British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Bath's 'foundered strata' - a re-interpretation

Physical Hazards Programme

Research Report OR/08/052

BRITISH GEOLOGICAL SURVEY

PHYSICAL HAZARDS PROGRAMME

RESEARCH REPORT OR/08/052

Bath's 'foundered strata' – a re-interpretation

P.R.N. Hobbs and G.O. Jenkins

Contributor

A. Forster

Keywords

Bath, landslides, cambering, foundering, geohazards, slope stability, mass movement.

Front cover

Cover picture details, delete if no cover picture.

Bibliographical reference

P.R.N. HOBBS AND G.O. JENKINS. 2008 Bath's 'foundered strata' - a re-interpretation. *British Geological Survey Research Report*, OR/08/052. 40pp.

Keyworth, Nottingham British Geological Survey 2008

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desks at Nottingham, Edinburgh and London; see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications including maps for consultation.

The Survey publishes an annual catalogue of its maps and other publications; this catalogue is available from any of the BGS Sales Desks.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Department for International Development and other agencies.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

Keyworth, Nottingham NG12 5GG

☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.geologyshop.com

Murchison House, West Mains Road, Edinburgh EH9 3LA

☎ 0131-667 1000 Fax 0131-668 2683
e-mail: scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE

☎ 020-7589 4090 Fax 020-7584 8270
☎ 020-7942 5344/45 email: bgslondon@bgs.ac.uk

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU

☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS

☎ 028-9066 6595 Fax 028-9066 2835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345

Sophia House, 28 Cathedral Road, Cardiff, CF11 9LJ

☎ 029–2066 0147 Fax 029–2066 0159

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Foreword

This report is the published product of a study by the British Geological Survey (BGS) … …

Acknowledgements

A large number of individuals have contributed to the project. This assistance has been received at all stages of the study. In addition to the collection of data, many individuals have freely given their advice, and provided local knowledge. The authors would particularly like to thank the following:

R. A. Ellison

R. J. Wyatt

A. Gibson

M. Harrison

K. Royse

Contents

FIGURES

TABLES

Summary

This report describes work carried out by the British Geological Survey to resolve the long-standing issue of 'foundered strata' on the 1:50,000 scale geological map of Bath (Sheet 265), and to investigate the nature of landsliding and cambering on the slopes around the city of Bath. The report describes the accompanying landslide map and explains the methodology behind it.

1 Introduction

What are ‘Foundered strata’?

The term ‘Foundered strata’ is used to describe areas where extensive landsliding and cambering have occurred, but beneath which the solid geology could not be determined by the mapping geologist. Foundered strata are shown on BGS 1:50,000 geology maps as horizontal black hachuring on a pale green background (Figure 1). This is distinct from the normal ‘landslide’ symbol of vertical hachuring on a white background, with the solid geology shown as dotted lines (Figure 1). Cambering is not depicted on BGS 1:50,000 maps. More recently, the term ‘foundered strata’ has been used to mean “collapsed strata . . . areas subject to natural or man-induced subsidence where no new deposits are produced, for example areas of collapse resulting from evaporate dissolution or extraction” (BGS, 2000).

The study area covered by this report, and shown in Figure 1, is that to the north and north-east of the city of Bath, covered by a large tract (45 km^2) of, what is referred to on the British Geological Survey (BGS) 1:50,000 geology map, as ‘foundered strata’. This forms part of the 1:50,000 scale ‘Bath’ geology map (265), which the BGS is currently re-mapping. As the use of ‘foundered strata’ is anomalous in terms of current geological usage, an attempt has been made in this report to re-interpret this area and hence resolve the anomaly. This work is a continuation of work which formed part of an environmental geology project for the then Department of the Environment (DoE) carried out in 1984/5 by BGS (Forster et al, 1985), covering the city of Bath and its environs, and for which a series of black and white ‘thematic’ maps was produced. One of these maps (No. 15 at 1:25,000 scale) was a re-interpretation by R.J. Wyatt in 1985 of part of the study area covering the central and southern parts of the zone of ‘foundered strata’ (Figure 2). This map does not show solid geology beneath the landslipped ground. It also does not show, in common with normal published BGS geology maps, the outline of individual landslides. BGS field-slips do, however, show and name some individual landslides.

The objective of the current work is to re-interpret the whole ‘foundered strata’ area, based on the previous work, described above, and on more recent developments in remote sensing and the understanding of cambering. This has not included mapping or remapping the geology of the area.

Figure 1 Part of BGS 1:50, 000 scale 'solid & drift' geology map – Bath (265)
The map shows 'foundered strata' (pale green with horizontal hachuring), landslide deposits (white with vertical hachuring), and solid geology (colour)

Site investigations for the re-alignment of the A46 trunk road on the eastern side of the Swainswick Valley were carried out during the 1970's and 1980's, and supplied valuable geological, geomorphological, and geotechnical data to the DoE project, and subsequently to the current project. Construction of the A46 re-alignment took place during the 1990's, and included extensive landslide stabilisation measures (Gosney et al., 1997).

The aerial photography currently available consists of a black & white set at 1:10,000 scale, flown in April/May 1975, and a colour set at 1:25,000 scale, flown in October 1997.

The geology of the study area was first systematically surveyed on the 1 inch to the mile scale and published on the Old Series Geological Survey maps between 1857 and 1873. Prior to that, several geological pioneers had been concerned with the rocks of the district, beginning with William Smith's work prompted by the construction of local canals in the late 18th century (Phillips, 1844; Winchester, 2001). Smith's famous circular geology map of Bath, dated 1799, is shown in Figure 3. The area was not mapped by the Geological Survey on the 6 inch to the mile scale until 1944-58. The results of that survey were included on the 1 inch New Series sheets 265 (Bath) and 281 (Frome) published in 1965.

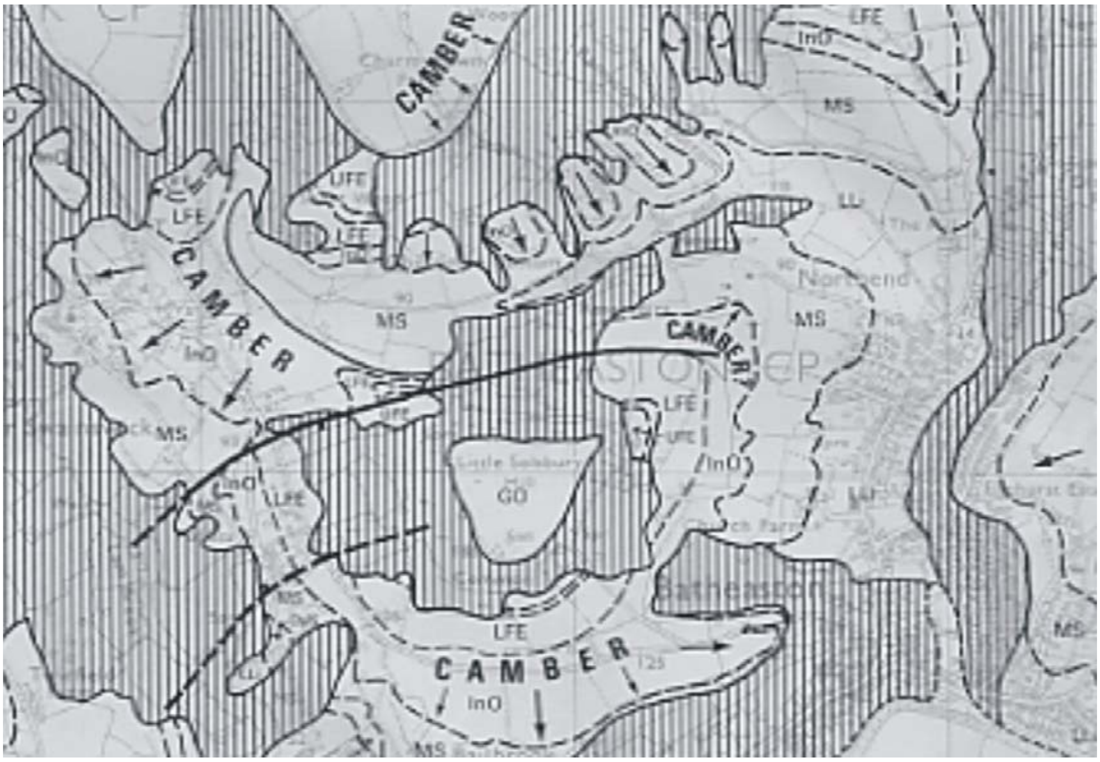


Figure 2 Extract from R. Wyatt's map depicting landsliding and cambering (Forster et al., 1985)
The map shows landslide deposits (vertical hachuring), cambering (arrows), and solid geology (dotted lines)

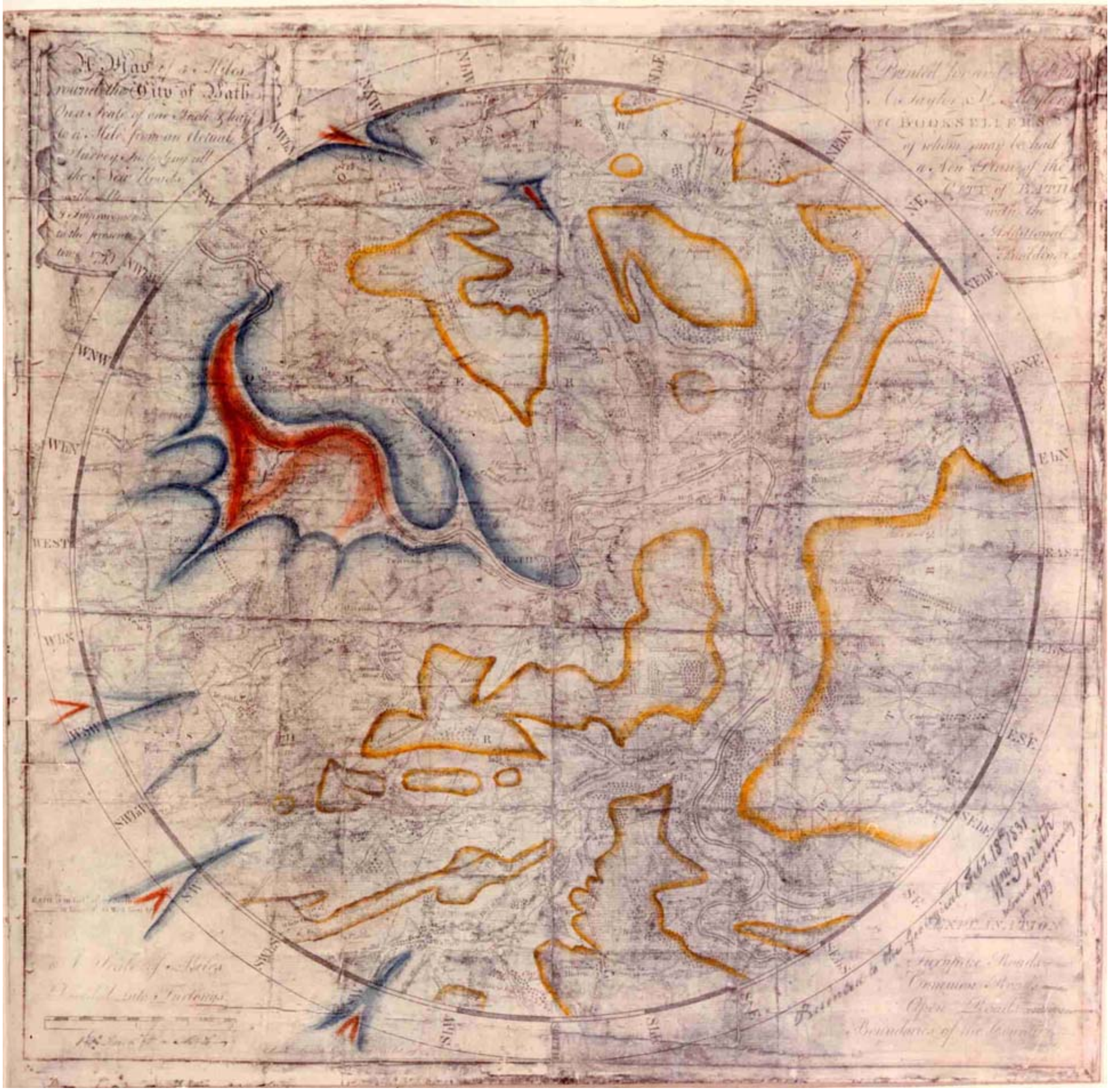


Figure 3 William Smith's 1799 map of Bath

The map reproduced above shows the country 5 miles around Bath (originally) at 1½ inches to the mile scale, and was 'coloured geologically' in 1799 by William Smith. It was presented to the Geological Society in 1831, and is believed to be the first map ever produced showing accurately the outcrop of strata according to an ordered stratigraphic sequence. *Lias (blue), Great Oolite (yellow), Trias (red)*

An important contribution to the interpretation of slopes in the Bath area was made during the 1970's by R. Chandler, G. Kellaway, A. Skempton and R. Wyatt (Chandler et al., 1976). This paper described in some detail the cambering geomorphology, hydrogeology, and likely mechanisms of slope failure for selected sections, based on trial pit and borehole data.

The undulating countryside characteristic of the study area is underlain mainly by Middle and Upper Jurassic clays, with subordinate limestones and sands. The massive limestones of the Great Oolite Group commonly form plateaux at elevations of between 120 and 160 m above the valley floor, whilst those of the Inferior Oolite Group give rise to subdued bench-like outcrops on mid-level valley slopes. The area is dissected by the incised valleys of the River Avon and its tributaries, which cut down through the Lias Group clays of the Lower Jurassic. Typically, the valley slope forms a concave cross-section. The shallower angled slopes (9^{o}) are characteristic of cambering and shallow landsliding, while the steeper slopes (14^{o}) are characteristic of deep-seated landslides (Chandler et al., 1976). Structurally, the Jurassic rocks dip gently to the east-south-east and are cut by several west-south-west trending normal faults. Where the outcrops have slipped or cambered, they commonly display considerable dips at variance with the regional trend.

The valley slopes have, in the past, been affected by shallow mass movements, which make ground conditions potentially unstable. The landslides mostly date from late glacial times and are commonly degraded. Some slides and mudslides are more recent in origin, however, and show fresh morphological features; a few being active at the present day. Evidence of small, shallow landslides tends to be rapidly removed by degradation produced by natural processes and by farming. Thus many slopes are likely to have been subject to many stages of shallow landsliding over the centuries. Cambering of the characteristic massive Great Oolite Group limestones, forming the plateaux caprock, is widespread and may be accompanied by ‘dip and fault’ structures, with open fractures or gulls, which may have solution cavities associated with them. Cambering of the more subdued mid-slope Inferior Oolite Group limestones is present in parts, but is more difficult to identify as it is highly degraded and obscured by shallow landsliding and solifluction Head deposits. In the valley floors, there has been limited evidence of valley bulging in the less competent clay strata.

Instability due to the extensive (18 ha) derelict freestone mines, in particular those underlying Combe Down, has been addressed (Stacey, 2002). These room and pillar mines remain for the most part open, unsupported, and only a few metres below ground surface, in built-up parts of the city of Bath.

2 Geology

The solid geological formations present in the study area are indicated in Table 1.

Table 1 Summary of stratigraphy on the Bath sheet

Member	Formation	Group	Former name
	Forest Marble F. (Fmb)	Great Oolite G. (GtO)	Forest Marble
Bath Oolite M.	Chalfield Oolite F *.		Bath Oolite
Twinhoe Beds			Twinhoe Beds
Combe Down Oolite M. (CoDo)			Combe Down Oolite
Upper Fuller’s Earth M. [27m]	Fuller’s Earth F. (FE) [41m]		Upper Fuller’s Earth
Fuller’s Earth Rock M. (FER) 4m			Fuller’s Earth Rock
Lower Fuller’s Earth M. [10m]			Lower Fuller’s Earth
	Salperton Limestone F.	Inferior Oolite G. (InO)	Inferior Oolite
	Bridport Sand F. (BdS) 31m	Lias G. (Li)	Midford Sands
	Dyrham F. (DyS)		Dyrham Silt
	Charmouth Mudstone F. (ChM)		Lower Lias Clay
Rugby Limestone M.	Blue Lias F. (BLi)		Blue Lias
Saltford Shale M.			Blue Lias, Unit B

(* proposed formation name, Wyatt & Cave, 2002)

2.1 FOREST MARBLE FORMATION

The Forest Marble Formation consists of mudstone with lenticular beds of limestone (shell-fragmental, ooidal grainstone and sandy limestone, often argillaceous, typically cross-bedded and forming banks and channel-fills) especially in the lower part.

The upper boundary is defined generally by mudstone in the upper part of the Formation, overlain sharply and non-sequentially by rubbly, ooidal shelly wackestone/packstone of the Cornbrash Formation. The lower boundary is defined (in the Cotswold region) as the base of limestone/mudstone resting on purer, less argillaceous ooidal or micritic limestone of the White Limestone Formation of the Great Oolite Group. It is marked (south of Mendips) by the Boueti Bed, a fossiliferous marl, resting on mudstone of Frome Clay/Upper Fuller's Earth.

2.2 CHALFIELD OOLITE FORMATION

The proposed Chalfield Oolite Formation consists (in ascending order) of the Combe Down Oolite Member, the Twinhoe Beds Member, and the Bath Oolite Member. These limestones, particularly the upper and lower members, have formed the basis of the Bath stone industry and were extensively mined as freestone around the city. The Combe Down Oolite Member rests with slight unconformity on the Fuller’s Earth Formation. The Member is about 18 m thick at Combe Down. The Twinhoe Beds Member has three distinct shelly and pisolitic limestone lithologies. They are up to 13 m thick. Finally, the Bath Oolite Member, up to 17 m in thickness, is a uniform oolitic limestone with few shells, though becoming a detrital limestone towards the margins. A key difference between the freestones obtained from the Combe Down Oolite and the Bath Oolite is the latter’s relatively high microporosity and water content. This makes it more susceptible to frost damage (Forster et al., 1985).

2.3 FULLER’S EARTH FORMATION

The Fuller’s Earth Formation contains a bed of ‘commercial’ fuller’s earth about 2 m thick and located about 10m below the top of the formation. This contains clay of ‘extremely high’ plasticity, which is highly susceptible to landslide movement. The bed is not present throughout the area (information about its location is held by the Laporte Corporation). The Fuller’ Earth Rock Member is about 4m thick, separates the upper and lower parts of the formation, and consists of rubbly, shelly limestones with thin marl bands. The Lower Fuller’s Earth Member contains a thin nodular argillaceous limestone midway. Clays of the Fuller’s Earth Formation play a key role in landslide development. The clays are typically of high plasticity and low shear strength (Hawkins et al., 1986). De-calcification is proposed as a factor in residual shear strength reduction, and hence landslide re-activation, in the Fuller’s Earth Formation clays (Hawkins & McDonald, 1993).

