Holocene alluvial-fan development in the Macgillycuddy's Reeks, southwest Ireland

E. Anderson
School of Geography and Environmental Management, Middlesex University, Queensway, Enfield EN3 4SF, UK

S. Harrison*
Centre for Quaternary Science, Geography, NES, Coventry University, Priory Street, Coventry CV1 5FB, UK

D.G. Passmore
Department of Geography, University of Newcastle-upon-Tyne, Newcastle-upon-Tyne NE1 8ST, UK

T.M. Mighall
Centre for Quaternary Science, Geography, NES, Coventry University, Priory Street, Coventry CV1 5FB, UK

ABSTRACT

Holocene alluvial landforms in the Macgillycuddy's Reeks, southwest Ireland, were investigated to determine the controls and timing of postglacial geomorphic activity. Detailed geomorphologic analysis of three alluvial-fan and debris cones within high-level cirque basins demonstrates evidence of episodic phases of late Holocene surface aggradation and incision. Radiocarbon dates from peat horizons above and below inorganic units show that phases of aggradation cluster into two distinct periods, the first after 230–790 calibrated (cal.) yr A.D. and the second from 1510 cal. yr A.D. to the present. An additional phase of fan aggradation at one site is dated after 1040–1280 cal. yr A.D. All three phases coincide with episodes of enhanced late Holocene valley-floor alluviation and debris-flow activity from upland Britain. Alluvial fans and debris cones have developed primarily as a result of the resedimentation of late Midlandian (Wisconsin) drift and talus slopes, and mobilization of materials involved flooding, transitional-flow, and debris-flow processes. Pollen analysis of peat horizons interbedded with alluvial-fan and debris-cone sediments indicates that land-use changes were an important factor in lowering the threshold for local slope erosion. Phases of aggradation also coincide with well-documented episodes of climate change, and, hence, fan development is probably a function of both anthropogenic and climatic forcing. A sequence of events may have involved initial slope destabilization due to overgrazing and removal of vegetation that was followed by debris mobilization and fan aggradation during intense rainstorms associated with climate change.

Keywords: alluvial fans, Holocene, southwest Ireland.

INTRODUCTION

Alluvial fans and debris cones are fan-shaped bodies of sediment which form at the foot of mountain escarpments, slope gullies, and tributary valleys by rapid deposition from channelized or unconfined waterfloods, transitional flows, and debris flows (Blair and McPherson, 1994). They can be mutually distinguished on the basis of surface gradient and bulk composition. Alluvial fans commonly consist of a variety of sediment facies types and display surface gradients generally between 2° and 12° (Blair and McPherson, 1994). In contrast, debris cones are generally steeper, with average gradients typically in the range of 12°–25° (Brazier et al., 1988; Blair and McPherson, 1994), and include predominantly superposed debris-flow lobes (Data Repository Table DR1[1]). In upland areas of the British Isles, the majority of alluvial fans and debris cones are deeply incised, partially or wholly vegetated, and show little sign of recent activity (Brazier and Ballantyne, 1989). Research on the chronology and paleoenvironmental significance of these landforms has demonstrated widespread evidence of Holocene surface aggradation and incision. This activity was particularly intense during the tenth to twelfth centuries (Harvey et al., 1981; Harvey and Renwick, 1987; Tipping and Halliday, 1994) and sixteenth to nineteenth centuries (Innes, 1983; Brazier et al., 1988; Brazier and Ballantyne, 1989).

Despite the body of evidence cited previously, uncertainties remain regarding several key research issues. First, discerning the respective roles of climate and land-use changes (external forces) in controlling geomorphic activity remains a contentious issue (Ballantyne, 1991a, 1991b). Alluvial records in upland basins are commonly incomplete, and materials suitable for dating are commonly lacking. Consequently, these proxy records are seldom of sufficient resolution to isolate a definitive climatic or cultural signal. Second, studies have focused on single sites where geomorphic responses to fluxes in external boundary conditions may be difficult to differentiate from internal stochastic or complex response (Schumm, 1973).

In the Macgillycuddy's Reeks, alluvial fans and debris cones are a common feature at the base of incised-valley and cirque slopes and reflect widespread slope destabilization during the late Quaternary drift and talus covers. Three of these alluvial-fan and debris-cone

*E-mail: s.harrison@coventry.ac.uk.

[1]GSA Data Repository item 2000112, description and schematic profiles of alluvial-fan depositional facies, is available on the Web at http://www.geosociety.org/pubs/ft2000.htm. Requests may also be sent to Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301; e-mail: editing@geosociety.org.

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complexes—located in the Coomloughra Glen, Hag's Glen, and Curraghmore cirque basins (Fig. 1 and Table 1)—contain buried peat horizons and hence facilitate an opportunity to address some of the research issues previously outlined. Accordingly, the principal aims of this paper are to (1) establish the geomorphic development and chronology of alluvial fans and debris cones and (2) determine the environmental controls responsible for periods of landform stability and accelerated geomorphic activity. The methodology employed in this study is described in the Appendix.

STUDY AREA

The Macgillycuddy's Reeks is a high-relief massif, consisting of Devonian sandstones and shales (Fig. 1). The legacy of Pleistocene glaciations has left the massif deeply dissected by several glacial troughs and numerous, well-developed cirque basins. The last phase of valley glaciation occurred during the late Midlandian Glenavy Stadial (26–13 ka). The Younger Dryas cooling (11–10 ka) also promoted the development of six small cirque glaciers (Anderson et al., 1998). The present climate of this area is temperate maritime, and the region is frequently affected by the passage of midlatitude low-pressure systems. Consequently, the weather is often stormy, and heavy rain is common throughout the year, particularly in the mountains, where annual precipitation probably exceeds 2500 mm.

Coomloughra Glen Alluvial-Fan and Debris-Cone Complex

Geomorphology and Stratigraphy

The alluvial-fan complex within Coomloughra Glen consists of two distinct fans, referred to here as fan A and fan B, and a series of inset bars and channel lags along the length of the main catchment stream (Fig. 2). Fan A is located at the base of an incised Younger Dryas till sheet (Anderson et al., 1998) and consists of an assemblage of superposed, transitional-flow lobes and splays. Investigation of the distal reach and marginal areas of the fan (fan Aii) reveals that component clasts display a greater degree of iron oxide staining and vegetation cover than the clasts that form the lobes of the central fan axis (fan Ai). Such contrasts may be explained by temporal weathering differences and duration of vegetation development, indicating that fan A may have been formed by two distinct depositional phases.

Fan B is a debris-cone and alluvial-fan complex that developed downslope of three distinct feeder channels incised into Younger Dryas till and is overlain by talus (Fig. 2). The proximal reach consists of superposed viscous-debris and transitional-flow lobes and splays, which grade proximally into poorly sorted channel fills. Distally, dilute debris flows and fluvial boulder lobes replace these facies, and the distal portion is made up of an expansive assemblage of superposed fluvial cobble bars and sheetflood deposits. Five stream-cut exposures (sections 1–5; Fig. 3) reveal that this surface assemblage, referred to here as lithofacies association (LFA) CG5, consists of clast-imbricated, gravel-cobble and cobble-boulder deposits, which fine distally into a sequence of laminated silts and sands and are overlain by sand-and-cobble gravel. Interstratified peats and clastic units underlie LFA CG5 in sections 1 and 2 (Fig. 3). Radiocarbon dating of peat samples from LFAs CG2 and CG4 produced dates of 1510–1930 cal. yr A.D. and 650–790 cal. yr A.D., respectively (Table 2). Uprooted vegetation in feeder-channel deposits demonstrates that the fan is still partially active.

Geomorphic relationships between fan A and fan B are inconclusive (Fig. 2), but stratigraphic evidence appears to indicate that at least part of fan A predates fan B. Paleocurrent analysis of the buried alluvial units (LFAs CG3 and CGi) exposed in sections 1–5 demonstrates that they were deposited by waterfloods derived from the catchment area of fan A and probably, therefore, represent the downstream washout debris of transitional flows which formed fan A (Figs. 2 and 3). Presently, it is not clear at what stage during the development of fan A that these alluvial units were deposited because this fan probably consists of two temporally distinct assemblages of superposed transitional-flow lobes. The stratigraphic evidence outlined here, however, does at least indicate that one of the transitional-flow events probably occurred after 650–790 cal. yr A.D. (Table 2).

Geomorphic Evolution

The presence of alluvial silts in the distal reach of the fan complex indicates geomorphic activity, and resedimented peat fragments in the complex demonstrate that they are Holocene (section 1). This geomorphic activity was followed by a period of surface stability and peat development. After 650–790 cal. yr A.D., surface aggradation was triggered by destabilization of the upstream catchment slopes of fan A. Initial activity commenced with the deposition of distal-reach silts and sands and was followed by the sedimentation of gravel-cobble bars. These deposits are possibly downstream washout debris from transitional flows that deposited a series of stacked lobes and lobes on fan A. Fan aggradation was followed by renewed peat development, although surface stability was interrupted briefly by the deposition of channelized sandy gravel in the distal reach (LFA CG4, section 2). The initial timing of this episode of peat formation is uncertain, but the thickness of the peat layer in section 1 (0.28 m; Fig. 3) indicates a prolonged period of surface stability prior to the return of alluvial deposition after 1510–1930 cal. yr A.D. Renewed slope instability after 1510–1930 cal. yr A.D. caused the deposition of fan B and possibly transitional-flow deposition on fan A. At this time, the principal basin stream flowed around the outer margin of fan B (Fig. 2). Following the cessation of fan aggradation, however, erosion by fan B surface streams and localized cobble-bar deposition appear to have caused the avulsion of the principal basin stream, leading to the formation of the present-day channel.

