THE ACQUISITION OF SPATIAL DATA FROM ARCHIVAL PHOTOGRAPHS AND THEIR APPLICATION TO GEOMORPHOLOGY

By

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Abstract

The acquisition of spatial data from archival photographs and their application to geomorphology

J.H. Chandler

This thesis discusses the development and application of an analytical photogrammetric technique which enables accurate spatial data, of known quality, to be derived from archival photographs. Such a facility represents an important advancement, particularly for geomorphologists, because the effects of geomorphological process can be assessed quantitatively and directly by comparing spatial data derived from photographs at different epochs.

Sources of archival photographs of England are identified and the type, quantity, range and age of each major collection is discussed. Existing methods of deriving spatial data from photographs are reviewed and illustrated by previous research, with particular emphasis upon the limitations associated with each method.

The technique that was developed is based upon a self-calibrating bundle adjustment and both the functional and stochastic models suitable for successful restitution of archival photographs were established. Five computer programs were developed and the algorithms associated with each are given. These programs are run sequentially and assist in rapid restitution of archival photography and to derive measures of data quality.

The technique is applied successfully to a forty year old sequence of archival photographs, obtained from a variety of sources, of the Black Ven landslide, Dorset, England. Spatial data was derived from five photographic epochs, at approximately 10 year intervals, using an analytical plotter. A secondary aim of the research was to extend existing techniques and devise new methods of processing these spatial data, for geomorphological purposes. Several techniques were found to be especially valuable including: the production of morpho-genetic maps; DTM's of difference; evolutionary models; animated sequences and distributions of slope angle. The latter has shown that the evolutionary model of 'dynamic equilibrium' is valid for the Black Ven landslides.

All aspects of data quality are examined, particularly the functional model used in the self-calibrating bundle adjustment. This least squares estimating procedure is found to be perfectly adequate for the successful restitution of archival photographs.

Notation

$f(x,l)$	Function of x parameters and l measurements
α	An angle of rotation In the context of statistical tests, α is the probability of a type I error; (equivalent to the significance level of the test)
β	Associated with statistical testing, β is the probability of a type II error; ((1-β) is equivalent to the power of the test)
δx, δy	Systematic errors
$\frac{\delta f}{\delta x}$	Partial differential coefficients of the function with respect to the estimated parameters
$\frac{\delta f}{\delta l}$	Partial differential coefficients of the function with respect to the measurements
θ, μ	A measured horizontal and vertical angle respectively
σ	Standard deviation of a random variable
σ^2	Variance of a random variable
ρ	Coefficient of correlation
J	Roe test statistic
Ω_0^u	Upper bound of measurement error
Γ	A scale factor
A	Coefficient matrix of observations (composed of partial derivatives of observations)
A^T	Transpose of matrix A
$\dot{A}$, $\ddot{A}$, $\dddot{A}$	Partitioned or sub-matrices of matrix A
Ar	An area
b	Vector of the ´observed minus computed´ terms
$\tilde{b}$	Vector representing the photo-base
b_x, b_y, b_z	Components of the photo-base
C	Covariance matrix
c	The camera constant, calibrated focal length or principal distance
D_t	A time increment
D_x	A distance increment
D_z	An increase in storage
dc	Correction to the focal length (c)
dx	Correction to x photo-coordinate
El	Mean change in elevation
$\mathbb{F}$	Fisher´s F distribution
f	Focal length

H	Flying height
H_0	The null hypothesis in statistical testing
H_1	The alternative hypothesis in statistical testing
h_i	Elevation of point i
I	The identity matrix
K_1, K_2, K_3	Coefficients of symmetric lens distortion
L_1, L_2 - L_{11}	Parameters of the direct linear transformation, (DLT)
l	A measured value
l_g	Dimension of a grid cell
l_s	Width of slit in a focal plane shutter
ni	Number of coordinates to be estimated
nm	Number of measurements
nm_0	Number of ground measurements
nm_p	Number of photo-coordinate measurements
np	Number of photographs
nu	Number of unknown parameters requiring estimation
Px, Py	Differential x and y comparator coordinates
P_1, P_2	Coefficients of asymmetric lens distortion
Q	Cofactor matrix
R	A rotation matrix
Rd	Radius of the earth
Rf	Refraction
r	Redundancy number, (equal to the number of degrees of freedom)
r_{ii}	Elements of a rotation matrix (R)
S	Photo-scale number
S_i	Sediment input
S_0	Sediment output
s	Radial distance
τ	The normal distribution
t_e	Exposure time
u	Velocity
$\tilde{V}_i$	Vectors in the object space
Vl	A volume
vl	a volume contained within one grid cell
v	A residual
W	Tau test statistic
W	Weight matrix, ($W = Q^{-1}$)
w, ø, k	Rotation angles around X, Y, Z axes, respectively
w_i	The tau test statistic, used for data snooping

χ	The chi-squared distribution
X, Y, Z	Object space coordinates
x^c, y^c	Corrected photo-coordinates
x_c, y_c	Comparator coordinates
x_i, y_i, z_i	Photo-coordinates- where $z_i = -c$
x_i', x_i''	x photo-coordinate of left and right hand photograph
x_m, y_m, z_m	Model space coordinates
X_0, Y_0, Z_0	Coordinates of the perspective centre
x_p, y_p	Displacement of the principal point
X_s, Y_s, Z_s	Three translations along the X, Y, Z axes, respectively
x	Vector of parameters to be estimated
$\hat{x}$	Vector of estimated values of parameters
$\dot{x}, \ddot{x}, \dddot{x}$	Partitioned vectors of parameters to be estimated

B:D	Base to distance ratio
CRAP	The Central Register of Aerial Photography
CRAPE	The Central Register of Aerial Photography of England
CU	Cambridge University Committee for Aerial Photographs
DLT	The direct linear transformation
DOE	The Department of the Environment
DTM	A digital terrain model
IMA	Intergraph InterMap Analytic analytical plotter
JARIC	The Joint Air Reconnaissance and Interpretation Centre
MAFF	The Ministry of Agriculture Fisheries and Food
NAPLIB	The National Association of Aerial Photographic Libraries
NCC	The Nature Conservancy Council
NERC	The Natural and Environmental Research Council
OMI	Ottico Meccanica Italiani
OS	The Ordnance Survey
PC	Personal computer
RAF	The Royal Air Force
RCHME	The Royal Commission on the Historical Monuments of England

Chapter 1

Introduction

1. Introduction

1.1 Definitions

The work of this thesis is inter-disciplinary and combines aspects of photogrammetry and geomorphology. Photogrammetry has been defined as:

> *'the art, science and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring and interpreting photographic images and patterns of electro-magnetic radiant energy and other phenomena'*, (Slama, 1980).

Geomorphology has been defined as:

> *' the science of the physical processes that shape the solid surface of the earth and the landforms created by them,'* (Machatschek, 1969).

By definition, the study of landforms is primarily concerned with the ground surface in three dimensions (Pitty, 1982). Photogrammetric techniques can provide the spatial data necessary to describe the ground surface and so the two sciences should be closely linked. Photogrammetric methods have been applied to geomorphological studies, (Section 1.4; 3.2) and this thesis attempts to extend this usage considerably, by tackling one of the main problems in contemporary geomorphology.

1.2 The Geomorphological Problem

The geomorphologist's main problem is that usually there is insufficient time to observe how landscapes evolve, (Paine, 1985) because geomorphological processes tend to operate slowly. Such observation would enable a more reliable determination of the rate of geomorphological processes and lead to a greater understanding of landform evolution. So far, geomorphologists have used three methods to circumvent this difficulty, (Paine, 1985). One is to build mathematical models based upon our present knowledge of processes and to extrapolate analytically or by numerical simulation. Another method is to model the landscape physically at a reduced scale, in which process rates can be controlled. The final approach is to assume that in the modern landscape we see landform at various stages of development and make inferences about changes through time based upon the variety of forms seen at present, (Paine, 1985). This latter approach uses aspects of an **ergodic transformation** or more correctly in this context a **space-time analogue**, (Thornes and Brunsden, 1977) or **location-for-time substitution**, (Paine, 1985). The method has been popular in geomorphology, (Savigear, 1952; Welch, 1970; Carson and Petley, 1970; Brunsden and Kesel, 1973) but relies upon two main assumptions: that processes and system structure identified today, also operated in the past; and that observed sequences reflect exclusively the passage of time and are attributable to no other cause.

1.3 Research Aims

This thesis attempts to add a fourth method of circumventing the geomorphological problem, without recourse to any assumptions, physical models or mathematical models of process. The ability to derive spatial data, of known quality, from a series of archival photographs would provide a direct method of measuring shape or **morphology** at the time of the photography. Measurements derived from a time based sequence of historical photographs would enable various stages of development of a landform to be reconstructed and to derive more reliable estimates of process rates.

Established photogrammetric techniques are available to use a certain proportion of the archive for photogrammetric measurement, but these are too restrictive and not universally applicable, (Section 1.4; 3.2). The main photogrammetric aim of this thesis was to develop a universal measurement technique that could be applied to a larger proportion of archival photographs than is possible using established photogrammetric methods. Such a technique has now been developed and is called the **archival photogrammetric**

technique. It is expected that this will be of considerable benefit not only to geomorphologists and other earth scientists but to planners, lawyers, historians and engineers.

