Landslide imaging techniques for urban geoscience reconnaissance

MALCOLM Z WHITWORTH[1], DAVID GILES[2] & IAN ANDERSON[3]

[1] *Geohazards Research Center, Univ. of Portsmouth. (e-mail: malcolm.whitworth@port.ac.uk)*
[2] *Geohazards Research Center, Univ. of Portsmouth. (e-mail: dave.giles@port.ac.uk)*
[3] *3D Laser Mapping Ltd. (e-mail: ian@riegl.co.uk)*

Abstract: Engineering geologists now have at their disposal a wide variety of imaging techniques and technologies available for rapid terrain evaluation and assessment. These techniques include the use of remotely sensed data sets, traditional aerial photography, geophysical imaging, terrestrial laser scanning (LiDAR) and derived digital terrain models (DTM). This paper will describe the use of these techniques for a road corridor hazard assessment for a road by-pass scheme in the Jurassic strata of the Cotswolds, UK.

The proposed road route would pass through an extremely problematic terrain that was prone to landsliding and general slope instability. Many active and relict slope features were present in the area including shallow rotational slides to more deep-seated features within the strata. Solifluction features were also present with many relict shear surfaces present. The reactivation or disturbance of these features would potentially have a severe impact on both the proposed construction project and to the urban environment in the immediate vicinity.

The paper will critically review the techniques used and will describe in detail the use of remotely sensed Airborne Thematic Mapper scenes (ATM), aerial photography and the use or LiDAR data for the hazard assessment.

Résumé: Les géologues de technologie ont maintenant à leur disposition une grande variété de techniques et de technologies de formation image disponibles pour l'évaluation et l'évaluation rapides de terrain. Ces techniques incluent l'utilisation des modem à distance sentis, de la photographie aérienne traditionnelle, de la formation image géophysique, du balayage terrestre de laser (LiDAR) et des modèles numériques dérivés de terrain (DTM). Cet article décrira l'utilisation de ces techniques pour une évaluation de risque de couloir de route pour un arrangement de déviation de route dans les strates jurassiques du Cotswolds, R-U.

L'itinéraire proposé de route traverserait un terrain extrêmement problématique qui était enclin à l'instabilité landsliding et générale de pente. Beaucoup de dispositifs actifs et de veuve de pente étaient présents dans le secteur comprenant les glissières de rotation peu profondes à des dispositifs plus situés en profondeur dans les strates. Les dispositifs de solifluction étaient également présents en présence de beaucoup de surfaces de cisaillement de veuve. La réactivation ou la perturbation de ces dispositifs aurait potentiellement un impact grave sur le projet de construction proposé et à l'environnement urbain à proximité immédiate.

Le papier passera en revue en critique les techniques utilisées et décrira en détail l'utilisation des scènes aéroportées à distance senties de cartographe thématique (atmosphère), de la photographie aérienne et de l'utilisation ou des données de LiDAR pour l'évaluation de risque.

Keywords: remote sensing, landslides, cambering, geological hazards, geomorphology, photogrammetry.

INTRODUCTION

Landslides directly affect the ground surface, which means that remote sensing techniques are well suited to their study (Soeters & Van Westen, 1996). Conventional airborne remote sensing for landslide mapping typically involves the stereoscopic interpretation of aerial photography, since their spatial resolution is most appropriate for landslide investigations and the morphological characteristics of mass movements are often visible under stereo viewing (Mantovani, Soeters & Van Westen, 1996). The advantage of airborne sensors for the acquisition of digital imagery and elevation data is that the spatial resolution of the resulting imagery lies between that of aerial photography and satellite imagery. While image acquisition requires detailed planning and is subject to weather conditions, the spectral and spatial resolution of airborne imagery provide an improved data set for landslide identification when compared to the SPOT and Landsat satellite systems (Eyers *et al*., 1998). Two types of data have been utilised in this project, firstly Airborne Thematic Mapper (ATM) imagery, which was acquired by the NERC Airborne Research and Survey Facility (ARSF), providing imagery with a high spatial and spectral resolution, but also a thermal infrared band whose spatial resolution is identical to the other spectral bands. This is in contrast to many satellite sensors, whose thermal imaging capabilities are either absent or degraded when compared to their other spectral bands. Secondly, the ATM imagery was supplemented with digital elevation data generated at a range of scales using a combination commercially available NextMap digital data and higher resolution data generated using digital photogrammetry and terrestrial laser scanning (LiDAR) techniques.

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STUDY AREA

The study area described in this paper is situated on the county border between Gloucestershire and Worcestershire in the United Kingdom (Figure 1). The area lies between 80 m and 250m AOD on the west facing scarp slope of the Cotswold escarpment between the towns of Willersey, Broadway and Snowshill (Grid Reference SP107396 to SP095338).

The solid geology of the area is summarized in Table 1, comprising of a sequence of Lower Jurassic marine clays, sands and limestones including the Charmouth Mudstone Formation, Dryham Formation, Marlstone Rock Formation and Whitby Mudstone Formation (Barron, Sumbler & Morigi, 2002). These rocks are overlain by limestones of the Middle Jurassic Inferior Oolite Group, which cap sequence in this area and form the plateau seen at the top of the escarpment.

The landslides found on the escarpment at Broadway are consistent with those found on other parts of the Cotswolds (Forster, 1992). The typical distribution of landslides on this type of Jurassic strata comprises the following classification:

1. Cambered strata in the Inferior Oolite which caps the upper part of the escarpment.
2. Zone of large scale rotational landslides below the Inferior Oolite.
3. Zone of successive shallow rotational landslides.
4. Extensive shallow mudslides and translational landslides.

At Broadway, the landslide sequence involves cambering at the edge of the Cotswolds plateau, large rotational slides on the upper slopes of the escarpment, which degrade down slope into shallow multiple rotational slides and mudslides, which mantle the lower slopes of the escarpment. There is extensive instability within the Broadway area, including lobate mudslides, shallow irregular mudslides, translational and rotational landslides.

