7 An armchair view of the geomorphology of the Rossendale Forest: New insights from LIDAR

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Introduction

The upland area known as the Rossendale Forest extends westwards from the Pennines north of Manchester. It is the source of two of the region's major rivers, the Irwell and the Roch. The geomorphology of the area is characterized by extensive plateau surfaces, cut by deep valleys and gorges and partly infilled by glacial deposits. Traces of landslides can be seen on many slopes, some dating from the end of the last glaciation and others still active. The geomorphology and the glacial deposits have been studied since at least the early 19th century, most recently by the British Geological Survey, who published updated maps of the bedrock and unconsolidated sediments in 2008 (Crofts, 2005; BGS, 2008). Early research in the Forest was carried out on foot, the most essential equipment being a decent waterproof jacket and good walking boots, with a very occasional application of sun cream. This approach provided a wealth of information, and had the additional advantage of improving the fitness of the researcher while often imbuing her or him with a sense of moral well-being (or smugness). Fieldwork is essential for examining the materials that form the landscape of the Rossendale Forest where, however, it can be difficult and time-consuming to collect data in bad weather.

In recent years, the quality and availability of remotely sensed material, often available freely through the internet, has improved. Images/photos collected by satellite and airplane are now widely available through the internet particularly through GoogleEarth. Elevation models of the surface topography of the planet, collected using interferometric synthetic aperture radar are also freely available. In this age of armchair geomorphology, it is possible to view the features of an area from the comfort of the office or home. Fieldwork can now be targeted precisely on areas of interest, minimizing time in the field.

One might suppose that the possibilities of new observations and insights into the geomorphology and glacial history of an area such as the Rossendale Forest are relatively limited. However, new technologies can reveal previously unrecognized features or provide new information on long-recognised features. One such technology is airborne light ranging and sensing (LIDAR). This is a remote-sensing technique that allows us to view geomorphology at an unprecedented high resolution, including in forested areas. This technique is transforming the way earth scientists and archaeologists view and measure the landscape. So much new information is being generated that the term "LIDAR revolution" has been coined.

What is LIDAR?

Airborne LIDAR surveying uses a pulsed laser beam to measure distance. The technique was first developed in the 1960s to search for submarines, but has been increasingly used in earth surface mapping from the mid-1990s. The plane containing the LIDAR sensor flies along a set path above the area to be surveyed. As it flies, the laser beam is bounced off the earth's surface below. The return time is measured and related accurately to the plane's position to calculate surface height (Figure 1). The beam is scanned from side to side as the airplane follows the survey line, and tens to hundreds of thousands of data points are collected each second, producing a LIDAR point cloud. Each pulse may produce a number of returns, depending on vegetation and building cover; the final return is from the 'bare earth' surface (Figure 1).

The point cloud of data is imported into a Geographical Information Systems (GIS) computer application to create a Digital Terrain Model (DTM). This is a model of the land surface, with any forestry, buildings and infrastructure removed. Such models have been produced in the past, but in the case of LIDAR, the DTMs have an unprecedented accuracy – the LIDAR data collected by the Environment Agency in England has a vertical resolution of between ±5cm and ±12cm, and horizontal accuracy is ±40cm. The horizontal accuracy is actually higher than the pixel resolution for many DTMs.

The UK's Environment Agency has been using LIDAR as a survey tool since 1998 and has completed over 10,000 surveys, covering 75% of England (Environment Agency 2016). Most of the Rossendale Forest has been flown, although some of the higher ground has been omitted as the data are collected primarily for flood assessment purposes. The LIDAR DTMs shown here were downloaded from the Environment Agency website and then hillshaded. This involves generating a relief model of the surface by simulating light hitting that surface at an angle from one or more directions. For the Rossendale DTMs, Relief Visualization Toolbox (RVT; Kokalj and others, 2011) was used to generate composite hillshades from light sources applied from 16 directions at an angle of 35° to the earth's surface. A vertical exaggeration of two was applied. The hillshaded DTMs were then viewed in ArcGIS to produce the final images and generate surface profiles. False colour has been applied to some images to indicate the change in height in the landscape.

Rossendale Forest geological history

It has long been recognized that the form of the Rossendale Forest area is controlled primarily by geological structure (Wright and others, 1927; Crofts, 2005). This can be seen in the DTM (Figure 2). The area is underlain by Carboniferous sandstones, shales, mudstones, coals and fireclay (fossilized soils) arranged in rhythmic units of varying thickness. Where these beds lie flat or

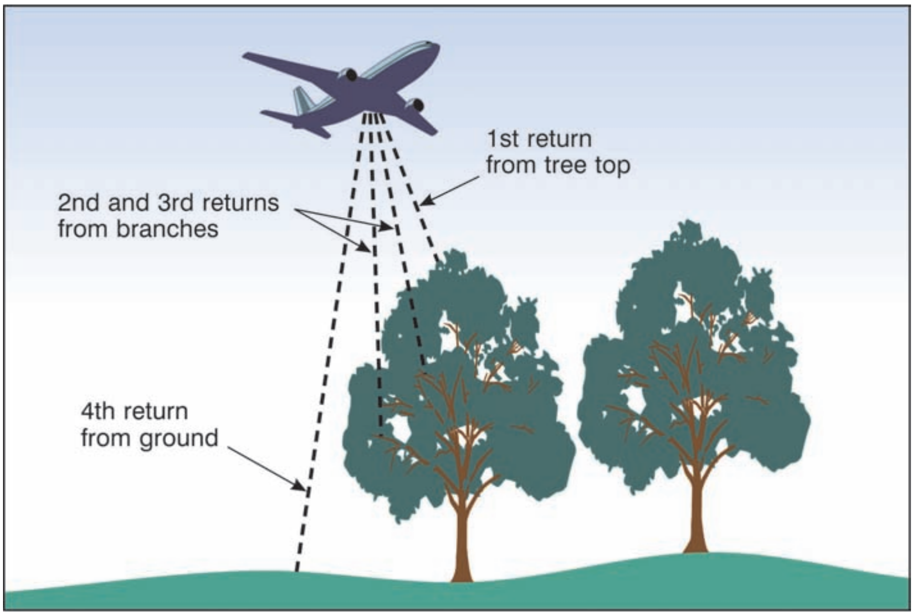

Figure 1: Airborne LIDAR data acquisition.

dip gently, they give a stepped appearance to the landscape, with the widest steps formed by the sandstones and gritstones. These beds are warped gently into the Rossendale Anticline, the broad crest of which forms the central plateau area, while the steeply dipping sides form the northern and southern margins of the Rossendale uplands (Figure 2). The eastern and western margins are formed by fault zones. Along the eastern margin, a zone of NW-SE trending faults extends from Burnley to Todmorden, a line now marked by the Cliviger Gorge (Figure 2). To the west, a further zone of faulting from Turton to Darwen marks the end of the upland areas. More widely spaced faults trending NW-SE also occur within the central plateau. The faulting pattern is reflected in the orientation of valleys and major gorges across the area (Figure 2).

Zooming in on the landscape

One of the most useful aspects of using LIDAR is the ability to view the landscape at a very wide range of scales. This is also one of the great difficulties of using LIDAR – there is so much to see, one hardly knows where to begin. Below, some of the geomorphological features visible in the landscape are considered.

Rivers and streams

The most impressive feature of the main rivers draining the Rossendale Forest is the extent to which their courses have been altered by human activity. In the main valleys, wherever flood plains are present, evidence of human activity is almost continuous and the river is effectively canalized (Figure 3A). Even in rural areas, embankments

