Sedimentology of proglacial rivers in eastern Scotland during the Late Devensian

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ABSTRACT: This paper reconstructs the characteristics of rivers which deposited proglacial fluvial sediments in east-central Scotland during the Late Devensian. Sediment depositional architecture and geometry, together with the relationship between high-stage and falling and low-stage depositional elements, were used to relate the proglacial sediments to the glacial meltwater discharge regime. The proglacial river systems studied were dominated by 'normal' ablation controlled discharge, rather than by high magnitude flood events. Consequently there is a great deal of spatial and vertical variability. Deposition occurred during short intervals of rapid aggradation, so that relatively fine-grained falling-stage sediments, as well as coarser, bar-core sediments are well preserved. Models relating the characteristics of the final deposit to the nature of the river are presented. These emphasise the role of stage changes and aggradation rates in controlling sediment architecture in braided fluvial deposits.

KEY WORDS: braided fluvial architecture, glacial meltwater discharge regimes, proglacial sediments

Studies of the sedimentology, as opposed to the geomorphology, of glaciofluvial sediments in Scotland are relatively rare. Most Quaternary sedimentological studies in Scotland have been concerned with glacial sediments (e.g. Menzies & van der Meer 1998), or glaciolacustrine and glaciodeltaic sediments (e.g. Thomas 1984; Thomas & Connell 1985; Aitken 1990, 1995). To date, the only detailed sedimentological studies of proglacial fluvial sediments in Scotland have been by Maizels (1976), Martin (1981), Maizels & Aitken (1991) and Aitken (1991, 1998).

Identifying the processes operating during the deposition of proglacial fluvial sediments can provide important information on the nature and rates of meltwater discharge, which are largely controlled by climatological or glaciological factors (Maizels 1995). Glacial meltwater discharge is highly variable on a diurnal and seasonal basis (Röthlisberger & Lang 1987) and sediments deposited by 'normal' ablation controlled discharge are likely to reflect variable flow stages and repeated reworking (Maizels 1995). In contrast, high magnitude–low frequency events such as glacial floods are likely to produce distinctive sedimentary successions reflecting high discharges and sediment availability (Maizels 1997). As such, reconstruction of the hydraulic characteristics of proglacial river systems can improve understanding of the nature and rate of deglaciation of the last Scottish ice-sheet, a topic of some debate (Clapperton 1997; Hall 1997). This paper describes proglacial fluvial sediments exposed in active sand and gravel quarries in eastern Scotland, and uses the sedimentary record to reconstruct the characteristics of the rivers which deposited the sediments.

1. Study area

The locations of the quarries used in this study are shown in Figure 1. Three are in NE Fife, on the 'Lindores fan', an alluvial fan in the Howe of Fife formed during deglaciation by meltwater from a glacier in the Firth of Tay flowing through a gap in the Ochil Hills into the ice-free Howe of Fife (Browne *et al.* 1981; Fig. 1B). The remaining three quarries are in the Lunan valley, northern Strathmore (Fig. 1C). Two of the latter quarries are just E of Forfar, close to a prominant glacier stillstand position identified by Rice (1960). The third quarry is 10 km downstream, near Friockheim. Like the Lindores fan, the Lunan valley was only fed by glacial meltwater for a short period of time. Once the ice retreated from Forfar, meltwater drained into the South Esk by the 'Oathlaw Channel' (Rice 1960).

2. Methods

Detailed sedimentological logging was carried out at each quarry. Particular attention was paid to those features which could be used to indicate the nature of the meltwater discharge regime. The detailed sedimentological information included measurements of unit thickness; presence and nature of erosional contacts; grain size, both as an average for units, and also for coarse units, the average and largest clast b-axes present; sedimentary structures, including any flow direction information recorded; grading (upwards-fining, upwards-coarsening or ungraded) of both individual units and of the succession as a whole; for coarse units, sorting and the nature, size and grading of the matrix and clast support (clast or matrix-supported).

Sediment architecture and depositional geometry were recorded on sketches made in the field and photo-mosaics. Many features on the vertical logs, such as the nature of the contact between units, were also recorded on the architecture diagrams. The lateral extent of individual units was measured, and particular attention paid to identifying the presence of depositional features which could be related to distinctive processes such as bar and bedform development, including foresets and lateral accretion structures. Formal architectural element analysis (Miall 1985) was avoided during the descriptive process as this technique confuses the description and interpretation of the sediments. Rather, sediment geometry and facies were described separately, and then, as a second stage, process-based interpretations of the sedimentary facies were produced. At this stage, the terminology of architectural

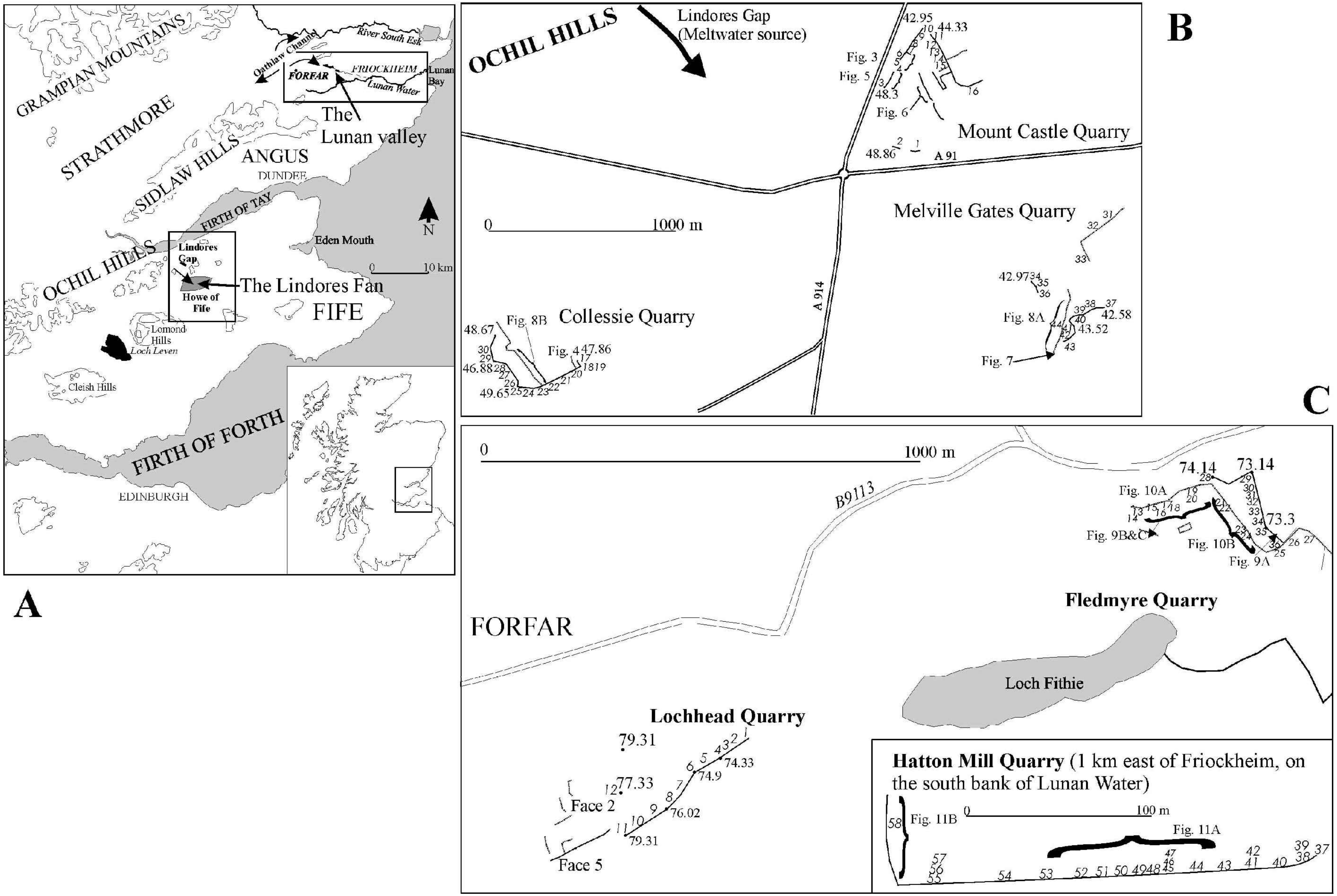

Figure 1 (A). Location map of east-central Scotland. The upper box shows the location of the Lunan valley, and the lower box the location of the Lindores fan within the Howe of Fife. Contours are at 183 m, 305 m and 427 m. Inset: location of the main map within Scotland. (B). Location of the study quarries within the Howe of Fife, showing the location and orientation of other diagrams. (C). Location of study quarries in the Lunan valley, showing the location and orientation of other diagrams. Inset: location of diagrams and clast orientation data for Hatton Mill Quarry. In Figures 1B and C, numbers in *italics* refer to Tables 2 and other figures are spot heights in metres.

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Table 1 Descriptive lithofacies codes used in this study (after Graham 1988).

Code	*Lithofacies*	*Sedimentary structures*
Gms	Massive, matrix-supported gravel	None
Gm	Masive or crudely bedded gravel	
Gt	Gravel, stratified	Trough crossbeds
Gp	Gravel, stratified	Planar crossbeds
St	Sand, medium to coarse, may be pebbly	Solitary or grouped trough cross-beds
Sp	Sand, medium to coarse, may be pebbly	Solitary or grouped planar cross-beds
Sr	Sand, very fine to coarse	Ripple marks of all types
Sh	Sand, very fine to very coarse, may be pebbly	Horizontal lamination. Parting or streaming lineation
Sl	Sand, fine	Low-angle crossbeds
Se	Erosional scours with intraclasts	Crude crossbedding
Fl	Sand, mud, silt	Fine laminations, very small ripples
Fsc	Silt, mud	Laminated to massive

element analysis and the sediment geometry classifications of Ramos & Sopeña (1983) were introduced. Sediment geometry is therefore based on descriptive, but not interpretative, classifications such as those presented by Friend (1983) and Bridge (1993b), and, where possible, geometry is described in three dimensions. Lithofacies codes are used as a 'shorthand' for labelling diagrams, but are used in a purely descriptive sense and do not imply specific interpretations (Table 1). The lithofacies codes are based on those presented by Graham (1988).

Data regarding sediment fabric, and particularly clast orientation, were also collected. Clast orientation data not only provide information on palaeoflow direction (Rust 1972a; Bluck 1974) but also on the discharge regime. High-magnitude floods are more likely to have a hyperconcentrated fluid–sediment mixture, with clast a-axes parallel to palaeoflow (Costa 1988). In fully turbulent water flows, clasts tend to align with their a-axes transverse to palaeoflow. Repeated reworking by variable stage flows is likely to increase the dispersion of the clast orientation around the mean flow direction, particularly of smaller clasts. In this study, the orientation and nature of imbrication (dip of the a–b plane) of clasts was recorded extensively across each quarry. Where possible, fifty clasts were measured at each site, avoiding clasts smaller than the median grain size for the unit, and well-rounded clasts. The clast orientation data were used to calculate a vector mean using the formula presented by Curray (1956). Two tests of dispersion were used, the vector strength (r) and the vector magnitude (L), which expresses the vector strength as a percentage (Curray 1956).

The following sections describe the principal depositional unit geometries observed in this study, followed by the associated sedimentary infills for each unit geometry. The two sets of descriptions are synthesised and interpreted, and then the overall character of the river systems studied is considered.

3. Depositional units

3.1. Depositional units description: geometry

Three main forms for the geometry of sediment bodies have been identified (Fig. 2): (A) tabular or rectangular, horizontal sediment layers, which when seen in two dimensions form sheets; (B) cut-and-fill units which have horizontal upper surfaces, and concave-up lower surfaces (i.e. hollows) in one direction: these units are frequently similar to (A) when viewed at right angles; (C) units with steep, sloping bounding surfaces.