2.4 SALPERTON LIMESTONE FORMATION

This limestone represents the Inferior Oolite Group in the area. It consists of pale grey to brown rubbly, fine- to coarse-grained ooidal, peloidal and finely shell-detrital packstone to grainstone (Clypeus Grit Member), generally with very shelly and coarsely shell-detrital ooidal grainstone and packstone (Upper Trigonia Grit Member) at base (Cambering tends to increase the downslope extent of the formation thus increasing its apparent thickness.

Figure 4). The formation is typically between 10 and 15 m in thickness and is generally well jointed (Chandler et al., 1976). The formation outcrops around Toghill, to the southwest and southeast of Fuddlebrook, and to the west of Tadwick, though there is little exposure in any of these locations. The presence or otherwise of cambering in the Salperton Limestone Formation is a major issue for mapping. Cambering tends to increase the downslope extent of the formation thus increasing its apparent thickness.

Figure 4 Apparently uncambered Salperton Limestone Formation exposed below Soper's Wood [37480 16810].

2.5 BRIDPORT SAND FORMATION

The Bridport Sand Formation, formerly known as the 'Midford Sands' or 'Upper Lias Sands', consists of up to 31 m of yellow-brown homogeneous silty sand, with several bands of cemented calcareous sandstone known as 'doggers'. Grey, weathering yellow or brown, micaceous silt, very fine sand and fine sand, locally with calcite-cemented sandstone beds and lenses, variably sandy clay/mudstone at base, including the Downcliff Clay [Member] of the type area.

The upper boundary is non sequential: at the base of the lowest limestone (commonly sandy) of the Inferior Oolite Group resting on sand/silt or mudstone. The lower boundary is at the base of sand/silt or mudstone, resting non-sequentially on limestone of the Beacon Limestone Formation.

The Bridport Sand Formation outcrops principally in the Limpley Stoke valley to the south-east of Bath, and to a limited extent in the Swainswick Valley to the north-east of Bath.

2.6 DYRHAM FORMATION

Formerly known as the 'Middle Lias Silts' (or Clays) or 'Dyrham Silts', the Dyrham Formation consists of pale to dark grey and greenish grey, silty and sandy mudstone, with interbeds of silt or very fine sand (locally muddy or silty), weathering yellow. It is variably micaceous with impersistent beds or doggers of ferruginous limestone (some ooidal) and sandstone, which tend to occur at the top of sedimentary cycles. Sporadic large cementstone nodules are found.

The upper boundary is at the base of ferruginous limestone or ironstone of the Marlstone Rock Formation or Marlstone Member of the Beacon Limestone Formation. The lower boundary is at a marked or gradational downward change from silty mudstones to smoother argillaceous sediments of the Charmouth Mudstone Formation. This commonly coincides with negative changes of slope and/or lines of seepage that may correspond with a sandy bed.

The Dyrham Formation is poorly exposed in the study area, this being limited to the lower slopes of the escarpment at Freezing Hill and Toghill to the north of Bath.

2.7 CHARMOUTH MUDSTONE FORMATION

Formerly known as the 'Lower Lias Clays', the Charmouth Mudstone Formation consists of dark grey laminated shales, and dark, pale and bluish grey mudstones. It is locally concretionary and has tabular limestone beds, and abundant argillaceous limestone, phosphatic or ironstone (sideritic mudstone) nodules in some areas, organic-rich paper shales at some levels, and finely sandy beds in lower part in some areas.

The upper boundary is at a marked or gradational upward change to coarser siliciclastic deposits of the Dyrham Formation. In the type section (Dorset), this is at the base of the Three Tiers Sandstone. The lower boundary is at the top of the Blue Lias Formation or Scunthorpe Mudstone Formation. The top of the Blue Lias Formation coincides with a marked upward decrease in frequency, thickness and lateral persistence of limestone beds.

The Charmouth Mudstone Formation is exposed in the west of the city of Bath, and in the area around Lower Hamswell, to the north-west of Bath, and in the Limpley Stoke valley.

2.8 BLUE LIAS FORMATION

The Blue Lias Formation consists of thinly interbedded limestone (laminated, nodular, or massive and persistent) and calcareous mudstone or siltstone (locally laminated). Individual limestones are typically 0.10-0.30m thick. In some areas, intervening mudstone units with relatively few limestone beds. Also includes littoral limestone facies of the Radstock Shelf - Mendip area and South Wales.

The upper boundary is defined at the base of the Charmouth Mudstone Formation. In any one section, this coincides with marked upward decrease in abundance of limestone beds, locally associated with marked decrease in their individual thickness and lateral persistence. The lower boundary is defined at the base of grey limestone or mudstone sharply overlying an irregular surface of pale grey or bluish and greenish-grey or reddish brown mudstone of the Cotham Member (Lilstock Formation) or eroded, commonly bored, locally conglomeratic surface of pale porcellanous limestone of Langport Member (Lilstock Formation). The lower boundary coincides with the base of the Lias Group, which is commonly markedly non-sequential.

3 Mass movement

The mass movements that have taken place in the study area consist of cambering, landsliding, and soil creep. Whilst these processes are interrelated, their timing is not necessarily synchronous. It is likely that several phases of cambering and landsliding have taken place. These have been interspersed with periods of inactivity and degradation. The periods of activity coincided with the cycles of glaciation and associated periglaciation, particularly at those points where bodies of ground ice were melting. The presence of a mantle of solifluction Head tends to disguise much of the underlying geology and evidence of deeper-seated mass movement processes. Head is a thin mobile deposit subject to mudslide and soil creep movement.

The slopes that are seen today in the Bath area are largely the result of the climatic conditions, which have prevailed since the end of the Devensian glaciation. However, it is believed that much of the cambering activity, particularly of the Inferior Oolite, took place prior to this (Chandler et al., 1976), possibly as early as the Anglian glaciation (Self, 1995). Currently, cambering is inactive and may have been so since the Hoxnian. However, landslides were probably most active in the saturated conditions of early post-Devensian times, and it is likely that the larger landslides recognised in the area were formed during this period. It is notable that most of these large landslides occupy the lower valley slopes. This may be because they are related to the accelerated downcutting of rivers following the last glaciation. Under current climatic conditions many slopes are only marginally stable (Forster, 1985, Chandler et al., 1976). This means that small adverse changes to the climate or slope profile may initiate re-activation.

Table 2 Summary of slope features

Zone	Camber	Landslide	Condition
Upper	Great Oolite on Fuller's Earth clays. Discrete and limited extents, associated with rock fall/slide.	Translational slides (rock & soil), topples, debris flows within Fuller's Earth clays. Mudslide complexes.	Cambering & landsliding well distinguished but tree-covered. Erosion by springs.
Lower	Inferior Oolite on Lias clays. Some draping & thinning downslope.	Debris flows, mudslides, solifluction, head thickening downslope, rotational slumps within Inferior Oolite & Lias clays. Occasional rotational in Lias by river erosion.	Cambering & landsliding poorly distinguished. Erosion by streams & springs. Surface features obscured by farming.

Many investigations have highlighted the significance of landslides in the Bath area (Cook, 1973; Chandler et al., 1976; Hawkins, 1977; Privett, 1980; Forster et al., 1985), particularly within the area of ‘foundered strata’. However, delineation and classification of these landslides is less well documented. The literature suggests that the dominant slope process is two-layered (Table 2): the upper zone of mass movement consisting of cambering and landsliding of Chalfield Oolite (Great Oolite) on Fuller’s Earth, and the lower zone consisting of cambering and landsliding of Inferior Oolite on Lias. In the upper zone instability has occurred on steeper slopes with less run-out and less extensive camber, while in the lower zones it has occurred on shallower slopes with greater run-out and more extensive camber. However, a small number of large, steeply scarped rotational landslides (e.g. North Stoke, Bailbrook) in the lower slopes have been produced by river erosion, and have occurred mainly within the Bridport Sand and Lias. Shallow mudslides in both upper and lower slopes are subject to re-activation and have been associated with springs. Table 2 shows a summary of slope features observed in the field and obtained from the literature. Spring sapping is also a feature, particularly within the Bridport Sand Formation. This tends to result in the formation of narrow, steep-sided gullies which then become susceptible to landsliding.

During the reconnaissance survey no examples of active landsliding were observed. However, on previous visits shallow mudslides have been observed at Swainswick, within areas of known landslide, which have rapidly become obscured by farming activities. It is believed that no new large-scale, deep-seated landslides have occurred in the area since the Devensian glaciation (Privett, 1980). Rotational slides of moderate size have occurred in recent times as re-activations of existing slides, but usually in association with the construction of roads, landscaping, and retaining structures (Forster et al., 1985). During the reconnaissance survey, sets of panoramic photos were taken of the main valley slopes of the ‘foundered strata’ area.

The literature contains descriptions of several medium to large-sized landslides within, and adjacent to the area of ‘foundered strata’ (Forster et al., 1986; Hobbs, 1980) and their locations are shown in Figure 1. Some of these are within the urban area of Bath city and have been engineered or landscaped in some way, making the natural features difficult to discern. As a result of the ‘foundered strata’ scheme, not all of these landslides are depicted on the BGS 1:50,000 scale geology map. However, widespread belts of landsliding are depicted in the following three areas:

1) to the SE in the Avon valley between Limpley Stoke and Bathford,
2) to the NW in the region of Freezing Hill, Lower Hamswell, and Tog Hill,
3) to the NE and E in the Doncombe Brook valley and at Colerne and Box.

It is the case that these ‘blanket’ depictions of ‘landslipped’ strata do not accurately reflect the true landslide extent. In fact, the extent of landsliding may have been over-estimated in some cases; this perhaps having resulted from the same mapping problems as encountered with the ‘foundered strata’. However, this is not unique to the Bath sheet, as is the ‘foundered strata’ category. Some areas depicted as ‘Head’ on the 1:50,000 geology map are found to be discrete mudslides (Privett, 1980). A large proportion of slopes are partially wooded; the trees concealing the upper and central parts, including most of the upper-slope landslides. Often the toes of landslides may be seen emerging from woods onto pasture

3.1 CAMBERING

Cambering is a mass movement process whereby a strong caprock layer overlying a weak, ‘extruding’ clay layer, usually at the edge of a plateau or hilltop, is subject to a gradual downslope movement. This often involves ‘hinging’ or ‘slumping’ downward and subsequent gradual break-up of the caprock into blocks, which become available for involvement in landslides on the slope. One effect of cambering is to give an exaggerated impression of the outcrop and thickness of the caprock, and conversely a reduced impression of underlying stratum thickness. In addition, the Bath area is notable for the 'mid-slope' cambering of the Inferior Oolite limestones. Whilst these limestones are not forming a caprock as such, the process is comparable, as are the results in terms of the apparent increases in outcrop and thickness described earlier.

Associated with cambering are 'gulls'. These are open or infilled tension cracks within the cambering caprock, usually formed along pre-existing joints and running mainly parallel with the valley. In some cases, gulls may be 'bridged', that is they occur only in the lower beds of the caprock, particularly where the caprock is thick and well bedded, and thus are not visible at surface. Such gulls occur in the Great Oolite Group and to a lesser extent in the Inferior Oolite Group. In some cases the Great Oolite Group gulls have developed into a complex network of distinctive orthogonal 'gull caves' deep within the hillside. These are unusual in cambered terrain, and are distinct from the more common solution caves found in limestone terrain. The mid-slope gulls within the Inferior Oolite are inferred from site investigation borings (Chandler et al., 1976), and are, by virtue of their subcrop, 'infilled'.

Various models developed for cambering were reviewed by Parks (1991) and Hutchinson (1991). The most likely sequence of events, according to Parks, based on observations at Empingham Dam (Horswill & Horton, 1976) is as follows:

1) Valley-bulge development caused by stress-relief during rapid river downcutting (glacial melt-water, river capture, etc)

2) Thawing of ground ice contained within the slope (increased pore pressures),

3) Downslope creep / extrusion of the softened plastic clay substrate.

The most commonly quoted morphology for cambering is the simple 'drape' profile shown in Figure 5. This profile features progressive forward tilting combined with subsidence of the caprock blocks into the underlying extruding clay formation. One of the features of the drape profile is that as blocks become separated, the underlying (and in some cases the overlying) clay material extrudes into the gap created. Such features were inferred for some slope profiles at Swainswick (Chandler et al., 1976). The drape may develop further to produce the 'dip and fault' structure shown in Figure 6. Here the dip of the bedding in individual detached caprock blocks is increased.

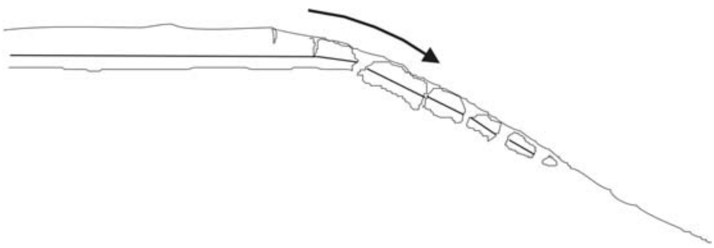


Figure 5 Cambering - simple 'drape' profile

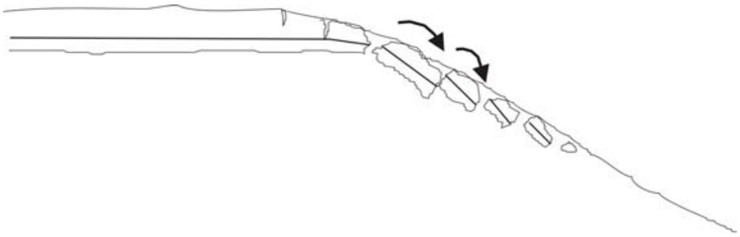


Figure 6 Cambering – ‘dip and fault’ profile

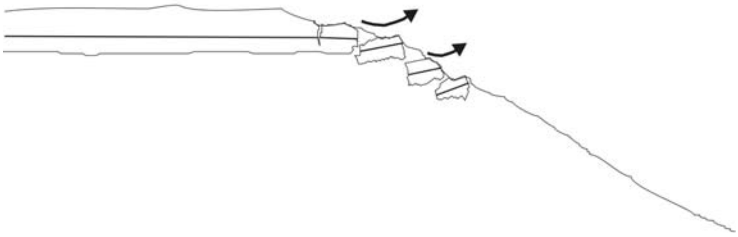


Figure 7 Cambering - back-rotation profile

An alternative back-rotation profile is shown in Figure 7. This occurs when individual cambered blocks are subject to rotational landsliding. Such processes were probably separated in time from the cambering itself, and being active have probably tended to degrade the original cambered profile. An example of the ‘hinge’ part of the cambering drape is shown in Figure 8. A possible example of the ‘dip & fault’ process is shown in Figure 9.

The periglacial model described by Parks (1991) is based in part on the fact that cambering, unlike landsliding, is inactive in the UK; that is, the process ceased following periglaciation. This would tend to discount any idea that cambering is purely a stress-relief process. Hutchinson (1991) and Parks (1991) point to ground ice formation and melting as essential factors in the development of cambering. Melting of periglacial ground ice tends to occur from both above and below. This tends to give the remaining body of ice a profile running parallel with the valley slope, and hence encourages the development of simple cambering (Figure 5). Several cycles of ground ice formation/melting would tend to disrupt this pattern, and final melting would initiate landslipping (Figure 6 and Figure 7).

Figure 8 Camber ‘hinge’ at Rowbarrow Wood, Monkton Farleigh

Figure 9 Possible dip & fault profile – Rowbarrow Wood, Monkton Farleigh

A classification of mass-movement processes related to gull-formation was put forward by Hawkins and Privett (1981). This is summarised, including additional elements taken from Self (1985), in Table 3.

Table 3 Classification of gull-forming mass movements (Hawkins and Privett,1981; Self, 1985)

Type	Description
A	Opening of single major joint to surface, formed on single slip plane, results in smooth-walled gull
B	Multiple bedding-plane slips between surface and lowest slip-plane, results in many small non-aligned smooth gulls
C	As for A but bounded by an upper slip surface, results in smooth ‘bridged’ gull
AB	Combines features of A & B. Movement increasing upward, results in stepped gull narrowing with depth
AC	Sliding of a C-type block followed by tilt, results in smooth gull narrowing with depth
D	C-type movement which induces a B type movement above it, results in single smooth gull at depth with shallower disconnected small smooth gulls
E	C-type movement combined with a wedge block fall at the rear, results in two-level smooth gull narrowing with depth

Physically similar, but glacially-unrelated, camber structures to those at Bath are found in Italy. A site of apparent active cambering has been described at Caramanico Terme, Pescara in the Central Apennines of Italy (Sciarra, 2000). Here, a plateau of partially karstic carbonate megabreccias overlies a thick deposit of Pliocene marly clays with sands; the junction being characterised by disturbance, in particular thrust shears. A large landslide occurred, at the edge of one large block already detached from the plateau, in October 1989 close to the village of San Vittorino. Finite element analyses (Sciarra, 2000) indicated that the plasticity of the substrate, the stress history, and traction forces on the caprock were key elements in the mass movement. Contemporary camber structures have also been noted by Hobbs et al. (1986) in Nicosia, Cyprus.

3.1.1 Cambering of the Great Oolite

As the Great Oolite limestone is for the most part highly permeable, springs develop at its base in the Bath area. Subsided blocks would have tended to act as ground water sinks at these points, resulting in seepage and local erosion. The undisturbed bedding dip is to the southeast and away from the valley. However, the dip is very slight (typically 1 to 2 ^{o}), is unlikely to significantly influence ground water flow, and is readily counteracted by the cambering process.

Evidence from gull caves (see section 0) indicates two phases of cambering movement at Gully Woods. A pre-Ipswichian date is given to the main cambering event at Bath by Chandler et al. (1976), and a possible Anglian or post-Anglian date by Self (1995).

An example of a bridged gull, visible in the south wall of a small (former) quarry, is shown in Figure 10. This may form part of a gull cave system similar to that at Gully Woods, Monkton Farleigh (see section 0), although the slope at Brassknocker Hill has a characteristically cambered profile (Hobbs, 1980), unlike that at Gully Woods.

