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STEADY STATE BEHAVIOUR OF THE BLACK VEN MUDSLIDE: THE APPLICATION OF ARCHIVAL ANALYTICAL PHOTOGRAMMETRY TO STUDIES OF LANDFORM CHANGE

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'Gilbert was primarily concerned with the manner in which equilibrium landforms became adjusted to geomorphic processes, and an interest in the progress toward such adjustment and the changes to which such adjustment is susceptible through time'
(Chorely, 1965)

ABSTRACT

The concept of dynamic equilibrium has provided geomorphologists with a challenging paradigm for studying landform evolution but quantitative evidence for its existence has proved illusive, particularly for complex geomorphological systems. The authors believe that the principle has now been verified through the application of the 'archival photogrammetric technique' to a sequence of historical photographs spanning 50 years of process at the Black Ven mudslide complex in Dorset, U.K.

The principles and limitations of the archival photogrammetric technique are described. The method is applied to oblique and vertical aerial photographs of Black Ven at five epochs, commencing in 1946, continuing at approximately 10 year intervals until 1988. The technique is used to generate plans/contours/sections and a dense and accurate digital elevation model (DEM) of the whole site at each epoch. This is used to generate 'DEMs of difference' and a 'distribution of slope angle' which suggest that the mudslides are in equilibrium despite the removal of 200 000 m^3 of sediment between 1958 and 1988. Extrapolation of the slope distribution through time suggests that the frequency of an episodic landform change model at Black Ven may be approximately 60 years.

KEY WORDS dynamic equilibrium; photogrammetry; DEMs; archival photographs

INTRODUCTION

An important aspect of modern geomorphological research is to examine, in time and space, the degrees of adjustment of landforms to processes. The importance of this subject relates to the application of a systems theory framework based on the general laws of thermodynamics (e.g. Defay, 1929; Bertalanffy, 1932, 1950, 1956). In geomorphology it dates from the keynote papers of Gilbert (1877, 1886, 1890, 1909) and those stimulated by him.

A crucial point in all these papers is the recognition (assumption?) of the interdependence of the components of the system at all scales. Form and process are considered to be so adjusted that the effect of a change in any part, process or control of the system will be transmitted throughout the system by complex feedback mechanisms. It is further assumed that these adjustments towards equilibrium of forces are dynamic and are reflected in the maintenance of steady state processes and characteristic forms. It also follows that any impulse sufficient to initiate landform change is therefore followed by a period of process

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variation, form adjustment and, as a new state is achieved, by a new stationary process and form distribution, (Brunsden and Thornes, 1979; Brunsden, 180, 1990).

Most authors would follow Chorley *et al.* (1984) in listing four geomorphological manifestations of equilibrium: the statistical stability of form, the correlation of form and process, a balance over time in the sediment budget, and a balance of energy over space. These are discussed below.

(1) A statistical stability of form in which, for a given set of controlling conditions of lithology, soils, vegetation and climate etc., the morphometric variables cluster around characteristic values. This yields a regular repetitive geometric form and an essential unity of landscape. If the system is very active then this unity might be expected to persist through time even though it is displaced in space and is thereby composed of new individuals. Any two samples drawn from the morphometric populations should yield similar statistical descriptions.

(2) A correlation of forms and processes, forms and forms is the common type of evidence that a steady state or a dynamic equilibrium may exist. The classic examples are stream channel and valley side slope angles, or stream discharge and channel morphometry which are capable of being intimately adjusted to one another. Attention focuses on the degree of coupling within the system for this permits the passage of impulses of change. The presence of shock absorbers, such as beaches or mobile gravel beds, or the passive resistance of the system provided by rock strength are important, as are the number and efficiency of the pathways of change (e.g. joints).

(3) A balance over time in the sediment budget. In this concept the steady state of processes may determine (require) that the rate of input equals the rate of output if form is to be maintained. The change in storage should also be reasonably low over time if the capacity of the system remains the same. If not, it may vary with the throughput rate to maintain the steady condition. Under these conditions the essential measure is the volume of the sediment in the system which may remain constant even though the form fluctuates about a mean value. The summer–winter equilibrium beach or dune profile represents a classic example.

(4) A balance over space may be necessary to maintain a uniformity of energy expenditure or work. The idea of a 'graded' stream having a continuity of work so that in each part it provides just the velocity required to transport the load supplied from upstream is a common statement (Mackin, 1948). An obvious implication of this is that what comes into the system from above cascades through the system to allow a similar volume to leave the exit. If this does not occur then net erosion or deposition must be occurring within the system with a necessary change in form.

Additions to these ideas are the definition of geomorphological time in relation to the concept of formative events. Following Melton (1958), Wolman and Miller (1960), Thornes and Brunsden (1977), Wolman and Gerson (1978), Brunsden and Thornes (1979) and Brunsden (1985, 1990), geomorphological time can be usually described in terms of the frequencies of formative or process change events, reaction time, relaxation time, characteristic time, transience and sensitivity.

This challenging theoretical framework is now firmly entrenched as the quantitative dynamic geomorphology paradigm (Strahler, 1992). Despite this, progress in actually using the concepts in the field is largely restricted to fluvial and occasional hillslope morphology studies, where relatively simple relationships have been examined (Wolman, 1955). Few studies have actually demonstrated dynamic equilibrium or steady state in terms of the four requirements noted above. The most successful uses appear to be in the study of plan and profile equilibrium beach forms (e.g. Tanner, 1958) and in mathematical modelling, e.g. Ahnert (1967, 1987), Culling (1987, 1988) and Kirkby (1976, 1986).

In general, however, the demonstration of system adjustment, steady state or dynamic equilibrium in more complex systems has proved intractable. As long ago as 1970, Young defined the concepts and terms of the new geomorphology for hillslopes and found that the concepts of interdependence, adjustments between forms and processes and the description of open-system steady state were virtually untestable in the field for many process domains. Further, since they had not been satisfactorily demonstrated, by implication, they may not be valid or useful.

Fortunately, science has a habit of overcoming such problems by successful technical innovation. This paper describes one such technique–archival, three-dimensional analytical photogrammetry. The method is used to attempt to portray, perhaps for the first time, the adjustments that take place within a very complex dynamic mass movement system during 40 years of process at Black Ven, Dorset, U.K.

THE ARCHIVAL PHOTOGRAMMETRIC TECHNIQUE

A technique has been devised which enables precise spatial data to be derived from a wide variety of historical or archival photographs. The method, known as the 'archival photogrammetric technique', has important implications to geomorphology for two reasons. It allows the detailed and intricate morphology of a feature to be recorded for further computerized processing and manipulation. More importantly, these data represent the landform at the period of time when the photographs were originally acquired and are therefore precisely dated. Although there are problems if we attempt to infer mechanism or rate from incidental archival records which are only 'spot' pictures in time, they do allow the effects of geomorphological process to be measured and quantified over long periods of time. This obviates the need for such traditional geomorphological tricks as the use of ergodic transformations or, more correctly, space-time substitutions (Paine, 1985). The supply of dense, accurate and dated three-dimensional spatial data challenges the interpretive skills of the geomorphologist and earth scientist to re-examine the relationships between form and process.

The archival photogrammetric technique represents a development of conventional photogrammetry, made possible using computerized analytical methods. Many of the principles of analytical photogrammetry were established in the late 19th century and interestingly an early application included the morphological mapping of Alpine glaciers (Finsterwalder, 1897). It is however, the unleashing of the computational power of the modern computer which has really enabled such a development to become practicable.

Photogrammetric overview

Technical aspects of the method have been reported (Chandler, 1989) and published already (Chandler and Cooper, 1988, 1989) but a brief overview will be useful. There are two major problems that must be solved if archival photographs are to be used for accurate spatial measurement.

