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Evidence for Paleolake Rawtenstall around Stacksteads, Upper Irwell Valley, Rossendale, U.K.

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Abstract

This paper presents new geomorphological and sedimentological evidence relating to the glaciation of the Upper Rossendale Valley, northwest England. We identify a previously unrecognised esker and associated glaciofluvial deposits within the valley, using high-resolution hillshaded Digital Terrain Models (DTMs) constructed using LiDAR data. A temporary exposure in a subaqueous outwash fan indicates the operation of an efflux jet from a conduit exiting an ice margin in the vicinity of the Thrutch (Stacksteads) Gorge. We propose that the gorge was formed primarily by incision due to the drainage of the ice-dammed paleolake Rawtenstall during a previous glacial phase, but later operated as a subglacial meltwater channel after a local readvance of ice during the last Glacial Termination. A similar approach in other areas is likely to improve our detailed understanding of glaciation in the North West.

Keywords

Rossendale, paleolake Rawtenstall, LiDAR, esker, readvance.

Introduction

It has been established that an ice-contact lateral lake, Paleolake Rawtenstall, existed in the Rossendale valley, around the Upper Irwell River, during the last glacial Termination (22-18,000 BP; Marine Oxygen Isotope Stage 2; Jowett, 1914; Crofts, 2005; Delaney *et al*. 2010). Evidence for the existence of this lake, including sedimentological evidence of glaciolacustrine sediments in boreholes and geomorphic evidence for shoreline terraces, has been found in the western part of the Rossendale valley, around Rawtenstall and Haslingden (Crofts, 2005; Delaney *et al*. 2010). However, evidence for the lake from the eastern part of the valley has not been recorded. This study presents new geomorphic and sedimentological evidence from the Stacksteads area and sheds light on paleolake Rawtenstall and the position of the ice margin during the early part of the lake's existence.

Previous work

The Rossendale valley cuts into the heart of the Rossendale plateau, a westerly extension of the Pennines. The valley follows a dog-legged path, with the upper Rossendale valley aligned east-west between Bacup and Haslingden, and the lower valley aligned north-south (Figure 1). The valley is cut into sandstone bedrock and is steep sided and relatively narrow, with gorges in two places – the Irwell Gorge in the lower N-S section, and the Thrutch Gorge at Stacksteads in the upper E-W section (Figure 1). A number of tributaries enter the Irwell along the northern side in the upper valley, forming a rectilinear pattern; tributaries on the southern margin are much shorter, with relatively steep paths as most of the southern Plateau drains southwards and south-eastwards (Figures 1 and 2).

The upper Rossendale valley is thought to have been fully covered by ice at least once in the past (Jowett, 1914). Extensive deposits of glacigenic sediment are recorded within the valley, particularly along the northern side, where boreholes indicate that a combination of diamictons, sands, gravels and clay infill the valley to a depth of up to 35m below the modern surface. The glacigenic infill is thickest along the northern side of the valley, forming a substantial terrace (Figure 2). Dean and Hodson (1947) suggested that these deposits lie within a buried valley, that the modern river lies south of its original path, and that much of its bed is cut into bedrock (Figure 3). The occurrence of an ice-dammed lateral lake in the Rossendale valley was first

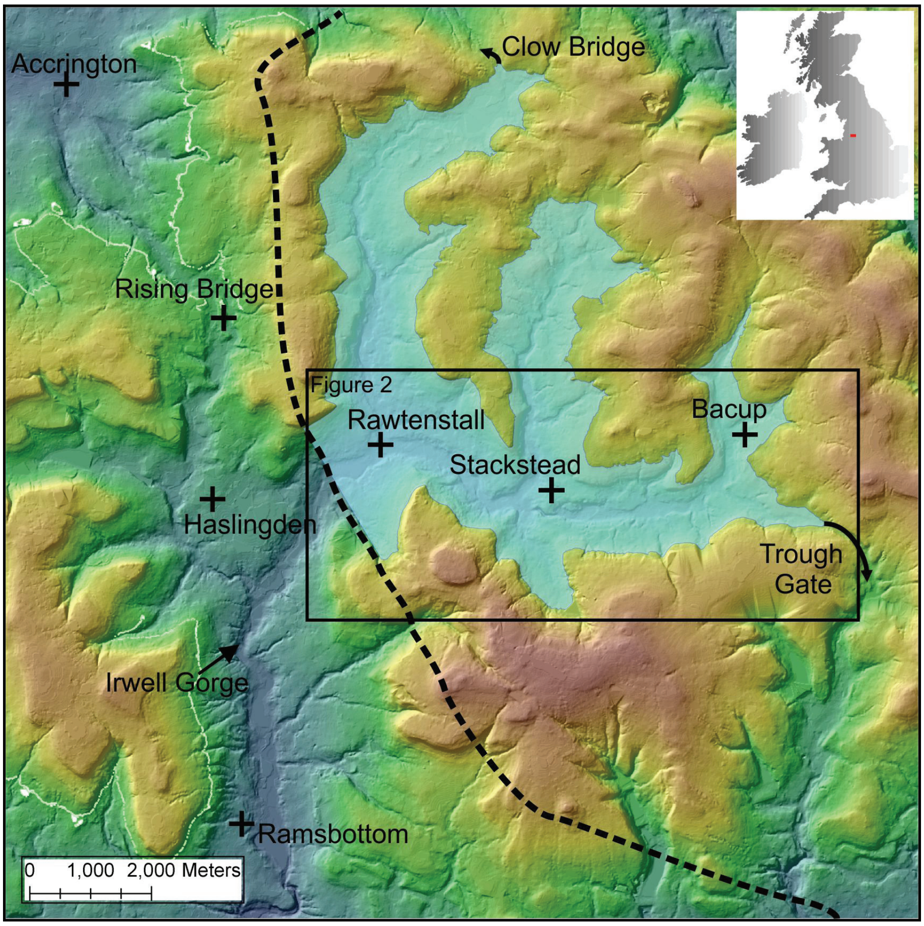

Figure 1: Digital Elevation Model of the Rossendale area, constructed using Ordnance Survey 1:10,000 profile data (resolution c.10m) showing position of places mentioned in the text. Likely extent of Paleolake Rawtenstall at 300m level is also shown, together with inferred ice margin positions at that time.

