These would repay investigation, as studies elsewhere in the Cheviots (Macklin *et al.*, 1991; Tipping, 1992) have shown that natural and human-induced environmental change, particularly during the late Holocene, has had a marked impact on valley floor development in the region.

Conclusion

Harthope Burn is a steep, boulder- and cobble-bedded stream in the Cheviot Hills which has particularly fine examples of contemporary and historical bar and channel-forms, recent coarse-grained flood deposits and Holocene river terraces. The channel changes have been documented using maps and lichen evidence.

SHAW BECK GILL, NORTH YORKSHIRE (NZ 000037–NZ 011059)

Highlights

The Shaw Beck catchment, North Yorkshire, contains excellent examples of deposition and erosion resulting from recent and historical large flood events. This site illustrates the important role of infrequent major floods in valley floor development in upland environments.

Introduction

Swaledale and Arkengarthdale, North Yorkshire, were severely affected by flooding on 25 and 26 August 1986 in the wake of 'Hurricane Charley'. This storm produced the wettest day ever recorded for England and Wales (Sawyer, 1987), and resulted in one of the most widespread flood events recorded in the century, especially in the North of England (Newson and Macklin, 1990). Of special geomorphological interest is a diverse and exceptional suite of alluvial deposits (boulder berms, debris-torrent lobes and fans) and landforms (channel avulsions, knickpoints and headcuts) produced by the flood in a series of small, north-bank tributaries of Arkle Beck, most notable of which is Shaw Beck (NZ 0005). In Shaw Beck there is also evidence of three earlier floods that appear to have been of a magnitude similar to that of Hurricane Charley. They are preserved as a series of boulder-covered terraces that, in some reaches, lie up to 5 m above the present river bed. Lichenometric age estimates show that the two younger flood deposits probably date to the 19th century.

Description

Shaw Beck is a very steep (0.045 m m^{-1}), boulder- and cobble-bedded stream (catchment area 7.5 km^2) draining part of the southern edge of Scargill Moor, which forms the interfluve between the Rivers Tees and Swale (Figure 5.1). Between 1700 hours on 25 August and 1500 hours on 26 August 1986, a total of 116.5 mm of rain was recorded in Arkengarthdale with a peak intensity of nearly 9.5 mm hr^{-1} (Newson and Macklin, 1990). This resulted in the overtopping and breaching of a small reservoir (0.2 ha in area, mean depth of 1.5 m), at the head of Shaw Beck, that sent a flood wave down the valley with an estimated peak discharge of 23.4 m^3s^{-1}. This broke through spoil heaps adjacent to the disused Stang Mine (NZ 009058) (Figure 5.23) and transported several thousand tonnes of coarse mining debris up to 300 m downstream, infilling and choking the pre-flood channel and burying the former floodplain to a depth approaching 1 m. Immediately downstream, however, at Shaw House (Figure 5.23), where the valley floor narrows, considerable erosion occurred during the flood, resulting in the stripping and flushing out of older alluvium and localized channel incision into bedrock in reaches underlain by interbedded shales and sandstones. There is a clear alternation between flood-eroded/incised and depositional reaches along Shaw Beck, their location being controlled primarily by valley floor width. Most coarse flood sediments were deposited at sites of flow expansion, where the valley floor