First, it is necessary to calibrate the camera used. In photogrammetry, it is necessary to know and understand the geometric properties of the camera used to obtain the photographs. Conventionally, photogrammetric cameras have been designed to fulfil certain geometric requirements and have undergone detailed calibration procedures to ascertain them. Photographs acquired with these expensive cameras are termed 'metric' because of such requirements. With archival material, camera calibration data are unlikely to be either available or completely known and can be regarded an non-metric photographs.

Second, control points are required. With any spatial measurement it is necessary to define a coordinate system and frequently in photogrammetry, a three-dimensional rectangular Cartesian coordinate system is used. Control points, visible on the photographs and with known coordinates, are used to define the ground coordinate system and to relate measurements made on the photographs to such a system. In the case of archival photographs, control points are unlikely to be available.

The archival photogrammetric technique overcomes these two problems by using a numerical photogrammetric procedure known as a self-calibrating bundle adjustment. This establishes, using least squares estimation, the relationship between the positions of a set of photographs and a ground coordinate system. This particular computational procedure offers several advantages. The solution is purely numerical, which avoids the optical and mechanical constraints enforced by traditional analogue photogrammetric instruments. The procedure includes a calibration of the camera, which resolves most of the geometric uncertainties associated with the original camera. The *in situ* calibration is achieved by extending the conventional functional model (Albertz and Kreiling, 1975; Ghosh, 1979) with a series of parameters to model the internal geometry of the camera. These include:

1. The *primary inner orientation parameters*, which model the displacement of the principal point relative to the reference marks and a correction to an approximate camera focal length.
2. *Lens distortion parameters* one, three, or five parameters of an even-powered polynomial used to model radial lens distortion, and optionally two parameters used to model tangential lens distortion.

The second main problem associated with archival photographs, the lack of surveyed control information in the object space, is overcome by two methods. A large-scale map can provide both plan and height control points; these data are included in the self-calibrating bundle adjustment with their comparative reliability controlled by their assigned standard deviations. Additional control can be provided in the form of measurements between points, (Wester-Ebbinghaus, 1985). These can include slope and horizontal distances, differences in height, and angles and azimuths between points. This form of control is important with archival photography because 'natural' measurements can be included. These can take a variety of forms, for example a zero height difference between a series of points defining a water boundary. If points are identifiable on the photography but not on the plan then measurements between these points can be obtained by a modern ground survey and included in the estimation.

If spatial comparisons are to be carried out between epochs then the same coordinate system must be defined for all estimations. The control points used at all epochs are derived from one Ordnance Survey (OS) plan and consequently the plan provides the definition of a datum. Providing that a common set of control points are used at all epochs, a datum is defined which can be regarded as sufficiently analogous.

The functional model used by the self-calibrating bundle adjustment is complemented by a full stochastic model in which the statistical properties of all data are combined in a rigorous way. The program estimates a series of parameters necessary to describe the relationship between measurements made on the photographs and a ground coordinate system. These are the positions and rotations of each photograph in three-dimensional space and a description of internal camera geometry.

Data extraction and processing

When a satisfactory estimation has been obtained, it is possible to extract the coordinates of new points anywhere on a site. The coordinate represent the basic data unit for all photogrammetrically based methods, and these can be combined to provide a variety of graphical and numerical data (see later). These new coordinates are derived from measurements taken from a pair of photographs and can be carried out using a stereo-comparator, but the procedure is far more effective if access to an analytical stereoplotter can be obtained. In this study, the Intergraph InterMap Analytic (IMA) photogrammetric workstation at the City University was used, which provides two methods of data extraction: (1) feature coding–delineation of boundaries, with lines of varying colours, line-type and thicknesses; and (2) digital elevation modelling (DEM) data collection–acquisition of a regular or grid DEM of varying size and density. Both of these programs enable high rates of data extraction, approaching 5000 coordinated points per day.

All acquired spatial data are stored on computer file in a form that can be analysed and displayed at a graphics workstation. A wide variety of data forms can be presented, suitable for many geomorphological requirements.

Technical limitations

Although the archival photogrammetric technique allows a much greater proportion of vertical, oblique and terrestrial photography to be considered of metrical value, there are certain limitations.

A minimum of two photographs must be available, acquired of the same object but from different positions. This should be regarded as an absolute minimum because additional photographs will yield a more precise calibration of the camera. The photographs must be taken at the same time, but not necessarily with the same camera. Only the original negatives or contact diapositives can be used, measurement of photographic prints would be considered generally too inaccurate to be of value. Finally, knowledge of analytical photogrammetry is required if the archival photogrammetric technique is to be used to obtain accurate spatial data. Experience is required to select suitable photographs, derive and measure relevant control points and to examine the results of the program. The procedures are non-trivial and take time and patience to use.

THE APPLICATION

The archival photogrammetric technique was developed and tested using a sequence of oblique and conventional aerial photographs of the Black Ven mudslide in Dorset. The Black Ven mudslide complex (Figures

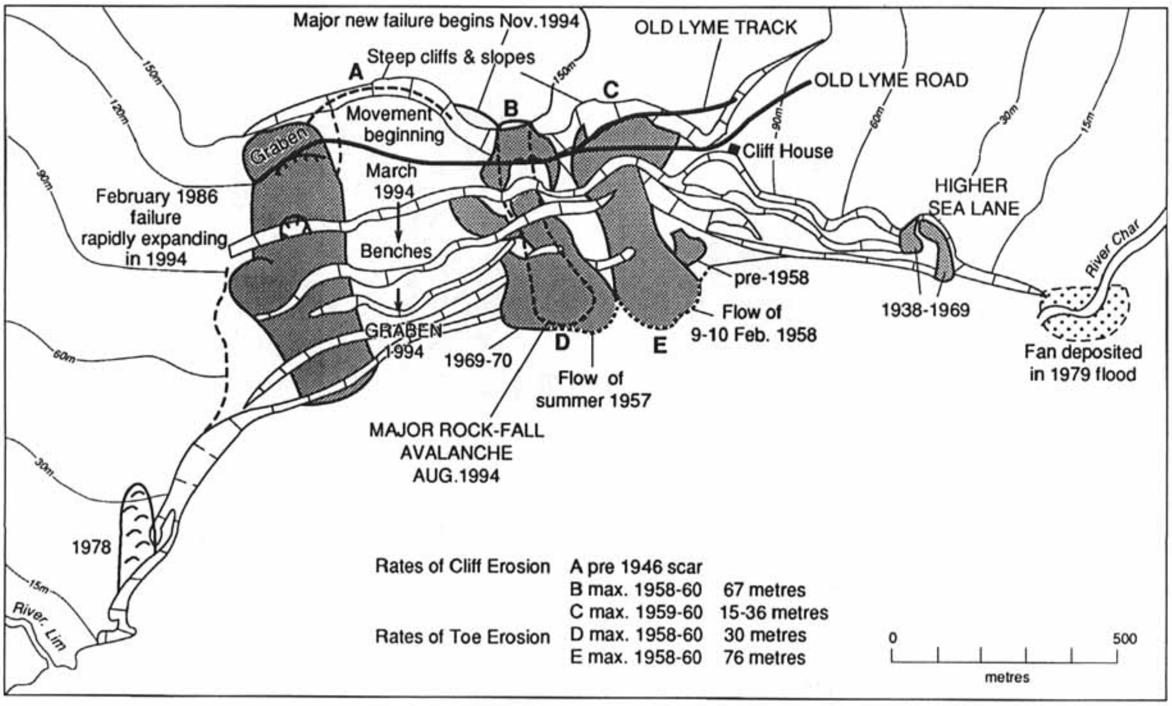

Figure 1. The Black Ven mudslide complex

1–6) is situated between Lyme Regis and Charmouth on the Dorset coast and consists of three distinct active mudslide sub-systems. The two main sub-systems possess the classic morphology of mudslides: a source region, a track, and a lobe or accumulation zone. The most eastern source region, which appears as a great amphitheatre-shaped hollow (OS Grid Ref. 357932), is Black Ven *sensu stricto*, whilst the area to the west is the Spittles. However, following Lang (1927), the whole section of cliffs between Charmouth and the Church Cliffs at Lyme Regis is commonly referred to as Black Ven. The name originates from the Dorset and Devon word ‘venn’ which refers to ‘fen’ or bog (Arber, 1941).