The Hag's Glen Alluvial Fan

Geomorphology and Stratigraphy

The Hag's Glen alluvial fan is located just south of Lough Callee (Fig. 4) at the foot of a gully cut into Glenavy Stadial till. The proximal reach of the fan consists of several transitional-flow boulder lobes. Although the mid-fan area is heavily vegetated, close inspection reveals an expansive assemblage of superposed streamflow boulder bars. Wells and Harvey (1987) pointed out that fluvial boulder bars could be interpreted as sieve deposits (cf. Hooke, 1967). The boulder bars in the Hag's Glen alluvial fan, however, overlie peat deposits that would prevent the rapid surface-water loss necessary to trigger sieve-like deposition. The surface geomorphology of the distal reach is also largely obscured by surface vegetation and organic topsoil. The facies characteristics of depositional units and the distal-reach stratigraphy, however, can be observed along stream-cut exposures (sections 6–13; Figs. 5 and 6). Cross-correlation of the upper distal-reach sheetflood splays exposed between sections 7 and 10 (LFA HGe) and the cobble-bar deposits seen in section 6 (LFA HGv; Fig. 5) is relatively straightforward because sections 6 and 7 are only 8 m apart. They are also at the same elevation (1.5 m) above the present stream channel and display similar lithostratigraphy and paleocurrent directions (Figs. 4, 5, and 6). These deposits are either equivalent in age or predate the superposed fluvial boulder lobes and transitional flow because the latter display onlapping re-

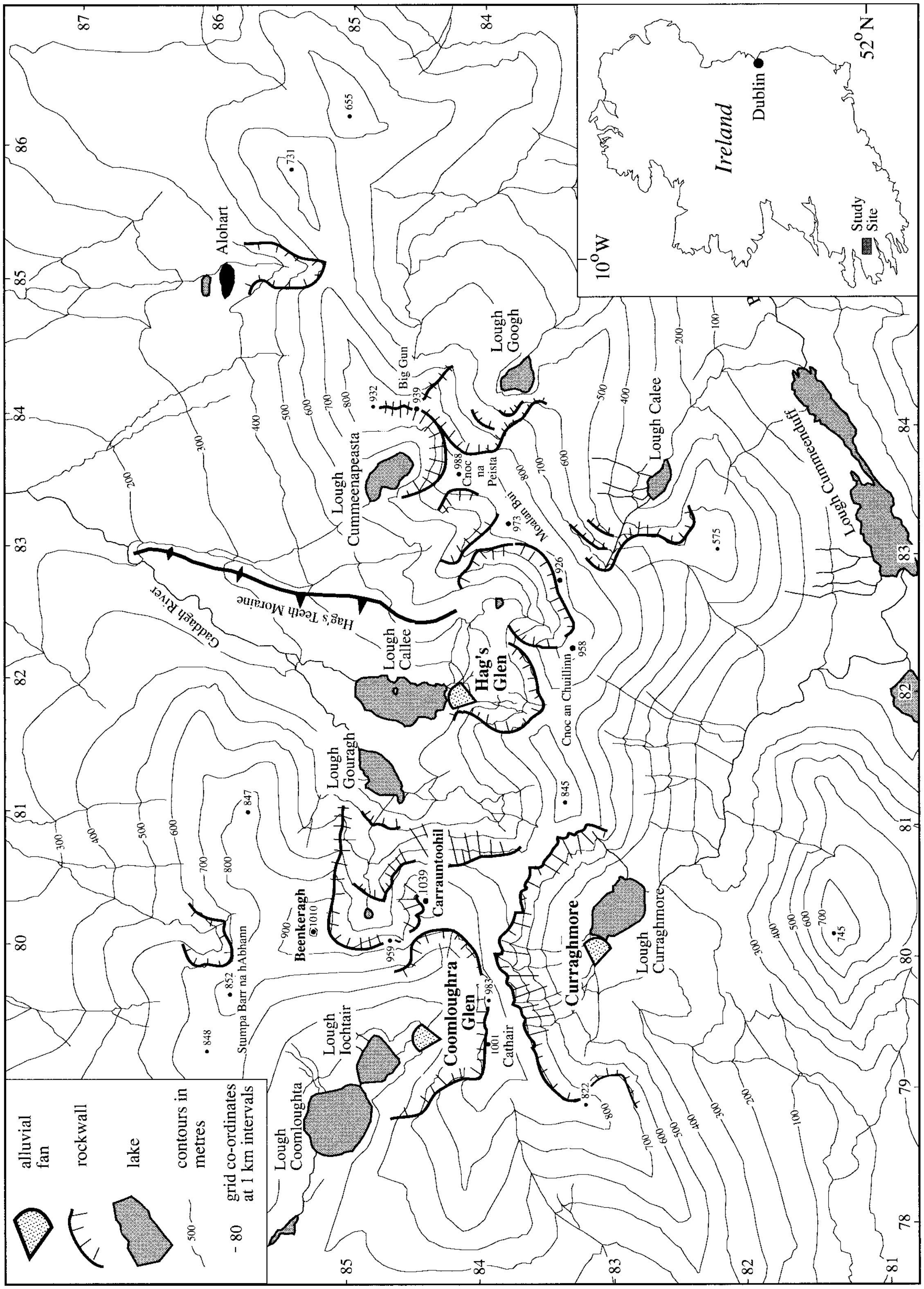


Figure 1. Location map of the alluvial-fan and debris-cone complexes studied in the Macgillycuddy's Reeks, southwest Ireland. Inset map shows study area.

TABLE 1. PARAMETERS FOR ALLUVIAL-FAN AND DEBRIS-CONE CATCHMENT AND MORPHOLOGY

Laboratory	Catchment area (m^2)	Basin relief (m)	Relief ratio	Feeder channel gradient	Altitude (m)	Surface area (m^2)	Apex-distal reach length (m)	Max thickness (m)
Coomloughra A	0.337	529	0.47	0.49	500	4600	101	4
Coomloughra B	0.095	481	0.73	0.72	500	13350	175	2.5
Hag's Glen	0.132	470	0.57	0.49	340	7640	120	5.5
Curraghmore	0.676	670	0.51	0.33	300	12000	215	3.5

lationships (Fig. 4). Therefore, the prominent depositional landform assemblages that form the central mass of the alluvial fan postdate the upper peat unit (LFA HGiv) in section 6 and were deposited after 1510–1930 cal. yr A.D. (Table 2). Radiocarbon dates from section 11 demonstrate the greater antiquity of the sediment sequence exposed between sections 11 and 13. Comparison of the radiocarbon dates from the base of LFA HGii (1040–1280 cal. yr A.D.) and from the top of LFA HG4 (1040–1270 cal. yr A.D.) indicates that LFA HGi and LFA HG5 are probably the same depositional unit. In turn, LFA HGi probably correlates with the lower sheetflood facies (LFA Hga) exposed in sections 9 and 10 (Fig. 6). Consequently, the sedimentary deposits exposed in sections 6–13 represent a semicontinuous vertical profile (Fig. 7).

Geomorphic Evolution

Formation of the Hag's Glen alluvial-fan complex commenced with the deposition of sheetflood gravel and vertical accretion of laminated silts in a low-energy environment. Resedimented peat fragments within the silt unit demonstrate that they are Holocene in age. After 1760–1520 cal. yr B.C., a period of surface stability and peat deposition occurred (LFA HG2), although it is not clear whether inactivity extended across the entire fan surface at this time because the peat layer may be a localized channel fill. Alluvial activity recommenced after 550–680 cal. yr A.D. with the deposition of channelized cobble bars and overbank sand and gravel. Following a brief period of possibly localized surface stability between 890 and 1270 cal. yr A.D., sheetflood gravel was deposited across a wide area of the distal reach. The planar-bedded, sheetflood couplets imply that the floodwater was associated with autocyclic development and washout of standing-wave antidune bedforms. These couplets, in turn, suggest that the whole unit may have been deposited during one flash-flood event. After 1040–1280 cal. yr A.D., a period of surface stability and peat deposition occurred across the entire fan. Peat formation was interrupted briefly between 1400 and 1630 cal. yr A.D. by the deposition of a localized drape of sand. This layer may represent the overbank fines from a channelized flood or washout debris transported distally following the sedimentation of a depositional lobe. Sometime after 1520 cal. yr A.D. but before 1930 cal. yr A.D., a thick and laterally extensive assemblage of transitional-flow lobes and splays, streamflow boulder lobes and sheet-flood gravel was deposited. Morphostratigraphic relationships between these depositional landforms indicate that they probably represent the geomorphic response to a single flash flood.

Pollen Diagrams

Pollen diagrams and zone descriptions of peat sampled from depositional units LFA Hgii and LFA HG1v from section 6 and from LFA HG2 and LFA HG4 from section 11 are presented in the Data Repository (see text footnote 1). These data are shown as Figures DR1 and DR2, respectively.

Curraghmore Alluvial Fan

Geomorphology and Stratigraphy

The Curraghmore alluvial fan is located immediately west of Lough Curraghmore (Fig. 1) at the foot of a gully cut into a Glenavy Stadial till (Fig. 8; Anderson et al., 1998). The fan consists of three distinct landform assemblages: (1) proximal- and medial-zone, transitional-flow lobes and splays; (2) a distal-zone sequence of interbedded alluvial units and peats buried beneath a surface cover of peaty soil; and (3) a series of fluvial, boulder lobes and cobble bars set between the proximal transitional-flow deposits and a flanking till sheet.

Inset around and between the frontal margins of the transitional-flow lobes are channelized alluvial fills (Fig. 8) consisting of clast-imbricated gravel cobbles with sparse boulders and sandy matrix (sections 15 and 17; Fig. 9). These deposits are interpreted as cut-and-fill deposits. These fill deposits unconformably overlie a buried sequence of fluvial boulder lobes or bars in section 15. The paleocurrent direction of the upper alluvial unit in section 15 is parallel with the general orientation of the transitional lobes and abandoned interlobe channels. Their geomorphic setting suggests that energetic waterfloods formed them immediately after the deposition of the transitional-flow sediment assemblage. The interbedded sequence of peats and alluvial units probably covers much of the distal portion of the alluvial fan, although its exact surface extent and thickness is not known because the sediment sequence is only partially exposed along one stream-cut section (section 14; Fig. 9). This section exhibits six distinct lithofacies units. Peat units bracketing the lower alluvial layer have been dated to 1505 ± 40 yr B.P. and 705 ± 40 yr B.P. (Table 2). However, the younger date may be erroneously old because the overlying contact is erosional. The upper alluvial units are dated to after 190 ± 90 yr B.P.