The archival photogrammetric technique will also permit greater use of a threatened archive. Concern about the maintenance of photographic archives of the UK was expressed at a recent symposium on the Photogrammetric archives in the UK, organised by the Photogrammetric Society, (March, 1988). The UK archive is particularly valuable as it begins in 1919 (Section 2.2) and is comprehensive. One regular qualitative user of UK archive sources, estimates that for any site in England, there are nine available epochs of air-photo coverage, (Henry, 1988a). The symposium has since led to the formation of The National Association of Aerial Photographic Libraries, (Section 2.1). A similar organisation, the National Committee of Photographic Collections was also established by the Royal Photographic Society, (Section 2.1). The development of photogrammetric techniques suitable for measurement of this archive material will extend the value of the archive by increasing the number of potential users.

Photogrammetric techniques provide a particularly efficient method of acquiring three dimensional data of any subject. It was realised that if suitable photogrammetric techniques were developed, then geomorphologists could attain historical spatial data of an unusually high quantity and of known quality. A secondary geomorphological requirement of the research programme was to improve existing methods of data processing, and to develop possibly new methods, so that any data derived from archival photographs, could be put to maximum geomorphological benefit.

1.4 Other Related Work

The qualitative importance of historical photographs has been recognised in geomorphology and engineering. Thornes and Brunsden (1977) regard an historical photograph as an example of:

> *an incidental measurement, made at fixed time but without consideration of the frequency of observation required for the surveyed subject and often for a purpose other than that finally employed by the geomorphologist.*

Although there are problems of inferring process from a series of 'spot' pictures, Thornes and Brunsden (1977) realise that such material can yield the rate of operation of processes, providing constant process rates are assumed between epochs. Erb *et al* (1981) and Dumbleton (1983) recognize that historic air photographs provide site investigators with invaluable information regarding previous land use. Whimster, of the Royal Commission on the Historical Monuments of England, likens historic air photographs to '*a pictorial Domesday book, that records every home, factory, farm and field exactly as it was,*' (Harris, 1988). Providing that certain simple geometric requirements are fulfilled, historical photographs provide the only source of spatial data which shows features as they actually were.

Historical air photographs and photogrammetric techniques have been used to examine certain geomorphological problems. Petrie and Price (1966) use a sequence of vertical air photographs to measure ice wastage on an Alaskan glacier. A sequence of air photographs from 1945, 1960, 1961 and 1965 is used by Welch and Howarth (1968) to record the development of glacial features. El Ashry and Wanless (1967) use sequential vertical photographs to estimate the amount of sediment carried by longshore currents. These three examples all make use of conventional aerial photography and analogue photogrammetric methods. This approach requires near-vertical aerial photographs, acquired with a calibrated metric camera, (Section 3.2.3.1). These requirements limit the proportion of the archive that can be used for quantitative measurement because a significant proportion of the archive (Section 2.3) consists of oblique aerial photographs acquired with uncalibrated reconnaissance cameras.

Oblique aerial photographs have been employed in geomorphology and archaeology. Matthews and Clayton (1986) use an historical sequence of oblique photographs of a small mudslide on Stag Hill, Surrey. The authors are able to establish the sequence of slope failures over a forty year period and to compile geomorphological sketch maps. Kalaugher *et al* (1987) recognise the potential of the oblique image for assessment of cliff stability in Devon. Large scale high oblique photographs are used to compile geomorphological sketch maps using qualitative methods and newly flown photography. These two applications both make use of non-rigorous reconnaissance mapping methods (Section 3.2) which yield low quality results. Rigorous photogrammetric methods are employed by Fraser (1983) to monitor a potential landslide, at Turtle Mountain in America. Oblique aerial photographs are used but these are acquired with a calibrated camera and are not historical. In field archaeology, the qualitative interpretation of oblique aerial photographs has detected many new archaeological sites, (Hampton, 1975). Recent work by Smith (1987) has provided the Royal Commission for the Historical Monuments of England (RCHME) with the ability to compile precise maps from their unique collection of oblique archaeological photographs, using a Kern DSR1 analytical plotter.

The archival photogrammetric technique is based on computerised analytical procedures, primarily a self-calibrating bundle adjustment. The standard bundle adjustment was originally developed by Brown (1956, 1976), but further additions, including self-calibration have been made by Kenefick *et al* (1972); Ebner (1976); Faig (1975, 1976); and more recently Granshaw (1980, 1982) and Wester-Ebbinghaus (1985, 1986). Self-calibration enables the camera to be calibrated through the inclusion of additional parameters necessary to model the camera's internal geometry, (Section 4.3.2). The main application of this photogrammetric procedure has been the refinement of existing methods of analytical aerial triangulation (Ackermann *et al*, 1973; Ebner, 1976; Slama, 1980; Grün, 1982; Förstner, 1985).

The bundle adjustment is a flexible analytical procedure, and is used by Smith (1987) for use with archaeological photographs. Fortunately, Smith (1987) was able to obtain and calibrate the original aerial camera used by RCHME to acquire the photographs. In this thesis it was envisaged that either the original camera or the camera calibration certificate would be unavailable and with conventional photogrammetric methods this would preclude the use of such photography. By employing a self-calibrating version of the bundle adjustment, this particular problem could theoretically be solved. The technique would not need to rely upon calibration records and would be universally applicable to most sources of oblique, terrestrial and vertical photographs.

The research work associated with the development of the archival photogrammetric technique has been and is due to be published. Various aspects of the technique are discussed in two papers by Chandler and Cooper, (1988, 1989). The use of analytical photogrammetry for monitoring slope instability is reviewed also (Chandler *et al*, 1987; Chandler and Moore, 1989). Finally, various analytical photogrammetric procedures necessary for the restitution of contemporary oblique aerial small format photographs are reviewed, tested and compared, (Chandler *et al*, 1989).

1.5 Structure

The thesis is divided into nine main chapters or twelve sections, including the appendix, glossary and bibliography.

Chapter 2 describes the nature, size and extent of the sources of archival photography in England.

Chapter 3 reviews the existing methods of deriving spatial data from photographs, which can be applied to archival material. The methods are illustrated by examples derived from the literature and the limitations associated with each are indicated.

Chapter 4 introduces analytical photogrammetry and discusses the various analytical techniques that could be applied to measurement of archival photography. One method is applied and found to be unsuitable.

Chapter 5 provides an overview of the archival photogrammetric technique and the theoretical aspects of the various programs that were developed.

Chapter 6 introduces the case study that was selected to test the technique. The sequence of historical photography that was acquired is given and some of the problems associated with their restitution are discussed.

Chapter 7 reviews the various forms of data that can be acquired from historical photographs and these are illustrated by data acquired from the case study. Although the derivation of these data was not a primary aim of this research, the results proved to be of considerable geomorphological importance and are discussed further.

Chapter 8 looks at both photogrammetric and geomorphological data quality and examines the accuracy, precision and reliability of the technique and problems associated with interpretation. The functional model used for the restitution of archival photographs is also re-examined and found to be adequate.

Chapter 9 reviews the thesis and outlines the achievements of the research project. Possibilities for future research work are also suggested.

Section 10 is an appendix, which contains a table of the main holders of the archive of historical photography in England. Also included is the output from the various computer programs necessary for the restitution and analysis of archival photographs.

Section 11 provides a glossary of photogrammetric and geomorphological terms.

Section 12 contains a list of references and a bibliography.

One of the main problems with writing a thesis which is inter-disciplinary is that few readers of it will possess a detailed understanding of both disciplines. In an attempt to avoid this problem some explanatory details of both photogrammetry and geomorphology have been included. It is hoped that specialists in any one subject will tolerate the explanatory text pertaining to their discipline and that sufficient explanation is available to appreciate the unfamiliar subject. The glossary (Section 11) will assist with the understanding of unaccustomed terms.

Chapter 2

The Aerial Photographic Archive Of England

2. The Aerial Photographic Archive of England

2.1 An Introduction to the Archive

The fundamental requirement of any photogrammetric project is a photographic image that can be measured. Unlike conventional photogrammetric methods, the archival photogrammetric technique relies upon existing and probably valuable photographic material. This poses a unique range of problems, of which the acquisition of suitable imagery, both at the required location and taken at a suitable time, is the most problematical. The photographic archive is the only data source and must be accessed by the user of the archival photogrammetric technique.

In this thesis the term photographic archive will be used to refer to all sources of aerial photography of England. The size of this archive is considerable and estimates of the exact size vary. Hampton (1975) estimates that 1.7 million vertical photographs of England were in existence in 1975. Although the archive was increasing by approximately 30,000 photographs each year, (Hampton, 1975) this statistic is today (1989) rather low. An estimate derived from major sources reviewed in this thesis (Section 2.3; 10.1.1) indicates that a figure of 6.2 million is a more realistic figure, (Table 2.1). To this total must be added the 1.3 million oblique aerial photographs which have been catalogued and can now be of quantitative use with the archival photogrammetric technique. Considerably more un-registered and unorganised collections exist for which no statistics exist.

Until recently, the importance of these archive sources has only been partially recognised. Many commercial organisations have simply destroyed their old and 'redundant' photography. Despite this, some learned societies are beginning to recognise the true value of the historical image. The Photogrammetric Society held a one day symposium on the 'Photogrammetric Archives in the United Kingdom', in March 1988. This has since lead to the establishment of the National Association of Aerial Photographic Libraries (NAPLIB), whose function will be to promote and coordinate activities between aerial archive sources. The much larger task of supporting all other forms of photographs, including terrestrial, has been accepted by the Royal Photographic Society. This organisation has formed The National Committee of Photographic Collections and has published the *'Directory of British Photographic Collections'*, (Wall, 1977) which identifies many of the UK sources of aerial photographs.