Each of these three forms can be further subdivided. Tabular units occur either as very thin units 0·05–0·1 m thick (Fig. 2Af), medium-scale units, between 0·2–0·4 m thick (Fig. 2Ac–e), and units 0·4–1·0 m thick (Fig. 2Aa–b). At one site on the Lindores fan, a single unit occurs which is at least 3 m thick (Fig. 3). The horizontal extent of units is also highly variable. Generally, thicker units are more extensive, both parallel and lateral to palaeoflow direction. The full extent of the >3 m-thick unit is not known as it extends for the length of the section (20 m transverse to palaeoflow, 5 m parallel to palaeoflow). In addition, the lateral termination of horizontally bounded units can vary. The termination can either be abrupt and vertical (Fig. 2Ai), or gradual and tapering. Tapering terminations can thin from either the base or top of the unit, or from both the base and top (Fig. 2Aii). Basal surfaces of all horizontal units tend to be erosive, and upper surfaces tend to be eroded by the overlying unit, although this is not always the case if the horizontal unit is overlain by a unit with a different geometry. Both basal and lateral contacts of the >3 m-thick unit were obscured. The upper surface corresponded to the ground surface, or was overlain by sharp, but non-erosive horizontal units, and a single erosive 'hollow'.

Variation in the form of cut-and-fill units is related to three factors (Fig. 2B): the width–depth ratio, the symmetry of the feature and the relationship between appearance in flow-parallel sections, and their form when viewed normal to palaeoflow. In terms of width–depth ratio, the main distinction is between narrow and shallow features (*c.* 1–2 m wide, 0·1–0·2 m deep, width-depth ratio 10), wide and shallow features (*c.* 5–10 m wide, 0·1–0·4 m deep, width–depth ratio 25–125+) and narrow and deep features (*c.* 2–5 m wide, 0·5–1 m deep, width-depth ratio <10). A single wide (25 m) and relatively deep (1–1·5 m) feature was observed on the Lindores fan (Fig. 4A). Care must be taken when describing width–depth ratios and symmetry, as they vary according to the orientation of the section relative to palaeoflow. Nevertheless, a broad distinction between symmetrical and asymmetrical hollows can be made. Finally, hollows with concave-up bases in both flow parallel and normal-to-palaeoflow sections are termed *scour*s, whilst features with convex bases in one orientation in one direction and horizontal upper and lower surfaces in a sub-perpendicular section are designated *channels*. Parallel to palaeoflow the channels can extend for the length of available exposure (up to 100 m in the quarries examined in this study) but are highly variable, and most commonly extend for 20–30 m before pinching out. The basal contact of all types of

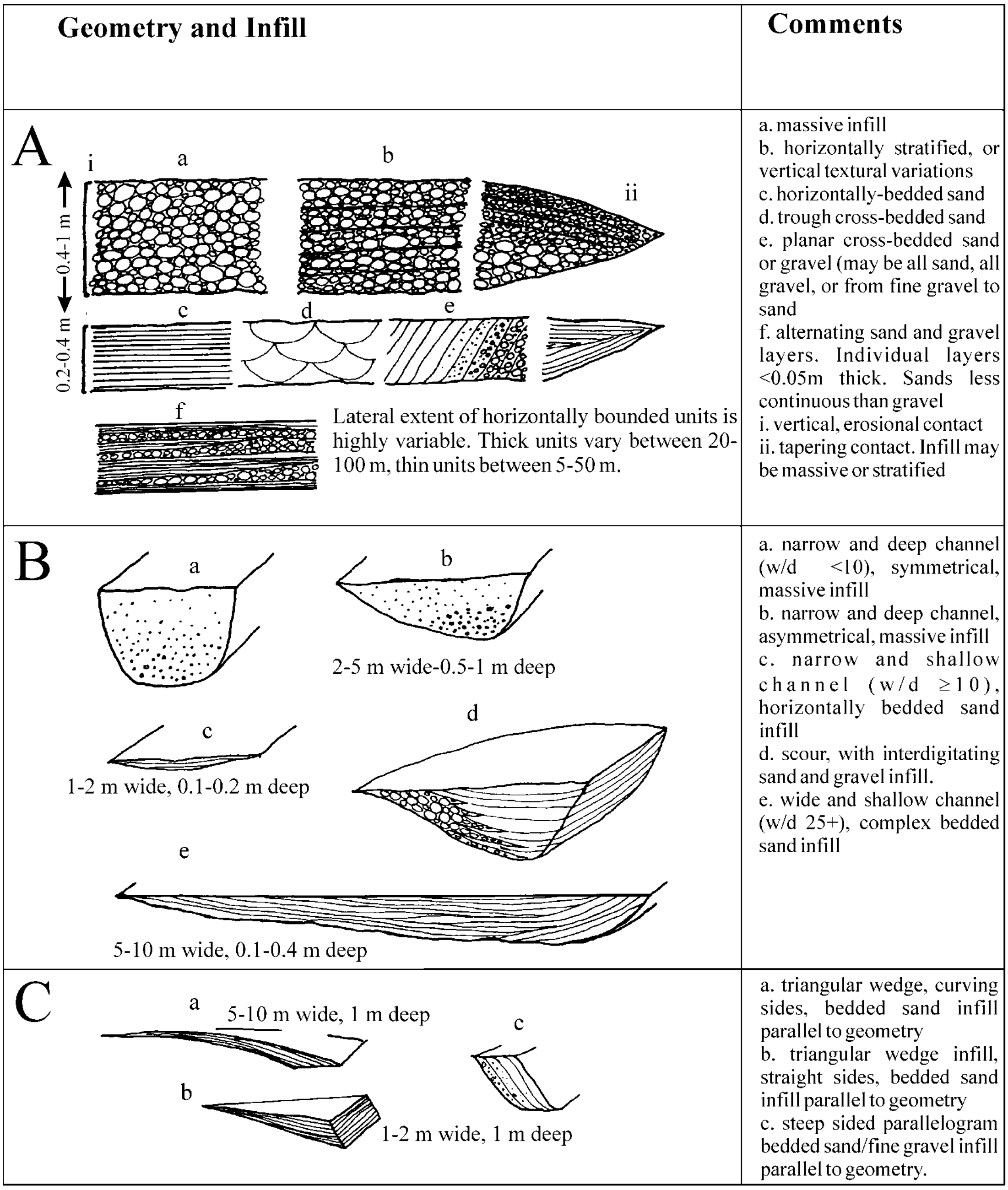

Figure 2 The main depositional geometries and associated infills found in this study: (A). depositional units with horizontal bounding surfaces, primarily interpreted as various types of bar structure; (B). 'scour' and 'hollow' depositional units, most of which are interpreted as channels. 'd' is interpreted as a confluence scour; (C). 'wedge' structures, interpreted as falling-stage accretion units.

cut-and-fill is invariably erosive. The upper contact may be erosive, or there may be no clear contact: in these cases the sediments of the overlying unit also infill the cut-and-fill. Gradational transitions between the facies infilling the cut-and-fill units and the facies of the overlying unit also occur in places.

The units with steep sloping margins are typically smaller than the other depositional units (Fig. 2C). Common forms for these features include parallelograms, with the upper and lower surfaces horizontal, and steep sides which are longer than the upper and lower surfaces (Fig. 2Cc). Alternatively, triangular wedges are common. Wedges either have a short, near vertical side and two longer, straight, near horizontal sides (Fig.2Cb), or a horizontal base and two long, curving sides (Fig.2Ca). These features are most common in sections at right angles to palaeoflow, but also occur in flow-parallel sections. When viewed at right angles, the parallelogram and wedge features are invariably rectangular, with horizontal upper and lower surfaces. Parallelogram and straight-sided triangular wedge features are generally up to 2 m in length, and 1 m thick, but can be up to 5 m in length. Triangular wedges with curved sides can be bigger, up to 10–15 m long, and 1–2 m thick. Basal contacts of all of the steep-sided units can be both erosive, or sharp, but non-erosive. Upper contacts are generally erosive.

3.2. Depositional units description: sediments

Each of the depositional geometries described above can be associated with a range of possible sediment facies, leading to further subdivision of the range of depositional units encountered in this study (Fig. 2). Gravel facies are dominant in the horizontally bounded units; both sand and gravel facies are

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Figure 3 View of thick (> 3 m) horizontally bounded gravel unit with infill of massive gravel on the Lindores fan; the basal contact and lateral margins of the unit are not exposed; upper surface corresponds with the ground in this location but is overlain by localised scour features infilled with bedded sand and gravel in some areas; notebook for scale is 0·21 m high; area of pale sand left of centre is quarry spoil.

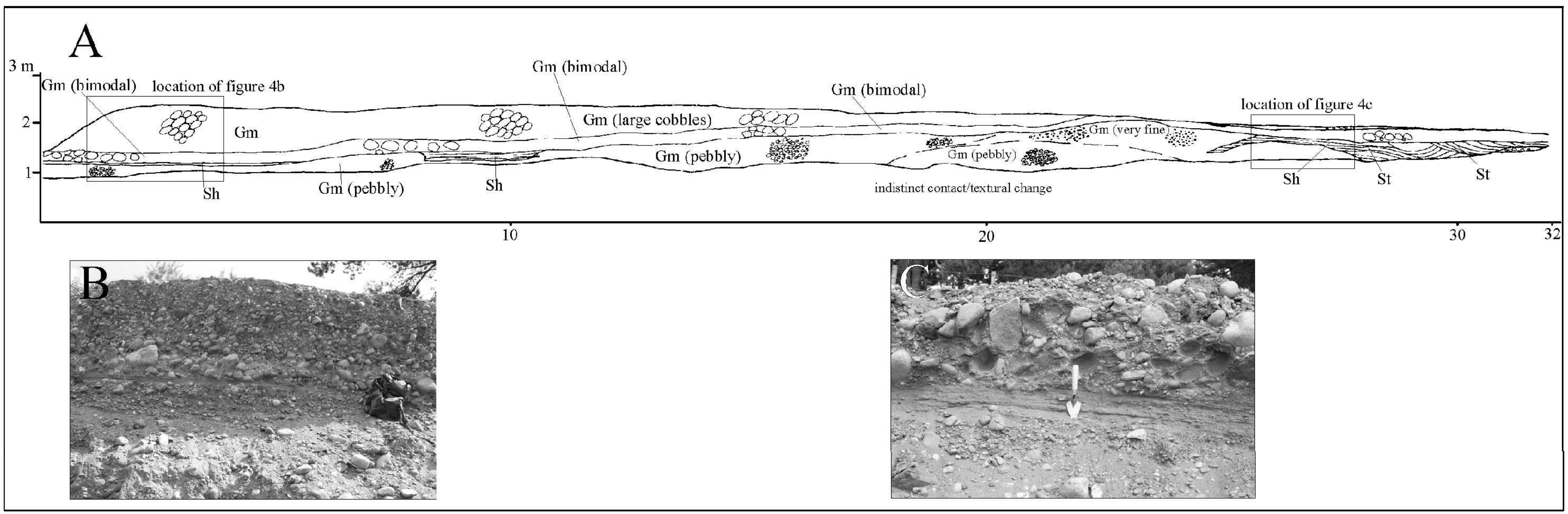

Figure 4 (A). Redrawn field sketch of the wide channel feature on the Lindores fan; base of the channel feature is marked by a thin but laterally extensive coarse bimodal layer; above the bimodal layer is a massive cobble gravel; the channel feature is incised into massive pebble gravel and bedded sands and gravels; flow was obliquely into the face to the SW (right); (B). detail of northern (left-hand) end of face shown in A, showing the tripartite succession of pebble gravel, coarse bimodal gravel and massive cobble gravel; rucksack for scale is 0·5 m long; (C) detail of southern (right-hand) end of face shown in A; the sands near the trowel handle form part of the sediments underlying the channel feature; the matrix-supported, bimodal nature of the overlying layer is shown by 'casts' formed by recently removed clasts; overlying the bimodal layer are coarse-grained, clast-supported massive cobble gravels; trowel is 0·27 m long.

common in the cut-and-fill units; and sand is dominant in the steep sided units.