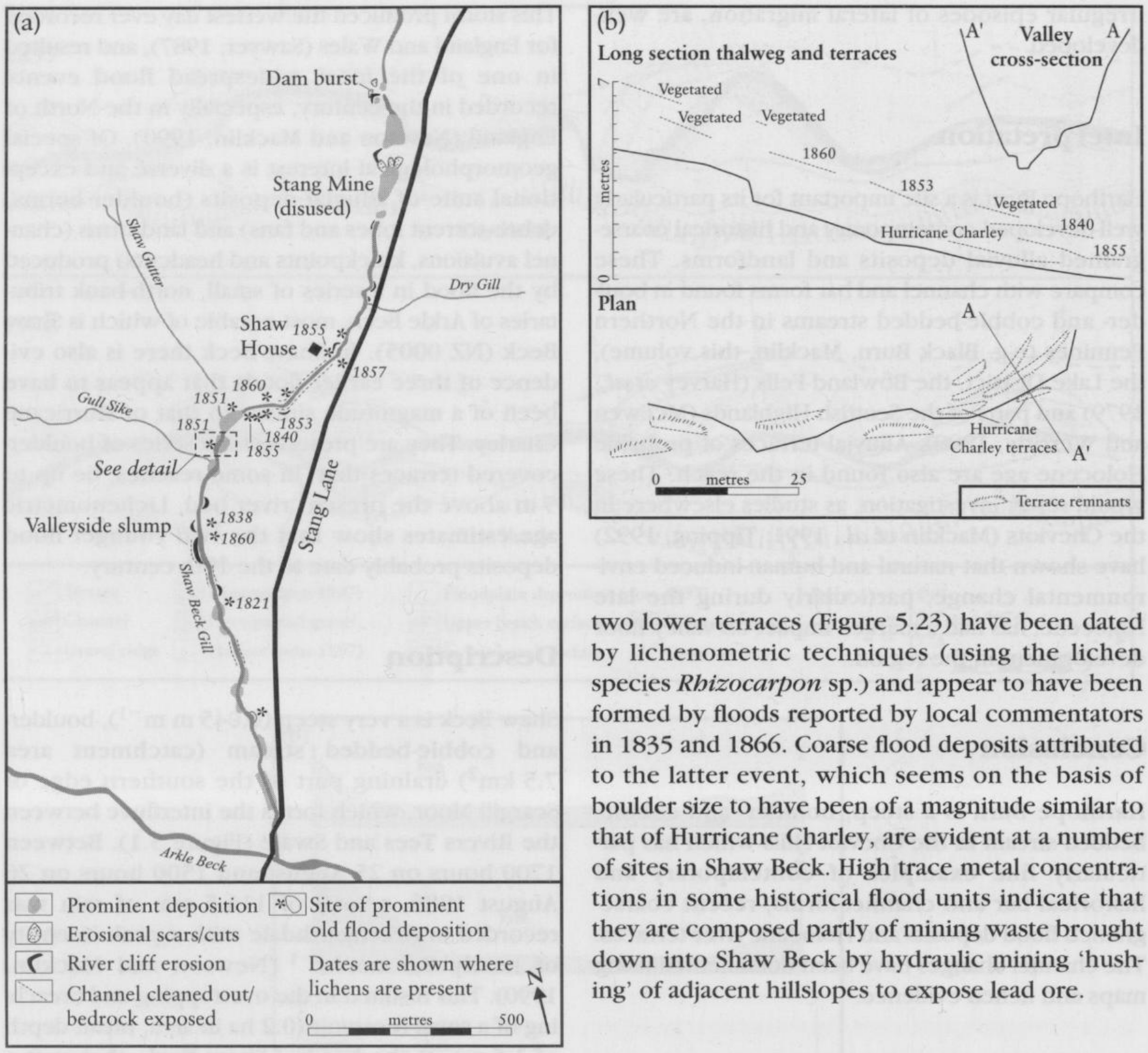


Figure 5.23 The plan (a) and sections (b) of the Hurricane Charley and historical flood sediments in Shaw Beck, Arkengarthdale, North Yorkshire. (After Newson and Macklin, 1990.)

widens, typically in the form of debris lobes which choked former channels and frequently spilt out over the adjacent floodplain. Channels were subsequently re-established either by headcuts migrating upstream re-excavating their pre-flood course or by avulsion across the floodplain around the coarse flood sediment blockage.

Several older flood deposits were eroded and exposed during the August 1986 flood event, all of which have morphologies and sedimentary features very similar to those of the Hurricane Charley flood sediments (Figure 5.24). Three major flood units are evident, which form a series of prominent terraces along Shaw Beck. Boulder deposits on the two lower terraces (Figure 5.23) have been dated by lichenometric techniques (using the lichen species *Rhizocarpon* sp.) and appear to have been formed by floods reported by local commentators in 1835 and 1866. Coarse flood deposits attributed to the latter event, which seems on the basis of boulder size to have been of a magnitude similar to that of Hurricane Charley, are evident at a number of sites in Shaw Beck. High trace metal concentrations in some historical flood units indicate that they are composed partly of mining waste brought down into Shaw Beck by hydraulic mining 'hushing' of adjacent hillslopes to expose lead ore.

Interpretation

Shaw Beck illustrates in a very dramatic fashion the impact of a major flood, with a return period of around 50 years, on a small upland valley system. The variety and spatial variability of river landforms and deposits produced during this single flood event is particularly noteworthy, especially when attempting to reconstruct the hydrodynamic environment and sequence of past floods. The formation of similar boulder berm and debris-torrent sediments has been described in Langden Beck, Teesdale and West Grain, Weardale, following a flash flood in July 1983 (Carling, 1986). In these streams, however, no older flood deposits were identified, and in this respect Shaw Beck is an important site, having both recent and historical coarse-grained flood deposits available for study in one catchment.

Figure 5.24 Shaw Beck: historical coarse-grained flood deposits overlying bedrock terrace. (Photo: M.G. Macklin.)

Conclusion

A diverse and spectacular range of coarse-grained alluvial sediments and landforms were produced by a major flood (Hurricane Charley) between 25 and 26 August 1986 in Shaw Beck, Arkengarthdale, North Yorkshire. Downstream patterns of erosion and deposition appear to have been controlled principally by the availability of coarse sediment, by channel slope and by valley floor width. The deposits of three earlier large floods (two of which date to the 19th century), which appear to have been of a magnitude similar to that of Hurricane Charley, are found also on a number of river terraces in Shaw Beck. Hurricane Charley demonstrated very clearly the geomorphological effectiveness of infrequent, high-magnitude events in shaping the alluvial floors of small catchments in the British uplands.

ADDITIONAL SITES IN NORTH-EAST ENGLAND

Three other potential GCR sites are considered very important in the network of sites within the Tyne basin. At the time of publication these are not established as GCR sites, but they are key to understanding the landform history, forms and processes in the region, and are considered to be of national significance because of seminal work carried out at them.

Lambley, River South Tyne (NY 675605)

Present GCR fluvial sites in the Tyne basin fall into two groups (Figure 5.1). First, there are those located within the Northern Pennine Hills (Blackett Bridge, River West Allen; Blagill, River Nent; The Islands, River South Tyne) where laterally active, near-braided channels are presently reworking their floodplains, and the linkages between historical metal mining and river sedimentation can be clearly demonstrated (Macklin, 1986; Macklin and Aspinall, 1986; Macklin and Lewin, 1989). The second group of sites, which includes Low Prudhoe and Farnley Haughs (not presently a GCR site) are situated in the lower part of the Tyne basin and comprise low-sinuosity, single-thread channels, characterized by vertical accretion of sands and silts, and relatively low rates of lateral channel movement (Macklin *et al.*, 1992a,c). The impact of mining on channel morphology and riparian vegetation is less obvious at these sites, but is recorded by high levels of lead and zinc in some alluvial units (Macklin *et al.*, 1994a).

There is, however, a third type of fluvial environment in the Tyne basin that may be termed 'piedmont rivers', which is presently not included in the region's GCR coverage but is well developed in the zone bordering the Northern Pennine uplands. River channels and floodplains in this so-called piedmont zone (*sensu* Newson, 1981) have, in many respects, morphologies and sedimentation styles intermediate to those of the other upland or lowland sites in the region. Their channel patterns generally resemble those of 'wandering gravel-bed rivers', as described by Church (1983), with channel division around overlapping active gravel bars and larger, relatively stable, vegetated islands. Late Pleistocene and Holocene age river terraces, often with palaeochannels preserved on their surfaces, are also a common feature of many valley floors in the Northern Pennine piedmont zone and attest to