A crosscutting relationship 7 m upstream from section 14 demonstrates that the cut-and-fill units postdate the distal-zone sequence of interbedded alluvial layers and peats (Fig. 8). Consequently, the bulk of the proximal- and distal-zone sedimentary landforms appear to be younger than the upper peat unit exposed in section 14 (Fig. 9) and were therefore deposited after ca. 1640 cal. yr A.D. This hypothesis, however, rests on the assumption that the transitional-flow deposits and adjacent cut-and-fill units are equivalent in age. Although the geomorphic evidence is compelling, it is not conclusive.

Geomorphic Evolution

Alluvial activity commenced after 440–630 cal. yr A.D. with the deposition of distal-reach sands and gravels, which may grade upstream into buried boulder lobes or bars (section 15). After 1390–1510 cal. yr A.D., peat formation occurred, although fan stability was interrupted briefly by the sedimentation of a localized sand layer. Assuming that the stratigraphic scheme discussed above is correct, the evolution of the fan after ca. 1640 cal. yr A.D may be outlined as follows. After ca. 1640 cal. yr A.D., geomorphic activity commenced with the deposition of distal-reach sands and gravels and sedimentation of transitional-flow deposits. The transitional-flow deposits may have been formed either by two or more geomorphic events or were possibly deposited during the same flood with each lobe representing a distinct sediment pulse formed as new supplies of debris were entrained upstream. Floodwaters associated with each pulse caused localized cut and fill of the preexisting fan surface adjacent to lobes and splays and incised to the present position of the distal-reach channel. In addition, the transitional-flow landform assemblage appears to have blocked and deflected the flow of the principal fan channel to the south, which in turn prevented further distal-reach surface aggradation. The boulder lobes and cobble bars inset between the transitional-flow deposits and late Midlandian till represent the last significant episode of geomorphic activity and were deposited by channelized floodwaters. They may have formed immediately after the diversion of the channel or may reflect more recent flood events.

DISCUSSION

Consideration of the external causes of Holocene fan-alluviation and debris-flow activity in upland areas of the British Isles has focused on the relative roles of human activity and climate change (e.g., Innes, 1983; Ballantyne, 1991a). Similar debates also have concerned geomorphologists and archaeologists working on valley-floor alluvial sequences in upland and lowland Britain (e.g., Macklin and Lewin, 1993; Macklin, 1999). The anthropogenic hypothesis recognizes that vegetation disturbance (especially by soil tillage and grazing) lowers the threshold for soil erosion, leading to debris mobilization and gullying during periodic high runoff. Conversely, the climatic hypothesis is based on the apparent coincidence between evidence of geomorphic activity and established periods of climate change, although Ballantyne (1991b) proposed that increased frequency of intense rainstorms as opposed to general climatic deterioration might be the key factor. Indeed, in a recent review of European alluvial records for the period 1300–1900 A.D., Rumsby and Macklin (1996) concluded that periods of enhanced river aggradation and incision coincided with phases of climatic transition, whereas the most severe phases of climatic cooling were associated with reduced fluvial activity.

Recent reviews of Holocene alluvial valley-floor development at various scales (Passmore and Macklin, 1997) and throughout the United Kingdom (Macklin and Lewin, 1993; Macklin, 1999) have argued that river response to anthropogenic activity and climate change should be viewed in terms of a continuum between these factors. In particular, they suggested that land-use changes might be critical for sensitizing river systems to changes in flood frequency and magnitude. It is commonly the case, however, that geomorphologic investigations lack either chronological controls and/or climate and land-use data at appropriate spatial and temporal scales (e.g., Tipping, 1994; Macklin, 1999). Intercalated peat horizons in the alluvial-fan complexes provide a rare opportunity to address some of these issues by facilitating investigations of the chronology of fan development and local vegetation history.

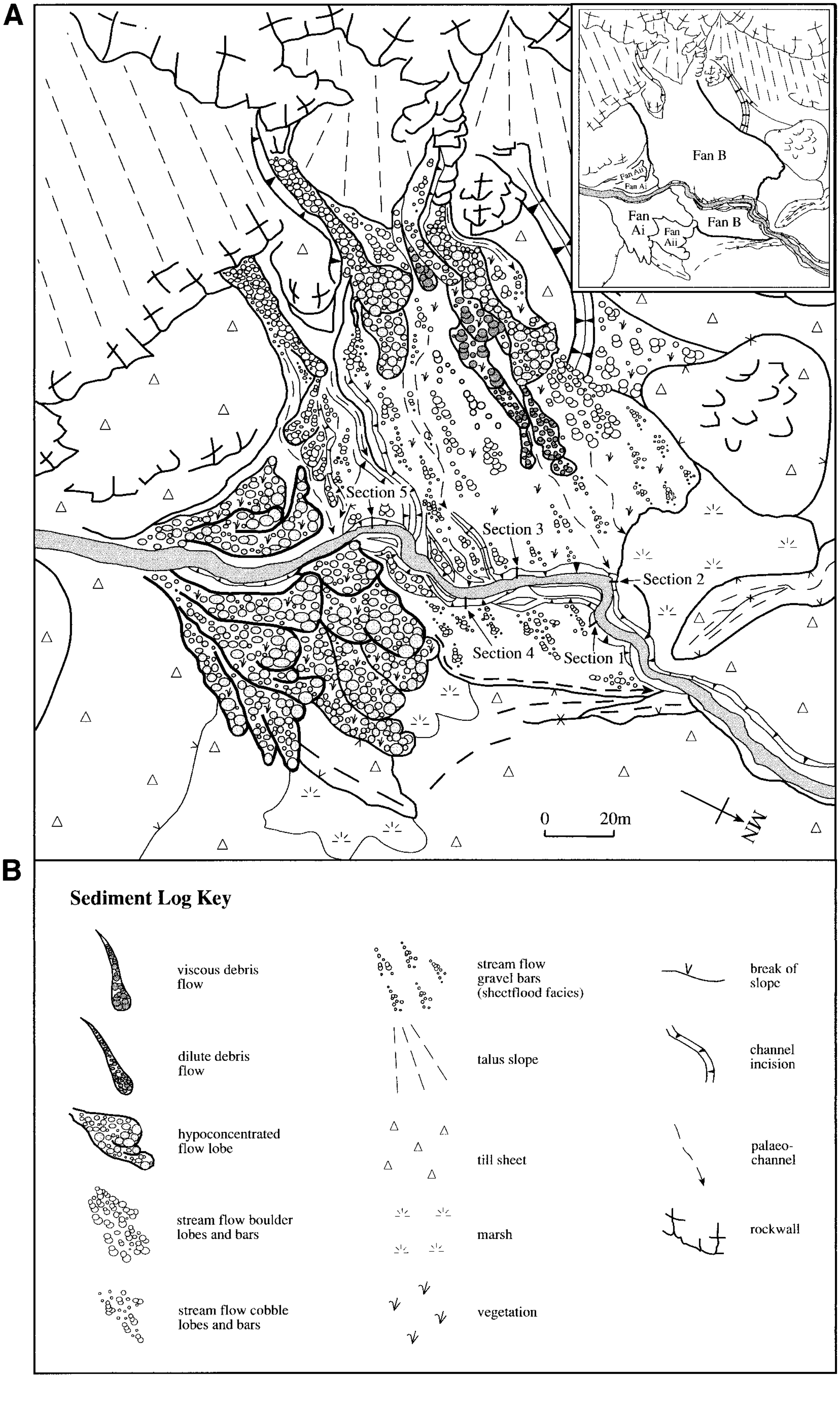
Alluvial-Fan and Debris-Cone Development During the First Millennium A.D.

Accelerated geomorphic activity is reflected by the occurrence of thin clastic units in the distal reach of all fans. Pollen spectra from the Hag's Glen alluvial fan indicate that the local vegetation cover after 550–680 A.D. consisted of acidic grasslands and woodlands characterized by birch, willow, pine, hazel, and oak prior to fan aggradation (Data Repository Fig. DR1). The pollen record also reflects the impact of human activity on the landscape at this time. This is not unexpected, and several other authors have reported evidence of Bronze Age and Iron Age land-use changes from pollen records from southwest Ireland (Dodson, 1990; Monk, 1993). Initial evidence includes high values of Poaceae pollen and a suite of herbaceous taxa that is normally associated with pastoral use. These herbaceous taxa include *Plantago lanceolata*, *Rumex acetosa*/*acetosella*, Lactucae, Asteroideae, *Vicia*-type, Brassicaceae, *Trifolium*-type, and *Pteridium* within local pollen assemblage zones (LPAZs) HG11a and HG11b (Fig. DR2). Because the arboreal pollen curve in LPAZs HG11a and HG11b fluctuates around 25% to 30% of total land pollen, it appears that agricultural activities were not associated with significant woodland clearance. The first noticeable loss of woodland cover took place at the beginning of LPAZ HG11c when *Pinus*, *Betula*, *Quercus*, and *Salix* pollen values all decreased (Fig. DR2). Charcoal values from this assemblage, however, suggest that fire was not involved in woodland clearance (Fig. DR2). This reduction in woodland coincides with the rise in *Calluna* values at 65 cm (ca. 2480 yr B.P.), indicating an expansion of acidic, organic soils. *Plantago lanceolata*, *Melampyrum*, Lactucae, Fabaceae, Brassicaceae, and *Pteridium* are also recorded in low percentages just before and/or during this expansion, suggesting that pastoral agriculture in the local vicinity may have created conditions conducive for peat growth by removing woodland cover and modifying the local hydrologic regime. Recovering arboreal percentages in the middle of LPAZ HG11c may reflect reduced agricultural activity, although *Betula* and *Salix* never attained their former values (Fig. DR2).