postulated at the beginning of the 20th century (Jowett, 1914). Mapping by the British Geological Survey identified extensive spreads of glaciofluvial sand and gravel along terraces in the upper valley, which have been interpreted as shoreline deposits (Figure 2: Wright *et al*. 1927). More recently, work by Crofts (2005) and Delaney *et al*. (2010) has shown that extensive glaciolacustrine sediments occur in the upper Rossendale valley between Haslingden and Rawtenstall. The lake in which these sediments were deposited is thought to have been ponded at the southern end of the valley by the inland margin of the Irish Sea Ice Stream, and to the north by ice emanating from the Lake District and Yorkshire. At its highest, lake waters would have filled the main valley and extended into the northern tributaries to the watershed.

Modelling of lake overflow positions using DTMs constructed from Ordnance Survey 10m contour data by Delaney *et al*. (2010) indicates that in its early stages the lake is likely initially to have drained northwards and south-westwards through cols at c.300m OD (Ordnance Datum) at Clow Bridge (north; Figure 1) and Trough Gate (southwest; Figures 1 and 2). During this phase an ice margin must have existed within the upper valley, east of Haslingden, in order to block drainage southwards along the lower valley, or northwards at Rising Bridge, northwest of Haslingden (Figure 1). As the ice receded westwards and then southwards down the lower Rossendale valley, the col at Rising Bridge was uncovered, allowing water to drain northwards and causing lake level to drop to c.250m (Figure 1). The occurrence of this latter lake level was supported by the occurrence of a number of terrace surfaces at c.240-250m OD in the western part of the Rossendale valley (Delaney *et al*. 2010).

Within the upper Rossendale valley, the modern Irwell river flows through the Thrutch Gorge at Stacksteads (Figure 1). Dean and Hodson (1947) suggested that the original course of the Irwell lay to the north of the modern gorge, but is now entirely infilled with glacial material and that the gorge was cut due to post-glacial diversion of the Irwell to the south (Figure 3). An alternative suggestion is that of Crofts (2005) who suggested that the gorge may have formed partly due to subglacial meltwater erosion, which would imply that meltwater flowed eastwards and up-stream through the gorge prior to ice recession westwards down the valley. Crofts has also suggested that the gorge may have formed over multiple glacial cycles.

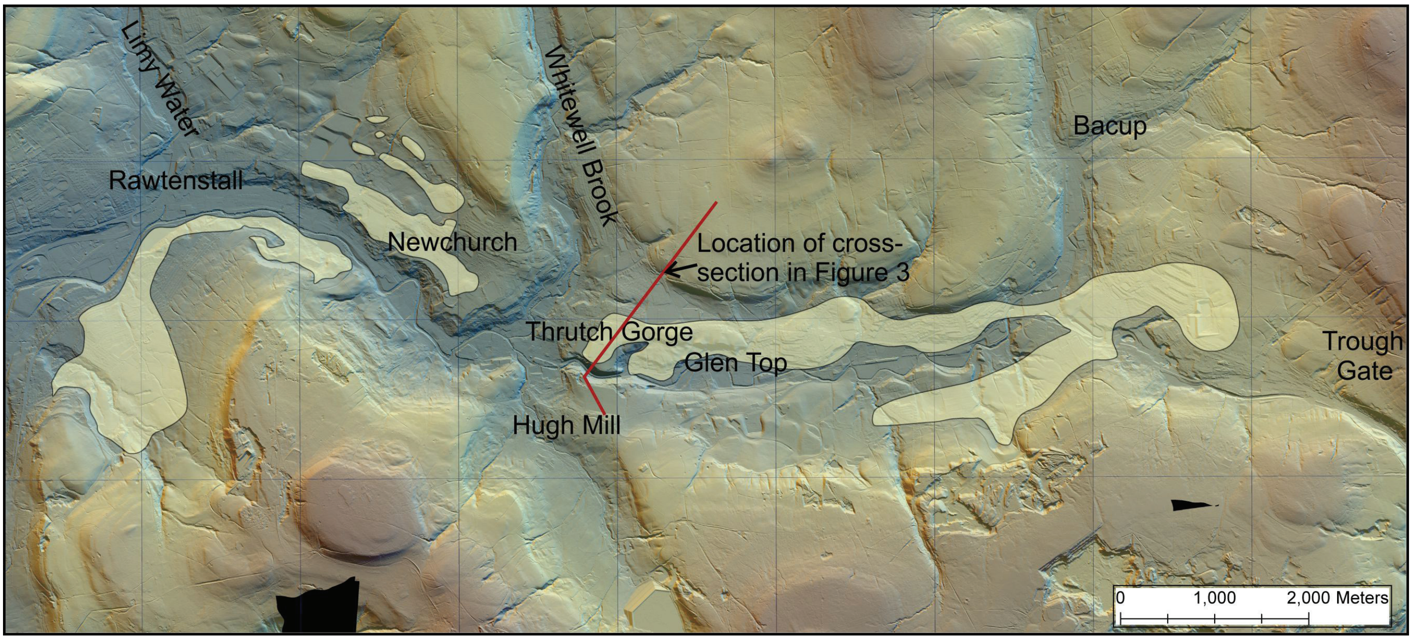

Figure 2: LiDAR DTM of upper part of the Rossendale Valley, showing position of places mentioned in the text. Areas mapped as underlain by sand and gravel are shown in yellow (data from British Geological Survey map); the position of the cross section in Figure 3 is shown in red. Black areas have no LiDAR coverage.