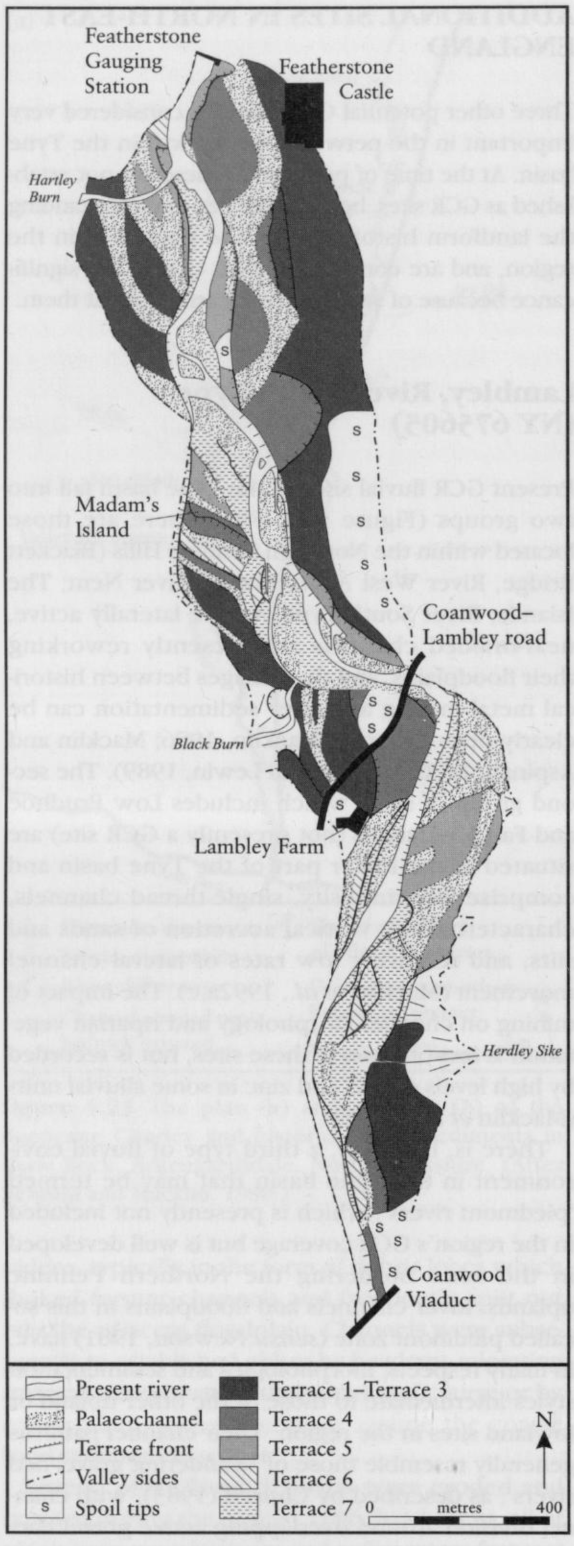


Figure 5.25 Pleistocene and Holocene river terraces and palaeochannel sequences at Lambley, River South Tyne, Northumberland. (After Passmore, 1994.)

long-term river instability in these reaches. The Lambley (NY6759) sedimentation zone (Macklin and Lewin, 1989) in the South Tyne valley is typical in this respect, and has been included in this review as an exemplar of piedmont river processes and dynamics (Passmore *et al.*, 1993; Macklin *et al.*, in press).

The Lambley site straddles the boundary between the upland and lowland parts of the Tyne basin and is located where the South Tyne River emerges from the confines of the Northern Pennine Hills. The Lambley reach is 2.75 km long and can be subdivided into two sub-reaches, each of approximately equal length, north and south of the Coanwood–Lambley road bridge (Figure 5.25). The channel in the southerly sub-reach is currently stable, after experiencing aggradation and braiding between 1860 and 1920, followed by incision until the 1970s (Figure 5.26) (Passmore *et al.*, 1993; Macklin *et al.*, in press). Conversely, downstream, and north of the bridge, low rates of lateral channel shift were evident between 1860 and 1952, although since the 1950s the river has become both laterally and vertically active with increasing channel division around elongate medial bars, high rates of bank erosion (> 5 m yr^{-1}) and aggradation in the lower part of the reach (Figure 5.27). As a result of high rates of contemporary bank erosion and recent channel incision, a sequence of Late Pleistocene, Holocene and historical age river terraces are particularly well-exposed along the reach.

Investigations of both long- and short-term river dynamics have been undertaken at Lambley centred around three main research topics:

1. Holocene river development, particularly the effect of climate-related changes in flood magnitude, and late prehistoric and historical farming on valley floor alluviation and erosion (Passmore *et al.*, 1993; Passmore 1994).
2. River channel metamorphosis resulting from historical lead and zinc mining (Macklin and Lewin, 1989) and the impact of metal pollutants from mining waste on riparian vegetation (Macklin and Smith, 1990).
3. Present-day sediment transport processes and fluxes investigated through repeat levelling of monumented cross-sections, sediment tracing experiments and mapping of bars and river-bed structures (Sohag, 1994). This latter research is on going and there is considerable scope for future studies, particularly sediment budgeting (Macklin *et al.*, in press).

