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Leeds Geological Association

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Geological Field Trip: The Chevin Landslides, Otley, West Yorkshire.

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Dr Martin Cross, Leeds Geological Association, 31st May 2025

Otley Chevin

Otley Chevin (OS Grid Ref. SE204 442) is a steep escarpment located on the north-facing slopes of a 5km east-west trending ridge which overlooks the historic market town of Otley in mid Wharfedale, West Yorkshire. The Chevin has attracted geological interest, notably for the exposed gritstone edges and fallen Millstone Grit blocks of Upper Carboniferous age at the summit and higher slopes and the large landslide complexes which affect approximately $4km^2$ of the upper and middle north-facing valley side slopes between Otley and Pool Bank. There are many large deep-seated rotational landslides; one of the largest located above Otley is known as Great Dib.

The field trip route traverses several of the Chevin landslide complexes including Great Dib; the route of the fieldtrip together with 12 No stop-off locations are shown on Fig 5. Brief notes on the features that can be observed at each stop-off location are provided towards the end of this geological field trip guide. The landslide complexes are discussed in relation the geology, geomorphology and hydrogeology. The factors responsible for their development are discussed, particularly, the deglacial unloading and paraglacial stress-release processes affecting the less competent mudstone strata forming the lower valley slopes together with the reservoir principle of mass movement.

The north-facing scarp slopes of the Chevin which have been affected by postglacial landsliding are dominated by the geological structure of jointed sandstone strata capping the slope crest (the reservoir), underlain by weaker and less permeable mudstones and shales where the deep-seated landslides develop. The current state of stability of the deep-seated rotational landslides which reside on the middle and upper slopes and the mudslide/mudflow complexes located on the lower slopes of the Chevin under the present climate regime is also briefly discussed. For further information on the Chevin landslides the reader should refer to the Leeds Geological Association paper by Cross 2024.

Study Area Location

Otley Chevin is a steep escarpment which faces north over the historic market town of Otley located in mid Wharfedale, West Yorkshire. The Chevin escarpment is approximately 5km in length and approximately 250m in height. Landslides affect the Chevin escarpment from Old Pool Bank to the east (OS Grid Ref. SE234 443) and Gill Brow to the west of Otley near Menston (OS Grid Ref. SE181 444). The highest point of the Chevin, Surprise View, reaches 282m (Grid Ref. SE 2043 4419). According to the 1:50,000 Solid and Drift Geological map of Bradford, Sheet 69 (BGS 2000); the north facing escarpment of the Chevin comprises landslides extending over an area of approximately $4.5km^2$. Over twenty one large deep-seated rotational landslide complexes, together with associated mudslides and mudflows extend downslope to 0.75-1.0km at their maximum extent. The relevant topographical maps of the study area are Ordnance Survey 1:50,000 Landranger Sheet 104 Leeds and Bradford and 1: 25,000 Explorer Sheet 287, Lower Wharfedale and Washburn Valley.

Historical Background

The name Chevin derives from the Brythonic *cefyn*, *cefn* or *cefu* meaning a ridge, or ridge of high land. The area extending from Otley Chevin to Caley Crags is a designated Local Geological Site (LGS). The West Yorkshire Geological Trust together with Leeds City Council and Friends of Chevin Forest have created 'The Chevin Park Geology Trail'. The 3km geological trial includes several carved marker stones which provide information about the geological features of the Chevin. There is also an audio for the geological trail available on 'The Friends of Chevin Forest' website, www.chevinforest.co.uk.

One of the earliest mentions of Otley Chevin was included in the prophecies of Old Mother Shipton (c. 1488-1561), where she predicted a catastrophic landslide would take place on the Chevin, with landslide debris covering parts of the town of Otley (Easton 1998; Araujo 2008). The Chevin was designated as one of the chain of beacons established as a nationwide communication system around the end of the eighteenth century when invasion by the French was threatened. A brief landscape history of Otley Chevin is provided by Laurence (2016).

Previous investigations of Otley Chevin have been concerned with the stability of the Chevin escarpment in relation to the engineering design of the A660 Leeds Road and Otley Bypass. Several Ground investigation reports have been completed by West Yorkshire County Council and the West Yorkshire Highways Laboratory between 1930 and 1967; these mainly relate to specific areas of the A660 between Otley and Pool Bank which have been affected by landsliding (Robinson 1967).

Geology

Geologically, the Chevin lies on the northern edge of the Yorkshire Coalfield. The geology of the area is shown on British Geological Survey 1: 50,000 Series, sheet 69, Bradford, solid and drift edition (BGS 2000). A brief explanation of the geology of the Bradford district is provided by Waters (1999). The geology of the northwest Leeds area is dominated by the solid geology of the Carboniferous Coal Measures and Lower Coal Measures, with the underlying Millstone Grit Group of the Namurian an important lithological unit within the site area (Waters *et al.* 1996).

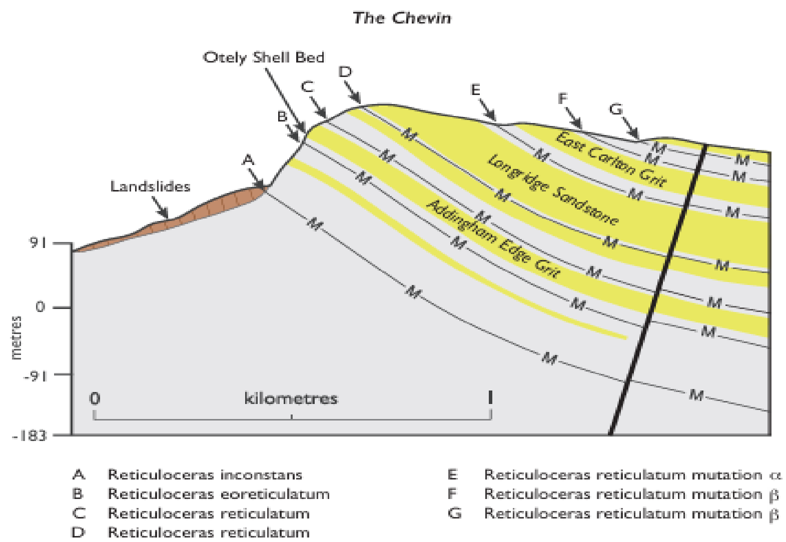

Fig. 1. Geological section of the Chevin showing main sandstone formations and marine bands.

The Millstone Grit Group comprises approximately 1,800m of interbedded mudstones, siltstones and sandstones (see Fig. 1). During Namurian times (c. 3.5 Ma) the rocks that crop out in the study area are interpreted as having been laid down in a deltaic environment, which eventually resulted in a sequence of generally coarse sandstones and fine-grained mudstones. The coals and seatearths towards the top of the sequence resulted from the decay of the remains of forests that covered swamp areas of the delta system. Occasionally, marine incursions allowed deposition of muds including fossiliferous marine bands, which provide important isochronous marker horizons such as the Otley Shell Bed.

Natural superficial deposits are present on the Chevin escarpment slopes, which comprise glacial, periglacial and postglacial deposits. Peat is present on the upper part of Otley Chevin. Quaternary deposits, including Glacial Till and Head are present on the mid and lower valley-side slopes. Fluvioglacial sand and gravel deposits are present in the flood plain of the River Wharfe; river terrace deposits and colluvial deposits are also present on the basal slopes of the Wharfe valley (Dean & Lake 1991; Waters 1999).

River Terrace Deposits, which represent fluvial depositional features isolated on the valley sides by entrenchment of the River Wharfe, are prominent on the north side of the river between Otley and Leathley. Deposits of Alluvium are widespread in the base of the Wharfe valley and typically comprise coarse granular gravel at the base with clays and silts present in the upper surface layers. The sand and gravel has been extensively worked historically, leaving several large, water-infilled sand and gravel pits and municipal landfills.