Borehole records from the western part of the upper Rossendale valley indicate that as much as 20m of rhythmically laminated silts and clays, characteristic of distal glaciolacustrine environments, occur under river gravels within the valley bottom at Rawtenstall. Further borehole records indicate that the area around Haslingden is underlain by extensive subaqueous outwash sediments deposited by meltwater (Crofts, 2005; Delaney *et al*. 2010). However, to date no sedimentary evidence has been found to support the existence of a glacial lake in the eastern part of the upper Rossendale valley above the Thrutch Gorge, other than spreads of sand mapped by Wright *et al*. (1927) and interpreted as ice-marginal shoreline deposits.

This Study

For this study Digital Terrain Models (DTMs), constructed using airborne LiDAR data collected by the Environment Agency Geomatics Group on an open government licence, were used to examine the geomorphology of the Upper Irwell (available for free download at http://environment.data.gov.uk/ds/survey). LiDAR utilises a pulsed laser beam to measure the distance between the aircraft and the ground surface with a high degree of accuracy. The measurements are then used to generate high resolution digital surface models (DSMs); subsequent processing to remove above-surface features, including buildings and trees, results in the production of DTMs. For this study, LiDAR with a spatial resolution of 1m was used; this has a vertical resolution of c.0.15m (Environment Agency, 2016).

The data were processed using ArcGIS to create a single raster DTM for the study area. A hillshaded model of the area was then created using the Relief Visualization Toolbox (Kokalj *et al*. 2013; available at http://iaps.zrc-sazu.si/en/rvt#v). This programme creates a hillshaded model of the ground surface using lighting from 16 azimuths in order to highlight topography. Further analysis, including slope classification and generation of valley cross-profiles, was undertaken in ArcGIS, version 10.2.

Geomorphology

The hillshaded DTM is shown in Figure 2, with close-ups in Figures 4 and 5. The Thrutch Gorge at Stacksteads is clearly visible in the centre left of the DTM, and the Trough Gate spillway (which leads to the Whitworth gorge) at the bottom right (SW) of the image (Figures 2 and 4). The DTM shows clearly that the Irwell valley above the Thrutch Gorge is a distinct basin, separated from the Irwell downstream by an area of bedrock that is dissected by the gorge (Figure 4). The gorge itself is sinuous, over 40m deep at its maximum depth, and less than 200m wide for much of its length (Figure 5a, b). However, gorge width has been modified by road and rail works, and the original gorge is likely to have been much narrower; a local story holds that local men used to impress their girlfriends by jumping across (Rossendale Free Press, March 2003).

There is considerable evidence of human activity in the upper basin, including bedrock quarrying, terracing, smoothing and levelling of surfaces for building and playing

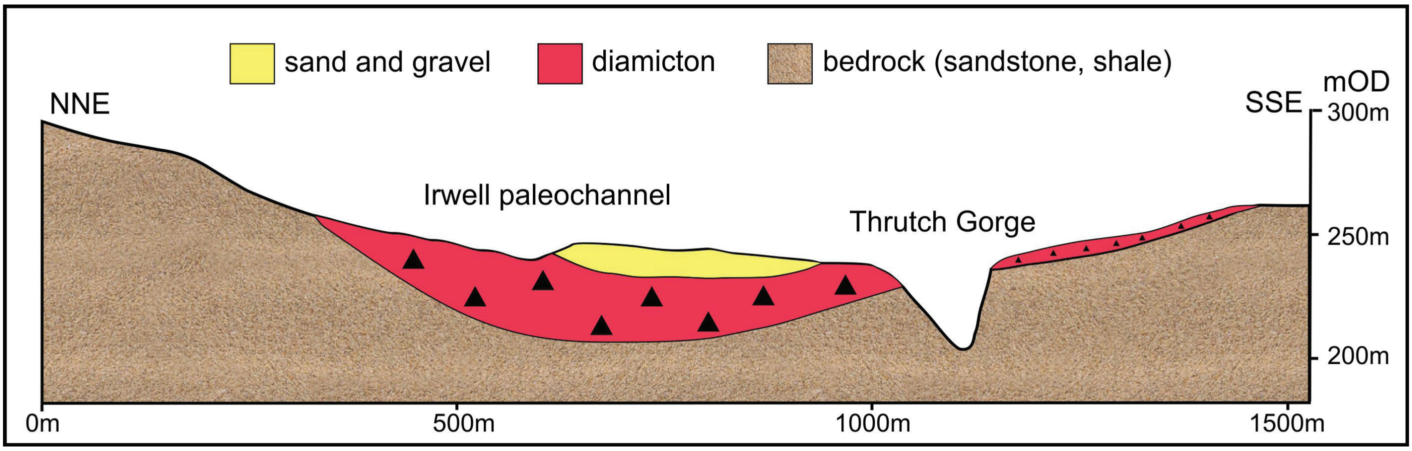

Figure 3: Cross-section of the Rossendale Valley at the Thrutch Gorge, redrawn from Dean and Hodson (1947). The proposed position of the former valley is on the northern side of the gorge, infilled with boulder clay.

fields, and many flat surfaces may be attributed to these activities (Figure 4). Nevertheless, there appear to be some distinct terrace surfaces that have not been created solely by human activity. These vary in height along the valley. East of the Thrutch gorge, a distinct terrace is visible above the modern flood plain at 240-250m OD (Figure 4). This is best preserved at the eastern end of the valley, but can also be clearly traced along the southern sides of the valley, with smaller sections preserved into Whitewell Brook and Hughs Mills, immediately west of the gorge. This corresponds to the height of the col between the Irwell and the Ribble catchment at Rising Bridge (Figure 1), and is partly underlain by sand and gravel (Figure 2; Wright *et al*. 1927). To the west of Whitewell Brook, an apparently similar terrace runs along the northern margin of the valley and into Limy Water, but drops in height eastwards, from 230m to 205m OD over a distance of c.3500m (Figure 2).