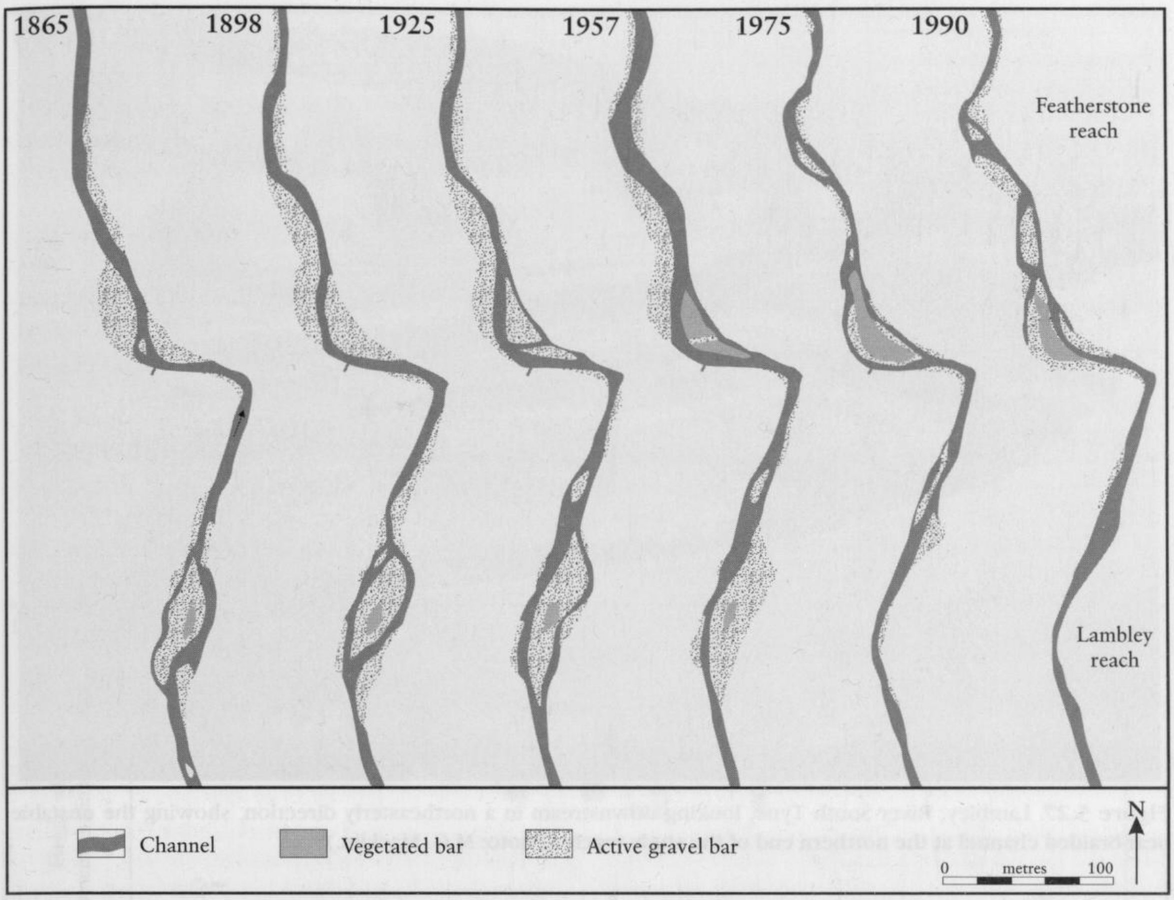


Figure 5.26 Successive maps of channel and bar morphology at Lambley and Featherstone, River South Tyne, derived from cartographic, aerial photograph and field mapping (1990) sources. (After Passmore *et al.*, 1993).

Lambley meets GCR selection criteria on two accounts: firstly, the range of research themes that have been explored, and, secondly, the opportunity to set present-day river channel processes in a longer-term context through stratigraphic and sedimentological investigation of Holocene alluvial landforms and deposits.

Thinhope Burn (NY 645535)

Thinhope Burn, a west-bank tributary of the River South Tyne, is a steep (< 1% to ~ 10%) and deeply entrenched stream that drains a small (12 km^2) moorland catchment on the north-west flank of the Northern Pennines, Northumberland (Figure 5.1). During the past 1600 years or so, the vertical tendency of this stream has been one of the marked incision, locally as much as 8 m, punctuated by extended periods of lateral channel migration and valley floor sedimentation (Rumsby, 1991; Macklin *et al.*, 1992b). Phases of accelerated incision have been shown to coincide with abrupt changes in hydroclimate (Macklin *et al.*, 1994b; Rumbsy and Macklin, 1994), registered by changes in peat stratigraphy evident within raised lowland mires in the region (Barber *et al.*, 1994). Indeed, until early historical times, Thinhope Burn appears to have been a vertically stable channel with fine-grained sediment accretion in overbank environments.

Geomorphological and sedimentological studies in Thinhope Burn constitute the most detailed investigation of late Holocene river alluviation and erosion hitherto undertaken in the British uplands. The wider regional and national significance of this research lies in the fact that this was the first site in Britain at which valley floor entrenchment, and the temporal clustering of major flood events, was related to abrupt, yet relatively modest variations in climate. In addition, episodic channel aggradation and braiding downstream in the River South

Figure 5.27 Lambley, River South Tyne, looking downstream in a northeasterly direction, showing the unstable near-braided channel at the northern end of the study reach. (Photo: M.G. Macklin.)

Tyne during the Holocene has been shown to be broadly synchronous with phases of accelerated erosion identified in Thinhope Burn (Passmore *et al.*, 1993; Macklin *et al.*, in press), highlighting the important influence that headwater tributaries have on sediment supply, and the sedimentation histories, of river systems fringing the British uplands.

Holocene river sequences are most clearly developed in the upper part of Thinhope, immediately downstream of the Faugh and Mardy's Cleugh confluence (NY 645535, Figure 5.28(a)) where four paired terraces are evident at *c.* 7.5, 6, 5 and 4 m above the present stream bed (Figure 5.29). The highest fill-terrace comprises cobble gravels overlain by 2 m of sands and silts which, in the upper part of the unit and towards the valley side, interdigitate with peat. ^{14}C dates of 7910 ± 30 (7060 - 6500 cal BC) and 1670 ± 50 (240 - 530 cal AD) from wood within the basal gravels and at the junction between silt and peat (0.5 m below the terrace surface), respectively, indicate relatively slow alluviation over most of the Holocene.

At some time after 250 - 530 cal AD, the first major phase of Holocene valley entrenchment occurred, resulting in nearly 4 m of channel-bed erosion (Figure 5.28(b)). ^{14}C dates of 1160 ± 50 and 1230 ± 60 from peat at the top and bottom, respectively, of the 6 m terrace show that the stream incision had slowed, or ceased, before 660 - 980 cal AD.