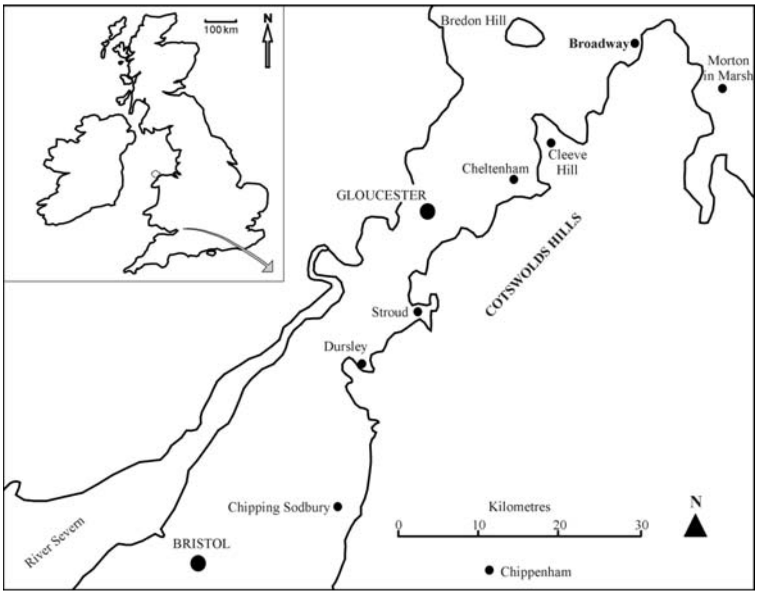

Figure 1. Location of the study area around the town of Broadway.

Table 1. Typical descriptions of geological units and corresponding slope morphology observed on the Broadway escarpment (adapted from Mott Macdonald, 1992).

Formation	Description	Surface Morphology
Birdlip Limestone Formation	Oolitic and sandy ferruginous LIMESTONE	Steep scarp face (260m OD) and Cotswolds plateau. Cambering and multiple rotational landslides.
Bridport Sand Formation	Fine to medium grained SANDSTONE.	Cambering and landsliding.
Whitby Mudstone Formation	Dark grey CLAY with some OOLITIC LIMESTONE	Gentle angle slopes with remains of degraded rotational landslides.
Marlstone Rock Formation	Strong brown closely jointed oolitic and fossiliferous LIMESTONE.	Cap rock to mid slope lithological bench (170 -180m OD).
Dryham Formation	Moderately weak orange brown SANDSTONE and SILTSTONE with subordinate bands of SILT and CLAY.	Steep scarp faces below the lithological bench. Occasional large rotational landslides (Colliers Knap).
Charmouth Mudstone Formation	Dark grey CLAY with occasional bands of argillaceous limestone. Grades at depth into weak mudstone.	Foot slopes and valley base. Mantled by superficial deposits and solifluction deposits.

LANDSLIDE IMAGING USING AIRBORNE REMOTE SENSING

Airborne multi-spectral imagery

Daedalus Airborne Thematic Mapper (ATM) imagery was acquired as part of an airborne survey of the Broadway study site by the NERC Airborne Remote Sensing Facility on the 8th February 1997 at a flying height of 800 metres (Flight reference 97/2). The imagery acquired consists of 11 bands (Table 2); bands 1 to 5 image at specific wavelengths in the visible part of the electromagnetic spectrum; bands 6 to 8 image in the near infrared; 9 and 10 in the middle infrared and band 11 images in the emitted thermal infrared. The ATM instrument has an instantaneous field of view (IFOV) of 2.5 milliradians and for this study the image data was re-sampled to a pixel size of 2 metres.

Imagery was acquired during February to take advantage of the low sun angle in order to enhance subtle topographic features associated with the presence of slope instability. Ground works for the new A44 Broadway bypass, which was about to commence at the time of data acquisition, further constrained flight planning since image acquisition had to be made prior to the start of site excavation if the area was to be imaged in an undisturbed state.

Table 2. Summary of the Daedalus Airborne Thematic Mapper (ATM) sensor.

ATM Band	Wavelength (μm)	Band Name
1	0.42 – 0.45	Visible
2	0.45 – 0.52	
3	0.52 – 0.60	
4	0.60 – 0.62	
5	0.63 – 0.69	
6	0.69 – 0.75	Near Infrared
7	0.76 – 0.90	
8	0.91 – 1.05	
9	1.55 – 1.75	Near–Middle Infrared
10	2.08 – 2.35	Middle Infrared
11	8.50 – 13.00	Thermal Infrared

Advanced colour composite images

Colour composite images take advantage of the multi-band nature of remotely sensed data. The technique allows three separate bands to be combined into one single digital image for interpretation. The resulting images require careful interpretation as non-visible bands are often used, which result an unusual colour combination. Due to its simplicity, colour composite image enhancement is a common interpretation technique, which has been widely applied as a method for enhancing landslides in remotely sensed imagery (Hervas and Rosin, 1996).

One of the simplest composite images to generate is a termed a true colour image in which three visible bands are combined to produce a single image, similar in appearance to a colour aerial photograph. From this starting point other image data can subsequently be incorporated to gradually increase the complexity of the composite image. Figure 2b illustrates the use of this type of colour composite image for landslide mapping at Broadway, here a true colour composite image has been combined with a principal component image. This colour composite image has proven particularly helpful in interpreting the complex landslide sequence observed in the Broadway study area. Figure 2 contrasts a conventional colour aerial photograph with the colour composite image alongside the corresponding field derived geomorphological map of the area.