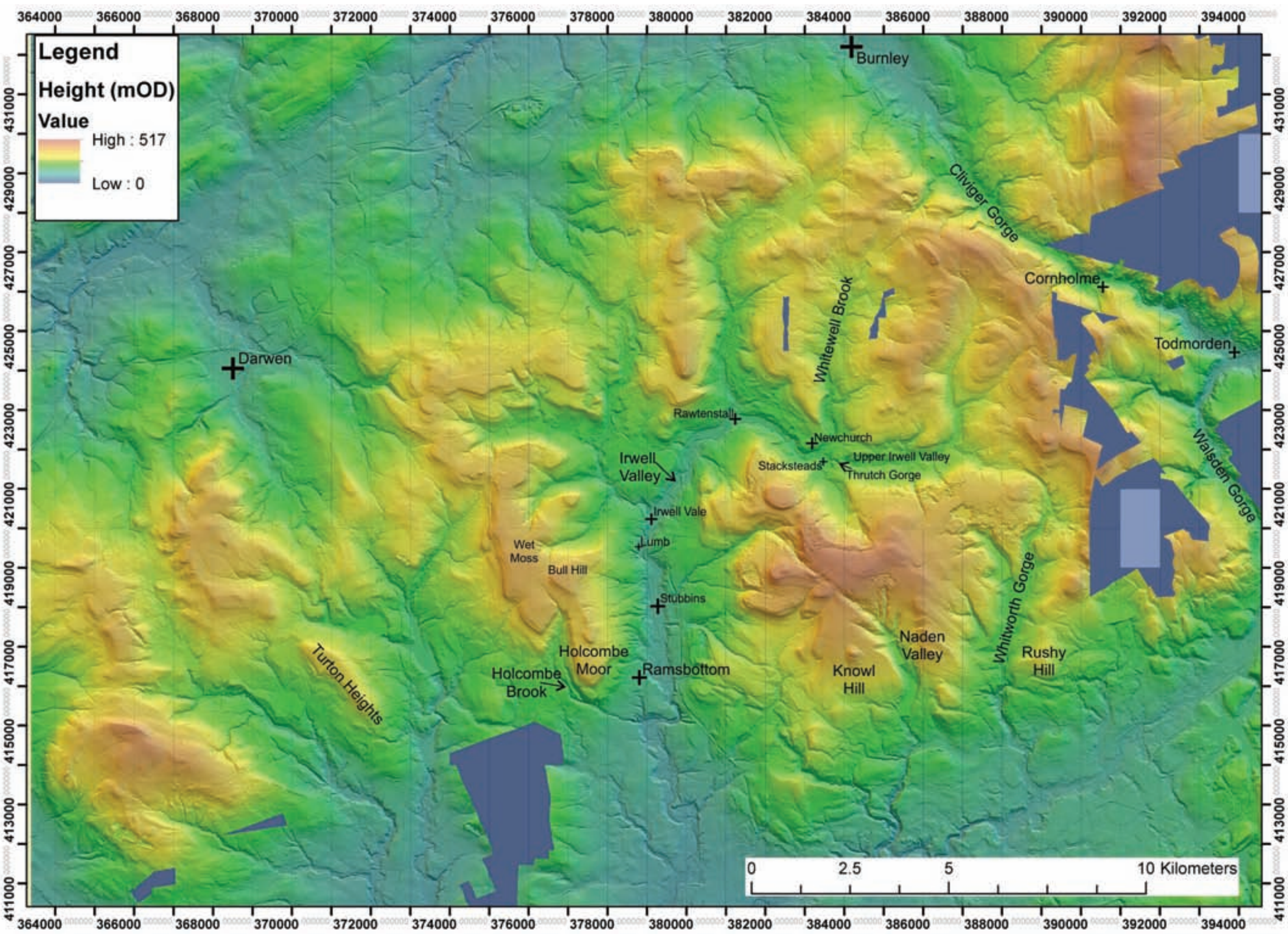

Figure 2: Hillshaded LIDAR DTM of Rossendale Forest, showing the location of places mentioned in the text. Matt blue areas indicate no LIDAR coverage. Horizontal resolution is 2m.

are clearly visible, as are the effects of channel straightening (Figure 3 B). Traces of the original river course are rarely preserved (Figure 3B), and it appears that the rivers are no longer receiving sediment from the many landslides on the surrounding slopes. Only streams draining from the upland plateau areas appear relatively undisturbed. In these areas the gully systems draining water from the blanket bogs covering much of the plateau areas can be clearly seen (Figure 4). Even these are indicative of human activity, as several studies have shown that increased peatland erosion in the Pennines has been enhanced by reduced biodiversity due to air pollution (e.g. Shotbolt and Thomas, 2006). The effects of this can be seen in the DTM of Bull Hill (Figure 4A), where remnants of the former peat surface remain as hags at the centre of the hill. At Wet Moss (Figure 4B) cross-profiles in the peat gullies indicate they are flat-bottomed, in contrast to gullies in bedrock on the slopes below. This indicates that the base of the gullies is likely to have reached the bedrock surface below and that lateral erosion is now dominating.

Landslides

Landslides have been mapped throughout the Rossendale Plateau by the British Geological Survey for hazard assessment (BGS 2008). The BGS survey does not distinguish between landslides with a distinct failure plane, where a block of material moves downslope, and flows, where smaller aggregates of particles and individual particles move in a watery flow. Landslides with distinct failure planes are very clearly visible on the DTMs, but flows are much harder to see. For slides with distinct failure planes, the LIDAR DTMs are useful in two ways: firstly, the characteristics of many previously identified landslides can be seen clearly and measured accurately; and secondly, previously unidentified landslides can be seen. As there are so many landslides, particular areas are considered here.

Cliviger Gorge

The landslides within the Cliviger gorge are thought to have formed after the recession of ice during the last glaciation (Figure 5). Removal of ice from the valley released pressure from the valley

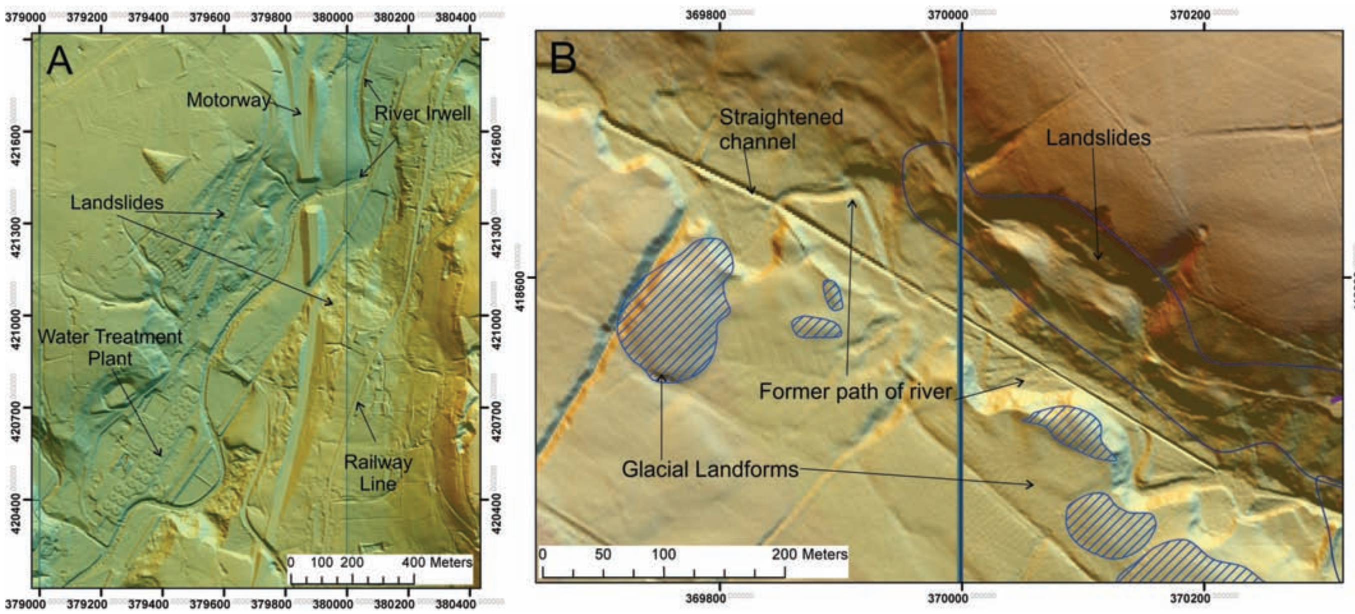

Figure 3: Modification of rivers and flood plains by human activity. A: The River Irwell at Edenfield – the river channel has been straightened and the flood plain used in various ways. B: Cadshaw Brook, near Edgworth. The brook has been straightened but the original river channel is still visible on the DTM. Cross hatched areas indicate glacial landforms; blue outline indicates position of landslide. LIDAR DTM horizontal resolution is 1m.