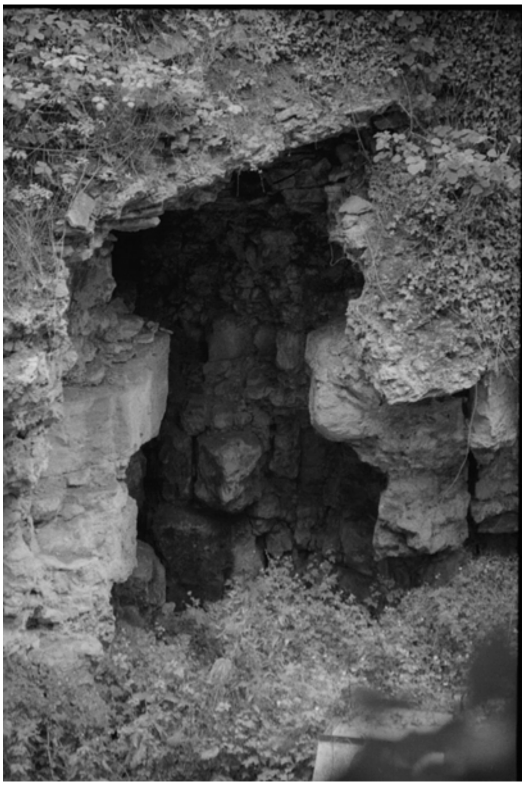


Figure 10 Bridged gull cave, Great Oolite, Brassknocker Hill, Monkton Combe [ST779628] (Hobbs, 1980) Note: slope from right to left

Figure 11 Cambered block of Great Oolite, Bathford Hill - March 2004 [37940 16136]

An example of a large cambered block of Great Oolite limestone is found in a clearing in the woods on Bathford Hill, on the east side of the Limpley-Stoke valley (Figure 11). Here the limestone has dips of 20 – 30 ^{o} downslope (westward).

3.1.2 Cambering of the inferior oolite

Evidence for cambering of the Inferior Oolite is less clear than for the Great Oolite. This is largely because of a general lack of cambered Inferior Oolite outcrop and of sub-surface information away from the east side of Swainswick Valley. The principal source of information and interpretation for cambering in the Inferior Oolite was found in Chandler et al. (1976). In particular, two cross-sections ('Swainswick 1 & 2') on the western slope of Little Solsbury Hill (Figure 12 and Figure 13). The data for these came from early site investigations for the re-alignment of the Swainswick Valley section of the A46. These included boreholes and trial pits. Later site investigations, whilst adding to the data set, borrowed from rather than altered the essential interpretation of Chandler et al. (1976). The interpretation of these two sections used a 'dip & fault' mechanism (see Figure 6) to explain the apparent and considerable downslope (westerly) drop by more than 30 m of the base of the Inferior Oolite on these slopes, despite an easterly regional dip. Whilst the interpretation is plausible, though not unique, it is difficult to prove and, perhaps more importantly, does not appear to be repeated elsewhere in the study area. Associated with the apparent 'dip & fault' cambering was considerable disturbance of all strata involved from the Fuller's Earth to the Lias.

In contrast to the Little Solsbury Hill area on the east side of the Swainswick Valley, described above, the limited outcrops of the Inferior Oolite suggest that cambering has not occurred universally; for example, on the west side of the Swainswick Valley below Soper's Wood (Figure 14).

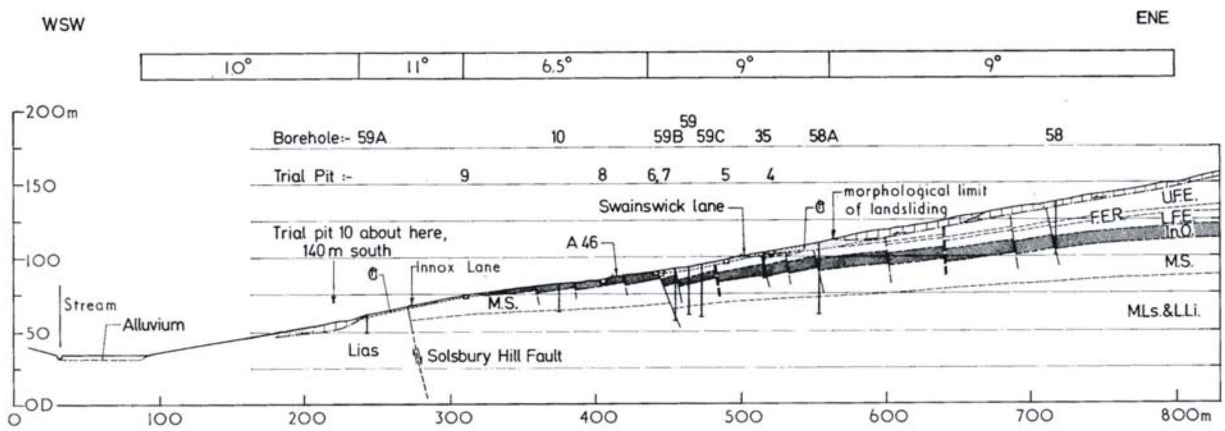


Figure 12 Cross-section 'Swainswick 1' (Chandler et al., 1976)

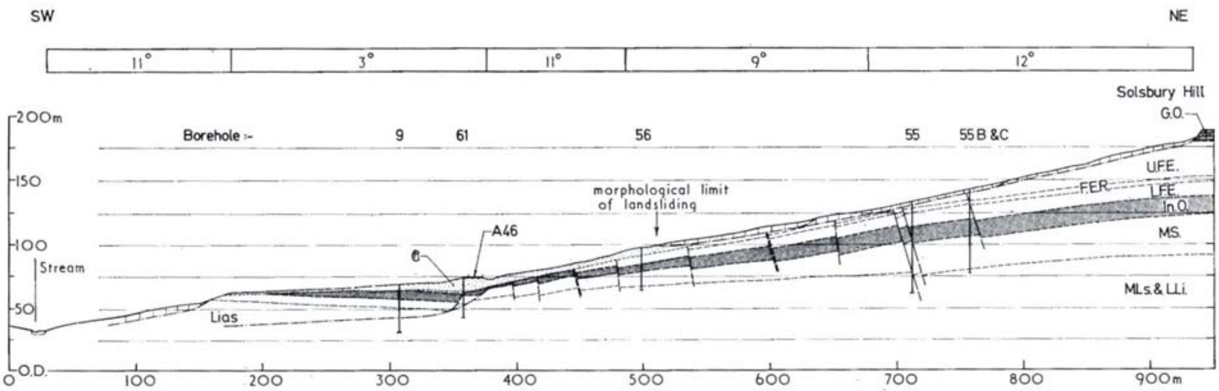


Figure 13 Cross-section 'Swainswick 2' (Chandler et al., 1976)

Figure 14 Apparently uncambered, though open-jointed, Salperton Limestone Formation (Inferior Oolite Group) below Soper's Wood [37480 16810].

3.1.3 Substrate mobility

A key pre-requisite for cambering to take place is the mobility of a weaker substrate. In the Bath area these are represented by the Fuller's Earth Formation mudstones which underlie the Great Oolite Group limestones, and the Lias Group mudstones and sandstones which underlie the Inferior Oolite Group limestones. The means by which a weaker substrate to the cambering rock-mass becomes mobile is a topic which has received little attention in the literature. One contribution was from Poulsom (1995) who described a process of brittle/ductile transition to explain the large-scale coastal displacements at Portland, Dorset and Ventnor, Isle of Wight. Whilst these well-known landslide complexes are not entirely a function of cambering, the process proposed does hold some interest for the likely genesis of today's Bath slopes. Poulsom (1995) related lateral stress relief to principal stress-paths within the clay substrate using pre-critical-state soil mechanics terminology. A brittle/ductile transition boundary defined by the principal stress equation (dashed blue line in Figure 15):

$$\sigma_1 = 2\sigma_3$$

where: σ_1 is vertical stress and σ_3 is horizontal stress

was derived from Barton (1976). In the same figure the strength envelope for the clay is shown as a black curve. The proposed sequence of (geological time-scale) events, as a point within the rock mass would have been approached by the valley side, is as follows (letters refer to Figure 15):

a) Initially, lateral stress (σ_3) exceeds vertical due to the over-consolidated nature of the clay deposit. This places an example point within the clay layer at point 'a' (Figure 15). Points at other positions within the clay layer would be located elsewhere on the right side of the graph. The Fuller's Earth Formation mudstones and clays are lightly over-consolidated. The Lias Group mudstones are generally heavily over-consolidated.

b) As the valley side approaches, the lateral stress (σ_3) at the example point reduces whilst the vertical stress (σ_1) remains constant. The clay layer is within the ductile zone but below the failure envelope. Deformation does not occur.

c) With closer proximity to the valley side, parts of the clay layer are within the zone of ductile deformation and have begun deforming and thinning. This allows the process of cambering of the overlying limestone to initiate. As the limestone is a brittle material, tension cracks (gulls) develop and the limestone blocks subside or rotate. However, the clay layer does not fail catastrophically as the ductile deformation zone is characterised by strain-hardening behaviour. Rather, a process of clay creep leads to gull widening and progressive lateral movement of the limestone blocks.

d) As lateral stress decreases further, the clay layer enters the brittle zone by crossing the blue line. As this is characterised by strain-softening behaviour, shear strength reduces to a residual value and displacements tend to concentrate in one or more shear surfaces at levels of common principal stress. At this point vertical stress has also decreased somewhat due to progressive thinning of the clay layer. As the overburden, and hence σ_1, within the clay layer is greatest at its base, the principal shear plane tends to develop here (Poulsom, 1996) and a deep-seated landslide is formed. Increased pore pressures would tend to reduce strength further and initiate shear failure at some point within the clay mass.

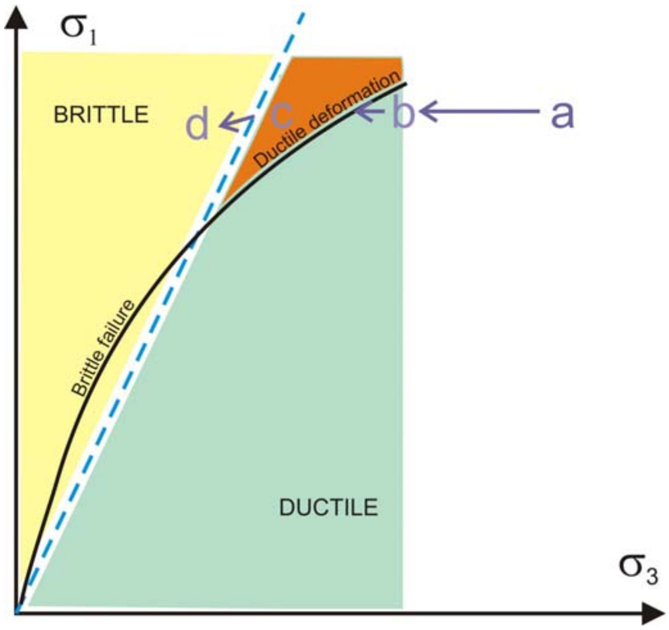


Figure 15 Brittle/ductile transition model for weak substrate deformation and failure (adapted from Poulsom, 1996) Note: refer to text for explanation

In the case of Ventnor and similar coastal sites the shear plane has developed on an essentially level shear plane, determined by the bedding, with subsidiary inclined shears forming at the rear and within the slip mass, to accommodate rotational and extensional (spreading) movements. Comparison of the Bath cambering situation with that summarised above, from Poulsom (1996) for Ventnor and Portland, is imperfect. For example, the thicknesses of the Fuller's Earth and Lias clay substrates at Bath are considerably less, and hence the tendency to produce large landslide complexes is absent. Also, the stress histories, glaciation and periglaciation histories, and stress/strain behaviours of the Fuller's Earth and Lias clays are different. Finally, unlike the Bath situation, the coastal models are currently active as a result of continuous marine erosion (Poulsom, 1996). However, the principles of this simple model appear to suggest how a mechanism described elsewhere as clay 'extrusion' could have occurred on a geological time scale. The likelihood is that such processes are not continuing at the present day.

Using the Poulsom model, described above, a conceptual model for cambering and landsliding at Bath is shown in Figure 16. Here, cambering movements in the two layers are shown with black arrows and landslide movements with grey. Many tens of metres away from the valley side, the sequence is considered stable with little or no lateral spreading. Closer to the valley side ductile deformation and brittle failure within the Fuller's Earth and Lias produce cambering of the Great Oolite and Inferior Oolite, respectively. Lias strata close to the valley floor are uplifted by valley bulging. This then produces occasional deep-seated landslides in the Lias and shallow landslides in the Fuller's Earth. Block slides of Great Oolite are found downslope of the escarpment. The Inferior Oolite is frequently, though not universally, cambered. The Poulsom (1996) model would suggest that the effects of cambering should be greatest in the Inferior Oolite for two reasons: firstly, the Inferior Oolite is weaker than the Great Oolite, and secondly the reduction in overburden is greater. Evidence from the Swainswick valley (A46) site investigations (Chandler et al., 1976) suggests that both Fuller's Earth and Lias clay (and sand) 'squeeze' into camber gulls within the Inferior Oolite. In addition, shallow head deposits tend to 'drape' the Inferior Oolite debris further downslope from the base of the actual outcrop.

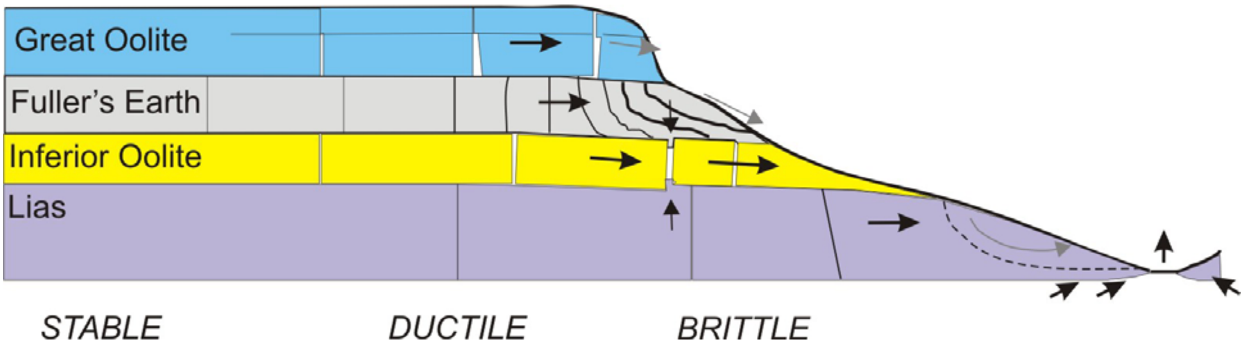


Figure 16 Cross section through idealised cambered Bath valley side showing brittle/ductile transition within the two clay layers (adapted from Poulsom, 1996) Note: refer to text for explanation

An interesting feature of the Bath area is the presence of small and narrowed plateaux. The model shown in Figure 16 then becomes more complex due to the fact that the stable zone is negligible or even absent. Stress relief, and hence cambering may then have developed on both flanks of any chosen cross-section through the plateau (Figure 17). Examples of this would be Little Solsbury Hill and the southern tip of Banner Down. However, the much larger Charmy Down plateau, east of the Swainswick valley, shows bedding-dip evidence which may suggest very deep-seated landsliding and associated hinging of the central plateau caprock (Figure 18). However, borehole evidence on the slopes around Charmy Down (Chandler et al., 1976; Mott McDonald pers. comm.) does not support this. The model in Figure 18 might conceivably result from dominantly deep-seated landslide processes, affecting a relatively thin caprock, rather than from cambering; that is, effectively the converse process to that shown in Figure 17. The Figure 18 model would tend to produce back-tilted limestone bedding which might appear similar to the familiar cambering model shown in Figure 7, and may in fact be more applicable to the slopes around Little Solsbury Hill.

Deep-seated landslides on this scale have been proposed, but not proved, for the Bath area in the past and are found in G.A. Kellaway's field notes and 6" map (Figure 19) prior to the publication of the 1965 1:50,000 solid & drift edition of Sheet 265 (but not indicated on the published map). Kellaway referred to the 'Solsbury Hill Landslip' which was considered to have slipped southward from Charmy Down plateau. Whilst this linear feature was no doubt mooted to explain the outlying Little Solsbury Hill, it fails to do so as the (scarp?) feature lies to the south of Chilcombe Bottom, and even further to the south of the Charmy Down plateau from which presumably Little Solsbury Hill was assumed to have slipped. This feature was later interpreted as the 'Solsbury Hill Fault' by Chandler et al. (1976).

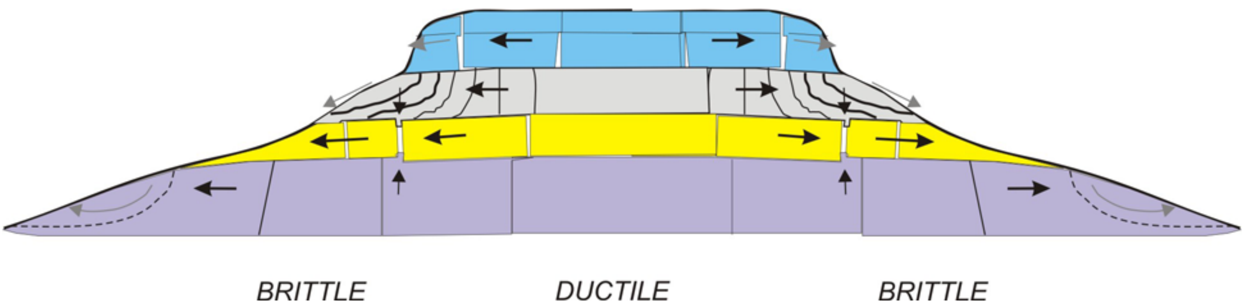


Figure 17 Cross section through idealised 'dip& fault' style cambered plateau

Such a fault could be of a 'listric' type replicating landslide type displacements but on a larger scale. Certainly, the sub-surface surrounding Little Solsbury Hill does show considerable bedding disruption and brecciation to depths in excess of 30 m (Chandler et al., 1976). The possible transition of scale from landsliding to faulting, in the context of gravity-driven mechanisms, merits further investigation.