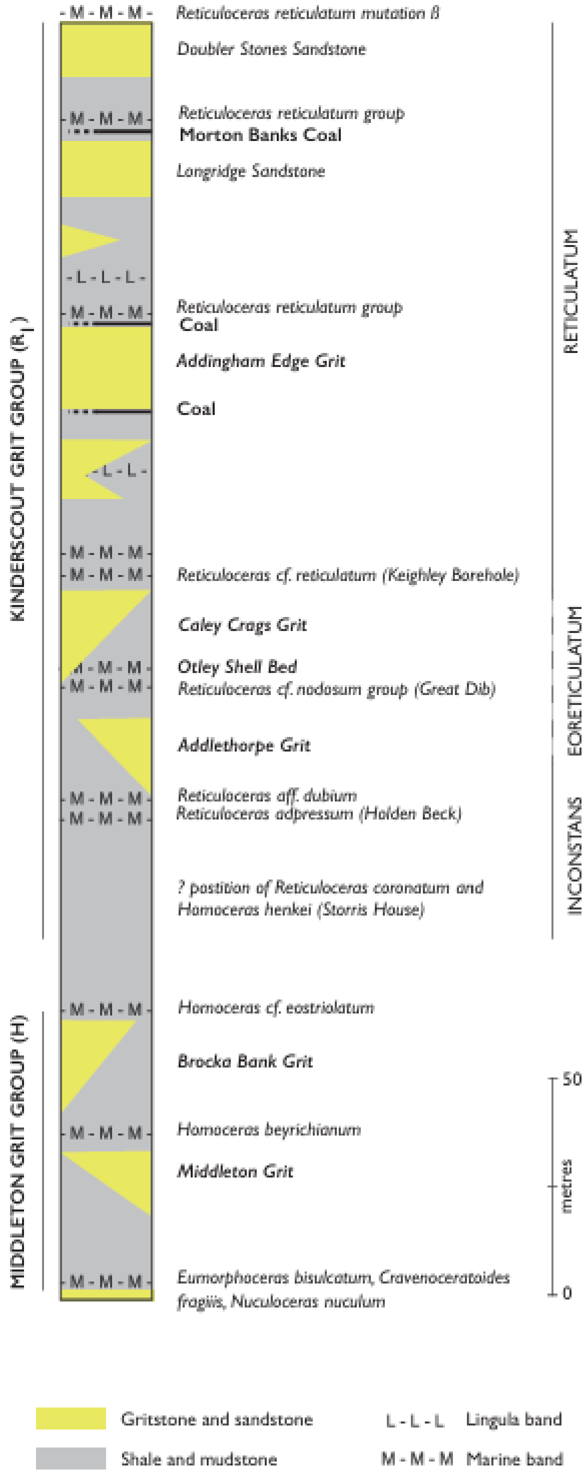

Fig. 2 Geological sequence of the sandstone and mudstone formations of the Chevin

The rocks forming the base and mid slopes of the Chevin comprise undifferentiated mudstones and shales, with some thinly bedded siltstones and sandstones, of Namurian (Kinderscoutian R_1) age (see Fig. 2). These strata are capped by strata of the Namurian Millstone Grit Group, the Addingham Edge Grit (formerly known as the Caley Crags Grit), a coarse-grained sandstone giving rise to a conspicuous ‘edge’ from East Chevin Quarry (Grid Ref SE 2121 4448) to West Chevin Road. The Addingham Edge Grit consists of massive cross-bedded coarse grit, 25 to 30m in thickness, with a mudstone parting near the top. Most of the grits are felspathic and contain pebbles of quartz and felspar.

The main bed of grit forms conspicuous rock faces along the top of the Chevin and is particularly well exposed at Caley Crags (SE2274 4436) and Great Dib landslide (SE 1998 4449), where it overlies the Otley Shell Bed. The Addingham Edge Grit is also clearly exposed in the disused East Chevin Quarry (SE 2121 4448), where it was once quarried and crushed for sand and gravel. About 25m of massive, coarse grit is exposed, with flaggy micaceous sandstone at the base, and a thin shale horizon.

The Addingham Edge Grit is overlain in ascending order by the Long Ridge Sandstone and Doubler Stones Sandstone (formerly known as the Bramhope Grit), each separated by undifferentiated mudstone. The top of the Chevin is capped by the High Moor Sandstone (Bramhope Grit) or Upper Kinderscout Grit and the Doubler Stones Sandstone (Bramhope Grit) or Lower Kinderscout Grit. The Doubler Stones Sandstone attains its maximum thickness at Beacon Hill (SE 199 442), just north of the former Yorkgate Quarry where it was quarried and crushed for sand. These units show a rapid variation in lithology, being dominated by gravel conglomerates and coarse pebbly sandstones, both of which have minor amounts of sand occurring interstitially. Clasts in these units are dominantly of white quartz, with <5% of other material. The coarser beds pass laterally into finer grained sandstones, and impressions of plant stems are common on bedding planes throughout the unit. Thin coals have been identified in beds close above the sandstone units. For example, the Morton Banks Coal seam overlies the Doubler Stones Sandstone (SE 1990 4412).

The dip of these formations slope to the south. The crest of the Chevin, which overlooks Airedale and the glacially eroded Guiseley Gap to the south, comprises the East Carlton Grit through to the Guiseley Grit, separated by undifferentiated mudstone (see Fig. 1). The dip of the units along the Chevin is consistent, being about 15-18° to the south. The main sandstone units forming the Otley Chevin Escarpment are listed in Table 1.

Table 1. Sandstones of the Otley Chevin Escarpment

Sandstone (Former name)	Thickness (m)	Lithology
High Moor Sandstone (Bramhope Grit) or Upper Kinderscout Grit	0-21	Sandstone, very fine-grained to coarse-grained, upwards-fining, cross-bedded or massive, locally very micaceous, thinly bedded towards the top; sharp top typically marked by a ganister.
Doubler Stones Sandstone (Bramhope Grit) or Lower Kinderscout Grit	8-60	Sandstone, fine-grained to granular, micaceous, cross-bedded and laminated.
Long Ridge Sandstone (Bramhope Grit) or Lower Kinderscout Grit	5-58	Sandstone, fine to very coarse-grained, upwards-fining, massive and cross-bedded; sharp erosive base.
Addingham Edge Grit (Caley Crag Grit)	15-55	Feldspathic sandstone, medium to very coarse-grained, in parts pebbly, thickly cross-bedded.
Brocka Bank Grit	0-55	Sandstone, coarse-grained and massive or cross-bedded; lower leaf is fine-grained and massive.
Middleton Grit	0-30	Quartz-feldspathic sandstone, medium to coarse-grained, locally pebbly and cross-bedded.

The Namurian Millstone Grit Group lithologies described in Table 1 are of Marsdenian age; with an approximate age of 318 Ma. This chronostratigraphical sequence was originally established by Edwards *et al*. (1950) and later by Stephens *et al*. (1953). Borehole data, well sections and field correlations have been used to develop a summary of the key geological units in the area (Dean & Lake 1991) (see Fig. 2). To conform to current usage, the Millstone Grit Group has been mapped as a lithostratigraphical unit that includes all strata of Namurian age above the Upper Bowland Shales Formation, which is dominantly argillaceous and therefore, part of the Bowland Shales Group. Important modifications of the Kinderscoutian (R_1) succession have arisen from British Geological Survey boreholes on Rombalds Moor (Aitkenhead & Riley 1996). The exposed Millstone

Grit Group Namurian strata comprises approximately 150m of alternating mudstone and sandstone (‘rock’ or ‘grit’) beds on the uppermost part of the northern escarpment of the Chevin (see Fig. 3).

