Landslides and mass movement processes and their distribution in the York District (Sheet 63)

Physical Hazards Programme

Open Report OR/07/004

BRITISH GEOLOGICAL SURVEY

PHYSICAL HAZARDS PROGRAMME

OPEN REPORT OR/07/004

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Front cover

Cover picture details, Birdsall Brow landslide looking to the north photograph taken from NGR 483195 463689, looking to the NE.

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Foreword

This report is the published product of the British Geological Survey's Physical Hazards Programme's Landslide Project. The report describes the study of the landslides and mass movement processes that have affected the geological formations in the York district. The report proposes the concept of Landslide Systems, which uses a hierarchical approach allowing a large area to be broken down systematically into smaller units depending on geology, hydrogeology and geomorphology. The work was undertaken in association with the Geology and Landscape Southern Britain mapping team of Anthony Cooper, Simon Price, Jon Ford, Helen Burke and Mike Hall who are thanked for their assistance in understanding the geological context of the area and for the many helpful discussions that took place during the project.

Acknowledgements

The authors of this report would also like to thank A Gibson and D Bridge for their advice and constructive comments during the drafting of this report. Mike Hall is also thanked for his help and advice with the operation of the aerial photograph analysis software used during the investigations. David Boon is thanked for contributing to the engineering geological section of the report. The authors would also like to thank the many landowners who provided access to their land during the survey.

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Summary

This report describes the extent and character of the landslides and the mass movement processes in the area covered by the 1:50 000 scale BGS map of York (Sheet 63). The work enabled over 80 newly surveyed landslides to be entered into the National Landslide Information Centre (formerly the National Landslide Database) and assisted the continuing study of landslides and mass movements in Great Britain.

1 Introduction

The existing York (Sheet 63) 1:50 000 geological map (Solid and Drift Edition) is based on the geological survey of Fox-Strangways in the late 19th Century (Fox-Strangways, 1884). As part of the resurveying of the sheet by the Geology and Landscape Southern Britain (GLSB) mapping team (Yorkshire and Humber District), the landslide survey team was approached to assist in the mapping of landslides in the region. The GLSB team reported extensive areas of complex landsliding in the Mesozoic sedimentary rocks of the region, and requested the expertise of the BGS landslide survey team in the mapping and classifying of the landslides for inclusion on the published 1:50 000 map.

This landslide survey involved an initial field reconnaissance campaign in October 2005 (Jenkins *et al*. 2006a). This was followed by an interpretation of aerial photographs, and a field survey in September 2006 to ground truth and make more detailed assessments of mapped landslides.

This campaign of work represents an evolution in the ‘Landslide Domain’ approach to landslide mapping and proposes the ‘Landslide System’ approach, which can be applied to landslide mapping on a regional scale.

2 SOCET SET™ aerial photograph interpretation

A new aerial photographic interpretation software package was utilised for the first time at BGS in the preliminary desk study phase of the project. To capture digital polygons of the landslides, SOCET SET™, a digital photogrammetry software package, was used to view ortho-rectified aerial photographs in stereo. This software was used in conjunction with the SOCET for ArcGIS add-on, which enables the accurate geospatial digitisation (in stereo) of landslide polygons as ArcGIS shape files. This allows the polygons to be accurately transferred to the published 1:50 000 digital and paper geological map output.

3 Study Area

The York 1:50 000 geological map (Sheet 63) is located to the north-east of the city of York, extending north-eastwards to the southern edge of the market town of Malton (Figure 1). The landscape in the western half of the map area is gently undulating due to the underlying, less resistant Sherwood Sandstone Group and Mercia Mudstone Group with a thick covering of superficial deposits. The generally low topographic relief of this area is not conducive for the widespread occurrence of landsliding. To the east lies the southern slopes of the Howardian Hills and the western escarpment of the Yorkshire Wolds and it is here, with the underlying Mesozoic sedimentary rocks that landslides are most prolific.

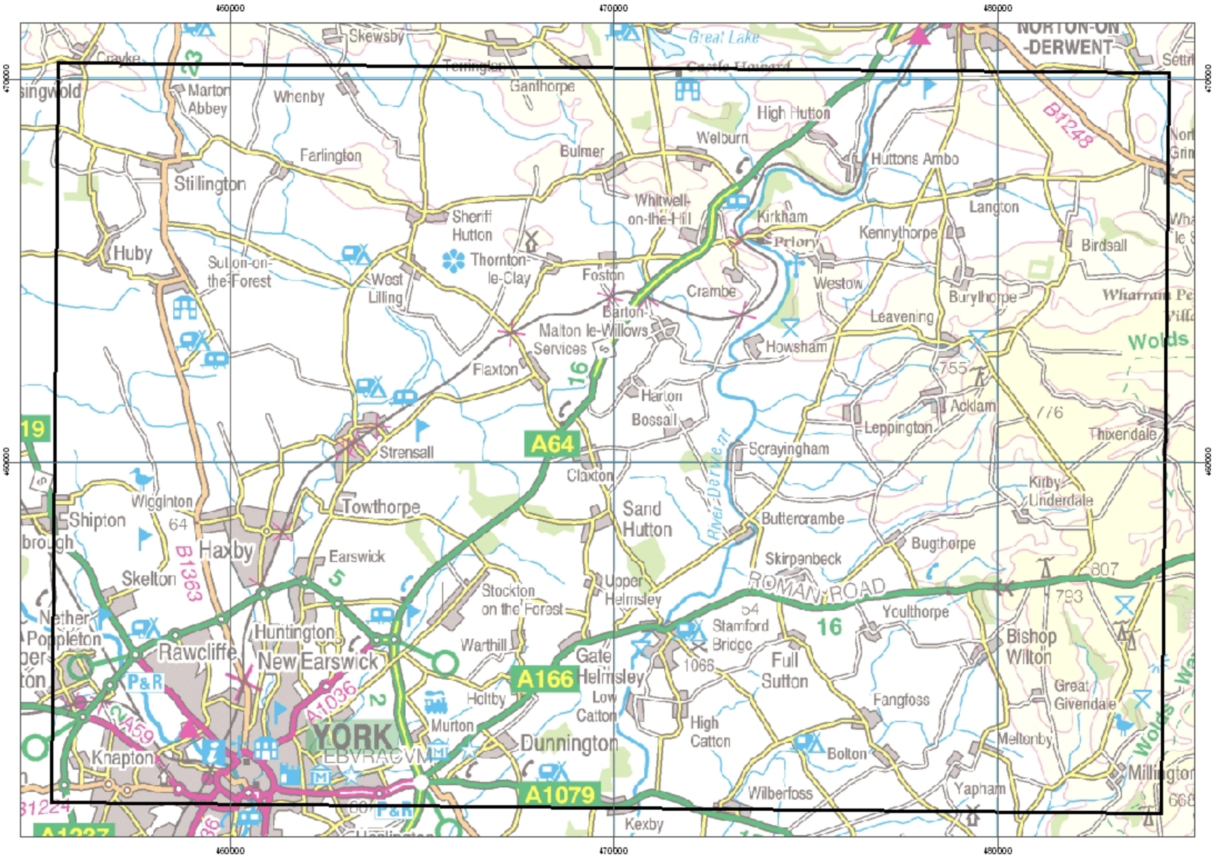

Figure 1. Location of the York 1:50 000 geological map sheet 63 (black outline).

4 Geomorphology

The most important period of geomorphological evolution of slopes within the York area was during the Quaternary. Climatic deterioration, which had begun in the Tertiary, continued in the Quaternary, leading to the formation of glacial ice that spread across much of Northern England (Boulton, 1992). The Pennines were glaciated as far south as Leeds whilst the Vale of York was occupied by a tongue of ice (Lee and Booth, 2006). Ice retreated from the Vale of York, as recently as 14,000yrs BP, depositing extensive glacial and pro-glacial sediments (Lee and Booth, 2006). The study area, which lies at the southern extent of the Vale of York, is sandwiched between two areas of Devensian ice and as such large parts of it were not subject to glaciation (Aitkenhead *et al*., 2002) (Figure 2). Whilst the study area falls just outside of the Devensian glacial limits it was probably glaciated during the Anglian, an earlier glaciation which reached as far as southern England (Rayner and Hemingway, 1974). The limit of the Devensian ice marks a change in geomorphology; outside the glacial maximum intense periglacial conditions dominated, an important factor affecting the evolution of slopes in the area. Associated with periglacial conditions were the extensive development of permafrost, which formed in the area. During warmer climatic phases, melting of the active layer of the permafrost occurred which became mobilised by sliding and flowing to form a solifluction deposit/sheet. (Jones and Lee, 1994). It is likely that clay rich lithologies affected by this process would have been subject to landsliding. As elsewhere in the UK, this is likely to have resulted in the creation of multiple shear zones, which may still be present and subject to activation (Ballantyne and Harris, 1994).

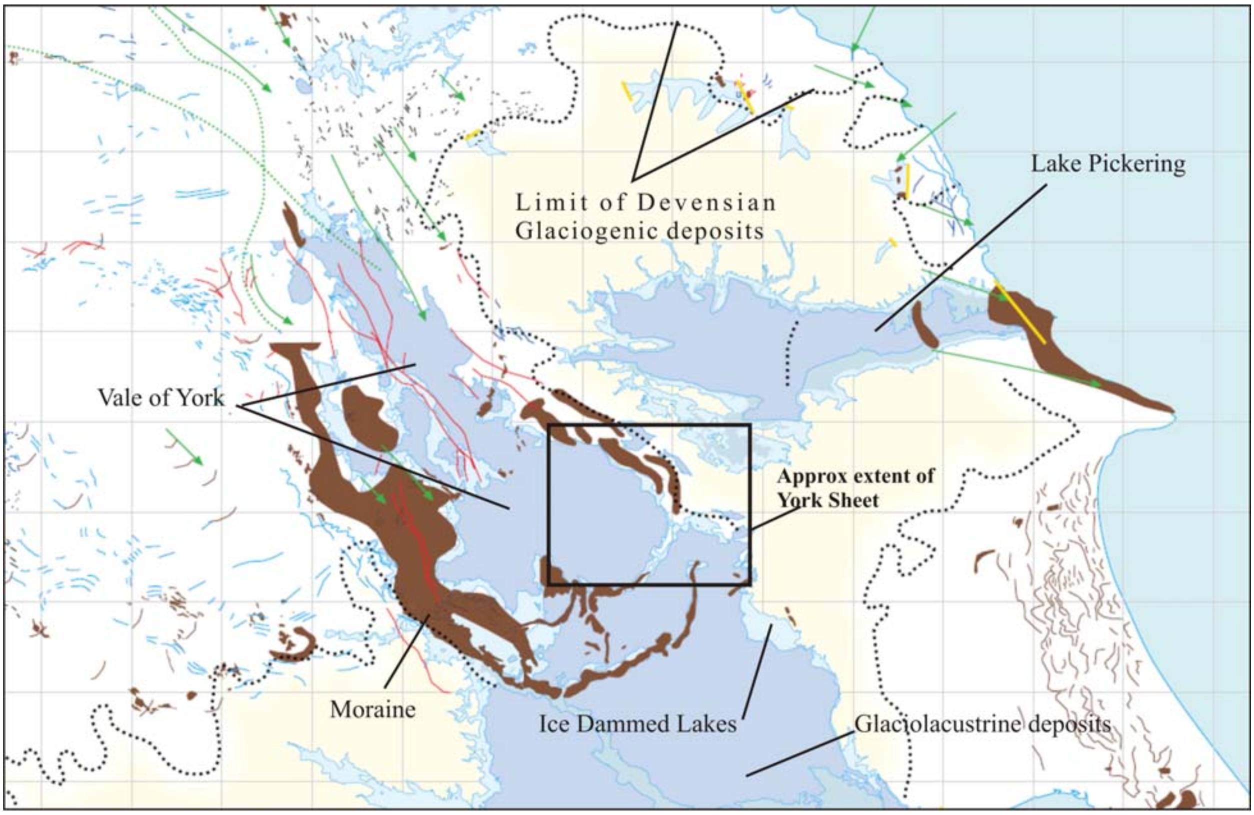

Figure 2. Glacial map of the study area. (After Clark *et al*., 2004).

5 Geology

The geology of the York sheet consists of a complex sequence of Mesozoic (Triassic, Jurassic and Cretaceous) sedimentary rocks deposited in fluvial, estuarine and marine conditions (Figure 3). It is necessary to understand the lithologies present, in order to understand the patterns and distribution of landsliding within the York region. Each of the stratigraphic units and lithologies present will behave differently due to its mechanical and structural characteristics and will be susceptible to different types of mass movement due to these factors. The stratigraphic relationships of these lithologies are also important to slope stability. Vertical differences in both mechanical strength and hydrogeological factors can influence slope stability and the type of landsliding (Jones and Lee, 1994). Common circumstances relating to landslides occur where an underlying clay formation is overlain by a more competent and porous formation such as sandstone, chalk or limestone. The presence of clay layers within a slope/landslide also allows water to be retained and therefore a quicker response to changes in precipitation (Baum *et al.*, 2003). A simplified stratigraphic table, outlining the main geological units within the area is provided (Table 1). Geotechnical and engineering properties will influence the susceptibility of a slope to failure and these characteristics of each formation will be discussed where available. Properties such as plasticity are important because it relates to composition and therefore soil strength, especially where clayey solids are concerned (a 1% increase in the water content of a stiff plastic clay produces about a 15% decrease in shear strength) (Abramson, 2001).

Table 1. Simplified stratigraphy of the York Sheet (63) area.

<table>
<tr><th>Period</th><th>Stage</th><th>Group</th><th>Formation</th><th>Simplified lithology</th></tr>
<tr><td rowspan="4">Cretaceous</td><td>Turonian/Coniacian/Santonian</td><td rowspan="3">Chalk Group</td><td>Burnham Formation</td><td>Chalk with flint</td></tr>
<tr><td>Turonian</td><td>Welton Chalk Formation</td><td>Chalk with flint</td></tr>
<tr><td>Cenomanian</td><td>Ferriby Chalk Formation</td><td>Chalk</td></tr>
<tr><td>Albian</td><td></td><td>Hunstanton Formation</td><td>Chalk</td></tr>
<tr><td rowspan="15">Jurassic</td><td>Kimmeridgian</td><td>Ancholme Group</td><td>Kimmeridge Clay Formation</td><td>Mudstone</td></tr>
<tr><td rowspan="3">Oxfordian</td><td rowspan="2">Corallian Group</td><td>Coralline Oolite Formation</td><td>Limestone</td></tr>
<tr><td>Lower Calcareous Grit Formation</td><td>Calcareous sandstone and limestone</td></tr>
<tr><td rowspan="2">Ancholme Group</td><td>Ampthill Clay Formation</td><td>Mudstone</td></tr>
<tr><td rowspan="2">Callovian</td><td>Oxford Clay Formation</td><td>Mudstone</td></tr>
<tr><td rowspan="6">Ravenscar Group</td><td>Osgodby Formation</td><td>Sandstone</td></tr>
<tr><td>Bathonian</td><td>Scalby Formation</td><td>Quartzite/sandstone</td></tr>
<tr><td>Bajocian</td><td>Scarborough Formation</td><td>Calcareous sandstone and limestone</td></tr>
<tr><td rowspan="4">Aalenian</td><td>Cloughton Formation</td><td>Sandstone and some coal</td></tr>
<tr><td>Eller Beck Formation</td><td>Limestone</td></tr>
<tr><td>Saltwick Formation</td><td>Sandstone and some coal</td></tr>
<tr><td rowspan="4">Lias Group</td><td>Dogger Formation</td><td>Sandstone and limestone</td></tr>
<tr><td>Toarcian</td><td>Whitby Mudstone Formation</td><td>Mudstone</td></tr>
<tr><td>Pliensbachian</td><td>Staithes Sandstone/Cleveland Ironstone Formation</td><td>Sandstone and Ironstone</td></tr>
<tr><td>Hettangian/Sinemurian/ Pliensbachian</td><td>Redcar Mudstone Formation</td><td>Mudstone and limestone</td></tr>
<tr><td>Triassic</td><td>Rhaetian</td><td>Penarth Group</td><td></td><td>Mudstone</td></tr>
</table>