The archive is distributed amongst numerous organisations of varying size and with differing scales of interest. These can be placed into four distinct categories, as shown in Table 2.1.

Table 2.1 The holders of the Archive (derived from Section 10.1.1)

Organisation	Scale	Approx. Nos. (million) Verticals	Obliques
1) Government Influenced sources	National	4.9	0.9
2) Commercial Companies	|	1.3	0.4
3) Museums/libraries	|	Unknown	
4) Individual Owners	Local	Unknown	

At the highest level are government influenced organisations such as the Ordnance Survey (OS) and the Royal Commission on the Historical Monuments of England (RCHME). These sources hold most of the archive, whilst the OS also holds and maintains the 'Central Register of Aerial Photography of England' (CRAPE). Beneath them in terms of scale of interest are individual survey companies and organisations which tend to obtain photography of specific locations when clients require. With the exception of Aerofilms, (Section 2.3.2) these survey companies acquire and retain almost exclusively, vertical survey format (230mm x 230mm) photographs which tend to be comparatively recent. At a local scale of interest are museums and libraries which have a concern for the local history of a region. These local sources can be very important in specific areas, but the usefulness of their photographs depends upon policies and interests of individual curators. Finally, at the lowest level of organisation is the individual or chance photograph that could be of very great use provided it can be traced.

It should be clear that the photographic archive of England is distributed amongst a variety of organisations. The aim of this chapter is to outline briefly the evolution of the archive; to identify the important organisations and the type of photography that each maintains; to outline the results of a recent questionnaire carried out by the Photogrammetric Society; and to discuss the nature and use of the archive.

2.2 Historical Perspectives

The origin of photography can be traced back to 1839 when Louis J.M. Daguerre invented a positive-image process for making portraits, (Avery and Berlin, 1985). The Daguerrotype was based upon light sensitising metal plates coated with silver iodide, (Wolf, 1983). The value of the aerial photograph was realised shortly afterwards. Colonel Laussedat was experimenting with balloon and kite mounted cameras as early as 1849, (Wolf, 1983). The photographic method quickly became established in England and numerous photographic studios were set up in London and at coastal resorts. Further developments continued in the following years, including the perfection of roll film in 1891, (Wolf, 1983) and the invention of the aeroplane by the Wright brothers in 1902 which provided the first reliable platform for acquiring air photographs. Twelve years later, the First World War provided a new impetus for development of both the airplane and film which culminated in the widespread use of aerial reconnaissance photography, (Avery and Berlin, 1985).

Commercial aerial photography began just after the cessation of hostilities with the establishment of the

Aerofilms Company in 1919, (Anon, 1965). This company originally concentrated upon oblique aerial photography but the potential of aerial mapping using vertical imagery eventually led to the development of the Hunting Air Survey Company. The Aerofilms section of the Company still exists today and with sixty years of photography, is an important component of the photographic archive, (Section 2.3.2).

The second World War again provided a powerful stimulus for the development of aerial photography. Aerial cameras had become larger and were precisely engineered for photogrammetric fidelity. The form of the present large format (230mm x 230mm) aerial camera used for photogrammetric mapping had also become established. The RAF again used reconnaissance photography for the identification of suitable targets and for evaluation of allied bombing. Perhaps of more relevance to the English archive is reconnaissance photography taken by the Germans.

The end of the second World War was an important phase in the history of the photographic archive. During the years 1945- 1948 a major program of aerial photography was carried out in the UK. This was undoubtedly due to the absence of any national photographic coverage necessary for the planning and redevelopment of the country. It was also due to the availability of under-used RAF squadrons prior to demobilisation. A variety of sorties were flown, but perhaps of key importance is the coverage at 1:28,000 scale, of the whole country, (Henry, 1988b).

The post war period also saw the establishment of all major organisations which now play an important role in the English photographic archive.

The Ordnance Survey was originally created in 1841, (Harley, 1975) but it was not until the Davidson Report in 1938 that the present organisational structure became established. The main function of the OS in 1945 was to satisfy the country's new mapping requirements at national and regional level. These requirements were filled by the acquisition of vertical air photographs and analogue photogrammetric techniques, (Section 3.2.3.1). A related organisation to the OS, the Directorate of Overseas Surveys aimed to fulfil a similar role in overseas countries, principally the old colonies, where British influence was still considerable. Rival commercial companies such as Hunting Air Survey Company, Clyde Surveys (previously Fairey Surveys), Meridian Airmaps and J.A. Story and Partners were also established to exploit this market. These companies also tried to find a position in the UK market in order to spread business interests away from unpredictable overseas regions.

The Cambridge University Committee for Aerial Photography was set in 1949 by J.K.B. St. Joseph, with the original aim of satisfying aerial photographic requirements of British academics, (St. Joseph, 1966; Hampton, 1975). The presence of redundant and therefore cheap aircraft and former RAF pilots was again a strong factor. The recording of archaeological features was of prime importance and oblique aerial photographs were acquired for this purpose.

In 1965 the Air Photography Unit of the National Monuments Record was established. This body was under the auspices of the Royal Commission on the Historical Monuments of England (RCHME). Its mandate was to build up a record of archaeological features and sites through the medium of oblique air photographs, (Hampton, 1975). This was a government subsidised organisation in which RCHME was able to catalogue and store photography acquired by sources in addition to their own programme of flying.

The Department of the Environment (DOE) provided a central coordinating body for aerial photographs at Prince Consort House, London. In 1970 the Central Register of Aerial Photography (CRAP) was established under their jurisdiction, (Henry, 1988b; Farrow, 1988). The aim of the register was to act as a clearing house, so enabling customers to identify suitable photography for their purposes and to obtain prints.

By 1975 the DOE was the largest single holder of aerial photographs in the UK with over two million photographs. These included RAF photography from the period 1940- 1960; 500,000 archaeological photographs; and some OS material prior to 1966, (Hampton, 1975). In 1982 there was a review of the existing organisation by the Government, known as the Rayner Scrutiny, (Farrow, 1988). This review recommended division of the collection. The RAF photography was transferred to the Joint Air Reconnaissance and Interpretation Centre (JARIC) at RAF Brampton. The archaeological photographs, known as the ´Specialist Collection´, went to RCHME. The remaining photography, including the central register, was given to the OS.

The OS itself was facing rationalisation and reorganisation in 1982 so the register was not finally taken on until 1984, when it was renamed the Central Register of Aerial Photography of England (CRAPE). The general format of the register is a series of flight diagrams that can be superimposed upon a 1:25,000 map. The supply of material for the register by other organisations has been entirely voluntary and so the quality varies greatly, (Farrow, 1988).

Since receipt of the Specialist Collection, RCHME have continued to acquire other material, including photographs acquired by Meridian Airmaps prior to liquidation in 1985. Important paper print collections have also been obtained, notably RAF photography between 1945-1964 and also OS prints between 1952-1984, (Whimster, 1988). A more recent acquisition is 250,000 RAF photographs taken between 1940-1945, (Harris, 1988).

The computerisation of the archive records has been an important issue over the last five years. It is apparent that to be effective any large collection must have an efficient system of storage and retrieval. The computer is ideally suited to this task, once suitable records have been entered into a database and efficient retrieval routines have become established. Both the OS and RCHME have considered computerising their records. The OS carried out a study in 1985 and concluded that it was not cost effective to computerise, (Farrow, 1988). The enquiring body felt that there was insufficient demand to justify the huge capital investment of transferring the records into digital form. The body did feel that computerisation may be worthwhile in the future, perhaps when optical disc technology had become established. In contrast, the RCHME carried out a similar review and decided to invoke a computerised system, (Whimster, 1988). The program of entering the records into the database began in 1985 using the Mapdata digitising system. A major financial saving was gained by the use of the Manpower Services Commission scheme, which provided cheap labour for this slow and otherwise expensive task. The stored information consists of the geographic coordinates of the flight lines, the photo-scale, date and copyright. The process continues and presently details of 750,000 photographs are stored on the database, (Harris, 1988). The other important component of a computerised system, data retrieval went into operation in February 1987. The retrieval system is based upon the PHOTONET system developed by T.Waugh at Edinburgh University and makes use of both the ORACLE database and GIMMS software package, (Waugh, 1988; Harris, 1988). The search routines are very powerful and enable searches to be carried out by a variety of ways, (Waugh, 1988).

As this brief historical review shows the major holders of photography in England are the OS, the RAF and RCHME. Other important sources are the University of Cambridge Committee for Aerial Photography and some of the commercial companies such as Aerofilms and Clyde Surveys. Important registers exist at CRAPE at the Ordnance Survey and RCHME. The latter is computerised.

2.3 The Distribution of the Archive

The classification of the archive into four levels of organisation (Table 2.1) will serve as a useful framework for describing each organisation. Section 10.1.1 provides a tabular summary.

2.3.1 Government Influenced Sources

The Ordnance Survey (OS) is based in Southampton and is the national mapping organisation for England, Scotland and Wales. Its principal role is the maintenance of national mapping and all map related products, ranging from motoring atlases to digital tapes representing an OS 1:1,250 sheet. The source of most of these products is vertical aerial photography originally flown by the OS. Many of these photographs were acquired for re-compilation of the old 'County Series' maps produced originally in the 19th century. The OS holds 4,900 rolls of aerial film, which cover a large proportion of the UK since 1950, principally at scales of 1:7,500, 1:25,000 and 1:50,000, (McKay, 1988a).