The thicker (> 0·4 m) *horizontally bounded* units have exclusively gravel infills. Massive gravel is the most common infill (e.g. Fig. 5). Typically, massive gravel infills are clast-supported, imbricated and ungraded or slightly upwards-fining. Maximum clast sizes tend to be in the range 0·15–0·2 m. The degree of sorting and clast roundness vary greatly across the study areas. Sorting varies from very good, to poor. Finer units are generally better sorted. Rounding varies from sub-rounded to well-rounded. Finer, better sorted units tend to contain well-rounded clasts. Within individual units, lateral and downstream fining are common. The second most common infill for thick, horizontally bounded gravel units is coarse gravel with horizontal stratification, or vertical textural variations. Horizontal stratification tends to be defined by thin, intermittent sand layers, or bands of sandier matrix. Vertical textural variations tend to consist of rapid changes in matrix content, which may be repeated several times throughout a unit. Typically, variations are from sandy, to less sandy, or from openwork to polymodal or bimodal gravel. Where horizontally bounded units pinch out, the infill can be either massive, or stratified. When the infill is stratified, the stratification is parallel to the upper bounding surface, forming low-angle cross-strata. The > 3 m thick unit on the Lindores fan was entirely composed of coarse, poorly sorted, ungraded, massive cobble gravel. The unit is dominated by subrounded to rounded cobbles, and the largest clasts have b-axes up to 0·25 m. Although sorting is poor, and the matrix is sandy in places, the unit is clast supported. There are no textural variations within the unit.

Horizontally bounded units between 0·2 and 0·4 m thick are dominated by sand facies. The sand may be horizontally stratified, planar or trough cross-bedded. Planar cross-bedded units may fine downstream from cross-bedded pebble gravel to cross-bedded medium-coarse sand. The very thinnest horizontally bounded units (0·05–0·1 m thick) consist of alternating horizontally bedded sand, and pebble gravel layers one or two clasts thick.

The infill of depositional units with *concave-up lower bounding surfaces* is similarly variable (Fig. 2). Coarse massive gravel units are, however, much rarer, as are horizontally stratified gravel units. The wide and deep feature on the Lindores fan is infilled with massive, ungraded, poorly sorted, clast-supported gravel (Fig. 4B, C). Maximum b-axis length is 0·2 m and imbrication is common. The basal layer of the infill consists of a laterally extensive coarse bimodal unit. B-axes in the bimodal unit range between 0·1–0·15 m, and the matrix is medium-coarse grained sand with occasional pebbles (Fig. 4B, C).

Of the other, more common forms for depositional units with concave-up lower bounding surfaces, massive gravel is confined to the narrow and deep forms. In these circumstances, the gravel is fine grained, and either massive, or upwards fining. Also common in narrow and deep cut-and-fill units (particularly asymmetrical features) is interdigitating fine gravel and sand, with the bedding lying parallel to the base of the feature (e.g. Figs 2Bd, 6). All of the shallow concave-up based features are infilled with sand facies. Thinly horizontally bedded sand is most common, occurring in both wide and shallow features. Planar cross-bedded sand is common in the wide features and occurs in some of the narrow features. Trough cross-bedded sand was only observed in the wide features. Medium to coarse-grained sand was most common, but some of the narrow features were infilled with fine sand, or coarse silt.

The smaller, *steep-sided depositional* units are always infilled with sand facies. Triangular wedge structures are infilled with either planar cross-bedded sand, or horizontally bedded sand which lies parallel to the lower boundary, and therefore forms low-angle cross-strata. The *four-sided structures* are typically infilled with high-angle cross-strata which lie parallel to the steep-sided margins.

3.3. Depositional units: interpretation

The coarse-grained, *horizontally bounded* units are interpreted as barforms. A longitudinal bar interpretation is preferred for the 0·4–1 m-thick, gravel-dominated units. This interpretation is based on the dimensions of the units and the character of the sediments. Longitudinal bars in fluvial deposits rarely exceed 1–2 m in thickness (Miall 1977), and depending on the size of the river can range in size from < 5 m to 100 m in length and width. These dimensions are compatible with the units observed in this study, although no distinct features interpreted as individual bars were longer than 40 m, or wider than 20 m. The most common lateral dimension for distinct barforms observed here is 5–10 m. The variations in lateral termination of the depositional unit geometry (tapering or vertical) result from the presence or absence of cut-bank sections on the margins of the bar. The downflow and lateral fining trends observed within the massive gravels are characteristic of longitudinal bar formation (Boothroyd & Ashley 1975; Hein & Walker 1977; Bluck 1982). In all cases the clast-supported, imbricated nature of the gravel indicates that bed-load transport in fluidal flows was the dominant mode of sediment movement.

A longitudinal, mid-channel braid bar origin is preferred for a number of reasons. Transverse bars (Hein & Walker 1977) are usually characterised by foresets, which are absent from the structures observed here. Lateral (or side bars) are difficult to identify in the sedimentary record (Bluck 1979). For a lateral bar to be distinguished from a mid-channel bar, there needs to be clear evidence of bank-attachment, or of a well-developed chute channel. Neither of these features could be identified in the Lunan valley or on the Lindores fan. Lateral bars may be present, but their presence cannot be demonstrated unequivocally.

Vertical textural variations observed within gravel units which are otherwise identical to those described above are attributed to fluctuations in flow stage. Variations in flow stage can lead to winnowing of the bar surface, producing openwork layers, and coarser layers within finer sediments (Smith 1974; Bluck 1979). Similarly, winnowing and deposition of sand on the falling and low stages can lead to horizontal stratification and deposition of sand layers within otherwise massive gravel (Boothroyd & Ashley 1975; Bluck 1979). Low-angle, cross-stratified pebble gravels which grade into massive gravels are interpreted as lateral accretion deposits due to their highly oblique relationship to flow direction (indicated by imbrication in the massive gravel) and their gentle inclination (Bristow 1996).

Thinner (0·2–0·4 m thick) *horizontally bounded* units infilled with cross-bedded sands and fine gravels are interpreted as large mid-channel bar-type bedforms. Gravel and gravel-sand planar cross-strata of similar thickness appear to be transverse bar deposits (Hein & Walker 1977). Textural variations within gravel foresets probably result from flow separation and particle over-passing on the bedform crest, a process which occurs in shallow (*c.* 1 m) flows (Carling 1990). Planar and trough cross-bedded sand units are regarded as the deposits of straight and crescentic crested sandy bedforms respectively (Allen 1984). Horizontally bedded sands are interpreted as upper-stage plane bed deposits (Allen 1984). The thinnest horizontally bounded units, comprising alternating layers of horizontally bedded sand and pebble gravel layers, one or two clasts thick,

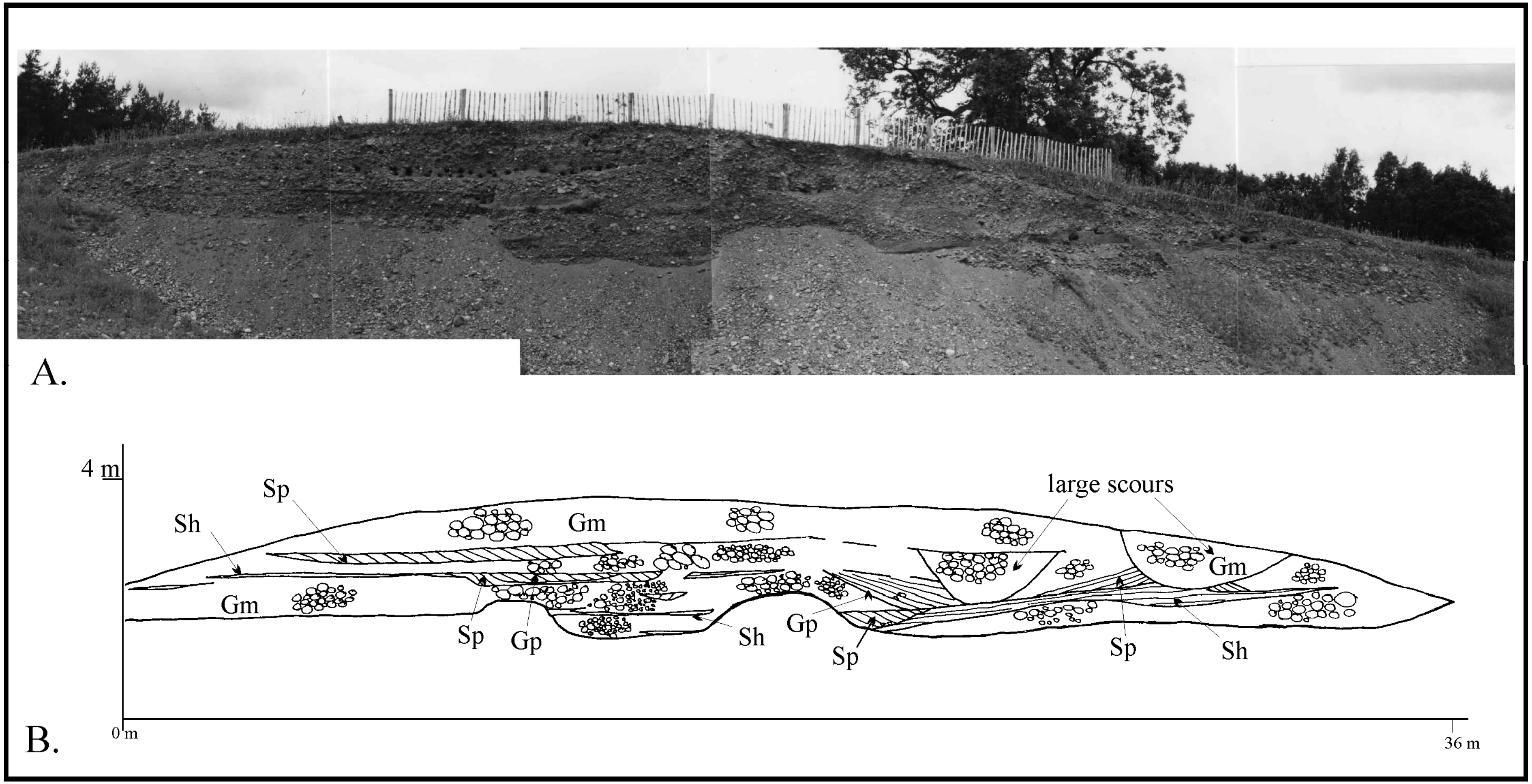

Figure 5 (A). Photomosaic of the upper part of the proximal Lindores fan sediments (association 'b'); fence posts above the section are 1 m tall; flow is out of the face; (B). Redrawn field sketch of the face shown in A; the face is dominated by laterally extensive, horizontally bounded gravel sheets, separated by shallow scour features infilled with sand-sized sediments, interpreted as second-order channels; the northern (right-hand) end of the face has low-angle cross-bedded sands and gravels, interpreted as bar margin accretion deposits, and large scours interpreted as first-order channels.

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are attributed to deposition in shallow, high velocity, variable flows.

The > 3 m-thick unit on the Lindores fan is interpreted as a high-magnitude flood deposit. This interpretation is based on a number of features of the unit. Firstly, there is the massive nature of the unit, with only very limited evidence for stage variation and possible reworking in the form of two sand wedges near the base of the unit. Secondly, there is no evidence for localised erosion surfaces, falling-stage erosion and reworking, and the lateral and downstream grain-size variations that might represent individual barforms. Thirdly, the absolute flow magnitude, as indicated by maximum and average clast size, is higher than for adjacent proximal units on the Lindores fan. The massive nature and simple depositional geometry of the unit is in marked contrast to sediments in adjacent exposures which can be ascribed readily to low magnitude–high frequency deposition. A similar facies is described by Siegenthaler & Huggenberger (1993), who ascribe their 'brown gravel' to high-magnitude flood deposition. However, these features do not entirely eliminate the possibility that the unit was deposited by low magnitude–high frequency flows.