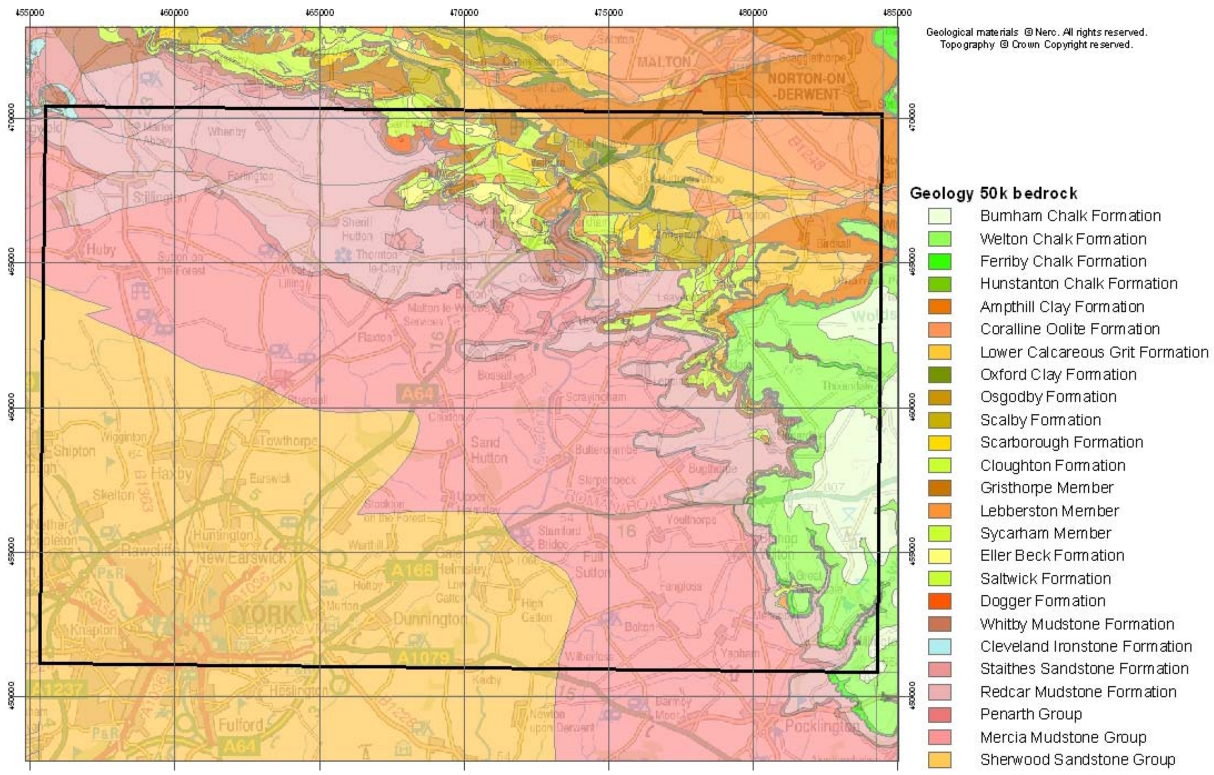

Figure 3. DiGMap V2, 1:50 000 bedrock geology of the York Sheet (63).

5.1 TRIASSIC – PENARTH GROUP

The Penarth Group, the Upper most division of the Rhaetic sequence, is mainly exposed in a strip trending northwest-southeast across the centre of the region, to the east of the Mercia Mudstone Group. The Penarth Group is divided into the Westbury Formation, comprising brown, dark grey or black, fissile mudstones, siltstones and very thin limestones, overlain by the Lilstock Formation, which consists of pale green, soft, soapy-textured mudstone and siltstone (Powell *et al*., 1992).

Unweathered Westbury Formation is generally ‘medium strong’ olive and black laminated, fissile, mudstone and siltstone. When highly weathered the Westbury Formations can be described in engineering terms as a highly plastic black and dark grey thinly interlaminated fissile silty clayey shale with ‘very weak’ and friable thin partings of yellow silty clay. Both natural and artificial slopes, formed in the Westbury Formation are renowned for instability.

In its ‘weathered’ state the bulk of the Lilstock Formation is generally described as a stiff silty clay, whilst in its slightly weathered state the material is described as ‘weak’ grey silty mudstone; it also contains thin beds of moderately strong shelly limestone (Duff and Smith, 1992).

5.2 LOWER JURASSIC – LIAS GROUP

The Lower Jurassic Lias Group in the Cleveland basin (Yorkshire) can be up to 1300 m, though it thins considerably across the York district onto the Market Weighton High in the south (Kent, 1980; Duff and Smith, 1992). The Lias Group comprises the Redcar Mudstone, Staithes Sandstone, Cleveland Ironstone and Whitby Mudstone. The Lower Jurassic Lias sequence is dominantly argillaceous and comprises mudstones, sandstones and limestones. The Cleveland basin is thought to have undergone burial to around 2 km, causing greater induration and greater strength (*strong* to *very strong*) than the mudstones in the southern basins and on the Market Weighton High. The Lias Group in much of the Cleveland basin has a thin weathering profile as it was recently partially glaciated and is resistant to weathering having undergone deep burial (Hobbs *et al*., 2005). The top 10 m generally tends to have been weathered significantly enough to change the properties of the materials. Weathering and degradation cause changes in properties, increasing the natural moisture content and liquid and plastic limits (plasticity) and decreasing cohesion and elasticity (Hobbs *et al*., 2005).

5.2.1 Redcar Mudstone

The base of the Lias Group is represented in the York area by the Redcar Mudstone Formation, comprising up to 200 m of mainly dark grey mudstones and siltstones. Thin subsidiary limestones (concentrated in the lower third), very fine-grained sandstones and ironstone beds/nodules are also present (Powell, 1984).

The Redcar Mudstone has a moderate level of slope stability owing to its moderate bearing capacity, high plasticity and medium shrink-swell potential. Hobbs *et al*., (2005) found the Redcar Mudstone to have a median natural moisture content of 18% with a plastic limit of 23%, lower than other lower Jurassic mudstones. There is no published data on the effective shear strength parameters of this formation but the material is thought to be more like the Carboniferous Coal Measures mudstones in strength characteristics. Hydraulic continuity values range in magnitude between 10^{-8} and 10^{-5}, significantly higher than the Whitby mudstone. This may be an important factor where water permeates into the Westbury Formation below.

5.2.2 Staithes Sandstone and Cleveland Ironstone

The Staithes Sandstone Formation and Cleveland Ironstone Formation form the middle units of the Lias Group. The Staithes Sandstone Formation varies in thickness from 20 to 25 m, and consists of fossilferous, micaceous, calcareous, fine- to medium-grained sandstone and sandy siltstone; the colour ranges from blue-grey (unweathered) to yellow-brown (weathered). The Cleveland Ironstone Formation comprises about 9 to 13 m of grey silty mudstone and siltstone with subordinate very fine-grained sandstone and beds ironstone (Powell *et al*., 1992).

5.2.3 Whitby Mudstone

The Whitby Mudstone Formation forms the upper part of the Lias Group and typically consists of bluish grey to dark grey, sparsely fossiliferous, fissile, locally bituminous mudstones and siltstones. Bands of calcareous concretions are common at some horizons. (Cooper & Burgess, 1993). It reaches about 25-30 m thickness in the study area (Fox-Strangways, 1884). Landslides within the Whitby Mudstone on the York sheet may be related to the presence of weak horizons; elsewhere these have been suggested as a contributing factor in mass movement processes in the Midlands and the Cotswolds. Cripps & Taylor (1987) note that large tracts of Upper Lias clay were brecciated by freeze-thaw activity during Pleistocene times, resulting in reduced average effective shear strength parameters (c' = 1.0 kPa, $\Phi'=23^o$) (Chandler and Skempton, 1974). Residual effective angles of shearing resistance (Φ'_r) range from 5 – 13.5^o indicating a two fold loss in shear strength on reworking (Cripps & Taylor, 1987). Results from shear box tests give even lower residual effective shear strength parameters, c'_r = 2 kPa, $\Phi'_r = 8^o$ (Hobbs *et al.,* 2005). This means that the Whitby Mudstone will be weaker where it has been periglacially weathered.

5.3 MIDDLE JURASSIC

The Middle Jurassic is represented in the York area by the Dogger Formation, Ravenscar Group and lower parts of the Oxford Clay Formation. The Middle Jurassic sequence provides a contrast to that of the Lower Jurassic through its abundant dominantly non-marine sandstone formations. Like the Lower Jurassic the sequence thins southwards on to the Market Weighton Axis, but there is little precise and modern information about the thicknesses in the York district. The thickneeses described in the Thirsk district (Powell, *et al*., 1992) is more typical of the northern part of the York district.

5.3.1 Dogger Formation

The Dogger Formation varies lithologically throughout the district. It ranges in thickness from 0-7 m and typically consists of shelly, sideritic ironstone with berthierine ooliths. However, other lithologies include: bioclastic, oolitic, commonly sideritic, cross-bedded limestone (wackestone – packstone), calcareous mudstone with sideritic concretions, calcareous fine-grained sandstone, and phosphatised pebbles (Powell *et al*., 1992).

5.3.2 Ravenscar Group

The Saltwick Formation is about 20 to 25 m thick in the district, and consists of sandstone, siltstone and mudstone deposited in fluviodeltaic and paralic environments (Powell *et al*., 1992). The Eller Beck Formation is a marine deposit, with heterogeneous lithological composition consisting of oolitic, sideritic, ironstone, silty mudstone, argillaceous limestone, siltstone with sandstone lenses, and sandstone; it has a thickness that varies from 4 to 6 m (Powell *et al*., 1992).

The Cloughton Formation is between 36 and 52 m thick and predominantly comprises sandstone, mudstone and thin, laterally impersistent, coaly siltstone beds, of fluviodeltaic facies (Powell *et al*., 1992). The Scarborough Formation ranges from 9 to 14 m in thickness and consists of calcareous sandstone and limestone. Over much of its outcrop the Scarborough Formation is subdivided into two members (Powell *et al*., 1992), the Brandsby Roadstone (limestone) and the overlying Crinoid Grit (sandstone).

The Scalby Formation is 32 to 48 m thick and is made up of mudstone, siltstone and sandstone, together with seatearths and thin coals (Powell *et al*., 1992). The Osgodby Formation ranges in thickness from 20 to 23 m. It is subdivided into the Kellaways Rock Member and the Hackness Rock Member. The Kellaways Rock Member ranges from 20 to 23 m in thickness and consists of orange, yellow and grey fine- to medium-grained, thick-bedded sandstone. Some beds show trough cross-bedding and the rock is usually decalcified at outcrop. The Hackness Rock, where present, is about 3 m thick, and consists of buff-grey siltstone with alternating soft and hard calcite-cemented bands (Powell *et al*., 1992).

5.4 UPPER JURASSIC

In the York area two of the three Upper Jurassic stages are present, represented by the Ancholme Group (Oxfordian-Kimmeridgian) and the Corallian Group (Oxfordian). The Portlandian Stage is absent in the Yorkshire area.

5.4.1 Ancholme Group

The Oxford Clay Formation is typically a green-grey mudstone and silty mudstone (Powell *et al*., 1992). It forms a narrow outcrop across the north west of the region. Thicknesses in this district range from 5 m at Garrowby (NGR 479906 457480) to 20 m at Hutton Bank (NGR 475609 467106) (Fox-Strangways, 1884). The Oxford Clay is a fissured, heavily over-consolidated, bituminous clay and clay shale. Within the Cleveland basin it is currently subdivided into the Peterborough, Stewartby and Weymouth members that were previously known as the Lower, Middle and Upper Oxford Clay, respectively. The Peterborough member is absent in North Yorkshire. The Stewartby Member (Middle) is pale grey silty mudstone with thin beds of calcareous siltstone in the upper part. The Weymouth Member (Upper) is over-consolidated, fissured, silty, rarely sandy, intermediate to high and occasionally very high plasticity clay (Reeves *et al,* 2006). Forster (1991), provides data for South-Central England and found the median bulk density of the Weymouth Member (Upper) =2.11 (2.02-2.15), slightly higher than the Middle Oxford Clay = 2.00 Mg/m^3 (1.95-2.07). Undrained cohesion, c_u of Middle =106 (70-190), Upper 270 (190 –390) kPa. Effective cohesion of Middle c' = 10, Φ'= 31, Φ'_r = 15 (Cripps & Taylor (1987). There is a negative correlation between undrained strength and clay 'activity' (the ratio between the plasticity index and clay content, as defined by Skempton, 1953) in the Oxford Clay (Russell & Parker 1979; Reeves *et al*., 2006) and a positive correlation with the presence of the cementing agents calcite and pyrite.

The Ampthill Clay is described as a fossiliferous, pyritic, pale grey mudstone with occasional thin nodular cementstone bands. It is typically fissured and may contain shear surfaces in the uppermost 1-2 m. It typically has a high to very high plasticity and a high clay content (Cripps & Taylor 1981; Reeves *et al*., 2006).

5.4.2 Corallian Group

The Lower Calcareous Grit consists predominantly of yellow, to light yellowish brown, fine- to medium-grained, calcareous sandstone, with subsidiary beds and concretions of bluish-grey, micritic limestone; both lithologies are variably oolitic and peloidal. Siliceous sponge spicules form much of the clastic component, and diagenesis of these has produced secondary, thin beds of chert, particularly in the lower part of the formation (Hemingway, 1974). The formation is 22 to 48 m thick (Powell *et al*., 1992).

The Coralline Oolite Formation consists of a varied sequence of grey, predominantly oolitic and peloidal limestone intercalated with wedges of light yellowish brown-yellow, sparsely oolitic, calcareous sandstone. The formation is between 37 and 87 m thick (Powell *et al*., 1992). The Ampthill Clay bounds the northern margin of the Chalk outcrop. The beds consist of grey and dark grey fissile mudstone, which is bituminous in parts with carbonate concretions in the lower part (Powell *et al*., 1992).

5.5 LOWER CRETACEOUS

The Lower Cretaceous Hunstanton Formation rests unconformably on the underlying Jurassic sequences. An extensive sequence of Lower Cretaceous rocks is absent from the York area including the Upper Greensand and Gault Clay, which are commonly involved in landsliding in other areas of the country. The Hunstanton Formation, formerly known as the Red Chalk, consists of rubbly to massive chalks with marl bands. It is typically pink to brick-red in colour (due to disseminated hematite), but locally the upper part may be grey, rather than red, due to the secondary alteration of the iron minerals. It is commonly sandy, particularly in the lower part of the Formation.

5.6 UPPER CRETACEOUS

Unlike the Chalk present in the southern provinces, that in the North is materially different and forms a lithostratigraphic Group of four Formations (Wood and Smith, 1977). Three of these four Formations are present in the Upper Cretaceous Chalk outcrop present in the York area. The Ferriby Chalk Formation is dominated by generally grey, predominantly marly chalks, which weather to light yellowish brown in exposures, and give rise to rather marly soils. Some discrete marl bands, 'gritty' bioclastic chalks and hard, cemented chalks are also found in the region (Sumbler, 1999). The Welton Chalk Formation is a white, massive or thickly-bedded, rubbly-weathering chalk with common flint nodules. The Plenus Marls Member forms the base of the formation and is a thin but complex unit of light yellowish brown to green and khaki coloured marls and marly chalks. In contrast to the massive chalks of the Welton Chalk Formation below, the Burnham Formation is characterised by thinly bedded chalks with common tabular and semitabular (discontinuous) flint bands. This formation forms the crest and plateau areas of the Yorkshire Wolds that occupy the south-eastern edge of the York Sheet.

6 Landslide Distribution

The classification of landslides used during the remapping was carried out in accordance the classification convention of Varnes (1978) (Appendix 1). Prior to remapping a search of the National Landslide Database for the York Sheet revealed three landslide records, those of Acklam (478000, 462000), Leppingon (477000, 462000) and Kirkham Abbey (474000, 466000). As a consequence of the recent remapping more than 80 additional landslides have been recorded, which are mostly concentrated in the east of the sheet (Figure 4), an area underlain predominantly by weak Jurassic mudstones (Figure 5).