The boundary between LPAZs HG11c and HG11d also coincides with a reduction of woodland cover associated initially with declining *Salix* values between 52 and 48 cm (ca. 1615 cal. yr B.P.). *Betula* and *Corylus avellana*–type briefly increase at this depth, possibly as a successional response to the loss of willow, but this is followed by a drop in percentages of both taxa. The fall in the arboreal pollen values during the first part of LPAZ HG11d is associated with a rise in herbaceous taxa, including Poaceae, Cyperaceae, *Potentilla*-type, Ranunculaceae, *Succisa pratensis*, and *Plantago lanceolata*, suggesting that both pastoral activity and the areal extent of acidic grasslands had increased. Again charcoal values remain low, suggesting that fire was not involved in woodland clearance (Fig. DR2). The ^{14}C date within HG11d (550–680 cal. yr A.D.) implies that this phase corresponds with the early Christian period, which was marked in Ireland by increasing agricultural activity and widespread forest clearance (Edwards, 1985).

The evidence from the pollen record demonstrates that catchment vegetation prior to the deposition of an inorganic layer (LFA HG3) had been modified by human activity between 1760–1520 cal. yr BC and 550–680 cal. yr A.D. Therefore, it is possible that fan aggradation may have been facilitated, at least in part, by the gradual removal of local vegetation and possibly overgrazing, which destabilized soil and sediment cover on the slopes adjacent to the fan. The phase 230–790 cal. yr A.D., however, also coincides with evi-

Figure 2. (A) Map of Coomloughra Glen alluvial-fan and debris-cone complex. MN—magnetic north. (B) Key to sediment types for geomorphic maps shown as Figures 2A, 4, 8.


A
Fan B
Fan Aii
Fan Ai
Fan Ai
Fan Aii
Fan B
Section 5
Section 3
Section 2
Section 4
Section 1
0
20m
MN
B
Sediment Log Key
viscous debris flow
dilute debris flow
hypoconcentrated flow lobe
stream flow boulder lobes and bars
stream flow cobble lobes and bars
stream flow gravel bars (sheetflood facies)
talus slope
till sheet
marsh
vegetation
break of slope
channel incision
palaeo-channel
rockwall

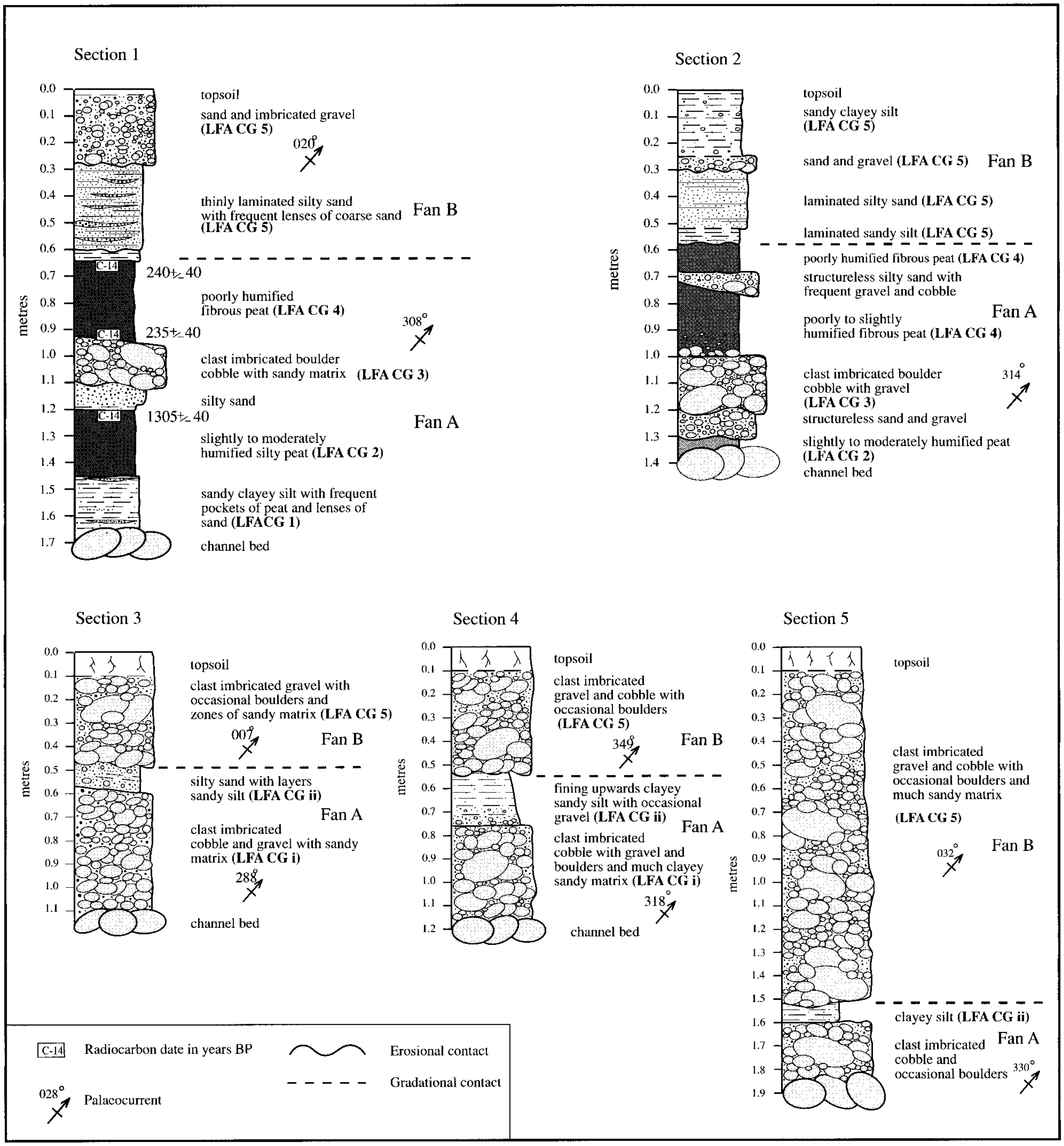


Figure 3. Coomloughra Glen, sections 1 to 5. LFA—lithofacies association.

dence of a major shift to wetter climatic conditions (Fig. 10). In blanket peats across upland areas of the British Isles, climatic change is reflected by increased surface wetness, and, in west Ireland, this phase has been dated to after 550–740 cal. yr A.D. (Blackford and Chambers, 1991). Furthermore, climatic deterioration at this time in Ireland is recorded by narrow tree-ring growth, especially around 541 A.D. (Baillie and Munro, 1988). Global climatic change during the fourth to sixth centuries A.D. was also proposed by Wendland and Bryson (1974). Therefore, climate change possibly associated with increased storminess may also have been a contributing factor in promoting geomorphic activity between 230 and 790 cal. yr A.D. Indeed, some evidence in the pollen record supports a climatic interpretation for fan aggradation. Cyperaceae pollen and *Sphagnum* spores increase simultaneously with the fall in arboreal-pollen values between 48 and 44 cm in HG11d (Fig. DR2). This increase combined with a decrease in *Calluna* pollen support a shift to locally wet hydrologic conditions. Fan aggradation, at least in the Hag's Glen, therefore, is most likely to be related to a combination of human activity and climate change and is primarily a response to external forcing. A sequence of events may have involved initial slope desta-

TABLE 2. RADIOCARBON DATES OF PEAT SAMPLES FROM ALLUVIAL-FAN AND DEBRIS-CONE COMPLEXES

Laboratory number	Location and depth	Uncalibrated age (yr B.P.)	Calibrated age
Coomloughra Glen			
SRR-5957	Section 1: 0.66m	240 ± 40	A.D. 1510–1930
SRR-5958	Section 1: 0.93m	235 ± 40	A.D. 1510–1920
SRR-5959	Section 1: 1.22m	1305 ± 40	A.D. 650–790
Hags Glen			
SRR-5960	Section 6: 0.68m	240 ± 40	A.D. 1510–1930
SRR-5961	Section 6: 0.80m	450 ± 40	A.D. 1400–1510
SRR-5962	Section 6: 0.84m	445 ± 45	A.D. 1400–1630
SRR-5963	Section 6: 1.14m	820 ± 45	A.D. 1040–1280
SRR-5964	Section 11: 0.23m	835 ± 40	A.D. 1040–1270
SRR-5965	Section 11: 0.28m	1020 ± 45	A.D. 890–1160
SRR-5966*	Section 11: 0.36m	1410 ± 45	A.D. 550–680
SRR-5967	Section 11: 0.74m	3360 ± 45	1760–1520 B.C.
Curraghmore			
BETA-117295*	Section 14: 0.30m	190 ± 90	A.D. 1640–present
SRR-5955	Section 14: 0.60m	705 ± 40	A.D. 1390–1510
SRR-5956*	Section 14: 0.72m	1505 ± 40	A.D. 440–630

Note: Peat samples extracted from beneath erosive contacts.

bilization due to overgrazing followed by debris mobilization and fan aggradation during an intense rainstorm or series of rainstorms associated with climate change.