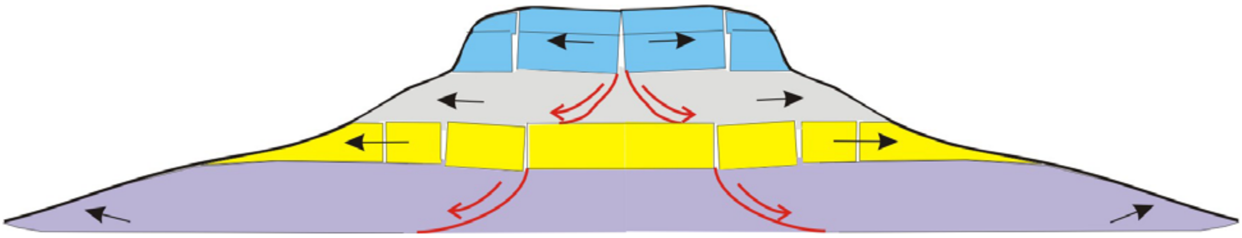


Figure 18 Conceptual cross section through small plateau showing ultra-deep-seated landslide model

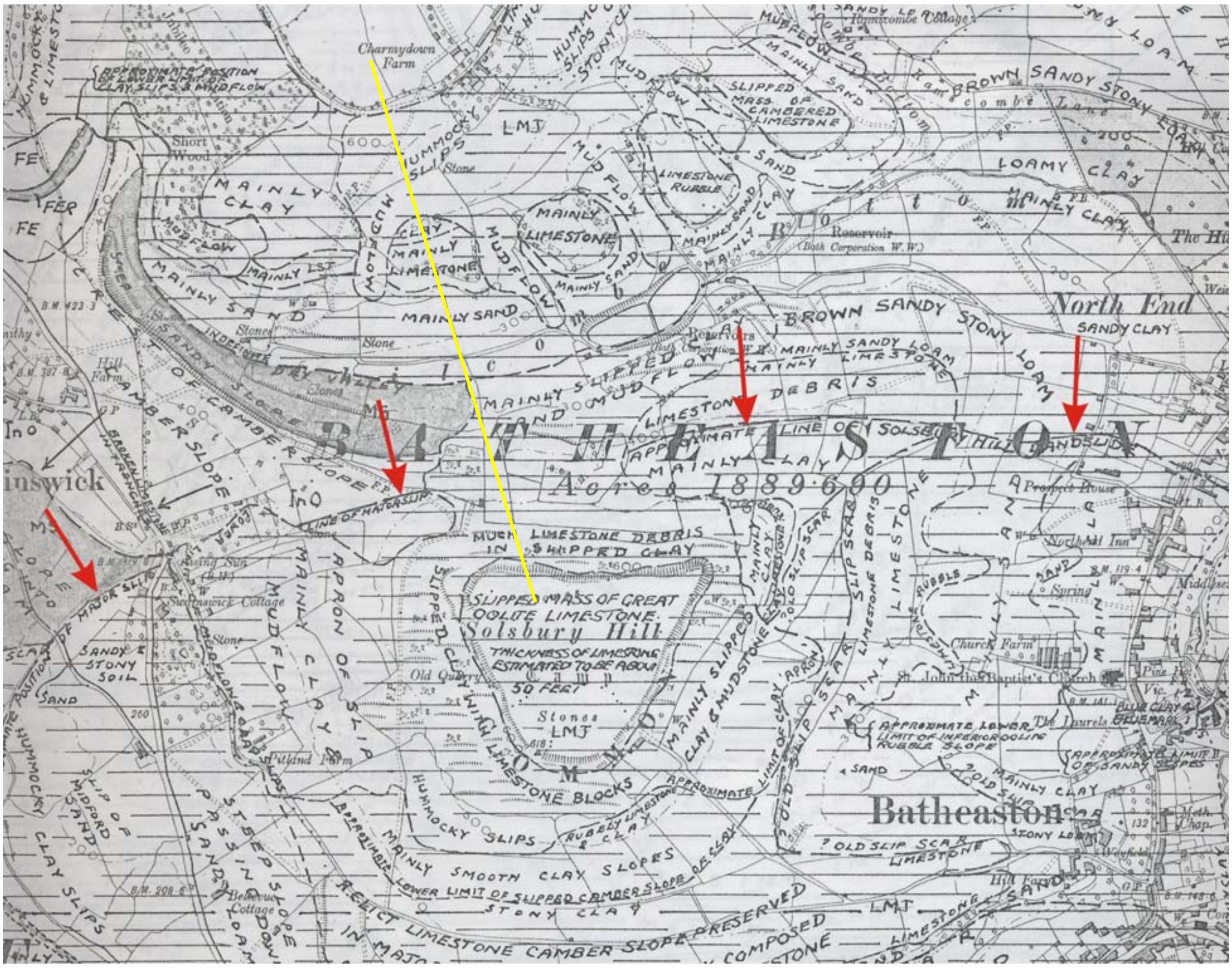


Figure 19 Extract from BGS County series '6 inches to one mile' Sheet Somerset VIII SW
Note: red arrows = location of "assumed position of Solsbury Hill major slip / slide"
Yellow line = cross-section (Figure 20)

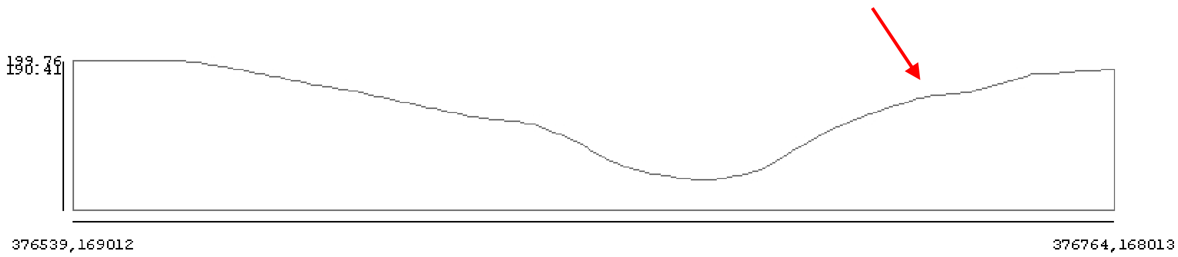


Figure 20 Cross-section from Charmy Down (left) to Little Solsbury Hill (right) across Chilcombe Bottom (refer to Figure 19) Note: Red arrow shows approximate position of 'Solsbury Hill Fault'

A north to south cross-section from Charmy Down to Little Solsbury Hill is shown in Figure 20. The summit of Little Solsbury Hill is about 9 m lower than Charmy Down. The approximate location of the Solsbury Hill slide (or fault) feature is shown by the red arrow. The two flanks of the Chilcombe Bottom valley are notably different in profile, but both have been subject to landsliding.

3.2 GULL CAVES

Although generally known to cavers for many years, the true extent and significance of gull cave formation in the Bath area has only become apparent in the last few years, as a direct result of detailed cave surveys by Bristol University speleologists (Self, 1985; Self, 1995; Self & Boycott, 1999). They have revealed remarkable natural cave systems penetrating deep (>60 m) into the hillside at depths (below plateau ground level) in excess of 25 m. These are distinct in character from nearby mines within the same strata. The proposed mechanisms leading to the development of these cave systems are shown in Table 4 and schematically in Figure 22. These were developed by Self (1985), and the block diagrams are adapted from the same source. The location to which the model refers is 'Sally's Rift' at Gully Woods [ST794650], to the south of Bathford, on the east side of Limpley Stoke valley. The proposed mechanism of Fuller's Earth clay softening, plastic extrusion, and the resulting 'traction' forces on the overlying Great Oolite limestone, is an unusual one not dealt with analytically in the literature (to the authors' knowledge). However, see section 3.1.3 for a simple 'soil mechanics' explanation. The mechanism is essentially analogous to a 'conveyor' driven by gravitational forces and stress-relief acting on the weak substrate and approximates to movement types D and AC in Table 3. The apparently purely horizontal nature of this deformation mechanism, at least away from the valley side, is difficult to visualise. However, it has been proved conclusively by the speleologists' surveys that horizontal movements, at least within the caprock, are the forming factors of the gull caves systems studied in this area (Self, 1985; Self, 1995; Self & Boycott, 1999). The gull cave system has been dated to at least 350,000 years BP (Hoxnian), and possibly as far back as 500,000 BP (pre-Anglian) (Self, 1995).

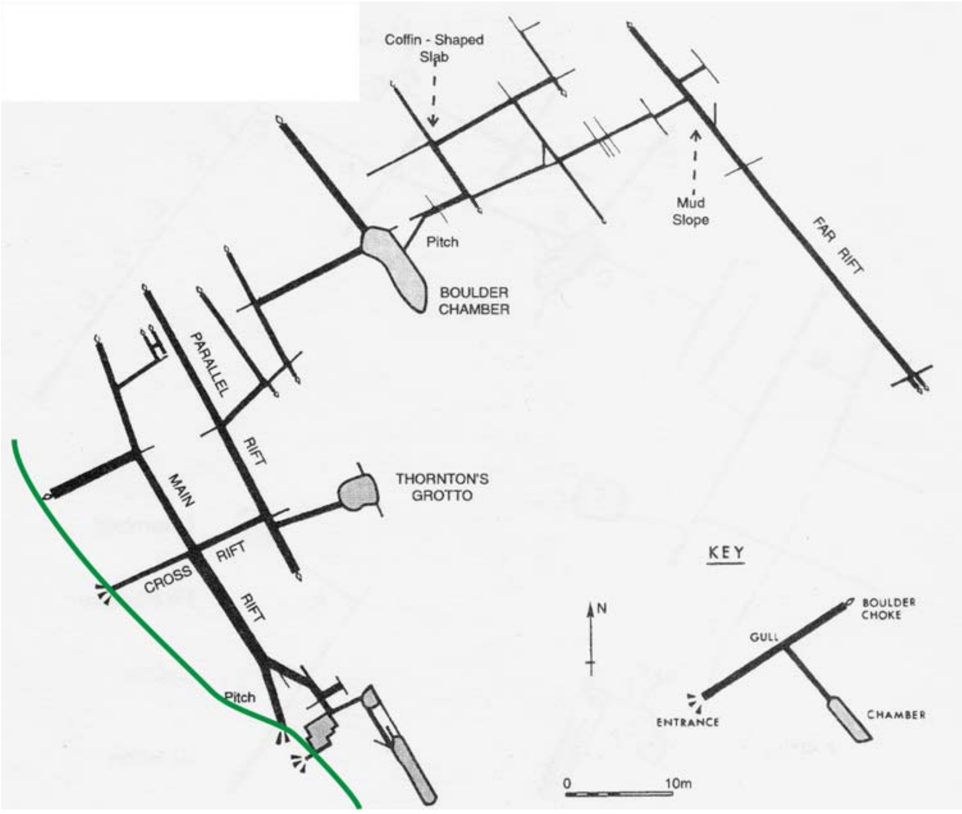
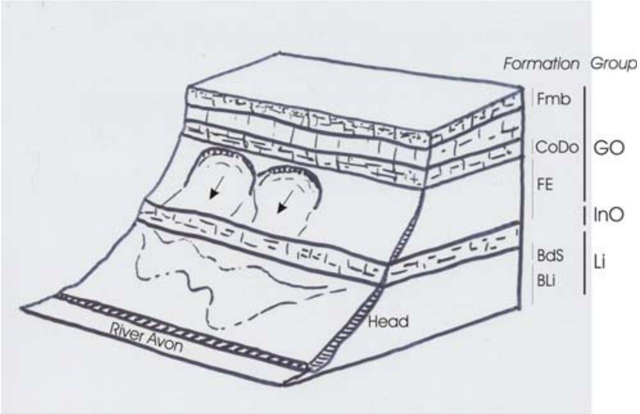
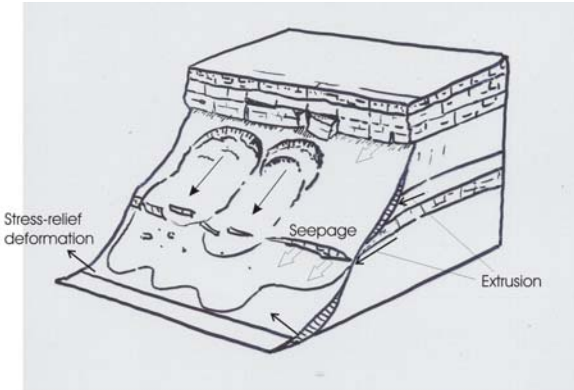


Figure 21 Map of gull caves at Sally's Rift, Gully Woods, Bathford (Self, 1995)
Green line = plateau edge

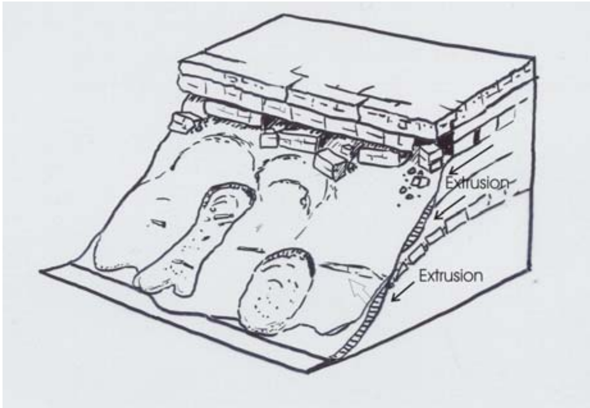
The cave system resulting from these processes (Figure 21) is distinctly angular in both plan and cross-section, and maps out as a trelliswork of open, en-echelon rifts parallel and perpendicular to the local valley crest (NW/SE and NE/SW, respectively). The rifts are 10 to 12 m high and 30 to 60 cm wide (Self, 1995). Apparently none of these features has any expression at ground surface. The contact between the Great Oolite limestone and the Fuller's Earth clay in the cave floor is highly irregular and poorly defined, due at least in part to a build-up of debris. Self (1985) reported that an analysis of rift volumes and polar directions indicated that net movement had been to the west (i.e. valleywards) at some point in the process, rather than solely south-west as might be expected from the polar directions alone. The rifts decrease in width away from the valley, but are still negotiable (by a caver) at a distance of 60 m at which point the cave roof is approximately 25m below ground. Self (1985) has identified two phases of mass movement, based on cave geometry and deposits, with net lateral movement of 20%. These range in age from >350,000 years BP (possibly as much as 500,000 years BP) and 78,500 years BP. Self (1985) also describes a similar cave system (Henry's Hole) to the northeast of Box (Wilts.) which is outside the study area.



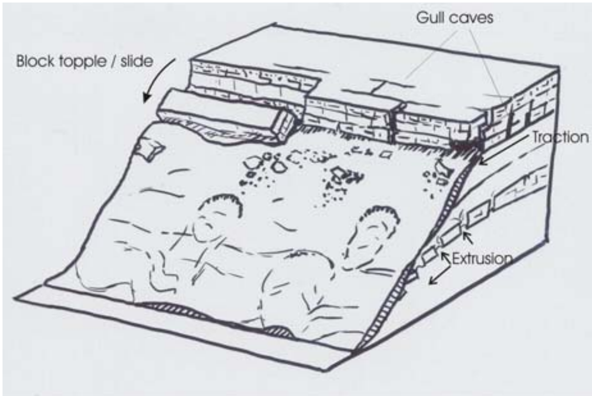
Stage 1



Stage 2



Stage 3



Stage 4

Figure 22 Proposed stages of slope, mass movement, and gull cave development at 'Sally's Rift', Gully Woods, Monkton Farleigh (adapted from Self, 1985) (Refer to Table 4) (not to scale)

The slope profile at Gully Woods suggests that the dominant process here is not the classic concept of cambering, at least not as far as the Great Oolite limestone caprock is concerned. The overall process may be considered in the same category as cambering, the difference being that the caprock is thicker and does not provide a continuous 'drape' as seen in the mid-slope Inferior Oolite, and elsewhere in the Great Oolite caprock (Chandler et al., 1976; Hutchinson, 1991; Parks, 1991; Humpage, 1976), and described in section 3.1.1 and shown in Figure 5, Figure 6, and Figure 7.

Table 4 Proposed stages in development of slope and mass movements (refer to Figure 22)

Stage	Process	
1	*Start condition*: Deeply incised valley. Rapid downcutting of River Avon. Toe erosion. Saturated ground conditions. Freeze/thaw action. Springs. Solifluction Head deposits involved in shallow landslides.	

2	Seepage from InO and GtO. Extrusion valleyward of softened FE clays resulting in loss of support to GtO limestones (lower). Shallow landslides continue. Deep-seated landslides develop in FE. Block formation in GtO (lower) resulting in detachment & sliding.	
3	GtO limestones (upper/mid) capable of cantilevered self-support. Block detachment continues, affecting lower & some mid GtO. Hydrostatic uplift due to cambering and artesian conditions at ‘buried’ InO subcrop. Gull network develops in GtO limestones (lower).	
4	Gull cave system propagates away from valley (limited surface expression). Driving mechanism is traction of GtO limestones (lower) caused by extensile forces within FE (upper) clays. Large block of GtO limestones (whole) topples and slides (>20^{o} tilt). Existing blocks break up. Extrusion of FE and BLi into cambered InO. Shallow landsliding continues.	

A detailed cross-section of the proposed gull-forming mechanism at Sally’s Rift (Gully Woods) is shown in Figure 23. This shows the lateral extensile movement and associated traction force (F in Figure 23), developing at some distance from the valley side, which then acquires a downward component at some point close to where it daylights at the valley side. These forces are analogous to those postulated for valley bulging, except that in the case of valley bulging the valleyward deformation vector tends to be upward. Both types of force are largely the result of the stress relief behaviour of clays, augmented by landslide movement as the valley side is ‘approached’. These traction forces diminish upward through the various limestone layers (as do the resulting fractures), and the uppermost layer is unaffected, it being subject only to cantilever forces and failure in the final stages. Self (1985) describes open gulls large enough to walk through which have roofs formed by the overlying bedding plane, i.e. bridged gulls. Self also describes separated asymmetric ‘fit’ features in the cave walls (e.g. at point X in Figure 23) further indicating that the rift had been formed by movement (rather than dissolution), and that this movement had been purely lateral in this area. The gull caves are described as being largely rectilinear with sharp-edged junctions and terminations. Such features are not indicative of solution processes associated with normal cave systems in limestone.

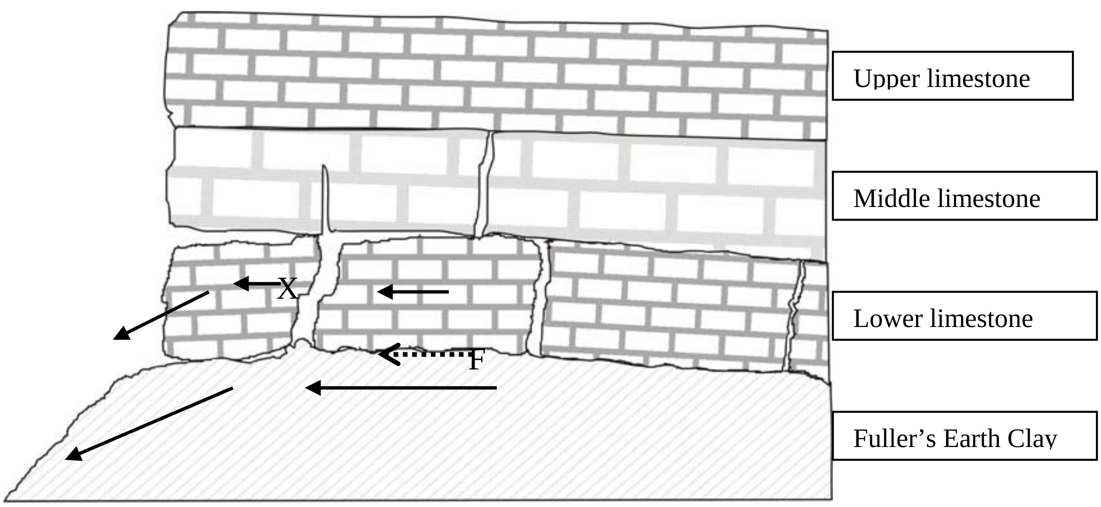


Figure 23 Schematic cross-section through gull cave system at Sally’s Rift showing possible displacement mechanism of lowermost limestone [adapted from Self, 1985] (not to scale)

Similar observations of 'foundering' of the lowermost Great Oolite bed have been made at Horsecombe Vale to the west of Limpley Stoke (Chandler et al., 1976).