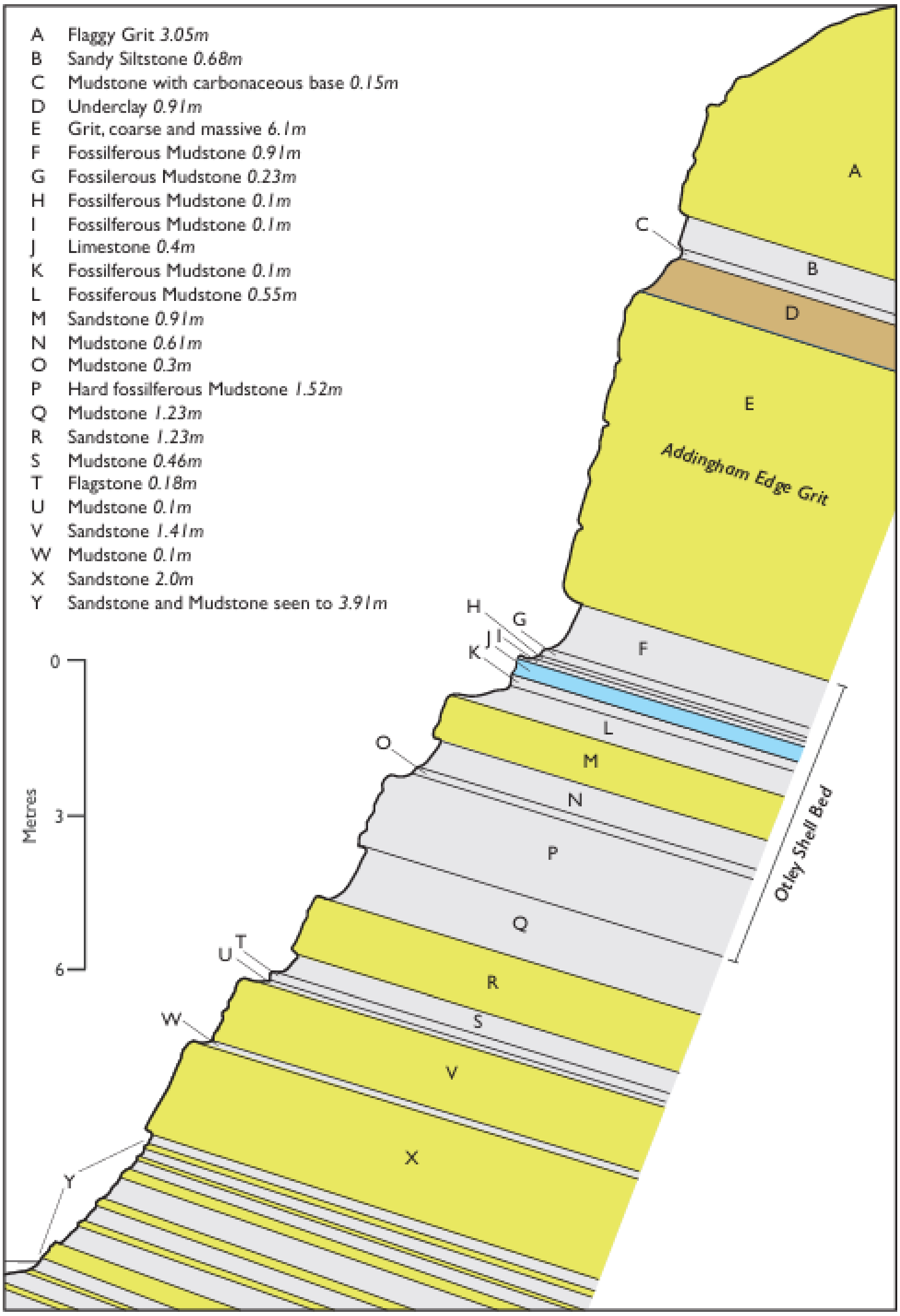

Fig. 3. Geological cross-section through Great Dib landslide back scarp.

The rocks forming the lower slopes of the Chevin consist of mudstone and thinly bedded shales containing thin discontinuous sandstone layers and the Otley Shell Bed (see Fig. 3). The mudstone units of the Namurian are medium to dark grey and locally contain nodular sideritic ironstone. The mudstone units are not well exposed as they have been eroded and commonly form ‘slacks’ between outstanding sandstone or grit units. Dark grey, micaceous shales also occur, and thin sandstone bands among the shales are typical.

Two sandstone bands lie within 100m of the base of the Addingham Edge Grit, each ranging up to 15m in thickness. Another sandstone unit can be traced parallel to the slope for 150m westwards from Pig Farm (SE 200 445) where several small exposures of medium grained micaceous sandstone occur.

True marine shales are confined to the marine bands, which commonly contain fossils and concretions of thin, impure limestones. These shales are typically dark grey or black and oily, and are usually calcareous, weathering to a yellow crumbling decalcified material termed 'gingerbread rock' (Stephens et al. 1953). One such unit is exposed just south of Chevin Hall (SE 191 442) and palaeontological evidence assigns these to *Reticuloceras eoreticulatum* zone (R_{1b}) (Dean et al. 2011).

The Otley Shell Bed is an important marine band and consists of a few metres of highly fossiliferous mudstone with sandstone beds and a limestone rib. A total of 16m of the Otley Shell Beds are located below the exposed Addingham Edge Grit within the Great Dib landslide (SE 200 443) (see Fig. 3). The Otley Shell Beds contain fossils of lamellibranchs and brachiopods with some cephalopods, trilobites and sponges.

Geological Structure of Wharfedale

During the Carboniferous, the Pennine Hills were part of a series of structurally controlled basins that strongly influenced sedimentation in the British Isles north of the Variscan Front. At the end of the Carboniferous period, a major collision between two tectonic plates culminated in the uplift of a high mountain range across southern Europe in a series of events called the Variscan Orogeny. From late Westphalian to early Permian times, during the Variscan Orogeny, basin inversion took place and the Carboniferous rocks of the Pennine region were uplifted.

Considerable faulting is thought to have occurred with some major faults reflecting deep-seated structures. Northern England was uplifted into the Pennine anticline, which trended north-south from the Midlands to southern Scotland. The Middle and Lower Wharfedale area was folded into an anticline which runs east-west along the Wharfe valley (Wharfedale).

Otley Chevin is located on the south side of the fold so that the rocks dip southwards towards Airedale. Reactivation of pre-existing faults, with the possible addition of minor fracturing and gentle folding of the Carboniferous rocks is likely to have occurred because of post-Variscan movements.

The regional dip of the Namurian Millstone Grit Series is gentle and mostly to the south-south-east. The strata are relatively undisturbed, with several major fractures and common instances of minor faulting (Dean & Lake 1991). The pattern of dominant faulting in the northern areas of the Leeds district is dominated by fractures which trend approximately NE-SE. Dean & Lake (1991), noted that subordinate sets of conjugate faults trending N-S and NW-SE link the major faults. Certain major faults are prominent, the most important of these to the Chevin being the Wharfe Valley Fault, which extends from Addingham Moor and enters Wharfedale south of Nesfield, where it has been traced beneath the alluvial deposits present within the valley floor to Otley.

Wharfedale Superficial Geology

Wharfedale Glacial Deposits

The Last Glacial stage (Devensian) was at a maximum about 17,000 B.P. and ice covered the high ground in the area of Otley Chevin. At the glacial maximum the Pennine Hills at the head of Wharfedale were dominated by a large ice cap which covered Blea Moor, Ribble Head and Widdale Fell (Stone et al. 2010). The outer fringe of this ice cap also covered Dodd Fell, Penyghent and Fountains Fell, and the eastern edge fed a glacier which moved south-eastwards down Wharfedale (Raistrick 1931, 1933). This glacier had a profound effect on the topography and geomorphology of Wharfedale and left widespread deposits of Glacial Till and Glacial Sands and Gravels within the valley (Waltham 2007).

As temperatures increased, ice melted, and ice sheets became thinner. The thickest ice was confined to valley glaciers in the final stages of the Devensian glacial period. It would have been possible to stand on the Chevin and look over glacial valleys, with ice moving down Wharfedale, Washburn Dale and Airedale and glacial meltwater streams filling the valley floors with glacial sands and gravels. By about 12,000 B.P., when the ice had melted completely, it left behind deposits of Glacial Till both within and on the valley sides of Wharfedale. During the Late Glacial and Post-Glacial periods, the Glacial Till present on the valley sides in places was either solifluted, washed away or modified by colluvial processes to form Head Deposits. The Head Deposits are up to 2.0m thick on the valley slopes of the Chevin.

The Glacial Till deposits on the valley sides of the Chevin are very sandy and rich in gritstone debris that is difficult to differentiate from the weathered residual soils of the Millstone Grit Group strata. The Glacial Till typically weathers at the surface to a brown or yellow/brown, decalcified clay, and maximum thicknesses of up to 50m have been reported in the valley floor (Gross 1979). However, a thickness of 10 to 15m is probably more usual in the valley floor, and the deposit thins to a shallow depth higher up the slopes of the Chevin, not extending much above the 120m contour (Burgess 1976).