A channel geometry for the *concave-up based depositional* units can only be confirmed where there is exposure in two directions. However, most of the convex-based units are interpreted either as channels and channel-fill deposits, or localised scour features. The narrow and shallow hollows are interpreted as second-order channels and falling-stage infills. Shallow scour features are always found above horizontally bounded gravel units interpreted as longitudinal bars. This association of bar and channel suggests that the hollows represent second-order channels (*sensu* Bridge 1993a) flowing across bar surfaces. These channels are likely to be infilled and abandoned during falling and low stages. Narrow and deep scours are less common. When they do occur, the sediment infills are of two types, either massive gravel, or interdigitating sand and gravel. Narrow and deep scours infilled with interdigitating sand and gravel are interpreted as confluence scours. Confluence scours are common in braided rivers, and represent overdeepenings compared to the 'normal' channel scours (Best 1988; Best & Ashworth 1997). Distinct facies associated with confluence scour migration and infill have been described by Siegenthaler & Huggenberger (1993). Specifically, asymmetrical 'spoon-shaped' scours, infilled with interdigitating sands and gravels that reflect different rates of sediment transport in the feeder channels, are thought to be characteristic of confluence scours. The geometry and infill of the scour features with interdigitating infills observed in this study is compatible with this interpretation, and is favoured over a simple channel interpretation since these scour features are always deeper than adjacent channel or bar features. Narrow and deep scours infilled with massive gravel are interpreted as the infill of abandoned first-order channels. The simple infill of these features is incompatible with the infill of confluence scours (Siegenthaler & Huggenberger 1993). Abandoned first-order channels are believed to infill progressively with bedload at high-flow stages (Bridge 1993a). As such, the fill of abandoned channels should fine both away from the proximal end of the channel, and upwards. Longitudinal fining is rarely demonstrable, but most massive scour infills fine upwards. Wide and shallow channel infills typically consist of planar, trough or horizontally bedded sands, similar to those found in the horizontally bounded units described above. Again, they are interpreted as the products of dune bedforms, or of upper-stage plane beds (Allen 1984).

The wide, massive-gravel-infilled feature with a bimodal basal unit on the Lindores fan is interpreted as a flood deposit within a channel. Other mechanisms capable of generating bimodality are discounted for a number of reasons. For example, bedrock differences (Sambrook Smith 1996) are discounted, as this is the only bimodal unit observed on the Lindores fan, and all sediments are sourced from the same area. Longitudinal and lateral sorting of bedload (Iseya & Ikeda 1987; Sambrook Smith & Ferguson 1995) are discounted since the nature of the bimodal unit is uniform across the exposure (40 m). If bedload sorting was the cause of the bimodality, then areas of non-bimodal gravel and gravel-poor areas would be expected at the same stratigraphic level. Foresets are absent, so methods of generating bimodality invoking flow separation on foresets can be discounted (e.g. Carling & Glaister 1987; Ankatell & Rust 1990; Carling 1990). The characteristics of the bimodal layer most closely resemble those of debris flow deposits (Nemec & Steel 1984). The bipartite nature of the vertical succession also displays some similarities with the traction carpet mechanism of flood deposition (Todd 1989). The massive, laterally extensive nature of the gravel overlying the bimodal unit and the absence of lateral textural variations in the gravel suggest that it was deposited rapidly by a large flow which occupied all of the feature interpreted as a channel. Taken together, the two units indicate an initial debris flow, accompanied by a turbulent water flood. These conditions are common in glacial floods as large volumes of debris are incorporated during the early stages of the flood (Russell & Knudsen 1999).

The steep-sided wedge features are regarded as falling-stage accretion deposits. This interpretation is based on the association between the wedge structures and underlying units interpreted as bar core deposits. Modern falling-stage deposits with similar geometries to those observed here have been described by Rust (1972b) and Boothroyd & Ashley (1975). Preservation of these features implies rapid aggradation.

4. Proglacial river characteristics

4.1. The Lindores fan

The Lindores fan is characterised by two main lithofacies associations, both of which are interpreted to have been formed by low magnitude–high frequency sedimentation processes (Figs 5, 6, 7 and 8). The lower of these two associations, association 'a' is dominated by longitudinal bar units (Fig. 6), although in more distal locations transverse bar units are increasingly common (Fig. 8A). Depositional units are generally thin, and not laterally extensive (Fig. 8A). There is a high degree of lateral and downstream variability in association 'a' (Figs 6 and 8A). The dominant grain size is a pebble gravel, with maximum b-axes of 0·05–0·08 m. Sorting is good, and most units show evidence for reworking. Clast orientations within the lower association are highly variable. There is also good preservation of sandy, falling-stage depositional elements.

The reworking, variable flow directions and preservation of falling-stage depositional elements are all indicative of deposition under highly variable flows. However, high lateral variability and preservation of confluence scour structures indicate that both lateral migration and aggradation occurred on the fan surface during the deposition of association 'a', and that neither was dominant.

The upper association on the Lindores fan, association 'b', occurs in all three quarries. Where exposed (in Melville Gates Quarry), the transition between the two units is well defined, and can be traced across the quarry (Fig. 8A). Association 'b' is similar to association 'a' in terms of the geometry of depositional units. The principal difference is that there are fewer scour features. Scours that do occur in association 'b' are frequently larger, such as the isolated example at 112 m in

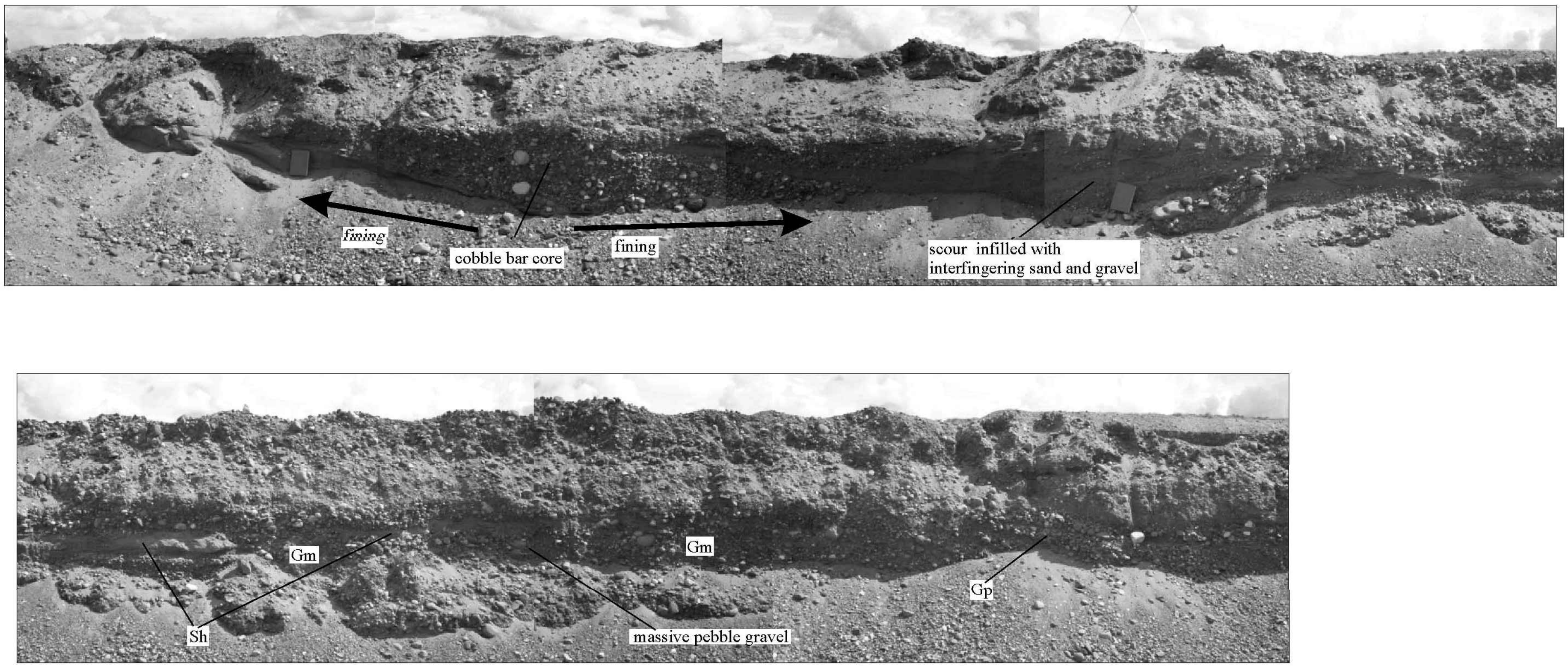


Figure 6 Example of the lower part of the proximal Lindores fan sediments (association 'a'): average and maximum grain size in association 'a' is lower than in association 'b'; distinctive features include horizontally bounded gravel units which fine laterally; thin sand layers and indistinct stratification within otherwise massive gravel units; asymmetrical scour features containing interbedded sand and gravel, thin horizontally bounded layers of interbedded sand and pebble gravel; notebook for scale is 0·21 m high; flow was predominantly from left to right.

Figure 7 Distal sediments on the Lindores fan showing the transition between the lower, sand dominated association 'a', and the gravel dominated upper association 'b'; fence posts above section are 1 m high.

Figure 8B (Collessie Quarry), and the scours in Figure 5 (Mount Castle Quarry). Preservation of falling stage depositional units is still common, but such units are less common than in association 'a' (Fig. 8A, B). Maximum and average clast sizes are larger (b-axes up to 0·2–0·25 m) and sorting is poorer. Clast orientations are variable, but indicate that the dominant flow was to the E and SE in Mount Castle and Melville Gates quarries, and the SE and S in Collessie Quarry. Variance around the vector mean is variable, but generally high (Table 2). Sand-dominated bar structures are absent. There is still evidence for reworking of bar surfaces in association 'b', although massive gravel units are more common (Fig. 8A, B). The lateral and flow-parallel extent of units is much greater than in association 'a'. The differences in sediment architecture between associations 'a' and 'b' is consistent with an increase in discharge magnitude and rapid aggradation, with less lateral migration. However, there is still much evidence for stage variability, including reworked bar units, and a large number of falling-stage depositional units.

Overall, the depositional record of the Lindores fan indicates that glacial meltwater discharge from the Tay glacier through the Lindores gap was dominated by low magnitude–high frequency deposition. Two different phases of meltwater discharge can be distinguished. The first phase was of relatively low discharge magnitude, and deposition consisted of both aggradation and lateral accretion. Discharge during the second phase was of higher magnitude, and aggradation rates were also higher. There was less lateral migration during the second phase.

In addition to the low magnitude–high frequency sedimentation which dominates the Lindores fan, the deposits of two high-magnitude events are preserved in the fan (Figs 3, 4). The character of the deposits formed in these events is described above (Section 3.3). Both of these events occurred late in the history of the fan. High-magnitude flood events are common during the deglaciation of large ice sheets (Maizels 1995; Tweed & Russell 1999) and are most frequently due to the rapid drainage of ice-dammed lakes. However, radiocarbon dates from marine deposits formed during the retreat of the Late Devensian ice sheet indicate that the retreat of the Tay glacier was rapid during the period of deposition of the Lindores fan (Peacock & Browne 1998). It is therefore possible that the flood deposits represent periods of rapid glacier melting. Other flood sources include subglacially stored water (e.g. Walder & Driedger 1995); drainage of supraglacial lakes (Russell 1990, 1993), or extreme meteorological events (Warburton & Fenn 1994; Walder & Driedger 1995). At present, no candidate ice-dammed lake sites likely to drain via the Lindores gap have been identified, and the specific origin of the flood deposits remains unresolved.

4.2. The Lunan Valley

At present the age of the glaciofluvial sediments in the Lunan valley is not known, and correlation between the Lunan valley and Lindores fan is not possible. According to the pattern of ice retreat in ^{14}C years inferred by Boulton *et al.* (1991), the Lunan valley sediments may be 0·5–1 ^{14}C ka older than the Lindores fan. The most complete succession in the Lunan valley is exposed in a quarry 4 km E of Forfar (Fledmyre Quarry; Fig. 1).