Self (1985) suggested that gull caves, of the kind found at Gully Wood and Box Hill, are likely to be common, though as yet unexplored, in the Bath area. In fact, there is no reason to suspect that such complex features are anomalous, though they are probably related to caprock thickness, plateau/valley relief, and the origins of the stress-relief.

Features which exhibited similar characteristics, but on a much smaller scale, were identified at The Rocks Rift (By Brook, St Catherine's valley) [ST 7896 7057], Guy's Rift (Slaughterford) [ST 8450 7372], Murhill Rift (Murhill) [ST 7956 6073], Gorton's Rift (Bradford-on-Avon) [ST 8225 6089], and at Bath University (Bathampton Down) [ST 7677 6452] (Self & Boycott, 1999).

3.3 LANDSLIDES

There are many types of landslide in the study area, in various stages of degradation, re-activation, and stabilisation under present climatic conditions. Landsliding in the area is closely related to cambering, and cannot be considered in isolation. Most landslides are believed to have an ancient origin, at a period when the climate was wetter than today; only a small proportion have shown any activity in historic times. However, several of these have disrupted the development of the city of Bath. Landslides have also had a major influence on road design and construction.

In general there is a 'double-layer' trend to landslides in the area; i.e an 'upper slope' and a 'lower slope' regime. The 'upper' occurs within the Chalfield (Great) Oolite and Fuller's Earth Formations, and the lower within the Inferior Oolite and Lias Groups (Table 2).

3.3.1 Upper slopes

The upper slopes are characterised by sharply defined backscars at the edge of the Great Oolite limestone plateau. These may have been either cambered or uncambered. Evidence of cambering may have been removed by large-scale landsliding. Alternatively, some elements of cambering may remain. The plan form of the backscars is usually either straight or slightly arcuate.

Debris flows are found particularly in the tree-covered upper slopes. These usually derived from deep-seated rotational or translational landslides upslope (for example, Figure 24).

Figure 24 Debris flow emerging from Soper's Wood, Swainswick Valley (west side)

Mudslides in the vicinity of the outcrop of the Fuller's Earth Formation, and to a lesser extent the Bridport Sand Formation, frequently have developed into complexes, which scour out characteristically shaped hollows. Frequently, little or no landslide debris remains within the hollow. Whilst individual mudslides tend to be shallow and very elongate with a wider head and wider toe (Figure 25), the mudslide complex tends to develop into a deeper bowl-shaped feature usually with degraded head and side scars. The individual mudslides are rapidly degraded, whereas the complex as a whole is long-lived, perhaps due to the fact that it is self-regenerating by virtue of the channelling effect of surface and ground water.

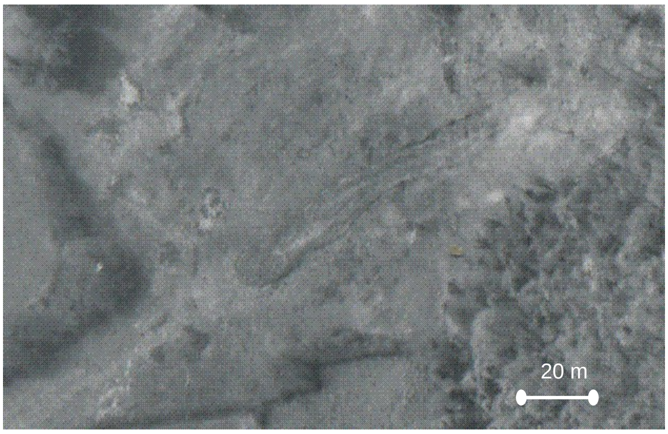


Figure 25 Fresh mudslide tracking top right to centre – Charmy Down (Chilcombe Bottom) (Cartographic Services Ltd. April 1975)

These are associated with back-sapping along spring-lines and, particularly within the Bridport Sand Formation and Fuller's Earth Formations. Good examples are seen on the southern slope of Holts Down facing Little Solsbury Hill (Figure 26), on a northwest-facing slope of Freezing Hill viewed from Toghill Farm (Figure 27), and on the western slopes of Swainswick valley (Figure 28). Due to the fact that their central portions are narrow, the complexes tend to be separated by 'unslipped' bedrock (that is, bedrock unslipped as part of the mudslide complex itself).

Figure 26 Southern slope of Holts Down (Pennyslait Wood) – two mudslide complexes Aug 2002

Individual mudslides are particularly transient in terms of their surface expression. Evidence for their presence usually lasts only a few years after the initial event. Processes of creep, erosion, and farm activity tend to be responsible. Mudslide complexes become re-vegetated and re-farmed very quickly unless activity persists over several seasons. Field boundaries often follow the edges of the complexes, or in some cases individual mudslides, which may attest to their longevity.

Figure 27 Recent mudslides at Freezing Hill viewed from Toghill Farm (Sep 2005)

Figure 28 Shallow landslides at Soper's Wood, Swainswick valley (west side)

3.3.2 Lower slopes

The lower slopes in the vicinity of Bath are characterised by deep-seated rotational landslides, such as Bailbrook at the western approaches to Batheaston and on the southern flank of Little Solsbury Hill (Figure 29). This landslide is 1.2 km long and the backscarp and toe are at elevations of 100 m and 20 m, respectively. The toe reaches to the River Avon in the eastern half and the former route of the A4 trunk road crosses its full width. The backscarp is clearly shown in the cross-section (Figure 30).

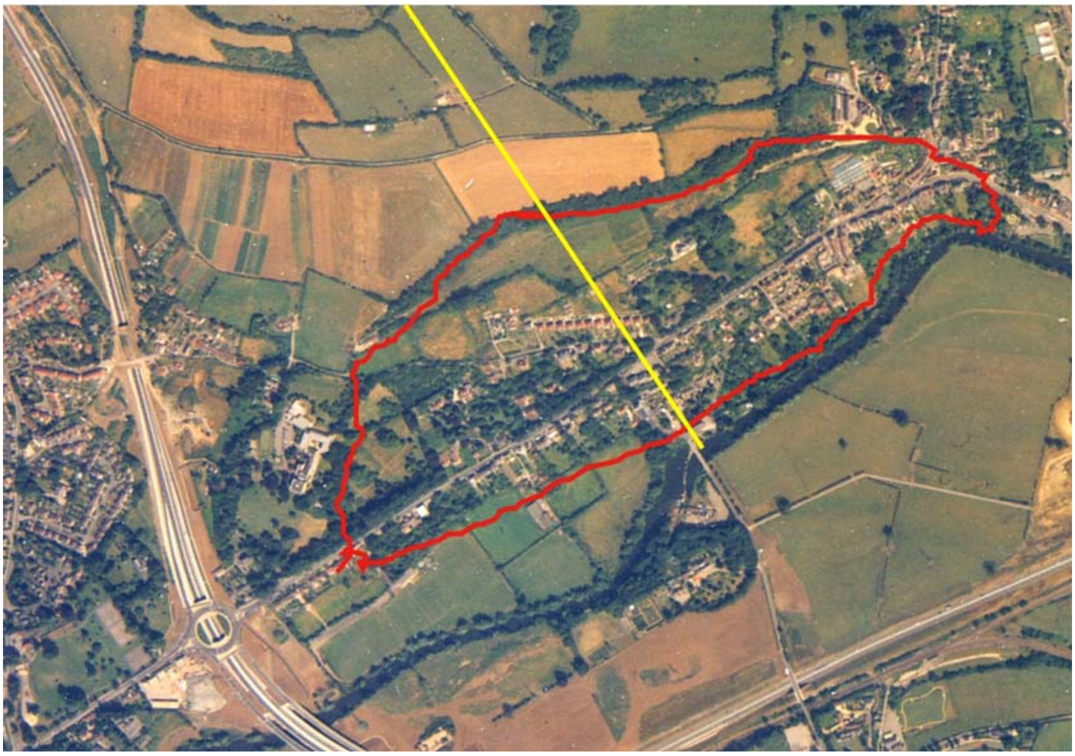


Figure 29 Bailbrook landslide showing cross-section (yellow line) (refer to Figure 30)

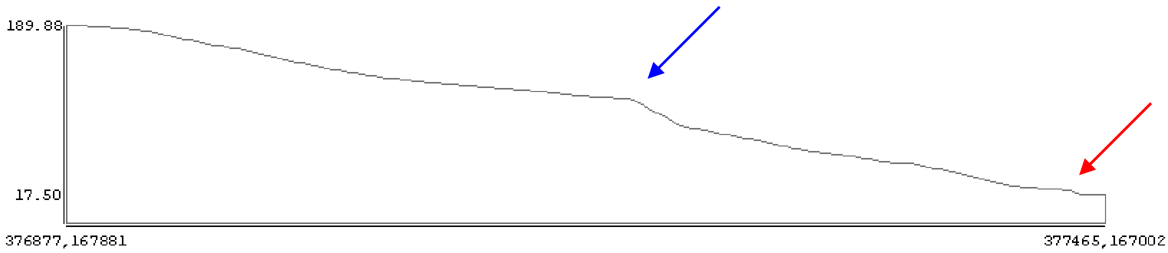


Figure 30 Cross-section CS4 at Bailbrook landslide, Batheaston (refer to Figure 29)

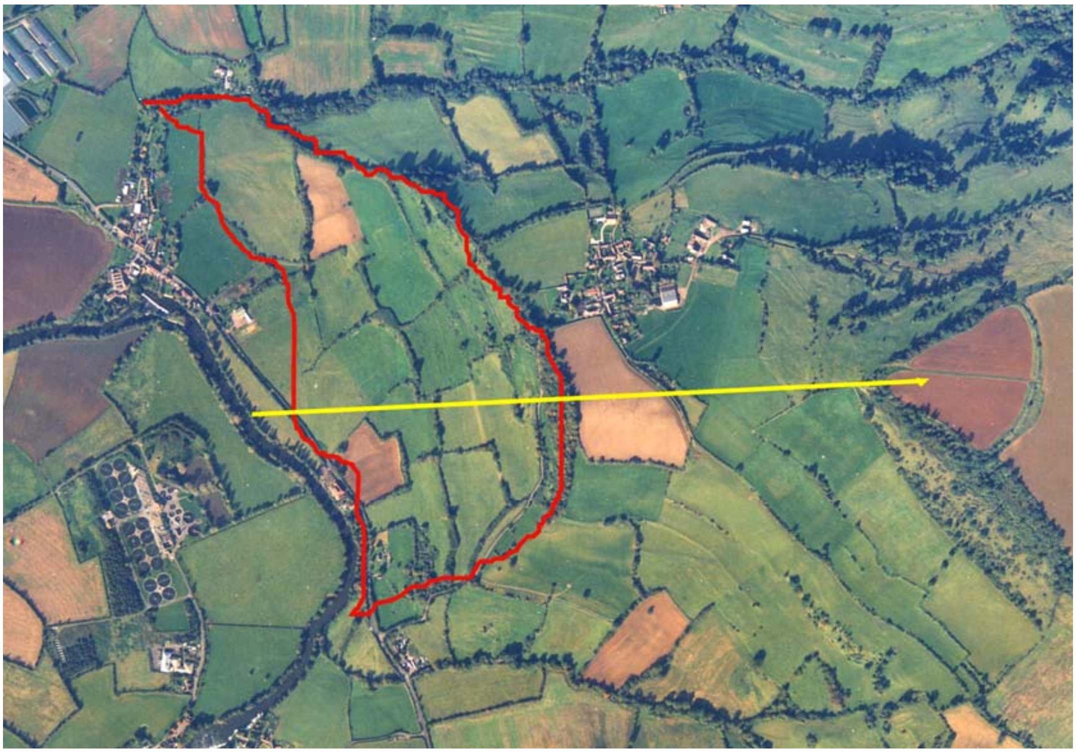


Figure 31 North Stoke landslide showing cross-section (yellow line) (refer to Figure 32)

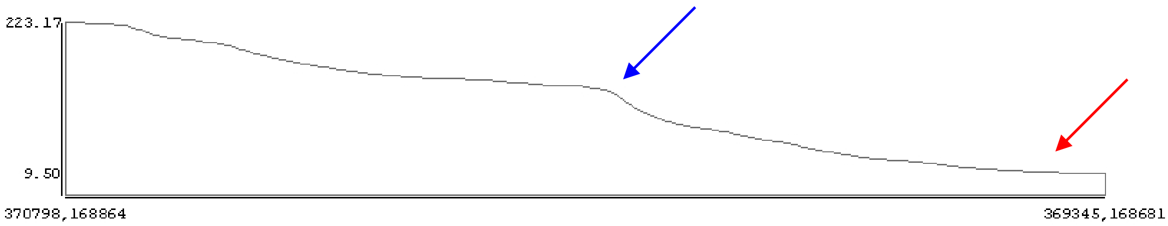


Figure 32 Cross-section CS7 at North Stoke landslide, North Stoke (refer to Figure 31)

The North Stoke landslide (Figure 31) is situated immediately west and downslope of North Stoke village. It is 1.2 km in width and drops from 105 m at the backscarp to 17 m at the River Avon. The cross-section (Figure 32) extends from Little Down at the western extremity of Lansdown Hill westward, and downslope, towards the River Avon near Swineford. The geomorphology of the North Stoke landslide is remarkably similar in form, size, and elevation to that of Bailbrook (Hawkins & Privett, 1979, 1980).

With the exception of a small number of other deep-seated landslides (refer to Appendix 1) the lower slopes are either unslipped or are covered by shallow landslides (for example, Figure 33), some of which have developed from landslides initiated in the upper slopes (see section 3.3.1).

Figure 33 Shallow landslides on the lower slopes at Twinfield Farm, Swainswick Valley (west side)

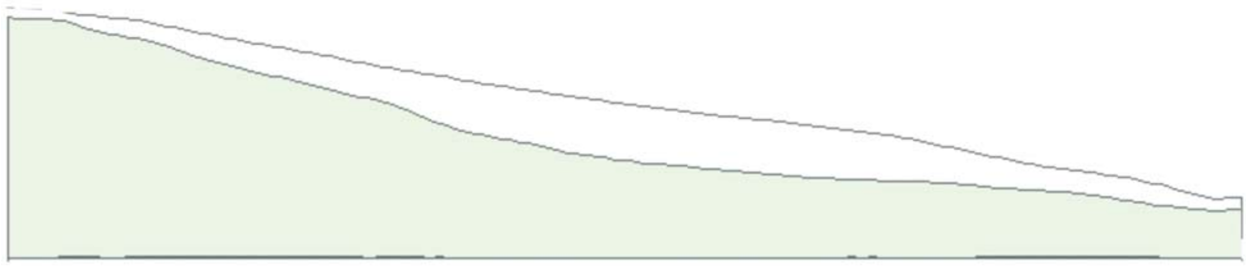


Figure 34 Comparison of adjacent cross-sections at Luccombe Farm (St Catherine's Valley, east side)
Section CS 17: partial landslides (white), section CS 17a: full landslide (green)

Figure 35 View eastward toward Bannerdown from Upper Northend Farm, Aug 2002 [37817 16907}
Note: Northern edge of Luccombe Farm landslide (right)

Comparative sections through part of the eastern side of the St. Catherine's Valley, below the Banner Down plateau, at Luccombe Farm are shown in Figure 34. A view of part of the same valley side is shown in Figure 35.

Table 5 Average slope angles for the major formations in the Bath area (Forster et al., 1985)

Ref.	Locality	Great Oolite (edge)	Fuller's Earth	Inferior Oolite (edge)	Inferior Oolite (camber)	Midford Sands	Lower Lias
Cook 1973	Lansdown		9 - 13				
	Swainswick 1		9		6.5	11	
	Swainswick 2		12		11		
Chandler et al. 1976	Swainswick 3		15.5	25	25	13 - 19	9 – 10.5
	Swainswick 4		11.5				
Privett 1980	Bath	15 - 30	8 - 17	30	6 - 9	6 - 18	6 - 20
	Brassknocker		11		11 - 13	7 - 17	
Hobbs 1980	Claverton	15	11 - 13		9 - 10	5 - 6	5 - 16
	Hengrove Wood	21 - 24	18 - 23	35		17 - 20	10 - 13
	Sheephouse	17	12		11	11	11
	Brown's Folly	21	13		10	6	8
Average		*22*	*13*	*30*	*9.6*	*12*	*10.8*

3.4 LANDSLIDE MAP

The landslide map, accompanying this report, is a digital map created in ARCMap9 and is not reproduced in this report. It encompasses the area previously referred to as 'foundered strata' on the published BGS 1:50,000 geology map of Bath (Sheet 265). It depicts the extent of landslipped ground including the backscarps and sidescarps, where known. It also shows the location of cambers. It does not show geology, as this is currently being remapped. Other geomorphological features are also shown: ridges, valley crests, valley floors, and significant changes of slope.

Most of the features depicted on the map were produced from aerial photo interpretation and from archive data and published literature. In some cases field inspection was carried out. NextMap Digital terrain models, and the cross-sections generated from them, were also used to help identify landslides and cambers.

The map was produced initially on topographic paper base Landplan maps (1: 10,000 scale), and subsequently digitised onto ArcMap 9. The area covered by the landslide map is shown in Figure 36.