Marked channel incision and/or aggradation during the third through eighth centuries A.D. has also been recorded in several tributaries and trunk reaches of the south Tyne basin, northern England (Fig. 10; Macklin et al., 1992a, 1992b; Passmore and Macklin, 1997). It is concluded herein, however, that climate change cannot have been the sole cause of valley-floor destabilization, because hydroclimatologic changes of a similar if not greater magnitude had occurred in the Tyne basin earlier in the Holocene without resulting in significant upland erosion. Instead, it is suggested that extensive deforestation during Iron Age and Roman times had lowered the threshold for valley-floor erosion by indirectly augmenting runoff rates and stream powers. Evi-

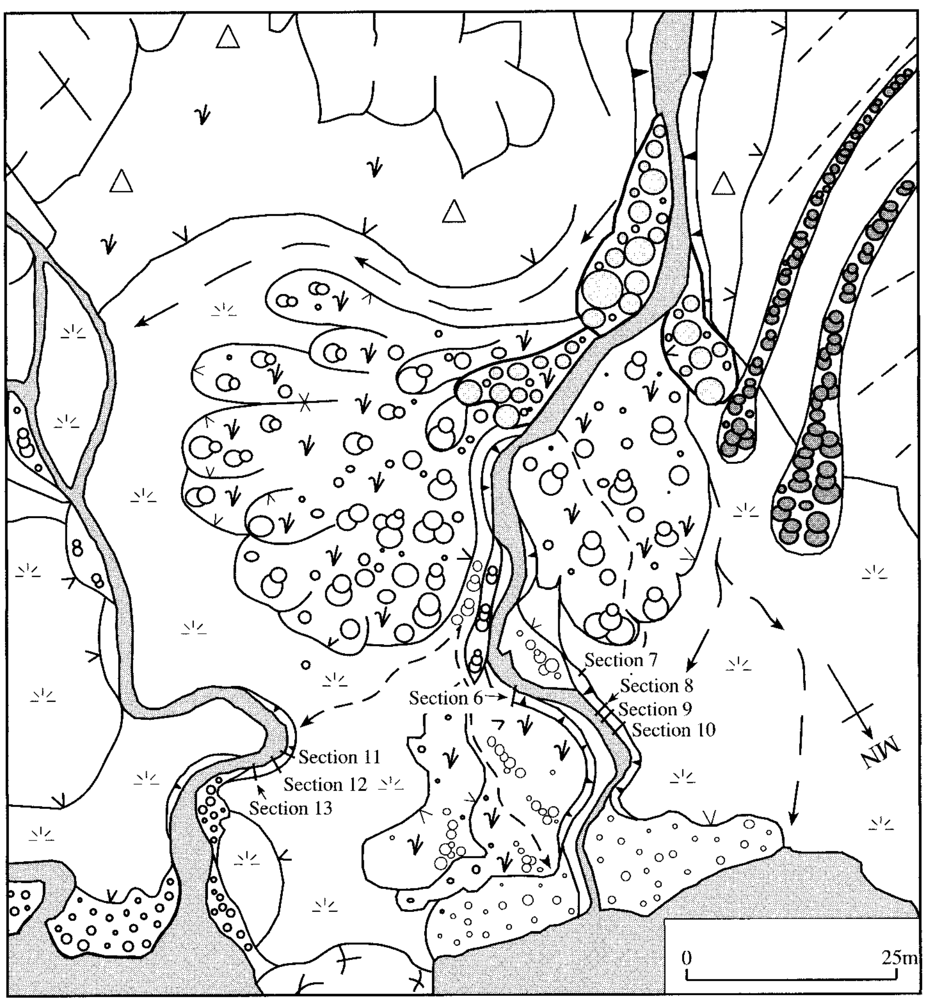


Figure 4. Map of Hag's Glen alluvial fan showing the location of sediment sections. See Figure 2B for explanation of sediment types. MN—magnetic north.

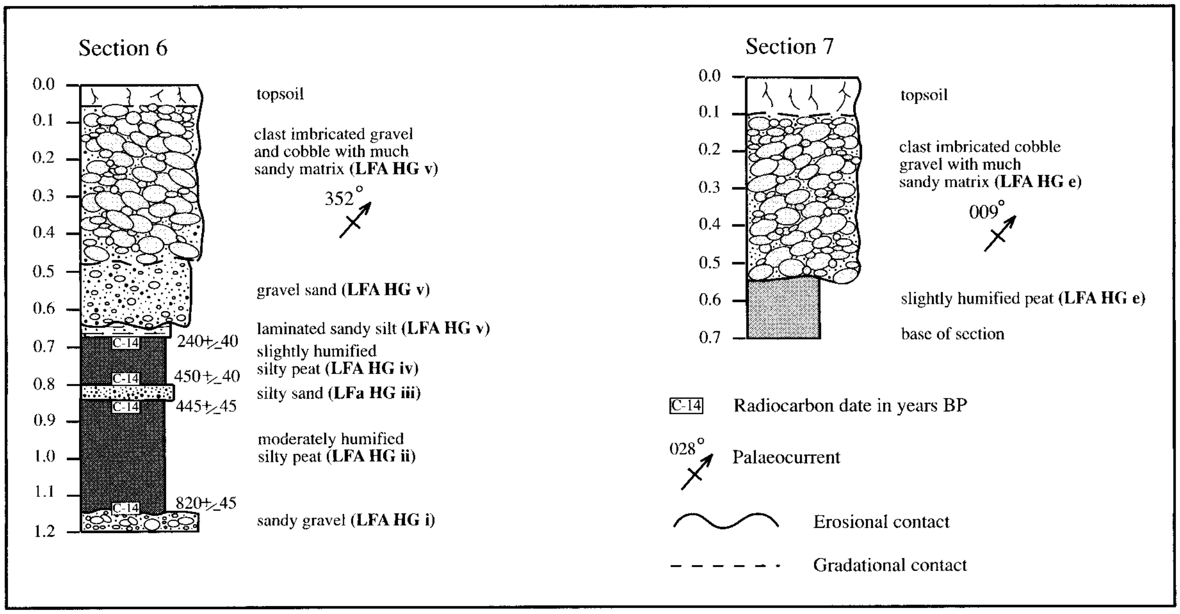


Figure 5. Hag's Glen alluvial fan, sections 6 and 7. LFA—lithofacies association.

dence of valley floor alluviation in Ireland, dated to between 1500 and 1200 yr B.P., has been reported by Glanville et al. (1997) from the upper catchment area of the River Liffey in the Wicklow Mountains (Fig. 10). Although these authors acknowledged that fluvial activity coincided with sub-Atlantic cooling and that local pollen records do not show land-use changes during this period of time, they did not speculate on the probable causes of alluviation. Evidence of valley-floor alluviation has also been reported from continental Europe at this time. For instance, Becker and Schirmer (1977) documented evidence of renewed flooding after 350 A.D. in the Danube basin, Austria, and after 560–711 A.D. in the Main Valley, southern Germany. In contrast, however, fluvial basins in North America were characterized by relative stability after 1800 yr B.P. (Knox, 1983).

Fan Aggradation in the Second Millennium A.D.

Geomorphic activity in the Macgillycuddy's Reeks after 1040–1280 A.D. is recorded solely on the Hag's Glen alluvial fan (LFA HG5; Fig. 6). Pollen analysis of an earlier peat horizon (LFA HG4; LPAZ HG11e) indicates a stable open landscape existed from 890–1160 cal. yr A.D. to 1040–1270 cal. yr A.D. The occurrence of high percentages of Poaceae and the presence of *Potentilla*-type, Campanulaceae, Gentianaceae, and Ranunculaceae suggests that the dominant vegetational community was acidic grassland with alpine elements such as *Jasione*-type. Evidence of grazing is demonstrated by the presence of *Rumex acetosa*/*acetosella*, *Pteridium*, Lactucae, Asteroideae, and Brassicaceae in the upper half of LPAZ HG11e and the gradual increase of *Plantago lanceolata* throughout LPAZs HG11e to HG11c to about 7% total land pollen (Fig. DR2) just beneath the overlying clastic unit LFA HG5 (Fig. 6). Consequently, fan aggradation appears to coincide with evidence for more intensive grazing around the fan and was, therefore, an important factor in conditioning slope response to rainstorm events. The rise in Cyperaceae values also suggests that soils become wetter during the last part of LPAZ HG11e, which may have lowered the threshold for soil movement.

Several other authors have documented alluvial-fan and debris-cone aggradation in upland Britain during the tenth and eleventh centuries (Fig. 10). Harvey et al. (1981) described a debris cone, which occurs at the base of a deeply incised solifluction slope in the Howgill Fells, northern England. This cone is made up of debris-flow deposits overlying a buried organic soil horizon dated to between 2580 ± 55 yr B.P. and 940 ± 95 yr B.P. Pollen analysis revealed that the soil horizon coincides with vegetational changes indicative of the rapid transition from a mixed landscape dominated by *Alnus* and *Rumex* to a more open landscape dominated by moorland vegetation, such as Ericaceae. Harvey et al. (1981) suggested that these pollen changes reflected a significant increase in the area of deforestation and inferred that this occurred in response to the expansion of sheep grazing following the arrival of Scandinavian settlers in the tenth century. Harvey and Renwick (1987) also attributed tenth century alluvial-fan aggradation in the Bowland Fells, northern England, to increased human activity. Tipping and Halliday (1994) demonstrated that the aggradation of a large tributary fan in the Southern Uplands extending onto the valley floor of the River Tweed occurred between 894–1045 cal. yr A.D. and 1282–1397 cal. yr A.D. However, they were unable to relate fan development with proxy records of climate change or anthropogenic activity.