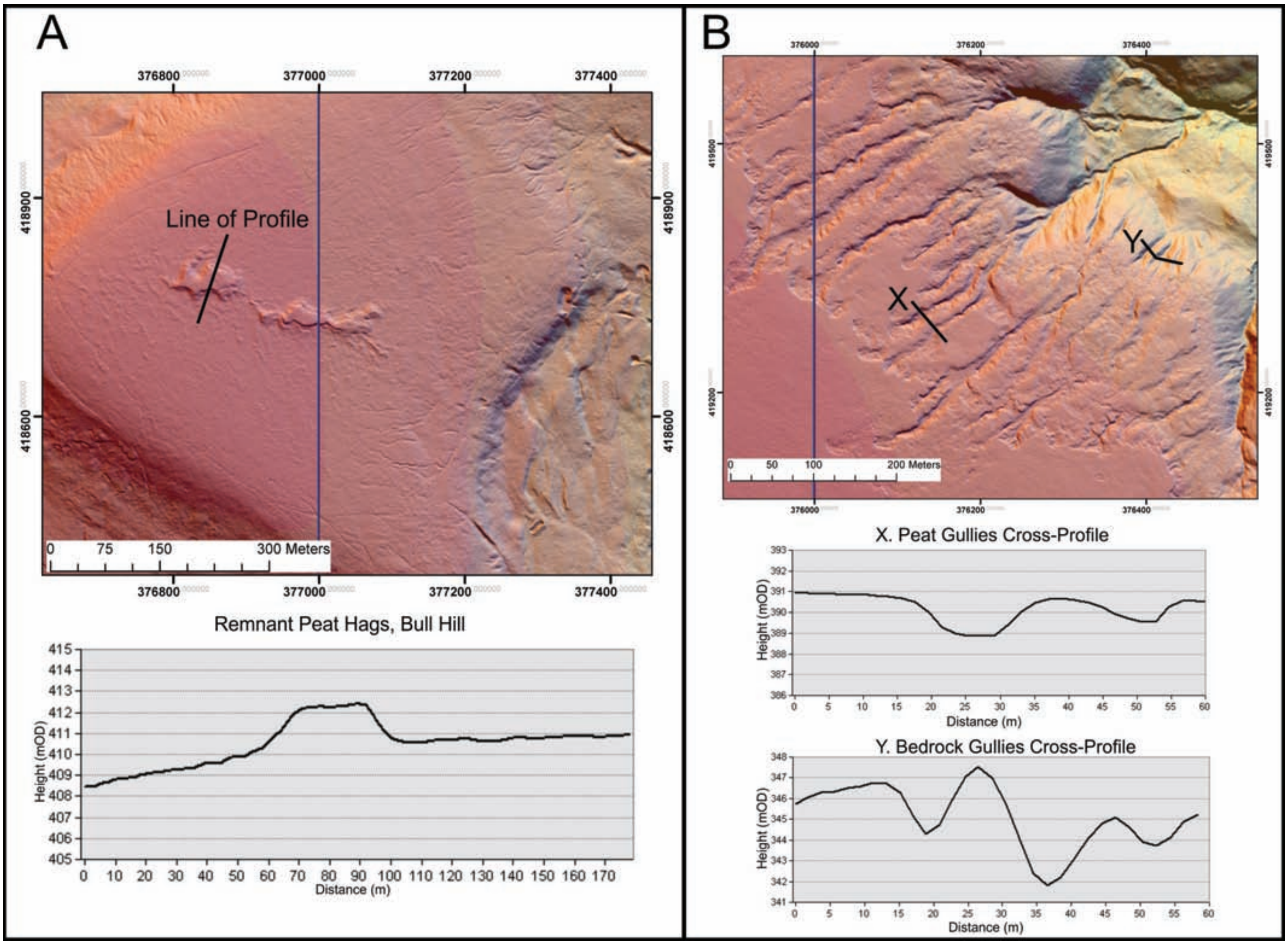

Figure 4: A: Plateau surface at Bull Hill. The low surface roughness is characteristic of peat covered areas, but is interrupted by peat hags up to 2m high. The morphology of the peat hags can be easily measured using the LIDAR data. B: Wet Moss and adjacent slopes. Gullies developed at the margins of the blanket bog are succeeded down hill by gullies cut in bedrock. The cross-profiles show characteristic cross sections. DTMs constructed with 1m resolution LIDAR rasters.

sides, and resulted in the opening of fractures along the line of bedding planes and pre-existing joints and faults. Slope failure then occurred along these planes. This can be best seen on the eastern side of the valley (Figure 6). Here bedding dips steeply into the valley along the sides of the main Pennine anticline, and is cut at intervals by E-W trending faults and joints. Multiple failures occurred, bound laterally by faults and joints. The DTMs show that the failure planes were both planar and curved, and that there are both translational and rotational slides (Figure 6). In one case, the slide extended out onto the valley floor in a lobe, indicate some flow also occurred.

The landslides along the western margin of the gorge are less clearly defined on the LIDAR DTM (Figure 6). This may relate to the geology, as bedding here is near horizontal, so the failure plane is less easy to see and may be more deep-rooted than on the eastern side of the valley. The development of gullies along the upper slopes is also confined to this side of the valley. This type of erosion results in the development of small fans at the base of the flow, and the morphology of the landslide below is likely to have been altered in this way.

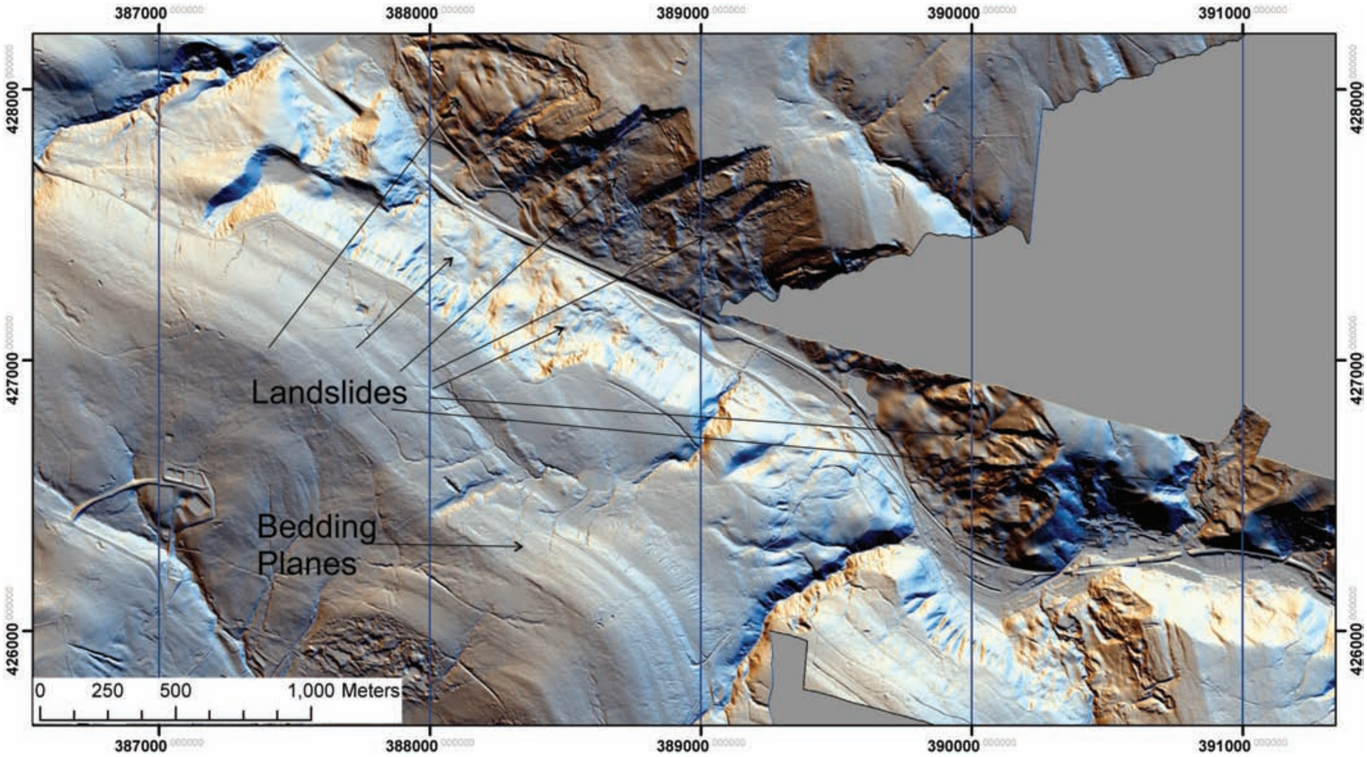

Figure 5: LIDAR 1m DTM of Cliviger Gorge between Cornholme and Holme Chapel, showing the position of landslides along the margins. The stepped appearance of the higher areas on the southwestern side of the gorge is due to the outcrop of near-horizontal bedding planes in the underlying bedrock. Bedding on the northeastern margin dips parallel to the sides of the gorge. Continuous grey area at right of image indicates area without LIDAR coverage. LIDAR DTM resolution is 1m.