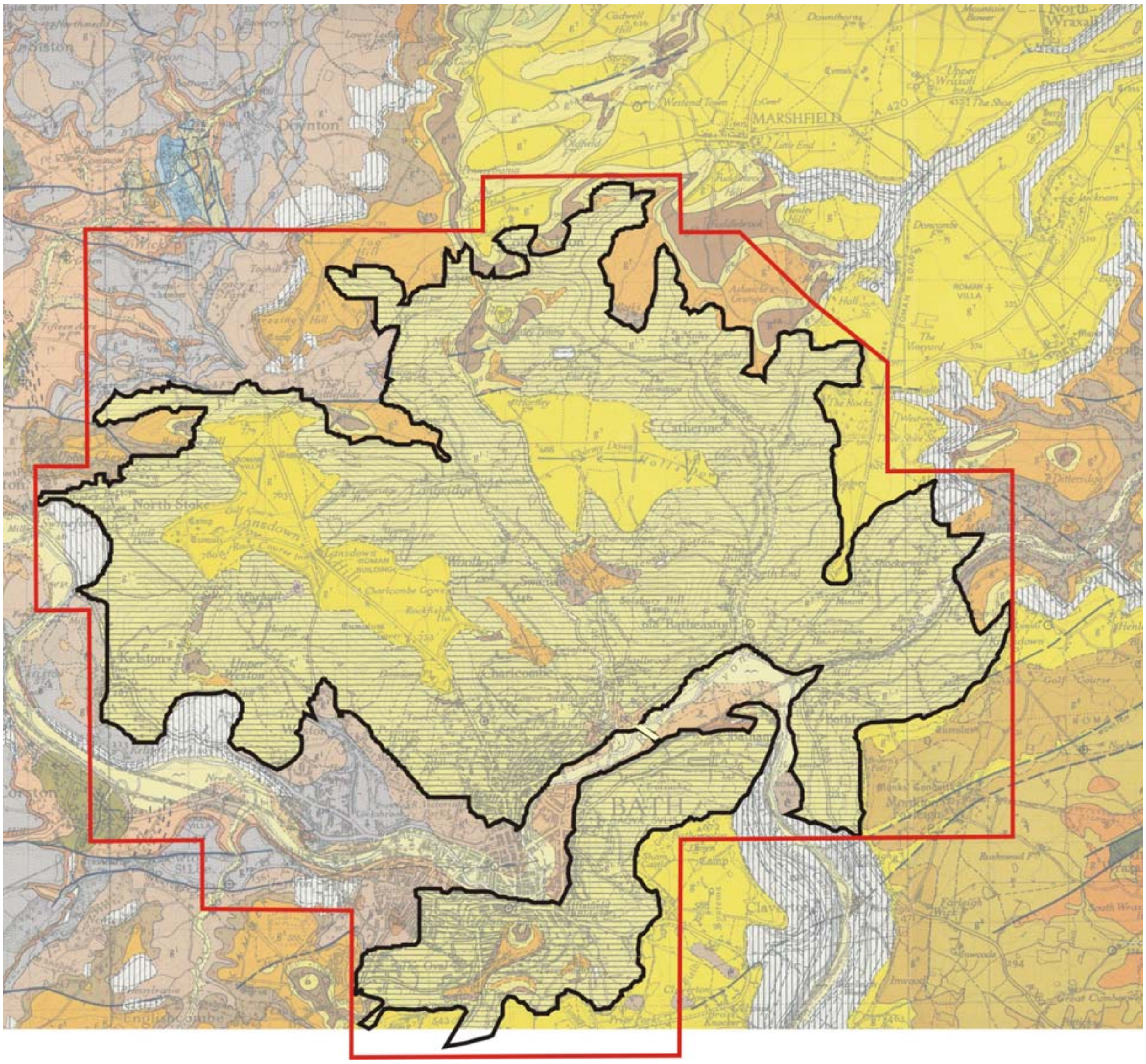


Figure 36 Geology map (published) of Bath (Sheet 265) showing outline of area of 'foundered strata' (black line) and outline of area of landslide map (red line)

3.4.1 Landslide

Landslides are depicted in two ways:

1) Vertical hachuring with lines depicting head and toe. This covers all areas of landslide.
2) Individual landslides, where known, depicted with complete boundary. These lie either within or without a larger hachured area of landslide. Well documented or major landslides in this category are named.

Lines depicting reasonably certain features are solid and those depicting uncertain features are dashed on the map. The map key is reproduced in Table 6.

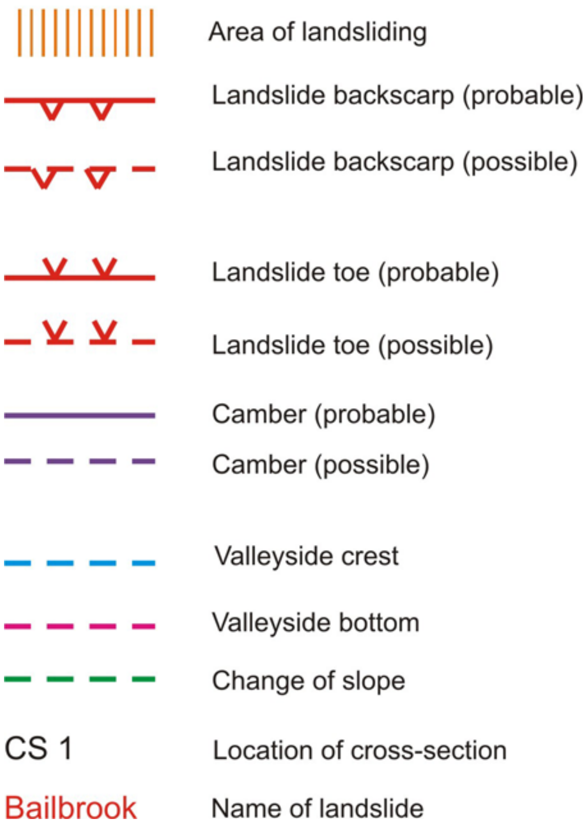
3.4.2 Cambering

Cambering is depicted as individual lines located at the estimated 'hinge point' of a camber or at the head of an area of cambering; the former usually being applicable to the Great Oolite at the plateau edge, and the latter to the camber 'aprons' of Inferior Oolite at mid-slope. Lines depicting reasonably certain features are solid and those depicting uncertain features are dashed on the map.

3.4.3 Other features

Major geographical features such as ridges, valley crests, valley floors, and changes of slope not thought to be associated with landsliding, are shown as dashed lines on the map. The locations of cross-sections taken from NextMap are shown as solid lines with numbers “CS x”. An example of a ‘change of slope’ feature unrelated to landsliding might be a geological outcrop.

Table 6 Key to landslide map



4 Remote sensing

Sources of remote sensing terrain data available to the project have been examined for the purposes of landslide recognition. These were as follows:

- Aerial photographs (BGS),
- Airborne radar (NextMap),
- Airborne LiDAR (ARSF - NERC),
- Terrestrial LiDAR or ‘laser scanning’ (BGS)

4.1 AERIAL PHOTOGRAPHS

Stereo aerial photos were examined, and used to identify and delineate landslide features. Several epochs (from 1975 to 1997) were consulted including both colour and black & white, at scales from 1:10,000 to 1: 25,000. The photos used are listed in Table 7.

Table 7 Stereo aerial photos used for landslide map

Supplier	*Type*	*Scale*	*Date*	*Series/Line*	*Photos*
Infoterra	Colour	1:25,000	10/1997	34/97	233-236
Infoterra	Colour	1:25,000	10/1997	34/97	237-240
Infoterra	Colour	1:25,000	10/1997	34/97	265-268
Infoterra	Colour	1:25,000	10/1997	34/97	269-272
Infoterra	Colour	1:25,000	08/1996	47/96	050-051
Infoterra	Colour	1:25,000	08/1996	47/96	071-072
Infoterra	Colour	1:25,000	08/1996	47/96	079-080
Infoterra	Colour	1:25,000	08/1996	47/96	100-101
Cartographic Services	B&W	1:10,000	05/1975	489	853-861
Cartographic Services	B&W	1:10,000	05/1975	489	97-105
Cartographic Services	B&W	1:10,000	05/1975	489	169-177
Cartographic Services	B&W	1:10,000	05/1975	489	29-47
Cartographic Services	B&W	1:10,000	05/1975	489	41-47
Cartographic Services	B&W	1:10,000	05/1975	489	8-16
Cartographic Services	B&W	1:10,000	05/1975	489	9925-9932

4.2 AIRBORNE RADAR (NEXTMAP)

Images produced from NextMap™ DTM data within Erdas Imagine™, and transferred to Arc9™ as image files, were used to help identify and delineate landslide features. Spot heights could also be extracted. The use of variable lighting directions and angles was found to aid in the identification of features. Problems have been experienced with the DSM version, which subtracts the height of objects such as tress and buildings from the model. In this regard the OS contour data set is preferable, but has less resolution than NextMap. Cross-sections, examples of which are shown in this report, have been taken from the raw NextMap data set using an Arc9 sub-routine developed within BGS.

An example of the problems experienced with the DTM data is shown in Figure 37 and Figure 38. This shows two cross-sections, obtained independently at the same location (Brown’s Folly, Limpley Stoke valley), which have been superimposed. The first (E2) was surveyed on the ground using Abney level and tape, and the second (CS27) derived from the NextMap DTM. The clear discrepancy (up to 19 m) in the upper part of the slope is due to tree cover.

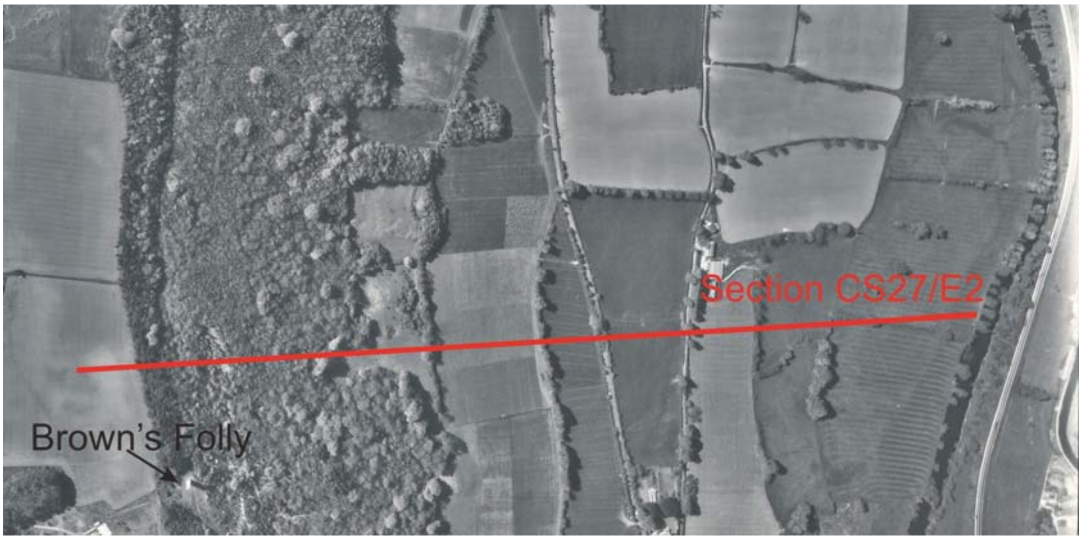


Figure 37 Aerial photo (Cartographical Services, 1975) showing cross-section CS27/E2 (red line), and Bathford Hill Woods

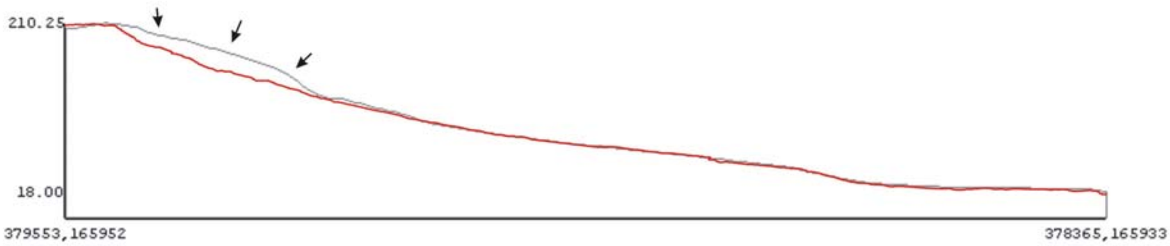


Figure 38 Comparative cross-sections demonstrating 'tree' effect on NextMap DTM
Black line= sectionCS27 (NextMap), red line=sectionE2 (Hobbs, 1980)

4.3 AIRBORNE LIDAR & PSINSAR

Airborne LiDAR has been flown for all or part of the study area by NERC's Airborne Research & Survey Facility (ARSF). However, no data have been made available to the project at the time of writing.

In addition, recent studies using the 'Permanent Scatterer Synthetic Aperture Radar' (PSinSAR) method of ground deformation detection have been interrogated to determine subsidence in the Bristol and Bath areas (www.terrafirma.eu.com). These data derived from monthly passes of the ERS satellite(s) have revealed that no subsidence has been detected during the period for which data have been available (1992-2005).

4.4 TERRESTRIAL LIDAR (LASER SCANNING)

Terrestrial LiDAR (laser scan) surveys at selected locations within the study area were carried out during March 2004. BGS's Riegl LPM2K 'very long-range' laser scanner and Leica SR530 geodetic-quality dGPS system were used in combination to produce 3D models of slopes in the Swainswick and St. Catherine's valleys, oriented to national grid co-ordinates. The main purpose was to determine whether the method, used elsewhere by BGS, was suitable for detailed mapping of type of slopes found at Bath and the production of high-resolution cross-sections. An example of the output is shown in Figure 43.

The method was found to be successful in terms of the reflectivity of the ground and the range of the instrument. However, the generally low angle of most vantage points meant that it was often difficult to resolve the subtleties of the geomorphology. In common with other remote sensing methods, the extensive tree cover also presented a major problem, particularly on the upper slopes. Refer to section 5.2.

5 Field Investigations

5.1 TOGHILL FARM

A slope profile with shallow trial-pitting was carried out at a location adjacent to Tog Hill Farm [3723 1723] in the north-west of the study area (Figure 39) for which the cross-section is shown in

Figure 40. Trial pits (TP1 to TP4) were excavated to a maximum depth of 2 m using a hydraulic backhoe (Figure 41) the results of which are summarised in Table 8. In addition, ultra-lightweight penetrometer tests were carried out at the trial pit locations, the results of which are shown in Figure 42.

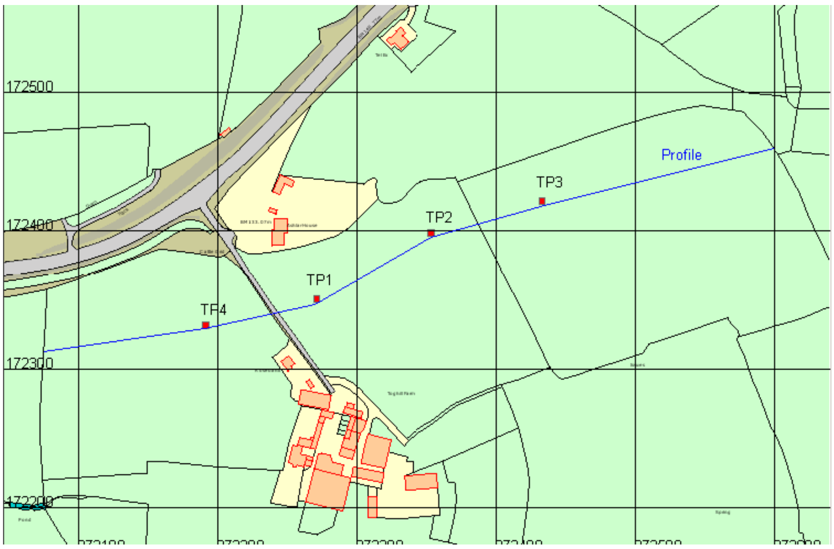


Figure 39 Map showing trial pit and slope profile locations, Toghill Farm

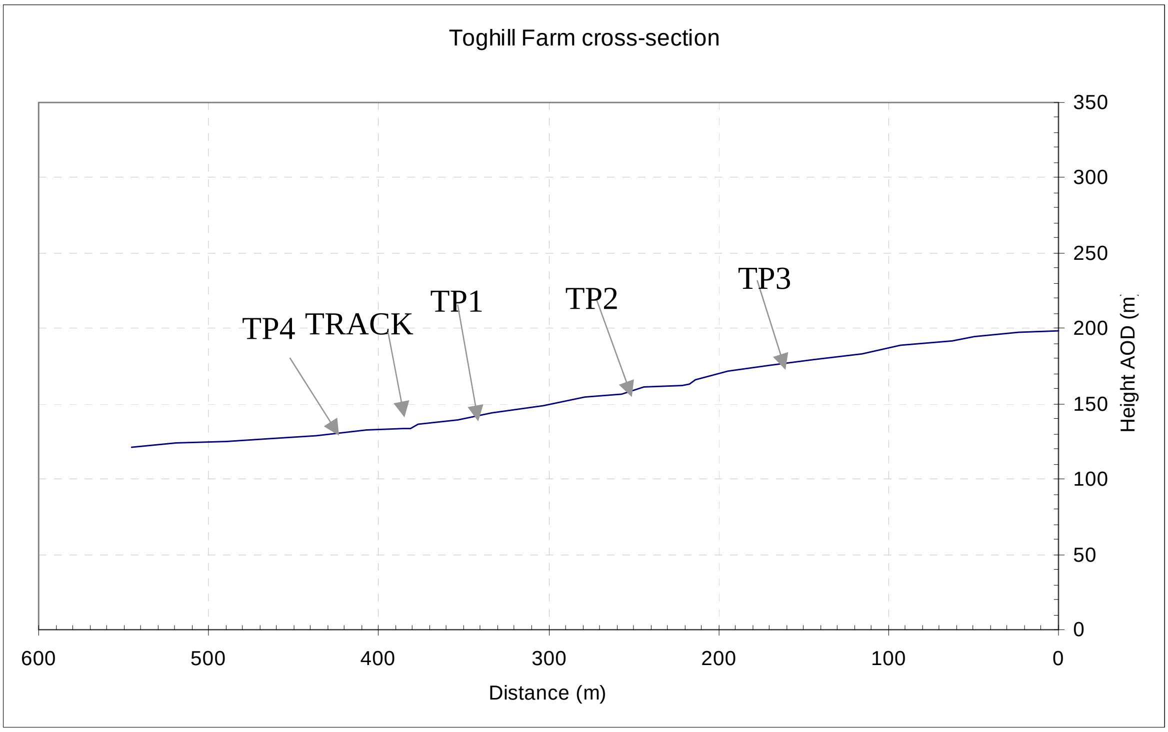


Figure 40 Cross-section at Toghill Farm (refer to Figure 39)

Figure 41 Trial pit TP3, Toghill Farm

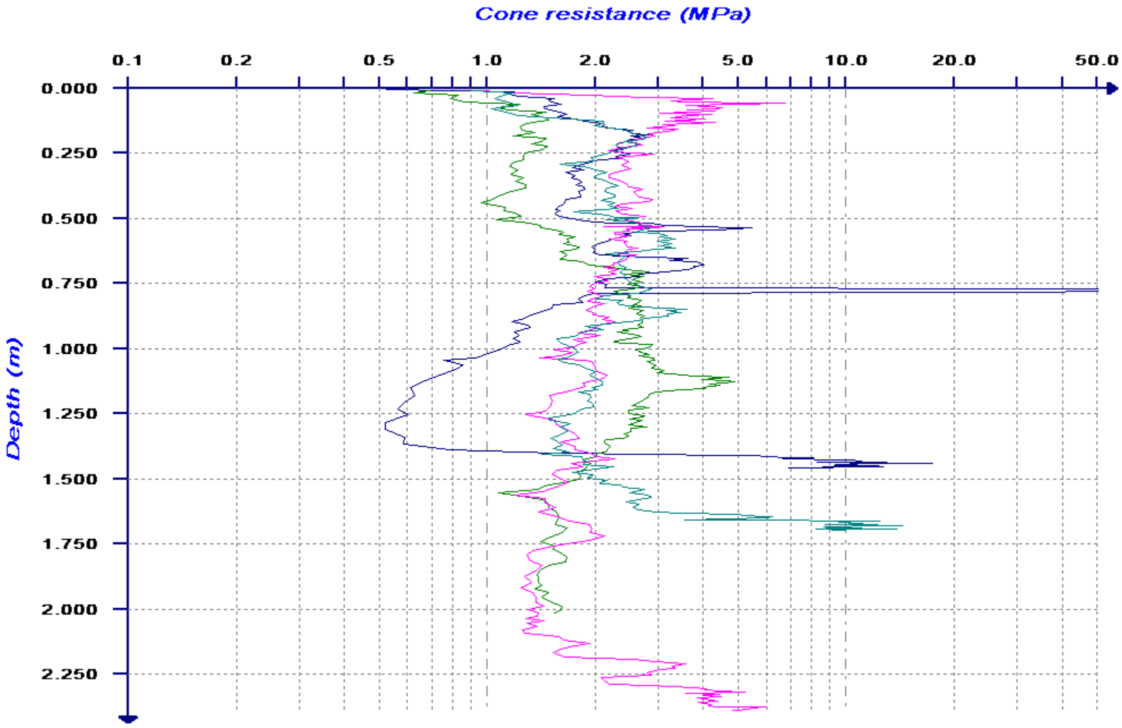


Figure 42 PANDA penetrometer profiles, Toghill Farm
[TP1 – dark blue, TP2 – green, TP3 – purple, TP4 – light blue]