These episodes of geomorphic activity from the British uplands together with the evidence from the Hag's Glen demonstrate that the tenth and eleventh centuries were associated with widespread slope destabilization. In turn, this suggests that the geomorphic activity may have been promoted by regional climatic forcing. However, other proxy records demonstrate that this period was associated with climatic amelioration and reduced North Atlantic storminess (Lamb, 1982), and alluvial records from North America (e.g., Knox, 1983) and Europe (e.g., Becker and Schirmer, 1977) indicate that this period was associated with valley-floor stability. Therefore, the high runoff rates that initiated debris mobilization proba-

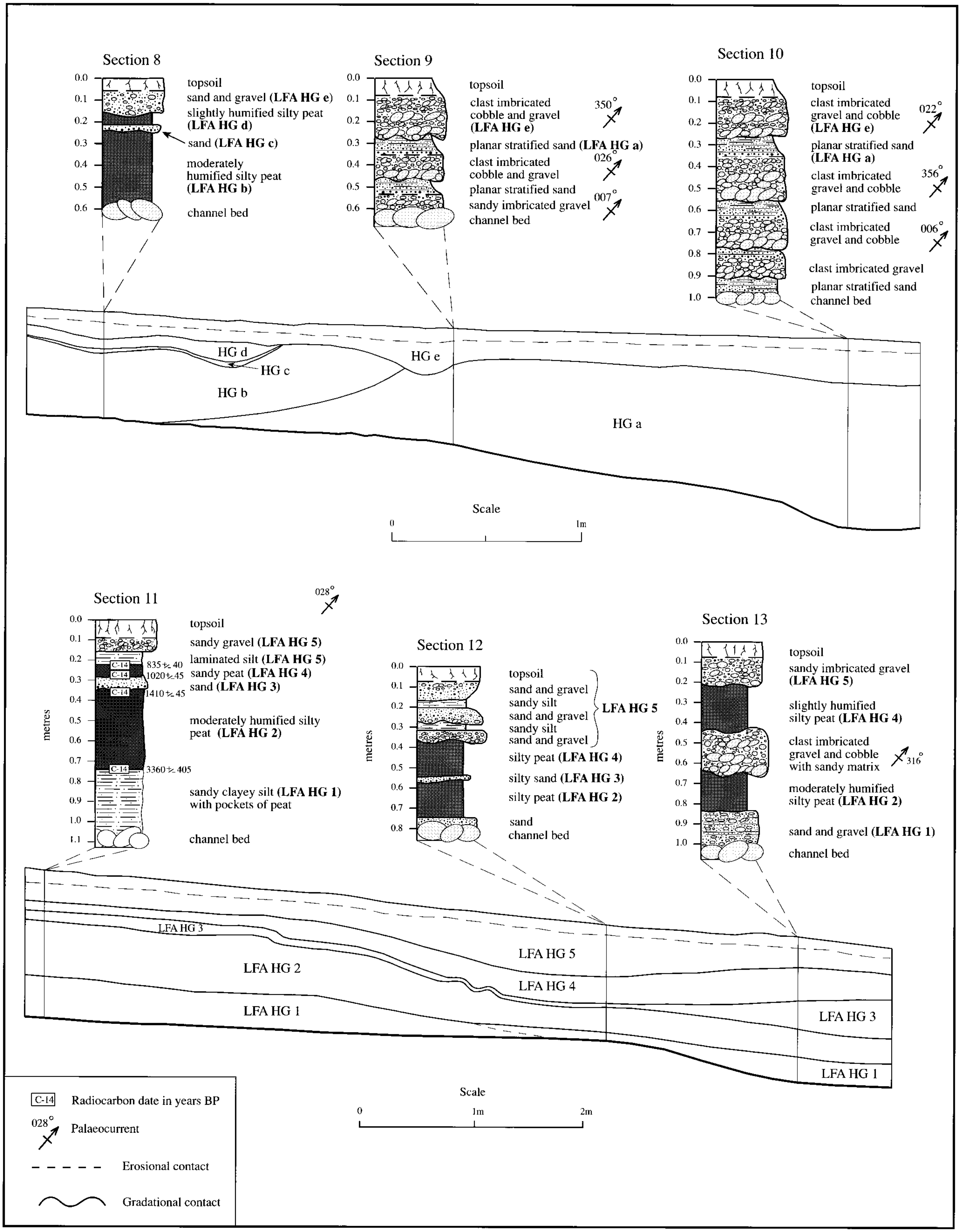


Figure 6. Hag's Glen alluvial fan, sections 8 to 13. LFA—lithofacies association.

C-14 Age	Fan Activity	Sections 11-13	Section 6	Section 7-10
	Fan Aggradation		LFA HG vi	LFA HG e
			LFA HG v	
1510-1930 AD 1400-1510 AD	Surface Stability	No Record	LFA HG iv	LFA HG d
	Fan Aggradation		LFA HG iii	LFA HG c
1400-1630 AD 1040-1280 AD	Surface Stability		LFA HG ii	LFA HG b
	Fan Aggradation	LFA HG 5	LFA HG i	LFA HG a
1040-1270 AD 890-1160 AD	Surface Stability	LFA HG 4		
	Fan Aggradation	LFA HG 3	No Record	
550-680 AD 1760-1520 BC	Surface Stability	LFA HG 2		
	Fan Aggradation	LFA HG 1		

Figure 7. Correlation and age of the Hag's Glen alluvial-fan lithofacies association. LFA—lithofacies association.

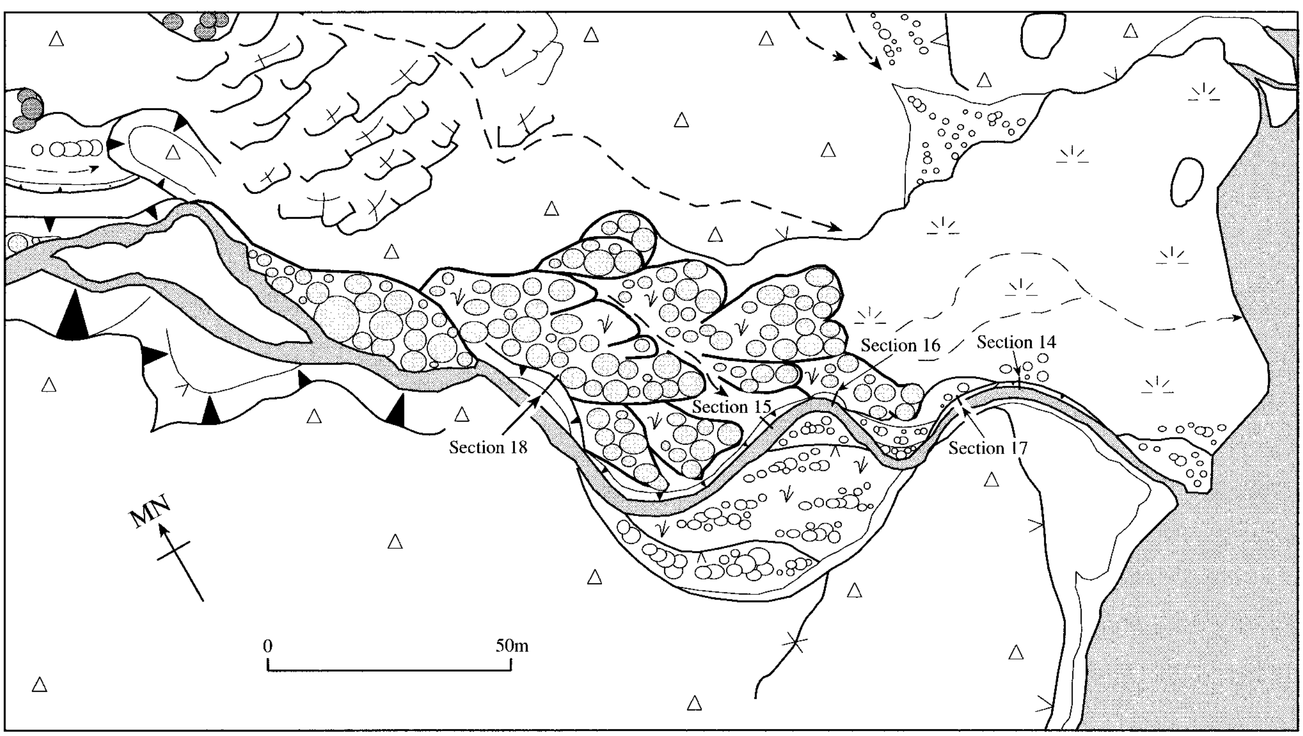


Figure 8. Map of Curraghmore alluvial fan showing the location of sediment sections. See Figure 2B for explanation of sediment types. MN—magnetic north.