As on the Lindores fan, there are distinctive lower and upper associations ('a' and 'b' respectively; Fig. 9). The lower, association 'a', is dominated by planar and trough cross-bedded sands and gravels, interpreted as transverse and linguoid bar units (Fig. 9). Massive pebble gravel units become more common up-succession throughout association 'a' (Fig. 9C). Gravel units never exceed 0·2 m in thickness and are interbedded with thin ($<$ 0·1 m) falling-stage sand units in second-order channels on the upper part of bar surfaces. Scour features interpreted as channels are common in association 'a' (Fig. 10). Frequently fine, silt-sized sediments are found in the base of channels. Channels rarely cross-cut each other, but are

Table 2 Summary of clast orientation data for quarries on the Lindores fan: sites 1–16 are in Mount Castle Quarry, 17–30 in Collessie Quarry and 31–44 in Melville Gates Quarry; data marked * indicate that the clast distribution was random or polymodal.

Site	*n*	*vector mean*	*Magnitude (r)*	*Magnitude % (L)*	*Site*	*n*	*vector mean*	*Magnitude (r)*	*Magnitude % (L)*
1	51	097·05	28·91	52·76	23	52	204·13	40·23	77·36
2	50	092·96	33·18	63·35	24	49	224·18	34·15	69·69
3	50	152·93	24·77	49·54	25	50	209·36	39·87	79·74
4	50	146·65	30·33	60·67	26	50	191·88	16·76	33·53
5	25	099·42	19·34	77·38	27	50	205·73	33·32	66·63
6	50	023·97	34·07	68·13	28	50	182·99	26·72	53·44
7	48	094·49	15·5	32·28*	29	50	146·38	37·56	75·12
8	50	129·98	14·2	28·4*	30	50	170·22	24·37	48·74
9	50	019·18	26·01	52·02	31	25	72·73	20·07	80·28
10	48	142·98	33·17	69·11	32	25	85·11	20·37	81·48
11	50	113·92	31·3	62·6	33	47	113·89	30·41	64·71
12	49	111·46	34·22	69·85	34	49	169·91	38·6	78·94
13	50	102·47	34·45	68·92	35	52	121·26	35·64	68·55
14	50	072·5	32·09	64·18	36	50	107·91	38·48	76·95
15	49	084·51	29·06	59·31	37	50	133·63	23·5	47·0
16	25	269	9·71	38·84	38	50	089·0	27·34	54·68
17	49	142·57	34·8	71·01	39	49	089·0	23·68	48·33
18	50	128·68	38·54	77·08	40	50	109·72	22·15	44·3*
19	51	160·42	31·83	62·41	41	50	102·36	30·79	61·57
20	49	179·86	39·4	80·41	42	50	114·78	32·79	65·58
21	50	157·01	30·69	61·39	43	50	075·51	21·32	42·63*
22	49	122·58	11·74	23·96*	44	50	145·15	19·89	79·57

commonly stacked (e.g. Fig. 10A, at 80 and 100 m). Palaeoflow directions, recorded from both cross-bedding and clast orientations, are highly variable.

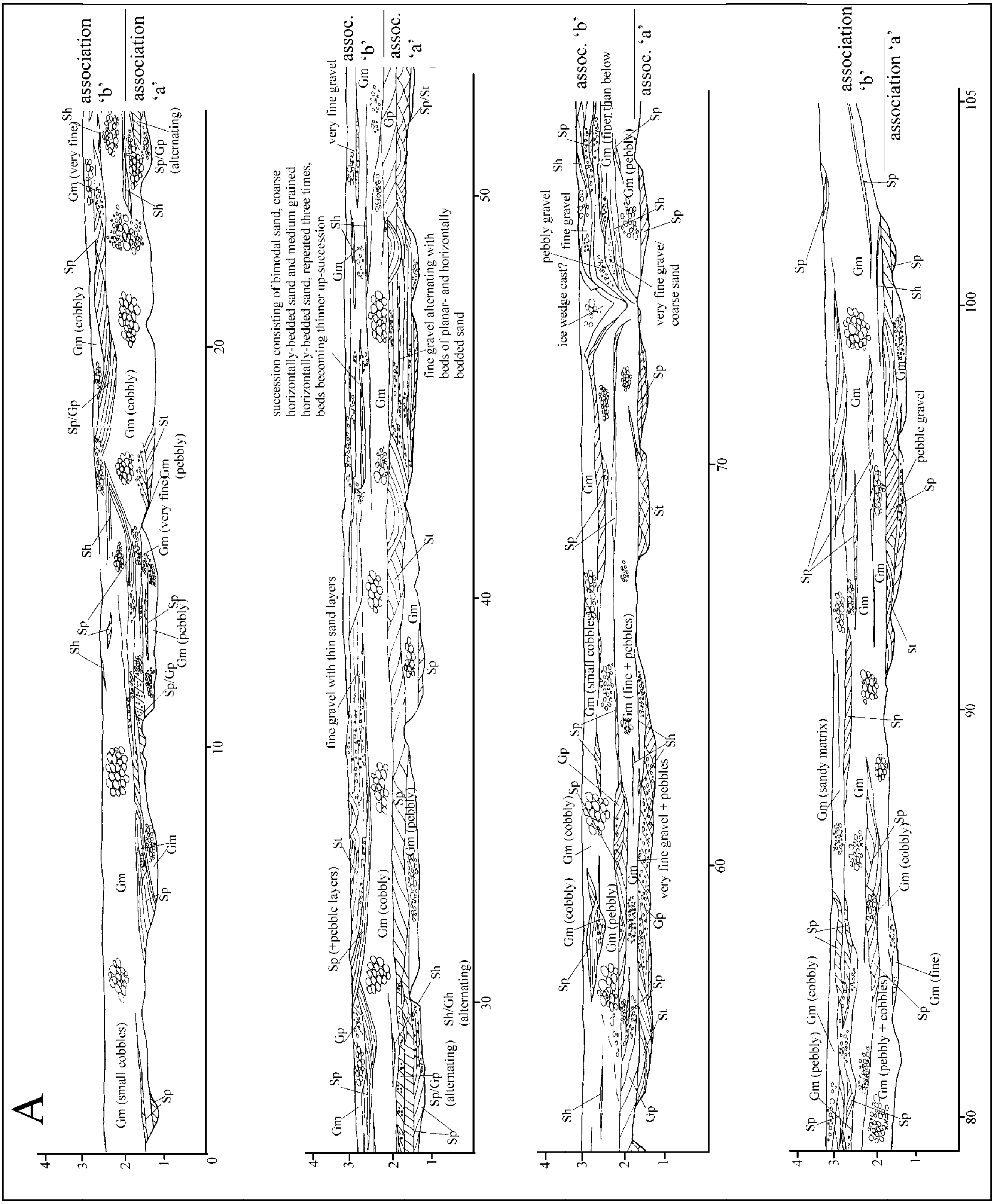
Association 'b' is coarser than association 'a', comprised mainly of medium to coarse cobble gravel (b-axes up to 0·2 m). The transition between associations 'a' and 'b' is extensive and well defined (Fig. 10). In places deep scours occur at the base of association 'b' (Fig. 9). Most of the scours are interpreted as confluence scours, but some are filled with massive gravel, and appear to have been infilled during abandonment. Association 'b' is dominated by gravel longitudinal bar units 0·5–0·75 m thick, which frequently extend for the full length of the exposed face (Fig. 10). Individual bars are interpreted as being up to 50 m long. There is only limited evidence for reworking of bar surfaces. Clast orientation data reveals that palaeoflow was predominantly to the E and NE. However, variance of clast orientation around the vector mean is variable, both at individual sites, and across the quarry (Table 3). Falling-stage sand units do not form a major part of the association, but do occur in all of the exposed faces as discontinuous lenses, at a number of distinct levels within the succession. Both shallow second-order channel infills occur (e.g. at 150 m in Fig. 10A, where shallow channel sediments occur at three distinct levels), and steep-sided bar margin deposits, especially in sections normal to palaeoflow (Fig. 10B). Similar sediments to those exposed in association 'b' are found in a more proximal location 1 km closer to Forfar. At this site sorting is poorer, and there is a greater maximum clast size (b-axes up to 0·3 m).

The sedimentological data indicate that association 'b' was deposited during distinct aggradational pulses, and that there was relatively little reworking of bar surfaces. The character of the gravel units is, however, not indicative of 'catastrophic' flooding, and the palaeoflow data suggest that deposition took place in a braided river depositional environment, with some variability of flow stage and direction. The dominant magnitude and frequency regime in the upper part of the Lunan valley was therefore intermediate between a true low magnitude–high frequency regime, where diurnal and seasonal variations are dominant, and a low magnitude–high frequency regime dominated by high-magnitude floods. The dominant magnitude–frequency regime is probably related to the seasonal discharge cycle, with many bar surfaces only being active during peak summer discharges. Unlike the Lindores fan, there is little evidence for lateral migration, and sedimentation appears to have taken place during periods of rapid aggradation. Sedimentation in the distal part of the Lunan valley, as revealed in a quarry 10 km E of Forfar, near Friockheim (Fig. 1), was highly variable in character, as shown in Figure 11. Figure 11A (flow parallel) shows predominantly planar cross-bedded horizontally bounded sand units, with horizontally bounded small-cobble gravel units forming a lesser component (Fig. 12). Individual sand units cross-cut and are not extensive. Gravel units are more extensive, both parallel to flow, and when viewed normal to flow (Fig. 11B). Falling-stage depositional units are common above the gravel units, and their limited lateral extent is well shown in Figure 11B.

5. Depositional models

Sedimentological evidence has been used to characterise Late Devensian glacial meltwater discharge as revealed by proglacial fluvial sediments in eastern Scotland. The observed sequences were subdivided into a range of distinctive depositional geometries and infilling lithofacies. Characteristic combinations or associations of these depositional elements represent different meltwater discharge regimes and their modes of sediment transport and accumulation. Especially significant features include the evidence for reworking of bar surfaces (horizontal stratification, openwork layers, cobble layers, highly variable clast orientations), the preservation of falling stage depositional elements, the preservation of deeper channel and confluence scour features, and the lateral extent of units.

Block diagrams summarising the inferred characteristics of the fluvial systems responsible for specific depositional features on the Lindores fan and in the Lunan valley are shown in Figure 13. A limited number of fluvial features, including longitudinal, transverse and linguoid bar cores, first and


A
association 'b'
association 'a'
assoc. 'b'
assoc. 'a'
Gm (small cobbles)
Gm
Gm (cobbly)
Gm (very fine)
Gm (pebbly)
Sp/Gp (alternating)
Sp/Gp
Sh/Gh (alternating)
succession consisting of bimodal sand, coarse horizontally-bedded sand and medium grained horizontally-bedded sand, repeated three times, beds becoming thinner up-succession
very fine gravel
fine gravel with thin sand layers
fine gravel alternating with beds of planar- and horizontally bedded sand
Sp (+pebble layers)
Sp/St
ice wedge cast?
pebbly gravel
fine gravel
very fine gravel/ coarse sand
Gm (finer than below
Gm (small cobbles)
Gm (fine + pebbles)
very fine gravel + pebbles
Gm (sandy matrix)
Gm (pebbly + cobbles)
Gm (fine)
pebble gravel
Sp
Sh
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0
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4