The geology

The cliff sections have always provided an important study area for geologists because the mudslides frequently reveal fossil specimens. Lang (1927) gives a detailed account of the stratigraphical succession. More recent geological work is contained within the Geological Survey Memoir, sheets 312 and 327 (Wilson *et al.*, 1958) and also in reports by Denness *et al.* (1975), Conway (1974) and House (1989).

The area is composed of alternating sequences of clays, mudstones and impure limestones of the Lower Jurassic (Lias), which are overlain unconformably by Cretaceous clays and sands. The stratigraphical succession is summarized in Table I.

The character of the sediments provides an important factor in controlling the general morphology of the site. There are several well developed terraces (Figures 2–6) at the base of the Upper Greensand, the Belemnite Marl and within the Black Ven Marls. These terraces are caused by the existence of resistant horizons within the Liassic sediments: for the upper terrace this is the Belemnite Marl, whilst for the lower terraces it is thin limestone bands. The Belemnite Marl and the mudstones in the Lias are also less permeable and impede the free passage of water. Pore-water pressures can be very high in sediments above these horizons and are a factor in promoting failure. The Upper Greensand, in the top 40 m of the section, is composed of the Foxmould with Chert Beds above. The latter are much harder than the underlying decalcified Foxmould sands and this has resulted in the development of a steep upper cliff (Conway, 1974).

The geological structure is a major controlling factor upon morphology and the potential for change. The

Figure 2. Aerial photograph for the 1946 epoch. (© Crown copyright/MOD)

Liassic beds dip approximately 2–3° in the SE/ESE direction, although the presence of gentle folds distorts this simple pattern, whilst the plane of the unconformity at the base of the Cretaceous dips 1–2° S/SSW (Conway, 1974). The strike of these two sedimentary groups is in a seaward direction, which produces a naturally unstable configuration.

Previous work

The mudslides at Black Ven have attracted considerable interest over the last century. Arber (1941) summarized events from as early as the beginning of the 19th century and provided a further review in 1973.

The development of the mudslide complex is graphically illustrated by Brunsden (1969), who used three vertical photographs to show the appearance of the mudslide in 1946, 1948 and 1958. Small differences are

Figure 3. Aerial photgraph for the 1958 epoch (Cambridge University Collection: © Crown copyright/MOD)

Figure 4. Aerial photograph for the 1969 epoch (Cambridge Univeristy Collection: copyright reserved)

Figure 5. Aerial photograph for the 1976 epoch (© Crown copyright)

noticeable between the 1946 and 1948 photographic epochs, but in the 1958 photographs the changes are much larger. The photographs were used to compile a geomorphological sketch map.

During the early 1970s the Institute of Geological Sciences carried out work in the area in an attempt to explain some of the mechanisms behind the movements (Dennes, 1972; Conway, 1974). Today these mechanisms can be interpreted in terms of the 'undrained loading hypothesis' of Hutchinson and Bhandari (1971).

From the literature it is possible to identify periods when morphological change has been greater than average. During the winter of 1957–58, a series of extensive failures occurred, resulting in two lobes of material extending 122 m into the sea (Brunsden, 1969). The remnants of these two lobes still remain,

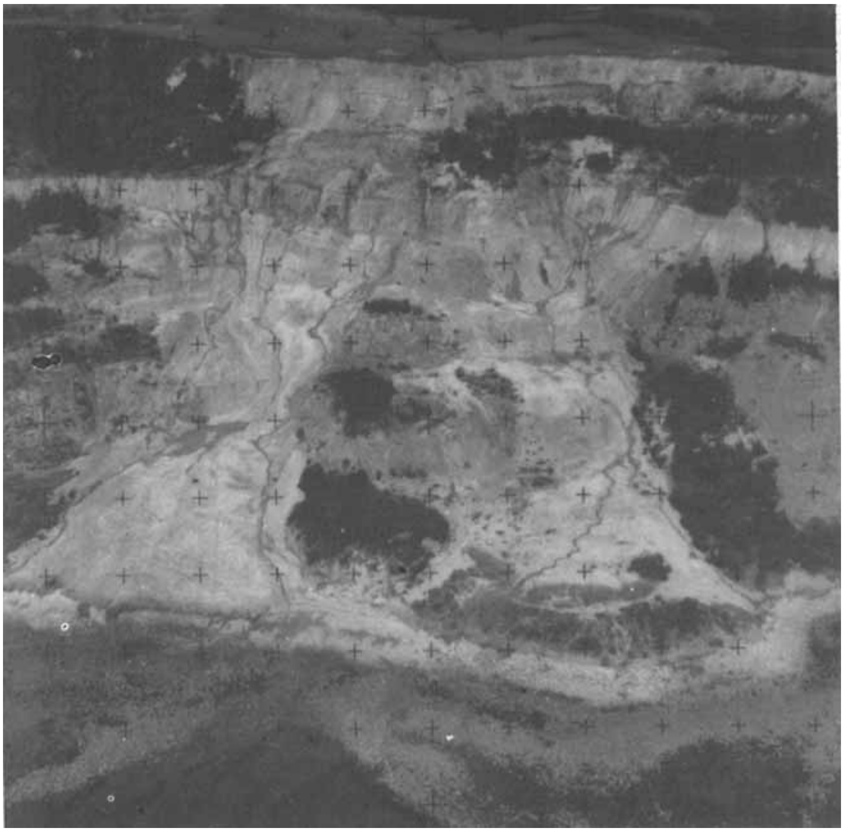

Figure 6. Aerial photograph for the 1988 epoch

although they have gradually receded as material has been eroded by the sea. The second phase of activity was not so dramatic but was marked by a general increase of morphological change between 1969 and 1971 (Brunsden, 1984). During this period, Arber (1973) reports the loss of several cliff paths and a wire fence enclosing the cliff-top golf links. Some of the later movements were summarized by Brunsden and Goudie (1981) and Chandler (1989). Koh (1990) discusses current monitoring experiments.

Photogrammetric restitution

A sequence of oblique and vertical aerial photographs of the site was obtained from a variety of archive sources and diapositives generated from the original negatives. The series began in 1946 and included epochs in 1958, 1969 and 1976 (Figures 2–6). The sequence was completed in January and June 1988 by hiring a light aircraft and using a hand-held Rolleimetric 6006 large format (60×60 mm) camera. All of the photographic material was processed successfully using the self-calibrating bundle adjustment. Control data were provided by the local Ordnance Survey 1:2500 map and zero height differences between points visible on well defined high water marks.

The stochastic model associated with the self-calibrating bundle adjustment gave an indication of the quality of the coordinates that were finally extracted. The standard deviations of the spatial coordinates of typical points of detail were of the order of ± 1 m, which was similar to the precision of the control coordinates that could be derived from the OS plan.

Re-measurement of the photographs, necessary to acquire new three-dimensional coordinates, was carried out using the IMA analytical plotter. Two distinct phases of data acquisition could be identified: feature coding and DEM data collection. The former entailed identification of important morphological

Table I. Geological formation of Black Ven (from Conway, 1974)

Period	Unit	Thickness (m)
Quaternary	Head Angular chert in sandy clay matrix	3
Lower Cretaceous	*Chert Beds* Broken chert beds in a firm coarse sandy clay matrix with some iron oxide cementation in lower part	7
(Upper Green-sand)	*Foxmould* Fine silty sand, lower 15 m shows patches of soft calcareous sandstone (Cowstone)	35
	Gault Soft, silty micaceous clay with some fine sand	7
	Unconformity	
Lower Jurassic	*Belemnite Marl* Hard well-jointed mudstones and marls	20
	Black Ven Marl Firm fissured clay with small nodules and thin bands of argillaceous limestone	35
	Shales-with-Beef Firm fissured clay with small nodules and thin bands of argillaceous limestone, together with fibrous calcite (beef)	20
	Blue Lias Alternations of thin bands of argillaceous limestone and firm clays	30

boundaries and classification according to a geomorphological coding system originally developed by Savigear (1965). Following identification, each feature was delineated and a series of three-dimensional coordinates digitized, which represented the feature. The features that were identified required approximately 8000 detail points to record at each epoch. The second phase of data acquisition made use of the DEM Data Collection software; this provided the ability to obtain a regular grid DEM or to measure directly any profile. The DEM that was subsequently measured consisted of a 10×15 m grid, which necessitated 3000 points to cover the area under investigation.