The OS is also the official holder of the Central Register of Aerial Photography of England (CRAPE). The aim of this central register is to enable a single body to maintain records of all aerial photographs that are taken in England, so that users need only make enquiries to this one organisation. The register contains details of over 20,000 sorties relating to all post war photography taken by the RAF; all photography taken by the OS since 1951, and a high proportion of commercial company coverage since 1961, (Farrow, 1988). Unfortunately, there has been no legislation to enforce commercial companies to register their photography. The form and type of records that have been supplied have not been standardised either. Consequently, the record is not comprehensive and the quality does vary. The register is actually held on a series of 'flight diagrams', these being either simple film, paper or microfiche map overlays which show the approximate position of the aerial photographs. The register is not computerised and so all searches must be carried out manually. CRAPE receives approximately 2,500 telephone and 1,200 written requests for searches each year and estimates that a search takes between two and four days, (Farrow, 1988). The client should be supplied with a list of the holders of relevant photography, with dates, scales and possibly an extract of a flight index diagram. In practice the OS only report its own air-photo cover and gives the addresses of other possible sources, (Henry, 1988b). No charge is made for the search, although 45% of the inquiries lead to the purchase of prints, whilst only 10% of the enquiries cannot be assisted, (Farrow, 1988). There is presently no facility to visit CRAPE in Southampton to view prints.

The Royal Commission on the Historic Monuments of England (RCHME) is funded by the Government to survey and record historical buildings and archaeological sites. The Air Photographs Unit of the National Monuments Record is a section within this Commission. The unit was originally set up to serve as a national centre for air photographs taken for archaeological purposes. This function has broadened as the collection and organisation has grown. Presently its 'National Library of Air Photographs' contains more than four million photographs, (Harris, 1988).

The library is housed in two locations; currently the organisational and administrative centre is at Fortress House, London where the 'Specialist' and 'Crawford' collections are held. The other site is Acton where the RAF and other photography is stored. The Specialist Collection consists of 500,000 low flying oblique aerial photographs which record archaeological features such as soil and crop marks, (Whimster, 1988). The Crawford Collection consists of photographs taken by Crawford, the first archaeological officer of the OS, prior to 1945. The Acton site keeps paper prints of RAF photography taken between 1940 and 1960 at scales between 1:25,000 and 1:30,000. This is a large collection, with approximately 2.5 million prints of predominantly vertical photographs. The Acton site also houses 0.5 million prints of OS photography taken between 1952 and 1982 at a scale of 1:7,500. Finally, Acton holds 0.5 million photographs and negatives taken by Meridian Airmaps, a company which went into liquidation in 1985, (Whimster, 1988).

A computerised indexing and retrieval system is operated at RCHME, although only the records of the Specialist Collection have been transferred into digital form. The search system is geographically based; a grid reference and optionally the required scale, date or other search parameters are given. The software then filters out unsuitable photography and presents the operator with a flight index map on the graphics terminal, (Waugh, 1988). The operator is then able to select the most relevant photography and can inform the client. The Royal Commission's National Library of Air Photographs is open to the public and photographs can be viewed there. All searches are carried out free of charge and both telephone and written enquiries are accepted. Searches are obviously rapid if the search is restricted to the Specialist Collection, but can take up to two weeks if other collections are accessed. There are plans to computerise all of the records, but this is a time consuming task and will take many years to complete.

The Royal Air Force (RAF) Film library is based at the Joint Air Reconnaissance and Interpretation Centre (JARIC) at RAF Brampton in Cambridgeshire. An extensive collection of aerial photographs covering the whole world is kept there. Statistics regarding English aerial cover are difficult to obtain (Hollin, 1986) but JARIC certainly retain many important national collections. Most importantly, the original negatives of all RAF photography, from which contact diapositives can be made, are held there. This is important as either the original negatives or contact diapositives should be used in association with the archival photogrammetric technique. Several important collections have been identified, from a source that asked not to be quoted.

Firstly, there are the aerial photographic projects that resulted in national coverage. These were flown in 1948 at a scale of 1:28,000; 1969 at 1:60,000 and finally 1980 at 1:50,000. There are also negatives from which the RCHME's RAF collection of 2.5 million prints originated. These date between 1940 and 1960 and so there is some duplication with the 1948 national coverage. Finally there are some large scale negatives of the whole of London taken in 1966 and 1971 at scales of 1:10,000 and 1:5,000 respectively. Other collections undoubtedly exist.

A partially computerised index and search system is in operation, perhaps similar to the RCHME system. Cover searches are carried out for the general public, but this takes several weeks and there is also a charge made for this service (presently £5.00: Longhurst, 1988). Prints and diapositives can be made from existing negatives but there are no facilities for viewing at JARIC.

The Cambridge University Collection has developed after forty years of aerial photographic sorties. There are close links with the University and research has been the main impetus for many of the photographs. An additional area of interest has been aerial archaeology and there are also links between the University Collection and RCHME. The University owns its own aircraft and does obtain aerial photography for clients on a commercial basis, (O'Donnell, 1987). The collection consists of over 400,000 aerial photographs and negatives, most of which are small format (130mm x 130mm) obliques taken with a Williamson F-24 reconnaissance type camera, (Darrell, 1988). A manual card index system assists retrieval of suitable photography. This allows searches to be undertaken by either subject matter or by place name. The collection has not been classified according to the national grid, and is not strictly geographical. Both postal and telephone enquiries are welcome and no charge is made for a cover search. If suitable photography is found then photocopies of the prints are sent to the client. This helps a decision to be made on the relevance of any particular photograph, and is useful and especially important with oblique imagery. Members of the public are encouraged to visit the library and as prints of all of the photography are held there, the results of a cover search can be viewed immediately. Full reprographic facilities are available so that prints, slides and most importantly contact diapositives can be produced from the originals, (O'Donnell, 1987).

The County Councils and many of the larger Metropolitan District Councils are important commissioners of vertical air photography in England, (Wright, 1973). Local Government requires this type of photography for regional development and land use planning. Photographic scales vary, depending upon the areas concerned and the purpose of the surveys. Common scales are 1:10,000 for the County Councils and 1:5,000 for the Metropolitan Councils. Photography is re-flown periodically, often every five years, depending upon the council and development in the region. The photography is generally obtained by one of the commercial air survey companies and this type of work generates a significant proportion of their annual workload. Although Councils own the copyright and usually hold prints, they rarely keep the original negatives, (Browning, 1986). This is due to the peculiar legal attributes of a photograph. By law, the person or body who commissions and pays for any photograph owns the image and its copyright. However, the person or body who actually obtains the image, on behalf of the client, owns all materials used to produce the image, including the original negative, (Cox, 1988). For this reason, the commercial air survey company retains the negatives and is the data source for users of the archival photogrammetric technique. If photographs are provided by a survey company, permission should be sought from the original client. Permission is usually granted and is generally a polite formality, particularly in the case of local authorities, (Henry, 1988b).

The Air Photographs Unit at the Ministry of Agriculture Fisheries and Food (MAFF) has been in operation since 1965.

Since then it has collected 200,000 vertical aerial photographs of a wide range of UK sites. The scales vary from 1:2,000 through to 1:25,000 although most are between 1:4,000 and 1:10,000, (Blakeman, 1986). The photographs that are taken are of a sensitive nature as they are used to check whether farmers are abusing UK and EEC farming regulations. This sensitive quality only lasts for the growing season and the air photo library is an attempt to increase the value of the photographs that have already been taken. A computerised indexing system is in operation and searches can be carried out. Recent photography is unobtainable for obvious reasons, (Blakeman, 1986).

The Nature Conservancy Council (NCC) is based in Peterborough and attempts to monitor and help preserve sensitive environments such as the Norfolk Broads, the Wash and Bridgewater Bay, (Fuller, 1986). The areas are predominantly coastal, inaccessible and cover significant areas. Aerial photographs have always provided an important tool for the monitoring of these vulnerable habitats, (Hubbard, 1973). Although some vertical and oblique aerial photographs are acquired by NCC, considerable use is made of existing vertical photographs flown by the RAF and the commercial sector, (Fuller, 1986). These original sources are preferable for use with the archival photogrammetric technique.

The Natural and Environmental Research Council (NERC) has run a program of airborne remote sensing since 1982. The principal aim is to satisfy academic requirements, especially those with an interest in forms of remote sensing other than just conventional air photography. Sensors carried by their aircraft include a multi-spectral and a infra-red line scanner, as well as standard vertical survey photography using panchromatic, colour and false colour infra-red film. The collection is partially in digital form and may become an important future archive. At present it is comparatively small, approximately sixty sites are flown each year.

2.3.2 The Commercial Sector

The organisations in the commercial sector can be categorised into two groups. First, there are those companies which are concerned with obtaining vertical, survey format (230mm x 230mm) photography for mapping purposes. These 'air survey' companies are comparatively large organisations, due to the large financial investments necessary for the purchase of photogrammetric equipment. Many own their own aircraft, tend to control all aspects of an air survey project and employ a wide variety of personnel such as: land surveyors, photogrammetrists, and cartographers. In order to support such a system these organisations operate nationally and internationally and have a multiplicity of functions in which air survey is merely one component. In contrast there are also a few commercial companies who supply oblique small format photography (130mm x 130mm; 60mm x 60mm) for illustrative and, so far non-quantitative purposes. These tend to be smaller organisations, perhaps consisting of one photographer, which charter aircraft and helicopters only when necessary. These companies are distributed throughout the country and tend to serve the requirements of a particular region.