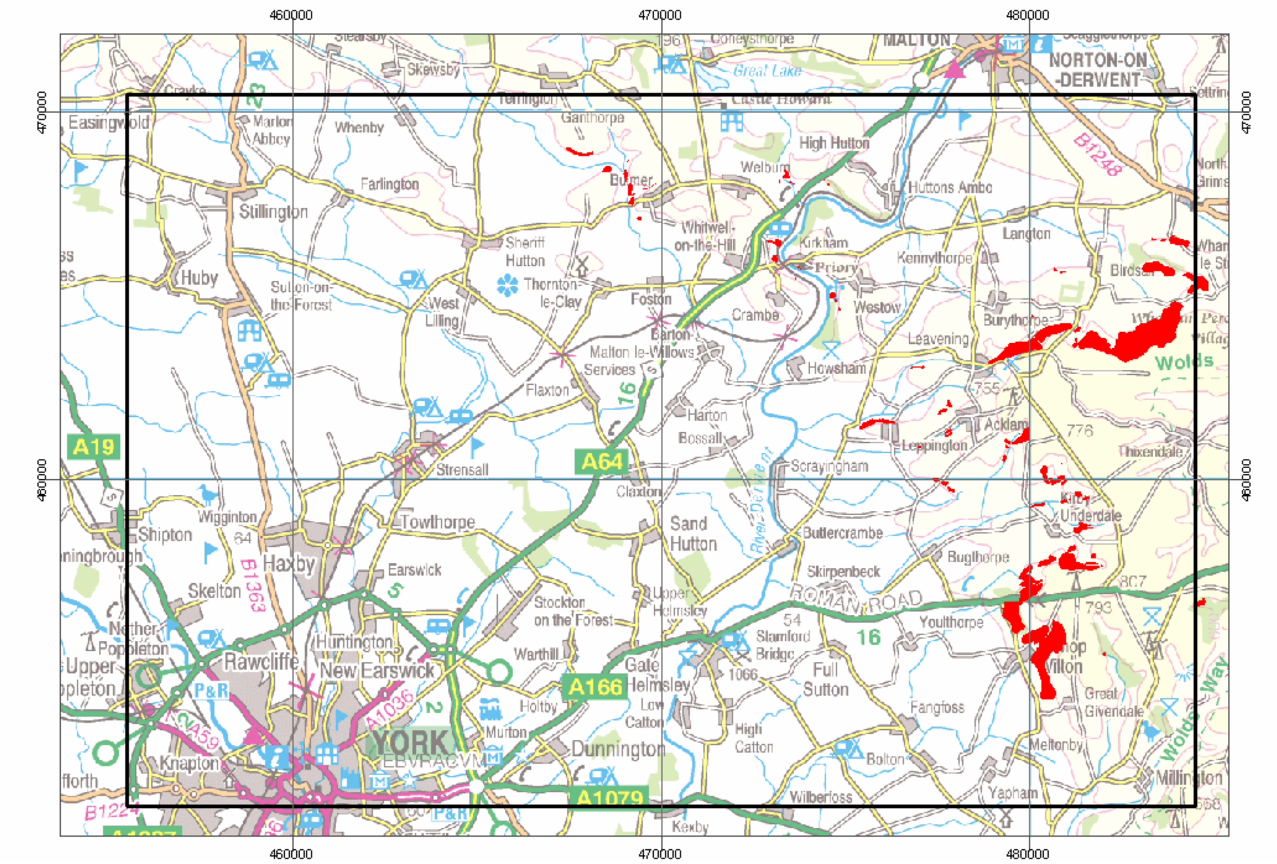

Figure 4. Landslides (red) mapped during the 2006-2007 survey of the York Sheet area.

Clustering of landslides has occurred on specific lithologies and in specific geomorphological settings. Concentrations of landslides are present on the Chalk where it forms steep escarpments as well as on the Penarth Group. The Penarth Group forms low-moderate angled ridges and spurs which appear to be susceptible to landsliding. Clusters of landslides are also found on the Whitby Mudstone Formation and Redcar Mudstone Formation (Lias Group) outcrop. These formations are typically present below the Chalk plateau and form moderately steep escarpment slopes. In the far west of the sheet there are no mapped landslides. This corresponds both to the presence of the more competent Mercia Mudstone Group and Sherwood Sandstone Group but also to the low relief of this area (Figure 6).

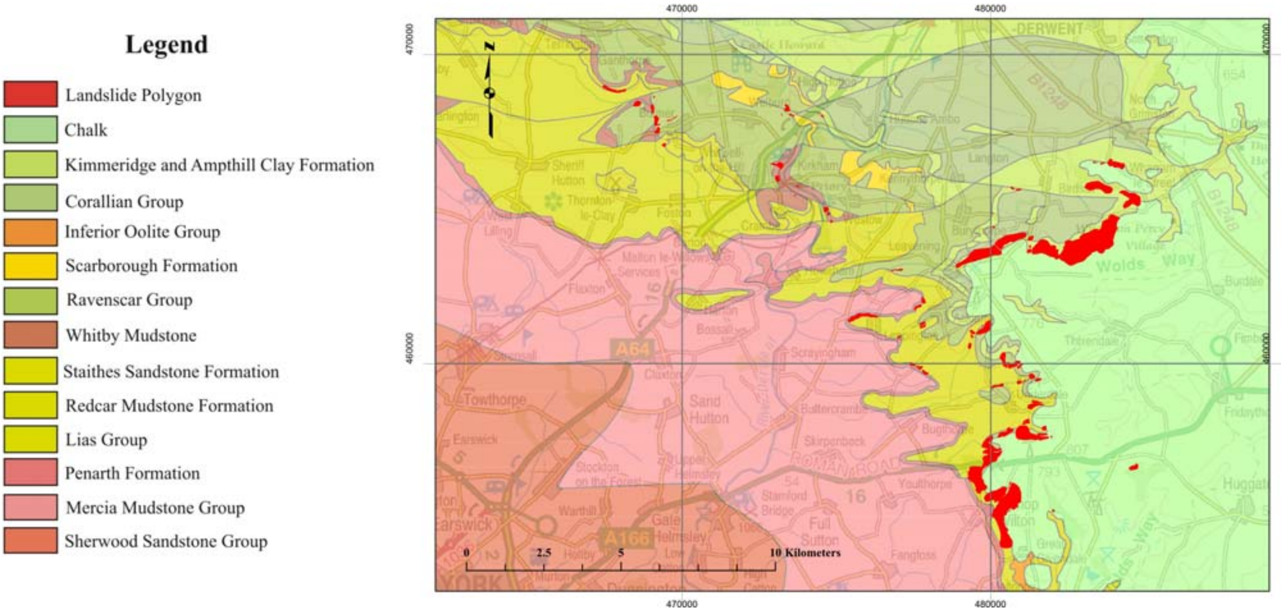

Figure 5. Geology and landslide distribution in the East of the District.

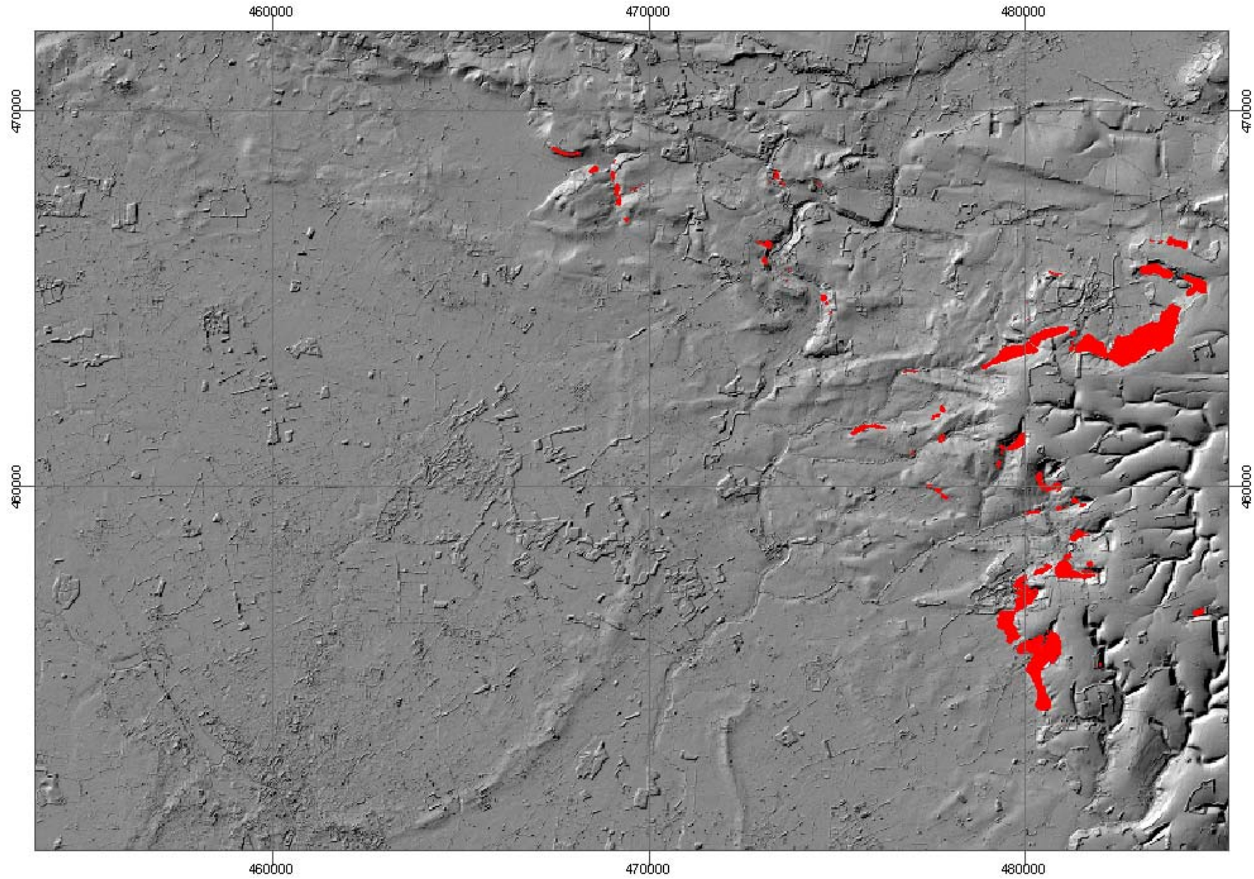

Figure 6. Digital Surface Model (NextMap DSM) for the York Sheet. Mapped landslide polygons are shown in red.

7 Landslide Analysis

7.1 GEOLOGICAL PATTERNS OF LANDSLDIES IN THE YORK AREA

In total, 83 landslides were mapped on the York Sheet, this equated to a total area of landsliding of 6.6km^2. Landslides occurring within Cretaceous and Triassic lithologies account for 19% and 7% of the recorded landslides respectively. Further analysis of the data collected shows that Jurassic sedimentary rocks are the most landslide-prone lithological units within the survey area. They account for 74% of the total area of landsliding (Figure 7). .This correlates well with the national pattern of landsliding produced by Jones and Lee (1994) using data from the now defunct Department of the Environment National Landslide Database. Analysis by Jones and Lee (1994) on the database was used to highlight eleven stratigraphic units which had the highest rate of inland landsliding in Great Britain. Six of these landslide prone stratigraphic units were Jurassic in age. Analysis of the database also highlighted the fact that some parts of the Jurassic sequence that crosses the UK have more than 25 landslides per 100 km^2.

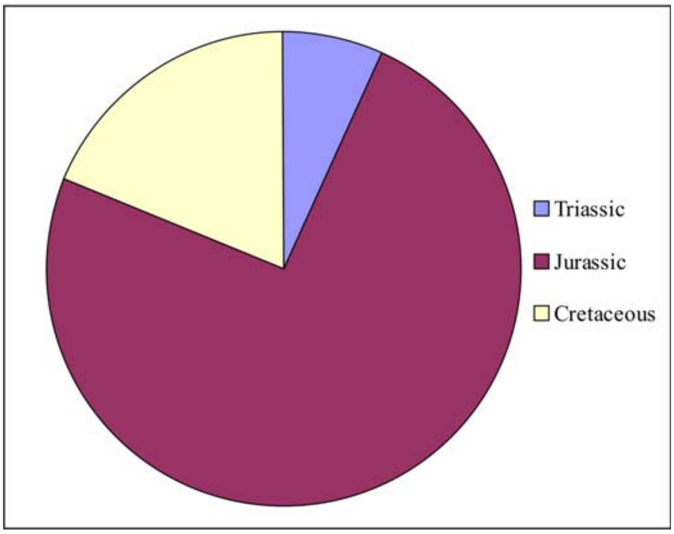

Figure 7. Age of lithologies involved in landsliding within the survey area.

Data obtained during the remapping of the York sheet shows that the Lower Jurassic (Lias Group) is the most prone to landsliding in the area (Figure 8). Figures collected during this study show that the Lower Jurassic of the York sheet has a much higher landslide density compared to that recorded nationally. Nationally the density of landsliding on the Lower Jurassic is 21 landslides per 100km^2 (Jones and Lee, 1994); whilst in York the figure calculated by this study is approximately 80 per 100km^2. This four fold increase is related to the detailed localised scale study carried out in York and the high density of landslides compared to area of geological outcrop. Across Great Britain the exposure of the Lower Jurassic is much greater in comparison with the number of landslides.

Nationally the Upper Lias is estimated to be mantled by landslide deposits across 51% of its outcrop (Jones and Lee, 1994). Data gathered by this study suggests that in the York area approximately 4% of the Whitby Mudstone Formation (Upper Lias) outcrop is mantled by landslide deposits. This analysis was carried out in ArcGIS using the digital landslide polygons generated during SocetSet analysis of aerial photographs and field mapping. In the York district the Whitby Mudstone had the most number of landslides involving a single formation. Nationally the Whitby Mudstone has been associated with high levels of landsliding such as along the Cotswold and Northampton escarpments where even gentle slopes are commonly associated with degraded rotational landslide deposits (Whitworth *et al*., 2005, Chandler, 1971). The Cotswolds and Northampton escarpment landslides are closely associated with the stratigraphic position of the Whitby Mudstone below a water bearing aquifer such as the Inferior Oolite. The reservoir principle of Denness (1972) who discussed the ability of geological aquifers to lead to instability. The principle states that when there is a supply of water to an impermeable layer of material this leads to sustained locally high pore pressures and the activation of landsliding (Whitworth *et al*., 2002). On the York sheet, landslides within the Whitby Mudstone are sometimes associated with the presence of the overlying Dogger Sandstone Formation which could be supplying water, leading to higher pore pressures and landsliding. The presence of an aquifer overlying a sequence of impermeable rocks may also account for the high comparative numbers of landslides involving the Chalk overlaying Jurassic units (Figure 9). Other combinations of formations that led to landsliding included the Middle to Upper Jurassic units overlying the Whitby Mudstone and the Redcar Mudstone overlying the Penarth Group.

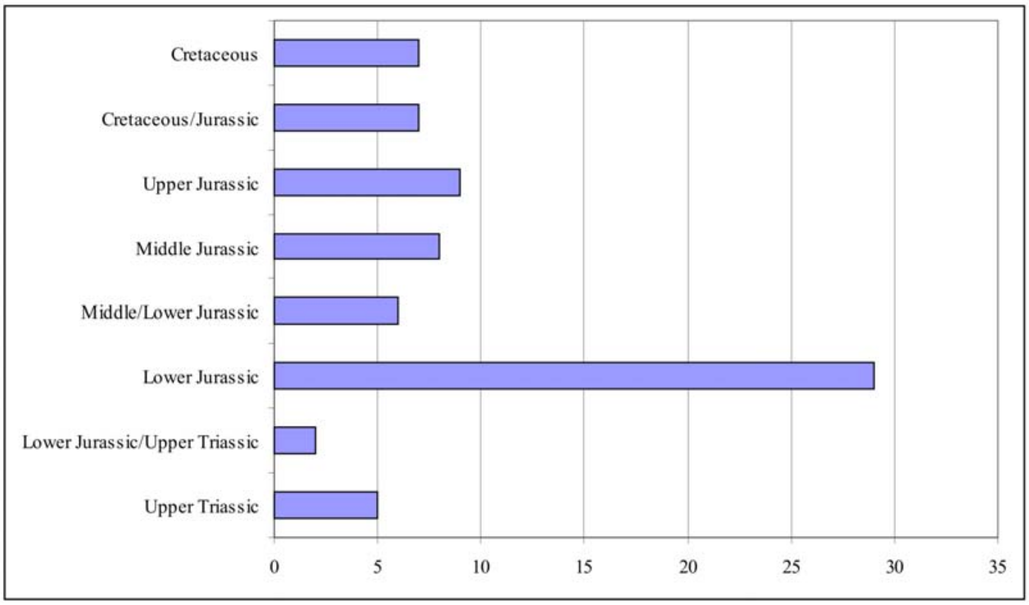

Figure 8. Number of landslides in chronostratigraphical intervals present on the York Sheet.