The oldest Holocene age coarse-grained, flood deposit so far recognized in Thinhope is a boulder berm (*sensu* Macklin *et al.*, 1992b) emplaced on the 6 m terrace and located on the north bank of the burn, 50 m downstream of the Faugh and Mardy's Cleugh confluence (Figure 5.28(a)). This flood unit consists of open-work, clast-supported boulders (with *b* axes up to 1.5 m) that are moderately well imbricated with steeply dipping A - B planes (mean dip 60°). It has a convex cross-section with steep sides which in places are curved, streamlined and aligned parallel to inferred flow direction. Deposits, the morphological form and sedimentary sequence of which resemble this and younger boulder berms in Thinhope, have been attributed to flows with high sediment loads, variously termed debris torrents, bedload and hyperconcentrated flood flows (see Macklin *et al.*, 1992b for a review). These, with respect to bulk density and shear strength, are intermediate

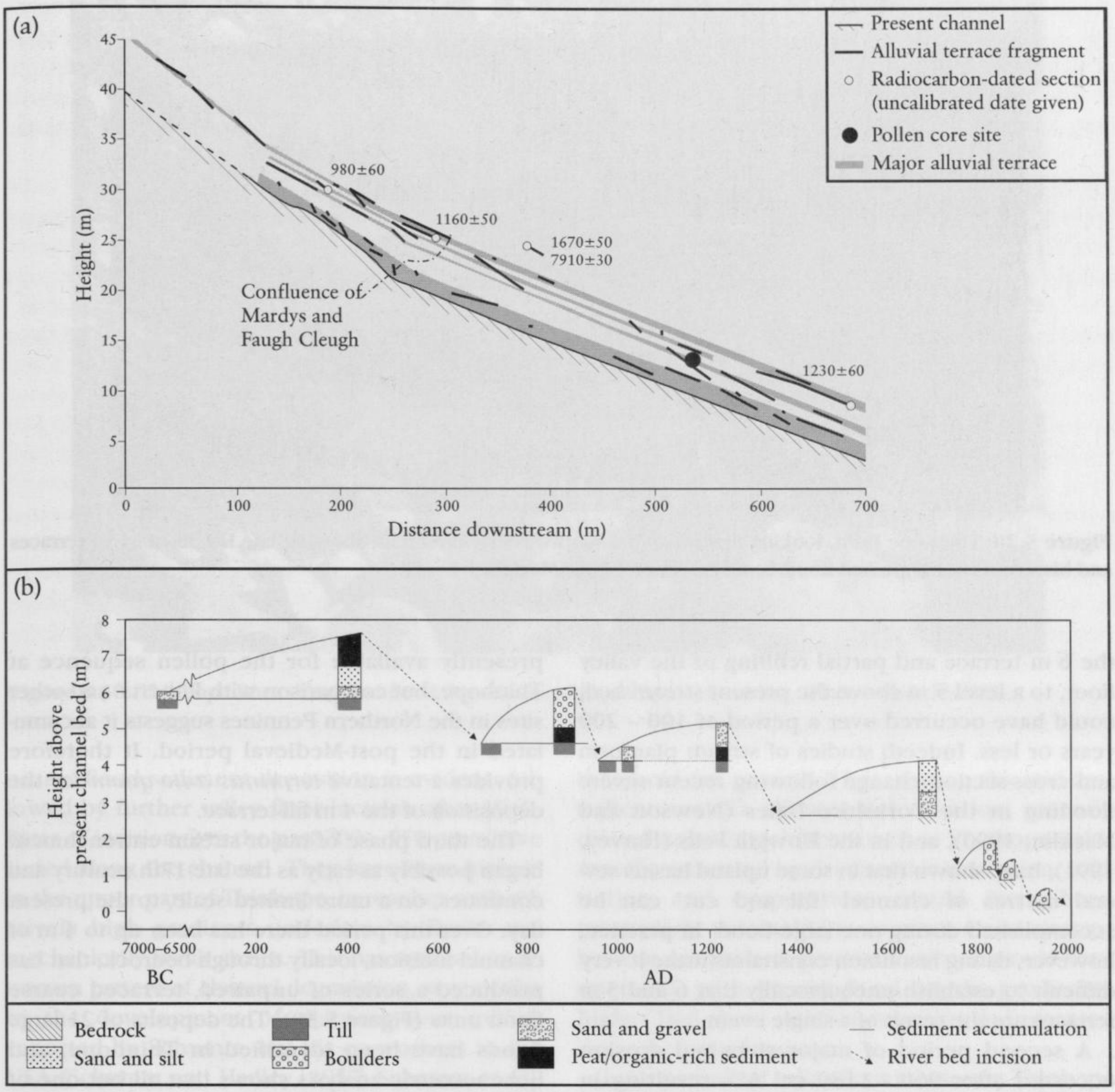


Figure 5.28 (a) A surveyed longitudinal profile of the study reach in Thinhope Burn, showing the positions, heights and sequence of dated Holocene alluvial fills and river terraces in relation to the present stream bed. (b) A time-level diagram for Holocene alluvial units in the Thinhope Burn study reach. (After Macklin *et al.*, 1994b.)

between stream and debris flows, and may be Newtonian or transitional in character depending on sediment concentration. Relatively well-developed imbrication, moderate sorting and open-work texture of boulder berms in Thinhope, however, are sedimentary properties more consistent with Newtonian flows.

Peat immediately below the boulder berm dated to 1160 ± 50 provides a *terminus post quem* for its emplacement, while a most probable *terminus ante quem* is likely to have been around 980 ± 60 on the basis of a ^{14}C date from a buried peaty soil within the younger 5 m terrace (Figure 5.28(a)). This flood event, which appears to have no precedent in the earlier Holocene alluvial record of Thinhope, can be dated reasonably precisely to between 720 – 1000 and 960 – 1180 cal AD. Its most probable age is around 890 – 1020 cal AD. It should be noted, however, that though the 6 and 5 m terraces are morphologically and sedimentologically separate units, they do have overlapping ^{14}C age ranges. It seems likely that incision to form

Figure 5.29 Thinhope Burn, looking upstream in a southwesterly direction, showing late Holocene river terraces and historical coarse-grained flood deposits. (Photo: M.G. Macklin.)

the 6 m terrace and partial refilling of the valley floor, to a level 5 m above the present stream bed, could have occurred over a period of 100 - 200 years or less. Indeed, studies of stream planform and cross-section change following recent severe flooding in the Yorkshire Dales (Newson and Macklin, 1990), and in the Howgill Fells (Harvey, 1991), have shown that in some upland basins several metres of channel 'fill and cut' can be accomplished during one large flood. In practice, however, dating resolution constraints make it very difficult to establish unequivocally that 6 and 5 m terraces are the result of a single event.