Isolated pockets of Glacial Till and erratic clasts do occur on the higher slopes, but are rarely more than a few centimetres deep, indicating that more extensive glacial deposits existed over the slopes of the Chevin but have been removed by erosional slope transportational processes during paraglacial relaxation (i.e., the period of readjustment from glacial to non-glacial conditions (Benn and Evans, 1998).

The crest of the Chevin was overridden by ice; relic patches of Glacial Till have been recorded on the Doubler Stones Sandstone (Hemingway 1957). Glacial striations were recorded in the same area, although these are no longer visible (Stephens *et al.* 1953) and agreed with the general eastward down-valley direction of the glacier movement proposed by Raistrick (1934).

Raistrick (1927) mapped a series of terminal moraines within Wharfedale; he recognised six halt-stages in the Wharfedale glacier at Pool (1), Burley-in-Wharfedale (2), Middleton (3), Drebley (4), Kilnsey (5) and Skirfare Bridge (6). The halt-stages of the active ice fronts provide evidence of a periodicity in the climatic conditions towards the end of the Devensian; the terminal moraines representing periods when conditions were coldest, and the interval between moraines representing warmer periods when melting ice was rapid. The terminal moraines formed dams to produce a series of elongated proglacial lakes in Wharfedale upstream of the terminal moraine. The lakes have now been infilled with laminated clays and silts which overlie Fluvioglacial Sands and Gravels to form flat, frequently flooded, sections of the valley floor. One of the proglacial lakes was located below the Chevin between Burley-in-Wharfedale and Pool. Raistrick (1926) suggested that the moraine dammed lakes persisted well into prehistoric times based on archaeological evidence.

Several lateral moraines run parallel to the Wharfedale valley sides at various levels; good examples can be seen at Farnley, Leathley and Stainburn on the north side of Wharfedale. These are often associated with large glacial overflow channels which either trench the valley sides or cut across spurs and were eroded by melt water flowing along the edge of the Wharfedale glacier. With the retreat of the ice, these channels were abandoned and now remain as pronounced dry valleys on the north side of the valley.

Along the southern side of Wharfedale, few such channels can be recognised, because they are not easily distinguished from, and may even follow the outcrop terraces of Millstone Grit horizons. However, Raistrick (1931) postulated that at one time such a channel was cut at about 225m AOD across the eastern end of the Chevin by water flowing from the SE/NW trending Guiseley Gap and along the north-facing flank of the Chevin; however, this was only a small channel and was soon superseded. At a later stage of glacial retreat, drainage reverted to the main Wharfedale valley, and the water passed along the ice edge on the northern face of the Chevin from the Guiseley Gap (Stephens *et al.* 1953). This will have resulted in significant over-deepening of the valley floor and over-steepening of the basal slopes of the south side of the valley below the Chevin escarpment. Any deposits associated with erosion features which may have existed along the north facing slopes of the Chevin cannot now be distinguished because of the significant erosion which took place on the south side of the valley slopes below the Chevin and also because they have been masked by deep-seated landslide deposits resulting from subsequent postglacial mass movement processes.

Wharfedale Periglacial Deposits

Periglacial climate processes controlled the geomorphological landscape adjacent to ice sheets and glaciers of Wharfedale. This climate resulted in a set of geological and geomorphological processes of which freeze-thaw was the most important. Mass transportation of soliflucted materials and wind action dominated the barren periglacial areas, where the ground was often perennially frozen (permafrost), and lead to the development of characteristic deposits such as Head and in some locations more deep-seated mass movement features.

Head Deposits consisting of rubbly solifluction deposits of local provenance occur on the lower slopes of the Chevin and extend to the valley floor. However, where the parent material involved in solifluction is sufficiently clayey, particularly on the lower mudstone and shale slopes, basal and internal shears can develop in the soliflucted material.

The apparent gradation between Head Deposits and River Terrace Deposits in Wharfedale was noted by Stephens *et al.* (1953), who attributed the deposits to the process of Late Glacial solifluction. Evidence of periglacial activity on the crest of the Chevin is provided where the action of permafrost has disrupted bedding in the Doubler Stones Sandstone and Addingham Edge Grit leading to the development of involuted and cryoturbated structures (Hemingway 1957). The development of such structures in the locality was favoured by the abundance of percolating meltwater available during the summer and the emergence of the area as a nunatak as the ice sheets retreated around it. The top of the Chevin was therefore, subject to frost action from an early stage, whilst much of the surrounding area was still under ice.

Geomorphology of Wharfedale

The present geomorphology of Mid Wharfedale is dominated geologically by the Millstone Grit Group, a thick succession of interbedded sandstones, siltstones and mudstones of Namurian age, the glacial and periglacial processes active within Wharfedale during the Devensian and the subsequent postglacial fluvial processes of the River Wharfe. As described, the Chevin escarpment is capped by sandstones and gritstones underlain by less competent interbedded mudstones and shales with thin sandstones. This bedrock series was partially covered by a layer of Glacial Till which extended over the lower part of the scarp slope up to approximately the 120m contour.

Large deep-seated complex landslides are common features in Wharfedale, occurring mainly on the northern facing valley side slopes. In some areas the whole of the mid and lower scarp slopes of the Chevin are affected by landslide, mudslide and mudflow deposits. Waters et al. (1996) noted that landslides have developed within Glacial Till and other superficial deposits on natural slopes at inclinations of 11-18°; whereas in the case of deep-seated rotational landslides involving rock, the natural slopes are generally greater than 20°.

The large rotational landslides on the Chevin are located on the upper parts of the valley side of the Chevin and have not been triggered by fluvial erosion but have been triggered by paraglacial processes. Large-scale rotational landsliding resulting from the paraglacial debutressing processes which took place during Late Glacial and Post-Glacial times would have been an important phenomenon affecting Pennine hillslopes including Otley Chevin (Shakesby & Matthews 1996; Ballantyne 2002).

The geomorphology of the Chevin has been greatly influenced during the Pleistocene by both ice sheets and valley glaciers and glacial processes. Wharfedale was affected by at least three glaciations, although evidence for the earlier two phases has been obliterated by the final Devensian phase (Waters 1999). There is growing evidence from the global sea-level record that the Last Glacial Maximum (LGM) occurred relatively early in the Late Devensian, from about 27ka BP and lasting about five thousand years (Lambeck & Purcell 2001).

Pennine valley glaciers would have occupied areas of low ground, such as the Aire, Wharfe, Nidd and Swale valleys, except during the maximum advance of the ice when they would have also extended over upland areas, resulting in the deposition of a range of glacial deposits. The maximum advance of the Devensian ice sheet in the study area is shown on the British Geological Survey 1: 50,000 Sheet 69, Bradford, to have extended south of Bradford (Waters 1999).

The most significant effects of the Devensian glaciation locally are the over-deepening of the Wharfe valley by over 40m, the deposition of Glacial Till, terminal and lateral moraines, glacial drainage channels and the formation, infilling and breaching of proglacial lakes, resulting in extensive lake flats. The final retreat of the glaciers left over-steepened valley sides in an unstable or metastable state with massive sandstone and gritstone strata overlying weak mudstones and shales.

The role of deglacial unloading and resulting paraglacial stress-release in conditioning or triggering slope failures in the weak mudstones and shale slopes was an important factor affecting Pennine valleys (Johnson & Walthall 1979; Donnelley 2008; Dowell & Hutchinson 2010; Cross 2011). Donnelly (2008) suggested that deep-seated landslide movements on Pennine slopes were possibly generated under conditions of periglacial erosion and weathering, during glacier retreat, deglaciation and associated processes of gravitational stress-relief of valley sides. This is most likely to have occurred during the Late Glacial and early Postglacial. This may have initiated the lateral spreading of upland moorland plateaux, subsequently resulting in fissuring, fault reactivation, tilting and subsidence. Research has shown that rock-slope failures tend to be concentrated on the middle and lower valley-side slopes within the area occupied by ice during the Last Glacial Maximum, and that their locations coincide with zones of inferred high glacial loading stress, consistent with interpretation of both bedrock disruption and large-scale rock-slope failures as paraglacial phenomena induced by stress-release following deglaciation (Ballantyne 2002; Ballantyne & Stone 2013; Ballantyne et al. 2014a; Cossart *et al.* 2008, 2017; Wilson 2009; McColl 2012).