The colour composite image shown in Figure 2 consists of a combination of visible bands 4 as red, band 3 as green and band 5 as blue, while a principal component image has been added as a separate intensity layer. Several morphological features are evident from this image, in particular the presence of back tilted slope units associated with degraded rotated blocks, backscarps and benching, which have been interpreted as the remains of a relict landslide system. The benches are limited to the upper slopes of the valley (on the right of the image) and are overlain by a series of lobes that represent the toes of a series of mudslides, which themselves have resulted from the degradation of landslides further upslope. The central transportation zone consists of a complex sequence of earthflows and isolated rotational landslides, which can clearly be identified in the composite image. At the bottom of the valley, the morphology of the lobate earthflows and zone of accumulation are clearly evident from the composite image, while the contact between the landslides and ridge and furrow cultivated fields is also well defined.

Image textural analysis

The texture of an image is determined by the overall smoothness or roughness of an image scene, which in turn is controlled by the frequency and distribution of pixels within the image. Those images with high pixel variation are termed rough, meaning the pixel values change abruptly over a small distance in an image (e.g. roads and field borders). Conversely, smooth images are those where the pixel values vary gradually over a large area, such as water bodies or large fields. When identifying landslides within aerial photography, image texture is one of the most important interpretation elements; the irregular surface produced by the landslide movement produces a characteristic *turbulent* texture within the image, especially when enhanced by shadow. These features, combined with sharp boundaries associated with the scarps and toe, provide useful evidence of landslides in aerial photography (Clayton, Simons & Matthews, 1982).

Several authors have extended this concept of image texture to the detection of landslides in digital imagery through the use of filters to enhance areas of image roughness associated with landslide activity. Mason, Rosenbaum & Moore (1998) applied filters to Airborne Thematic Mapper (ATM) and Landsat TM imagery to highlight the hummocky main body and the accumulation toe of the landslide. Similarly, Eyers *et al*. (1998) found that simple textural filters were successful in revealing crown wall shape of the landslide, the translated material and the nature of disturbed ground associated with slope instability. In quantifying image roughness, statistical measures can also be used, from simple functions such as calculating the range, variance or standard deviation of pixels in an image scene through to more complex statistical methods such as the grey level co-occurrence matrix (GLCM). The results of the application of a GLCM entropy filter applied to the original ATM scene are show in Figure 3b.

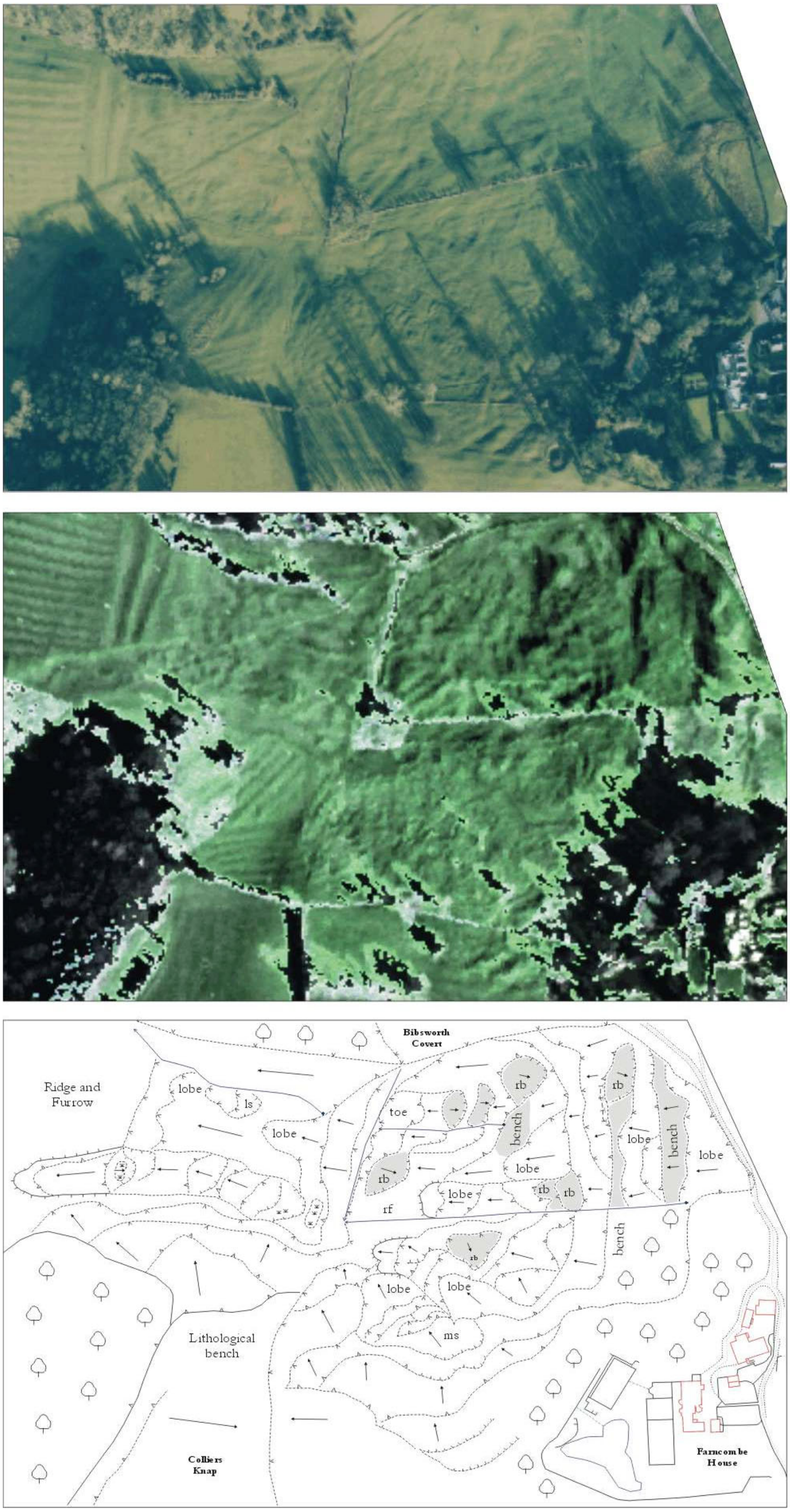

Figure 2. Landslide morphological mapping of the Farncombe Valley using ATM colour composite and principal component analysis. (a) NERC colour aerial photograph of the area, (b) RGB colour composite produced by a combination of a true colour composite of ATM bands 4-3-5 combined with an intensity layer and (c) corresponding geomorphological map of the Farncombe Valley showing the location of benches, lobes and rotated blocks (rb)

