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Reconnaissance survey of slope instability in the Bath area

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Introduction

The current BGS 1:50,000 scale geological map of Bath (265) shows a large area (45 km^2), mainly to the north of the city, identified as 'foundered strata' (Figure 1). This area has no other information within it. Unlike areas shown as 'landslipped', no attempt has been made to indicate stratigraphy. The 'foundered stata' category on the Bath map is unhelpful for map users who are unfamiliar with the geological materials and processes involved, and which have led to this unique categorisation. The reason for the use of the term 'foundered strata' stems from the difficulty experienced by the mapping team in differentiating landslipped ground from cambered ground and from ground unaffected by either slope process. The areas contain steep slopes many of which are heavily wooded. Non-wooded areas are subject to agricultural processes which tend to obscure landslides and other slope related and geological features. The purpose of the reconnaissance survey, carried out by the authors by vehicle and on foot, with the assistance of K. Royse (geologist, BGS), was to examine the area categorised as 'foundered strata' and to assess the possibilities for re-mapping in order to show the stratigraphy and slope processes. Factors such as tree cover, access, ground conditions were considered. The ability to discern surface features which may be indicative of slope instability was considered. Comparison between the 'foundered strata' area and adjacent areas was made. A brief assessment of existing available sub-surface data was made.

Desk study

The main sources of data for the area are the many site investigations for the A46 trunk road including the Swainswick/Batheaston By-pass (completed engineering report in Gosney et al., 1997), some of which are held in NGRC, and the Department of the Environment (DoE) thematic project carried out by BGS (Forster et al. 1985). Re-mapping of that part of the 'foundered strata' area contained within the DoE study area (Figure 1), was carried out in 1985 by R.J. Wyatt. This identified areas of cambering, landslide, and formational boundaries (where mappable), though the landslide areas themselves do not have formational boundaries. These are shown on Map 15 of Forster et al. (1985). above. This re-mapping by Wyatt was carried out in 6 man-weeks by conventional feature mapping and augering (the aerial photography available was poor and was not used extensively). This has dealt with about three-quarters of the 'foundered strata' area. Geomorphological and geotechnical survey work was also carried out in the area by Privett (1980) and Anson (1996). A list of selected A46 (Swainswick) site investigation reports is given after the references. A list of reports (up to 1985) for the whole area and a comprehensive geotechnical / lithological database was produced (Forster et al., 1985). 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.

Location

The city of Bath is England's only world heritage city and contains famous Roman remains and Georgian architecture dominated by the use of local Bath stone. The city has featured a spa, making use of hot springs since Roman times. The countryside to the north and east of the city is designated an Area of Outstanding Natural Beauty (AONB). The area's industrial heritage is also of interest, in particular stone mining and canals, but also coal and fuller's earth extraction. The 'father' of British geology, the engineer William Smith, lived and worked in the area and produced the world's first stratigraphic map of the city and its environs. The city attracts many visitors from around the world. The surrounding villages are picturesque and blend with countryside, again by the almost universal use of local stone.

The area around Bath is characterised by distinctive limestone plateaux incised by steep-sided valleys formed by the River Avon and its tributaries, penetrating mudstones and limestones of the Jurassic. The relief reaches a maximum of 160 m. Transport routes from the 18^{th} century to the present have been affected by slope instability. A significant part of the cost of the A46 Swainswick/Batheaston By-pass was in the investigation and remediation of slope instability (Gosney et al., 1997). The wooded areas represent about 15 % of the total area and appear to have become denser and less managed during the latter half of the 20^{th} century. They typically have thick undergrowth, and mainly occupy the steeper slopes and escarpments. Hedgerows and wood boundaries often follow the edges of landslide features and geological boundaries, either having been displaced by the landslide or replanted by the farmer (Privett, 1980). Landslide backscars, for example, are often marked by a hedgerow.