The Aerofilms and Huntings Air Survey Company are an exception to these generalisations. Both companies were part of the same company group, Huntings Associated Industries and have always been associated. Aerofilms was originally set up in 1919 and was the first commercial aerial photography company in the world, (Anon, 1965). Mr P. Hunting acquired an interest in the company in 1939 and in 1945 re-organisation lead to the establishment of two companies, each with a different function. Aerofilms returned to its original role of concentrating upon acquiring oblique aerial photographs, whilst Huntings Air Surveys was established as an air survey company. Huntings Air Surveys developed into the largest air survey company in the UK, until in 1986 Huntings Associated Industries put the company into liquidation. The photographic records collected by Huntings

Air Surveys were transferred to Aerofilms and so Aerofilms now own a very important archive, both due to size and age. Statistics suggest that 400,000 black and white and 100,000 colour negatives are available, some almost seventy years old, (Evans and Evans, 1986).

The commercial importance of this archive has not been ignored and a library has been set up to promote and sell the photography in Borehamwood, Hertfordshire. Visitors are encouraged and photo cover searches are performed free of charge. Searches are carried out manually and there are presently no plans to automate this task. Results of the cover search include photocopies of prints, which are particularly useful for oblique aerial photographs. Full reprographic facilities are available at commercial rates, (Cox, 1988).

Fairey Surveys was originally established in India during the 1920's and is a commercial air and ground survey mapping organisation. The Company is based in Maidenhead and now trades under the name of Clyde Surveys. The bulk of its commercial work has been carried out overseas but it holds 287,000 black/white and 3,200 colour negatives of the UK, some of which should theoretically be almost thirty years old, (Anon, 1986). These are predominantly vertical, survey format (230mm x 230mm) photographs, which were originally taken for mapping purposes. A card index system is operated, based upon two files. The 'index of the UK sorties' is the most important and this contains the basic records of all of the photographic sorties such as the locality, scale, sortie number and client. The 'film register' is an index of the films currently stored and their location. Searches are carried out free of charge and there are facilities for producing prints and contact diapositives. A disturbing policy that was in operation in November 1986 was the destruction of the films over a certain age. This was being carried out in order to recover silver from the photographic emulsion, which could then be sold. This activity seems common within the commercial sector, (Anon, 1986).

J.A. Story and Partners is a commercial air and ground survey company based in Mitcham, London. The Company holds 250,000 vertical survey format photographs, (Browning, 1986). Although the collection only began in 1971 the archive is of interest because the photographs are mainly colour. J.A. Story and Partners has recently recognised the importance of its archive and has set up 'JAS Photographic Ltd' to promote and sell these historical colour photographs. A manual index system is operated and is based around the 'film index' and film reports. The former is similar to that in existence at Clyde Surveys and gives basic information such as scale and approximate location. Additional data such as the camera details and exact coverage has to be divulged from film reports.

Other commercial air survey companies are in existence, most being of a similar structure and nature to Clyde Surveys and J.A. Story and Partners. They are based in regions throughout the country and tend to serve the needs of local councils. Larger companies include:

Cartographical Services Ltd	Salisbury, Wiltshire.
B.K.S. Surveys Ltd	Coleraine, N.Ireland.
Engineering Surveys Ltd	W. Byfleet, London.
Mason Land Surveys Ltd	Dunfermline, Scotland.
Plowman Craven Associates	Harpenden, Herts.
Photarc Surveys Ltd	Wetherby, Yorkshire.

The other category of organisation in the commercial sector is the aerial photographic company, which tends to be smaller than commercial air survey organisations. The Aerofilms company is an exception to this generalisation and has been classified as an Air Survey Company.

Airviews is based at Manchester Airport and is one of the oldest air photographic companies. The organisation was established in 1947 and now holds approximately 50,000 black/white and 25,000 colour negatives, of a wide variety of urban and rural subjects. The photographs are mainly small format (130mm x 130mm; 60mm x 60mm) obliques. A card index system is in operation and cover searches are carried out free of charge. Copies are available for sale, (Wall, 1977).

West Air Photography is based in Weston-Super-Mare and became established in 1969. Its collection is composed entirely of small format oblique photographs; approximately 35,000 black/white and 8,000 colour. The company's main market is the illustration of travel brochures and articles, but industrial and archaeological subjects are included, mainly from the South West of England and Wales, (Evans and Evans, 1986).

Chorley and Handford Aerial Surveys Ltd was set up in Croydon, S. London to serve the London and south east region. Again oblique small format photography predominates and its collection provides a valuable record of the evolution of London since the war. This is best exemplified by its sequential coverage of the London Docklands region.

2.3.3 Museums and Libraries

In an assessment of the photographic archives of England the local sources should not be ignored. Local archives can contain material that is significantly older than that kept in the large national collections. If a site has generated considerable local interest, for natural reasons such as beauty and even geomorphic activity, then it is likely tc have been a popular subject for many generations of photographers. Much of this material is likely to be terrestrial or ground based photography, which has been taken with simple amateur cameras. In the past these would have been recognised as important only for qualitative purposes. Using the archival photogrammetric technique this source, although not ideal, can be used for quantitative measurement. The usability of random terrestrial photographs depends upon factors discussed in Section 5.1.1.

It is unnecessary to state individual sources of archival photography as these are site specific, but broad generalisations are possible. Undoubtedly the most important sources are local museums and libraries where sometimes collections of photographs are bequeathed by the public. The usability of this material depends greatly upon the Curator of such an establishment. The photographs can be catalogued and archived; merely stored and therefore effectively lost; or simply destroyed. Obviously the Curator must be selective and it is very difficult to assess the worth of historical photography, (Section 2.5). One of the main problems with this type of archive is that the original negatives will have often been lost or destroyed and only the prints remain. Such a print is possibly only of marginal use with the archival photogrammetric technique.

A more reliable source of photography, which can occasionally be used, is that kept by the photographer of a local paper. This form of archive may be comparatively recent, but should be more organised. The existence of suitable photography does depend upon the extent that the subject captures local interest.

2.3.4 The Chance Photograph

The chance photograph is perhaps the most elusive and exciting archive source. Over the last one hundred years literally millions of photographs have been taken of the English landscape. Only a fraction has been catalogued and archived and although many photographs have been destroyed, a large number must still remain. The optimistic researcher must work on the premise that the right photograph taken at the right time does probably exist, the only problem being to find it! Local museums and libraries are a good place to start a search as they will often know of the existence of people who have had both an interest in photography and local history. These people or their families can be contacted and are often appreciative of the interest in their work and experiences. Success can never be guaranteed but does depend upon the diligence and stubbornness of the researcher. The final requirement is luck!

2.4 The Photogrammetric Society's Questionnaire

Prior to the one day symposium on 'The Photogrammetric Archives in the UK', in March 1988, the Photogrammetric Society conducted a survey with the holders of the photogrammetric archive. The use of the term 'photogrammetric archive' is broadly similar to the term 'photographic archive' that has been used in this chapter. However, only those organisations that make use of conventional photogrammetric techniques were involved, (Section 3.2.3). Vertical imagery was of principal interest as it is this type of imagery for which mapping and quantitative potential is unequivocal.

The survey took the form of a three page questionnaire, with four main aims: to establish the approximate size of the photogrammetric archive; to identify types of photography archived; to see what supporting data are stored and finally to establish what indexing and organisational systems are in operation. The results of this questionnaire were briefly presented at the symposium (McKay, 1988a) and are due to be published in the Photogrammetric Record. Due to the relevance that these results bear to this thesis, the author was able to obtain the results, (McKay, 1988b). The response to a survey conducted by a learned society such as the Photogrammetric Society will always be greater than that conducted by a single interested research student.

The full questionnaire is reproduced in Section 10.1.2, but the ten main questions and some explanatory notes are summarised below:

1. **Does your organisation keep any archival photogrammetric material?**
2. **What type of material is stored?**

This includes the film and camera type: black/white or colour; metric/non metric or digital data from multi spectral scanners or satellites. Finally, the approximate size of the source, between specific ranges.

3. **What type of camera/sensor was used to generate the materials held?**

   Principally whether a metric or non-metric camera was used, and if the data is digital, the form of sensor.

4. **What supporting data and materials are held?**

   Whether camera calibration and photo-control information is held. This is an important question if conventional photogrammetry is to be carried out.

5. **Data Management?**

   This refers to the storage facilities and whether a computerised index and retrieval system is in operation.

6. **Do you have any facilities for reproducing your data for others?**

   Is it possible to supply clients with prints and diapositives?

7. **Charges for research and supply of information and/or materials?**

   Is the client charged for a cover search, and are charges levied for prints and diapositives?

8. **Do you advertise your archive?**

9. **Statistical data known on level of usage of data?**

   Are data kept on the number of transactions each year and are you prepared to give this information?

10. **Do you forward the details of newly acquired photographic/ sensor information to a central register?**

11. **Any further relevant comments you wish to make?**

The respondents to the questionnaire were prompted to give either a yes/no answer to sub questions under each of these main topics. They were also allowed to complete the questionnaire anonymously. The commercial companies are very competitive and it was felt that this approach would result in a high response rate. Exact statistics and details of individual sources are therefore impossible. This was done in order to obtain at least some information from the more secretive sources such as JARIC and MAFF.

Ninety questionnaires were sent, principally to the sources outlined earlier in this chapter. The only omissions were some of the commercial air photographic companies such as Airviews and West Air. The Photogrammetric Society was only concerned with the 'photogrammetric archive' and were mainly interested in vertical aerial photography. Of the ninety questionnaires that were sent out, fifty seven were returned. The complete results are summarised in the Section 10.1.3, but a review of the principal findings follows here.