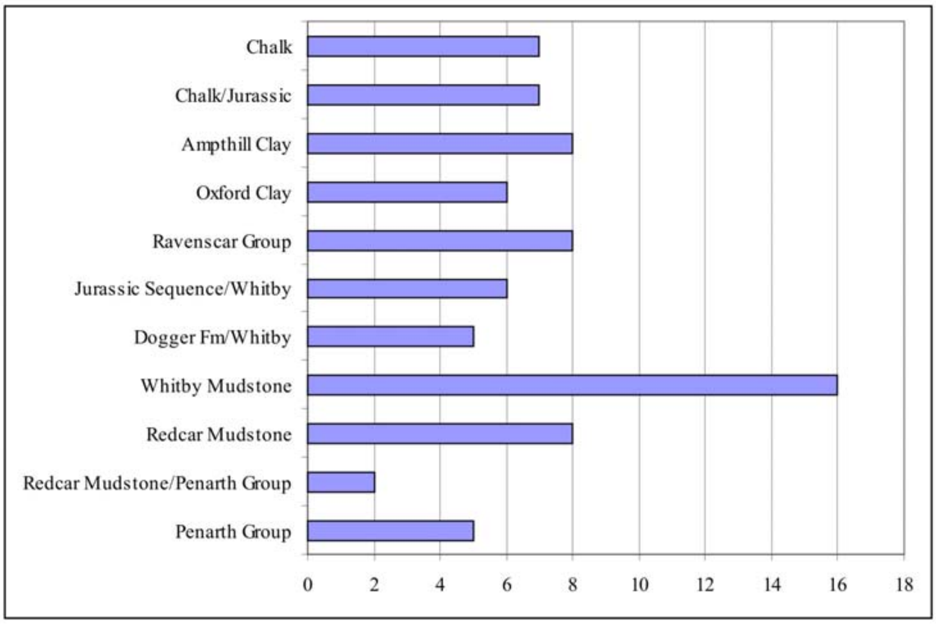

Figure 9. Landslide numbers for a range of groups, formations and formation combinations on the York Sheet.

7.2 STYLE AND MECHANISM OF LANDSLIDING IN THE YORK AREA

The dominant style of landsliding observed in the area of the York sheet was rotational failures; these are particularly prevalent on slopes in the Chalk Group (Figure 10). Failures occurring on the Chalk were characteristically multiple rotational landslides, occurring in slopes where the competent Chalk formed a caprock over relatively weak Jurassic formations. This situation, typified by Birdsall Brow (483309 463764), is common to horizontally/sub-horizontally bedded sequences of weak rocks overlain by stronger more competent rocks. Competent cap rocks, such as Chalk, can also instigate continued failures. After a rotational failure occurs; the cap rock, impedes the degradation of the back scar and maintains unstable conditions allowing further rotations to occur (Jones and Lee, 1994).

Whilst the Whitby Mudstone is known to be involved in larger scale rotational failures along the Cotswolds escarpment it displays a range of shallow failure mechanisms, including planar sliding or flows on the York sheet. In circumstances where the Whitby Mudstone is underlying other formations rotational failures are more prevalent (Figure 10).

Flows were also commonly recorded; characteristically on slopes of the Penarth Group, Whitby Mudstone and Ampthill Clay. Flows occurring on the Chalk were mostly associated with secondary failure or failure of the toe of a larger rotational slide. Weathering of the toe of a slide, along with ingress of water over an extended period of time, leads to a weakening of the displaced material and degradation by flows and small earth slides. Flows at the base of the Chalk Escarpment may actually be in the Ampthill Clay or other weaker material which is indistinguishable from the degraded Chalk landslide material that has fallen on to it and therefore been recorded as a flow in Chalk.

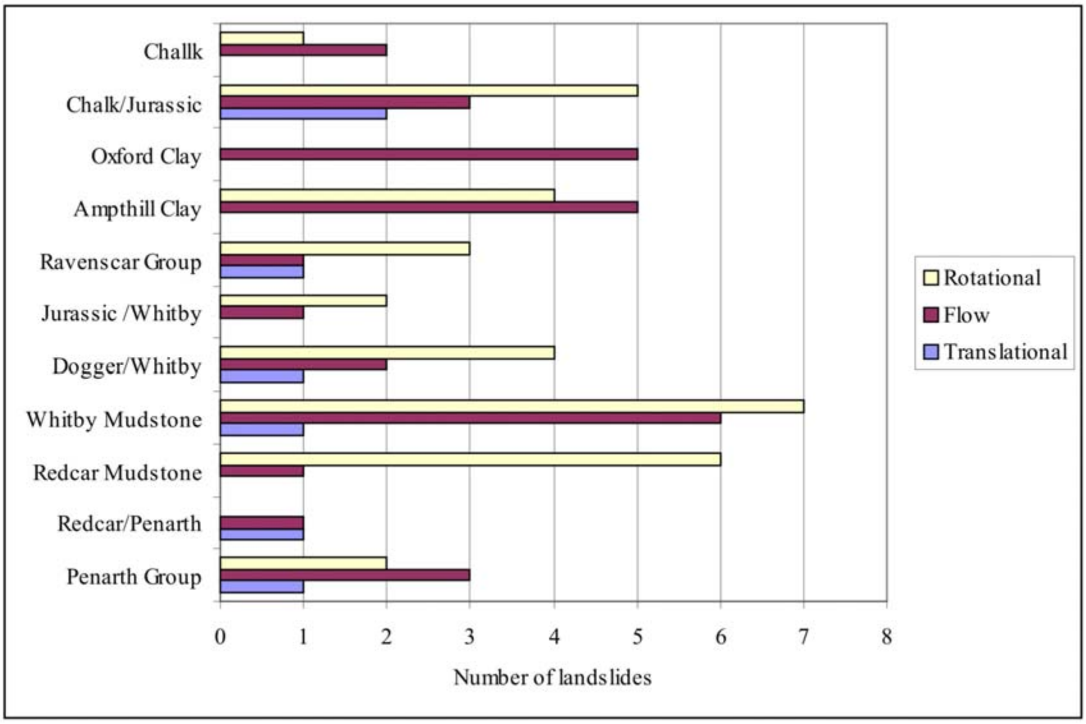

Figure 10. Numbers and style of landslides for different groups, formations and combinations of formations on the York Sheet.

7.3 AGE AND ACTIVITY OF LANDSLIDES IN THE YORK AREA

The level of activity and estimated age of landslides varied according to different geological successions (Figure 11). Most of the landslides found on rocks of Jurassic age, especially the Lower Jurassic, were thought to have occurred relatively recently (within the past 100 years). Although there is no conclusive evidence for age, the overall morphology, degree of degradation, over-printing by farming activity and consideration of the environmental conditions under which a failure could have been expected to occur, indicated an age of around a century. It was considered unlikely that a very shallow landslide would still be clearly visible more than a hundred years or so after taking place. Landslides associated with the Chalk group, were thought to extend to over 1000 years in age. Again, based upon morphology, degradation, archaeology and consideration of failure conditions, it was considered that these very large features, involving considerable thicknesses of bedrock were of greater antiquity and were probably associated with periglacial conditions, last experienced much more than a thousand years ago, generally being older than about 12 000 years.

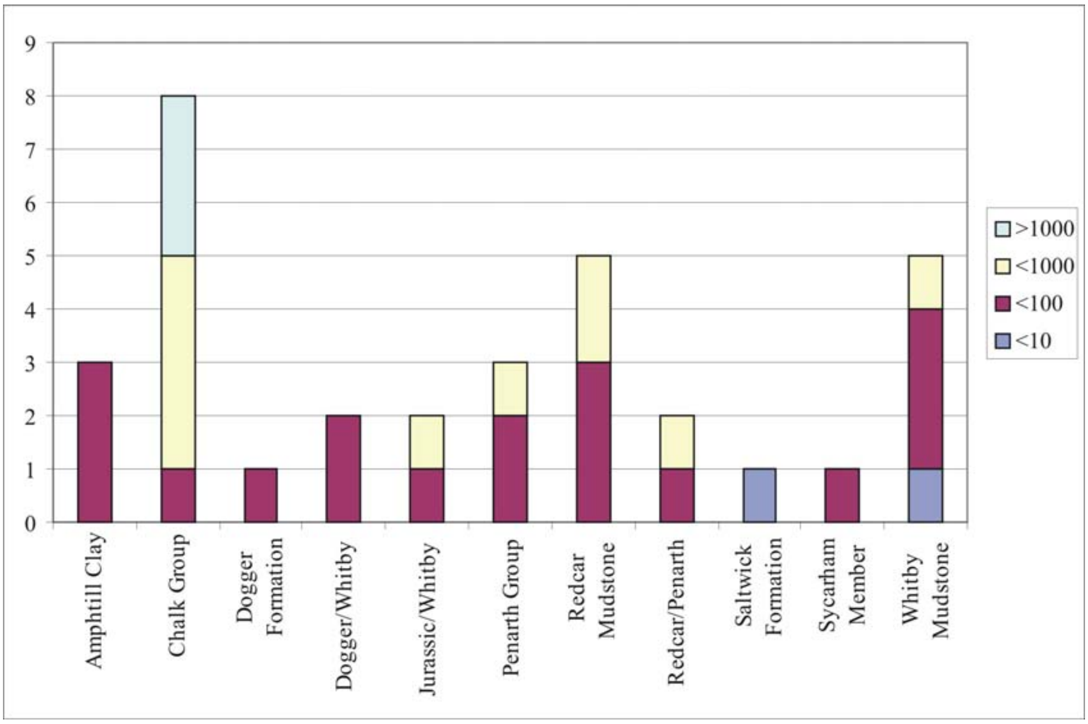

Figure 11. Estimated age of landsliding associated with units on the York Sheet (range less than 10 years to more than 1000 years).

8 Landslide Systems of the York Sheet

Mapping of known, visible landslides is essential, however it is also useful to know where conditions are favourable for landsliding to occur in the future and what type of failure this may be. During the remapping of the York sheet a slightly different approach was taken to mapping the distribution of landslides. The Landslide System approach aims to identify the characteristic geological and geomorphological conditions, which are prone to landsliding and to identity the types of landslide these conditions can cause. In this way a small area of landslide mapping can produce information that is relevant to a larger regional area, such as the Lias escarpment. This approach builds on Terrain Evaluation or Land System mapping which originated during the 1930’s and 1940’s in Australia (Lawrance *et al.*, 1993). Interactions between geology, climate and landforming processes produce patterns of recurring landforms mappable at different scales (Lawrance *et al.*, 1993). Land systems mapping uses a hierarchical approach allowing a large area to be broken down systematically into smaller units depending on geology, hydrology and geomorphology. Griffiths *et al*., (2005) established that land systems mapping can provide an effective tool in the investigation of landslide distributions at a regional scale, therefore this approach was incorporated into this research.

This study identified nine landslide systems based broadly on geology (Table 2), as has already been established (Section 6) geology acts as a controlling factor determining the nature, distribution and style of landsliding within the York area. Each landslide system consists of a type and style of landsliding that is characteristic of the local geology and topography. Of the initial nine systems, three were identified which form the final landslide system model for the areas.

Geology	Style	Nature	Type landslide	Landslide System
Penarth Group and Redcar/Whitby Mudstone Formations	Flows and translational slides	Shallow. Degraded. <100 yrs olds. 2-3m deep maximum	Hanging Cliff	System One
Redcar Mudstone	Multiple Rotational failures	Moderately deep-seated. Recent. Active	Salamanca Beck	System Three
Redcar and Whitby Mudstone Formations, Penarth Group	Complex landslides	Deep Seated. Rotational slides and flows	Boot and Shoe Plantation	System Three
Penarth Group and Redcar Formation	Rotational slides and flows	Deep-seated. Active.	Bishop Wilton	System One
Full Jurassic Sequence	Translational slides and flows	Recent. Shallow.	Acklam Brow	System One
Ampthill/Oxford Clay Formation	Flows	Active, Shallow slope angles.	Swindham Woods	System One
Whitby Mudstone Formation	Rotational slides	Recent. Active	Acklam Beck	System Three
Chalk over Ampthill Clay Formation	Multiple/ Successive rotational slides.	Degrade into flows. Old. Degraded	Birdsall Brow	System Two
Chalk overlying Jurassic	Complex-	Deep-seated. Rotational and flows	Back Warren Plantation	System Two

Table 2. Initial landslide systems present on the York Sheet.

8.1 LANDSLIDE SYSTEM ONE

Shallow landsliding involving Upper Triassic to Upper Jurassic mudstone/clay dominated lithologies.

Landslides within this system were relatively widespread across the entire eastern side of the area. The geological formations associated with landslide system one are the Penarth Group, Redcar Mudstone Formation, Whitby Mudstone Formation and the Ampthill Clay Formation. The spatial extent of these formations is shown in Figure 12. The landslide mechanisms commonly present in this system are earth flows and earth slides. It can however be difficult to determine the precise mechanism of these landslides due to the degraded nature of some of the morphology and the remote nature of data collection. Flows in this field area are unlikely to be the type of fast moving, saturated movements that take place in more mountainous regions. However, it is likely that slow earth flows, as defined by Varnes, 1978, do take place. Slow earth flows are common in plastic materials derived from clay or weathered clay rock, where there is a moderate slope and adequate rainfall (Varnes, 1978). In the context of this system these characteristics are likely to be met in the York region where slopes overly the lithologies listed above. In order to differentiate an earth flow from an earth slide it is necessary to determine whether there are any shears present (earth slide) or whether there is strong internal deformation (earth flow).

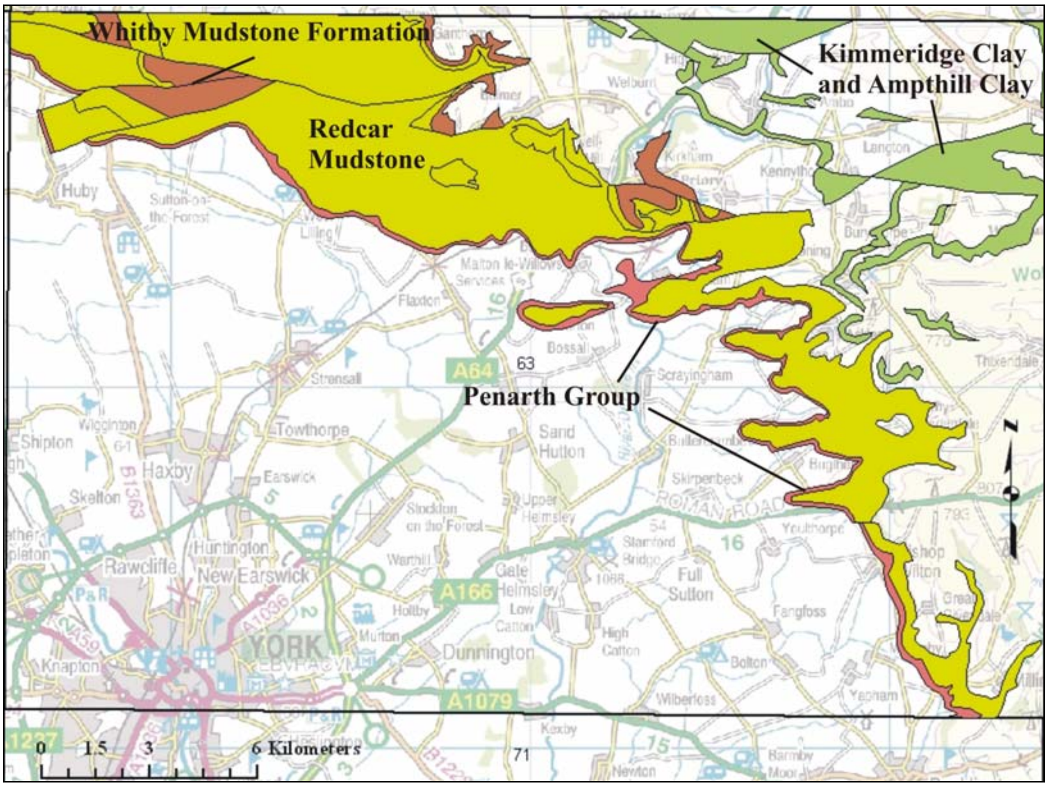

Figure 12. Location of the geological formations associated with Landslide System One within the York Sheet.