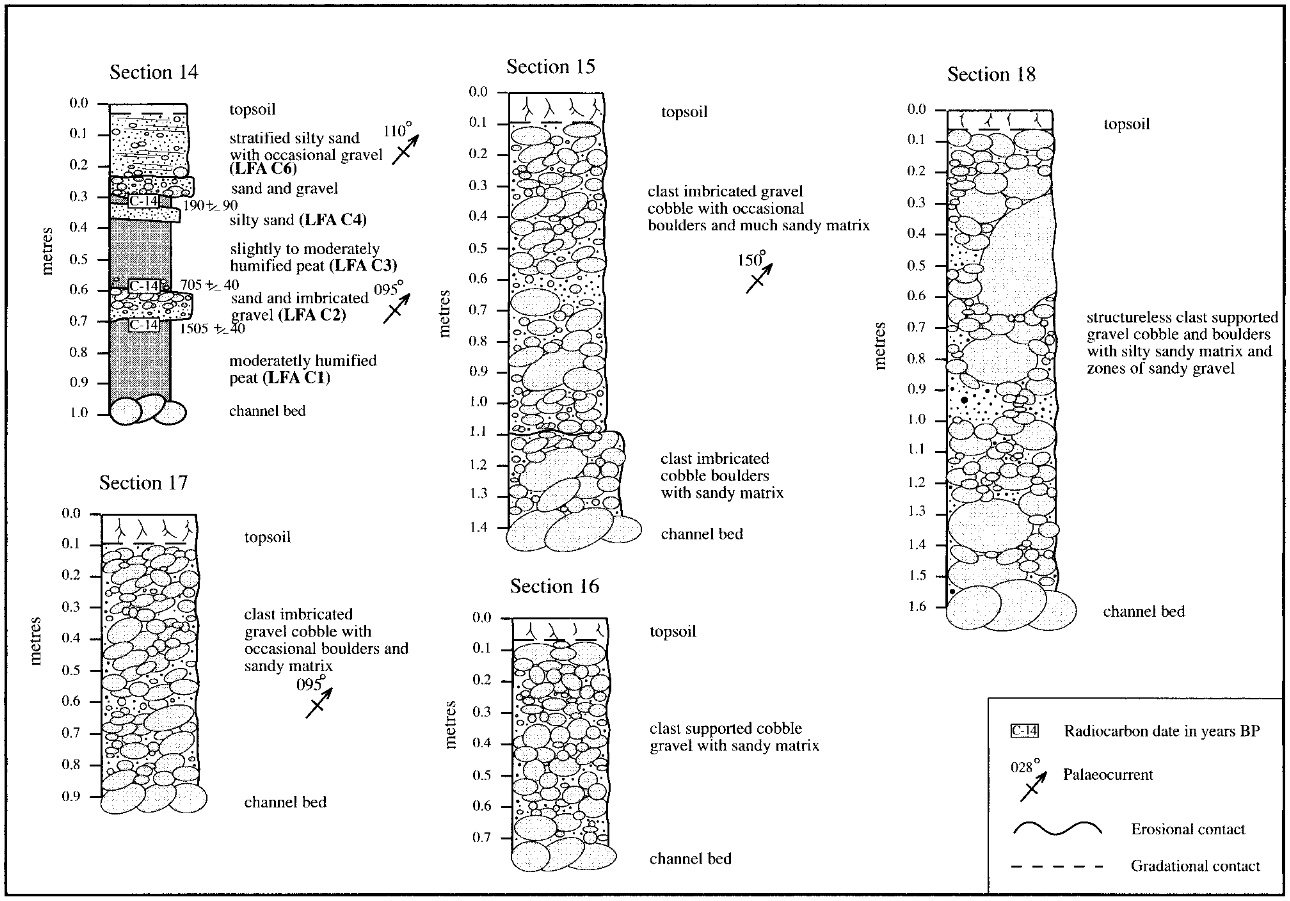


Figure 9. Curraghmore alluvial fan, sections 14–18.

bly were caused by exceptionally intense frontal or convection storms, and the apparent coincidence in the timing of fan aggradation is probably a function of site-specific factors and the poor data set on regional alluvial-fan development.

Fan Aggradation after 1510 Cal. Yr A.D.

This period represents the most significant phase of fan aggradation recorded in the Macgillycuddy's Reeks. Historical records reveal that the forest cover in upland areas of County Kerry was substantially modified in the sixteenth to eighteenth centuries following the arrival of Elizabethan settlers. Woodland destruction then resumed during the seventeenth and eighteenth centuries for the production of charcoal for local ironworks (McCracken, 1971; Watts, 1984). The pollen diagram for section 6 (Fig. DR1) of the Hag's Glen alluvial fan, however, suggests that a stable open landscape, dominated by wet acidic grasslands and small amounts of birch and oak woodland (~15% total land pollen), existed in this locality from 1040–1280 cal. yr A.D. to 1510–1930 cal. yr A.D. Indeed, these vegetation characteristics are very similar to the present-day flora. Agricultural activity, particularly grazing, is reflected throughout this time by *Rumex acetosa*/*acetosella, Urtica dioica*–type, *Artemisia,* and *Plantago lanceolata.* There is no evidence of increased grazing in the upper part of HG5 (Fig. DR1), but a sharp charcoal peak just beneath the overlying clastic unit LFA HGv indicates that vegetation burning may have affected slope stability.

Pollen evidence for wetter conditions (either climatic changes or reflecting hydrologic changes) in the Macgillycuddy's Reeks during historical times is unclear. *Sphagnum* spore values remain below 5% total land pollen, whereas Cyperaceae values are much higher compared to prehistoric times (Fig. DR1) but fall gradually throughout LPAZ HG4 prior to the deposition of unit LGA HGiii. Higher Cyperaceae values during LPAZ HG5 (up to 30%), suggest that wetter soil conditions allowed the spread of sedges, but these values dip before the deposition of LFA HG5. A number of factors suggest that climatic forcing, however, triggered slope instability. First, based on radiocarbon dating, fan aggradation after 1510 A.D. appears to have been broadly synchronous. Second, the generation of multiple transitional-flow lobes and waterflood deposits implies a number of high-discharge events in response to a distinct phase of intense rainstorms and increased wetness. Last, this period of geomorphic activity coincides with the well-documented phase of increased storminess during the Little Ice Age of the sixteenth to nineteenth centuries (Fig. 10; Lamb, 1979, 1982).

Increasing evidence exists that short-term hydroclimatic changes during the Little Ice Age caused widespread slope destabilization and valley-floor alluviation throughout the Northern Hemisphere (Grove 1988), including western and central Europe (cf. Rumsby and Macklin, 1996), Scandinavia (cf. Matthews et al., 1997), and the western United States (cf. Meyer et al., 1997). In Britain, increased river flooding in response to Little Ice Age storminess has been demonstrated in the Tyne basin

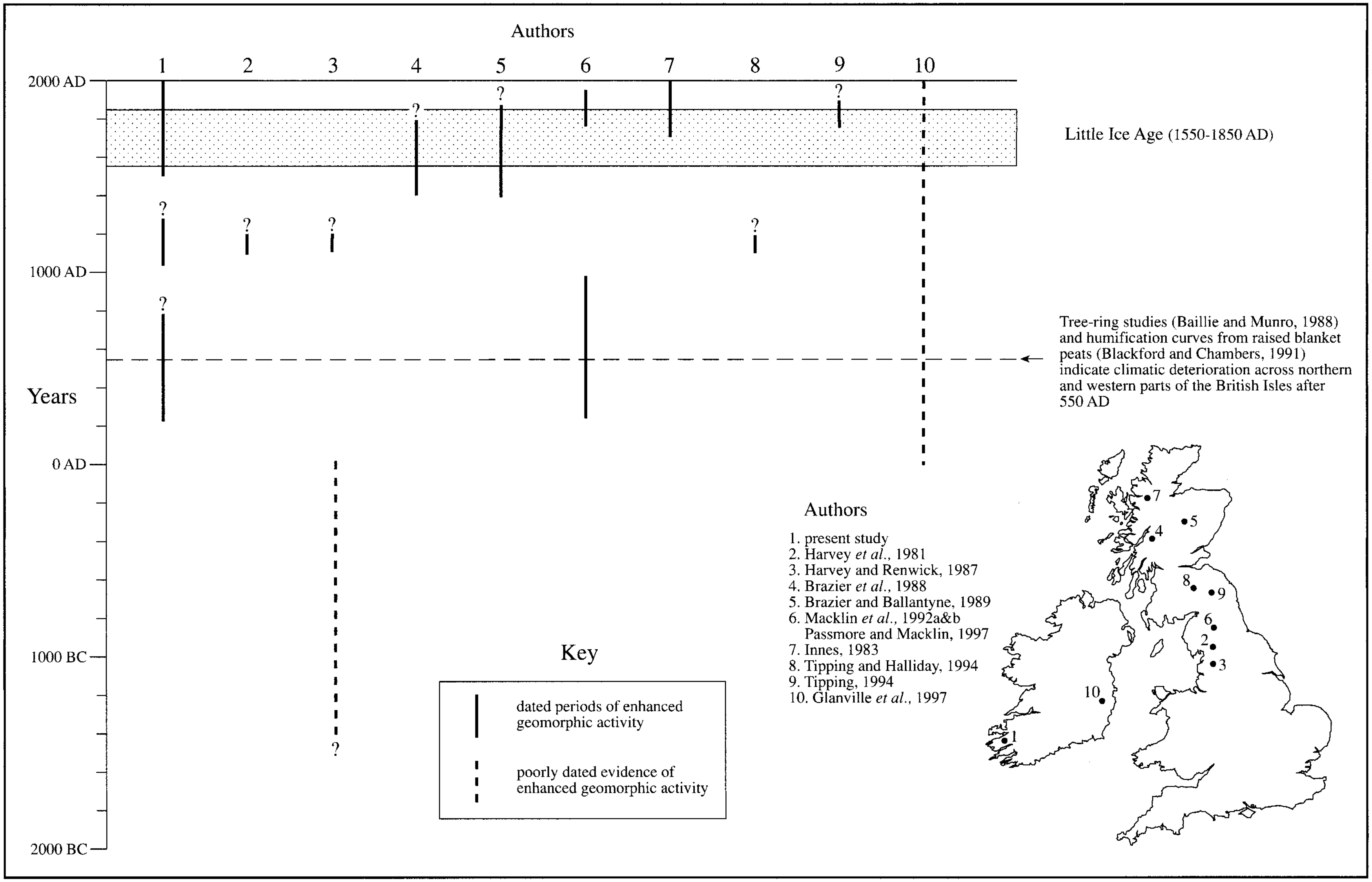


Figure 10. Episodes of late Holocene alluviation and debris-flow activity in upland areas of the British Isles. Study areas shown in map of Great Britain and Ireland, and investigators depicted by numbers and key.