Of the organisations who replied, 93% kept archival data of the UK. Most sources kept metric photography, rather than non metric, the ratio being 2:1. More collections consisted of prints rather than negatives, both for metric and non-metric photography. The ratio between black/white and colour was 3:2, closer than may be expected. Only 20% of the archives included digital data such as multi-spectral scanner, SPOT, and Landsat.

Unfortunately, the total size of the UK archive cannot be determined, but results suggest that there is in excess of 50,000 rolls of aerial film in existence. Assuming 240 photographs per film this is approximately 12 million photographs. This value is greater than the figure of 6.2 million mentioned in Table 2.1, but many of these films would hold considerably less than 240 photographs. The estimation is at least of the same order. The distribution of the archive is predictable, with perhaps three major organisations, the OS, the RAF and RCHME, holding most of the archive. The commercial air survey companies hold a smaller, but still significant proportion. Finally there are many small organisations who keep less than 100 rolls of film. The average percentage rate of increase in material was between 6% and 10% for film; 1% and 5% for prints. The distribution for rate of increase of digital tapes was bi-modal, most holders were not involved with digital imagery, whilst a few were increasing their stock at a rate of 20% per year.

In 40% of cases, the focal length of the metric aerial cameras used was 152mm. This is predictable as many air survey cameras are fitted with the all purpose 'wide angle' lens. The format size of non-metric cameras is more surprising as 35mm cameras appear as widespread as 70mm small format cameras. It should be remembered that the statistics refer to the number of organisations that make use of each type of camera, rather than the total number of photographs that are taken with each type. Finally, Landsat images form most of the multi-spectral archive.

In terms of the supporting data and materials held it appears that only 26% of users keep calibration data for the camera, although 38% keep ground control information. This seems surprising as both are necessary for conventional mapping. Only one organisation has a fully computerised index and retrieval system, although six were partially computerised.

Only 10% of the organisations who carry out cover searches, make a charge for the service. Most seem to recoup this loss with charges made for prints and diapositives. Only 58% of organisations sell photography, many replies came from local authorities who rarely hold original negatives.

Only 13% of the archive sources are active advertisers. Trade literature and hand-outs seem the most popular method of those that do, although professional journals, newsletters and direct mailing are also used.

Perhaps the most important question for the national archive and its usability, was whether details are forwarded to a central register. Only 30% of the sources presently forward details to some central body, presumably CRAPE. When asked about the future, 45% seemed willing to contribute although 49% decided not to comment. Only 5% stated that they would make no contribution, presumably for military reasons.

The questionnaire was a valuable exercise and has certainly awakened interest in the importance of the photographic archive. It is unfortunate that the questionnaire could not have been more specific and perhaps included all sources of aerial photography.

2.5 The Nature of the Archive

The preceding review described the main holders of the aerial photographic archive of England. The aim of this section is to discuss some of the issues and questions concerning the archive as a source of spatial data.

It is difficult to justify the maintenance of the photographic archive on purely financial terms. Despite this, it should be clear that the archive is of distinct national importance and should be maintained. The historical aerial image is the only true and accurate record of the landscape as it was at the time of photography, (Dumbleton, 1983). Whimster, of the RCHME, likens historical aerial photographs to *'a pictorial Domesday book that records every house, factory, farm and field exactly as it was'*, (Harris, 1988). Historical maps are of course valuable items, but the process of simplification and generalisation removes much of the original data. The aerial photograph retains all information and is a very efficient form of data storage which can now be accessed with the archival photogrammetric technique. Even if it was felt that historical photographs are not of sufficient value at present, we have a moral responsibility to maintain such a data source for future generations.

The proper storage of historical photographs is a specialised science and is very expensive. In order to ensure the longevity of a data storage medium that will eventually decay, it is necessary to consider both the 'general' and 'intimate' environment of the photographs, (Rumsey, 1988). The requirements of the general environment are stringent and are best provided by a purpose built storage area. In this the relative humidity should be kept between 35% and 40% with the temperature at approximately 10° Celsius. The storage area should be well ventilated and there should also be as little contamination from hydrocarbons and ultra violet light as possible. The intimate environment refers to the manner in which the negatives are stored within the general environment. PVC negative bags have been popular because they are convenient for viewing but these provide the worst intimate environment possible. The slow decomposition of the silver image releases gasses which if prevented from escaping accelerate decomposition. Paper negative bags should always be used, preferably constructed with edge seams joined by non-reactive glue. Collections of negatives should also be kept in chemically inert metal storage cabinets, these being mounted upon plinths in case of minor flooding, (Rumsey, 1988).

The life of negatives stored also depends upon the type of film base. Modern films, made from a polyester base, should have a 300 year life if stored in a carefully controlled environment. Older film bases are made from either cellulose nitrate or cellulose acetate. The former ceased production in 1950, is a fire hazard and decomposes. Cellulose acetate was first produced in 1920 and was originally dimensionally unstable and has always been brittle. The long term storage solution for these older materials is to produce contact copies on polyester based films. The 300 hundred year life may then be sufficient until other forms of storage, perhaps digital, are found.

The storage of film is obviously very expensive and demand for reprints is generally insufficient to justify the financial investment necessary for the specialised storage environments. As a result very few of the archive sources in England take full precautions. Commercial survey companies could be criticised the most but these companies need to operate at a profit and do not have financial support, unlike RCHME and the RAF.

It is very difficult to state the absolute value of an historical photograph, although relative comparisons are possible. Value also varies substantially with time. Initially the photograph is taken for a particular purpose, perhaps for a client who is prepared to pay a significant sum of money for its acquisition. Once the photograph has been used for this initial purpose its value is significantly reduced. Occasionally a third party may be prepared to pay a smaller sum for prints, but generally there follows a period of approximately thirty years in which the value of that photograph is very low. After this period the photographs are old enough to be considered truly historical, the value increases and the infrastructure necessary for maintenance and indexing can be justified in economic terms. The Aerofilms company is in this fortunate position due to its heritage. Many of the photographs held by the commercial companies are in the thirty year danger period. These photographs are generally neglected, even destroyed for the recovery of silver, (Anon, 1986). It is these photographs that will be the valuable images for future generations and must be protected.

2.6 The Use of The Archive

There are a variety of organisations and individuals who make use of the photographic archive. These may be insufficient to justify its maintenance on purely economic grounds, but the numbers are increasing. Perhaps with the archival photogrammetric technique these numbers will grow still further. Present users include civil engineering consultants, lawyers, archaeologists, historians, and a wide variety of earth scientists.

There are presently three civil engineering consultancies in the UK who regularly make use of the photographic archive, (Henry, 1988a). Historical photographs are used for qualitative geotechnical analyses of sites prior to construction. Potential problems owing to previous land use can be identified, such as slope instability and chemical pollution. The financial savings can be large and in some cases have been considerable, (Henry, 1988a).

Archaeologists have always recognised the potential of the oblique aerial image and this led directly to the establishment of the air photo unit at RCHME. The advantage to field archaeology has been the ability to detect patterns, known as crop marks, in dry soil. These are most apparent when the sun is low in the sky and shadows are long. This unique property can be efficiently recorded using oblique aerial photographs and a combination of views built up from differing seasons can be a powerful interpretative tool, (St Joseph, 1966).

A sequence of aerial photographs over many years provides historians and urban geographers with a unique record of land use change. This record is especially important in studies of urban growth since the second world war. The photograph is a far more efficient medium than the map as no subjective interpretation has occurred, (Dumbleton, 1983).

Geological air photo interpretation (API) is a distinct science within geology, (Allum, 1966). Geological structures and lineaments can be detected and interpreted far more efficiently than on the ground, although air photo interpretation alone can never replace field work. Interpretation is considerably enhanced by the use of stereopairs. The exaggerated third dimension allows the detection and appreciation of relief, which is often related to the underlying geological structure.

In geomorphology the value of the photographic archive has not been ignored. Brunsden (1969) uses historical photographs to illustrate the scale and nature of land sliding at Black Ven, Dorset. Even over the ten year period between these historical photographs, changes are large enough to be detected merely by visual comparison of the photographs. Other important work has been carried out by Petrie and Price (1966), Welch and Howarth (1968) and El Ashry and Wanless (1967), (Section 1.4).

There are undoubtedly many other individuals and organisations who make use of the archive in its present form. There is potential for even greater access and diversity in its use.

First time users of the photographic archive are often frustrated by the seeming complexity of the archive, once it is realised that it is fragmented between many sources. Many simply contact the Central Register believing that it holds records of all aerial photography of England, thereby losing a significant proportion of possibly relevant material. It may be useful to define suitable guidelines which may be useful when accessing this particular source of spatial data.

Initially the purpose for which the photographs are required should be established. If the photographs are required for photogrammetric measurement and only analogue photogrammetric instruments are available then vertical metric photography, camera calibration and ground control information are all required. Many commercial organisations levy additional charges for this information and these extra costs can be high. If the photographs are used for qualitative interpretation then obliques tend to be more useful for the inexperienced, (Matthews and Clayton, 1986) and are also more cost effective. Users of the archival photogrammetric technique can make use of obliques, verticals and possibly terrestrial photographs, with or without camera calibration and ground control. There is substantial photographic coverage of England, it has been estimated that at least nine separate photographic sorties exist for every location in the country, (Henry, 1988a, 1988b). A degree of choice is therefore available and users can decide upon an optimum photographic scale, or perhaps an optimum date, this again depending upon the purpose of the work. Finally the Ordnance Survey grid reference and the name of a local village and the county should be established.