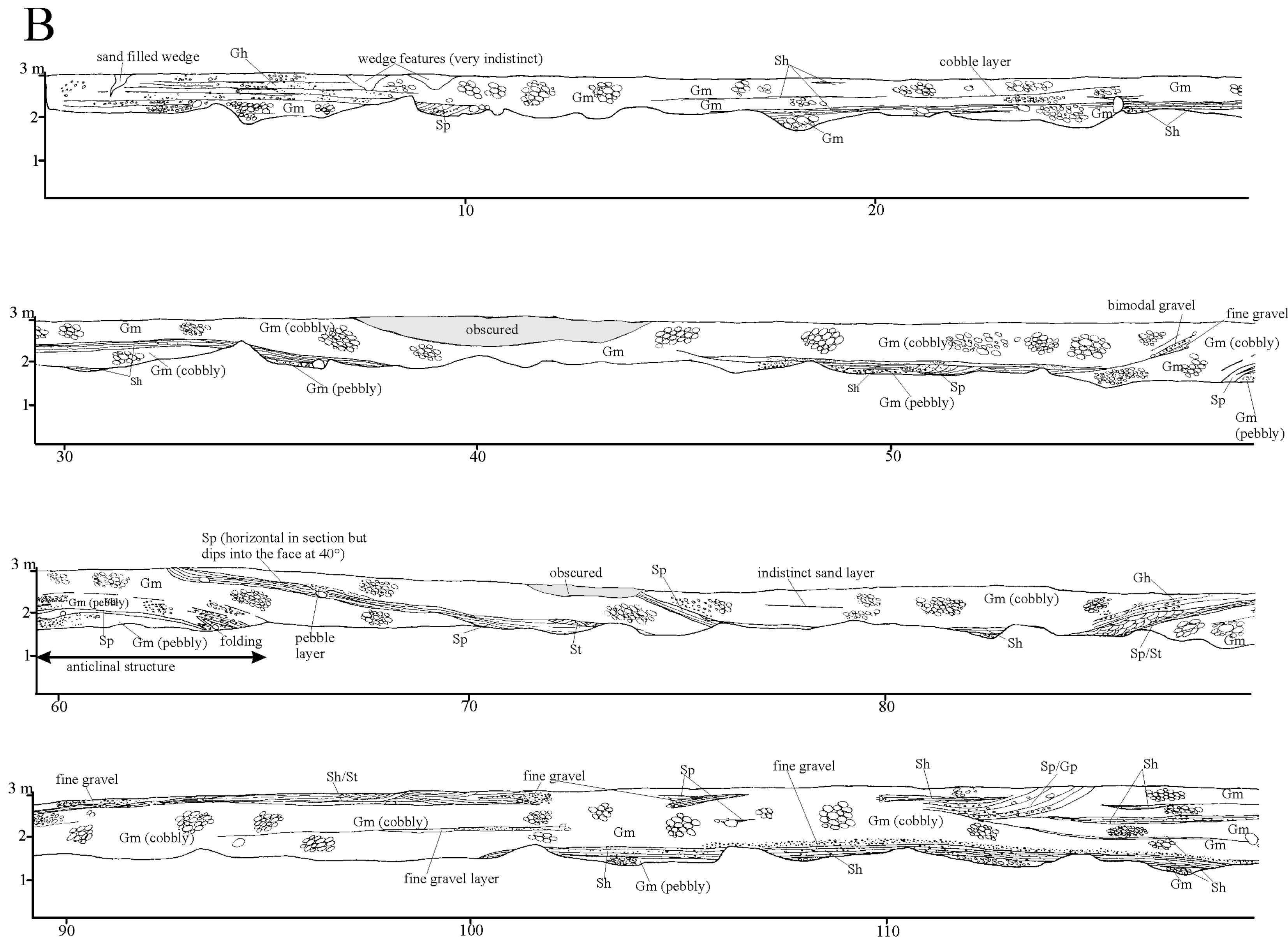

Figure 8 Redrawn field sketches illustrating the architecture of sediments on the Lindores fan: (A). distal sediments, showing both associations 'a' and 'b' (compare with Fig. 7); note the abrupt transition from predominantly planar cross-bedded sand and fine gravel, to massive gravel interbedded with discontinuous sand layers; (B) proximal association 'b' sediments, located approximately 2 km W of those shown in Figure 5; note that although massive gravel units are more common, there is abundant evidence for reworking (e.g. between 0–10 m and 115–120 m), and falling-stage accretion on bar margins (e.g. between 60 m and 70 m)

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Table 3 Summary of clast orientation data for quarries in the Lunan valley: sites 1–12 are in Lochhead Quarry, 13–36 in Fledmyre Quarry and 37–58 in Hatton Mill Quarry; data marked * indicate that the clast distribution was random or polymodal.

Site	*n*	*vector mean*	*Magnitude (r)*	*Magnitude % (L)*	*Site*	*n*	*vector mean*	*Magnitude (r)*	*Magnitude % (L)*
1	49	122·38	18·05	36·84*	30	50	001·62	40·47	84·31
2	50	159·81	32·55	65·1	31	48	333·56	43·86	89·52
3	50	158·44	28·29	56·58	32	49	035·55	31·41	62·83
4	50	100·68	30·78	61·55	33	50	068·66	28·34	56·69
5	50	100·75	15·92	31·85*	34	50	046·66	38·56	75·6
6	50	105·92	27·05	54·1	35	50	046·58	18·9	37·81*
7	50	075·78	13·93	27·86*	36	50	038·56	41·26	82·52
8	49	30·81	13·52	27·59	37	50	103·17	27·51	55·03
9	50	81·18	24·27	48·54	38	50	089·0	31·59	63·17
10	50	75·13	4·28	8·56*	39	20	063·47	18·1	90·48
11	50	002·08	36·39	72·78	40	50	084·14	28·62	57·24
12	32	089·0	9·37	29·29	41	50	102·31	31·99	64·9
13	15	048·7	12·65	84·3	42	50	084·97	23·42	46·83
14	15	082·91	12·27	81·79	43	50	207·05	12·78	25·56*
15	11	092·91	10·07	91·54	44	50	047·18	39·72	79·44
16	16	049·38	13·95	93·0	45	15	085·23	12·26	81·76
17	15	048·6	14·59	97·23	46	15	093·14	12·65	84·31
18	15	094·64	11·86	79·09	47	12	093·14	10·62	88·51
19	15	022·31	12·54	83·6	48	50	086·4	25·23	50·45
20	15	004·51	6·94	46·25	49	50	178·97	31·66	63·32
21	15	104·93	12·17	81·1	50	50	138·71	30·19	60·39
22	15	019·43	10·76	71·74	51	25	084·84	22·25	89·0
23	15	095·47	11·86	79·05	52	50	095·67	28·28	56·57
24	15	118·93	12·42	82·83	53	48	069·64	41·38	82·75
25	15	026·11	13·57	90·46	54	50	067·53	39·56	78·92
26	15	051·22	13·57	87·17	55	15	068·62	13·26	88·37
27	15	012·66	12·9	85·98	56	25	063·49	22·61	90·46
28	50	053·94	32·24	64·49	57	25	074·41	21·92	87·69
29	50	055·94	26·64	53·28	58	25	070·4	21·2	84·8

second-order channels, confluence scours and falling-stage accretional structures appear to be responsible for the diversity of depositional architectures observed. The variety of sediment architectures results from differences in scale, grain size and the relative proportions and ordering of the various depositional geometries outlined in Figure 2, which in turn are controlled by the nature, magnitude and frequency of the dominant discharge regime.

Depositional Models A–C (Fig. 13A–C) represent lower, association 'a' sediments, from both the Lindores fan and Lunan valley. Depositional models A and B are both based on Mount Castle Quarry on the Lindores fan. Model A is dominated by thin, pebble-dominated longitudinal bar units and contains a high proportion of laterally extensive sand units, representing the fill of wide and shallow first-order channels. Depositional model B is thought to be the product of very shallow, variable flows, most probably on the margins of the main channel system. The association 'a' sediments, exposed in Melville Gates Quarry on the Lindores fan, and Fledmyre Quarry in the Lunan valley, are very similar, and both have been used to construct depositional model C. The characteristic features of depositional model C are a high proportion of cross-stratified sand and gravel units, with thin longitudinal bar deposits forming a lesser component. Models A–C are all thought to form in association with very variable, relatively low-magnitude flow, and represent proximal, channel margin and more distal settings, respectively.

Depositional Models D–G (Fig. 13D–G) represent the upper, association 'b' sediments from both the Lindores fan and the Lunan valley. In all cases, longitudinal bar deposits are dominant, and individual units are thicker and contain coarser gravel than in models A–C. Depositional models D–F are all based on Lindores fan sediments, and are similar in terms of the constituent depositional elements. These models illustrate how differing depositional geometries can be formed from similar depositional units. Depositional models A–F all feature evidence for bar reworking, lateral accretion and preservation of falling-stage sediments. The sedimentological evidence indicates that Depositional Models A–F formed in association with highly variable low magnitude–high frequency deposition, such that large variations in discharge occurred very frequently. Depositional model G (Fig. 13G) represents association 'a' sediments from the Lunan valley. In this model, discharge appears to have been higher and, although variable, there is less evidence for repeated reworking. As discussed earlier, it is thought that the Lunan valley sediments record seasonal (i.e. peak annual discharge), rather than within season (diurnal?) variations. Depositional model H (Fig. 13H) is from a more distal setting (Hatton Mill Quarry). The characteristics and inferred depositional setting of model H are intermediate between model C and models D–F.

6. Conclusions

Both the Lunan valley and Lindores fan are located in areas which only received meltwater for short periods of time during the deglaciation of the last Scottish ice sheet (Marren 2000) and the sedimentary records reflect these short-lived periods of meltwater input. In particular, the rapid aggradation rates, and the absence of widespread or progressive incision and terrace formation, are a consequence of the 'pulsed' nature of the meltwater inputs. The observed upwards increase in overall discharge magnitude at both sites suggests that locally, meltwater discharge rates increased during deglaciation, indicating

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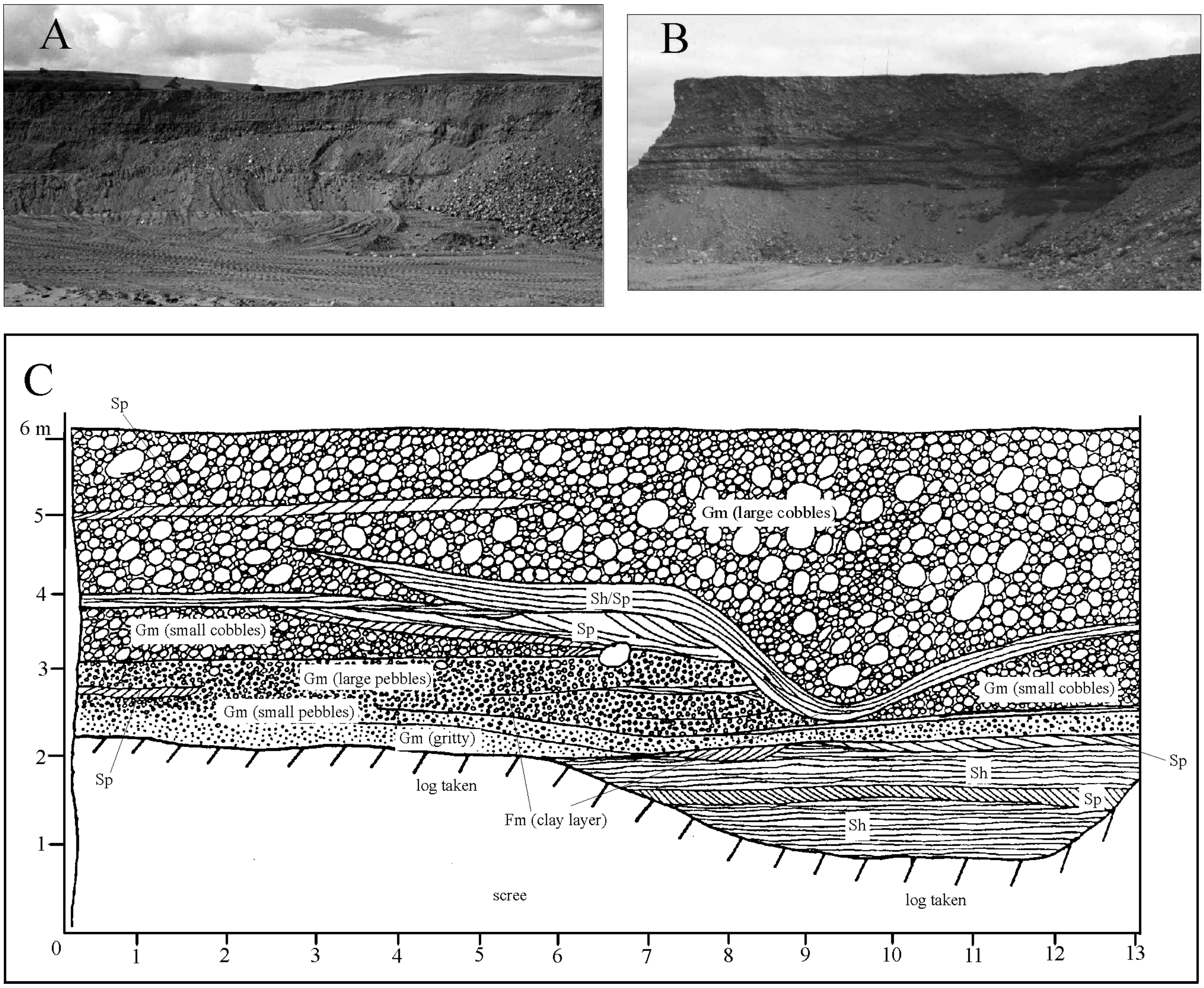