Table 8 Summary log of trial pits at Toghill Farm

Trial Pit [Grid Ref]	**Depth Interval (m)**	**Description**
TP1 [ST72270 72351]	0 – 0.15 0.15 – 0.30 0.30 – 1.80	Topsoil Desiccated Sand & Clay with clasts of limestone *[Head]* Weathered orange/brown, mottled grey, stiff to very stiff sandy silty Clay, fissured with some sub-horiz. slickensiding with v. coarse sand-size gypsum on surfaces, fossils. Ped/matrix (1-2 mm) structure in upper 0.2 m *[Landslide - Charmouth Mudstone F.]*
TP2 [ST72353 72398]	0 – 0.30 0.30 – 1.30 1.30 – 1.50 1.50 – 1.90	Dry, friable, buff silty Topsoil Soft, buff, mottled light-grey, Clay with silt & v. fine sand patches, reduction veins. Siltstone clast with Liesegang rings *[Head]* Weathered, moist, open-textured, Siltstone blocks in Clay matrix, with ironstone nodules (4-5 cm) *[Dyrham F.]* Micaceous, very soft, Silt & Clay, fractured but no apparent shears *[Dyrham F.]*
TP3 [ST72433 72422]	0 – 0.15 0.15 – 1.90	Soil containing coarse gravel size Limestone fragments *[Inferior Oolite G.]* Sand with clayey patches, slightly cemented, with blocks (up to 0.5 m) of friable, fine-grained, buff, v. fine gr. calcareous sandstone with minor soft to hard Silt & Clay. Sandstone block content increasing with depth. Discontinuous bed of calcareous, v. fine sandstone at 1.3m. *[Bridport Sand F]*
TP4 [ST72192 72331]	0 – 0.10 0.10 – 1.40 1.40 – 1.60	Rich loamy Topsoil Fissured, slickensided, stiff, orange-buff, veined with grey, Silt & Clay with small boulders (up to 0.2m) chalk with some race nodules in upper 0.5 m, with concretionary, rounded to sub-rounded, boulders of grey limestone (up to 0.4 m) with some tabular grey micritic limestone. Seepage *[Landslide – Charmouth Mudstone F]*. In-situ, dark grey/blue-grey, green-grey, weak to very weak, fissured Mudstone, with pockets of med-coarse dark orange ferruginous sand. Complete fossil bivalves, belemnites *[Charmouth Mudstone F.]*

The penetrometer results (Figure 42) show a progressively weakening Charmouth Mudstone F. between 0.55 and 1.30 m depth in TP1, reaching a low of 0.5 MPa. Similarly, in TP3 the Bridport Sand F decreases in penetration resistance from 0.15 to 2.1 m, reaching a low of 1.1 MPa. Trial pit TP4 shows a relatively unchanging profile down to 1.6 m, below which resistance increases. Trial pit TP2 shows a resistance 'high' between 0.5 and 1.5 m with a peak of almost 5MPa at 1.15 m. The profile for TP4 is slightly more irregular than the others. It appears to represent a 1.4 m deep landslide consisting of Charmouth Mudstone F, overlying unslipped Charmouth Mudstone F. It is notable that the landslipped Charmouth Mudstone F between 0.75 and 1.3 m in TP1 is significantly weaker (less penetration resistance) than that downslope in TP4. However, the in-situ Charmouth Mudstone Formation gives the same values for penetration resistance (approx 10 MPa) in TP1 and TP4. The soundings for TP1 and TP4 met refusal at 1.45 m and 1.69 m, respectively.

It should be noted that the sub-surface investigations carried out at Toghill Farm were too shallow to make any conclusions about the presence or otherwise of deep-seated landslides or cambers.

5.2 TERRESTRIAL LASER SCANNING

Terrestrial (LiDAR) laser scans were made of various valley slopes within the study area using the BGS's 'very long-range' laser scanner (Riegl LPM2K). The advantages of this method for areas such as Bath are as follows:

- Completely remote,
- High levels of detail can be captured
- Results more accurate than alternatives.

The disadvantages experienced in Bath may be summarised as follows:

- Generally poor vantage points, particularly of upper convex slopes where most mass movement features occur.
- Tree cover an insurmountable obstacle, as it is to most types of remote sensing.

The method was capable of detecting relatively minor surface features (> 1 m height) at distances of up to about 500 m. This is a distinct improvement on the NextMap data. However, whilst the laser was capable of range finding at distances well in excess of 1 km, the density of points at this distance was poor. Also, obliquely angled, poorly-reflective surfaces (e.g. grass) proved problematic. Details of the survey are shown in Table 9 and Table 10.

Table 9 Laser scan survey

Scan site	*Scan location*	*Date*	*Scans*	*Subject*
Swainswick (Innox Lane)	ScanPos1 (S1)	02/03/04	Scan6	W side (N end, incl Sopers Wood)
			Scan7	repeat (less dense)
			Scan8	repeat (less dense)
			Scan9	repeat (less dense)
			Scan10	repeat (less dense)
Swainswick (Little Solsbury Hill -Piezo *I15*)	ScanPos2 (S2)	03/03/04	Scan1	W side (lower, S end)
			Scan2	repeat (less density)
			Scan3	repeat (less density)
St. Catherine's (FP stile, Upper NorthEnd Farm)	ScanPos3 (S3)	03/03/04	Scan1	E side (overall)
			Scan2	repeat (less dense)
			Scan3	detail (upper slope)
St. Catherine's (gate on Steway Lane)	ScanPos4 (S4)	04/03/04	Scan1	W side (towards ScanPos3)
			Scan2	detail (upper, N end)
St. Catherine's (track Orchard Farm)	ScanPos5 (S5)	04/03/04	Scan1	E side below Rodney Farm
			Scan2	detail – upper slope
			Scan3	Slope below Dicknick Woods (to N)

The Leica SR530 'base station' dGPS unit was located on a tripod at Leigh House, Bradford-on-Avon (B&B) in the paddock/garden for the duration of the field survey.

The scan positions and one tie-point per scan position were located in static mode, on the same tripod as the laser scan, using the roving GPS unit. These were also located using the GS50 unit in a rucksack, as a back-up. On Day 2 (3/03/04) the battery unit of the base station failed and no records were saved. Due to the separation of base station and field sites (approx 10 km) the durations for each location were relatively high (around 1 hour).

Table 10 Differential GPS survey

Point ID	**Point Class**	**Epoch**	**Easting**	**Northing**	**Ellip. Hgt.**	**Ortho. Hgt.**	**Geoid Sep.**	**Pos. & Hgt. Qlty**
s1	Measured	02/03/2004	*375780*	*168265*				
s2	Measured	03/03/2004 13:18	376313.1137	167812.2933	153.0533	103.9497	49.1036	0.0052
s3	Measured	03/03/2004	*378169*	*169074*				
s4	Measured	04/03/2004 13:40	378830.5867	168814.0269	135.3042	86.2781	49.0261	0.0035
s5	Measured	04/03/2004 17:13	378149.082	169678.2278	122.9615	73.8974	49.0641	0.0007
t2	Measured	03/03/2004 11:39	375575.0799	167243.7946	146.9894	97.8661	49.1233	0.0232
t5	Measured	04/03/2004 15:52	378336.1626	169903.209	103.5853	54.5245	49.0608	0.0016
x (1)	Averaged	02/03/2004 09:53	382953.1532	161990.4183	144.2491	95.4681	48.781	0.0103
x (2)	Averaged	03/03/2004 09:03	382953.1809	161990.3533	144.2554	95.4744	48.781	0.012
x (3)	Averaged	04/03/2004 12:00	382953.4511	161990.591	144.2359	95.4549	48.781	0.0133

Key: laser scan locations, s
Laser targets, t
dGPS base station, x

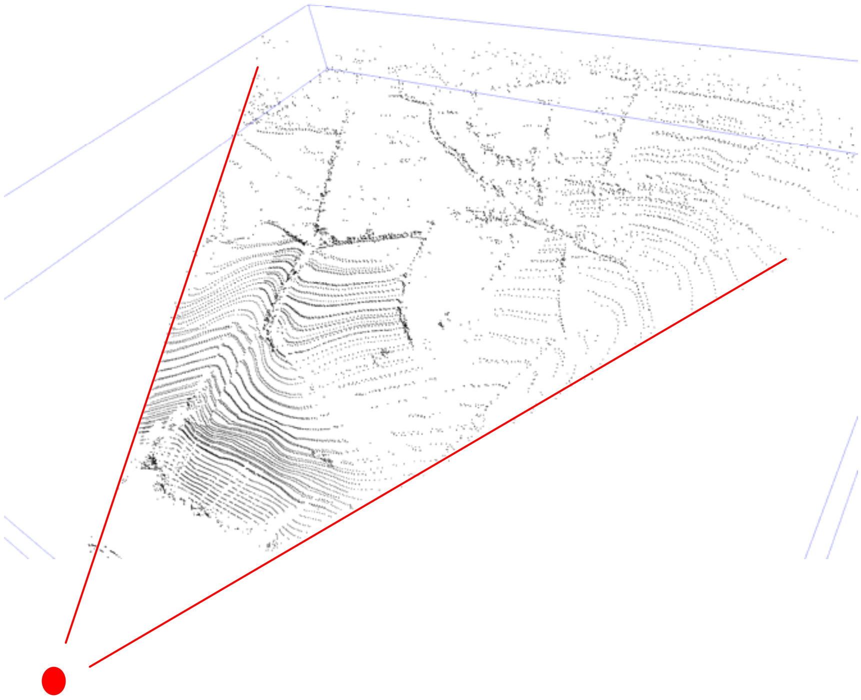


Figure 43 Laser-scanned 3D point-cloud model, Swainswick (west-side), ScanPos1
Note: viewed towards SW, red dot is location of scanner, Soper's Wood landslide in top right corner

The laser-scanned image shown in Figure 43 gives a good indication of the nature of raw terrestrial LiDAR data. The points are distributed in a 'scatter-gun' pattern with the data nearest to the scanner being the densest, and the furthest data the least dense. This distribution is accentuated by the fact that the overall slope angle is low, hence detail in the upper part of the slope is low, and as such does not lend itself to triangulation and surface rendering. However, the image does show geographical features (e.g. hedgerows) and relatively subtle changes in ground surface, at least in the lower and middle slope, of a scale undetectable using NextMap. Whilst the image in Figure 43 resembles a contour map, it is not and should be viewed in 3D to obtain the full effect. From such scans accurate cross-sections can be produced.

Appendix 1 Major recorded landslides in the Bath area

The following account is taken from Forster et al. (1985):

NORTH STOKE [700 687] Ref. Hawkins and Privett (1980)

This landslip is situated 3 km north-west of Bath and extends from the western edge of the village of North Stoke westwards onto the alluvial flats, of the River Avon. The backscarp is arcuate.

The slip has taken place in cambered Inferior Oolite, Midford Sands and Head and is complex and degraded. Hummocky slip debris extends from the Inferior Oolite/Midford Sands backscarp to the margin of the River Avon. Erosion by the river has caused minor slips to take place in the toe of the slip which have affected the road at [696 684] for many years.

2. HEATHER FARM [723 682] Ref. Hawkins and Privett (1979, 1980)

This slip is situated l km north west of Bath on the south facing slope of Lansdown Hi11. The semicircular backscarp is formed by the Upper Fuller's Earth clays and the Great Oolite limestones which cap them.

The main slip mass is composed of Fuller's Earth and Head, and is the result of numerous individual flows and slides. It extends some 400 m downslope from the base of the backscarp.

A steep sided gully has been cut within the slip by water discharging from the springs at the base of the Great Oolite and from thin limestone bands within the Fuller's Earth. It is thought that much of the landslipped material has been removed down this gully thus accounting for the small amount of debris present below a large backscarp.

3. BAILBROOK [773 673] Ref. Hawkins & Privett (1979, 1980), Gibb (1984)

The Bailbrook slip has been recognised as such on the grounds of its morphology which is dominated by a l km, long, arcuate backscarp 25 m high at an angle of slope of 30-40 degrees. Hawkins and Privett compare the Bailbrook slip to the North Stoke slip in terms of mode of origin and style of movement i.e. over-steepening of the slope by river erosion caused a deep rotational failure to take place. The subdued topography within the Bailbrook slip is considered to be the result of many years of agricultural use. The site investigation carried out in 1983 for the proposed A4/A36 Batheaston/Swainswick bypass included several boreholes through the Bailbrook slip which provided the first subsurface data of the area. The evidence of the boreholes does not wholly support the existence of a major landslip at this location. The top of the Lias clay encountered by the boreholes within the boundary of the slip does not appear to have suffered vertical displacement, although there are an unusually large number of slickensided joints and bedding planes.

The backscarp could have originated by spring sapping at the base of the Midford Sands, an origin favoured by the straightness of the scarp. The report by Sir Alexander Gibb and Partners concludes that in any engineering design both possible origins of the morphology must be taken into account.

4. SALLY-IN-THE-WOODS [791 652 to 795 647] Ref. GKN Rep.SM 361 1959; GKN Rep.SM 475 1960; Foundation Engineering F69/977 1969; GKN Rep.S 1575 1969; Nott Brodie 1979

The section of the A363 which passes through Sally-in-the-Woods has been subject to minor slipping for many years. The ground movements are shallow, 4 m deep rotational slides in Head and landslide debris. The section of road investigated in the listed reports is cut by the ENE/WSW trending Monkton Farleigh Fault. North of the fault the slips appear to be associated with the junction of the Inferior Oolite and Midford Sands, and south of the fault with the base of the Lower Fuller's Earth. The local geology is not well established despite a number of site investigations.

5. BEACON HILL [751 659] Ref . Kellaway & Taylor 1968; Hawkins & Privett 1979; Strata Surveys Rep. B20907 1973

The extensive area of landslipping which forms the south-east slope of Beacon Hill. is considered by both Kellaway and Hawkins to be a deep rotational slide caused by the over-steepening of the hillside by the erosive action of the

River Avon, probably in the latter part of the late Devensian glaciation. The failure took place in Lower Lias shales overlain by cambered Inferior Oolite and Midford Sands. The backscarp behind the body of the slip cuts the base of the Lower Fuller's Earth which caps Beacon Hill.

A report by Strata Surveys for M.P. Kent, however, appears to indicate, on the evidence of a borehole into the slip mass, that the slip may be relatively shallow and more translational in character. The area on and around the slip has been extensively built upon, making accurate mapping of the landslip very difficult except for the backscarp. It is, however, reasonable to assume that the landslip debris extends downslope to the present course of the River Avon. Several areas within the assumed limits of the Beacon Hill slip have been active since the late eighteenth century when the development of the area commenced. Since that time at least six instances of earth movement have been recorded and it is probable that many other cases before and after that date have not been recorded. Recorded movements include:

a) **Camden Crescent** [749 657]

The construction of Camden Crescent in 1794 was delayed by a series of shallow landslips which destroyed some houses and caused the abandonment of others. Camden Crescent remains uncompleted, a crescent in name alone, although no further movements have taken place since that time. Movement also took place in 1889 when houses below Camden Crescent collapsed.

b) **Hedgemead slip** [750 656]

The Hedgemead area which lies downslope and to the south-east of Camden Crescent was developed between 1860 and 1875. The first signs of slipping probably occurred in the early 1870's and continued periodically until the late 1800s. In total 2.5 hectares of land were affected and at least 135 houses destroyed or demolished due to the direct or indirect effects of the movements that occurred on November 1878, July 1881, Hedgemead Park was opened in 1889.

The landslips were shallow translational movements in Head composed of Fuller's Earth, Midford Sands and Inferior Oolite which had been barely stable prior to development. The slips were largely triggered by increased water input into superficial material as a result of the service works associated with the housing i.e. infiltration from leaking sewers, water supply pipes and storm water soakaways.

The improved water flow in the Midford Sands caused by natural piping induced by water abstraction from wells may also have proved detrimental to stability because, when wells were abandoned, water continued to be brought into a critical area but was no longer removed.

The presence of confined aquifers in the limestones of the Lower Lias, which could have supplied water under pressure to the Head/bedrock interface, may also have played a part in the failure. No remedial measures proved effective, with the result that the area was turned over to recreation purposes, as Hedgemead Park.

c) **Beacon Common Slip** [751 662]

In 1958 a small rotational slip l0 m across occurred in the outcrop of the Fuller's Earth clay where the backscarp of the Beacon Hill slide cuts Beacon Common. The failure had undergone 5 m of vertical displacement by 1961 and had generated a mud flow which extended down slope for 120m. The movement was finally stabilised by the installation of herring bone drains in the hillside.

d) **Perfect View Slip** [752 662]

On the 5th of December 1972 during a period of wet weather, a 50m long crack appeared in the roadway of Perfect View, and the downslope side dropped 75 mm. The movement ruptured a water main which supplied copious amounts of water to the area. On the 6th December the downslope side had dropped a total of 0.75 m but no further movement took place. Piezometric measurements showed porewater pressure had dropped in the main body of the slip by the 10th December. No reference to further movement has been found.

e) **St. Stephen's Hill** [750 659] Ref. BA69 S.W.I.R.L. Rep 1495

During January 1979, in St Stephen's Road, a masonry retaining wall 0.5m thick and 3 - 5m high underwent a 5 degree rotation accompanied by cracking of the upper road level pavement. The conclusion of the site investigation was that the wall failed due to inadequate design and that it was only effective in the past because of the use of good quality back fill. The site investigation also pointed out that the area around the site was in a state of marginal stability. Boreholes and trial pits showed the area to be underlain by coarse to fine granular hillwash on weathered, disturbed and fissured Lias clay.

f) **Mount Road** [750 659] Ref: BA 49 Somerset C.C. Lab Rep. 48/77 (ACC)

During the autumn of 1975 a failure occurred in the masonry retaining wall supporting the east side of Mount Road. The wall was founded on 4 m of Lower Fuller's Earth lying on Inferior Oolite limestone. Water percolating from behind the wall had caused leaching and erosion of the Fuller's Earth to the detriment of the structural integrity of the wall. Remedial measures suggested included grouting and various configurations of ground anchors which were designed to tie the wall back into solid stable ground.