The over-steepened southern side of the Wharfe Valley was therefore, particularly vulnerable to the development of large rotational and complex landslides on the middle valley slopes where massive sandstone strata overlay weaker mudstones and shales. Some research has shown that many landslides did not take place immediately following deglaciation but took place 1000-3000 years after ice-sheet deglaciation (Cruden & Hu 1993; Soldati et al. 2004; Dowell & Hutchinson 2010).

The long delay probably reflects progressive rock-mass weakening initiated by deglacial stress-release and associated tensile rock mass damage. The Chevin landslides affect all bedrock strata up to, and including, the Addingham Edge Grit and were probably first initiated 12-15,000 years ago in the Late Glacial with landsliding continuing to take place during the Loch Lomond Stadial (nominally 11-10 ^{14}C ka BP) and Early Postglacial times during the late Boreal to mid-Atlantic (nominally 7.7 to 5.5 ^{14}C ka BP), (Dowell & Hutchinson 2010). Much of the lower slopes of the Chevin are covered by extensive mudslide and mudflow deposits; these are likely to be younger and took place throughout the postglacial period.

Wharfedale Landslide Morphology

Large deep-seated complex landslides are abundant throughout Wharfedale, particularly on the steep over-steepened scarp slopes which form the north facing side of the valley. They are especially well developed along the 5km face of Otley Chevin between Otley and Pool Bank. An overall geomorphological appraisal of the area reveals that the landslides can be generally split into two types and in two areas parallel to the slope.

Firstly, above the 120m contour, large rotational deep-seated landslides are located on the steeper slopes, affecting solid bedrock; these also include associated smaller secondary rotational slides and mudslides on their surfaces.

Secondly, downslope of these large rotational deep-seated landslides, secondary instability has led to the development of mudslides and mudflows which emerge from the debris apron toes of the higher deep-seated landslides to cover much of the lower slopes. These processes have been exacerbated by the emergence of redundant springs from below the debris apron toe of the deep-seated landslides. The deep-seated rotational landsliding was probably induced to a large extent by glacial over-steepening and debutressing of the north-facing slopes of the Wharfe valley, and movement probably commenced sometime after the Wharfedale glacial ice retreated after the Late Devensian glacial maximum and continued during early postglacial times.

Along the upper slopes of the Chevin several large back scarps have developed at the rear part of large deep-seated rotational landslides e.g., Chevin Hall, Great Dib and Danefield Wood landslides. Below the back scarps the landslide morphology comprises a series of large, rotated blocks relating to a series of retrogressive rotational failures. Some of the landslides on the upper parts of the Chevin escarpment comprise a series of benches and terraces that run parallel to the contour lines. This morphology suggests multiple, successive rotational and translational landsliding. The deep-seated landslides therefore show evidence of various types of sliding mechanisms and can therefore be classed as ‘complex landslides’ (Varnes 1978). In addition, many of the retrogressive and successive landslides have been denuded by shallow slumping, mudsliding and mudflow mass movement processes (Cruden & Varnes 1996).

Below the rotated blocks which occur in the mid slope areas of the Chevin escarpment (i.e., elevations between 165-105m) are large spreads of hummocky landslide debris material. The morphology of the landslide debris area comprises of shallow slumps, shallow ridges and highly denuded mounds. A series of drainage channels and gullies have developed below springs and along seepage areas. In some areas within the landslide debris accumulations, poorly drained depressions have formed, sometimes containing small ponds.

Much of these landslide debris accumulations have been reworked by successive mudslides and in wetter places as discrete mudflows. The mudslides and mudflows extend over most of the lower slopes of the Chevin escarpment and are particularly well developed between slope elevations of 105m and 60m. The morphology of the mudslides comprises of a series of shallow spreads of material leaving discrete toe ridges and lobate features. The mudflows tend to be confined to more linear tracts within poorly drained shallow downslope drainage channels and gullies. The mudslides and mudflows have developed from the lower sections of the large deep-seated landslide debris aprons and are particularly well developed in the lower parts or the toe area of these landslides.

The mudslides and mudflows comprise of reworked landslide debris, Glacial Till and solifluction Head Deposits. Some of the shallow lobate mudslides and mudflows on the lower valley side slopes comprise 1-2m depth of soliflucted Head Deposits below the ground surface.

Although the general pattern of landsliding is as described, there are exceptions where discrete areas of mudsliding, and mudflows occur on the upper and mid slopes and smaller shallow rotational failures also are present in some areas located on the lower slopes underlain by mudstones and shales. Burgess (1976) postulated that there may have been the potential for large deep-seated slip surfaces to develop and extend to the lower part of the Wharfedale valley. However, it should be noted that no deep-seated slip planes were identified in the main programme of site investigations for the A660 Otley Bypass in November 1972 (West Yorkshire Metropolitan Council Highway Engineering Technical Services (HETS) Laboratory 1972, Culshaw & Duncan 1975).

Brief Notes on the Factors contributing to the development of mass movement features on the Chevin

For a more detailed explanation of the factors contributing to the development of mass movement features on the Chevin the reader should refer to the Leeds Geological Association paper by Cross 2024. Some brief notes on the main factors contributing to the development pf mass movement processes are presented below.

Rockfalls: The sandstone and gritstone strata show three dominant joint sets, two vertical and one horizontal. The prevalent mode of failure in the sandstone and gritstone exposed edges is toppling accompanied by some sliding. The main cause of toppling is the cambering of the sandstone and gritstone edges caused by plastic deformation of the underlying mudstone and shale strata.

Paraglacial – Over-deepening: The most significant effect of the Devensian glaciation was the over-deepening of the Wharfe valley by 40m below the north facing Chevin escarpment. The final retreat of the glaciers left over-steepened valley sides in an unstable or metastable state with massive sandstone and gritstone strata overlying weak mudstones and shales.

Paraglacial – Unloading and stress-release: The role of deglacial unloading and resulting paraglacial stress-release in conditioning or triggering slope failure in the weak mudstone and shale slopes was an important factor affecting the north facing Chevin escarpment.

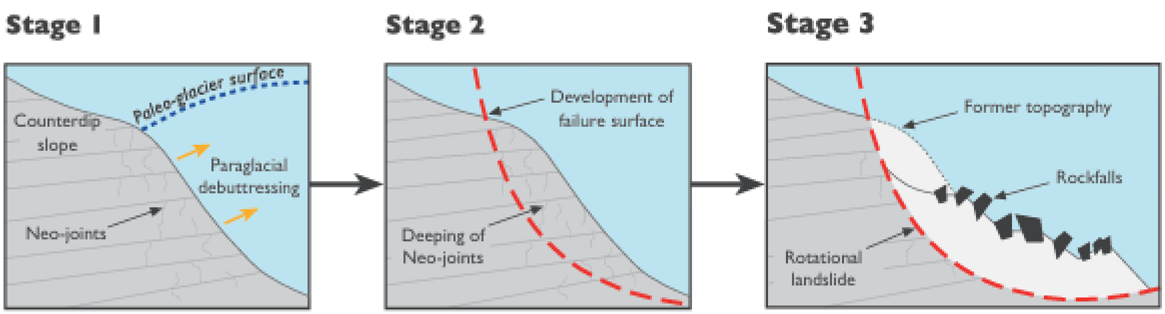

Fig. 4 Development of rockfalls and rotational landslides as a result of paraglacial debutressing and over-deepening at the base of the Chevin escarpment with a counter dip geological structure.

Fig. 4 shows the stages resulting from paraglacial debutressing on deglaciation of Wharfedale, the formation of neo-joints as a result of stress release processes in the rocks forming the mid and lower slopes of the Chevin and the development of rotational landslides in the weakened mudstones forming the mid and lower slopes of the Chevin.