Figure 9 Proximal sediments in the Lunan valley: (A, B) views of the extensive transition between the fine-medium gravel dominated lower association 'a' and the medium-coarse gravel dominated association 'b'; both photos also show deep scours at the base of association 'b', infilled with low-angle bedded gravel (A) and massive gravel (B); the section is 6 m high in both A and B; (C) redrawn field sketch of B, emphasising the variations in grain-size and structure between associations 'a' and 'b'.

that rapid melting of the ice sheet was more significant than the reduction in ice sheet catchment size over short time periods. These localised increases in discharge need to be integrated with the long-term history of deglaciation, which suggests that over time the meltwater discharges decreased with the reduction in size of the glaciers (Maizels & Aitken 1991). Thus, there is still much to be learnt about meltwater discharge during deglaciation, and how the sedimentary record reflects these changes. In particular, it needs to be determined whether deglaciation was constant, and whether fluctuations in meltwater discharge were related to non-glaciological factors such as local topography. Alternatively, deglaciation may have been punctuated by periods of rapid melting, alternating with glacier stillstands or readvances. Recent research is providing evidence for active recession with numerous repeated stillstands (Brown 1993; Merritt *et al.* 1995; Benn 1997; Brazier *et al.* 1998; Peacock & Merritt 2000). Investigation of other glaciofluvial systems in Scotland will help to resolve these issues. In particular, comparison between those systems which were influenced by glacial meltwater throughout deglaciation, and systems such as those described here which only received meltwater inputs for limited time periods, will be especially important. It is also important that these fluvial systems are dated well, in order that they can be placed into the overall context of deglaciation history. Further progress will also be made through integration of the proglacial fluvial evidence with other sources of morphological, stratigraphic and sedimentary evidence.

7. Acknowledgements

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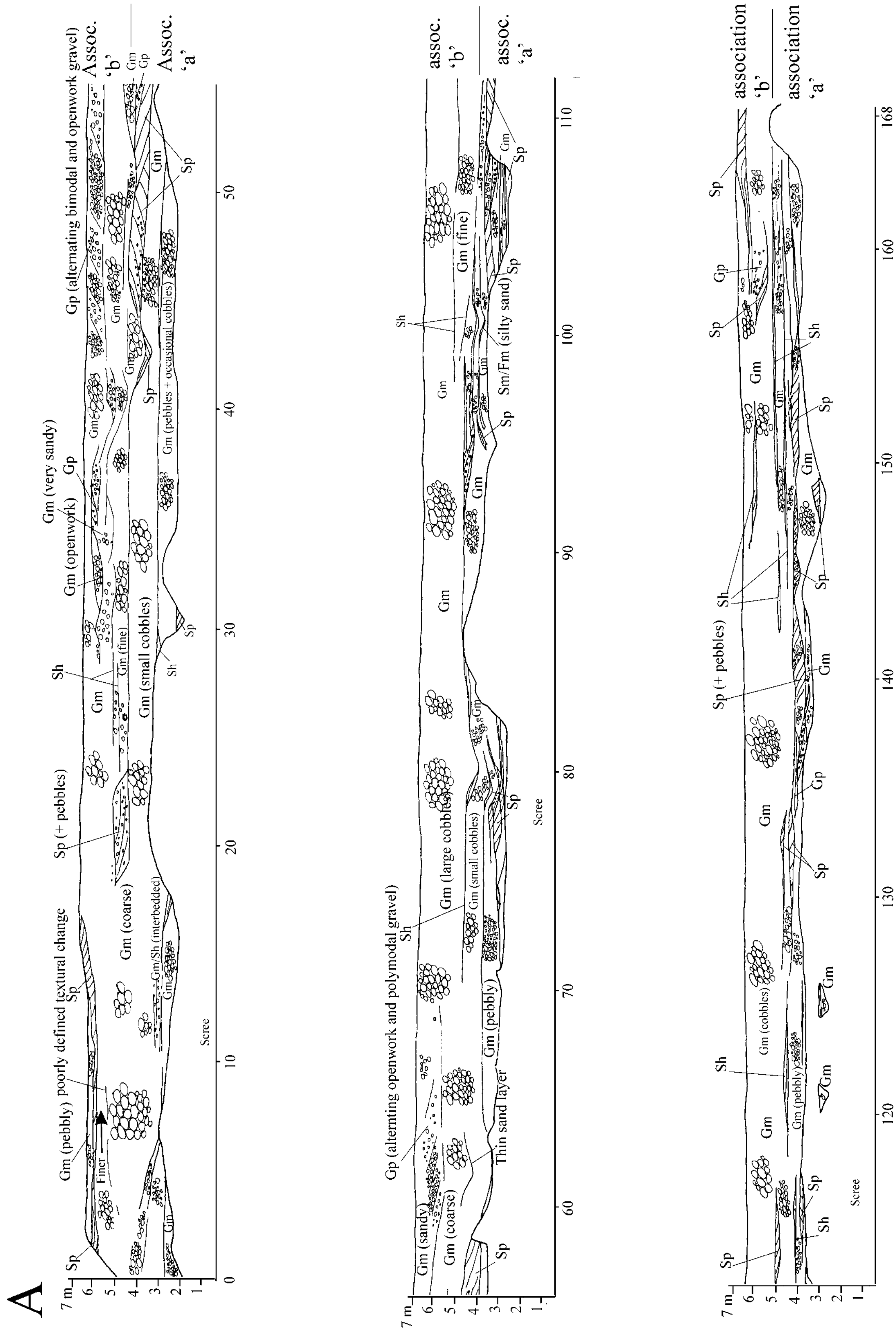
A
Assoc. 'b'
Assoc. 'a'
Gp (alternating bimodal and openwork gravel)
Gm (very sandy)
Gm (openwork)
Sp (+ pebbles)
poorly defined textural change
Gm (pebbly)
Finer
Gm (coarse)
Gm/Sh (interbedded)
Gm (small cobbles)
Gm (fine)
Gm (pebbles + occasional cobbles)
Scree
assoc. 'b'
assoc. 'a'
Gp (alterning openwork and polymodal gravel)
Gm (sandy)
Gm (coarse)
Thin sand layer
Gm (pebbly)
Gm (large cobbles)
Gm (small cobbles)
Sm/Fm (silty sand)
Gm (fine)
association 'b'
association 'a'
Sp (+ pebbles)
Gm (cobbles)
Gm (pebbly)
Sp
Sh
Gm
Gp
7 m
6
5
4
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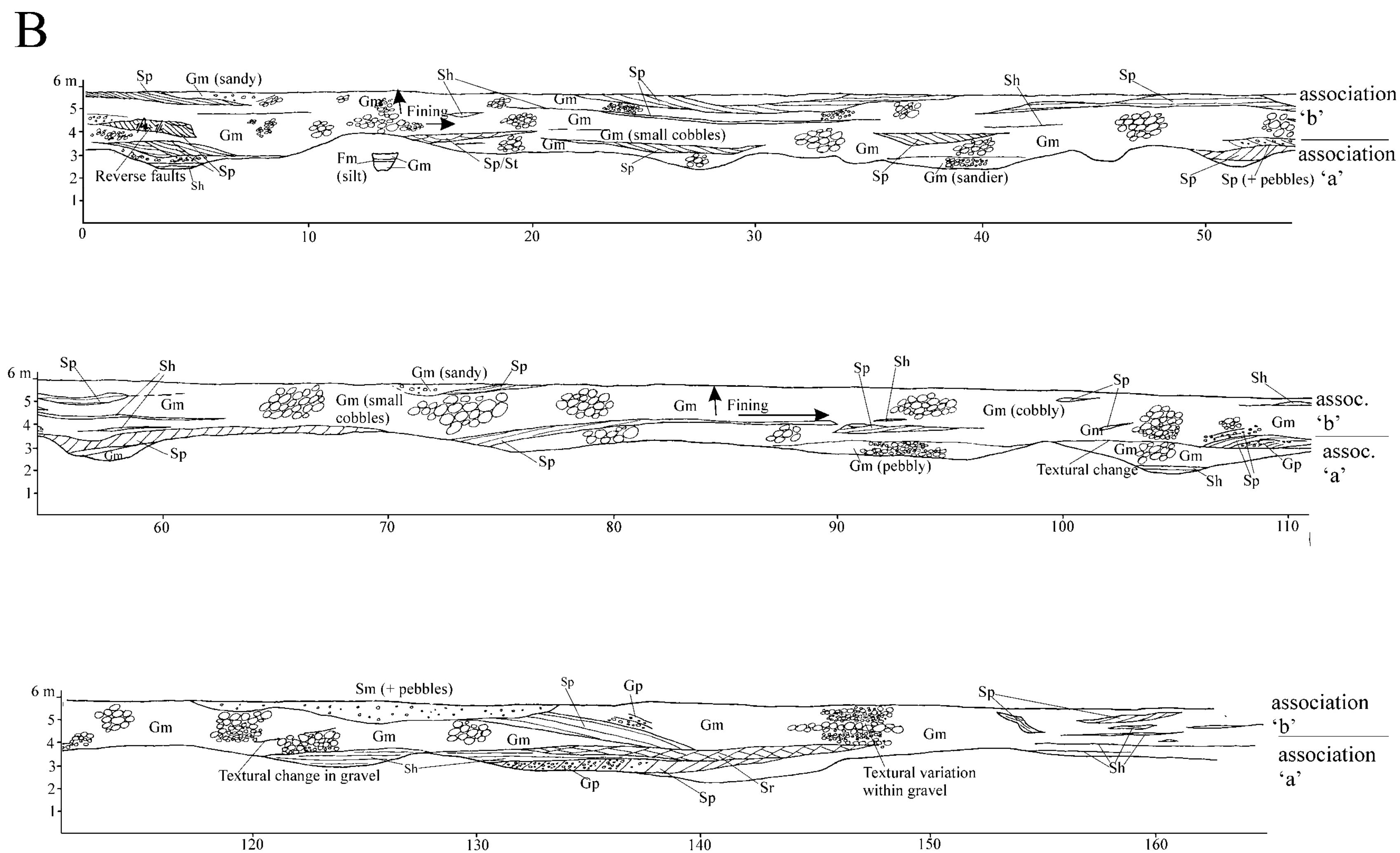
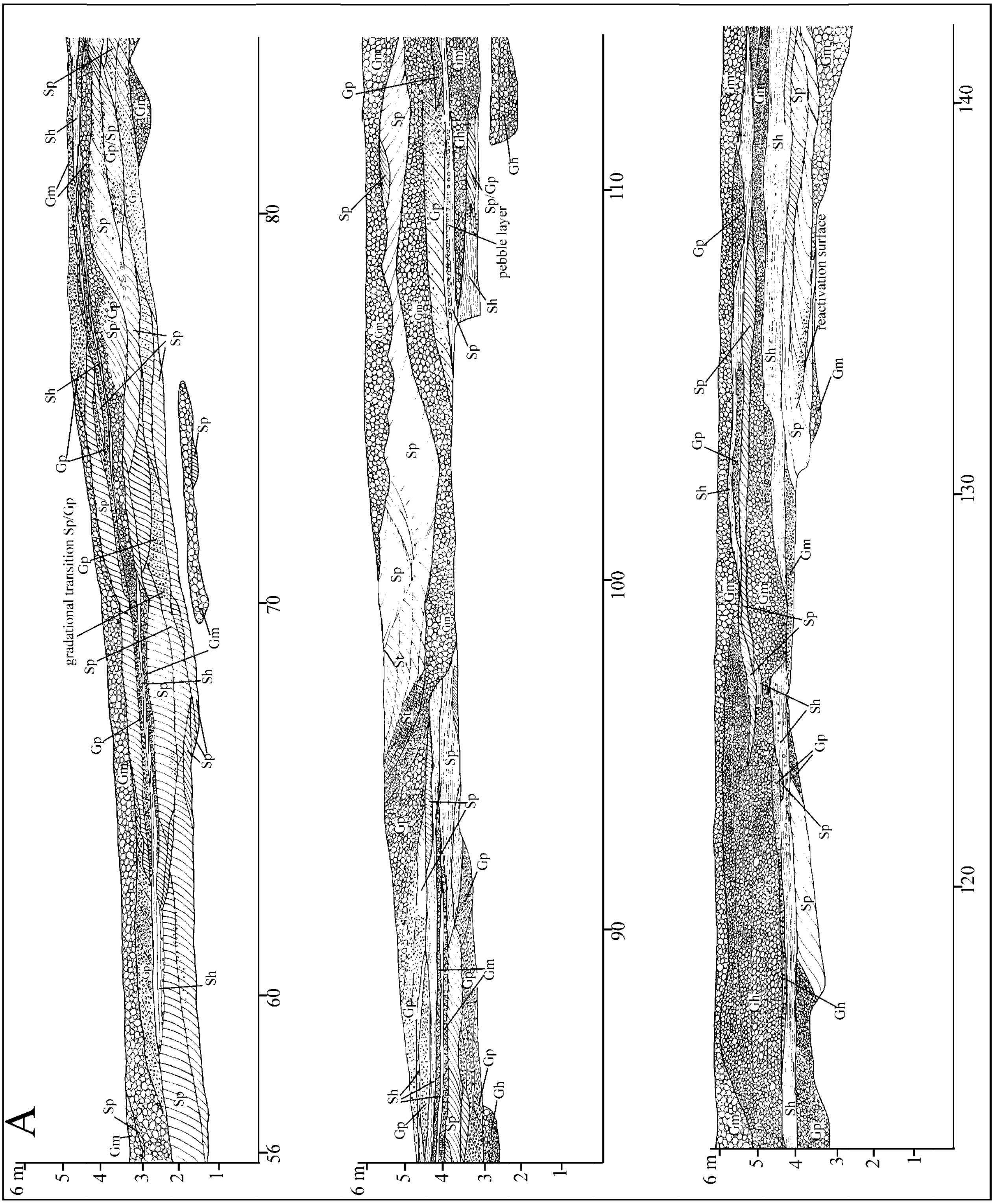