Geology

The geological sequence in the area may be summarised as follows (Table 1):

Table 1 Summary of stratigraphy

Member	Formation	Group	Former name
	Forest Marble F.		*Forest Marble*
Bath Oolite M.			*Bath Oolite*
Twinhoe Beds	Chalfield Oolite F *.		*Twinhoe Beds*
Combe Down Oolite M.		Great Oolite G.	*Combe Down Oolite*
Upper Fuller's Earth M.			*Upper Fuller's Earth*
Fuller's Earth Rock M.	Fuller's Earth F.		*Fuller's Earth Rock*
Lower Fuller's Earth M.			*Lower Fuller's Earth*
		Inferior Oolite G.	*Inferior Oolite*
	Bridport Sand F.		*Midford Sands*
	Dyrham F.		*Dyrham Silt*
	Charmouth Mudstone F.	Lias G.	*Lower Lias Clay*
Rugby Limestone M.	Blue Lias F.		*Blue Lias*
Saltford Shale M.			*Blue Lias, Unit B*

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

The Bridport Sand Formation is predominantly a sand, but containing calcite-cemented sandstone and clay. The sand is partially cemented or 'locked' in its undisturbed state. However, it is susceptible to frost and internal erosion, and becomes mobile, tending to drape the lower slopes with a hillwash, making identification of the underlying solid geology difficult. Displacement of the Bridport Sand Formation initiates cambering of the Inferior Oolite Group limestones.

The Fuller's Earth Formation forms the lower part of the Great Oolite Group and consists of silty, calcareous mudstones and shaly mudstones with a shelly limestone/mudstone band mid-sequence (Fuller's Earth Rock Member). In the upper part of the Formation is a band of bentonite-rich 'commercial' fuller's earth. The mudstones weather to a highly plastic clay. Slopes in the area are characterised by shallow translational landslides and mudflows.

In the area of 'foundered strata' (Figure 1) the BGS's digital stratigraphic database currently gives 'Lower and Middle Jurassic rocks (undifferentiated)' as the stratigraphy. The principal limestone members of the proposed Chalfield Oolite Formation (Wyatt & Cave, 2002) of the Great Oolite Group are the Combe Down Oolite and Bath Oolite Members. These have been the principal sources of freestone in the area. The Bath Oolite has a significantly higher porosity than the Combe Down Oolite (Forster et al., 1985). The freestones are massively-bedded, widely-jointed, homogeneous oolitic and shell-fragmental limestones. However, other parts of the Formations contain marl, conglomerate, infilled-borings, and tend to be closely-jointed and thinly bedded with dissolution features. Weathering of limestones tends to produce a thin surface 'brash' which spreads beyond the limestone sub-crop as hillwash, head, and landslide. To the south, the Chalfield Oolite Formation changes lithology to become the Frome Clay.

Superficial deposits consist of alluvium, alluvial fan deposits, river terrace deposits, head, and deposits of 'unknown age'. Head is a problematic deposit because of its variability over short distances, hence difficulty in identifying it, and consequent under-representation of it on geological maps. Changes in head content are observed downslope, as source material from the various underlying lithologies becomes incorporated in it. A mantle of head over limestone may result in locally artesian conditions (Privett, 1980). Head usually contains relic shear planes, although hillwash deposits on the lower slopes, whilst resembling head, does not. Small areas of head are shown on the 1:50,000 geology map at Claverton, Bathford, and Kelston.

Slope stability

The slopes that have developed 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). Landslides were probably most active in the wet conditions of early post-glacial times, and it is likely that the larger landslides of the area were formed during this period. 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.	Cambering & landsliding well distinguished but tree-covered. Erosion by springs.
Lower	Inferior Oolite on Lias clays. Extensive, draping & thinning downslope	Debris flows, mudflows, solifluction, head thickening downslope, rotational slumps within Inferior Oolite & Lias clays. Occasional large rotational in Lias by river erosion	Cambering & landsliding poorly distinguished. Erosion by rivers & 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: the upper zone of landsliding consisting of cambering and landsliding of Chalfield 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 mudflows 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:

During the reconnaissance survey no examples of active landsliding were observed. However, on previous visits shallow mudflows have been observed in the Swainswick area, within areas of known landslide, which have rapidly become obscured by farming activities. It is believed that no large-scale, deep-seated landslides have occurred in the area since the Devensian (Privett, 1980). Rotational slides of moderate size have occurred in recent times, but usually in association with 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. The minority of these landslides are depicted on the BGS 1:50,000 scale geology map, due to the 'foundered strata' scheme. Widespread tracts 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 and Tog Hill,
3) to the NE and E in the Doncombe Brook valley and at Colerne and Box.