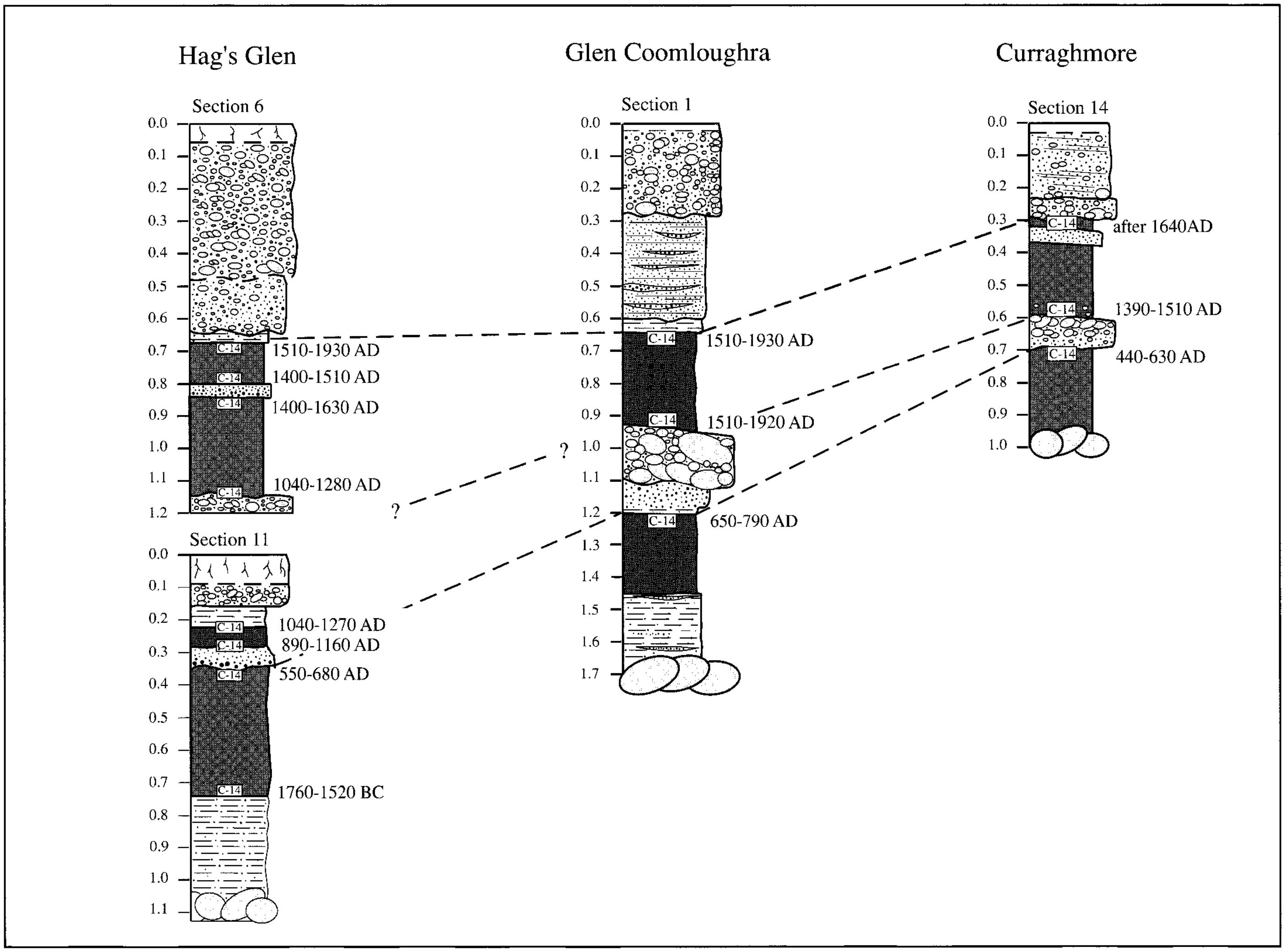


Figure 11. Correlation between sections at Hag's Glen, Glen Coomloughra, and Curraghmore of alluvial-fan and debris-cone inorganic layers.

(Macklin et al., 1992b; Passmore et al., 1993; Rumsby and Macklin, 1994) and inferred by Tipping (1994) to interpret Holocene alluvial fills in the Tweed valley, southern Scotland (Fig. 10). Brazier and Ballantyne (1989) attributed accelerated debris-cone aggradation since the fifteenth century in the western Cairngorm Mountains, Scotland, to climatic forcing and were able to reject anthropogenic activity as a forcing agent because the slopes above the debris cones were thickly wooded and there was no evidence that this woodland cover had ever been disturbed. Instead, they suggested that debris mobilization might have followed a rare and exceptionally intensive rainstorm that stripped away surface vegetation and lowered the threshold for subsequent gullying and fan aggradation. Recently, a number of high-resolution climate reconstructions based on proxy and historical sources have demonstrated that the Little Ice Age consisted of a complex series of alternating and nonsynchronous, cold and warm episodes (Bradley and Jones, 1995). Significantly, Rumsby and Macklin (1996) have demonstrated that phases of enhanced fluvial activity across Europe coincided with periods of climatic transition. Nevertheless, the impact of hydroclimatic forcing must have been conditioned to some degree by land-use changes despite the strong association between debris mobilization and climate change during the Little Ice Age in catchments with a long history of pastoral or arable farming.

The evidence presented here suggests that anthropogenic activity and climate forcing cannot be viewed as mutually exclusive causes of late Holocene alluvial-fan and debris-cone development in upland areas of the British Isles. Instead, it appears that such activity was conditioned by land-use changes and driven by increased storminess. A sequence of events may involve initial slope destabilization related to overgrazing and removal of vegetation and followed by debris mobilization and fan aggradation during an intense rainstorm or series of rainstorms associated with climate change. Across the British Isles, periods of late Holocene valley-floor alluviation and slope destabilization in upland areas cluster into three phases: (1) third to eighth centuries, (2) tenth to eleventh centuries, and (3) sixteenth century to the present (Fig. 10). Such regional synchroneity of geomorphic activity also implies that climatic forcing was the primary driver of geomorphic responses. That all three phases are associated with alluvial development in the Macgillycuddy's Reeks also suggests that this area was particularly sensitive to increased storminess. Indeed, this is not unexpected considering the close proximity of this area to the North Atlantic seaboard and highlights the potential of geomorphic records in southwest Ireland as sensitive indicators of late Quaternary climate fluctuations driven by changes in North Atlantic thermohaline circulation. The importance of land-use changes in conditioning alluvial-fan development also may explain why there is no evidence of Holocene geomorphic activity in the Macgillycuddy's Reeks before the rise of agriculture. For instance, fluvial records from central Europe (Becker and Schmirer, 1977), North America (Knox, 1983), and lowland Britain (Macklin and Lewin, 1993) demonstrate episodes of landscape destabilization in response to early and middle Holocene hemispheric climatic forcing. Therefore, the absence of corresponding aggradation units in an area that appears to be climatically sensitive implies that the natural vegetation cover prevented debris mobilization.

CONCLUSIONS

Examination of two alluvial fans and an alluvial-fan and alluvial-debris complex in the Macgillycuddy's Reeks reveals evidence of episodic phases of late Holocene aggradation and incision. Radiocarbon dates from peat horizons above and below inorganic units indicates a high degree of synchroneity between phases of aggradation, which cluster into two distinct periods: after 230–790 cal. yr A.D. and 1510 cal. yr A.D. to the present. An additional phase of fan aggradation is dated from after 1040–1280 cal. yr A.D. (Fig. 11). The interstratified peat horizons imply that these episodes were separated by phases of relative surface stability. Evidence of land-use changes prior to aggradation from the Hag's Glen alluvial fan suggests that agricultural activity was an important factor in lowering the threshold for slope erosion. Conversely, episodes of fan development also coincide with well-documented phases of climate change—climate deterioration after 550–740 cal. yr A.D. (Blackford and Chambers, 1991; Baillie and Munro, 1988) and the Little Ice Age of the sixteenth to nineteenth centuries (Grove, 1988). Fan aggradation is therefore, probably a function of both anthropogenic and climatic forcing.

APPENDIX. METHODS

Depositional landform assemblages and morphostratigraphic relationships were determined by geomorphic mapping at scales ranging from 1:1000 to 1:4000 using enlarged aerial photographs as base maps and by topographic surveying. Lithostratigraphy of the fans was established by sediment logging of exposed stream-cut sections. Depositional facies (Data Repository Table DR1) were classified as debris flows, transitional flows, and streamflows on the basis of surface morphology, texture, sorting, and internal structures using the criteria set out by Wells and Harvey (1987), Costa (1988), Blair and McPherson (1994), and Meyer et al. (1997). Debris flows are non-Newtonian fluids that possess high-yield strengths (>40 Pa), and consist of viscous slurries of sediment and water moving as a single phase (Costa, 1988; Meyer et al., 1997). Deposition occurs as the slurry thins out, resulting in the formation of prominent depositional lobes characterized by steep flanks and sharp lateral margins. These lobes consist of very poorly sorted debris with weakly developed stratification and clast fabrics that strongly reflect compressional and extensional flow regimes (Costa and Jarrett, 1981; Wells and Harvey, 1987; Costa, 1988; Meyer et al. 1997). In contrast, streamflows are turbulent Newtonian flows that have no yield strength and low sediment loads (Costa, 1988). Facies types, therefore, consist of well-sorted and clast-supported deposits that form low-relief sedimentary landforms with indefinite lateral margins (Meyer and Wells, 1997; Blair and McPherson, 1994). Transitional or hyperconcentrated flows represent the stage between non-Newtonian and Newtonian flows and possess a small but measurable shear strength (10–40 Pa; Costa, 1988). Facies types are, therefore, intermediate between debris-flow and streamflow deposits and form prominent landforms consisting of moderately to poorly sorted deposits, which may be both clast and matrix supported and display crudely developed stratification and clast imbrication (Wells and Harvey, 1987; Costa, 1988; Meyer et al., 1997).

A total of 14 peat samples, from in situ horizons exposed in stream-cut sections, were selected for radiocarbon analysis. Where possible, peat samples were extracted from horizons above and below nonerosive contacts with inorganic sediments to minimize gaps in the timing of the onset and cessation of fluvial activity and peat accumulation. Samples were analyzed at the Natural Environment Research Council Radiocarbon Laboratory, East Kilbride, Scotland, and Beta Analytical, Miami, Florida, USA. All radiocarbon dates were calibrated using OXCAL (version 2.18; Stuiver and Kar, 1986). Pollen and charcoal analysis was carried out on samples (sections 6 and 11) collected in aluminum monolith tins (15 cm $\times$ 50 cm) from the Hag's Glen alluvial fan. Subsamples of 0.5 cm thickness and 2 g wet weight were prepared for pollen analysis using the procedure described by Barber (1976). One *Lycopodium clavatum* spore tablet was added to each subsample to calculate charcoal concentrations using the point-count estimation procedure outlined by Clark (1982). At least 500 land-pollen grains were counted for each subsample. Pollen grains were identified using the keys of Faegri et al. (1989) and Moore et al. (1991) and by comparison with a modern type-slide collection. Nomenclature follows Stace (1991) and includes nomenclature changes as recommended by Bennett et al. (1994).

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