The first organisations that should be contacted and asked to carry out a cover search are CRAPE at the Ordnance Survey, RCHME, University of Cambridge Committee for Aerial Photography, Aerofilms and JARIC, the latter only if there is no objection to paying a charge for the cover search. The Ordnance Survey grid reference and local name should be specified along with the desired date, approximate scale and type of photography that is desired. It is useful to request photocopies of prints, especially for oblique photographs, to establish exact coverage. The results of this initial search may be positive, and lead to further enquiries. If the initial search is unsuccessful then the regional air survey company and perhaps the local County Council should be contacted. Other sources may be traced by consulting publications which contain the details of various collections. Two possible directories are *'the directory of British photographic collections'* (Wall, 1977) and *'the picture researchers handbook'* (Evans and Evans, 1986). The local air photographic companies are also a final possibility. If photography prior to 1945 is required then the initial source of material has to be local museums. Writing to the museum can be useful initially, but there is no substitute for actually visiting and talking to the Curator.

The process of tracing historical photographs is slow. Cover searches take at least a week, despite the claims of many of the organisations. When suitable photographs have been traced and an order has been placed for contact diapositives then the process becomes even slower. Most organisations take between six and twelve weeks to supply material.

Chapter 3

Acquisition of Historical Data, Existing Methods and Applications

3. Acquisition of Historical Data. Existing Methods and Applications

High quality spatial data is an important requisite for a science that studies landform. A wide range of techniques and sources are used in geomorphology to acquire such spatial data. At large scale, of Order VI and VII in the classification by Tricart (1965), direct survey and reconnaissance techniques developed for engineering mapping are employed, (Anon, 1972). At smaller scales, maps and plans are important and the original source material for most of the world's maps has been the aerial photograph (Slama, 1980). Such topographic mapping requires photogrammetric techniques and allows photographs to be used in a quantitative way. Photographs can also be used for interpretation, (Matthews and Clayton, 1986) and this has been important to geographers and geomorphologists, (Lo, 1976; Verstappen, 1983). Photo-interpretation makes qualitative use of photography.

The purpose of this chapter is to review existing methods of acquiring spatial data, particularly those involving photographs, and to illustrate by previously published work. An important aspect of this commentary is the identification of limitations associated with each method.

3.1 Historical Maps

Historical maps provide one important source of historical spatial data in geomorphology as a sequence of such maps can illustrate the development of a landform through time. Historical maps represent a partial solution to the geomorphological problem (Section 1.2) although maps suffer from several important restrictions. Historical maps only provide planimetric positional data and perhaps a limited amount of height information, normally in the form of spot heights. Also, maps only represent a selective proportion of the available spatial information and this is generalised and modified for cartographic reasons, (Dumbleton, 1983).

Photogrammetric methods of standard map production began in America and Europe during the 1930's (Slama, 1980). Prior to this, maps were produced by conventional field survey. In England the first triangulation network was observed during the 1780's under the supervision of General Roy, (Harley, 1975). The Ordnance Survey (OS) was formally established in 1791, but it was not until the mid-19th century that reasonably accurate large scale plans (1:10,560) became generally available (Carr, 1962). In a review of these historical cartographic sources by Carr, (1980) positional inaccuracies are found, probably because instrumental techniques and plotting methods were of a lower standard in the 19th century. On close examination Carr (1980) also finds examples where actual survey errors or anomalies are present. Other problems that must be considered are; scale distortions due to deformation of the base material of old maps; and the need to transform spatial measurements from imperial to metric units. When comparing historical maps with recent OS plans the different map projections must be considered. The early OS 'County Series' plans were established upon the Cassini projection, whilst present maps are cast upon the Transverse Mercator projection. Direct comparison is incorrect and grid transformations are required.

Despite these problems, historical maps represent an important source of spatial data in geomorphology, (Carr 1962). Carr (1969) uses these sources to assess the effects of long-shore drift at Orford Ness. Similar work had been carried out at Spurn Head by de Boer (1969) and Brunsden and Jones (1976) use historical maps to help establish the sequence of landslides at Stonebarrow, Dorset. Although historical maps are significant, the loss of the third dimension and the selective abstraction of reality imposes critical restrictions. Vertical height is particularly important in geomorphology as this is a measure of the potential energy available to carry out geomorphic work, (Pitty, 1982).

3.2 Photogrammetric Techniques

Air photographs show all features visible from the air as they actually were and can allow three dimensional measurements to be taken, (Dumbleton, 1983). There are a wide variety of photogrammetric techniques that can be used to extract positional data from photographs. Some take full account of the spatial and geometric relationship between the photograph and object and are 'rigorous'. Others are approximate or 'non-rigorous' and make use of assumptions, these allow the use of simpler and cheaper instruments.

Most methods have been designed to be used in conjunction with conventional vertical aerial photographs. Such photographs are generally within +/- 3° from being true vertical photographs and have been taken with an aerial survey camera. A full description of this type of camera can be found for instance in Wolf (1983), and the Manual of Photogrammetry (Slama, 1980). Briefly, the camera possesses a very large format (230mm x 230mm) and a high quality, virtually distortion free lens. The format plane contains fiducial marks which, after full calibration define the position of the principal point. Calibrated or 'metric' cameras of this type are responsible for the majority of air photographs which are acquired for mapping using rigorous photogrammetric methods (Slama, 1980).

There is a progression from the simplest single photo techniques for gaining positional data, through to the more rigorous methods, requiring overlapping stereoscopic images and first order stereoplotters. Full explanations of the theoretical and practical aspects of these techniques can be found in several sources. Photogrammetric textbooks, Wolf, (1983), Kilford (1979), Burnside (1979) and the Manual of Photogrammetry (Slama, 1980) provide full explanations. The simpler non rigorous techniques are also covered in the geomorphological and geographical literature, for instance Woodruff and Evenden (1962), Lo (1976) and Van Zuidam, (1986).

3.2.1 Techniques using Single Photographs

There are several 'single photo' techniques which have been used to obtain planimetric spatial information from aerial photographs (Slama, 1980). Two simple techniques makes use of the 'camera lucida' principle and optical projection. The **Vertical Sketchmaster** (Aero Service Corp.) and the **Aero Sketchmaster** (Carl Zeiss, Oberkochen) are examples of instruments that use the camera lucida principle. Both of these instruments employ a semi-transparent mirror which allows a photographic print and an existing map to be viewed simultaneously. The map and photograph are adjusted so that alignment in both position and scale is achieved. Small camera tilts are removed by altering the photographic plane. The alternative method is based upon optical projection. The photographic image is projected onto an existing base map using a projector similar in principle to a photographic enlarger. Scale and position are adjusted until the image is correctly superimposed upon the base map, and the map plane is tilted until the distortion due to the non-verticality of the photograph is removed. Detail can then be manually scribed directly onto the base map. The **Caesar-Saltzman Reflecting Projector** (J.G. Saltzman, Inc.) is an example and although similar to an enlarger is much larger due to the large format size of aerial film.

Each of these techniques can be useful for intensifying planimetric detail or for map revision using vertical aerial photographs. Although a correction for photo tilt is provided this is approximate, especially in those instruments employing the camera lucida principle. Two important assumptions are made. First, insignificant errors will be introduced when a perspective projection is superimposed upon an orthographic map; secondly, displacement due to varying relief is zero. The method is only really valid at small scale and in regions where the terrain is comparatively flat. The two methods suffer from a similar restriction as using historical maps. All derived data are two dimensional and the essential vertical height cannot be obtained.

A single photo technique has recently been devised by Collins and Madge (1981) and applied to the monitoring of a landslide in Cardiff, S. Wales (Collins and Madge, 1985). The method makes use of a ground based photograph taken with a Wild P32 metric camera. Marker poles are positioned in the object space at those points which need to be coordinated. Three similar 'control' poles are also placed around the object and coordinated by conventional survey methods. The marker poles are graduated at 0.5 metre intervals and so provide scale in the object. Spatial positions of points are determined by measuring the image positions of pole graduations at both the 'control' poles and the point whose spatial position is required. The horizontal distance and difference in height between the camera and the poles can be determined by simple mathematical equations using similar triangles. The camera position can be resected from the measurements to the control poles and the coordinates of the uncontrolled pole can then be determined. Accuracy of the technique is quoted as between 1:500 and 1:5,000 which is useful for some purposes. The main weakness with the technique is the reliance upon principles of 'subtense measurement' for the determination of the distance between the camera and the poles. There is a rapid deterioration of accuracy with increasing distance and the effective range of the technique is less than 150 metres.

3.2.2 Non-Rigorous Techniques Using Photo Pairs

When vertical aerial photographic coverage of a particular area of interest is requested, it is normal practice to arrange that exposures are taken to ensure that successive photographs overlap each other. This overlap is usually about 55% to 60% (Kennie and Matthews, 1985) and the photographs can be used to form a three dimensional **stereomodel** of the terrain. This stereomodel is an aid to interpretation and can be used to provide height information. A wide variety of techniques have been developed and these have been useful to geologists (Allum, 1966); geographers (Lo, 1976) geomorphologists (Woodruff and Evenden, 1962; Van Zuidam, 1986; Griffiths and Marsh 1986) and engineering geologists (Norman, 1970; Norman and Huntingdon, 1974; Norman *et al*, 1975).

Basic planimetric data can be obtained by using instruments such as the **Radial Line Plotter** (Hilger and Watts). This instrument makes use of the 'radial line assumption' which states that:

> *'when aerial photographs are taken with the camera axis nearly vertical the plumb point and principal point are nearly coincident so that displacements resulting from differences in ground elevation or photo-scale always occur radially from the principal point'*, (Slama, 1980).