It is possible 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; this perhaps having resulted from the same mapping problems encountered with the 'foundered strata'. However, this is not unique to the Bath sheet, as is the 'foundered strata' category. These areas of 'landslip' were not visited during the field-work. At least one of the areas depicted as 'head' (Heather Farm, ST723 682) on the 1:50,000 geology map is in fact a mudflow (Privett, 1980). A typical valley side is shown in Figure 2. In this view both landslides and cambering are seen. The slopes are partially wooded. The trees conceal the upper and central parts of some landslides. An example of open joints, or 'gulls', formed by cambering is shown in Figure 3.

Recommendations

Clearly, there have been major difficulties in geological mapping in the Bath area. Neither the stratigraphic sequence nor the nature of the slope instability have been correctly identified or described prior to the mid-1980's work. As a result, important parts of the current Bath geology map (Sheet 265) have not provided a useful source of information for engineers and other users, other than as a general warning: "*beware instability*". Given the problems associated with conventional geological mapping in the area, and the lack of resources to solve them comprehensively, for example by extensive sub-surface investigation, a new approach may be required. It may be possible to bring up to date the geomorphological processes of slope profiling and classification by the use of digital elevation models and other three-dimensional computer techniques. Another alternative may be to 'zone' the problem area according to hazard intensity, based on slope angle, relief, and geology. The difficulty with this approach is that the area would remain an anomaly in terms of nationwide geological coverage, in the same way as 'foundered strata'. However, this approach could be used as a subsidiary map in the same way that magnetic anomaly maps are depicted on some modern 1:50,000 sheets. The relationship between cambering and displacement (by landsliding) of the sub-stratum requires further research. This is probably beyond the scope of the proposed mapping.

A summary of possible approaches to re-mapping of 'foundered strata' (and possibly also some areas of 'landslide') is shown in Table 3:

Table 3 Re-mapping options for 'foundered strata' areas

Type	Approach	Methods	Advantages	Disadvantages
On the ground	Conventional	Feature mapping /hand augering	First-hand observatn.	Slow. Access problems. Experience required.
	Slope profiling	Walk-over, hand instruments	First-hand observatn.	Slow. Access problems.
	Terrestrial surveying	GPS	First-hand observatn.	Tree cover. Slow. Access problems
		Total station	Accurate. First-hand observatn.	Slow. Target required. Access problems.
	Sub-surface	Drilling	First-hand observatn	Extremely slow. Expensive. Access.
		Trial pitting	First-hand observatn Large-scale features visible.	Very slow. Access problems. Safety problems.
		Probing (eg Panda)	Portable. Minimal invasive.	Slow. No sample obtained.
		Window sampling	Towable. Sample obtained.	Slow. Noisy. Motorised.
		Geophysics	Non-invasive	Very slow. Access. No 'ground truthing'.
Remote (field)	Terrestrial surveying	Laser scanning.	Rapid. Few access problems.	No first-hand observatn. Range limitations. Tree cover.
		Reflectorless total station.	Few access problems. Accurate.	Slow. Range limitation. Tree cover.
Remote (aerial)	Remote sensing	Stereo air photos	Rapid. No access problems.	No first-hand observatn. Tree cover.
		LiDAR, TM, IR etc.	Rapid No access problems	Expensive. Tree cover. No first-hand observatn
	3-D modelling	Digital elevation model	No access problems.	Availability? No first-hand observatn.

The options above do not have to be used in isolation. Distinct benefits could be gained from combining methods, and only deploying methods to areas where they are best suited. For example, in areas of dense tree-cover, there are no cost-effective alternatives to 'on the ground' approaches. However, terrestrial surveying to cover such large areas would be prohibitively expensive. Staff cost is likely to be the major controlling factor. Remote sensing methods may be appropriate if costs can be reduced. Purchase of air photos is cost effective. The availability of aircraft-borne sensors such as Light Detection & Ranging (LiDAR), Thematic Mapper (TM), infra-red (IR) photography etc. may be applicable if accessed through NERC. The NERC capabilities should be assessed. As monitoring of landslides is not really an issue here, a one-off expenditure to obtain full coverage with one or more techniques may be considered worthwhile if the opportunity arises. Much of the cost of these remote methods lies in the processing and interpretation of data by skilled staff. It is not clear what the precise outputs of these methods would be. Expert advice would have to be sought to determine the applicability (if any) to the Bath conditions, in particular with regard to vegetation cover.