Upper Irwell Valley at Newchurch and Waterfoot

The very large landslide in bedrock on the valley's southern side (Figure 7) has been mapped by the BGS. It has a similar morphology to those along the western margin of the Cliviger gorge. It has also been modified by human activity. The landslides on the valley's northern side have not been mapped previously, as they are covered in forest (Figure 7B). These slides have developed in glacial sediments, including glacial lake sediments which are relatively impermeable and likely to have acted as a failure plane. Undercutting of the base of these slides in the past, by the River Irwell and its Whitwell Brook tributary, seems to be the cause of destabilization.

The Irwell Valley between Irwell Vale and Stubbins

A number of landslides have been mapped by the BGS in this area (Figure 8). Along the valley's eastern side, slides that developed in glacial sediments are clearly visible. The LIDAR DTM shows that some of these slides are more extensive laterally than previously thought. These areas are either masked by trees or have a smoother surface than most slides. Slides on the western side of the valley are developed in bedrock near the river, and in bedrock and glacial deposits higher up the slope. In the upper valley, a landslide indicated on the BGS map cannot be seen clearly on the LIDAR DTM (Figure 8), although there is a subtle change in topography. This may be a flow, generated in the thin cover of glacial sediments draping the bedrock in this area.

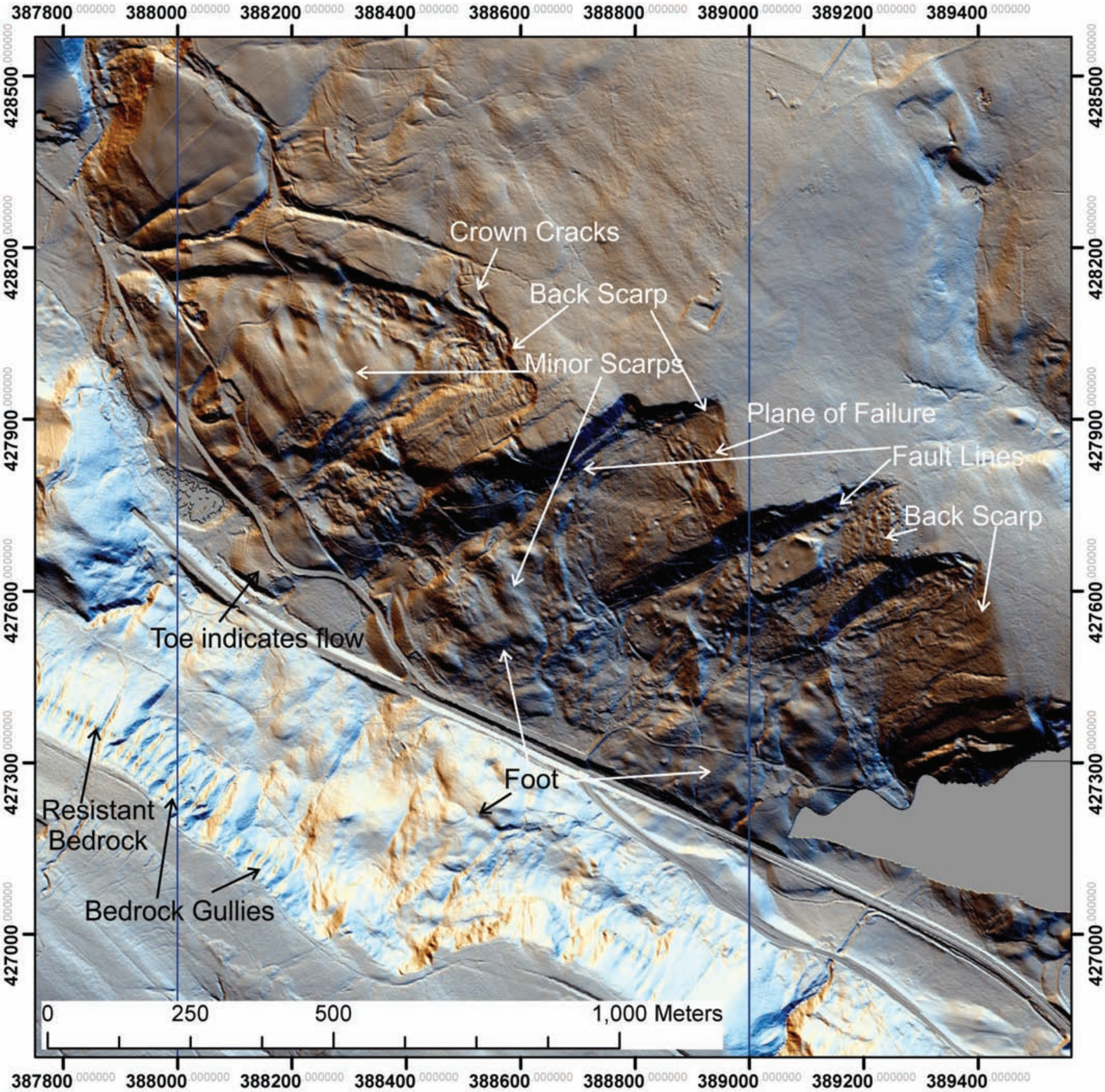

Figure 6: Close-up of translational and rotational landslides along the eastern margin of Cliviger Gorge, showing characteristic features. Continuous grey area at bottom right of image indicates area without LIDAR coverage. LIDAR DTM resolution is 1m.

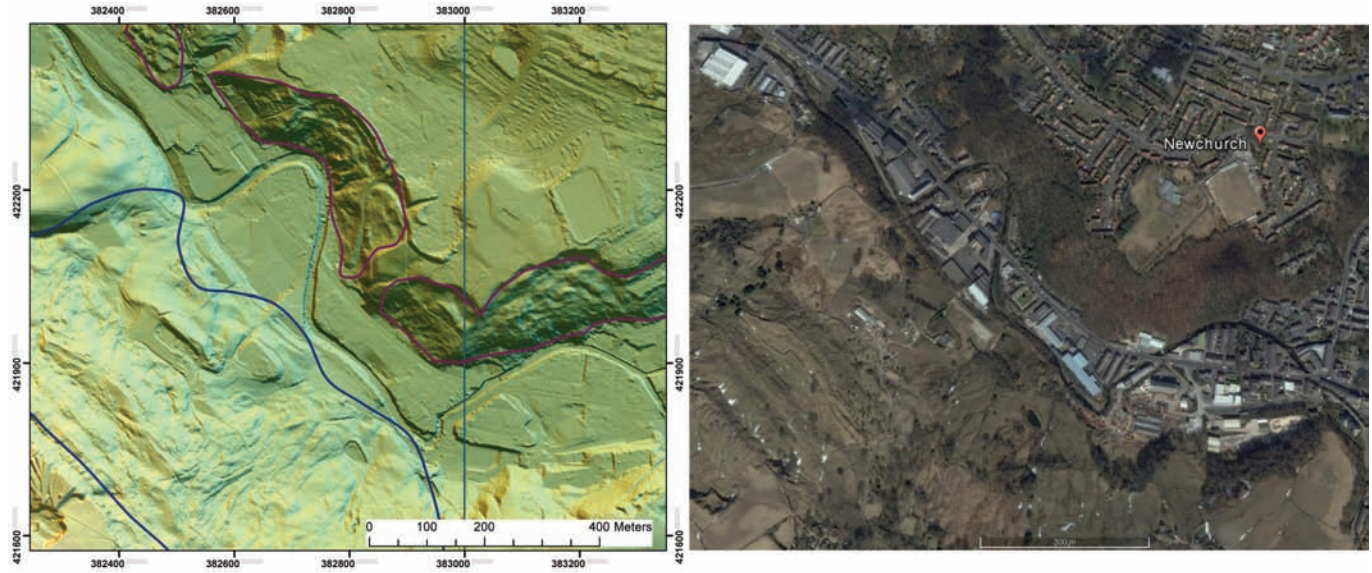

Figure 7: Landslides along the upper Irwell valley around Newchurch. A: LIDAR image showing position of landslides. Scarps are clearly visible in the upper parts of landslides along the northern bank of the river. Blue outlines indicate landslides mapped by the BGS; purple lines indicate the location of previously unmapped landslides. B: Google Earth image of the same area (©Google Earth 2016). The large landslide along the southern side of the valley is clearly visible, but those on the northern side are masked by trees. LIDAR DTM resolution is 1m.