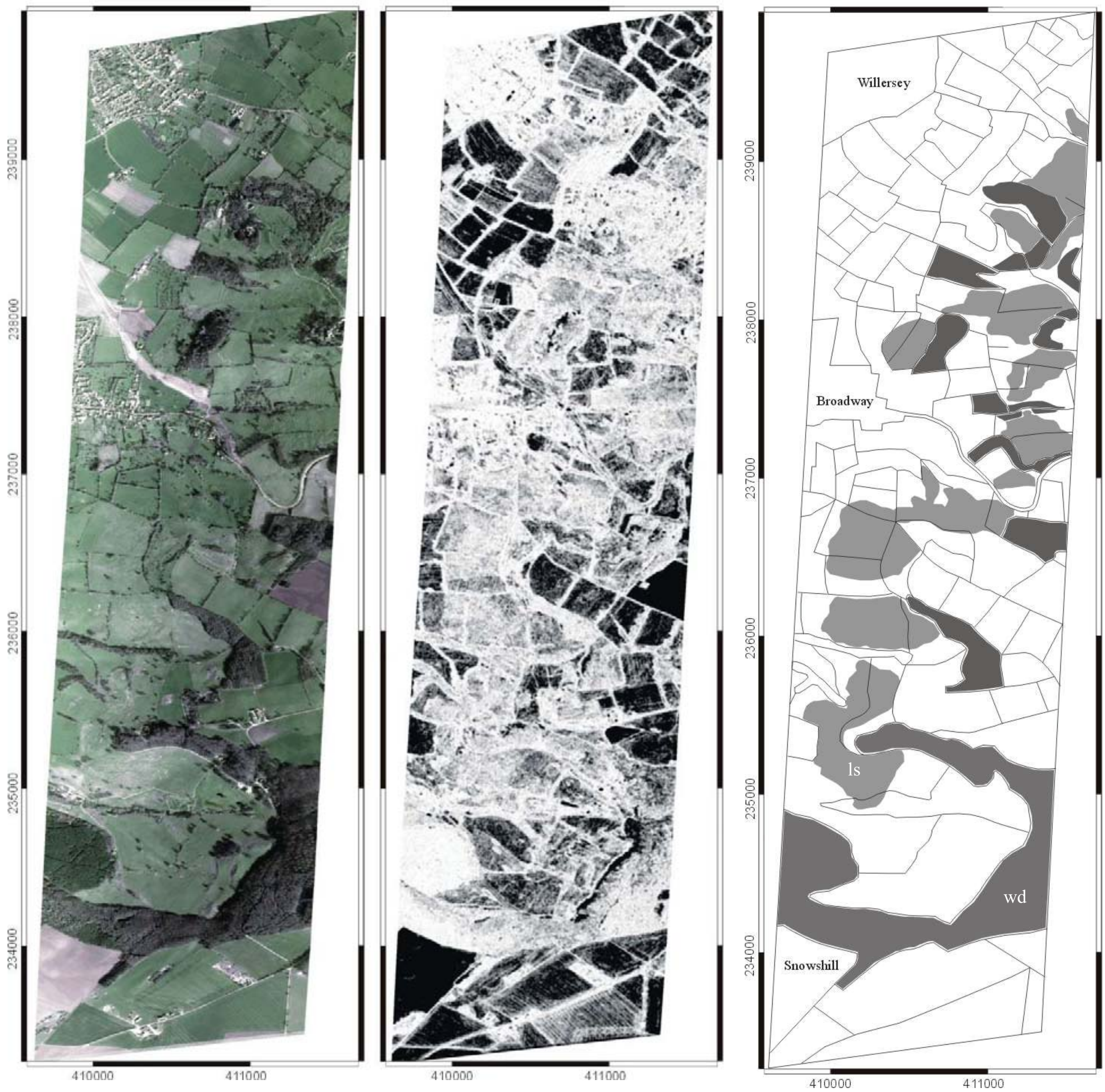

Figure 3. (a) True colour composite Airborne Thematic Mapper (ATM) image of the Broadway ATM flight line (bands 4-3-5) (b) Grey Level Co-occurrence texture image generated from the original Airborne Thematic Mapper (ATM) image using grey level co-occurence matrix (GLCM) entropy function and (c) map showing the location of the areas of landslide activity (*ls*) and woodland (*wd*) on the Cotswolds escarpment.

To assist with interpretation, the original image scene is also shown alongside. There are three main areas of interest within the texture image. Firstly, areas of very low texture associated with flat cultivated fields and pasture at the top of the escarpment and in the Vale of Evesham. These represent areas of stability, which show no evidence of movement. Secondly, areas of maximum texture and image variation associated with dense woodland canopy and hedgerow systems; and finally areas of intermediate texture associated with the presence of slope instability on the escarpment slopes. What is clear from this analysis is that by exploiting image variation, texture enhancement is able to quickly identify landslides within the imagery and differentiate them from nearby stable slopes.

In this study, a range of textural filters were tested for their ability to enhance areas of landslide activity on the escarpment slopes. The results indicated that the GLCM statistical measure was the most successful at differentiating the landslides in the image.