A second period of major river-bed erosion occurred after 960 - 1180 cal AD, resulting in Thinhope Burn trenching through Pleistocene till and soliflucted material and, in the study reach, coming to rest directly on Carboniferous sandstone and shale bedrock. Subsequently, the valley floor was refilled, predominantly with fine-grained sediment, to a level *c.* 4 m above the present stream bed (Figure 5.28 (a)). This fill-terrace is the most extensive Holocene alluvial unit in Thinhope. It has a number of well-developed palaeochannels on its surface that have generally higher sinuosities and lower width : depth ratios than the present channel. Pollen analysis (Heap, unpublished) of organic-rich silts that infill one of these palaeochannels (Figure 5.28(a)) showed a vegetation sequence very similar to that recorded by Roberts *et al.* (1973) in nearby upper Weardale, which has been ^{14}C dated to 1700 - 1780 cal AD. No ^{14}C dates are presently available for the pollen sequence at Thinhope, but comparison with Roberts' and other sites in the Northern Pennines suggests it accumulated in the post-Medieval period. It therefore provides a tentative *terminus ante quem* for the deposition of the 4 m fill-terrace.

The third phase of major stream entrenchment began possibly as early as the late 17th century and continues, on a more limited scale, to the present day. Over this period there has been up to 4 m of channel incision, locally through bedrock, that has produced a series of unpaired, terraced coarse flood units (Figure 5.30). The deposits of 21 large floods have been identified in Thinhope, and lichenometric analysis shows that all but one of these (discussed above) date from the mid-18th century. Over this period, there is evidence that large floods were more frequent from 1780 to 1820, 1840 to 1880 and 1920 to 1950, corresponding with secular hydroclimate change recorded in both northern Britain and north-west Europe (Rumsby and Macklin, 1994). Lichenometric dating of levelled flood deposits has also enabled the timing and pattern of channel incision in the Thinhope catchment since 1766 to be examined in detail. This shows that incision ended earlier in downstream (*c.* 1780) than in upstream (*c.* 1820) reaches of Thinhope (Macklin *et al.*, 1992b). In the 19th century valley floor sedimentation took place (with particularly high rates during the 1820s and 1830s) until *c.* 1870 when channel trenching was renewed. During the 1920s and 1930s significant

Figure 5.30 Thinhope Burn: historical flood deposits overlying a bedrock terrace. (Photo: M.G. Macklin.)

coarse flood sediment deposition is evident, followed by further valley floor incision after 1940. Rates of incision over the past 200 – 250 years have varied along the channel. They have been highest in the upper part of Thinhope, in reaches with relatively high gradients underlain by fissile and mechanically weak shales. This has resulted in an uneven pattern of channel degradation, very similar to the development of discontinuous gullies reported by Schumm and his co-workers in the USA (Schumm and Hadley, 1957; Schumm *et al.*, 1984).

Valley-floor erosion in Thinhope Burn coincides with a shift to wetter conditions around 550 – 690 cal AD, recorded at this time by humification changes in both upland blanket peats (Blackford and Chambers, 1991) and lowland raised mires (Barber, 1981) in western and northern Britain. However, climate change cannot have been the sole cause of valley destabilization, given that climatic fluctuations of a similar magnitude had occurred earlier in the Holocene (e.g. 1350 – 550 cal BC) without resulting in significant erosion in the Tyne basin uplands (Macklin *et al.*, 1992b). Coming shortly after extensive deforestation in Iron Age and Roman times (Turner, 1979), it is quite possible that vegetation degradation and destruction triggered gulleying by lowering the threshold for erosion. Thus, during the mid-first millennium AD, climatic deterioration, recently cleared upland catchments such as Thinhope (with runoff augmented by decreased interception, infiltration and evaporation) would have been particularly vulnerable to erosion. Once streams became entrenched, positive feedback would have operated, with greater flood depths producing higher bed shear stresses resulting in increased rates of channel incision.

Later periods of valley-floor incision in Thinhope at around 890 – 1020 cal AD, 1200 – 1400 cal AD and in the 18th century also appear to have occurred during periods of cooler, wetter climate as shown by stratigraphic analysis of peat profiles in north-west England (Barber, 1981; Barber *et al.*, 1994). The most recent phase of channel and floodplain metamorphosis in Thinhope, which started at some time in the latter part of the 17th century, however, witnessed many more dramatic changes than those that occurred in earlier periods of river instability. It saw the replacement of a relatively stable meandering stream and floodplain accreting fine-grained sediment by a vertically and laterally unstable low-sinuosity boulder-bed channel with a high coarse sediment load. This transformation appears to have followed widespread entrenchment and extension of the drainage network in the

Thinhope catchment. Major erosion of bedrock by the main channel, together with dissection of bouldery till by tributaries on adjacent slopes, resulted in a significant increase in both the supply and calibre of coarse sediment to the system (Macklin *et al.*, 1992b). A sharp rise in effective precipitation during the Little Ice Age, shown clearly by widespread evidence of exceptional flooding in north-east England in the late 17th and 18th centuries (Rumsby, 1991), appears to have been the principal cause of channel incision and river transformation. Land drainage and agricultural enclosure in the South Tyne valley during the mid- and late 18th century, as noted by local commentators (Palmer, 1882), also augmented runoff, resulting in shorter times to peak flow and greater flood magnitudes. The main impact of human disturbance, however, is considered to have been one of increasing the sensitivity of channels, floodplains and drainage basin networks to climatically induced changes in flood frequency and magnitude (Rumsby and Macklin, 1994).