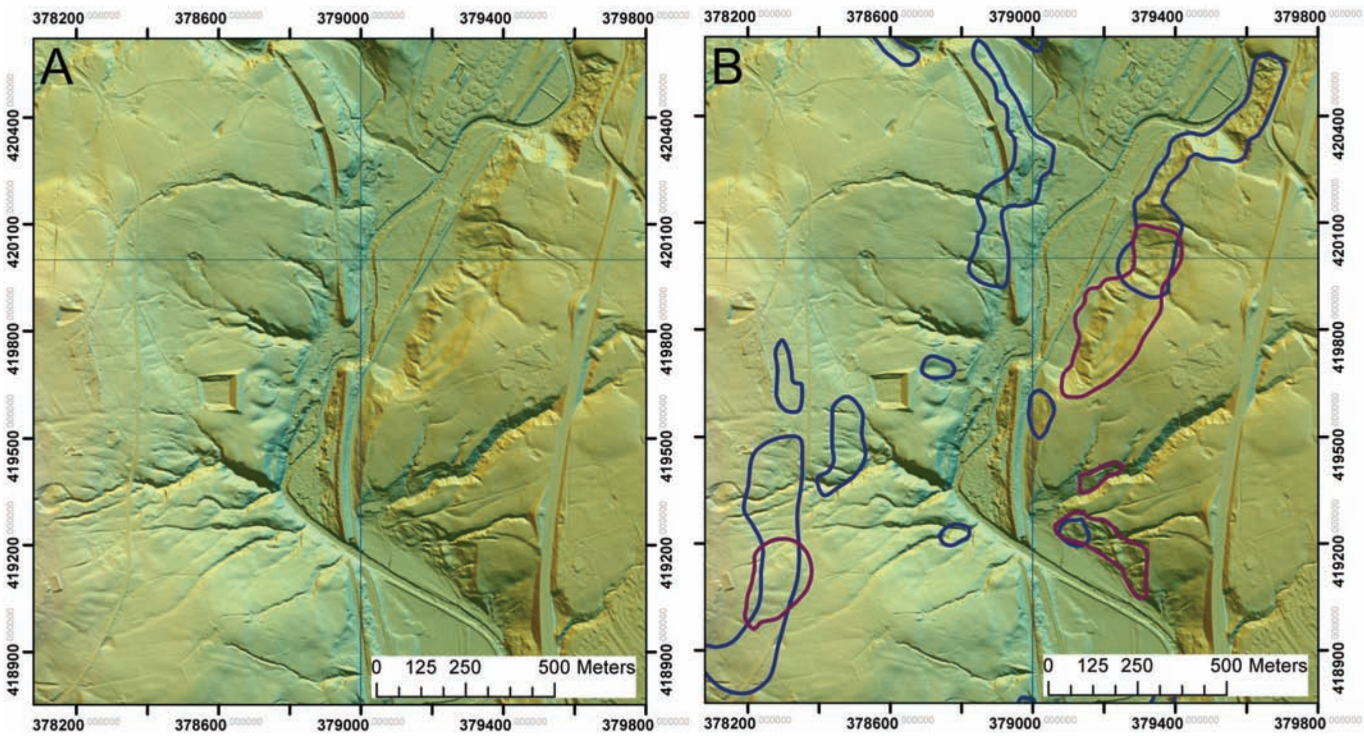

Figure 8: The Irwell valley between Irwell Vale and Stubbins (just out of image to south). Rotational landslides developed in glacial deposits can be clearly seen along the eastern margin of the valley. On the western side, slope movements mostly occur as flows, which cannot be clearly seen. Blue outlines indicate landslides mapped by the BGS; purple lines indicate the location of previously unmapped landslides. LIDAR DTM resolution is 1m.

Knowl Moor

The landslide on the southern side of Knowl Hill, a sandstone remnant on the moor, is beautifully captured by LIDAR (Figure 9). It has an arcuate scar, indicating a rotational landslide. Almost half of the surface of the hill is formed by this slide.

Glacial depositional landforms

Mapping of glacial deposits, or drift, in the Rossendale Forest commenced before the widespread acceptance of the Glacial Theory, and the approximate extent of these deposits has been known since before the First World War (Jowett, 1914). The area was influenced by two main bodies of ice. Ice from Scotland and the Lake District, which moved down the Irish Sea basin and adjacent lowlands, is thought to have covered most of the Forest area, swinging eastwards onto the Manchester Plain to abut against the western margin of the Pennines. Ice from Yorkshire is thought to have covered the eastern margin of the Forest and the western Pennines beyond the Cliviger Gorge, extending down the Cliviger Gorge to around Cornholme (Figure 2; Jowett 1914, Wright and others 1927). During recession, the Irish Sea Basin ice receded

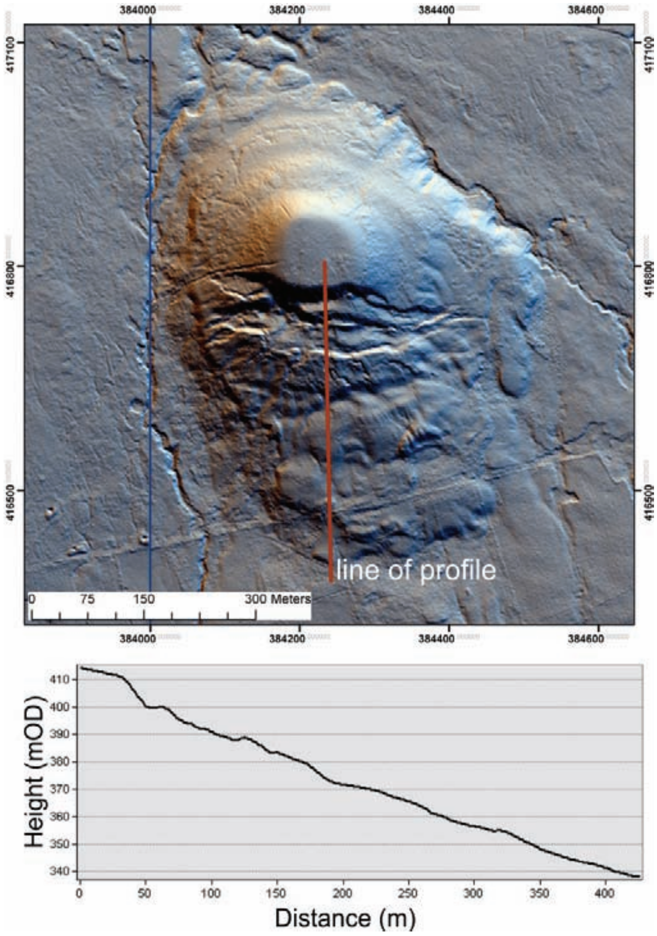

Figure 9: Knowl Hill, with the landslide along the southern side clearly visible. LIDAR DTM resolution is 1m.

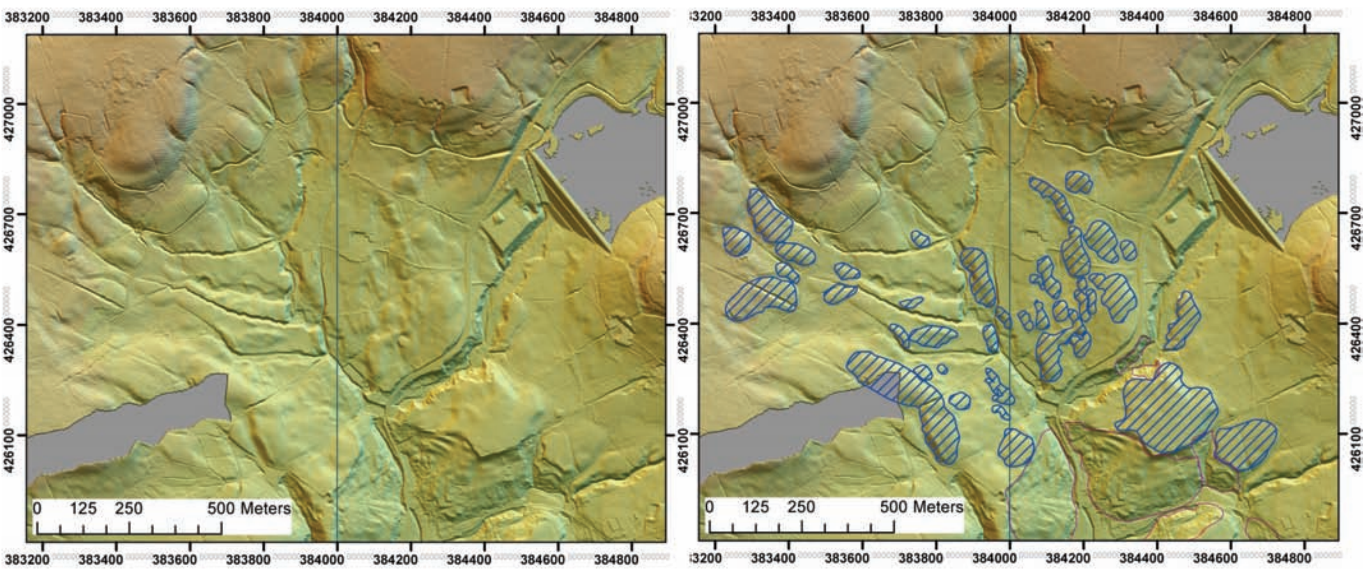

Figure 10: Hummocky moraine at the northern end of Whitewell Brook. Linear arrangements of the ridges may be due to formation around the margins of an ice lobe, as latero-terminal moraines. Cross-hatched areas indicate glacigenic landforms. Grey areas indicate no LIDAR coverage. LIDAR DTM resolution is 1m.