Data processing for geomorphology

The basic data unit acquired during feature coding and DEM data collection was simply a set of three-dimensional coordinates. The aim of geomorphic data processing was to find ways of using this basic unit to provide products which were of maximum benefit from a geomorphological context. Several processing options were investigated and it was found that the following graphical and numerical products were valuable.

Maps and plans. Delineation of boundaries between distinctive land units is a basic requirement in the production of both conventional and all types of geomorphological maps. In geomorphology, the identification and categorization of morphological boundaries is an initial stage in interpretation and understanding of form and process. Traditionally, geomorphological maps have been compiled by sketching detail onto a conventional large-scale base map (Savigear, 1965; Van Zuidam, 1986). The accurate definition and coding of geomorphological boundaries by rigorous photogrammetric techniques combines the benefits of geomorphological interpretation with positional relevance. Five geomorphological maps were produced,

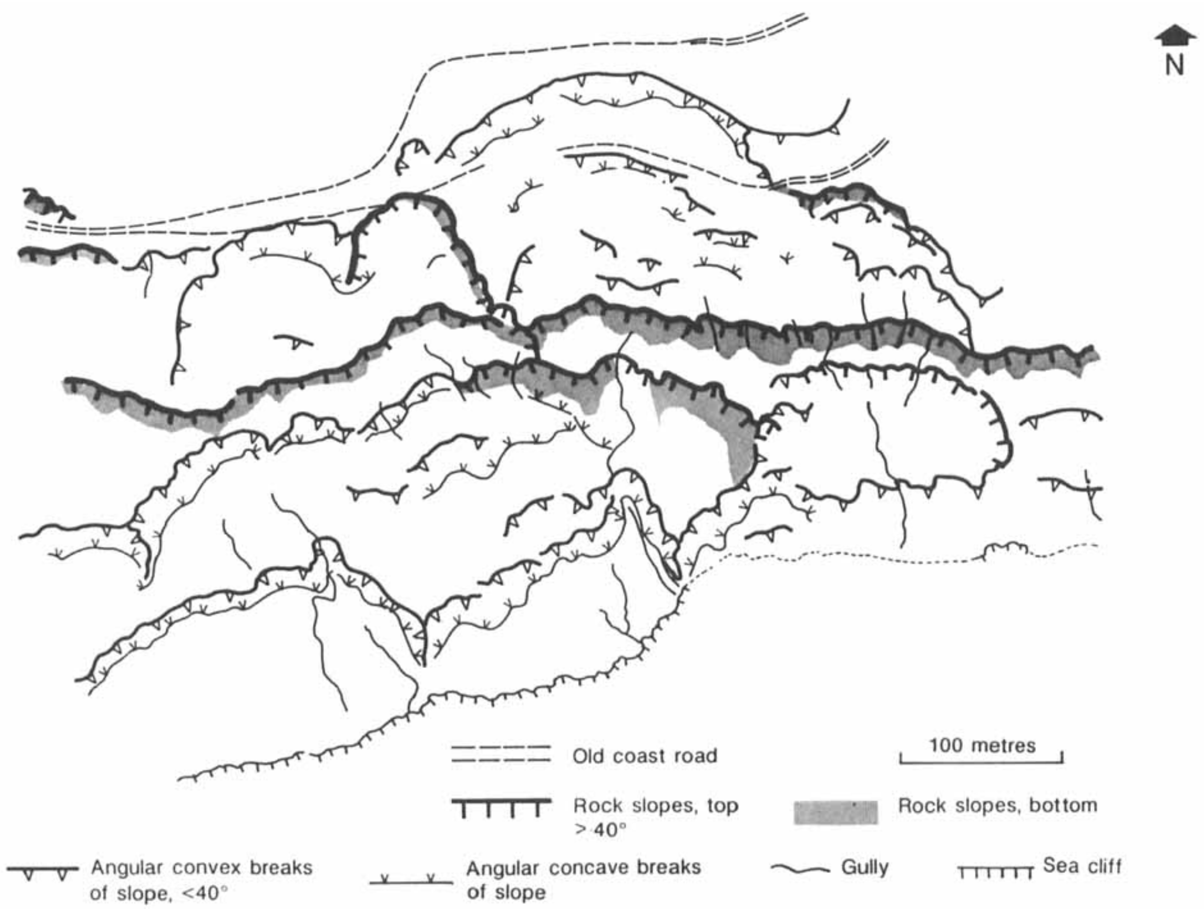

Figure 7. Example of a geomorphological map (much simplified) produced for the 1946 epoch

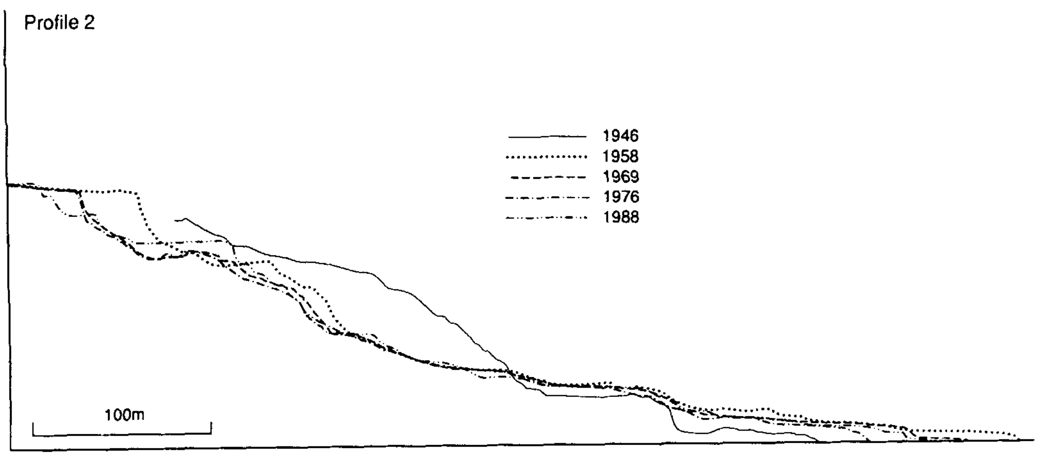

Figure 8. Slope profiles for each epoch on a central line for the mudslide. Note that it is possible to obtain profiles even for 20 m high vertical cliffs.