Late Holocene patterns and rates of valley-floor development in Thinhope Burn, Northumberland, are shown to have been exceptional when viewed in the context of earlier postglacial river activity. Accelerated rates of channel entrenchment appear to have been caused by an increase in flood magnitude, associated with periods of wetter and cooler climate, with flow augmented by early historical woodland clearance and drainage of the catchment in more recent times. The deposits of 21 large floods have been identified, and lichenometric analysis shows that all but one of these events date from the mid-18th century. Over this period there is evidence for the clustering of major floods, particularly in the periods 1780 - 1820, 1840 - 80 and 1920 - 50. They also correspond with phases of increased flow in a number of European rivers (Probst, 1989) and suggest that the timing of floods in the upper South Tyne between *c.* 1766 and 1960 follows major hydroclimatic fluctuations over the same period in western Europe.

Farnley Haughs, River Tyne (NZ 004633)

Farnley Haughs (NZ 004633), Northumberland, in the middle Tyne valley (Figure 5.1) is the only sand and gravel pit in the Tyne basin in which Holocene age alluvial deposits are currently being worked. Farnley Haughs pit is located at the eastern end of a large alluvial basin centred on Hexham. Excavations have exposed a 300 m long and up to 6 m high section running across the terraced Holocene valley floor, from its junction with Late Pleistocene coarse-grained alluvium on the south side of the valley, northwards to within 50 m of the present channel (Figure 5.31).

Farnley Haughs pit presently provides the most extensive and accessible exposure of Holocene river sediments in the Tyne basin, and constitutes one of the best dated Holocene alluvial sequences in the Tyne valley (Macklin *et al.*, 1992a; Passmore, 1994). Detailed sediment provenance studies have also been carried out at this site, and have employed geochemical analytical techniques to establish links between valley-floor alluviation and accelerated catchment erosion caused by late prehistoric deforestation and land-use change (Passmore and Macklin, 1994). Progressive channel bed incision during the Holocene at Farnley Haughs has resulted in the formation of a staircase of river terraces, with both lateral- and vertical-age sequencing on each of the terrace treads (Figure 5.32). Architecturally, this alluvial sequence is very similar to 'row terraces' described by Schirmer (1983) in German river valleys, produced by lateral channel shift and accretion separated by shorter periods of river incision. Palaeochannels preserved on the surface of several terrace units at Farnley have a morphology similar to that of the current channel, indicating that long-term valley-floor development in this reach has been associated with the down-valley translation of a confined meander bend. Holocene fluvial terrace units at Farnley Haughs comprise imbricated sandy cobble-gravels overlain by fine-grained sands and silts that are either flat-bedded or display lateral accretion elements (Figure 5.33) (cf. Miall, 1985). The lower coarser member represents river bed and bar material, and the finer-grained upper member bar top, floodplain or channel-fill sediments resulting from overbank or slackwater deposition. Four major Holocene alluvial units have been identified and their ages determined using ^{14}C, palaeomagnetic, luminescence, geochemical and cartographic analyses. These units date to: between 4940 - 4600 and 1350 - 550 cal BC; around 510 BC; between the late Medieval period and the late 18th century; and the 19th and early part of the 20th century (Macklin *et al.*, 1992a; Passmore, 1994). Dating evidence suggests that sedimentation of the fine member of each alluvial fill occurred over a relatively short period (several decades to a few hundred years), which is consistent with the well-preserved flood-related sedimentary structures, low

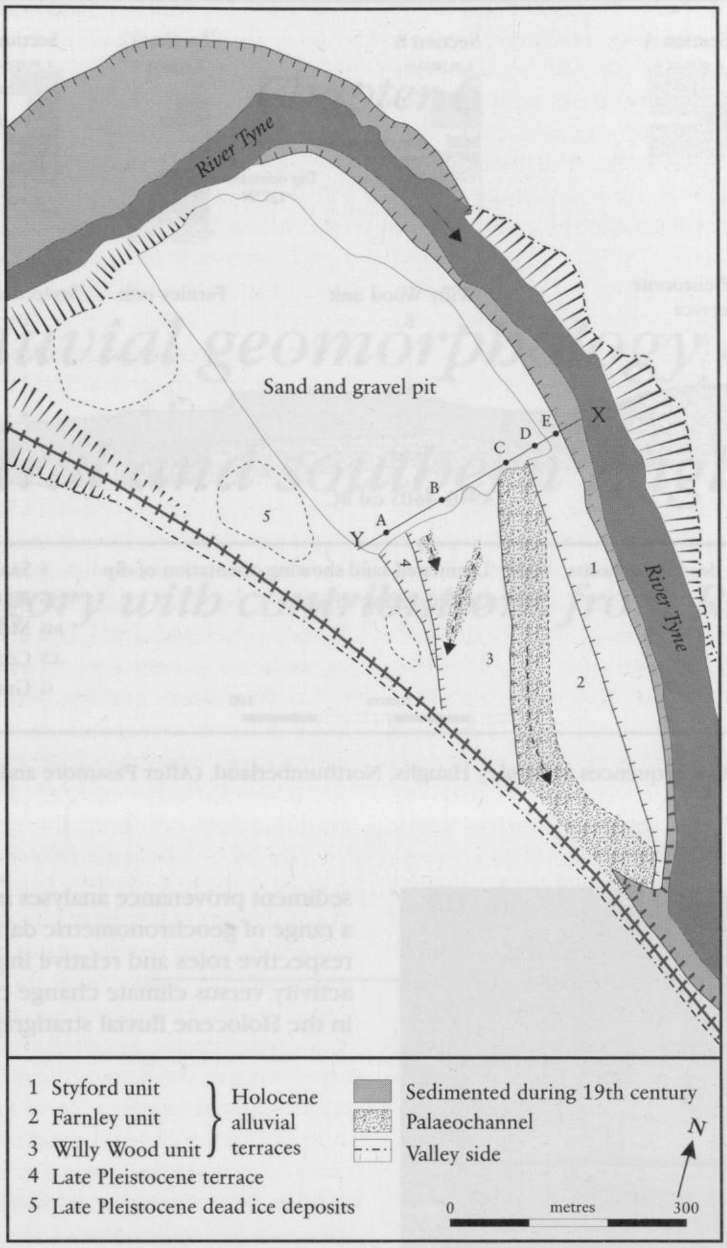


Figure 5.31 Late Pleistocene and Holocene river terrace morphologies at Farnley Haughs, Northumberland. (After Passmore and Macklin, 1994.)