8.1.1 Penarth Group

The Penarth Group outcrops between the Whitby and Redcar Mudstones and was found to be characterised by widespread landslide activity. This research has shown that the Penarth Group in the York area is susceptible to shallow flows and translational slides. Examples of these types of shallow failures were mapped near Barthorpe and Leppington. The Barthorpe landslides varied in their stage of development with a degraded landslide (Denn Ings Plantation landslide - NGR 477543 460013) and two recent, fresh slides (Barthorpe Grange - NGR 477977 459715, and Ash Tree Farm - NGR 477767 459928 landslides) being present. The landslides occurred mainly within the Penarth Group, although the back scar of the Ash Tree Farm landslide was in the Redcar Mudstone Formation, (though this interpretation could however relate to mapping inaccuracies) (Figure 13). The failures, which were shallow, primarily involved weathered mudstone and earth as no superficial deposits were mapped at the site. The landslides occurred on a low angled slope (7-8°) facing South-Southwest and were between 150-175 m wide, 60-100 m long and less than 2 m deep. Two areas of recent activity were identified as hummocky ground during the air photo interpretation, (Figure 14). The older, degraded landslide (Denn Ings landslide) had subdued hummocky topography but was still identifiable as a landslide. No steep back scars were present and the series of hummocky terraces indicated shallow translational sliding had taken place.

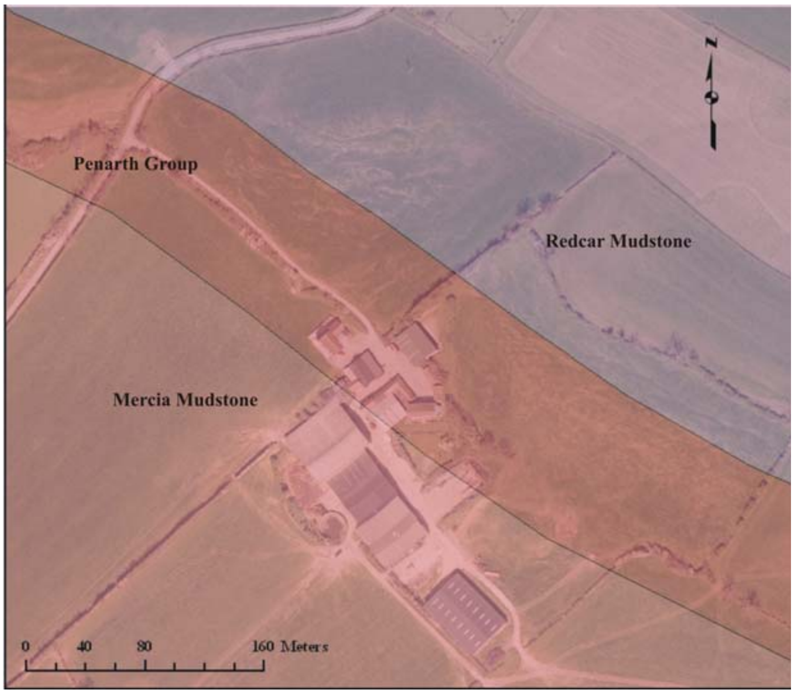

Figure 13. Geology at the site of the Denn Ings and Barthorpe Grange landslides.

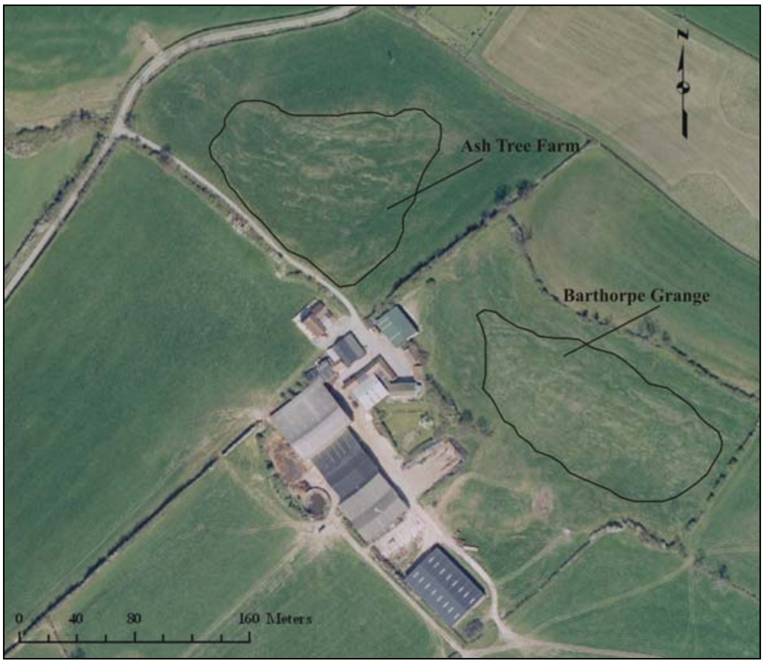

Figure 14. Outline of landslides in the area of Figure 13 showing hummocky topography of translational sliding and flowing.

Whilst the Barthorpe and Deng Ings landslides exhibited both shallow translational landsliding and possibly flowing, those at Leppington (Hanging Cliff landslide) were more characteristically flow like, comprising a cluster of earth flows that stretched for nearly 1 km. This cluster of landslides was similar in morphology to that of a landslide in the Penarth Group on the Warwick sheet. This landslide was attributed to the occurrence of springs at the base of the Langport Member, a thinly bedded limestone which acts as an aquifer above the less permeable calcareous mudstones of the Cotham Member (Old *et al*., 1987). The landslides on the Warwick Sheet occurred at similarly low angles as those at Leppington, roughly 8-10º. The presence of earth flows in the Penarth Group is not surprising as these types of failure are common in clay dominated lithologies where there is an adequate slope angle and moisture (Baum *et al*., 2003). The low slope angles at which failures were occurring at are most likely due to the material being at residual strength following prior failures and the presence of relict shears within the slope. As well as the presence of relict shears, the input of water is equally important to stability within slopes of the Penarth Group. With the addition of water, the weight of material increases which in turn increases the shear stresses. The increase in water content also leads to an increase in the pore water pressures and a reduction in effective stress therefore reducing the shear strength of the soil and the stability of the slope (Baum *et al*., 2003).

8.1.2 Whitby Mudstone Formation

Another formation involved in extensive landsliding within system one is the Whitby Mudstone Formation. The Whitby Mudstone Formation is present on slopes of the Lower Lias succession across the whole sheet. This research has shown that the Whitby Mudstone Formation is mostly involved in rotational landslides and flows. In parts of the sheet the River Derwent incises the Whitby Mudstone and a landslide (Kirkham Priory 2 landslide) has occurred close to its banks near Kirkham Priory (**Figure 15**). The back scar of the landslide lies at the boundary of the Dogger Sandstone Formation and the Whitby Mudstone Formation (NGR 473794 465715) (Figure 16). The landslide is recent and fresh features were identifiable from the aerial photographs. The scale of the landslide is much smaller than that of the Penarth Formation slides previously described (Length 50 m Width 30 m). The Kirkham Priory 2 landslide faces southwest on a slope of c.10° and is relatively shallow, involving only the weathered mudrock and soil. The initial landslide movement appears to have been translational in nature, which has developed into a flow involving the displaced material. Further evidence of instability within the Whitby Mudstone was observed on the opposite side of the River Derwent at Oak Cliff (NGR 473643 465414) during the field visit. A recent shallow translational landslide was present along with what appeared to be degraded mudflow lobes. The lobes, flowing from beneath the tree line, are near to a normal fault that has been mapped on the current 1:50 000 map sheet. This landslide was mapped as a single deposit as the cluster of mudflow lobes was degraded and access was not possible during the field visit to confirm that these were mappable landslide deposits.

Figure 15. Kirkham Priory landslide. Photograph taken from NGR 473669 465547, orientation 025° NE.

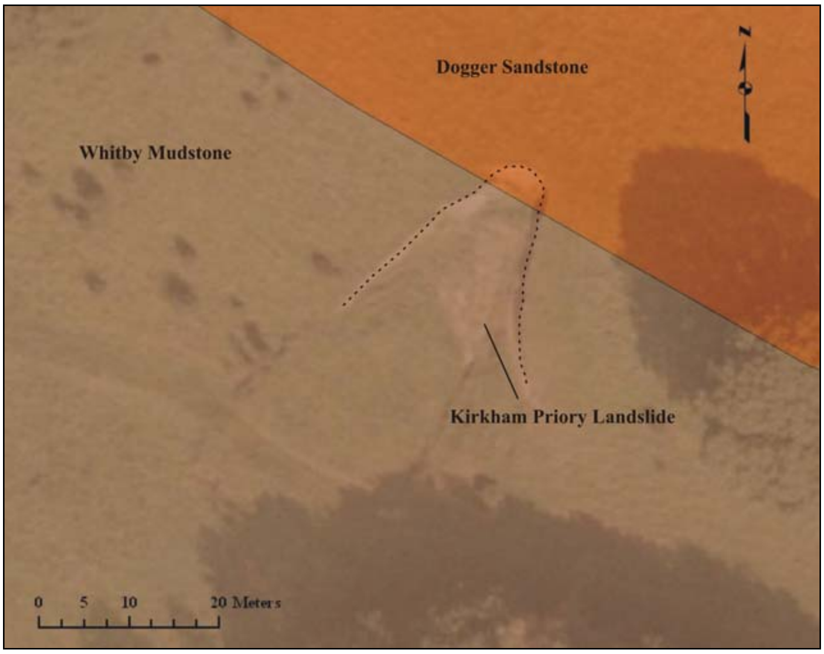

Figure 16. Geology and aerial photograph of the Kirkham Priory landslide site.

8.1.3 Redcar Mudstone formation

The third unit involved in landsliding in system one is the Redcar Mudstone Formation, which was extensively landslipped in the south of the sheet despite having a larger spatial extent in the NW. A large landslide was mapped here on a moderate (9-10°), south facing slope, near the village of Bishop Wilton (NGR 479876 455277). The Ochrepit Lane landslide (NGR 480160 455921) has an element of rotational failure at the head of the slide as well as shallow successive slides within the main body. The landslide seems to degrade into shallow flows near the toe (Figure 17). Unlike with many of the other slides recorded on the York Sheet, the Ochrepit Lane slide occurs close to infrastructure. The toe of the slide underlies the road and is less than 50 m from a street of houses. Active landslides in the Redcar Mudstone are widespread around the village of Bishop Wilton (Figure 18).

Figure 17. View of the Ochrepit Lane landslide, Bishop Wilton. Degraded blocks and lobes are visible in the landslide mass. Photograph taken from NGR 480163 455251, orientation 355° N.

Figure 18. Aerial view of the Ochrepit Lane landslide. Movement is from the north to south. The larger, more deep-seated Bishop Wilton landslide is also clearly visible.

8.2 LANDSLIDE SYSTEM TWO

Deep-seated rotational landsliding in Upper Jurassic to Upper Cretaceous mudstone and chalk

Landslides within this system are confined to the north-western margin of the chalk escarpment that forms the Yorkshire Wolds. These landslides form very large geomorphological features that are easily identifiable from aerial photographs. Within the area of the York sheet, the Birdsall Brow, Leavening Brow and High Barn Plantation landslides are categorised under landslide system two.

8.2.1 Birdsall Brow

The Birdsall Brow landslide (NGR 482830 463395) is located on a northerly facing slope with an average slope angle of 9° (Figure 19). The landslide is 800 m wide and 3000 m long. It is not known with any degree of accuracy how deep the shear plane is. The landslide has formed as a result of large chalk blocks (up to 420 m in width and 90 m in length based on geomorphological evidence) successively rotating on the underlying Ampthill Clay Formation. These rotated chalk blocks now produce successive ridges down the slope (Figure 20). The displaced chalk blocks have formed a disrupted, ridged topography, with the leading edges of successive chalk blocks forming ridges up to 30 m in height, with broad troughs, up to 70 m wide in between. Towards the lower part of the landslide complex, more distant from the chalk escarpment, the landslide style changes to shallow flows, probably in the Ampthill Clay Formation. As above, the overall topography, assumed failure mechanism and degree of degradation indicate that this landslide probably occurred during a climate more aggressive than presently found.

Figure 19. Aerial photograph of the Birdsall Brow landslide. Mapped landslide polygon in red.

8.2.2 Leavening Brow

The Leavening Brow landslide (NGR 480292 463503) is also located on a northerly facing slope 2 km to the west of the Birdsall Brow landslide (Figure 21). The average slope angle is 9°. The landslide is 1000 m in width and 350m in length. The proposed mechanism of failure is similar to that seen on Birdsall Brow, with the overlying chalk successively failing in a rotational manner on the underlying Ampthill Clay. However, the ridged slope profile observed at Birdsall Brow is not replicated here. Those ridges which do have a topographic expression are less frequent and on a smaller scale (10m in height, with 30 – 40m troughs). The landslide style changes to shallow mudflows in the lower part of the landslide, distal to the source of the chalk upslope. Leavening Brow forms a west-east trending peninsula at the western end of the Yorkshire Wolds escarpment. The drainage catchment is considerably smaller in comparison with the Birdsall Brow landslide, and therefore the landslide features are less developed.

Figure 20. View of the eastern edge of the Birdsall Brow landslide, note ridges formed by the leading edge of chalk blocks. Photograph taken from NGR 483309 463764, orientation 045° NE.

Figure 21. Aerial photograph of the Leavening Brow landslide. Mapped landslide polygon shown by red outline.

8.2.3 High Barn Plantation

The High Barn Plantation landslide is probably a continuation of the Leavening Brow landslide that has been incised by a drainage channel running southeast-northwest across the slope (NGR 480713 463927 (Figure 22). Again the slope angle is approximately 9°. The landslide is 1000 m in width and 270 m in length. This landslide displays the most subdued topography of those in this system. It is thought that this is possibly because the main drainage of this section of slope was directed away from the landslide, and therefore the landslide and its associated geomorphological features are less developed The topography formed by rotated blocks within the chalk is clearly seen. Drainage features are visible in the ploughed field to the east of the area indicating that there has been sufficient time elapsed since the landslide formation for a fairly complex drainage system to have formed.

Figure 22. Aerial photograph of the High Barn Plantation landslide. Mapped landslide polygon shown by red outline.

8.3 LANDSLIDE SYSTEM THREE

Rotational failures involving a sequence of Jurassic lithologies with a Chalk cap rock <u>or</u> Rotational failures within a single formation.

Landslide System Three encapsulates a large number of relatively shallow failures within Jurassic lithologies, unlike Landslide System 2 these rotational failures predominantly occur without a cap rock. Location/distribution of lithologies.

8.3.1 Multiple Rotational failures (with a cap rock)

The landslide at Back Warren Plantation, 1 km south-west of Acklam (480008, 461133) is an example of a rotational failure not involving a caprock. This landslide was approximately 65 m wide and 250 m long and involves a range of formations from the Cretaceous Chalks through to the Middle Jurassic Ravenscar Group (Figure 23). Topographic benches were observed at different elevations down the slope. Although these could be lithological in nature, it is thought that they represent landslide blocks as the same stratigraphic sequence occurs on the opposite side of the valley, yet no similar bench features are observed (Figure 24). The landslide has been interpreted as a multiple rotational failure. Landslides of this type are common where relatively stiff fissured clays are underlain by a more competent unit and overlain by a strong cap rock. In this instance the presence of the Oxford Clay underlain by the Saltwick Formation and overlain by the Chalk may have provided suitable geological conditions to produce multiple rotational failures. The presence of the Whitby Mudstone underlying the whole sequence may have also aided instability.