While the section east of Thrutch Gorge corresponds in height with terraces further west and the col between the Irwell and Ribble catchment at Rising Bridge (Delaney *et al*. 2010), and most likely indicates the shoreline position of the ice-dammed lake, the dipping surface west of the gorge indicates either formation as a glaciofluvial terrace prior to post-glacial downcutting to the modern river level, or erosion of the terrace after deposition. Further surfaces east of Stacksteads at 255m and 260m (Figure 4a, b) do not correspond to any spillway levels, but may reflect lake levels at a point prior to downcutting in the Rising Bridge spillway, possibly in earlier glacial phases. A higher terrace at 300m, the same height as the Trough Gate and Clow Bridge spillways (Figure 4a, b), is poorly developed along the northern part of the valley; it is interpreted as a glaciolacustrine shoreline remnant. Terraces above this level dip northwards and are thought to reflect differential erosion along bedding planes in the Millstone Grit, rather than water controlled erosion surfaces.

Within the valley, distinct glacial landforms can also be clearly seen on the DTM. To the NE of the Thrutch Gorge, a broad, low ridge c.900m long and c.10m high runs along the northern side of the valley on the 240-245m terrace, within the area mapped as sand and gravel (Figures 4, 5a). This feature widens eastwards. To the west of Stacksteads, in Newchurch (Figures 2, 5c), a further set of low mounds can be seen on the 205-230m surface, again underlain by sand and gravel. Upslope, a more pronounced series of ridges are arranged linearly, extending from 230m to 245m eastwards; these also are underlain by sand and gravel (Figures 2, 5c). These ridges appear to have originally formed a single continuous ridge, as they are separated from each other only by short breaks associated with post-glacial stream erosion. The ridges are steep sided and widen eastwards, in a ‘tadpole’ shape. We consider all of these ridges to be glaciofluvial in origin, formed within channels or conduits within the ice sheet. This is discussed further below.

East of the Thrutch Gorge an erosional scarp can be seen along the southern margin of the eastern ridge and associated 240-245m terrace, below which lies a wide, fan-shaped feature with a hummocky surface, whose deposition appears to postdate the formation of the scarp (Figure 5c). At least some of these hummocks are attributable to human activity, and may be spoils from small borrow pits. The southern margin of this feature has also been truncated, presumably by fluvial erosion.

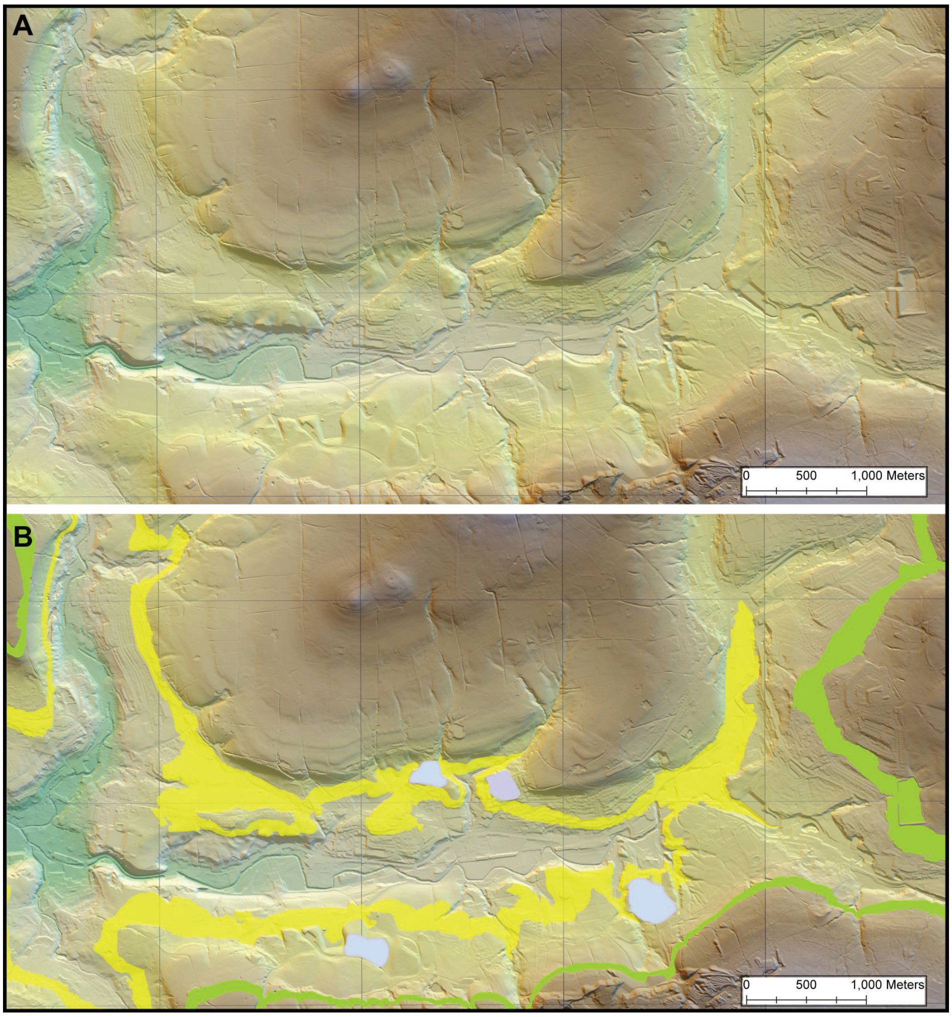

Figure 4: LiDAR DTM of the area east of the Thrutch Gorge, showing position of terraces discussed in the text. A terrace at 240-250m is shaded yellow and one at 300m is shaded green; remnants of smaller terraces at 250-260m are shown in pale blue.