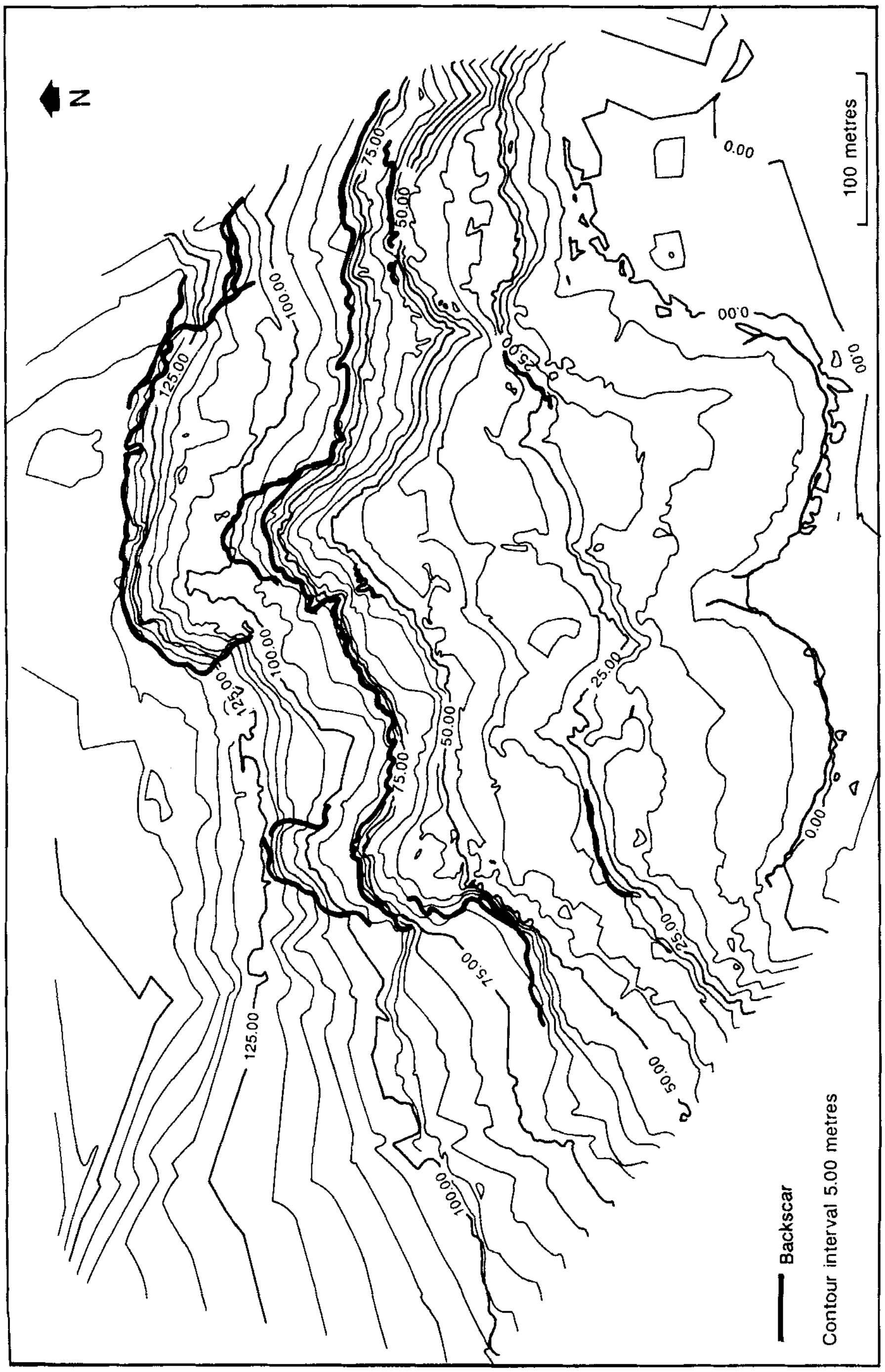

Figure 9. Example of contour plot producd from interpolation of the 11 000 point data set for 1958

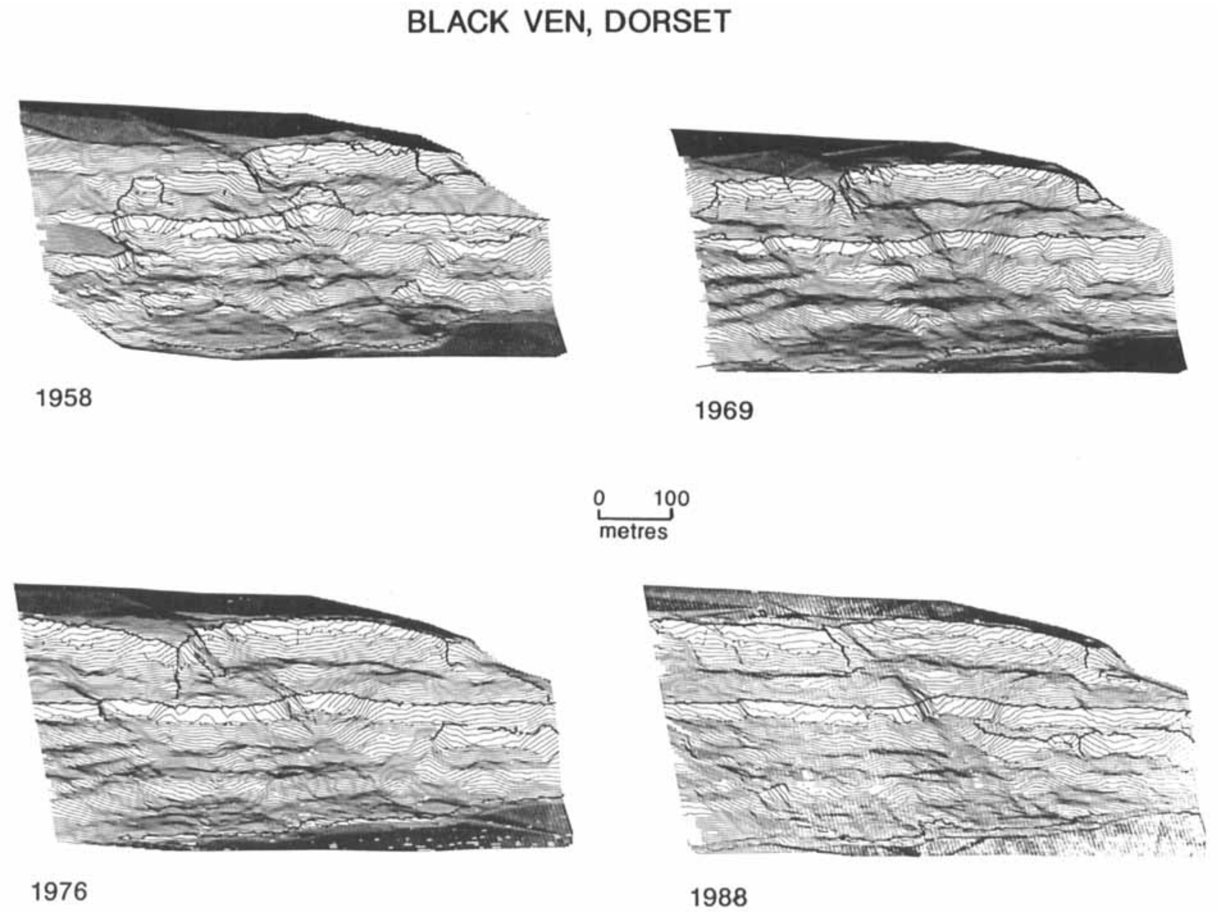

Figure 10. Isometric views for the various epochs showing how the system can give a clear visual three-dimensional image of landscape change

one for each epoch. These maps provide a basic planimetric description of the site at each date and some relevant morphometric data can be scaled from them (Figure 7).

The compilation of a single plot containing the same morphological boundaries at different epochs provides an additional tool that can be used to identify, quantify and interpret areas which display change. Such a morphogenetic study can be quantified by measuring the horizontal displacements of important morphological boundaries through time. This type of morphogenetic analysis was carried out for the Black Ven mudslide in order to establish process rates.

Direct profiles. Historical photography and the analytical plotter are ideal for obtaining both profiles and contours for several reasons. The measurement technique is 'non-contact' and retrospective and consequently any plane can be measured with a density of data points that is variable. In the analytical plotter, measurement of data is controlled by interactive software and ensures that only points lying on the desired profile or contour are collected. Provided that the density of data points is high, an accurate representation of shape or form of the ground surface along the plane of interest can be displayed. The observation procedure can be repeated for the same plane or along process vectors, but using photography from a different epoch. This enables quantitative morphogenetic comparisons to be made (Figure 8). Even totally inaccessible areas near vertical cliffs can be measured without recourse to arduous and dangerous slope profiling techniques on site.