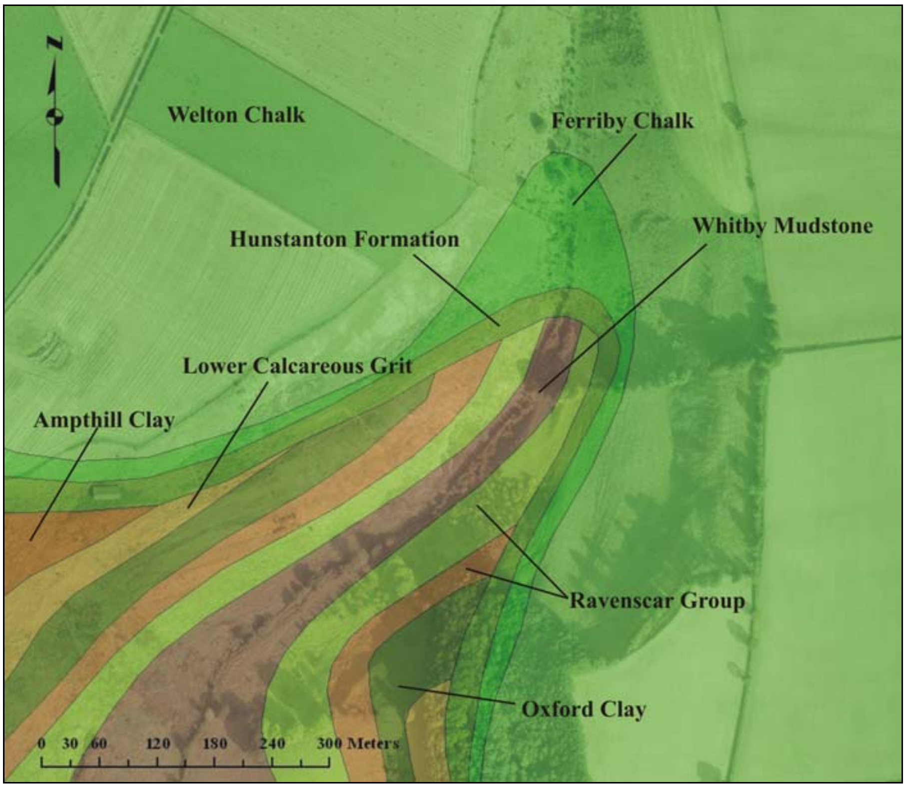

Figure 23. Geology of the Back Warren Plantation landslide.

Figure 24. A view of the Back Warren Plantation landslide taken from NGR 480024 461270, orientation 335° (NW). A: Rotated blocks, B: Back scar.

8.3.2 Successive Rotational failures (without a cap rock)

At Mowthorpe (468387, 468258) a moderately deep-seated successive rotational failure (Mowthorpe Bridge landslide) was observed within the Redcar Mudstone Formation (Figure 25 and Figure 26). This landslide had a distinctive rear-scarp, zone of depletion and a series of hummocks, characteristic of shallow rotational failure. Elsewhere in the UK, successive rotational failures are predominantly confined to the weathering mantle and are generally shallow to moderately deep-seated (Hutchinson, 1988). Successive failures on slope gradients in the range 8-13° are also common in the London Clay (Hutchinson, 1988) and other stiff fissured clays such as those of the Lias or Weald. Along the Upper Lias Clay escarpment at Rockingham the slope angle for failures in these lithologies is generally 8.5-9° (Chandler, 1971). At Mowthorpe the landslide is occurring on a slope of 8°, which fits into the ranges of landsliding on the Rockingham escarpment and slopes overlying the London Clay.

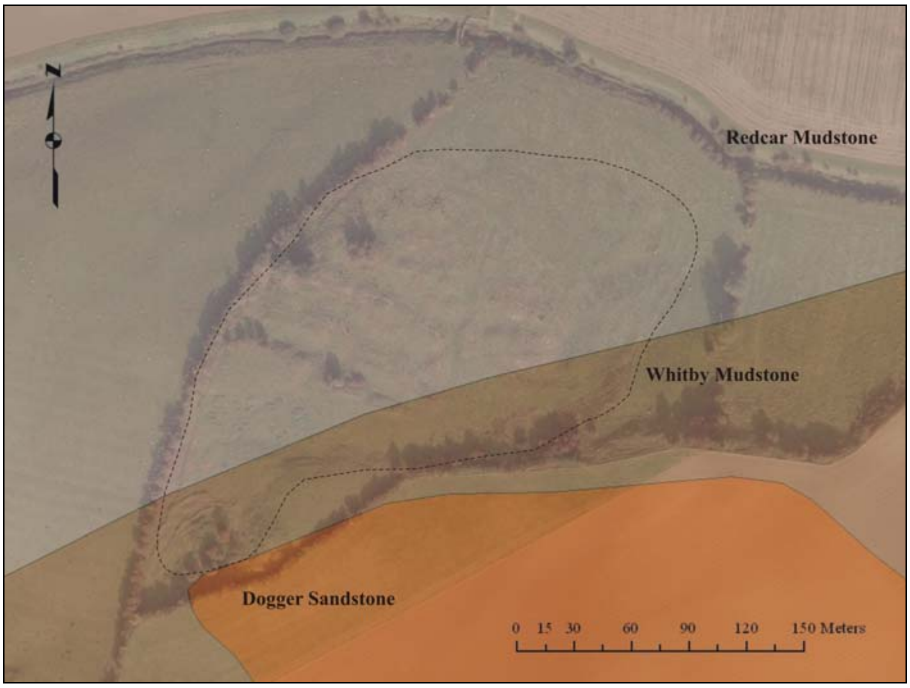

Figure 25. Geology and aerial photograph of the Mowthorpe Bridge landslide

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Figure 26. Mowthorpe Bridge landslide. Photograph taken from NGR 468695 468946, orientation 200° S. Note, shallow, sub-parallel ridges, indicating successive rotational sliding.

8.3.3 Single Rotational Failures

A smaller rotational landslide was observed at Salamanca Beck (480333, 459259) in the Redcar Mudstone Formation (Figure 27 and Figure 28). Unlike the Mowthorpe landslide this failure is a single rotational landslide stretching over 450 m but with a length of only 50 m. Single rotational failures such as this are most common in relatively homogenous material such as clay or shale, especially when undercut by the sea (Jones and Lee, 1994). Rotational failures can also occur in more granular material if the pore water pressures are significantly high enough (Hutchinson, 1988). Whilst there is no influence of the sea at this site the landslide may have been caused by river undercutting, there also springs present at the base of the overlying Saltwick Formation feeding the main landslide body with water possibly contributing to instability. The Salamanca Brook landslide has a slope angle of between 7-9°, slightly lower in places to that of the successive rotational failure in the same material at Mowthorpe. The lower slope angles in some section of the Salamanca Brook landslide may be due to an increased pore pressure from springs and the additional removal of support at the toe by river incision.

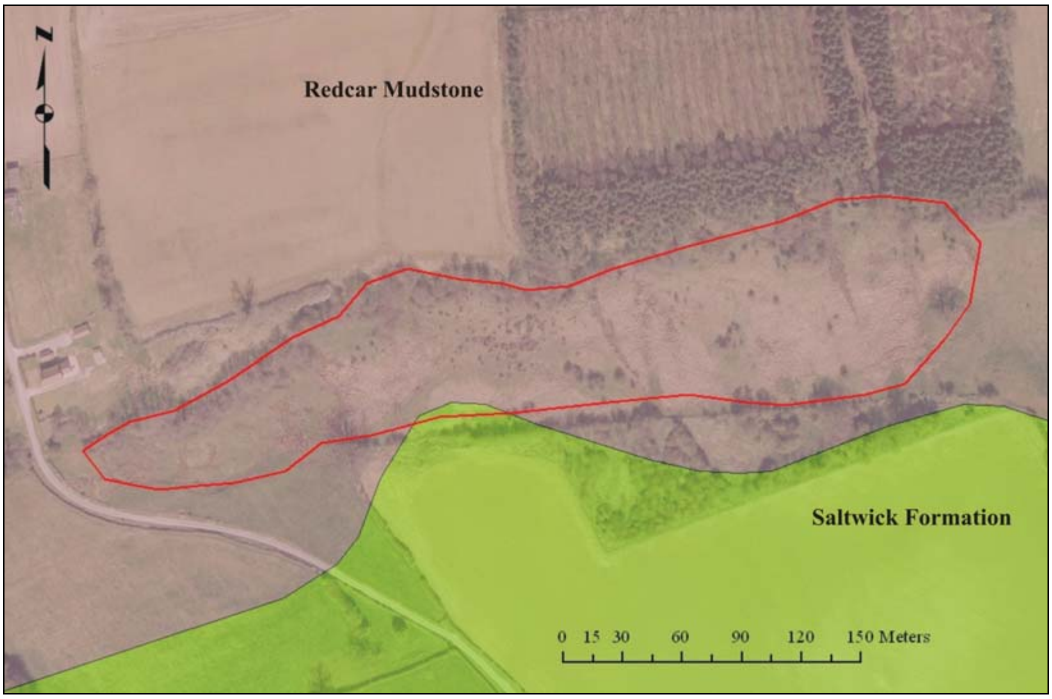

Figure 27. Geology and aerial photograph of the Salamanca Beck landslide. Mapped landslide deposit shown in red.

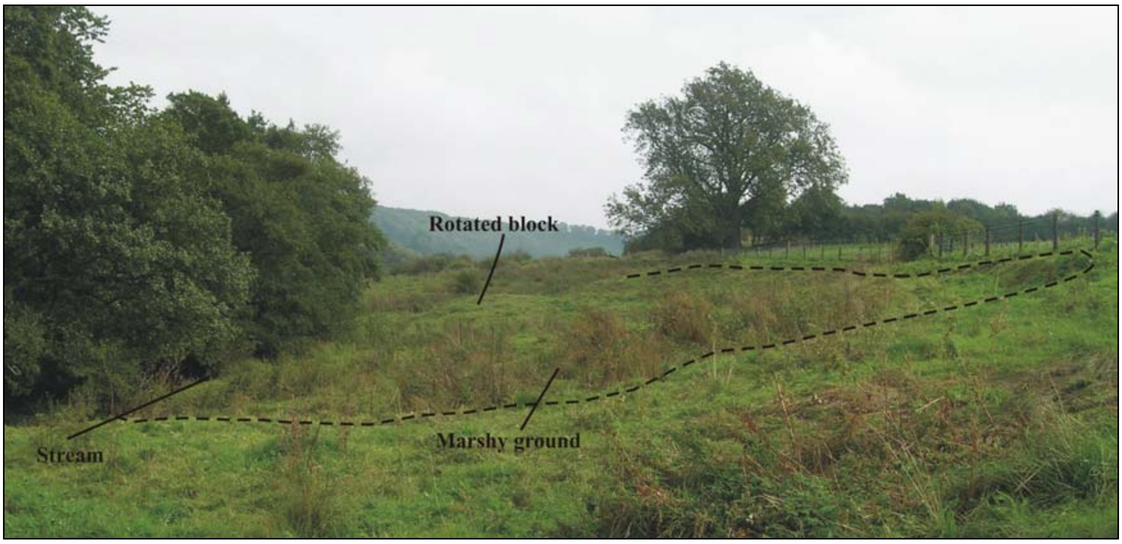

Figure 28. Salamanca Beck landslide. Photograph taken from NGR 479975 459220, orientation 080° E. Note that a single block has been involved in this movement.

Near the banks of the River Derwent, at Fulsty Head a single rotational failure was observed measuring 190 m wide and 160 m long (472991, 465995). Like the Salamanca Brook landslide the movement has only taken place in one lithology, the Whitby Mudstone. Due to the degraded nature of the landslide it was not mapped during the aerial photograph interpretation and was only detected during field reconnaissance. The most visible landslide feature was the presence of a back tilted block near the head of the landslide, indicative of a rotational failure mechanism (Figure 29). The steepness and extent of the rear scarp indicates that this landslide is deeper seated than that at Mowthorpe and Salamanca Beck, however, this landslide is more degraded and probably occurred under different climatic conditions to that of the more shallow landslides.

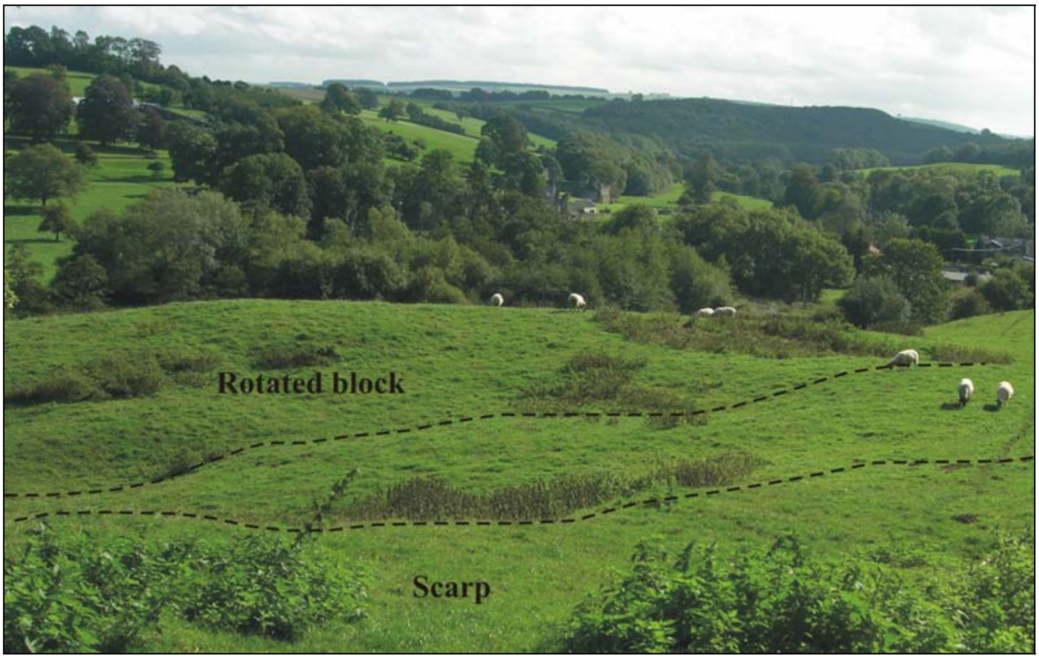

Figure 29. Fulsty Head landslide. Photograph taken from NGR 473010 466042, orientation 120° SE.

9 Mapping of features from the NextMap DTM

Within the Landslide System Two the landslides were of a size significant enough to allow mapping of their features using the NextMap DTM. West of the Leavening Escarpment landslides and also on the escarpment another landslide was observed, although its mapping was made difficult by the subdued nature of the features seen in the field. However, landslide features were visible from NextMap, which showed a series of arcuate scars that may indicate the presence of deep-seated rotational failures (Figure 30). These features had not been observed during the aerial photograph interpretation stage of the project. A brief study of other Chalk escarpment was undertaken to determine if these features were indicative of failures on the Chalk. The features were not found to be present on any other large-scale landslides involving the Chalk. The only other presence of these features is on the Scarborough sheet, which is next to be surveyed; however it is not known whether these features are indicative of large-scale landsliding. In the field these scars do not form strong geomorphological features that would be readily mapped. The presence of these features may suggest a mechanism for system two landslides similar to that displayed at Folkestone Warren. At this location the landslide was triggered by lateral extension in the Gault Clay which led to stress in the overlying Chalk and the generation of a shear surface near the base of the Chalk (Figure 30 I) (Hutchinson, 1969). The lack of support for the Chalk at the base of the slope led to the development of a series of slips (Figure 30 II) which continued until these slipped blocks were supported by the slope behind it (Figure 30 III). At Leavening, the Atherfield and Kimmeridge Clay Formations would replace the Gault if this analogy were to be true. This method of failure was also proposed for the Castle Hill landslide where lateral extension and expansion of the Gault through denudational unloading led to the formation of numerous shears (Birch and Griffiths, 1996). Oversteepening occurred during late-glacial to early post-glacial times. This led to movements which are believed to have used some of the pre-existing shears in the Gault that were at or close to residual strength (Birch and Griffiths, 1996). Further evidence of landsliding at Leavening was provided by a faunal study undertaken by M. Woods at the western edge of the escarpment (Figure 31). Based on faunal and lithological evidence it is suggested that at the top of the slope forming the flat lying Wolds is Burnham Chalk, whilst the slopes are formed in Welton Chalk. However at location A on Figure 31, Burnham Chalk or Welton Chalk from high in the sequence was discovered and this is clearly out of place. This suggests a block of material that has been displaced from higher up the slope, most probably due to mass movement and being deposited at site A.