Saturated Unconfined Compressive Strength (UCS) of rocks: Laboratory UCS and point load testing on sandstone, gritstone, mudstone and shale demonstrate a significant reduction in strength when saturated (Dyke & Dobereiner 1991, Vasarhelyi 2003). The strength of mudstone and shale across the bedding planes is relatively high but parallel to the bedding planes the strength is almost zero. The residual strength of mudstone and shale in the saturated condition is significantly lower than their unsaturated peak strength. The hillslope angles within the landslide/mudslide disturbed areas are near to their angle of repose (Cross 1987, 2010, 2011, 2019).

Combination of factors contributing to mass movement: The main factors contributing to instability of the hillslopes are geological structure, paraglacial over-steepening and stress-release processes, lithological variations of the strata augmented by the availability of excess water. Although the overall dip of strata forming Otley Chevin is 15°-18° to the south, towards Airedale, there was enough percolating groundwater to supply springs and seepage areas on the north-facing escarpment of the Chevin. The movement of water towards the north-facing escarpment slope of the Chevin would have been assisted by the following:

- Intense jointing of the sandstone/gritstone beds, which are crossed by two sets of long and open joints. This jointing pattern extends into the underlying mudstone/shale strata;
- Faulting of the Chevin supports the establishment of continuous zones of percolation along zones of fault-disturbed strata;
- The existence of an established proglacial lake following deglaciation between Burley-in-Wharfedale and Pool will have affected base-flow conditions, resulting in maintaining high groundwater levels and the rapid recharge of aquifers in the watershed;
- Disruption of the gritstone/sandstone bedding by periglacial processes following deglaciation, including freeze/thaw and cambering processes, together with paraglacial stress-release processes forming neo-joints sets within the underlying mudstones and shales, will have resulted in highly fractured rock masses, allowing greater transmissivity of groundwater through strata on the north-facing escarpment; and
- Large volumes of meltwater would have been generated at times of thaw following deglaciation of the Wharfedale glacier.

Reservoir Principle of Mass Movement: All the above factors would have resulted in the high secondary permeability characteristics of the strata forming the north-facing escarpment of the Chevin. The hydrogeological conditions of the Chevin therefore, satisfy the conditions required for applying the Reservoir Principle (Denness 1972). The Reservoir Principle of mass movement is applicable to the Chevin landslides, where groundwater was supplied continuously by the overlying beds of jointed sandstone and gritstone, developing and maintaining high pore-water pressure within the underlying mudstones and shales.

As a result, the surface zone of the mudstone layer beneath the overlying sandstones softens due to the intake of groundwater, while at the same time deforming due to processes of stress relief due to debutressing and over-deepening following deglaciation and loading forces exerted by the overlying heavy gritstone edges.

In the event of slope failure, usually in the form of deep-seated rotational failure, the landslide debris which accumulates below the rotated block(s), permits easier access of the groundwater. The abundance of groundwater within the landslide debris apron which develops after the initial rotational mass movement, therefore, tends to generate a viscous flow of landslide debris. This process, therefore, creates extensive debris aprons, often including discrete debris flows within the landslide complex.

The Reservoir Principle of mass movement therefore, resulted in the development of a complex landslide system on the Chevin which is demonstrated by the geomorphology of the landslide complex. The geomorphology of the Chevin landslides corroborates that the landslides degenerated rapidly after initial stages of rotational failure from a solid state to a more saturated viscous flow of debris, thereby creating widespread debris aprons extending several hundreds of metres downslope. The effect of the available water, therefore, is to facilitate rapid mass movement of landslide debris as multiple or successive failures or mudflows, so steepening parts of the landslide system and thereby, generating further landslides to renew mass movement of already failed material.

The continuous supply of water from the sandstone aquifer overlying the relatively impermeable mudstones resulted in setting up and maintaining high pore-water pressures in the mudstone strata below the sandstones attributing to rapid failure of the slope. Many of the larger landslides on the Chevin involved deep-seated rotational movements with accompanying cambering of the competent sandstone strata at the crest of the slope.

Continued destabilising factors after initial movement: After the initial deep-seated rotational slide had developed, further movement was initiated by the following factors:

- Deglacial unloading and paraglacial stress-release processes affecting the weak mudstones and shales on the lower valley slopes;
- Reduction of the unconfined compressive strength of rocks due to saturation;
- The reduction of the shear strength of materials along the slip planes of deep-seated landslides to a residual value;
- The disruption of the former drainage channels caused by the large deep-seated rotational failure;
- The increased softening of disturbed and fractured mudstone through unchannelled groundwater flow; and
- Remoulding of mudstone material during failure, which resulted in increasing the water-holding capacity of the material and reducing their shear strength to residual values.

Favourable Climate Conditions: Favourable conditions for the Reservoir Principle would have occurred in Wharfedale after the last glacial maximum when excess meltwater penetrated the aquifers on the crest and north-facing slopes of the Chevin from melting ice. The water released during thaw, could not penetrate beyond the permafrost barrier on the lower slopes, hence superficial and residual weathered materials would have become saturated promoting solifluction and widespread mudflow mass movement processes. This sequence of events helps explain why the large deep-seated rotational slides and hummocky debris aprons are located on the upper slopes of the Chevin and the mudslides, mudflows and solifluction materials are located below the debris aprons on the mid and lower slopes.

Age of the Chevin Landslides: The causes and timing of large Pennine landslides are poorly understood. There are still major gaps in the understanding of Holocene geomorphological activity in the Pennines. However, dating of Pennine landslides suggests that larger deep-seated landslides did not take place immediately following deglaciation, but took place 1000-3000 years after deglaciation (Dowell & Hutchinson 2010, Cross 2024). The long delay reflects the importance of progressive rock-mass weathering initiated by deglacial stress-release processes and associated tensile rock mass damage. The mudslides and mudflows affecting the lower slopes of the Chevin are younger than the deep-seated landslides on the upper and mid slopes and took place throughout the postglacial period.

Climate Change: The present hydrological conditions are different from those that initially caused the Chevin landslides (Cooper 1984, Cross 2024). However, there is still enough water entering the landslide disturbed areas on the lower slopes of the Chevin. The existing drainage provision on the Chevin is inadequate and further drainage development is required.

The deep-seated landslide areas on the upper and mid slope areas of the Chevin appear to be in equilibrium and relatively stable under the present hydrological conditions without interference of the natural slopes (Cross 2024). Climate change involving long wet autumn, winter and spring months has resulted in raising groundwater levels to near ground surface within areas affected by previous shallow landslides, mudslides and mudflows on the lower slopes of the Chevin. This has caused reactivation of mudflows and mudslides on parts of the lower slopes of the Chevin (Cooper 1984, Cross 2024). Changes to slopes affected by shallow landsliding, mudslides and mudflows such as by undrained loading or over-steepening may cause reactivation of former slip surfaces and the initiation of slope failure (Cross 2024). The A660 is still being affected by shallow landslides and mudslides due to insufficient road drainage measures.

Chevin Landslide Risk Management: A greater emphasis is required in relation to landslide risk management and the resilience of the engineering measures adopted as part of the landslide risk management process for future development taking place on the Chevin. These assessments should include the compilation of engineering geological / geotechnical hazard plans for the Chevin area; these plans should be used to support planning decisions for any future development on the Chevin. Regular inspection and special guidance for planning and construction activities are required for any proposed development within mapped landslide areas on the Chevin. Special guidance for ground investigation, foundation design and engineering climate resilience is also required for proposed development taking place within mapped areas of landsliding on the Chevin. Periodic LIDAR surveys should be completed to determine any areas indicating continued movement on the Chevin. Geotechnical instrumentation including surface movement monitoring and groundwater monitoring should be considered within key areas to monitor areas of potential high risk of landsliding which may affect existing infrastructure.