DEM data processing geomorphometry. DEM techniques use three-dimensional data in order to provide

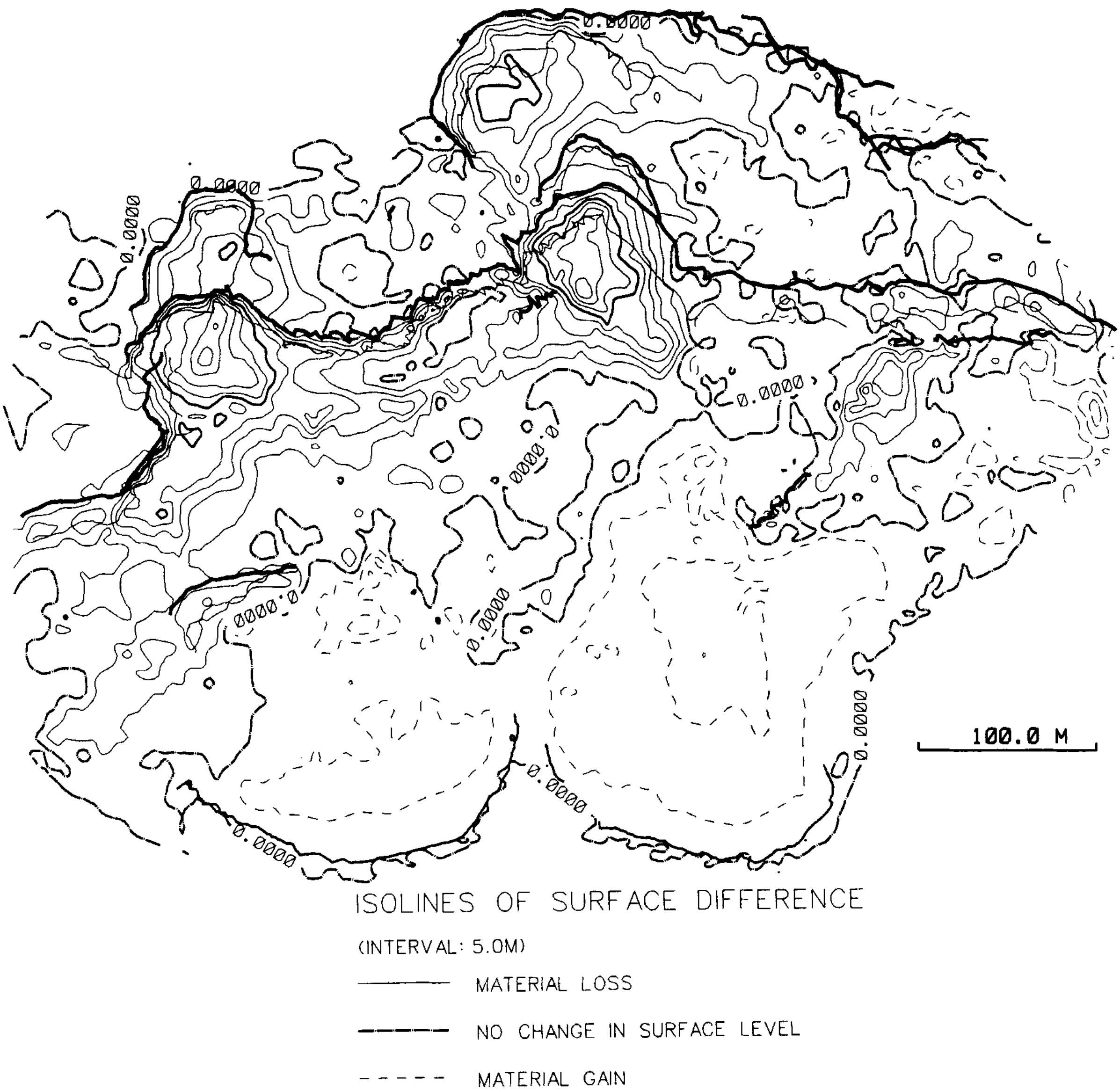

Figure 11. Contours of surface difference (i.e. erosion–deposition–no change) for the periods 1958–1946 (a), 1969–1958 (b), 1976–1969 (c), 1988–1976 (d). The period 1958–1946 (a) shows the location of erosion and deposition caused by the 1958 failures. This can be regarded as the reaction or 'event'. The interval between 1969 and 1958 (b) demonstrates continuing expansion of the erosion wave (diffusion), erosion of the toe but a very significant, no-change in the track (i.e. input equals output). The period 1976–1969 (c) continues the pattern experienced between 1969 and 1958 but will full relaxation achieved in the easternmost mudslide. Between 1988 and 1976 (d) slow adjustments continue in the east with input equalling output in both systems

either graphical or statistical forms of output. It is these techniques that really exploit the spatial quality of the photogrammetrically acquired data. A composite DEM was used for the more advanced DEM data processing and interpretation methods; this comprised both feature-coded data and regular DEM data combined.

(1) *Contour plots.* Contour plots can be produced by triangulating the DEM coordinates, so forming a faceted surface. For Black Ven, contour plots were produced at each epoch and these were overlain