Sedimentology

Available borehole records do not record sediments that are clearly glacial in origin. However, a temporary exposure at a building site in Glen Top (Figure 2, 5a), at the base of the hummocky fan described above, is interpreted as glacigenic and provides some insight into the local environment during its formation. The exposure is shown in Figure 6 and a log of the sediments is shown in Figure 7. The sediments consist of interbedded cobble and pebble gravels, sands, silts and clays consistent with subaqueous deposition. The following units were recognised:

Unit A, the lowest unit, is at least 0.4m thick and consists of irregular interbeds of inorganic, sandy silt and silty clay up to 20cm thick, with occasional pods and lenses of sand. The highest bed in the unit consists of a cohesive silty clay up to 0.08m thick, which has been partly removed (Figure 6, 7a). These sediments are similar to sediments seen further west at Rawtenstall and Haslingden (Delaney *et al.* 2010) and are interpreted as glaciolacustrine in origin.

The glaciolacustrine sediments are truncated along an erosional plane that dips gently northwards (Figure 6). This surface is interpreted as the base of a channel; the lowest part of this surface is overlain by up to 50cm of pebble and cobble gravel with a sandy matrix (Unit B; Figure 7a). These sediments are poorly exposed, but indicate the occurrence of high energy watery flows within the channel.

The overlying Unit C extends across the entire channel and consists of cross-cutting sets of planar to undulating and cross-laminated coarse to fine, silty sands. Planar and undulating laminae sets dip both upstream and downstream and truncation surfaces occur repeatedly upwards through the unit (Figure 6, 7b, c). Individual sets commonly become finer-grained upwards, with increasing silt, and the base of the overlying set commonly contains small pebbles and infraclasts (rip-up clasts) of silt and clay (Figure 7d). The unit contains sub-normal faults interpreted as growth faults throughout. These sediments are interpreted as plane bed, antidune and in-phase wave lamination, formed in episodes of high energy flow, both sub-critical and super-critical. The combination of fining-upwards of sediments and the transition from super-critical to subcritical flow is indicative of deposition from repeatedly rapidly decelerating flow, and is characteristic of turbidity current deposition at a point of flow expansion, where a

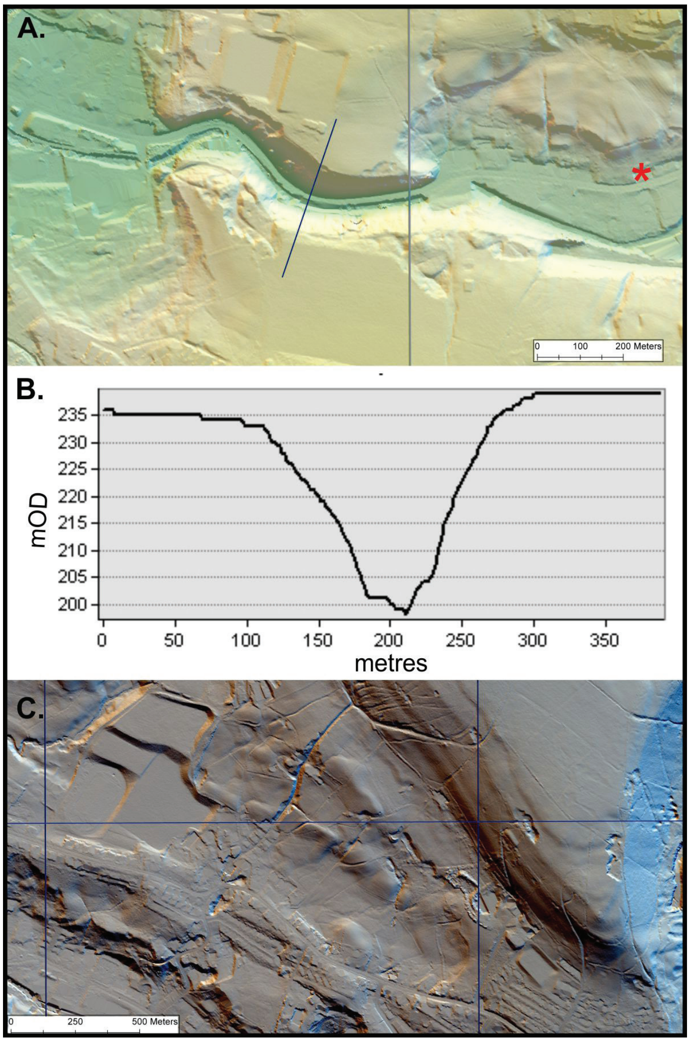

Figure 5: A. LiDAR DTM of the Thrutch Gorge and area immediately to the east. The position of the exposure at Glen Top is shown by a star. The position of the cross-section shown in 5B is shown in blue.
B. Cross-profile of the Thrutch Gorge.
C. LiDAR DTM of the area around Newchurch, to the west of the Thrutch Gorge, showing a series of ridges interpreted as an esker.

hydraulic jump may form (Figure 8; Banerjee, 1977; Arnott and Hand, 1989). Truncation of the upper part of sets, and the incorporation of infraclasts of underlying sediment, indicates erosion. Scouring on the bed also is associated with a hydraulic jump (Postma *et al.* 2009). Such areas of flow expansion commonly occur at the exit point of a conduit within a glaciolacustrine setting (see below).