organic content and the absence of buried soils. The principal features of the Holocene alluvial record at Farnley Haughs are an episode of major valley floor entrenchment between 1350 and 550 cal BC, coinciding with a significant deterioration in climate (Barber *et al*., 1994), followed by accelerated fine-grained sedimentation, beginning around 500 cal BC. On the basis of sediment provenance studies, this period of alluviation can be connected to erosion in the River North Tyne catchment resulting from Iron Age agricultural practices (Passmore and Macklin, 1994).

In Britain, a very active on-going debate concerns anthropogenic and climatic controls of Holocene river alluviation and erosion (see Ballantyne, 1991; Macklin and Lewin, 1993). Investigations at Farnley Haughs are very pertinent to this debate, as they illustrate how, by using

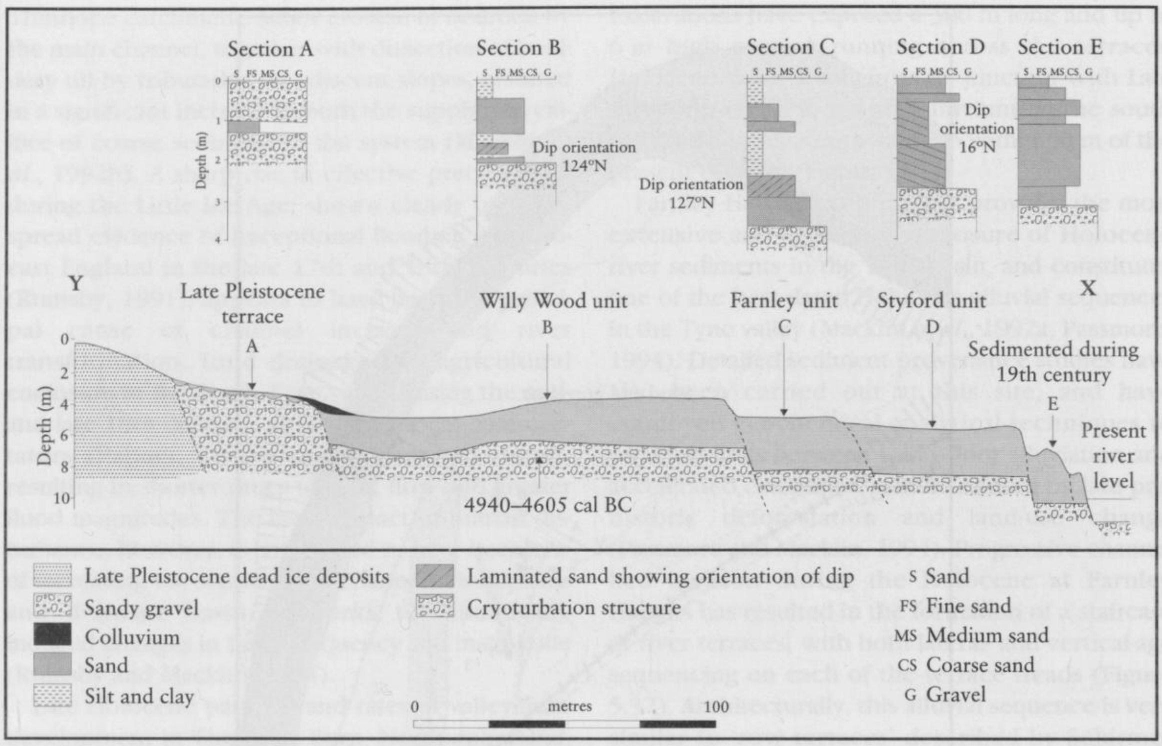
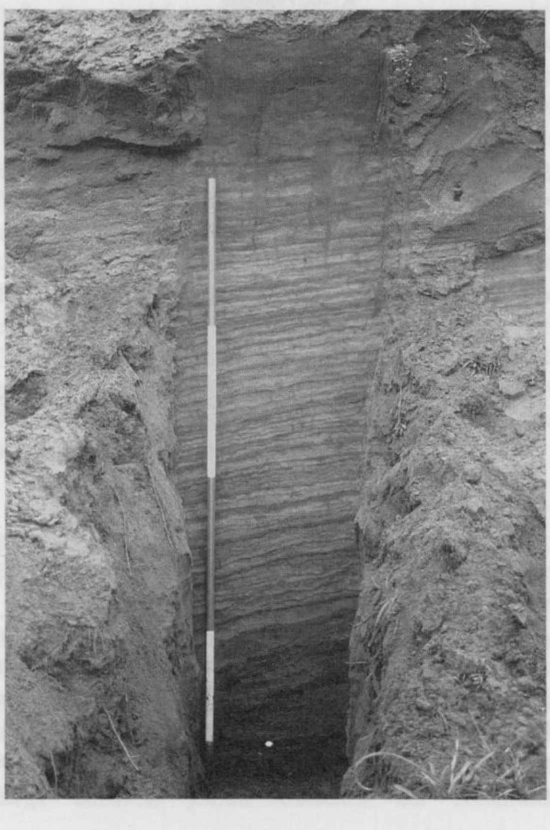


Figure 5.32 Sedimentary sequences at Farnley Haughs, Northumberland. (After Passmore and Macklin, 1994.)



sediment provenance analyses in combination with a range of geochronometric dating techniques, the respective roles and relative importance of human activity versus climate change can be disentangled in the Holocene fluvial stratigraphic record.

Figure 5.33 Farnley Haughs, River Tyne: fine-grained alluvium in Styford unit, showing lateral accretion features. Scale: 2 m. (Photo: D.G. Passmore.)