IMAGING OF CAMBERING USING REMOTE SENSING DATA

The alternating nature of strata of the Cotswolds in which competent limestones overly relative incompetent weak clays beneath, provide almost ideal conditions for the development of cambering and valley bulging. It is best developed where the Inferior Oolite is displaced over the Whitby Mudstone Formation (Upper Lias clay) beneath. The

Inferior Oolite limestone that caps the Cotswolds escarpment above the Broadway is known to be cambered; the British Geological Survey 1:10,000 geological map (SP13NW) identifies a zone of cambering in the Inferior Oolite on the top of the escarpment to the south-east of Broadway. The cambering in this area has produced a series of large elongate troughs that lie parallel to the escarpment edge running approximately north south, which have developed as a result of the cambering of the Inferior Oolite over the Whitby Mudstone Formation (formerly the Upper Lias Clay) beneath. Barron *et al*. (2002) have described up to five gulls in the vicinity of Broadway Tower up to 1.2 kilometres in length, which have formed where a much greater thickness of Inferior Oolite is present. Field mapping and airphoto interpretation indicates that this large gull system marks the boundary between the stable limestone plateau to the east and a cambered slope on the escarpment edge to the west. The cambered zone to the west of these gulls dip westward toward the Broadway valley; while the slopes east of the gulls have variable dip toward the east (Figure 4).

Airborne multispectral imagery

Thermal remote sensing has also been used to investigate the landforms associated with cambering at the top of the escarpment at Broadway. The thermal imaging capabilities of the Airborne Thematic Mapper (ATM) sensor all the delineation of surface features associated with cambering in the Inferior Oolite at the top of the Broadway escarpment. Figure 4 shows the thermal image of this cambered zone derived from ATM band 11; the main gull system is visible in the centre of the image, comprising a series of linear en-echelon depressions. In addition, the thermal band provides evidence of the presence of a series of subtle surface landforms in the fields to the east of the gulls, which are not visible in the corresponding aerial photograph. While the gulls represent the surface expression of a deep joint system, the morphology of these subtle image features present in the thermal image indicate a zone of potential landslides associated with the movement of material into the voids associated with the gulls. The evidence derived from the thermal imagery indicates a zone of relict landslide activity on the slopes that flank the deep gull system not previously identified in aerial photography or during field mapping; this in turn indicates a much wider zone of cambering and gull formation than previously thought in this area.

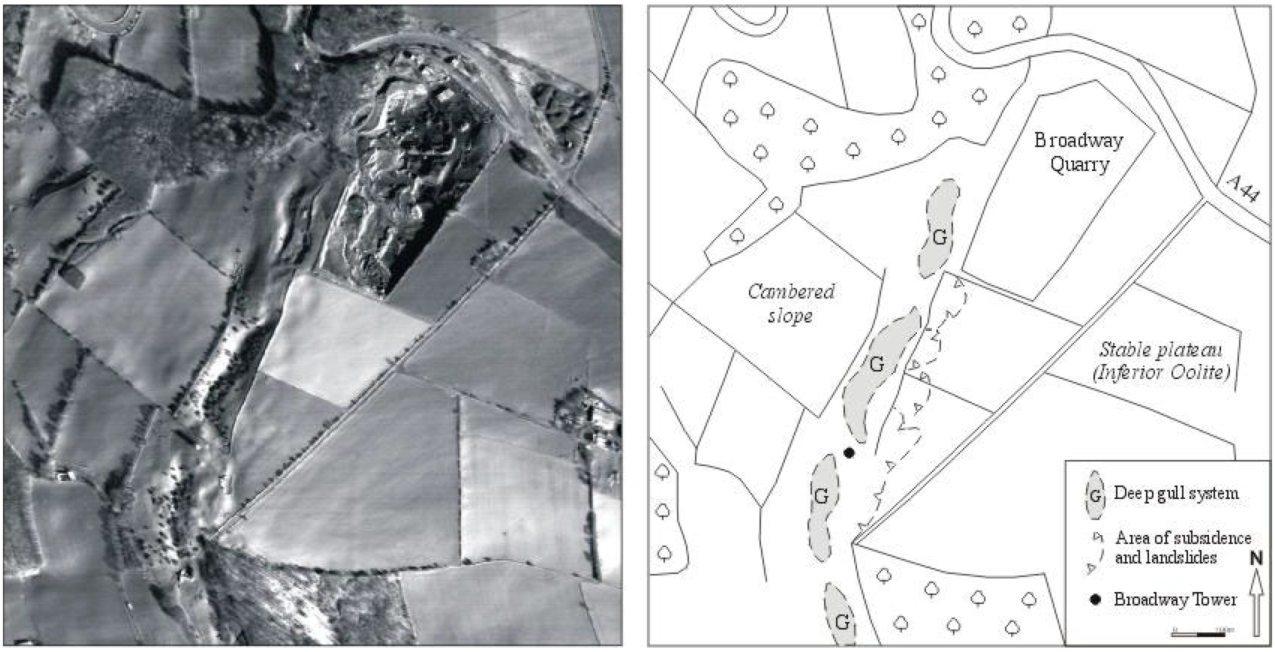

Figure 4. Thermal image analysis of the cambered slope at the top of the escarpment in the vicinity of Broadway Tower. (a) Thermal infrared ATM band 11 and (b) map showing the main cambered gulls system beside Broadway Tower and location of subtle features visible in the thermal imagery.