Unit C is capped by a thin, discontinuous lamination of grey silty clay <1cm thick. The overlying Unit D, consists of highly distorted laminated fine sand and silt which thickens downslope and is in turn overlain by a cap of organic-rich silts and occasional clasts interpreted as slope deposits and made ground.

The sediment sequence indicates the occurrence of eastward flowing, high-energy flows within an otherwise low-energy glaciolacustrine environment. This type of sequence in a glacial environment is typically found in subaqueous outwash fans formed by efflux jets (sediment-rich, often pressurized flows into a standing body of water) emerging from a conduit or channel at the ice margin (Figure 8; e.g. Russell and Arnott, 2003; Winsemann *et al.* 2009). The rapid expansion of flow is associated with a rapid reduction of velocity as the flow enters standing water, rapid expansion of the jet laterally and rapid deposition of a wedge of sediment close to the conduit mouth. These sediments appear to have formed after the deposition of the ridge on the terrace above, as they are deposited against an erosional scarp in this feature. The most likely source for the efflux jet is from the mouth of the Thrutch Gorge immediately to the west.

Discussion and Conclusions

Our research confirms the occurrence of a suite of glacial to ice-marginal glaciofluvial and glaciolacustrine landforms and deposits in the Upper Irwell Valley. Although the relationship between the different features is not always clear, a number of propositions can be made.

Firstly, we suggest that the glaciofluvial landforms along the northern margin of the valley most likely formed during the last termination. This does not preclude deposition of the underlying diamictons in a previous glaciation(s), but the relatively fresh appearance of the higher ridges at Newchurch in particular indicates they are relatively recent. We consider the upper ridges at to have formed by glaciofluvial deposition in an ice-walled channel or conduit draining towards the ice margin, i.e. as an esker. The uphill pathway of the ridges indicates a subglacial origin, within a pressurized conduit. The 'tadpole' shape of the higher ridge at Newchurch is common in eskers and is thought to form due either to widening of the conduit towards the ice margin (Hooke and Fastook, 2007) or by deposition of a fan at the conduit portal (e.g. Banerjee and McDonald, 1975; Delaney, 2001).

The lower ridges at Newchurch and the ridge east of the Thrutch gorge also appear to form a single group, although more widely separated and poorly-defined than the upper 'tadpole' ridge. They too may be englacial features, possibly formed in a supraglacial or englacial conduit, or channel deposits whose form was modified as buried ice melted during ice recession. However, this would require the underlying terrace surface to have formed prior to ice advance. This seems unlikely in the eastern part of the

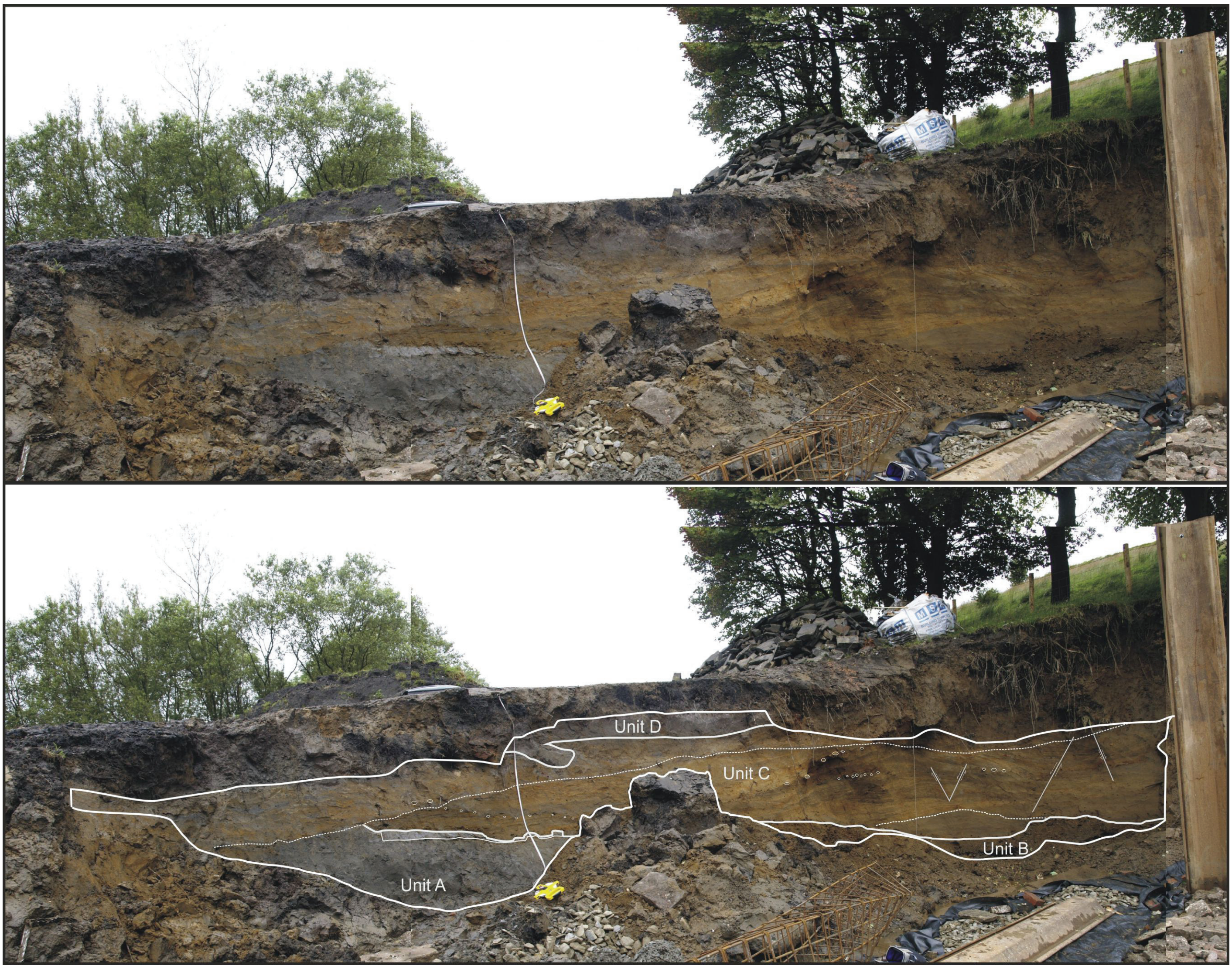

Figure 6: Temporary exposure in glaciolacustrine sediments at Glen Top, east of the Thrutch Gorge. The division of the sediments into units is shown in the lower image.