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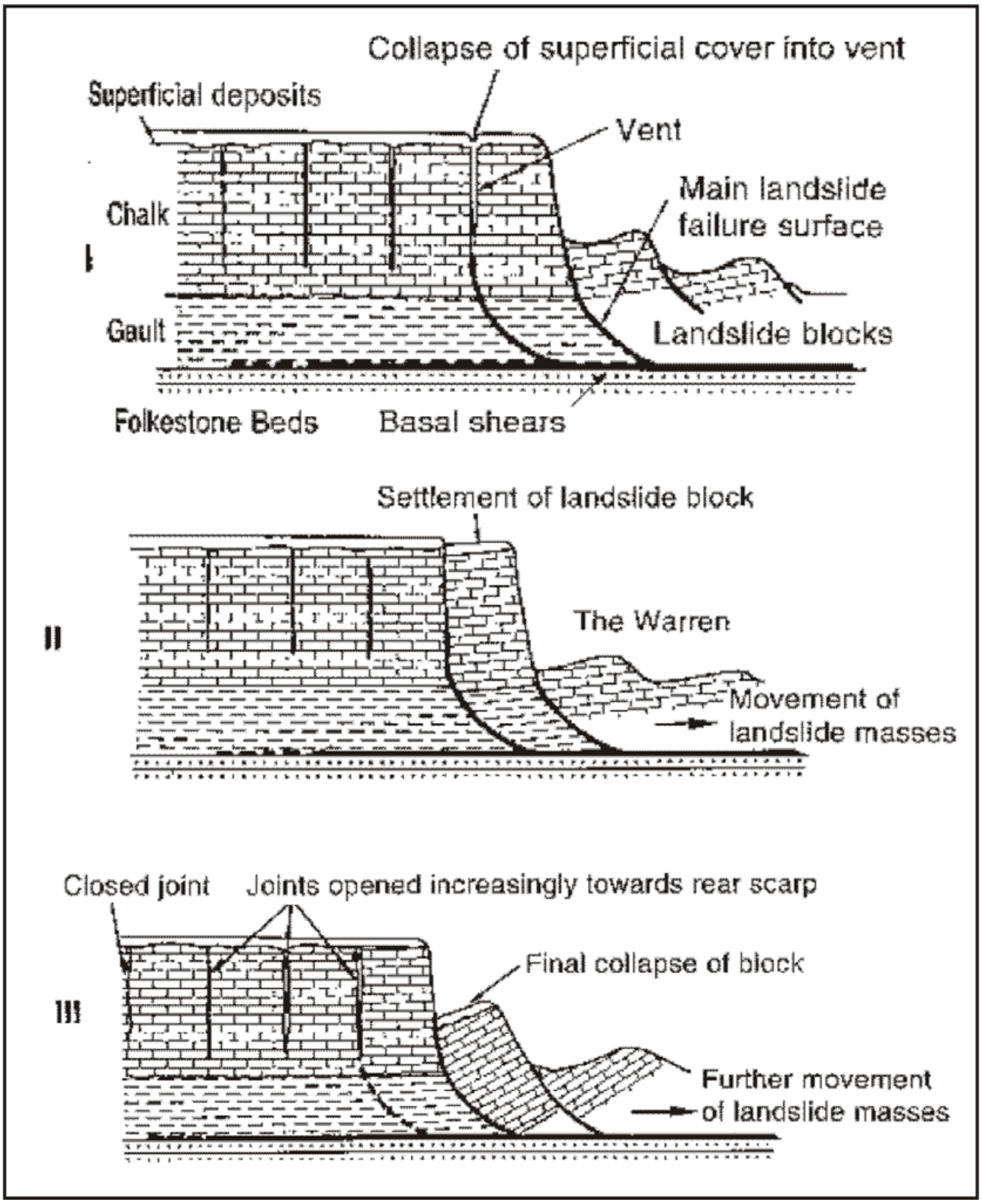

Figure 30. Mechanism of landsliding at Folkestone Warren (After Hutchinson, 1969)

Figure 31. NextMap image of western limit of escarpment near Leavening. The red dotted line indicates the furthest inland extent of the arcuate scars.

10 Comparison of GeoSure results with mapped landslides.

GeoSure is the BGS's national digital assessment of hazard potential for Great Britain, developed using the 1:50,000 DiGMap-GB data. Using a deterministic approach the causative factors of slope stability were identified and an algorithm developed to assess the stability of an area depending on the geology, slope and discontinuities. GeoSure is divided into five hazard ratings, from A to E. These ratings are classified as follows:

Table 3. Geosure hazard ratings.

Hazard rating	Description of hazard rating
A	No indicators for slope instability identified.
B	Slope instability problems are unlikely to be present.
C	Slope instability problems may be present or anticipated.
D	Slope instability problems are probably present or have occurred in the past.
E	Slope instability problems almost certainly present.

To assess how accurate GeoSure is in the York area, examples of GeoSure data have been derived for areas coincident with landslides described in this report. At the site of the Deng Ings landslide cluster, discussed in landslide system one (Figure 32), the GeoSure rating is a C, indicating that slope instability problems may be present or anticipated. A few isolated pixels with a D rating are present. The presence of three landslides in this area and the lack of a higher GeoSure rating is in direct contrast to the landslide at Hanging Cliff (Figure 33). In this example the landslide, which was mapped without consulting the GeoSure data, fits almost exactly to the area of D rated pixels. As the geological material is identical, the Penarth Group, the factor that is making the difference in rating is the slope angle. For the Deng Ings example the slope is an average of 7-8° whilst on Hanging Cliff the slope is generally 10-11°. This may indicate that the slope angle values for the Penarth group in the York area needs to be reduced to be more representative of the landslides that are occurring.

In the Bulmer area five landslides are present in a range of lithologies (Figure 34). Hollin Hill receives a D rating which is appropriate as the landslide is active and in an advanced state (Jenkins *et al*., 2006b). At Mowthorpe the landslide gets a C rating which is probably too low. However the landslides concentrated around Bulmer only receive a B rating on the whole. Some localised C and D rated pixels are present however they do not cover a large area of the landslides. The reasons for this discrepancy are the geological formations that are present. Whilst the mudstone dominated lithologies of the Whitby Mudstone and Redcar Mudstone are highlighted as susceptible to landsliding, the more competent Saltwick and Eller Beck Formations, along with the Sycarham Member, have limited susceptibility due to the low slope angles on which the landslides have occurred.

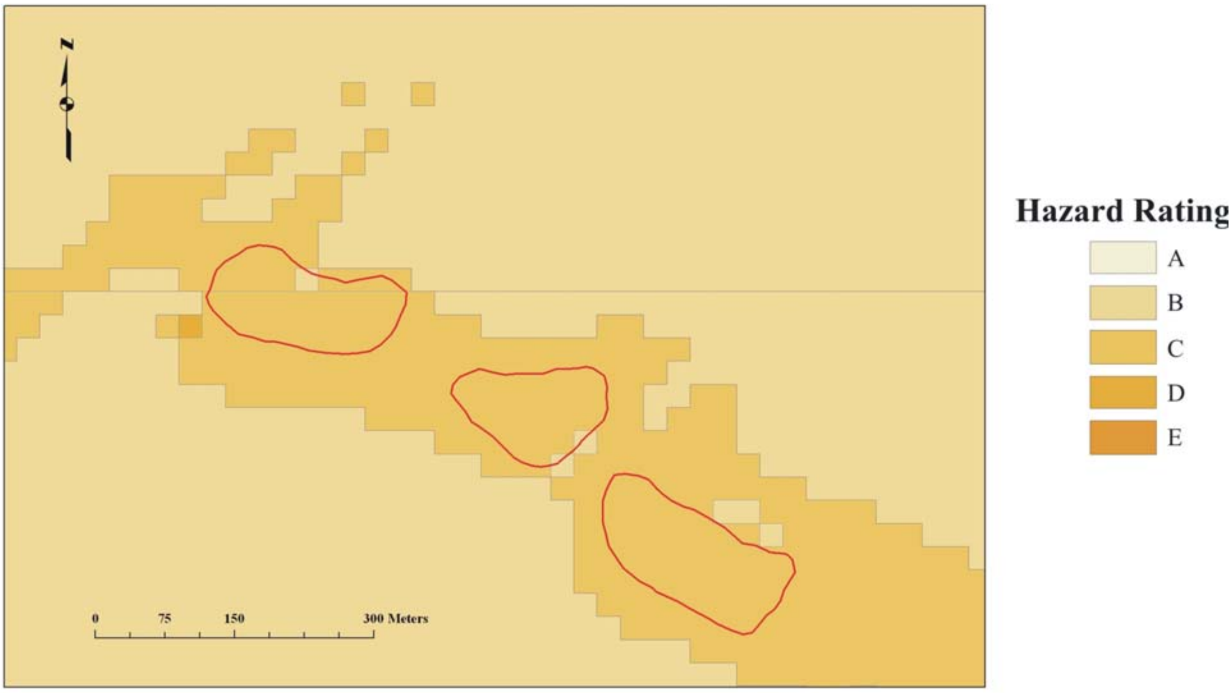

Figure 32. Geosure slope instability hazard rating for the Denn Ings landslide cluster. Red line indicates outline of mapped landslide deposits.

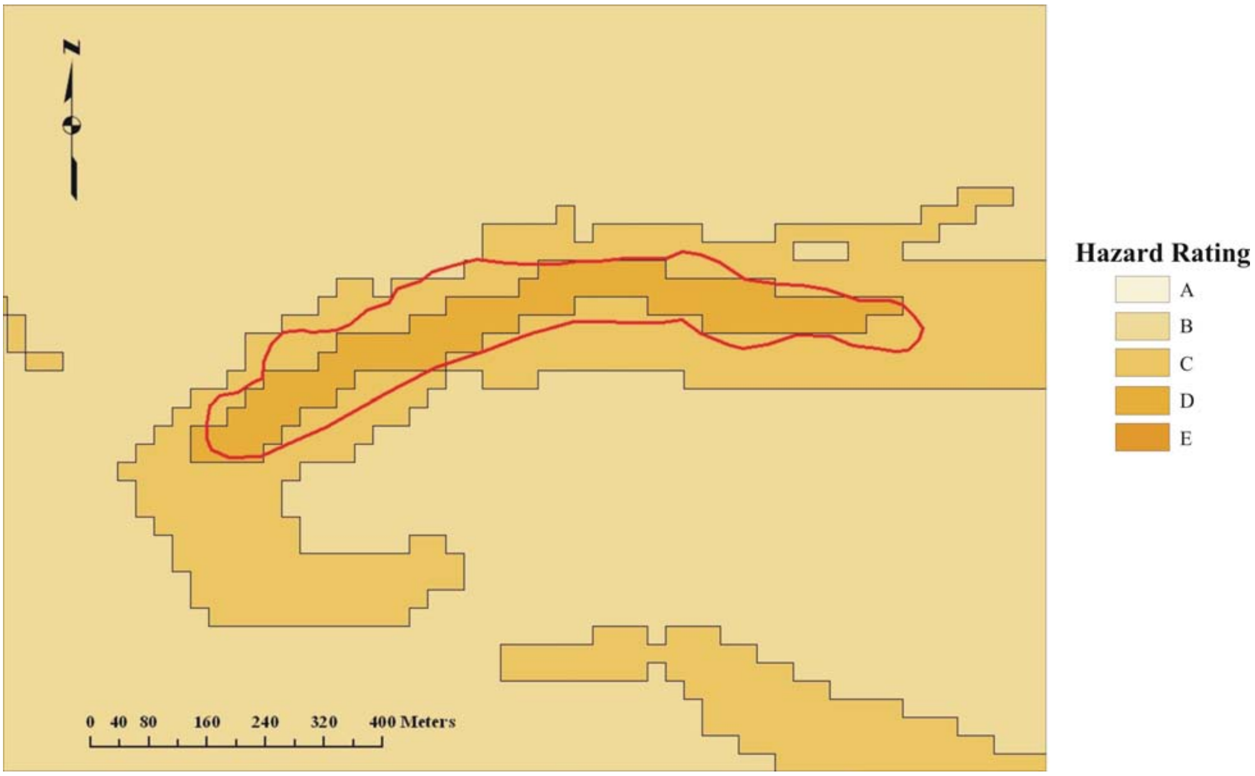

Figure 33. Geosure slope instability hazard rating for the Hanging Cliffs landslide. Red line indicates outline of mapped landslide deposit.

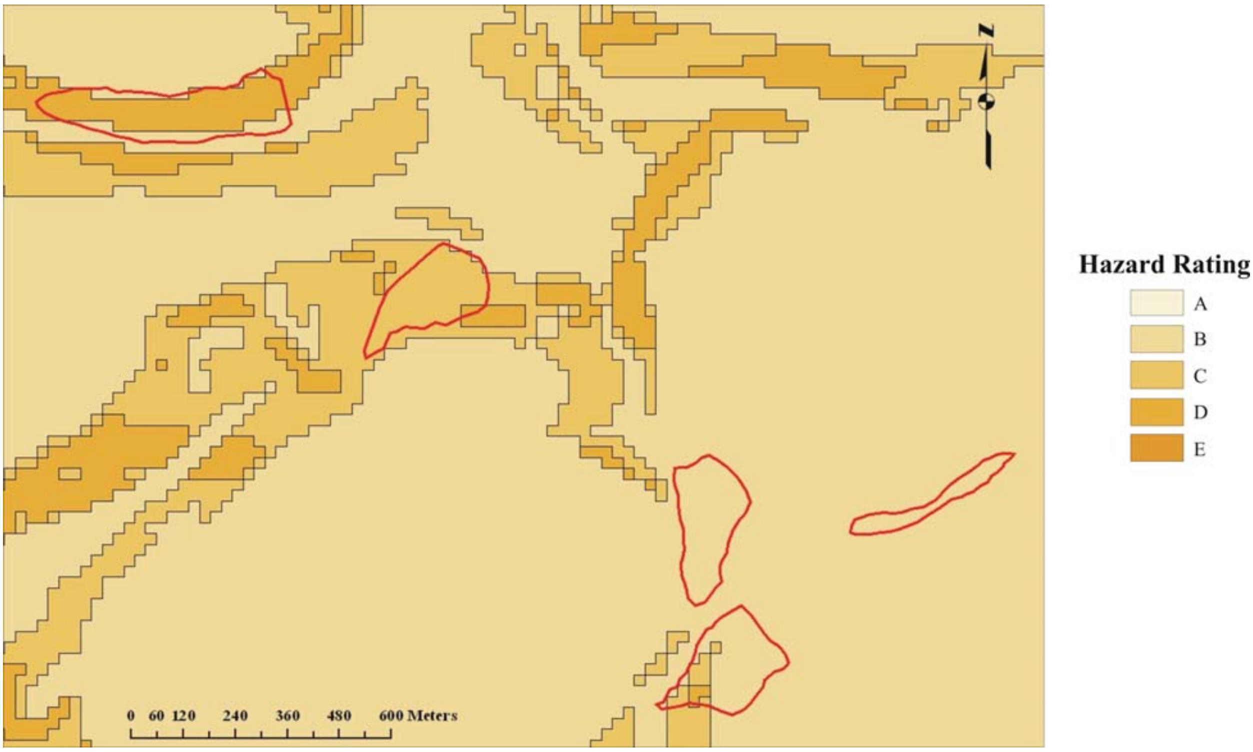

Figure 34. Geosure slope instability hazard rating for landslides in the Bulmer area. Red line indicates outline of mapped landslide deposits.

11 Discussion

The investigation into landslides on the York sheet involved a variety of methods and resulted in the mapping of over 80 new landslides. Terzaghi (1950) classified the major controls on landsliding as passive or active. The distribution of landslides on the York Sheet reflects the controlling factors of lithology, stratigraphy, topography (passive) and weathering (active). The following discussion attempts to explore the distribution of landslides in the York Sheet and how these relate to these controls.

11.1.1 Lithology

The physical properties of rocks and soils are varied and properties such as shear strength, permeability and durability influence how stable a slope will be (Bell, 1999). Landsliding on the York sheet appears to show a correlation towards certain lithologies, particularly the weaker mudstone dominated formations. Generally the higher the clay content of a lithology the weaker the material is and the more prone to landsliding it becomes (Jones and Lee, 1994). Of the formations on the York Sheet the Redcar Mudstone Formation, Whitby Mudstone Formation, Oxford Clay Formation, Ancholme Clay Formation and the Penarth Group appear to be particularly susceptible to instability. The Penarth Group is known to be susceptible to landsliding nationally, with numerous failures recorded in the South-west (Gibson *et al.*, 2004). Although the Penarth Group does not have the highest numbers of landslides on the York Sheet it does have a high landslide per km^2 ratio. Nationally Triassic Mudstones such as the Penarth Group have a landslide density of 3.9 landslides per 100 km^2, whilst in this study it was found that the Penarth Group had 1 landslide per 1 km^2 (Jones and Lee, 1994).