Field Trip Stop-off locations

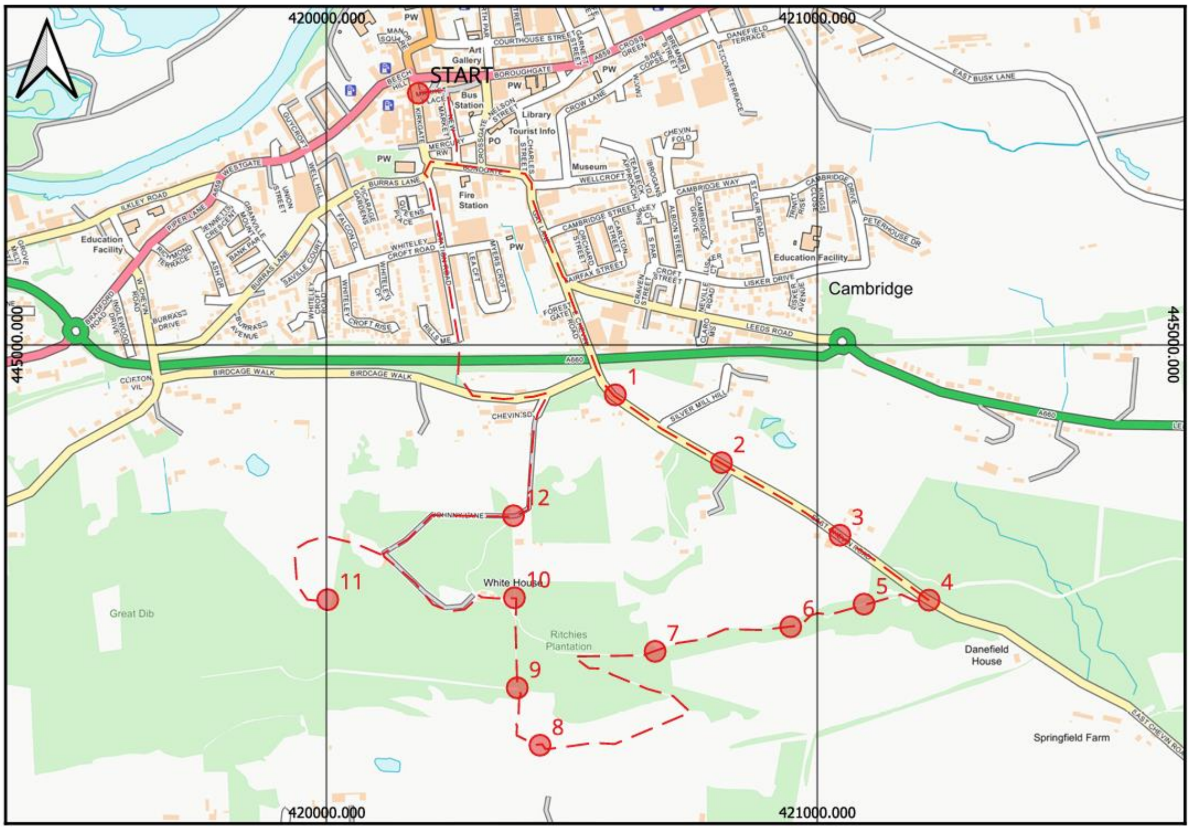

Fig. 5. Location map showing the field trip route and twelve stop-off locations.

Fig. 5 shows the twelve numbered field trip stops along the route of the Otley Chevin landslide field trip. A short description of the features which can be seen at each stop are provided below.

1. **The Otley Bypass**

The Otley Bypass was constructed within the former alignment of a disused railway. The former railway was constructed through an area of complex mudslides located on the lower slopes of Otley Chevin (Culshaw & Duncan 1975, Burgess 1976). Cooper (1984) described the geology, hydrology and stability of the landslides between the east side of Otley near Menston and Old Pool Bank in the west of the Chevin. The British Geological Survey completed a geological desk study and aerial photograph interpretation together with fieldwork to map the landslides affecting the A660 Leeds-Otley Road (Cooper 1984). Cooper (1984) noted evidence of active landslide movement and recorded associated hydrological features such as surface water courses, springs and poorly drained areas.

The first UK reported anchored reinforced earth retaining wall (Silver Hill Mill Retaining Wall) was constructed in 1984 on the Otley Bypass (Snowdon *et al.* 1986). The retaining wall was constructed in an area comprising a complex series of mudslides and within an existing railway cutting constructed in 1860. The retaining wall supports the southern cut slope of the bypass adjacent to Bird Cage Walk and provides support for the bank-seat of the footbridge over the bypass to between Bird Cage Walk and Station Road.

2. ***Landslide Complex Northeast of Manby House***

The area southeast of Manby House (SE20952 44645) shows little evidence of landslide disturbance, although solifluction Head Deposits are widespread in this area. Northeast of Manby House and downslope of East

Chevin Road is a complex of small rotational landslides (SE20825 44786). This area comprises hummocky ground and extends northwards into an area of mudflow extending to the A660 and further downslope to the north of the A660. A small artificial pond (Silver Mill Pond SE 20926 44808) is located on a rotated block of the Manby House landslide. Silver Mills Reservoirs (SE 20954 44852) were also constructed and fed from the Silver Mills Spring east of the pond and Silver Mills Cottages (SE 209 448). More recent smaller rotational landslides can be seen at (SE 21028 44888) and (Orchard House, SE 21061 44967). These have developed within the older mudslide and mudflow complexes. Orchard House is located within a former clay pit located at the roundabout junction between Otley Bypass and the A660. The north facing slope of the former clay pit has exposed former mudslide deposits comprising reworked Glacial Till and shows evidence of continued instability.

3. *The Birches Landslide Complex*

North and east of The Birches (SE 210 446) extends a complex of deep-seated multiple rotational landslides (Landslides (SE21143 44350) and (SE21143 44762). These landslides have well developed steep back scarps in the Addingham Edge Grit. North of the initial rotated blocks of landslides are secondary rotational failures within an extensive area of mudslides and mudflows extending north of the A660 Leeds Road and Willow Bank House (SE 21177 45023). A series of well-developed mudflows can be seen north of the A660 Leeds Road around Willow Bank House (SE 21141 45061), Brunswick House (SE 21230 44971) and Arnwood House (SE 21402 44954).

4. Recent Rockfall (Birches Landslide) affecting East Chevin Road

Recent and active rockfall associated with the Birches landslide complex below east Chevin Quarry. Recent rockfalls have affected the former back scar of the Birches landslide. The concrete fence has been undermined by the rockfalls, and further movement may now affect the northern side of East Chevin Road located opposite the former East Chevin Quarry.

5. *East Chevin Quarry*

East Chevin Quarry (SE 211 444) and the exposed Addingham Edge Grit crags extending westwards to Ritchies Plantation show evidence of rockfalls. A schematic cross-section through East Chevin Quarry and the Birches Landslide complex below is shown in Fig. 6. The slopes below the crags are covered with large grit boulders which decrease in size and number down slope. These are particularly evident in the field adjacent to Ritchies Plantation (SE 207 444) which has not been cleared for cultivation. The rockfalls have been mainly caused by toppling failures.

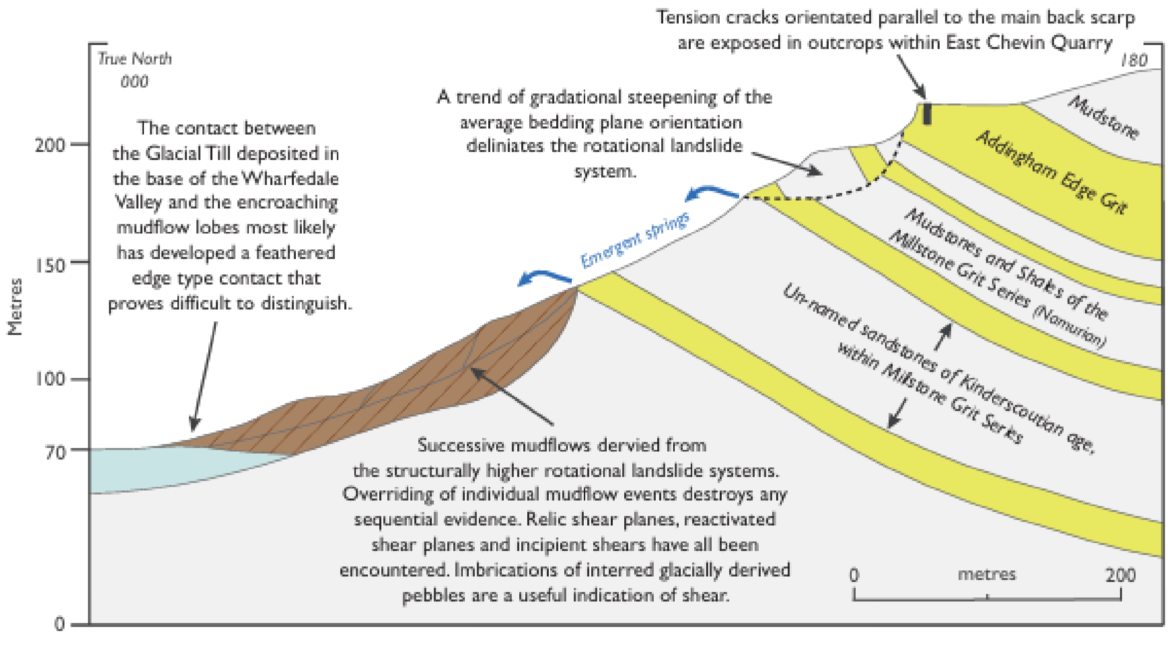

Fig. 6. Schematic cross-section through East Chevin Quarry and the Birches Landslide complex.