valley, where the 240-250m terrace is well-developed, but may be possible in the western part, where the equivalent terrace dips westwards. An alternative possibility is that the glaciofluvial mounds are erosional remnants of a more extensive deposit which has been partly eroded by wave action during formation of the terraces with which they are associated. Under this scenario, the underlying diamicton may relate to previous glacial cycles, or may have formed shortly before deglaciation. Similarly, the sand and gravel deposits may have survived a glacial advance, may have formed within the glacier during retreat, or may be proglacial sediments deposited in front of the receding ice margin.

In any case, we consider the terrace surface east of the Thrutch gorge to have formed during the last deglaciation, as it is very well-preserved. This 240-250m surface is clearly associated with an ice-dammed lake surface, as it corresponds closely in height to a spillway and surfaces further west. Incision of the deposits underlying the terrace may have commenced prior to formation of the terrace surface by erosion, but is at least partly post-glacial as it ties to modern river levels.

Deposition of the subaqueous outwash fan at Glen Top postdates deposition of the glaciofluvial mounds on the terrace above as the southern margin of the ridge is truncated and the fan deposited against it. We consider this subaqueous outwash fan to have been deposited by an efflux jet from an ice margin located around the Thrutch gorge, possibly pinned on the cross-valley bedrock high at this point, and it is likely that this jet emerged from a subglacial Nye channel in the vicinity of the gorge. However, this cannot have happened immediately after deglaciation of the valley east of the gorge, as an ice margin extending across the valley would have ponded a lake to a height of 300m,