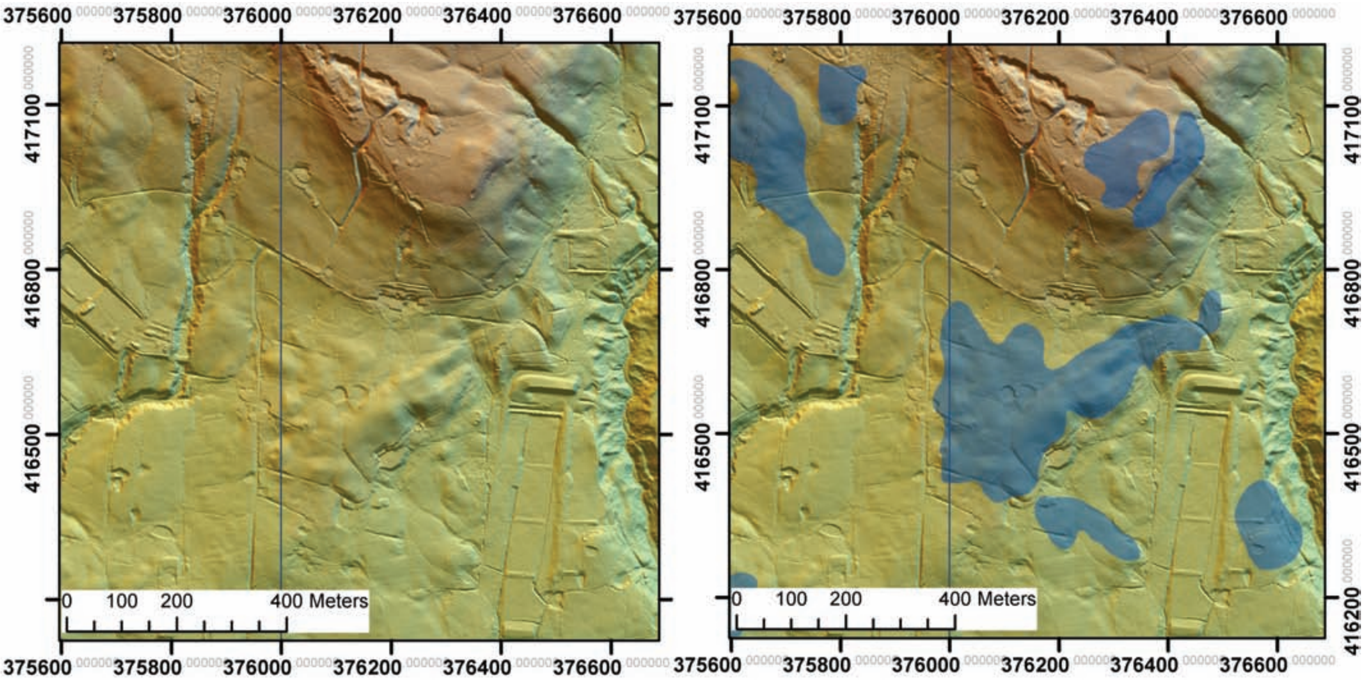

Figure 11: Ice flow-transverse ridges formed in sand and gravel at Holcombe Fold, west of Holcombe Moor. Grey-blue areas are underlain by sand and gravel. LIDAR DTM resolution is 1m.

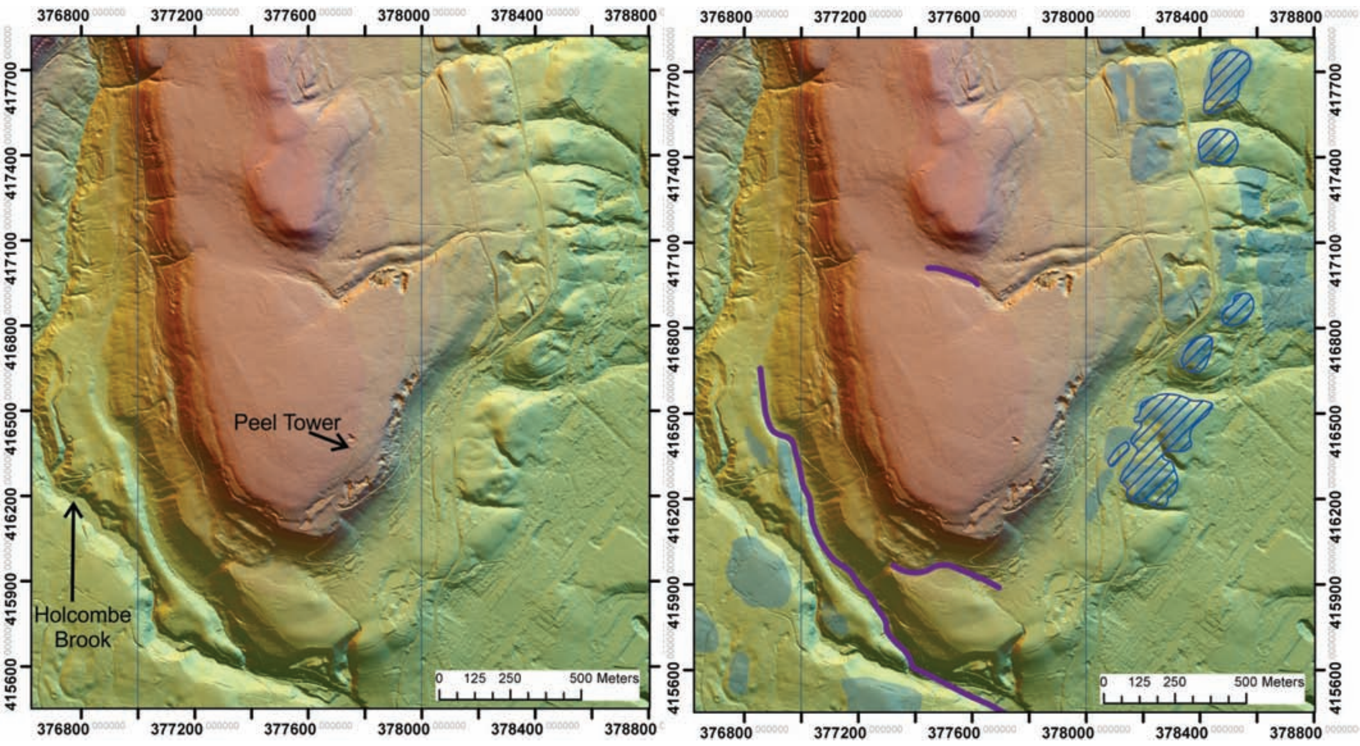

Figure 12: The southern margin of Holcombe Moor, showing location of meltwater channels, glacigenic landforms and sand and gravel deposits. The buildings of Ramsbottom are visible at the bottom right of the image. Grey areas indicate the extent of sand and gravel; crosshatched areas indicate the position of glacial landforms; purple lines indicate the path of meltwater channels. LIDAR DTM resolution is 1m.

westwards, remaining as a lobe in the Manchester Plains to the south, and damming lakes in the southern valleys of the Forest (Jowett 1914, Crofts 2005, Delaney *et al.* 2010). Lake District and Yorkshire ice also retreated northwards, damming more lakes along the northern margin of the Rossendale plateau.

Despite extensive glaciation, distinctive glacial landforms are not widespread across the Rossendale Forest. The most prominent are meltwater erosional landforms, including glacial meltwater channels formed in contact with the ice sheet, and the large gorges (Cliviger, Walsden and Whitworth), thought to have been carved by meltwater discharging from the ice sheets through several phases of glaciation (Figure 2; Crofts, 2005). Slot gorges within the Irwell valley occur at Stacksteads (the Thrutch gorge; Delaney and Sikora 2016; Figure 2) and Lumb, and may have formed due to a combination of subglacial pressurized water flow and early post-glacial erosion linked to the drainage of former ice-dammed lakes. Streamlined bedrock mentioned by early authors is not widespread.