6. Addingham Edge Grit Exposure

Exposure of the Namurian Millstone Grit Group, the Addingham Edge Grit (formerly known as the Caley Crags Grit), a coarse-grained sandstone giving rise to a conspicuous 'edge' from East Chevin Quarry (Grid Ref SE 2121 4448) to Ritchies Plantation in the west. The Addingham Edge Grit consists of massive cross-bedded coarse grit, 25 to 30m in thickness, with a mudstone parting near the top. Most of the grits are felspathic and contain pebbles of quartz and felspar. The main bed of grit forms conspicuous rock faces along the top of the Chevin and is particularly well exposed at Caley Crags to the east (SE2274 4436) and Great Dib landslide (SE 1998 4449) in the west, where it overlies the Otley Shell Bed. The Addingham Edge Grit is also clearly exposed in the disused East Chevin Quarry (SE 2121 4448), where it was once quarried and crushed for sand and gravel. About 25m of massive, coarse grit is exposed, with flaggy micaceous sandstone at the base, and a thin shale horizon.

7. Upper Part of the Birches Landslide Complex

The upper part of the Birches Landslide comprises a complex of deep-seated multiple rotational landslides (Landslides SE21143 44350 and SE21143 44762) (see Fig. 6). These landslides have well developed steep back scarps in the Addingham Edge Grit. North of the initial rotated blocks of landslides are secondary rotational failures within an extensive area of mudslides and mudflows extending north of the A660 Leeds Road and Willow Bank House (SE 21177 45023). A series of well-developed mudflows can be seen north of the A660 Leeds Road around Willow Bank House (SE 21141 45061), Brunswick House (SE 21230 44971) and Arnwood House (SE 21402 44954).

8. Beacon Hill and view over Wharfedale Valley

Refer to sections of this field guide on Wharfedale superficial geology, periglacial geomorphology and Wharfedale geomorphology.

9. Top of the White House Landslide Complex

Several single deep-seated rotational landslides are located to the east of Great Dib Landslide and north of Ritchies Plantation (Landslides (SE20076 44569), (SE20156 44513), (SE20304 44551) and (SE20308 44442).

10. The White House Landslide

The White House (SE 20309 44488) is located on the rotated block of Whitehouse landslide. The ruins of another old house are also located on the same rotated block south of the White House. Several small slumps are located along the back scarp extending from the former Pig Farm (SE 200 445) to the White House. The old building formerly located to the south of the White House was demolished due to severe structural damage caused by landsliding. To the north of the former Pig Farm is an active mudflow area extending towards Birdcage Walk (5E).

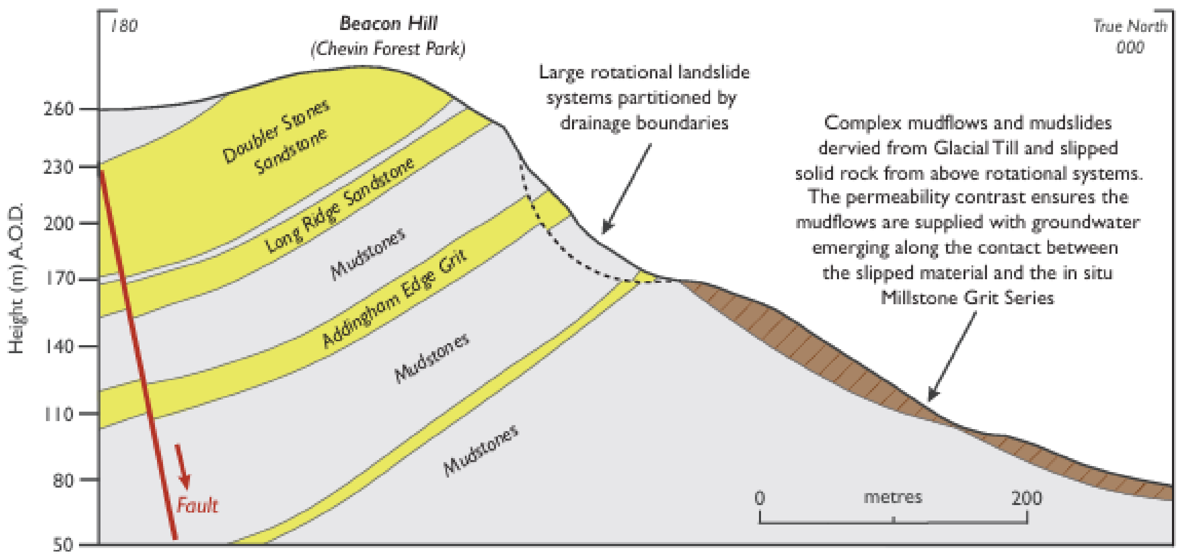

Fig. 7. Schematic cross-section through Beacon Hill and Great Dib Landslide

11. Great Dib Landslide

Great Dib is the name given to the steep back scarp of a very large deep-seated multiple rotational landslide (SE19983 44492). A schematic cross-section through Beacon Hill and Great Dib Landslide is shown in Fig. 7. The Great Dib landslide represents one of the largest rotational landslides on the Chevin. The back scarp comprises 20m of Addingham Edge Grit and the landslide includes a considerable thickness of underlying mudstone strata (see sequence through the Great Dib back scarp in Fig. 3). Below the back scarp is a complex of large, rotated blocks which extend downslope to north of Spring Side House (SE 19943 44843). The failure appears to have occurred along a non-circular slip plane, as the landslide has a significant translational element in its lower parts. The upper part of the Great Dib landslide, lying generally above 120m, consists of a series of large slump features which affect the higher beds of the argillaceous rock, and often involves the capping strata of the Addingham Edge Grit. Several secondary slumps have taken place on the steep edges of the rotated blocks. The large failures are separated by smaller multiple rotational landslides which have been modified by subsequent mudslide and mudflow mass movements. A small pond is present on a rotated block (SE 19854 44756) to the south of Spring Side House. This area is characterised by numerous small springs and boggy hollows. The lower part of the Great Dib landslide comprises a complex of frequently overlapping mudslides and mudflows which have developed from the higher rotational landslide debris aprons. Pronounced mudslides and mudflows have developed down slope north of Oakdene House, Spring Side House and Woodlands House to Birdcage Walk and extend north of Otley Bypass and probably are present further north in the now built-up area (SE 19797 45091) which comprises of highly disturbed and reworked Glacial Till. The mudslides and mudflows are typically composed of numerous sub angular, poorly sorted fragments of bluish grey to brown, friable mudstone, 0.5 to 5cm in diameter, in a soft remoulded clayey matrix, but also incorporates large amounts of Glacial Till, which often contains rounded grit cobbles. This implies that the mudslides and mudflows post-date the maximum glaciation in this area.

12. Example of Mudflow

Area of mudflow deposits extending below the White House landslide complex towards Birdcage Walk. The geomorphology of the Chevin landslides corroborates the Reservoir Principle of mass movement that the landslides degenerated rapidly after initial stages of rotational failure from a solid state to a more saturated viscous flow of debris, thereby creating widespread debris aprons extending several hundreds of metres downslope. The effect of the available water, therefore, is to facilitate rapid mass movement of landslide debris as multiple or successive failures or mudflows, steepening parts of the landslide system and thereby, generating further landslides to renew mass movement of already failed material (Denness 1972).

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