Table 4 Applicability of options for re-mapping of 'foundered strata'

Type	Approach	Locations
On the ground	Conventional	All areas (access permitting).
	Slope profiling	All areas (access permitting).
	Terrestrial surveying	Open ground only.
		All areas (access permitting).
	Sub-surface	All areas (access permitting).
Remote (field)	Terrestrial surveying	Open ground (short grass only).
		Open ground (short grass only).
Remote (aerial)	Remote sensing	Open ground only.
	3-D modelling	Availability? Scale?

It is important to note that the sole use of 'remote' methods, either in the field or in the office, would rely on the ability to relate slope forms to geology and instability features (landslide and cambering). Such relationships may be extrapolated from previous investigations, which have involved sub-surface 'ground truthing'. Slope profiling is time consuming, only 2-dimensional, and because it provides only a 'sample' of a valley side, its representativity is an issue (Hobbs, 1980). 3-D modelling is an ideal objective to aim at, as the overall geomorphology can be assessed and viewed unobstructed. Various map elements and sub-surface data can be overlain onto the model to produce a very effective geomorphological tool. However, the availability (or cost) and resolution need to be determined. The input of specialised staff is a key factor. The methods grouped under 'on the ground' (Tables 3 & 4) have the advantage that they generally provide first-hand information about the terrain and any features in it. For example, soils and outcrops in stream banks may be observed at close hand, and subtle changes of slope, unobservable from a distance, may be observed (and located using hand-held rangefinders, GPS etc.).

Sub-surface investigations are highly attractive as a means of identifying geology and processes, but are considered to be prohibitively expensive as a means of routine mapping. The only application would be for a small number of trial locations. Trial pitting would cost around £300 - £500 per day depending on plant and shoring. Drilling would probably be too expensive (£100 per metre) to merit consideration. It may also be less informative than pitting in these materials. A third possibility is probing. This would use a light-weight, non-motorised, portable (or semi-portable) kit measuring cone penetration resistance to depths of up to 5 m. However, these kits would probably give ambiguous results in head, and cambered or landslipped limestone. Surface geophysics would not be considered for the same reason, although it has been used successfully to locate camber 'gulls' (Privett, 1980). Heavier duty 'window' samplers produce a loggable core, but would require vehicular access and more time to deploy.

Conclusions

The slopes in the area outlined in Figure 1 are considered to be broadly similar, despite local variations in elevation, drainage, aspect etc. Similar slope processes have taken place (where topography has allowed) and are continuing, though not particularly actively at present. Changes in climate or alteration of slopes by man, are capable of reactivating landslides on slopes currently with marginal stability. Most recent re-activations have been of shallow mudflow or creep. Cambering is closely associated with landslides at two levels within the slope. Tension cracks (or ‘gulls’) within the limestone formations, produced by cambering, are capable of producing significant underground voids, which remain undetected without major sub-surface investigation. The combined effect of many millennia of cambering and landsliding has been to produce complex shallow solid geological structures where formations extend downslope well beyond their sub-crop, and where inter-mixing of superficial deposits (head, hillwash, mudflow) has taken place. Only a small number of mappable large-scale, deep-seated landslides have been recorded. Geomorphological mapping, whilst a useful tool, is alone insufficient to solve the ‘foundered strata’ problem. It needs to be adapted to 3-D modelling and combined with geological mapping in order to succeed.

The Wyatt re-mapping requires checking, and possibly some re-assessment, in the light of more recent work. The parts of the ‘foundered strata’ not covered by Wyatt require re-mapping.

The most cost-effective re-mapping of ‘foundered strata’, selected from the options listed above, would be based on the following approaches:

1) Carry out comprehensive conventional feature mapping over the area of ‘foundered strata’ not covered by Wyatt, and spot checking of Wyatt’s area.
2) Carry out a set of detailed slope profiles by walk-over geological and geomorphological survey and relate these to site investigations containing surveyed profiles and sub-surface data elsewhere in the area (e.g. Swainswick).
3) Create a 3-D digital elevation model using pre-existing data *if available*, or by airborne LiDAR survey, *if available* to augment 1) and 2).
4) Make use of remote sensing (aerial) methods *if subsidised* to augment 1) and 2).