6. BEECHEN CLIFF [751 641] Ref. Hawkins, A.B. 1976; Kellaway, G.A.d. Taylor, J.H. 1968; Soil Mechanics (1967) SM 4734; Hawkins (1980) Rep. to Bath City

The Beechen Cliff slip is considered to be a deep-seated rotational slide of Late Devensian age which has affected strata from the Inferior Oolite, limestone capping the hill, through the Midford Sands into the Lower Lias clays and silts which outcrop at its foot. A backscarp at a slope angle of 38 - 52 degrees is present above the debris apron.

A series of boreholes through the slip mass proved the debris to be 18m thick. Another borehole nearby showed fissuring in the Lias clay to a depth of 24m, indicating that a slip plane in the Lias clay may also be present.

Beechen Cliff is situated on the outside of a curve of the River Avon and it is thought by Kellaway and Hawkins that the slip occurred in late Devensian times as a result of over-steepening of the hillslope by river erosion.

The effect of tree and vegetation cover on the face of Beechen Cliff is considered by Hawkins in his report to the Bath City Engineer in 1980. The steep cliff area appears to be currently stable and no movements during the last hundred years are recorded. However, movements did take place in the slip mass below the cliff at Calton Gardens in 1973 and at Calton Road in 1974.

8. CALTON GARDENS [750 641] Ref. M.P. Kent 1972 Soil Mechanics 1973 Rep.6173

In December 1972 a landslip took place south of Calton Gardens, opposite house numbers 45 to 50. The movement had been, initiated by the excavation of the foot of the slope in order to construct a lay-by next to the road; the slope was to be supported by a retaining wall. Heavy rainfall occurred before the wall could be completed and movement of the hillside took place.

An investigation of the slip showed it to be approximately 50m wide across the toe by 30m up the slope, and relatively shallow in depth. It was confirmed that the slip had taken place by the partial reactivation of an ancient slip due to removal of support at the bottom of a 22 degree slope. The situation was aggravated by the existence of a confined aquifer in the Lias Clay below the slip which supplied water under pressure to the slip plane at the slip/bedrock interface. Remedial measures recommended were drainage of the confined aquifer and an improved retaining wall founded well into the Lias Clay.

9. CALTON ROAD [752 642] Ref . Geotechnical Engineering SM/S/1 974

An investigation into the failure of a retaining wall in Calton Road showed that the wall had failed due to deterioration of its structure. However, the investigation looked at the stability of the retained slope itself and found that the slope angle of 70 degrees and cutting height of 2.5 - 3.5 m in slip debris composed of silty, sandy, limestone rubble, was only marginally stable. The recommendation was made that the slope either be regraded to one of 35 degrees or that a more effective retaining wall be designed and built to replace the old one, preferably in sections to minimise the risk of failure during construction.

10. HENGROVE WOOD [780 650] Ref. Gibb 1984; Somerset C.C. Rep.4068; Hobbs 1980

The Hengrove Wood slip was described by Sir Alexander Gibb and Partners in their report as having a length of at least 700m, and maximum depth of 20 m and as having taken place in Lias clay.

BGS records show Hengrove Wood to be only part of a belt of landslipped ground which runs the entire length of the valley side, affecting strata from the limestones of the Great Oolite at the top, to the Lias clays at the base. The area was described in detail by Hobbs, (1980) who considered the Great Oolite to be uncambered but to have given rise to a number of minor rotational and translational failures which had slid and toppled onto the Fuller's Earth outcrop below. The Fuller's Earth outcrop is heavily wooded and the severity and style of movement was not clear. The main failure on this section of the valley side appeared to be on the lower valley slope below a 10 m scarp of Inferior Oolite limestone and Midford Sands. The movement is a shallow translational slip in cambered Inferior Oolite and Midford Sands with a slip plane possibly extending into the Lias Clay. Alternatively the slip may have simply overridden an original ground surface of Lias Clay.

The marginal stability conditions which are present in some parts of this slip are demonstrated by the movements which took place within it in 1966 near Dry Arch [781 6551].

11. DRY ARCH BATHAMPTON [781 655] Ref. AV20 Structural Soils Rep. 4068

In 1966 a site investigation into the cause of cracking of the tarmac of the A36 near Dry Arch, Bathampton, was carried out by Structural Soils. The cause was found to be a slip 90 m long by 50 m wide which had started as a small rotational failure of the road embankment and developed into a translational slide in the Fuller's Earth/Inferior Oolite/Midford Sands Head. The bedrock below the site is Lower Lias clay and the junction with the Midford Sands is a short distance upslope, above the road. The area had been subject to earth movements in the past and the latest slip was considered to have been triggered by heavy rain causing an increase in water flow from the Midford Sands/Lias spring line, possibly aggravated by earth moving operations which had been carried out below the slipped part of the hillside.

12 TWERTON [726 644] Ref. Chandler 1976

Chandler refers to this slip as being 700 m wide and extending more than 300 m upslope from the No.1 terrace. The slip is important because of its relationship to the terraces of the River Avon which enable the time of its movement to be established. Field evidence shows that it pre-dates the aggradation of the No.1 terrace and post-dates the deposition of the No.3 terrace which indicates that the slip took place in late Devensian times.

The slip is in Head and Lower Lias clay below a backscarp of Midford Sands and was probably caused by over-steepening of the hillside by river erosion on the outside of a river bend.

13 SWAINSWICK LANDSLIP BELT [760 765] Ref. Gibb 1984

The Sir Alexander Gibb report on the proposed A46 bypass refers to the east side of the Swainswick valley as “the Swainswick Landslip Belt”. This valley side is only one example of landslipped valley sides in the Bath area and is not unique in any respect, other than its significance to the construction of the A46 Bypass.

14 OLD HOUSE SLIP [763 674] Ref. Gibb 1984

A Sir Alexander Gibb report describes this slip as being “200 m wide and 11 m deep in Lias clays”. BGS records show the backscarp to be of Inferior Oolite and Midford Sands, and coincident with a NW/SE fault with a downthrow to the SW.

15 A46 [7563 6896] Ref. Foundation Engineering Rep. F69/977/2

This slide occurred on the downhill side of a newly constructed three lane section of the A46 north of the intersection with the A4. Surplus material, mainly clay, had been dumped into a gully on the downslope side of the road. Heavy rain in July 1968 caused the tipped material to become saturated and f low downhill for a distance of 300m. Investigation of the event showed that previous movements of this type had taken place through natural causes, the last occurrence having been some 60 years previously.

The bedrock below the site is Fuller's Earth clay. Water is fed into the area by the spring line at the base of the Great Oolite limestone which outcrops upslope of the road.

16 A46 ABOVE SWAINSWICK [754 694 - 752 700] Ref . AV93 Exploration Associates 1977

This investigation concerns a 500 m section of the A46 which had been subject to subsidence prior to 1977.

The road had been built on Upper Fuller's Earth clay below the junction with the Great Oolite limestone which is of ten the site of an active spring line. The report concludes that the Great Oolite is not cambered at this locality and that the movements are shallow f lows and translational slides. Stabilisation of the road embankment by drainage, and the interception and diversion of water inflow into the area was recommended.

17 MEADOW LANE [770 662] Ref. Gibb 1984

A series of landslips in Lias clays covering an area of approximately 250 m wide and having a depth in excess of 10 m. This is part of the general occurrence of slipping on the valley sides around Bathampton Down.

18 A36 LIMPLEY STOKE [780 611] AV 92 Exploration Associates 1977

This investigation looked at a 100 m section of the A36 downslope from Limpley Stoke village, which had suffered disturbance by minor landslip movements. Boreholes in the slipped material indicate a thickness of 7 to 15 m of slip debris lying on cambered Inferior Oolite in the north and on down-faulted Great Oolite in the south. The landslipping is considered to be typical of the stability state of the valley side as a whole.

19 HINTON HILL [756 582] Ref . AV73 Somerset C.C. Rep 67/78ACC

Cracking of the road surface at the top of Hinton Hill required an investigation to be carried out in 1978 by Somerset County Council. The investigation showed the road to be constructed on the edge of the outcrop of the Great Oolite limestone above a landslip-covered slope of Fuller's Earth. The angle of slope of the hillside was 12 degrees and the slip was between 6 and 7.5 m thick. The report concluded that the subsidence of the road was being caused by ground water seeping through the permeable Great Oolite limestone and creating a mudflow condition in the Fuller's Earth clay downslope of the road. Drainage measures alone were considered insufficient to ensure the long term stability of the site and some form of retaining structure was recommended, the most economical being piles. Further subsidence and cracking was expected to occur to the west of the existing unstable section.

20 BANNER DOWN [794 687] Ref. AV68 C.J. Associates 51001

A section of the unclassified road (Fosse Way) on the eastern side of Banner Down had suffered slipping and required an investigation to be carried but in November 1975. The road had been built on 2-3 metres of previously slipped material lying on the Upper Fuller's Earth clay downslope of the junction with the overlying Great oolite limestone. No details of the cause of the failure or recommendations for remedial measures were included in the report.

21 MAGDALEN AVENUE [746 642] Ref. Wilcox Cooper Associates Rep. S4687

Structural cracks in No. 28 Magdalen Avenue, Bath were investigated in November 1981. The building had been constructed on fill and landslip debris lying on Lower Lias clay. Natural landslipping was therefore suspected as the cause of the problem. However, the investigation found that structural inadequacies of the building and disturbance of the foundations by excavations nearby were the cause of the failure.

22 BLOOMFIELD ROAD [739 630] Ref. Larnach 1963 Rep. to Bath City; Underwood 1963 Rep. to Bath city

In 1963 a slip took place in a field north of Bloomfield Road after the field had been used as a waste disposal site. An inspection of the site showed the tipped material to be Fuller's Earth clay and the ground on which it had been dumped to be Fuller's Earth Head lying on Fuller's Earth bedrock. The loading of the slope, which stood at an angle of between 25 and 30 degrees, had caused a circular rotational failure to take place in both the tipped material and the Head below. The initial failure developed into a translational slide and ultimately a mudflow as it progressed downslope. The mudflow was particularly wet, probably due to the water issuing from the base of the Great Oolite limestone which capped the hill.

Remedial measures recommended were the drainage of the slip mass and the careful regrading of the slope with the removal. from the site of all- excavated material.

23 LANDSOWN [727 679] Ref. Cook 1973

A shallow, 3 m thick landslip 210 m long, affecting 12 acres of ground on the south facing slope below the Great Oolite plateau at Lansdown, took place between October 1969 and January 1971. The slip developed in three main phases which were mainly movements of mudflow type but with some degree of translational sliding. The slip was started by the dumping of rubbish into an old abandoned quarry at the base of the Great Oolite limestone. Springs had been observed issuing at this level of the hillside, and the blocking of these drainage paths resulted in the saturation of the fill and underlying Head deposits causing failure. Once slippage had started, minor aquifers in the Fuller's Earth under the slip mass may have aided further movement.

Appendix 2

Selected SI reports for A46 Swainswick area

County of Avon (1977) A46 Swainswick Hill. [Final SI report-Ashcombe Wood area] Exploration Associates, 2 vols. (NGRC Ref. No. 16389).

Department of Environment (1970) Bath to M4 feasibility study. Manders, Raikes & Marshall. (NGRC Ref. No. 16389)

Department of Transport (1983) A46 Upper Swainswick to A420. Manders, Raikes, & Marshall. (NGRC Ref. No. 16389)

Somerset County Council (1966) [Stabilisation assessment for A46 at Swainswick] Ground Exploration Ltd Rep. No. 3739 (Nov. 1966) (NGRC Ref. No. 16389)

Somerset County Council (1969) [Landslide investigation A46, North of Swainswick] Foundation Engineering Ltd. Rep No. F69/977/2 (Feb 1969) (revised Sept 1969) (NGRC Ref. No. 16389)

Somerset County Council (1968) [Landslide investigation A46, Ashcombe Wood] Foundation Engineering Ltd. Rep No. F69/977/3 (Feb 1969) (NGRC Ref. No. 16389)

Somerset County Council (1960) [A46 Butcher's Wood] Sub Soil Surveys, Rep No. 60/13 (May 1960). (NGRC Ref. No. 16389)

Department of Environment / Department of Transport (1984) A4/A36 Batheaston / Swainswick Bypass & A36 link. Site investigations, 1983, Factual Report. Sir Alexander Gibb & Prtnrs. 2 Vols. Jan 1984.

Department of Environment / Department of Transport (1984) A4/A36 Batheaston / Swainswick Bypass & A36 link. Site investigations, 1983, Interpretative Report. Sir Alexander Gibb & Prtnrs. 2 Vols. March 1984. (not found in NGRC)

Mott MacDonald / W S Atkins / Raynesway Construction Southern / Interoute (2003) A46 Four Winds Farm and Hartley Bends

.

References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

Anson, R. 1996. The study of an active landslide in the Swainswick Valley, North of Bath. P*hD Thesis, Bristol University, 46-14573*

BGS 2000 Specifications for the preparation of 1:10,000 scale geological maps (2nd ed.) *British Geological Survey*, Research Report RR/00/02

Chandler, R. J., Kellaway, G. A., Skempton, A. W. and Wyatt, R. J. 1976. Valley slope sections in Jurassic strata near Bath, Somerset. *Philosophical Transactions of the Royal Society, London* A283, 527-556

Cook, D. A. 1973. Investigation of a landslip in the fullers earth clay, Lansdown, Bath. *Quaternary Journal of Engineering Geology*. 6, 233:240.

Cook, D. and McCombie, P. 1999 Superficial Landslipping in the Area of the City of Bath, England, an Approach to Maintenance and Repair. *2nd International Conference on Landslides, Slope Stability & The Safety of Infra-Structures*, July 1999, pp.147-154.

Forster, A., Hobbs, P.R.N., Monkhouse, R.A., and Wyatt, R.J. **1985**. An environmental geology study of parts of West Wiltshire and South east Avon. *British Geological Survey Internal Report*, WN/85/25. *Department of the Environment*

Gosney, R.F.C., Gellatly, G., Kerr, A. and Petch, K.A. 1997. A4/A46 Batheaston/Swainswick Bypass. *Proc. Instn. Civ. Eng*., 1997, 120, Aug., pp101-110.

Hawkins, A. B. 1977. The Hedgemead Landslip, Bath, Avon. Conference on Large Ground Movements and Structures. (ed. Geddes, D.) *Conference papers session V. University of Wales. Department of Civil Engineering and Building Technology*.

Hobbs, P.R.N., Loucaides, G. and Petrides, G. 1986 Geotechnical properties and behaviour of Pliocene marl in Nicosia, Cyprus by Report No. EGARP KW/86/1 in series: Engineering Geology of Cohesive Soils associated with Ophiolites with particular reference to Cyprus. 1986.

Hobbs, P.R.N. 1980 Slope stability studies in the Avon Valley (Bath to Limpley Stoke) *British Geological Survey, Engineering Geology Unit Internal Report* No. 80/10

Hobbs, P.R.N. and Jenkins, G. 2002. Reconnaissance survey of slope instability in the Bath area. *British Geological Survey, Internal Report* IR/02/146

Horswill, P. & Horton, A. 1976 Cambering and valley bulging in the Gwash Valley at Empingham, Rutland. *Phil. Trans. Royal Soc. London*, Series A. No. 283, pp427-451.

Hutchinson, J.N. 1991 Periglacial and slope processes. *In:* Quaternary Engineering Geology. Eds. A. Forster. M.G. Culshaw, J.C. Cripps, J.A. Little & C.F. Moon, pp283-331. *Geological Society Engineering Geology Special Publication No. 7*, London.

Jordan, C. J. 2001. A Brief Review of Remote Sensing and 3D Surface Modelling Applied to Urban Geoscience, *British Geological Survey Internal Report* IR/01/076. 16pp

MacDonald, D.M.J., Whitehead, E.J., and Butcher, A.S. 2001 Data review leading to a conceptual model of the hydrogeology of the Combe Down area, Bath. British Geological Survey, Hydrogeology Series, Technical Report WD/00/35.

Marsh, S. H. 2000. Remote mapping technologies for temperate, vegetated terrain. *Proceedings of the 14th International Conference on Applied Geological Remote Sensing*. .11-18

McCombie, P. and Cook, D. 2000 Deformation of masonry in shallow landslips in the Bath area - the use of reinforcement in maintenance and repair. *8th International Symposium on Landslides, 2*, Cardiff, 2000, pp.1041-1046.

Parks, C.D. 1991 A review of the possible mechanisms of cambering and valley bulging. *In:* Quaternary Engineering Geology. Eds. A. Forster. M.G. Culshaw, J.C. Cripps, J.A. Little & C.F. Moon, pp373-380. *Geological Society Engineering Geology Special Publication No. 7*, London.

Phillips, J. (1844) Memoirs of William Smith, LLD., author of “The map of the strata of England & Wales” by his nephew & pupil John Phillips, FRS, SGS. First published 1844. Additional material by Hugh Torrens. Publ: *Bath Royal Literary & Scientific Society*. Limited edition, June 2003.

Privett, K.D. 1980. The engineering geology of slopes in the south Cotswolds, - *Thesis: University of Bristol, 1980*

Raines, M.G. Greenwood, P.G. and Morgan, D.J.R., 1999 Geophysical survey to investigate the internal structure of gulls and cambered strata in the north Cotswolds: *British Geological Survey, Regional Geophysics Series, Technical Report* WK/99/13

Self, C.A. 1985 Two gull caves from the Wiltshire/Avon border *Proc. Univ. Bristol Spelaeol. Soc*., 1985, 17(2), pp153-174.

Self, C.A. 1995 The relationship between the gull cave Sally’s Rift and the development of the River Avon east of Bath. *Proc. Univ. Bristol Spelaeol. Soc*., 1995, 20(2), pp91-108.

Self, C.A. and Boycott, A. 1999 Landslip caves of the Southern Cotswolds. *Proc. Univ. Bristol Spelaeol. Soc*., 1995, 21(3), pp197-214.

Tragheim, D. et al. 1999. Investigating internal structures in Jurassic Limestone of Southern England using digital photogrammetry ground probing radar, electrical resistivity imaging and multispectral ATM data. *Abstract 13th International Conference of Applied Remote Sensing*.

Winchester, S. 2001 The map that changed the world: The tale of William Smith and the birth of a science. *Chivers, Windsor, Paragon & Co*.

Wyatt, R.J. and Cave, R. 2002 The Chalfield Oolite Formation (Bathonian, Middle Jurassic) and the Forest Marble overstep in the South Cotswolds, and the stratigraphical position of the Fairford Coral Bed. *Proc. Geol. Ass*., 113, pp139-152.

Mott McDonald