Digital elevation data

NextMap digital elevation model (DEM) data was acquired at a 5 metre pixel resolution in order to provide topographic information for the entire escarpment above the village of Broadway. The morphology of the Cotswolds escarpment between Willersey and Broadway is clearly evident in the sun-shaded image in Figure 5a generated from the NextMap DEM data. The image highlights the areas of the Inferior Oolite plateau at the top of the escarpment, the main escarpment slopes and the flat lying Vale of Evesham. The slope angle map derived from the NextMap elevation model (Figure 5b) highlights a series of linear slope angle changes at the edge of the Inferior Oolite plateau. This is illustrated in Figure 5b and the inset 5c in the vicinity of Broadway Tower (Figure 5d). These alternating slope changes indicate the presence of a series of linear troughs that coincide with the known area of cambering near Broadway Tower (Whitworth, Giles & Murphy, 2005; Barron *et al*., 2002). Their pattern and orientation match the known gulls system present in this locality (Figure 5e). Using this topographic signature, it has also been possible to identify two further areas of cambering nearby; both sites are identified in Figure 5b.

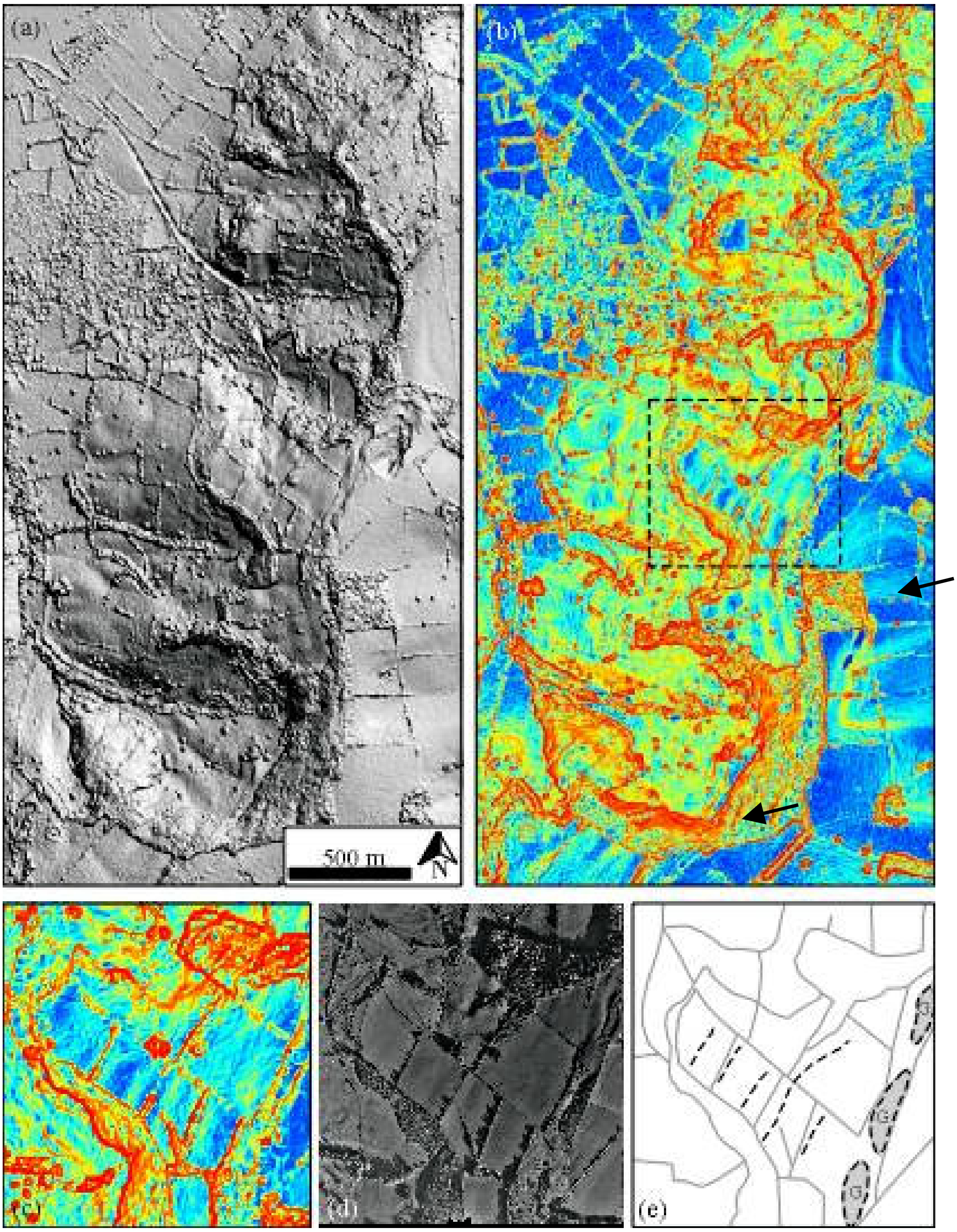

Figure 5. Mapping surface expression of cambering using NextMap digital elevation data (a) sun shaded surface map of the area of the Broadway study area; (b) pseudocolour slope angle map with inset shown (c) inset slope map showing the cambered slope in the vicinity of Broadway Tower (d) black and white aerial photograph of the area and (e) map indicating the location of main cambered gulls and linear surface depressions seen in the slope map. The arrows indicate the locations of other slopes which show topographic signatures indicative of cambering.

TERRESTRIAL LASER SCANNING FOR INLAND LANDSLIDE MAPPING

Recent developments in the use of ground based laser-scanning systems for the study of terrain present landslide researchers with a tool for the rapid acquisition of digital elevation data. Terrestrial laser scanning has been used to study both coastal and inland landslides (Hobbs *et al*., 2002; Gibson *et al*., 2003; Rowlands, Jone & Whitworth, 2003) and rock slope stability (Mikos, Vidmar & Brilly, 2005; Ruiz *et al*., 2004). While other studies have taken advantage of the survey repeatability for change detection and temporal studies of landslide movement (Hsaio *et al*., 2004).

The scanning technology is based on that used in traditional total stations, however, the laser scanner is an automated system that is able to acquire a dense point cloud of data from surfaces at significant distances from the scanner location. The scanner produces a representation of the world through the collection of x, y, z coordinates of points measured by the laser. The technique is rapid and accurate; current scanners are able to collect up to 12,000 points per second with accuracies of 10mm allowing the terrain to be modelled accurately. Terrestrial laser systems generate terrain data using time-of-flight to determine the distance between the laser and a point on a reflective surface while concurrently recording the relative direction and elevation angle of each measurement.