The Redcar Mudstone Formation and the Whitby Mudstone Formation both have higher than average numbers of landslides on the York Sheet. Both of these formations fall within the Lower Jurassic Lias Group, which this study showed to be the most prone to landsliding in the area.

Nationally the density of landsliding on the Lower Jurassic is 21 landslides per 100km^2 (Jones and Lee, 1994). Around the York district the density of landslides for Lower Jurassic formations present was calculated. For the Redcar Mudstone Formation the density was 10 landslides per 100km^2 whilst for the Whitby Mudstone Formation the figure was 230 per 100km^2. The figure was much higher than the national average for the Lower Jurassic Formations due to the small area of the Whitby Mudstone Formation locally and the prolific nature of landslides on the Formation. A more appropriate way of presenting these figures may be though the percentage of outcrop mantled by landslide deposits, as mapped by this study. An analysis of data gathered during this study suggests that in the York area approximately 8 % of the Whitby Mudstone Formation outcrop was mantled by landslide deposits, whilst this figure was 1.5% for the Redcar Mudstone Formation.

The Oxford Clay of the Ancholme Group has a national landslide density of 1.9 landslides per 100 km^2 compared to 0.5 landslide per km^2 for the Ampthill and Kimmeridge Clay (Jones and Lee, 1994). Within the York Sheet area the Oxford Clay has a landslide density of 20 landslides per 100 km^2. Figures from the study also suggest that the Oxford Clay is mantled by landslides across 4.5% of its outcrop extent. The Oxford Clay is a stiff unconsolidated clay that is subject to loss of strength over time due to the removal of overburden, leading to a loss of strength (Anderson and Richards, 1981). The shear strength of the Oxford Clay can be reduced by up to 50% by weathering with residual angles of friction of about 15°.(Reeves *et al*., 2006). The average slope angle for landsliding involving the Oxford Clay on the York sheet is 11°, slightly lower than the residual friction angle quoted by Reeves *et al.* 2006. The weathering history, clay mineralogy and high plasticity of the Oxford Clay may account for the high density of landslides on the formation on the York Sheet.

Its clear from the results of this study that lithology is a strong controlling factor on the location of landsliding. These landslides may have been triggered by different mechanisms but the controlling factor of lithology was important in producing slopes that were susceptible to movement. The research carried out by the study shows that the lithologies most susceptible to landsliding in York fit with those that are failing nationally. However the figures of landslide density are much higher in some instances in the York area than those obtained from the original National Landslide Database, highlighting the difficulties in publishing density data before the full extent of landslide distribution is fully known.

11.1.2 Stratigraphy

Stratigraphic sequences of geological material can lead to the juxtaposition of material with different strength and water bearing capacities. Where a weak and a strong rock are brought together or an aquifer and an aquitard slope stability problems can be encountered. In particular this is a problem in places such as the Cotswold where the clay rich aquitard of the Upper Lias is present below the permeable Inferior Oolite, leading to ubiquitous landsliding around Stroud (Butler, 1983). In the York area the presence of the Cretaceous Chalk unconformably overlying the Ampthill Clay has led to numerous large scale landslides, similar in scale and form to those formed by the Upper Greensand resting on the Gault. In these instances the failure occurs in the weaker underlying material leading to the rotation of large intact blocks of the more coherent overlying material. Strong material like the Chalk, which would not normally be involved in landsliding, is able to fail because of the presence of a weaker unit.

11.1.3 Weathering History

The York Sheet lies near the eastern most extent of the Vale of York ice sheet. It therefore has a complicated history of landform evolution. Glaciated in the Anglian and again in the Devensian the area also suffered from periglacial weathering beyond the ice sheet limit. Large scale landslides such as those at Birdsall Brow are unlikely to have formed under the present climatic conditions. It is likely that they formed during a glacial climate such as in the Anglian or

Devensian glaciations. It is hoped that further investigation may enable a more accurate picture of their formation to be gained. The current theories concerning the origin of these landslides are

- The escarpment landslides are ancient and possibly formed as glacial ice retreated from the Vale of York at the end of the Anglian glaciation approximately 400 000 years BP. The retreat of ice from the area would result in the removal of support from the glaciated valley side.
- The large chalk landslides occurred during the Devensian glaciation. During this period, glacial ice was present to the northwest and east of the Yorkshire Wolds. It is postulated (Price, pers comm.) that the presence of this glacier ice raised the local groundwater levels in the Yorkshire Wolds. This would have had the effect of raising the effective pore water pressures, facilitating the large-scale landsliding observed at Birdsall Brow.

Quaternary climates would have also led to smaller failures occurring due to periglacial weathering. In the York area failures were recorded on the Penarth Group at slope angles as low as 7° and up to 10°. These angles compare to those published by Hawkins and Privett (1981) which suggest that the Westbury and Cotham Members of the Penarth Group have a residual shear angle that can be as low as 6°. The formation of shear surfaces within the Penarth Group by landslides and mass movement during the Quaternary could lead to reactivations and failures which could also affect the overlying units such as the Redcar Mudstone.

11.1.4 Topography

As well as the geological material, stratigraphy and weathering history the topography of an area is important to its slope stability. Suitable topographic conditions are vital to allow failures to take place. For a landslide to occur gravitational forces must overcome the shear strength of the material, therefore before failures can occur a suitable angle must be achieved (Jones and Lee, 1994). This angle is however dependant on the material strength properties of a lithology as well as the local pore water pressures and is therefore changeable across formations as well as within them.

The Whitby Mudstone had the most prolific rate of landsliding for any lithology on the York Sheet. An analysis of failures occurring on the Whitby Mudstone was carried out to determine whether there was a limiting slope angles for the failures on the York Sheet. This was to enable a comparison with figures generated by other studies on the Whitby Mudstone carried out by Forster (1992), Penn *et al*., (1983), Chandler (1970) and Biczysko and Starzewski (1977). Forster (1992) undertook an analysis of landslide slope angles along the Lincolnshire Escarpment between Grantham and Welbourne where the Whitby Mudstone was involved in numerous failures as well as calculating the maximum stable slope using the Skempton-Delory equation. Within the Lincolnshire Escarpment area, Forster (1992) calculated that the Whitby Mudstone had a mean residual friction angle of 13º and by using the Skempton Delory equation a maximum stable slope angle of between 3.8-12.5º (mean of 6.3º) was obtained. A comparison of maximum calculated slope angles for the Whitby Mudstone across the country is shown in Table 4. Along the Lincolnshire Escarpment steep and upper slopes were measured to compare with the maximum stable slope angle. This comparison showed that whilst the mean calculated slope angle for stability was 6.3º the mean upper slope angle was 8º and many of the slopes were close to their threshold of stability (Forster, 1992). In the York area, figures for bulk density and internal angle of friction are not known so that does not allow the Skempton Delory equation to be used to produce a maximum stable slope angle. However, an analysis of average slope angles for both the Whitby Mudstone and landslides occurring within the formation was carried out. The analysis showed that within the York area the mean angle for Whitby Mudstone slopes was 8.5º, similar to the upper slope values for the Lincolnshire Escarpment. The mean slope angle for failures was 11º, calculated both manually and also derived from a GIS calculation. To further this analysis of slope angles, data from the National Geotechnical Database for the Whitby Mudstone concerning residual friction angle and plasticity index were plotted. The spread of data showed that there was an increase in residual friction angle when the plasticity index fell below a threshold value about 20-35% as decribed by Lupini *et al.* (1981) (Figure 35).The correlation of index properties and residual friction angle can be related to the clay fraction. In soils with a high clay fraction the liquid limit and plasticity index are likely to be higher and therefore the residual angle of friction is likely to be lower (Kaya and Kwong, 2007). Figure 35 does show that for Whitby Mudstone samples with more than 20-30% PI the residual friction angle is between about 5-11°. This residual angle of friction is similar to the angle at which landslides in the Whitby Mudstone were occurring at in the study area.

Location	**Residual Friction Angle**	**Maximum stable slope angle (mean)**
Lincolnshire Escarpment[1]	13	6.3
Lincoln[2]	9	4.3
Daventry[3]	13	6.3
Wellingborough[4]	17	9.1
Wothorpe[4]	18	9.7

Table 4. Mean calculated stable slope angles for the Whitby Mudstone. ***1: Forster (1992) 2: Penn et al., (1983), 3: Biczysko and Starzewski (1977), 4: Chandler (1970).***

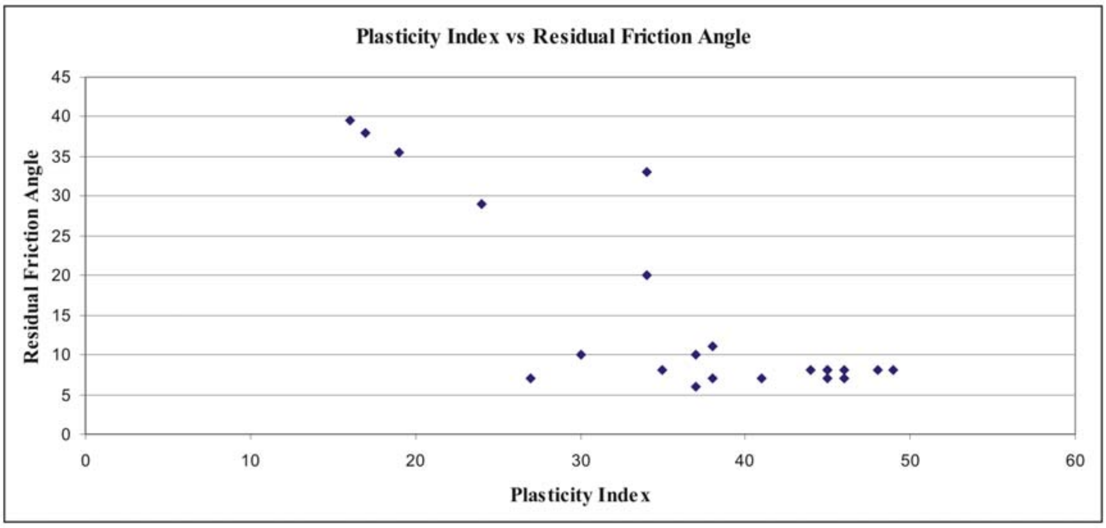

Figure 35. Plasticity vs. Residual friction angle for the Whitby Mudstone Formation

12 Conclusions

A number of conclusions can be taken from this work. As might be expected, the geological succession exerts a strong influence upon the nature, distribution and style of landsliding within the area of the York sheet. The lithologies most prone to landslide activity are the mudrocks and sandstones of Jurassic age, with landslides also occurring within the Penarth Group and Chalk. The most common style of landsliding in the York sheet area is rotational failures, although many of these are also associated with flows.

Landslides in the area can be classified into one of three systems:

1. Shallow landsliding involving Upper Jurassic to Upper Triassic mudstone/clay dominated lithologies.

2. Deep-seated rotational landsliding in Upper Jurassic to Upper Cretaceous mudstone and chalk.
3. Rotational failures involving a sequence of Jurassic formations with a Chalk cap rock or rotational failures within a single formation.

Most of the 83 landslides identified occur within landslide system three.

Without definitive dating of individual slides it is difficult to make proper assessments of the age of landsliding. However, at least two distinct phases of activity can be identified from field survey and air photo interpretation. The most recent of these are a series of shallow flows and translational slides. When considering the preservation potential of the geomorphological features produced by shallow landsliding it is considered these failures are less than 100 years old. Recent degradation of larger landslide masses has also taken place, which is likely to be part of an ongoing process of degradation since the formation of these slides. Larger scale failures, typically involving deep-seated rotational failures with a chalk caprock (system two) are very unlikely to have occurred under current climatic conditions. These landslides are considered to be at, the least, 1000 years old, probably associated with a periglacial climate.

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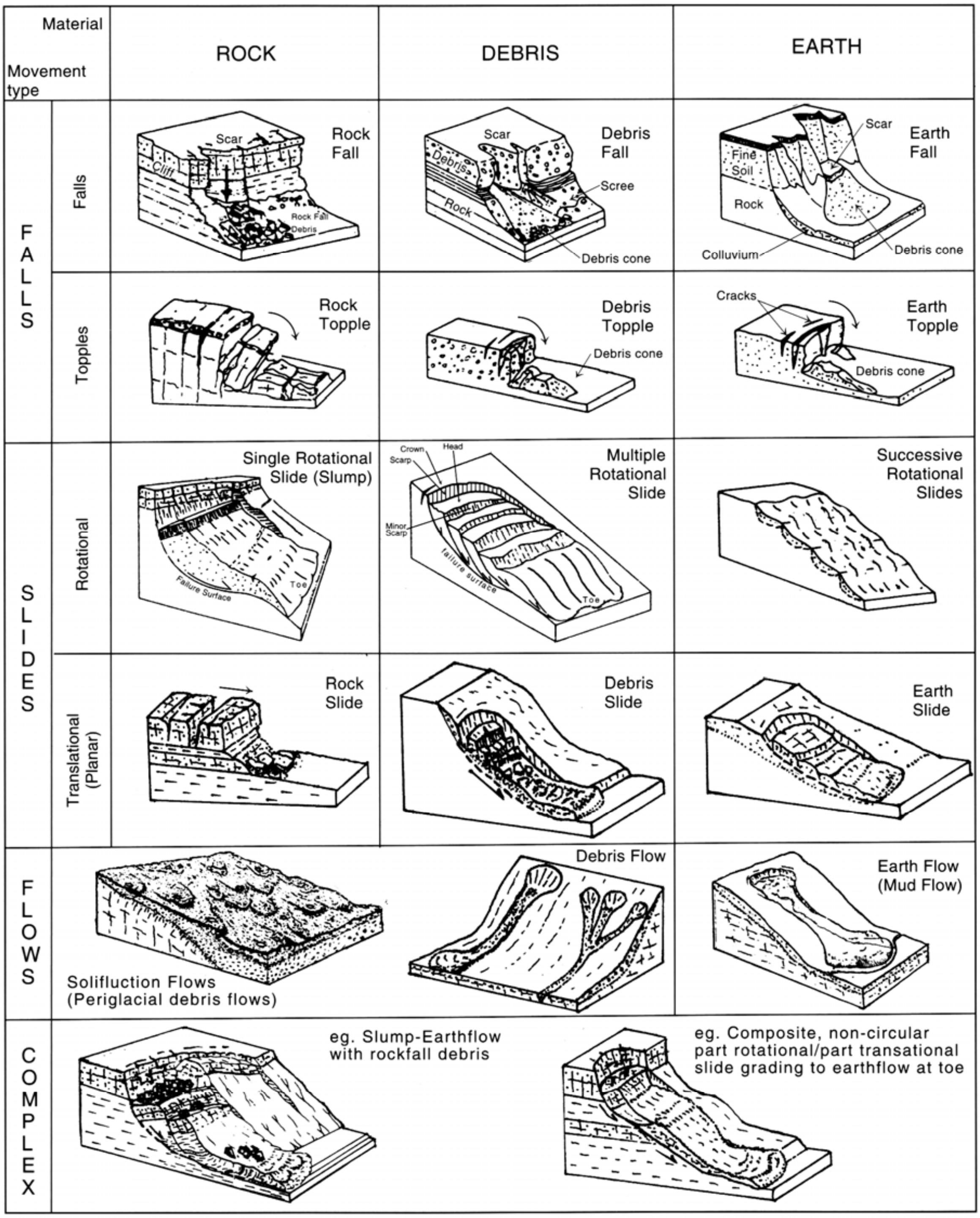
APPENDIX ONE: CLASSIFICATION OF LANDSLIDE TYPES (VARNES, 1978).



Falls - Mass detached from steep slope/cliff along surface with little or no shear displacement, descends mostly through the air by free fall, bouncing or rolling; Topples - forward rotation about a pivot point; Rotational slides - sliding outwards on one or more concave-upward failure surfaces; Translational (planar) slides - sliding on a planar failure surface running more or less parallel to the slope; Flows - slow to rapid mass movements in saturated materials which advance by viscous flow, usually following initial sliding movement. Some flows may be bounded by basal and marginal shear surfaces but the dominant movement of the displaced mass is by flowage; Complex slides - slides involving two or more of the main movement types in combination.