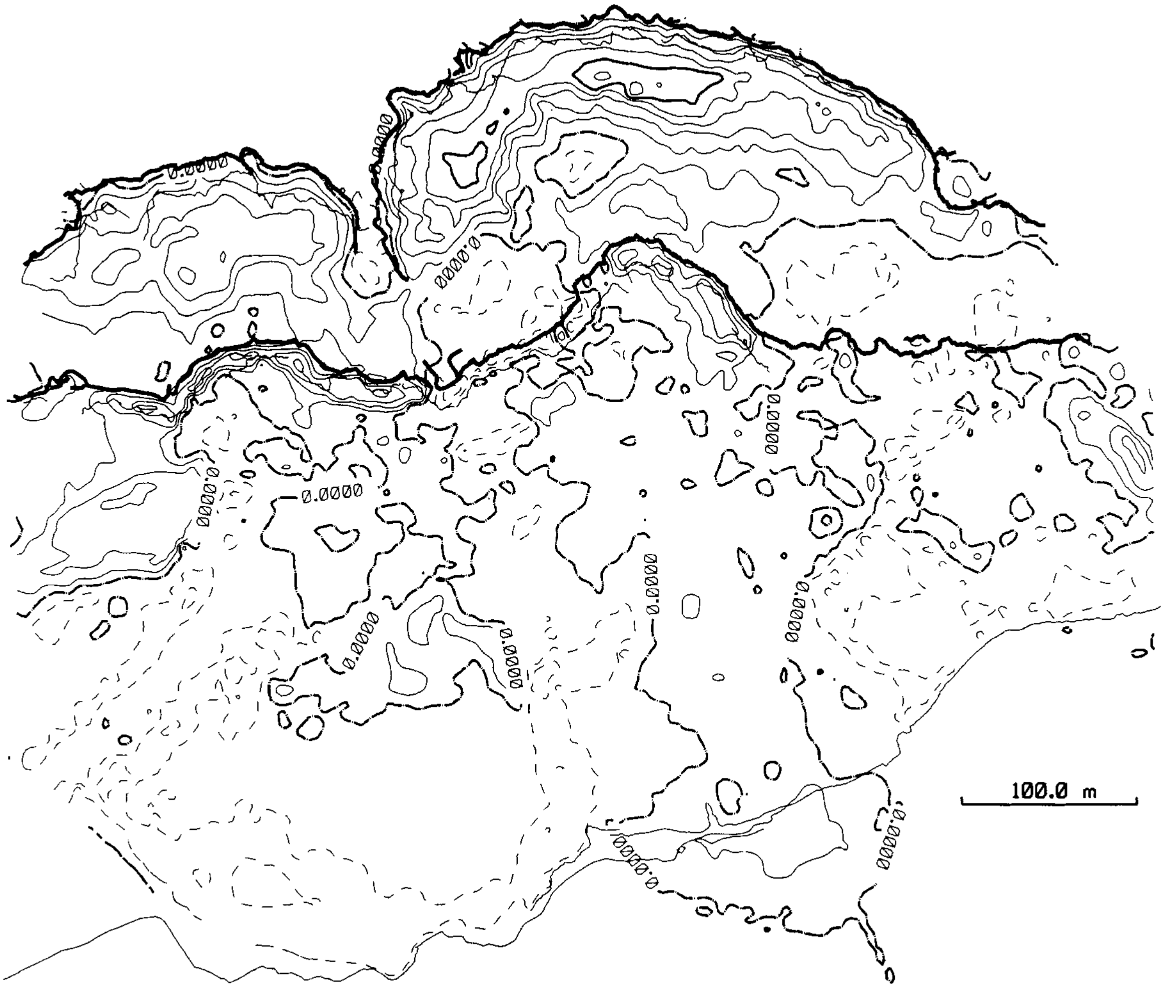

Figure 11b. Continued

with important morphological boundaries. The contoured plots give a reasonable representation of site morphology, indicating steep areas and breaks of slope. The addition of the major morphological boundaries was found to be important because this provides strong visual clues, essential to help identify particular locations (Figure 9).

(2) *Perspective and isometric views.* A grid file of varying density can be produced from the triangulated surface and this grid file forms the basis for more advanced processing. The grid can be used to produce perspective and isometric plots which provide a good representation of site morphology (Figure 10). The isometric plot can be useful if the site is unfamiliar because the surface can be viewed from any direction in space and at any scale.

(3) *Contours of surface difference.* Although contour plans provide a full description of site morphology at the different epochs, it is difficult to identify areas of change by mere visual inspection. One advanced technique consists of subtracting a grid surface at one epoch from a grid at an earlier epoch. This creates a grid surface which represents the change of form over the period defined by the photographs. The surface of change or 'DEM of difference' can be contoured and will quantify the effects of geomorphological processes (Figure 11a–d). Areas experiencing removal of material, and therefore at a lower elevation, will be indicated by troughs; areas receiving material and at greater altitude, by peaks. The interpreter must

Figure 11c. Continued

exercise caution because areas which appear to exhibit no change are not necessarily inactive regions. These can represent areas where the input of material has equalled output, over the defined period. This problem can only be resolved by consulting the contour plan with some understanding of the geomorphological processes. It is of obvious relevance to the geomorphological purpose of this paper, namely as a test of the steady-state criteria at Black Ven.

(4) *Slope maps/histograms.* The grid file can be used to create a grid file of slope angle, because slope gradient is the first vertical derivative of altitude (Evans, 1972). The slope grid can be used to derive slope maps and reliable histograms representing the distribution of slope angle.

The are two important advantages associated with histograms derived from spatial data acquired using the archival photogrammetric technique. First, a 'location-for-time' substitution is completely avoided; histograms can be produced at differing epochs and then combined to show how the distribution has actually changed with time. Second, a substantial number of coordinates can be used to derive the histograms, providing reliable distributions at each period in time. In the case of the Black Ven case study, histograms of the distribution of slope angle were derived, employing approximately 11 000 data points at each epoch (Figures 12a,b).

SPECULATIVE DISCUSSION

The archival photogrammetric technique yields a versatile representation of landform change. The visual

Figure 11d. Continued

impact is impressive and is enhanced by the fact that the images and maps are based upon a large number of accurate three-dimensional coordinates. Interpretation is still required by the geomorphologist and the following observations and speculations are offered for the Black Ven study. These suppositions illustrate the potential of the technique as an aid to hypothesis generation.

One view of geomorphological change is that landform change takes place when a state of process equilibrium and morphological stability is perturbed by an impulse of change of sufficient character to overcome the tolerance of the system (Brunsden and Thornes, 1979; Brunsden, 1985, 1990). The impulses may be 'preparatory' in that they predispose a system to change, and 'triggering' in that they actually step over a threshold which might only have been reached by the preparatory factor after a further period of time.

In the case of Black Ven there is evidence that the system was prepared for a new phase of mudsliding by the erosion and steepening of the cliffs (Figure 13a) to a mean angle in excess of 19°. In the discussion that follows, the pattern shown by the 1958–59 mudslides, namely a failure at or about a mean slope angle of 19°, is regarded as a failure threshold. This assumes that the actual occurrence in 1958 has a general significance. It is necessary to bear in mind that this value could change, depending on the unknown variability of the controlling variables. It is not known if there was a triggering factor, nor whether there were additional

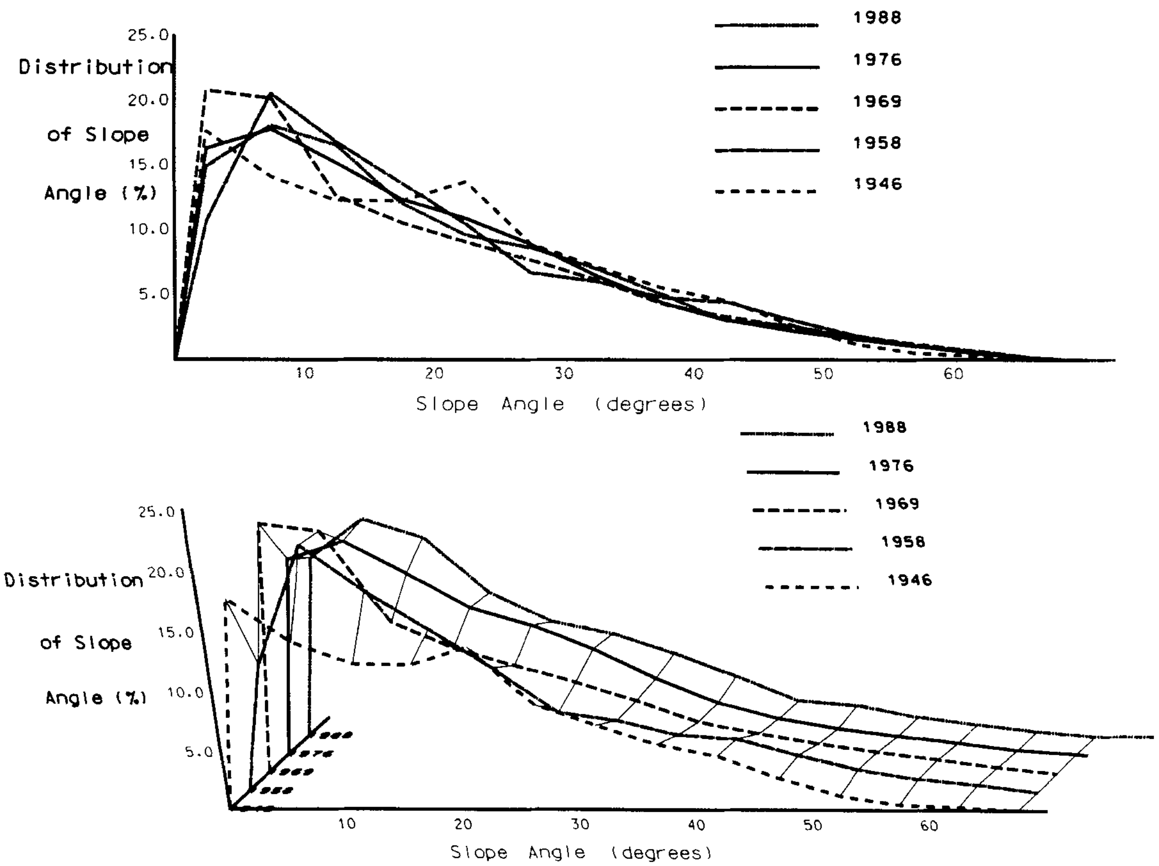

Figure 12. (a) Slope distributions, all epochs. (b) The initial form of 1946 is altered by an impulse of change in 1958. This episodic event is then followed by a short period of adjustment to a new characteristic but dynamic form

preparatory causes such as progressive weathering. It is known that the onset was sudden enough to actually trap a man on the beach. The 1958 data are therefore for the first epoch soon after failure, rather than the failure activity threshold angle itself.