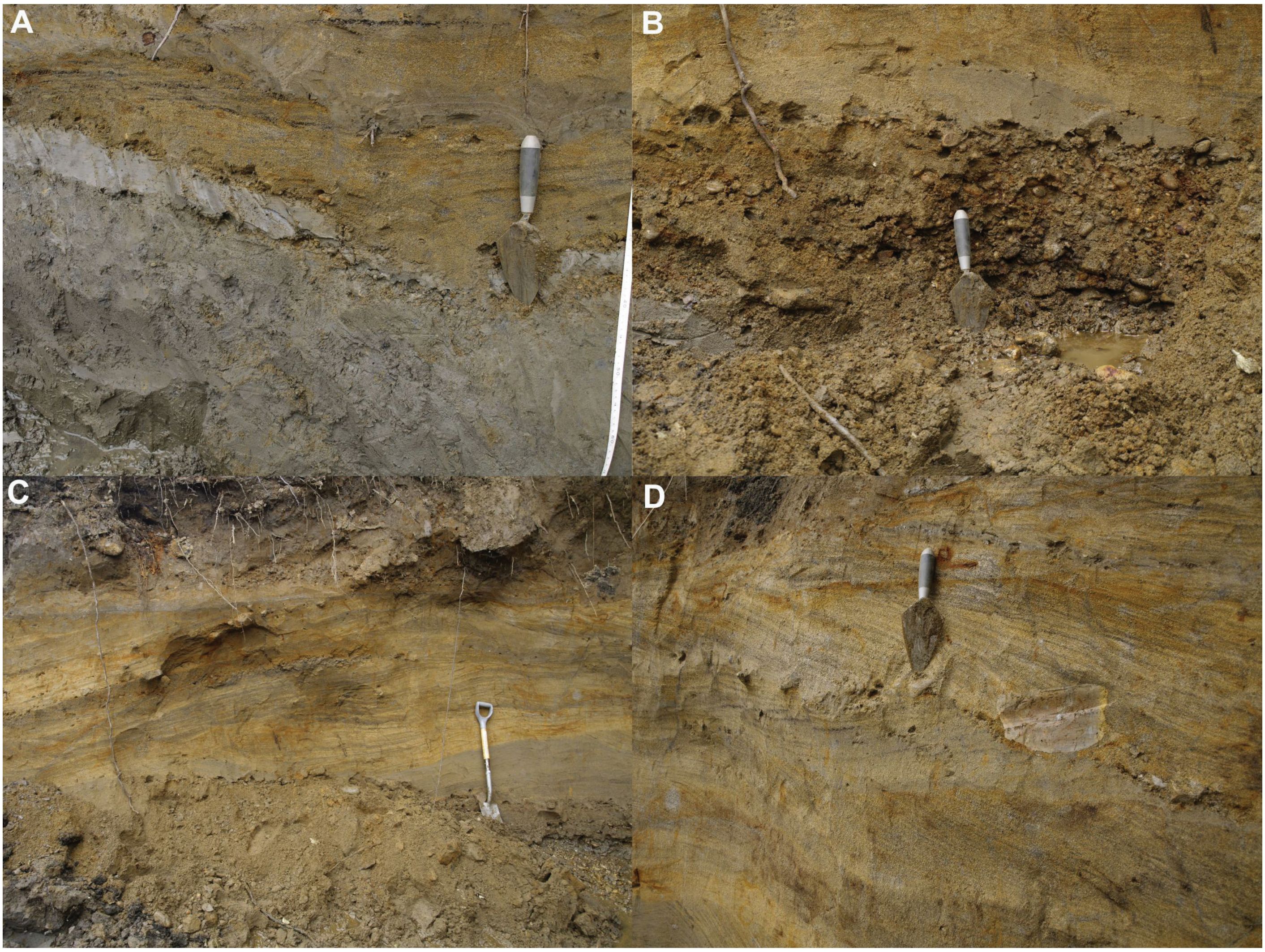

Figure 7: A. Unit A sediments consisting of massive clayey silt with sand, overlain by an 0.8m thick drape of silty clay, truncated by Unit C sediments. These are interpreted as glaciolacustrine sediments, deposited at some distance from the ice margin.
B. Unit B sediments consisting of a clast-supported cobble and pebble gravel with sandy matrix, deposited by a high energy water current.
C. Unit C sediments consisting of cross-cutting sets of planar to undulating and cross-laminated coarse to fine, silty sands, and truncation surfaces, interpreted as upper plane bed and antidune structures deposited from high energy super-critical to sub-critical flows.
D. Infraclast of silty clay within Unit C sediments indicating erosion of underlying beds associated with a hydraulic jump (transition from super-critical to sub-critical flow).

the height of the Trough Gate spillway. Consequently, we consider the existence of this deposit to indicate recession of ice beyond the mouth of the Rossendale Valley to allow incision to occur, followed by a readvance of ice up the valley as far as the Thrutch Gorge area, after incision of the 24-250m terrace side (although the terrace surface may have been planed flat at a later date).

Subsequent recession of the ice margin south of Haslingden resulted in a 50-60m drop in lake level, and the formation of a new terrace at 240-250m throughout the upper Irwell, probably through a combination of wave erosion and deposition of beach sediments. At this stage, the position of the Thrutch gorge would still have been under water. However, further recession later in the deglaciation resulted in a drop in lake water levels to 200m or lower and, ultimately, drainage of the lake (Delaney *et al*. 2010).

One issue that remains unresolved is the timing of the formation of the Stackstead Gorge. One possibility is that the gorge has been formed over multiple glaciations, as has been suggested for inner gorges within the Swiss Alps, on the basis that the incision rates required to form these gorges during a single glaciation are unrealistic (Montgomery and

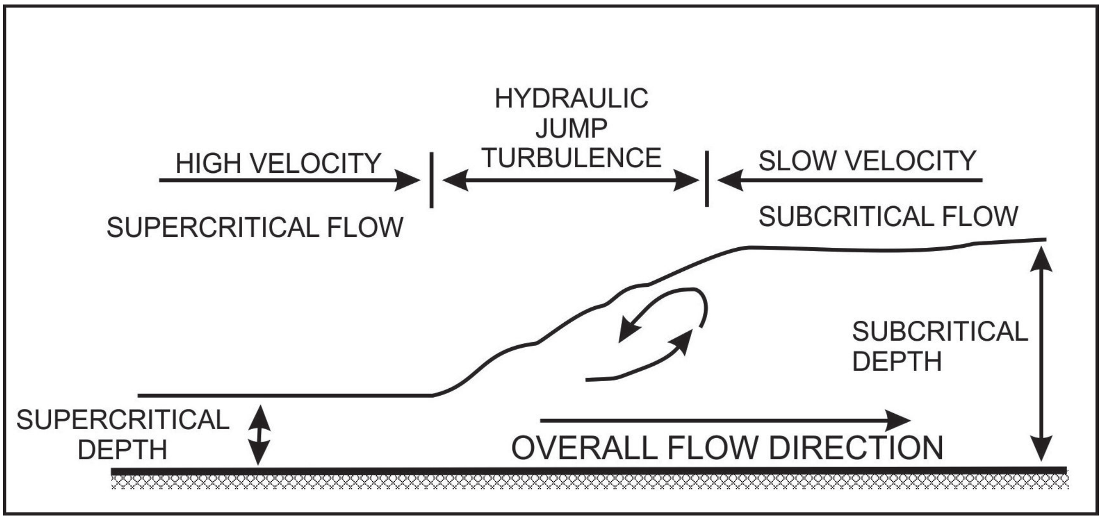

Figure 8: Diagram showing structure of hydraulic jump. Erosion can take place at the transition from super-critical to sub-critical flow.

Korup, 2011). Certainly, the gorge is likely to have formed prior to our proposed readvance as far as the Stackstead area, as incision of the 240-250m terrace had commenced prior to this readvance. However, recent exposure dates from Sweden suggest that smaller inner gorges on the scale of the Thrutch Gorge formed rapidly during the last Glacial Termination (Jansen *et al*. 2013), and one possibility is that much of the Thrutch Gorge formed during drainage of Paleolake Rawtenstall, prior to a final readvance along the valley. Erosion rates during such catastrophic floods are considerably higher than long term rates – for example, a dam-release flood in Texas in 2002 caused up to 12m vertical incision in less than three days (Lamb and Fonstad, 2010). Consequently, we think the likeliest time for formation of the Thrutch Gorge is immediately after recession of ice from the southern end of the Rossendale Valley, allowing drainage of the ponded ice-contact lake, but prior to the last advance of ice into the valley. These events may have occurred over more than one glacial cycle, or as regional changes in ice extent during the last glacial cycle.

We emphasise that the sequence of events suggested above is speculative, and further data, particularly dating evidence, may considerably alter this interpretation. Nevertheless, although the evidence available is fragmentary, the LiDAR DTMs and sedimentary evidence indicate that the Upper Irwell has been significantly modified by the events of deglaciation. A similar approach to adjacent valleys is likely to considerably improve our understanding of deglaciation in the North West.

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