Depositional glacial landforms are relatively subdued. Hummocky terrain has been described previously in a number of valleys within the Forest. On the LIDAR, some of this terrain has a clear structure. For example, at the top of Whitewell Brook, towards the northern margin of the plateau, the hummocky terrain is composed of a combination of round-crested, elongate ridges and flat-topped forms (Figure 10). The round-crested ridges are arranged in parallel groups, in a pattern close to that expected from an ice tongue extending down the valley from the NNE.

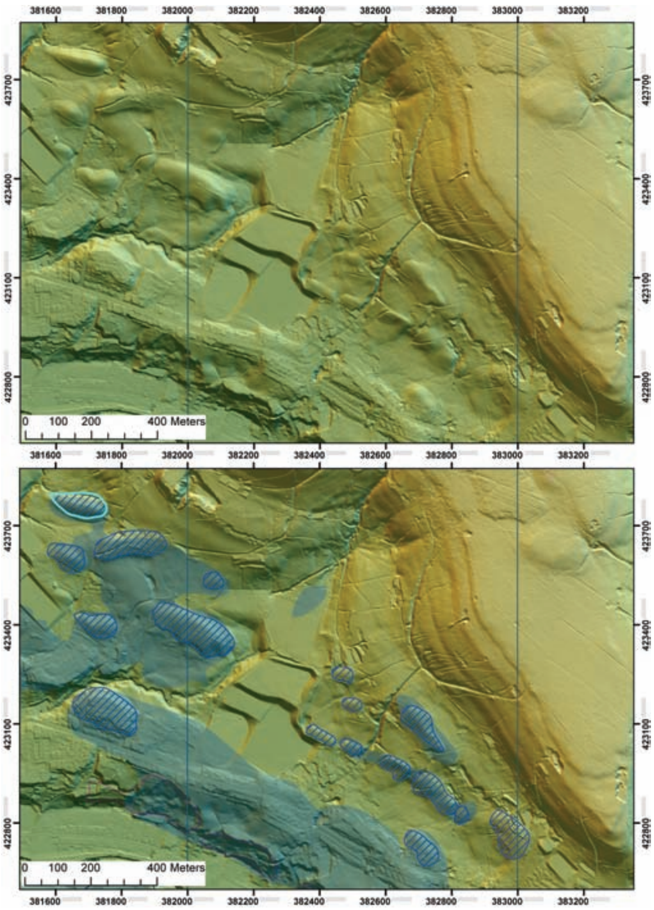

Figure 13: Ridges formed in sand and gravel between Rawtenstall and Newchurch, upper Irwell Valley. The narrow string of ridges on the right side of the image may be an esker. Grey areas indicate the extent of sand and gravel; crosshatched areas indicate the position of glacial landforms. LIDAR DTM resolution is 1m.

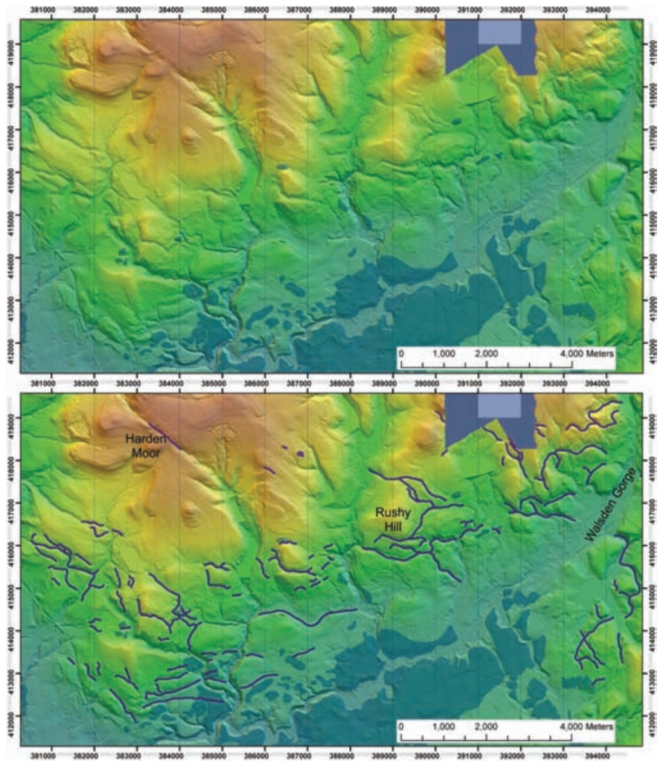

Figure 14: Location of meltwater channels along the southern margin of the Rossendale Plateau between the River Irwell and the River Roch at Walsden Gorge. Channels are shown in purple, areas of sand and gravel in grey-blue. LIDAR DTM resolution is 2m; continuous blue areas at the top of the images lack LIDAR coverage.

Flat-topped forms lie outside these ridges and may be remains of a sandur, or glacial lake sediments. Further west, hummocky topography on the lower ground west of Holcombe Moor has a distinct linear arrangement transverse to ice flow, and is also interpreted as an ice-marginal feature (Figure 11).

Some glacial mounds are composed of sand and gravel, indicating deposition by meltwater. A series of such mounds can be traced on a bench around the southern margin of the Holcombe Moor uplands, and up the Irwell Valley through Ramsbottom (Figure 12). These are the remnants of a kame terrace, deposited along the lateral margin of an ice lobe extending into the Irwell Valley from the Irish Sea Ice to the south, and formed by meltwater running along the margin of the ice sheet.

A series of ridges runs along the northern margin of the Irwell valley between Rawtenstall and Newchurch. They also are underlain by sand and gravel, but have rounded crests and are elongated (Figure 13). These are more likely to be the infill of an ice-walled channel or conduit within the ice sheet – in other words, an esker.

Glacial Meltwater Channels

Glacial meltwater channels have long been recognized in the Rossendale Forest, running along the margins of the plateau, and occasionally within the plateau (Figure 13). Those within the plateau are thought to have formed as spillways from the glacial lakes dammed by ice in the valleys. The channels along the margins probably formed within, or close to, the margins of the ice sheet, by meltwater moving partly under pressure (Crofts 2005). The meltwater channels often are large, but can be distinguished from post-glacial fluvial valleys by morphology, as meltwater channels are flat-bottomed and steep sided, rather than V-shaped. This is best seen in Figure 12, where the modern valley of Holcombe Brook runs parallel to a meltwater channel at the base of Holcombe Moor. Water in meltwater channels that formed