A Reigl Z420i laser scanner was tested at Broadway in order to evaluate the ability of the scanner to collect terrain data on inland landslides. The chosen study area was located in the central valley above the village of Broadway, shown in Figure 6, centred on OS Grid Reference [411000 237500] between the A44 road and Farncombe House. The valley contains a number of landslides on either side of river including shallow and lobate mudslides, rotational landslides and the presence of ridge and furrow cultivation remains which have been disrupted by landslide activity (Whitworth *et al*., 2000).

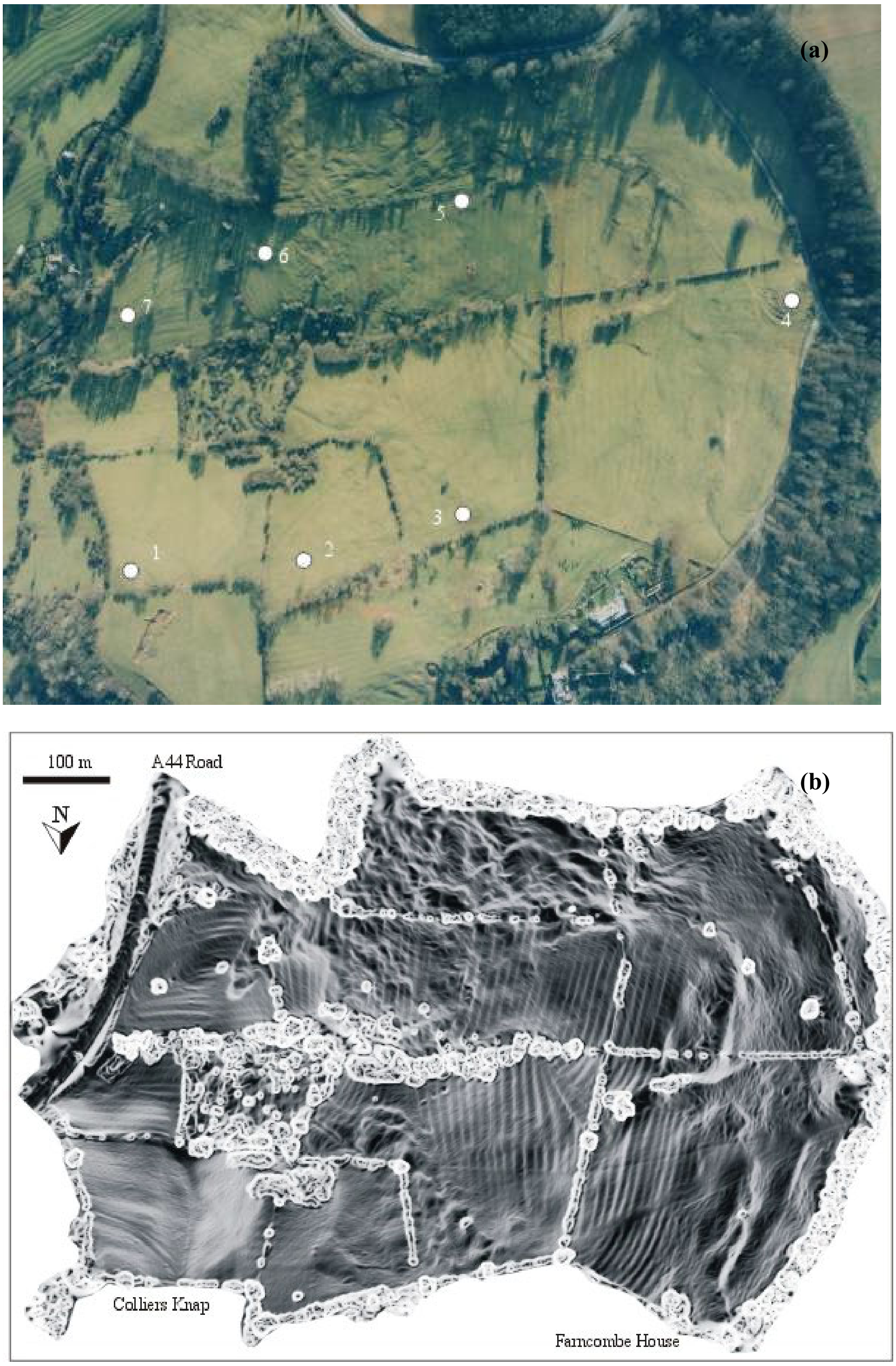

Figure 6. (a) Colour aerial photograph of the Broadway valley site indicating the location of each of the laser scan sites and the nature and extent of the slope instability. (b) Slope angle map derived from the digital elevation model of the Broadway valley generated using terrestrial laser scanning (resampled to 1 m grid spacing). In this image the steepest slopes appear white and are associated with landslide scarps and boundaries, frontal lobes and the top of the woodland canopy and hedge boundaries. The linear ridge and furrow features are also clearly visible in the slope map.

The study area was imaged during February 2005 using a Reigl LMS-Z420i scanner operated by 3D Laser mapping (3DLM), which is summarised in Table 3. The scanner is a tripod-mounted system with a range of up to 800 metres and a scan rate of up to 12000 points per second. The scan head is able to rotate in a 360 degrees arc around the scanning location with a rotating mirror, which is able to scan vertically up to an 80 degree angle, 40 degrees above and below the horizontal plane. A connected laptop collects recorded data on range, angles and signal amplitude for each returned laser pulse via a network connection. The scanning system also collects simultaneous photography from a digital camera, which is situated on top of the scanner head. These can be used to generate ortho-photography when combined with the topographic data during post-processing.