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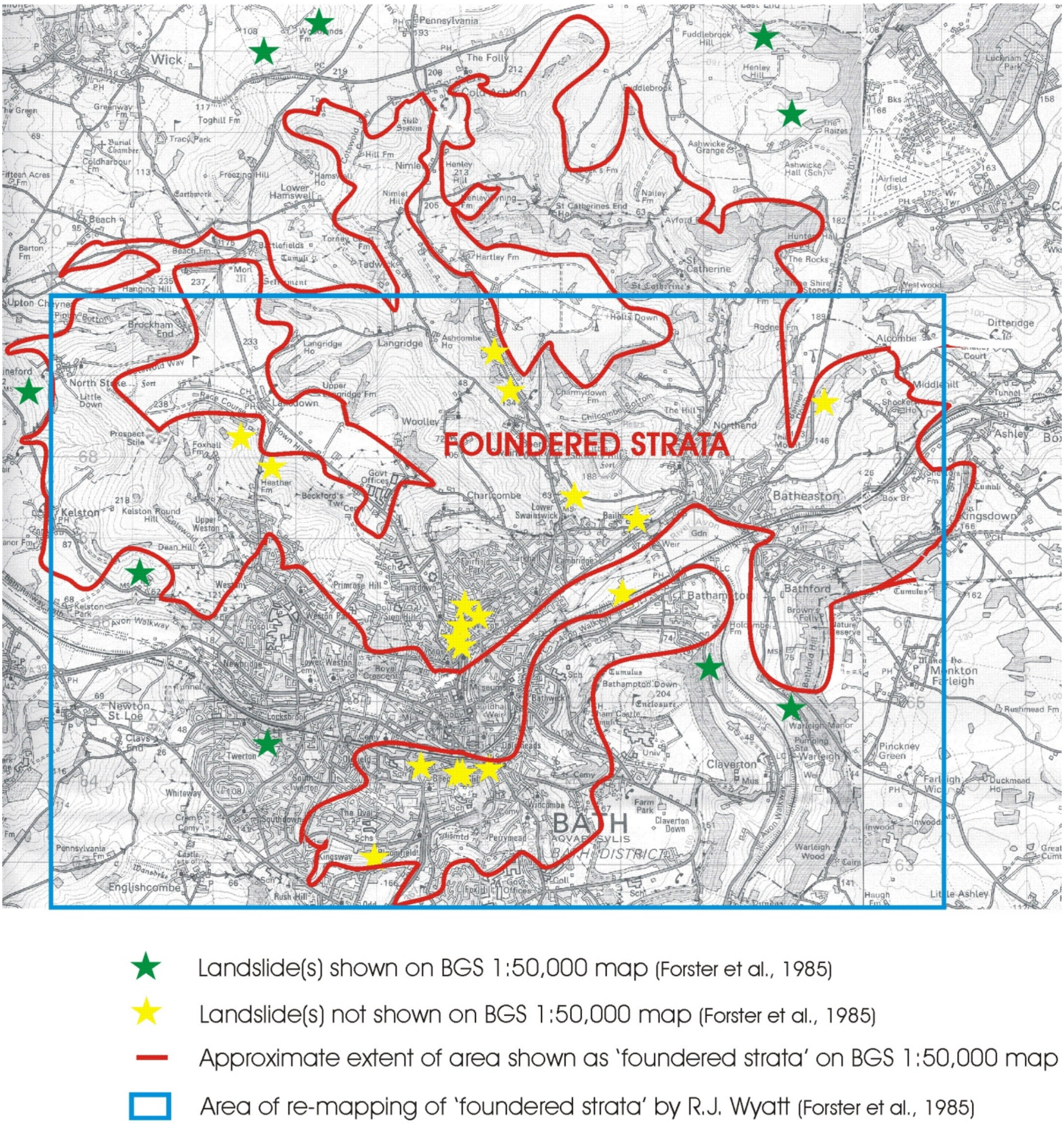

Figure 1 Map of the Bath study area

Figure 2 View of west side of Swainswick valley (Soper's Wood)
[*note:* shallow landslides upper left & middle right; camber upper far left]

Figure 3 Camber 'gulls' in Great Oolite Group limestone,
Little Solsbury Hill, NW corner (GR 767 681)