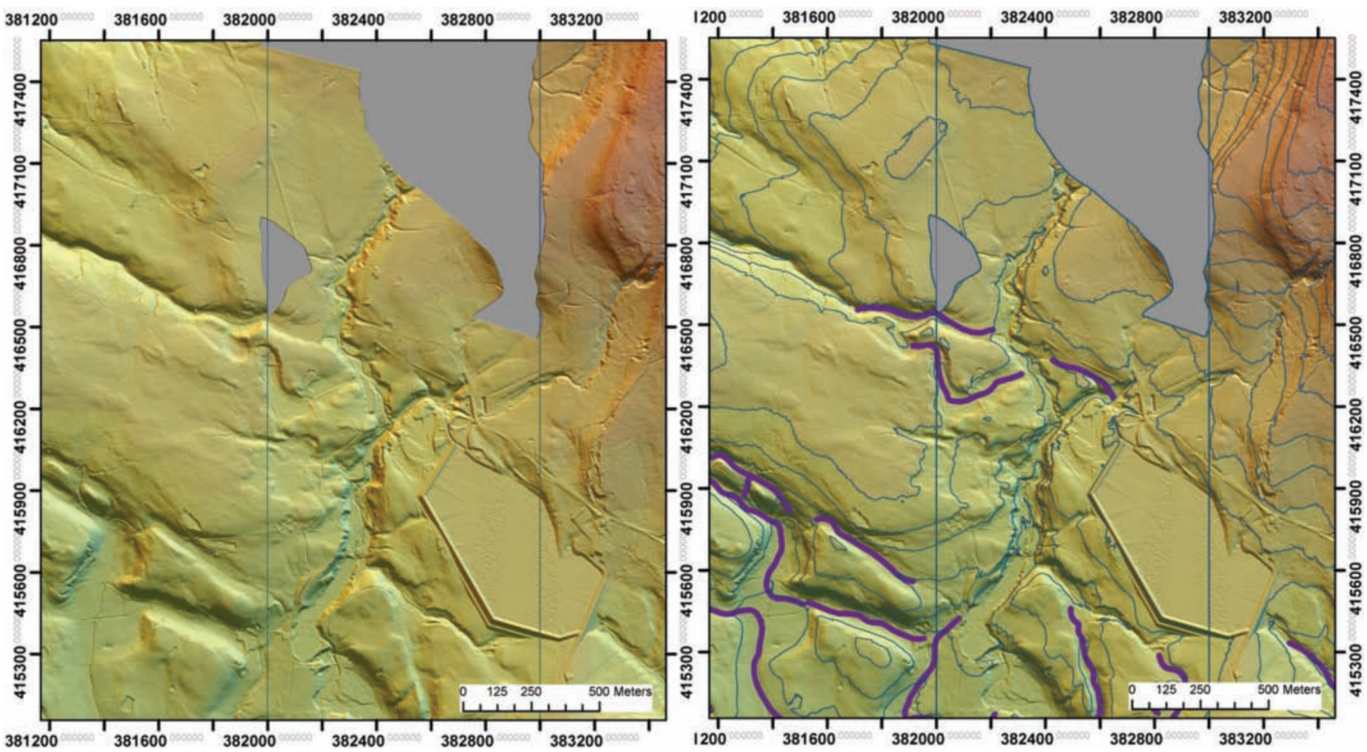

Figure 15: Meltwater channels at Harden Moor, connecting a tributary of the River Irwell to the NE with Cheesden Brook, a tributary of the River Roch, on the SE side of the image. The upper valley of Cheesden Brook has been dammed to form a reservoir. LIDAR DTM resolution is 1m; grey indicates areas without LIDAR coverage.

under the ice sheet was flowing under pressure, and these channels often have a "humpbacked" profile, crossing high points on the land surface, like the meltwater channel south of Harden Moor shown in Figure 15. Channels flowing at, or just beneath, the lateral margins do not have this profile, but are cut parallel to the ice margin, so do not follow the slope of the ground. Along the southern margin of the plateau they are cut across interfluves, disappearing in the valleys between (Figure 13), either because the channel was cut into the ice that infilled the area during their formation or because it was removed by fluvial erosion after glaciation.

These channels are commonly arranged in parallel series along a hillside, the lower channels being cut as the ice surface dropped during ice recession. At Rushy Hill, for example, three parallel channels run eastwards across the southern side of the hill, linked by short, steep chutes (Figure 16A and B). These chutes probably were cut as the higher channels were abandoned, diverting water down the hillside to the new position of the ice margin.

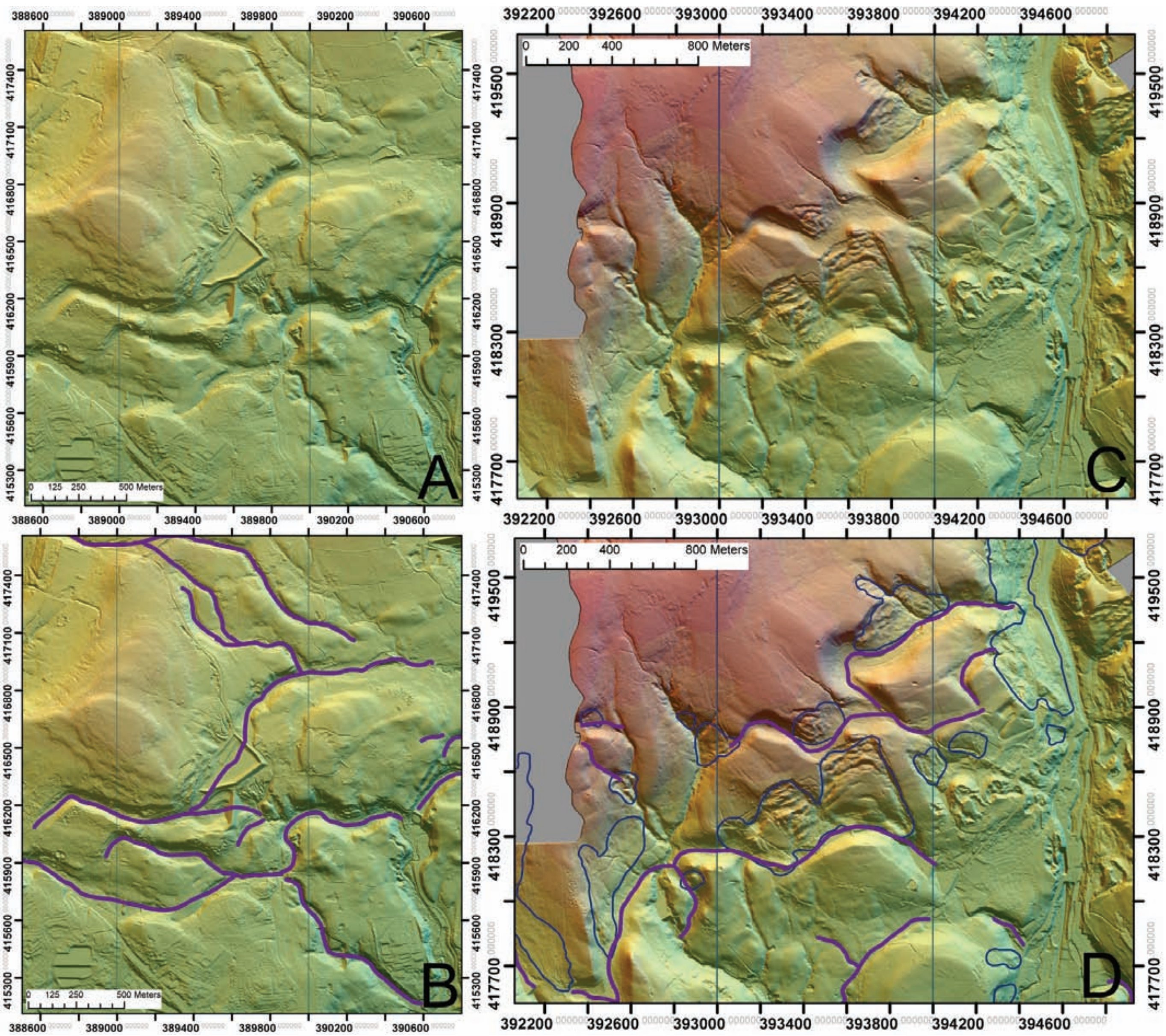

Figure 16A and B: Meltwater channel network on the side of Rushy Hll, north of Rochdale. C and D: Meltwater channel network along the western side of the Walsden Gorge, north of Littleborough. Landslides can be seen along the northern margins of many channels. LIDAR DTM resolution is 1m; grey indicates areas without LIDAR coverage.

The meltwater channels around the mouth of the Walsden Gorge are different in plan form to other groups of channels and form a trellised pattern, which follows the local bedrock fault and joint pattern. The cutting of channels has removed support from the slopes upstream and landslides can be seen at many points along the channels' northern margins (Figure 16C and D).

Conclusions

LIDAR DTMs can provide new information on the landscape, even in an area which has been previously studied in detail. They have enabled identification of new landforms, particularly landslides, in the Rossendale Forest, particularly in forested areas. This is important in the case of landslides, as they may be active and form a potential hazard. For many previously identified landforms, LIDAR allows measurements of topography at a higher resolution than previously possible, and in places not accessible on the ground. In the Rossendale valleys, the morphology and alignment of glacial ridges indicates previously unidentified ice-marginal positions during the recession of the last ice sheet. In addition, the ability to view the same features at a range of different scales makes it easy to see relationships between landforms and with the underlying geological structure.

Not all landforms are easily visible on the DTMs – sediment flows, for example, are difficult to detect – and there are many questions that LIDAR does not answer. In particular, although differences in materials may be inferred from the nature of slope breaks and the surface texture, confident interpretation requires exposures in the landforms. LIDAR clearly does not replace all fieldwork. However, it does allow identification and targeting of field sites without the necessity for on-the-ground surveys.

Accessing LIDAR

The availability of the Environment Agency LIDAR on open access provides an opportunity to view the British landscape in unprecedented detail. For England, the LIDAR DTMs are available on open access and can be downloaded from: http://environment.data.gov.uk/ds/survey. The data comes in ASCII raster file format and requires specialist Geographical Information software to open it, versions of which are available for free download (see https://en.wikipedia.org/wiki/List_of_geographic_information_systems_software. LIDAR jpegs of hillshaded DTMs are also available to view at: https://www.flickr.com/photos/environmentagencyopensurveydata/collections.

The hillshaded DTMs used in this study were produced using a free desktop application, developed for use in archaeology by Kokalj and others (2011), and available to download at: http://iaps.zrc-sazu.si/en/rvt#v. In this application, ASCII files can be converted, mosaicked into larger tiles and hillshaded, but cannot be viewed.

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