Following this initial rapid movement, the cliffs adjusted by building lobes of mud into the sea, and over another 10 years, by diffusing the erosional wave upslope to form low-angle slopes on the upper benches. In this upper degradation system the form is maintained even though the whole complex moves inland by as much as 90 m. It is worth emphasizing that each slope histogram is derived from 11 000 new individuals (three-dimensional coordinates) in space and time and yet maintains a remarkable similarity. There is a change in the frequency of low-angle slopes between 1969 and 1988 because the accumulation lobes are being removed by the sea, but the degradation slopes are maintaining their form. The main processes involved are the cascades of material over the terraces, the parallel retreat of the undercliffs and the rapid transport of material away from the foot of the cliffs and across the benches by the mudslides. This is a good example of a retreating but unchanging slope form being maintained by an efficient basal removal condition.

The data suggest that following an impulse of change, the Black Ven system adjusts dynamically and searches for a new characteristic form. There is a rapid transmission of energy and material through the system and a remarkable interdependence of the slope–process components. The retreat of the cliffs and the total basal removal of each bench demonstrates almost perfect component coupling. The statistical stability, clustering of characteristic values over time and the repetitive geometric form, even though it is

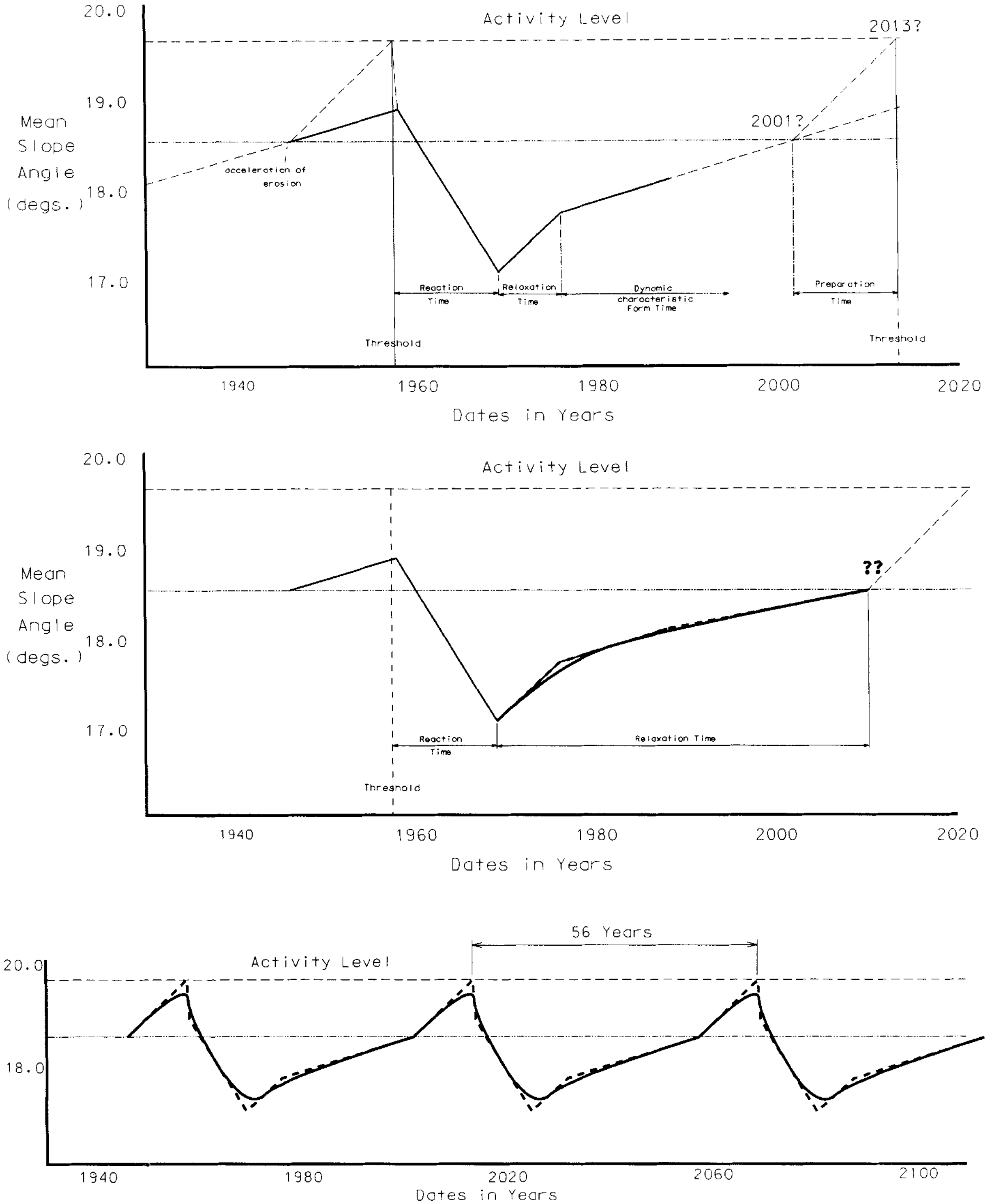

Figure 13. (a) Linear model of the Black Ven activity. (b) Exponential model of the Black Ven activity. (c) Speculation of the Black Ven activity over a 10^{-2} year time span

episodically displaced in space, appears to fulfil, over a 30 year period, most of the requirements of a system in steady state.

This opinion is supported by the extraordinary record of the DEMs of elevation difference between 1958 and 1988. These show that over 200 000 m^3 of sediment was transported from the cliff top to the sea through one of the mudslide systems (BD, Figure 1). The striking fact, however, is that after the initial phase of adjustment when the lobes accumulated, the elevations of the track and lobe remain similar even though they are receiving an input from the eroding slopes above. This can only mean that the input from the mudslide feeder bowl is transported through the system into the sea in such a manner that input equals the output.

The remaining questions concern the time scales of landform change. By manipulating the mean slope angles at all epochs in a computer-aided design system it is possible to produce projections of the mean slope angle into the future (Figures 13a–c). This can be used to set up a working hypothesis of the possible time adjustments required. The impulse of change or threshold activity crossing is followed by a rapid reduction of slope angles as the mudslides form and the seaward lobes accumulate. This was probably achieved early in the 1960s but the epoch interval (1958–1969) only permits a resolution of the reaction time to 11 years.

The system then relaxed over a further period of 7 years. This model thus suggests that it takes approximately 20 years to achieve the current form, which has itself now been maintained for 16 years (to present). The data suggest that for this period the elevations have changed very little, that input is close to output, and that, overall, the erosion volumes are diminishing. Nevertheless, the mean slope angle, based on 11 000 points and therefore not a trivial data set, does show a change from 17·7 to 18·1°. If this is significant it suggests that the characteristic form is a dynamic one of change at a constant rate. This would allow a linear projection and a prediction of the next major dynamic phase in *c.* 2016 AD, a frequency of *c.* 60 years. This may then be used as a basis of an episodic landform change model (Figure 13c) based on the marine erosion rate that prepares the system by steepening the slope angle.

The linear model is, however, almost certainly incorrect. The 1969, 1976 and 1988 data points (Figure 13b) are probably suggesting an exponential decay towards the threshold activity angle. In this case, the characteristic form has not yet been achieved, the relaxation time is in progress and a long period of slow slope degradation can be expected. The length of time before the next active phase will then be determined by the rate at which the accumulation lobe, plus any input from upslope, is removed and the cliffs steepened towards the threshold. Because of the unknown input to the lobes during this basal removal phase, this will no doubt prove to be an example of complex response!

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