Table 3. Summary of the properties of the Reigl laser scanner used in this study (Manufacturer's Data).

	Reigl LMS-Z420i
Vertical scan angle	80°
Horizontal scan angle	360°
Scan range	Up to 800 m
Measurement accuracy	5 mm
Measurement resolution	5 mm
Measurement rate	Up to 12000 pts/sec
Laser wavelength	Near-infrared (0.9 μm)

The use of terrestrial scanners requires careful planning when dealing with complex terrains. Multiple scans are often required where the extent of the area exceeds the scanner's range or where the ground surface is obstructed by trees or buildings. The Broadway study area itself was 1000 metres long and 800 metres wide and consisting predominantly of pastureland with isolated pockets of woodland and hedgerows. In order to provide complete coverage, the area was imaged using seven scanning sites located at vantage points along the valley sides (Figure 6a).

Once all the scans were combined, the elevation data was exported to an image processing application for visualisation. The resulting slope angle map is shown in Figure 6b and as with the previous slope maps the landslides are clearly visible in the resulting image, including zones of rotational failures indicated by flat low angle benches alongside steep, often arcuate backscarps, shallow landslide activity and mudslides. The lobate mudslide on the slopes below Farncombe House is clearly visible along with a detailed image of the internal morphology of the landslide, which is enhanced by the slope angle map. On the opposite side of the valley, an area of disturbed ridge and furrow is present which has been disrupted by shallow landslide activity; upslope of this area the field contains extensive instability including rotational landslides, mudslides and debris flows. In this area, a sequence of successive rotational landslides is evidenced by the repeated slope changes that reflect the backscarps of these individual failures. The upper slopes below the main Inferior Oolite scarp face consist of a series of benches reflecting landslide activity towards the top of the Whitby Mudstone Formation. These have been overprinted by more recent mudslide activity and the slope angle map highlights the frontal lobes of these landslides. At the top of the slope, the remains of a large rotated block identified during field mapping can be identified in the image.

DISCUSSION

The spatial and spectral resolution of the ATM sensor provides very detailed images of the Cotswold escarpment and the landslide features present. The generation of colour composite images of the study area revealed detailed geomorphological information about the landslides not possible using standard aerial photography. These images enabled the identification of individual landslide features and differentiation of different landslide types. The presence of a thermal band (ATM band 11) provided imagery able to detect subtle topographic and moisture variations, revealing the extent of the cambering above Broadway well beyond the gulls seen in the aerial photography.

The utilization of image roughness has proven to be the most powerful tool for the detection and mapping of landslides in this area. The texture enhancements respond to the presence of sharp landslide boundaries and hummocky (irregular) topography associated with surface disruption, so where a landslide is present, the texture image response reflects the image variation that results. The power of the technique lies in the ability to differentiate between rough landslide areas and smooth stable ground within the image. In this study, the GLCM filter was used to quantify image texture. The resulting image (Figure 3b) highlights areas of increased image variation associated with woodland, hedgerows and more importantly, slopes that have been disturbed by landslide activity. The GLCM image contains dark areas of low texture associated with flat cultivated fields at the bottom and top of the escarpment, while highlighting slopes on the escarpment face that lack evidence of landslide activity. In terms of landslide mapping, image texture is able to highlight areas of landslide scarps, main hummocky landslide body, zones of shallow mudslide movement and mudslide accumulation zones, as well as delineating landslide boundaries within the imagery. This texture measure is also able to distinguish between stable slopes and slopes affected by landslide movement, where the flow component of the movement produces a distinctive image texture (Hervas *et al*., 1996).

The survey undertaken at Broadway has demonstrated the application of terrestrial laser scanning to terrain evaluation in inland areas. In particular, the technique represents a rapid method for generating high-resolution topographic data at a scale, which allows clear delineation of landforms associated with slope instability. Initially, sun shaded surface models were used to visually identify the presence of landslides within the digital elevation models as these have been shown to be effective products for landslide mapping (Van Den Eeckhaut *et al*., 2005), however, these were supplemented using grey scale slope angle maps, which were found to more effective for landslide delineation in the digital topographic data. Slope angle was found to enhance the presence of steep slopes associated with the arcuate landslide scarps and accumulation lobes, while flat slope units associated with the remains of back tilted blocks could also be delineated in the slope angle map.

CONCLUSIONS

This paper has shown that the high spatial and spectral resolution of the Airborne Thematic Mapper sensor provide an excellent multi-spectral tool for the detection and delineation of landslides and cambering associated with clay dominated slopes. The use of colour composites images offers significant advantages over conventional aerial photography in allowing non-visible data to be incorporated into the image, which in this case has provided detailed information on the morphology of the landslides on the Cotswolds escarpment. The presence of a high-resolution thermal band can be used to map subtle topographic features and moisture variations across a large area, providing important indications of the ground conditions. The image can be used in isolation or combined with other spectral bands (visible, near or mid-infrared) since it is acquired at the same resolution as all the other ATM bands.

The nature of the landslides on clay dominated slopes mean that textural analysis of ATM imagery represents the optimum method of automated landslide detection. Clay dominated slopes are common in southern United Kingdom and the associated slope instability can represent a significant problem in engineering geology. The image processing techniques described in this paper are all available as standard components of modern remote sensing and image processing software applications. The increasing availability of airborne and other high-resolution imagery combined with high accuracy digital topographic data derived from terrestrial laser scanning provides a powerful and under-utilized tool that can be employed effectively by engineering geomorphologists for landslide mapping in clay dominated temperate terrains.

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Corresponding author: Mr Malcolm Whitworth, Geohazards Research Centre, Univ of Portsmouth, Burnaby Building, Burnaby Road, Portsmouth, Hampshire, PO1 3QL, United Kingdom. Tel: +44 23 92842264. Email: malcolm.whitworth@port.ac.uk.

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