Figure 10 Architecture of proximal sediments in the Lunan valley: (A) flow-parallel view (flow from left to right); (B) flow-perpendicular view (flow into page); the transition between associations 'a' and 'b' can be seen in both A and B; note the greater lateral and downstream continuity of units in association 'b', and the division of the superficially massive gravel into at least three layers by discontinuous sand layers at distinct levels within this association.



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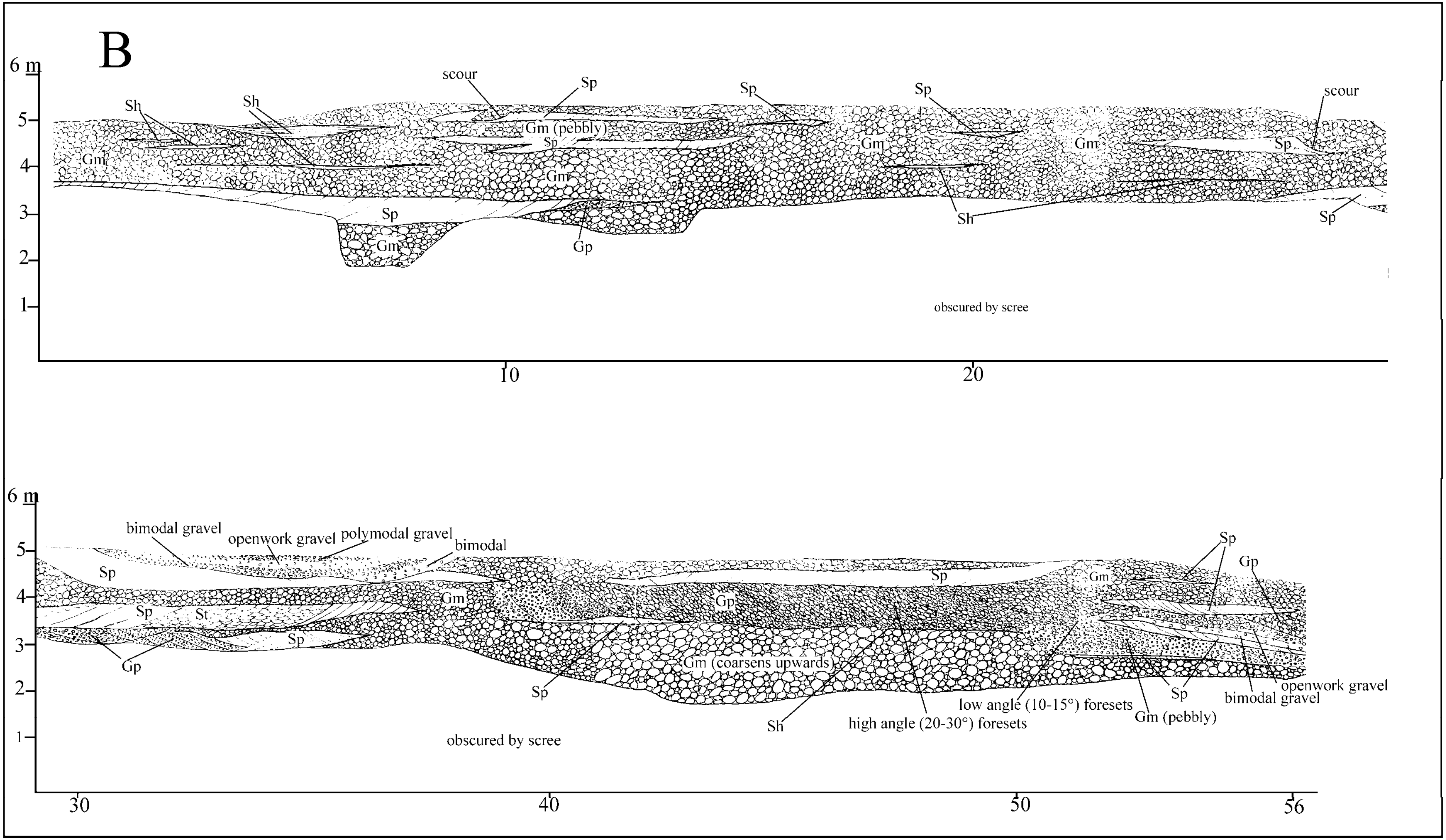

Figure 11 Architecture of distal sediments in the Lunan valley, located approximately 10 km downstream of the sediments in Figure 10: (A). flow parallel view (flow from right to left); (b) flow out of the face; sediments at this location are characterised by high lateral, downstream and vertical variability, although sand units tend to be less extensive when viewed normal to palaeoflow (B).

Figure 12 Detail of Figure 11A (flow parallel section); flow from right to left; figure for scale is 1·85 m tall.

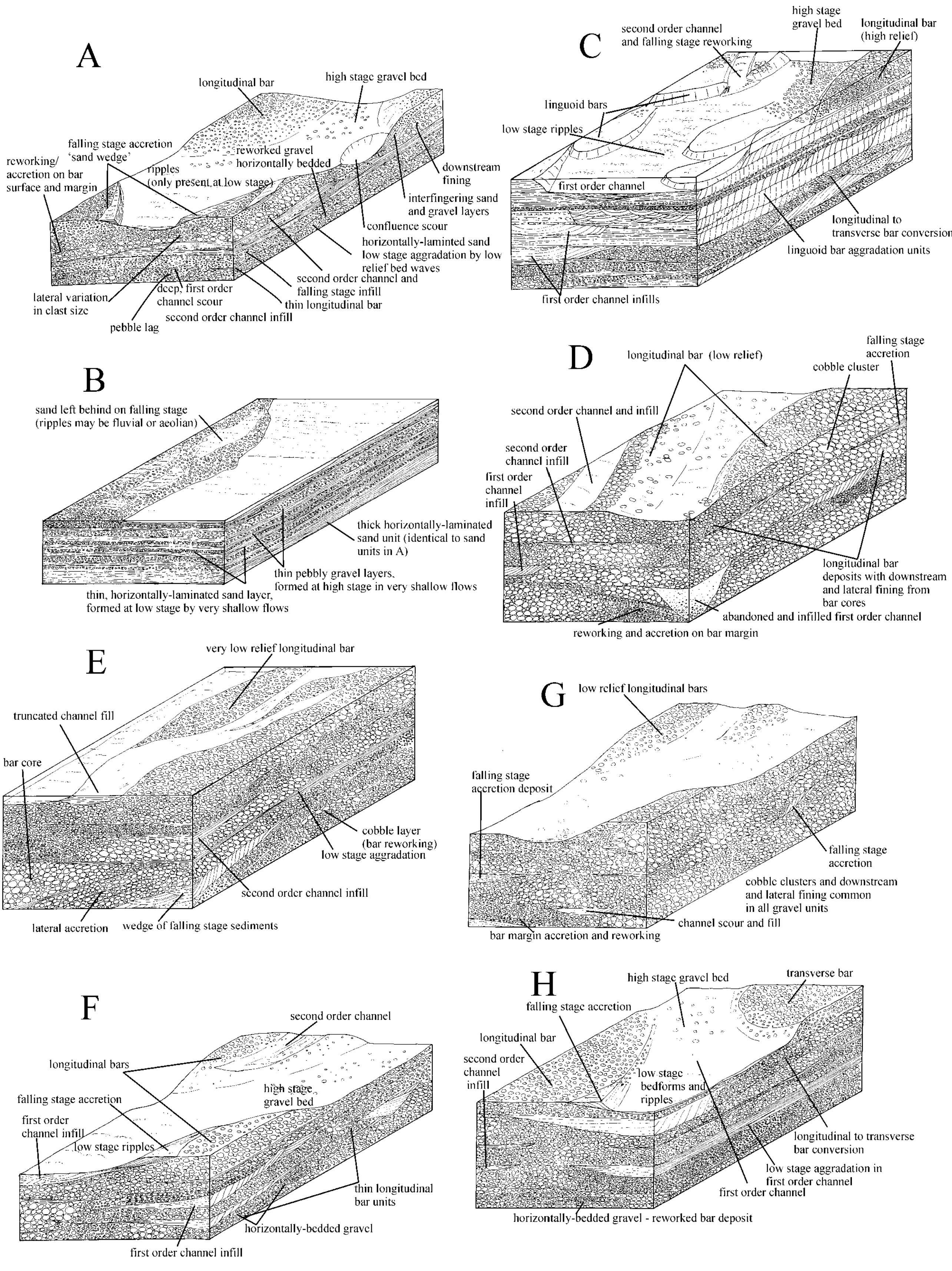

Figure 13 Depositional models based on the proglacial fluvial sediments examined in this study; (A, B) are based on association 'a' on the Lindores fan; (C) is based on association 'a' from both the Lindores fan (Melville Gates Quarry) and the Lunan valley (Fledmyre Quarry); (D–F) are all based on association 'b' on the Lindores fan (based on Mount Castle, Collessie and Melville Gates Quarries respectively); (G) is based on association 'b' as exposed in Lochhead and Fledmyre Quarries in the Lunan valley; (H) is based on Hatton Mill Quarry in the lower Lunan valley. A–F and H are all thought to represent highly variable (intra-seasonal variation) flow discharge, although of varying magnitudes and ranges of magnitude; G is thought to represent dominance by annual peak discharges.

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