This assumption is reasonable and realistic if photo-tilts are less than 3° and relief is less than 10% of the flying height, (Kilford, 1979). The radial line plotter automates a process of radial intersection by mechanical means. A pair of overlapping vertical photographs are placed upon the stages of the instrument, centred at the principal point by means of a small pin. The instrument possesses a mirror stereoscope and the photographs are rotated and 'base-lined' so that a stereomodel is perceived. Two transparent arms extend radially from the pinned principal points, upon which a fine black line is etched. When viewed stereoscopically these appear to intersect and provide a reference mark. A mechanical linkage connects the apparent cross with a pencil chuck and as the model is scanned, the pencil replicates the model scanning onto a map sheet. When the model has been scaled to fit an existing map, simple planimetric data can be extracted from the photographs.

Another simple method of map production using multiple vertical aerial photographs is to form a photo-mosaic. Various types of mosaic can be produced, depending upon the quality of ground control that is used to join the photographs together, (Wolf, 1983). Photo-mosaics have been used for route planning (Spagna, 1979) in which geomorphological units surrounding the proposed alignment could be rapidly identified and mapped.

Engineering geologists have used these simple techniques to compile engineering geology maps (Dearman and Fookes, 1974; Rengers, 1979; Soetors and Rengers, 1981). Site instability mapping has provided another important application; Burton (1970) used 1:30,000 scale aerial photographs to identify landslides and areas of potential instability. In geomorphology air photographs have been used to compile geomorphological sketch maps, (Rao, 1975; Brunsden *et al*, 1975).

All of the non-rigorous techniques using single photo or pairs suffer from two important restrictions. The positional quality (Section 8.2) of the derived data is low as non-rigorous techniques are used, although this can be tolerated if the scale of the analysis is sufficiently small. The more important restriction is the loss of the third dimension as only planimetric spatial information can be obtained.

One of the main advantages of using overlapping stereo-pairs is the possibility of perceiving relief. This can be used to provide relative height information using the concept of 'parallax'. This is the:

> *apparent displacement in the position of an object, with respect to a frame of reference, caused by a shift in position of the position of observation,'* (Wolf, 1983).

In the case of near vertical aerial photography the size of this displacement is dependent upon the elevation of an object. The parallax can be measured by monoscopic methods but it is more convenient if stereoscopic measurements are made using a 'parallax bar'. By measuring the parallax difference between pairs of points and applying simple algebraic formulae, the difference in height between the points can be determined. The formulae are given in most photogrammetric textbooks, for example Wolf (1983), Kilford (1979) and Burnside (1979). Height difference and an associated horizontal distance enable the gradient to be computed. This is important in geomorphology, as gradient is a measure of the energy available on a slope (Pitty, 1982). Turner (1977) reviews the techniques available to determine gradient and identifies parallax methods, comparative methods and graphical procedures. The parallax methods depend upon readings made with a parallax bar and incorporate horizontal distances deduced using a 'templet'. Comparative procedures include the stereoscopic comparison of a slope segment with a surface generated by mechanical means. Graphical procedures involve the determination of slope angle by means of various geometrical and trigonometrical relationships. They rely upon monoscopic measurements made using a transparent overlay and although require little equipment are time consuming.

An alternative range of **approximate instruments** have been developed to obtain fully three dimensional data from near-vertical aerial photographs. The methods are non-rigorous as it is assumed that the photographs are co-planar. Elaborate correction devices have been developed to correct for certain aspects of tilt and relief displacement and were developed and are explained by Thompson, (1974). One such instrument is the **Stereo-micrometer** (Officino Gallileo). This instrument is more convenient and comfortable to use than the radial line plotter as it is possible to remove y-parallax over a large proportion of the model. It also permits the direct reading of heights, rather than making use of parallax bar readings and computation. Corrections for photographic tilt are provided by a compensating tilt of the plotting table. A correction to height measurements due to photo tilt is provided by the 'cavalcanti surface' which attempts to physically model the distortion. The **CP1 Plotter**

(Cartographic Engineering) is a similar instrument that differs only in the detail of the correction devices.

3.2.3 Rigorous Methods

The compilation of topographic maps is the most widely practised application of photogrammetry (Wolf, 1983) and is carried out in an instrument known as a **stereoplotter**. Such an instrument must be able to relate or **restitute** the image coordinates of a point on a pair of photographs to the corresponding ground coordinates of that point. In order for this to be fully rigorous, full corrections are necessary for the displacements due to photographic tilt and ground relief. As maps are cast upon a variety of projections, sometimes orthographic but often of some other design, other corrections need to be applied. A whole range of stereo-plotters have been designed to apply these corrections. Various classifications of instruments have been used in the past, including the manner in which the light rays are reconstructed; optical, opto-mechanical and mechanical. Classification can also be in terms of the potential accuracy: 1st order, 2nd order and 3rd order. Recent developments with computerised solutions suggest that a more suitable classification would be a dichotomy between the traditional **analogue** plotter and those instruments which make use of a computerised **analytical** solution.

In an analogue instrument the spatial relationships between the photographs and the ground are physically recreated in the plotter at a reduced scale. In instruments such as the analytical plotter, where a computerised solution is being used, there is no such physical recreation. Instead, the image coordinates of a point are related to its corresponding ground coordinates by a mathematical function. All plotters have three common sub-systems. There is the system to relate the photographs to the ground. In an analogue instrument this is done by using some form of optical, opto-mechanical, or mechanical projection. In analytical instruments a numerical calculation is used. There is also an optical system for viewing the photographs stereoscopically, so that the operator perceives a **stereomodel**. Finally there is a measuring system which enables spatial measurements to be acquired from the stereomodel. Operating these instruments is similar also. A sequential three stage orientation process of inner, relative and absolute orientation (Slama, 1980) is performed, (Section 6.5.1), although details do differ with analytical instruments.

3.2.3.1 Analogue Instruments

The traditional stereoplotters are based upon either optical, opto-mechanical or mechanical methods of relating the photographs to the ground. The earliest and simplest stereoplotters were **direct optical projection instruments**. Instruments such as the **Multiplex** (Williamson) and the **Balpex** (Bausch and Lomb) are examples and were developed as early as 1940 (Slama, 1980). In these instruments the actual stereomodel is formed by optical projection. The two positions of the aerial camera are replaced by two projectors which hold reduced sized diapositives. After the three stage orientation process (Slama, 1980) in which the projectors are physically rotated and translated, the bundles of rays from each projector intersect as the image forming rays did at the time of photography. The scaled three dimensional model is perceived by either the anaglyph, the polarised platen viewing system (PPV) or the stereo-image alternator (SIA). The function of these devices is to separate the left and right projector images so that the brain can perceive the stereomodel. Measurement of the stereomodel is carried out by moving a white disc or 'platen' which possesses a small light measuring mark. Attached to the platen is a pencil chuck and as features on the model are traced, the pencil duplicates these movements on a map sheet fixed to a reference surface. The platen and measuring mark can be raised and lowered within the stereomodel, permitting the recording of elevations.

In **opto-mechanical** and **mechanical projection instruments** the projected ray is replaced by a mechanical 'space rod'. In the mechanical projection instrument the lenses are also replaced by mechanical joints or gimbals. The viewing system consists of two separate optical trains, one for each diapositive, so that the stereomodel is perceived directly using a binocular system of viewing. The space rods intersect at a tracing stand which can translate around the reference table, permitting the tracing of planimetric detail. Movements of the tracing stand are transmitted mechanically to a coordinatograph, which produces a plot of the traced motion. Elevations of points in the model are determined by the intersection of the space rods. This class of instrument has been most popular in Europe, (Wolf, 1983). A good example is the **Wild A7**, which was first introduced in 1952 and remained in production until 1970.

Mechanical instruments are more flexible than direct optical projection instruments. First, there is only a limited depth of field available with an optically based instrument which ensures that this class of instrument can only restitute photography of a specific focal length and at a small range of photographic scales. With mechanical instruments, the focal length range is only a mechanical limitation, although this is still restrictive. The binocular viewing system is more convenient than the simpler and rather crude methods associated with the direct optical instruments. Only a small proportion of the diapositive needs to be illuminated at a given instant so there are no problems with obtaining sufficient illumination. Several developments increased the flexibility of the mechanical range of instruments. The introduction of the Zeiss parallelogram (Slama, 1980) enabled a strip of photographs to be measured conveniently. Similarly, the introduction of the 'universal' mechanical plotter enabled the direct plotting of terrestrial photographs, but still with restrictions on focal length, convergence of the photographs and height variation of the ground.

Rigorous analogue methods have been employed in geomorphology and related studies. Vertical aerial surveys have been applied in glacial geomorphology, for example; Petrie and Price (1966), Jania *et al* (1984) and Small *et al* (1984). Analogue methods have been used in engineering geology (Dearman and Fookes 1974; Rengers, 1979; Spagna 1979), in landslide studies (McConchie, 1986) and in studies of coastal changes, (El Ashry and Wanless, 1967). Micro-scale geomorphological features have been studied using photographs taken from overhead gantries using 'aerial' analogue photogrammetric methods, (Welch and Dikkers, 1978). Poulin (1962) uses this method to measure the development of frost patterns in the soil. Photogrammetric techniques have been developed for the use with ground-based or **terrestrial** photographs. Applications of these **close range photogrammetric** techniques include surveys of slopes in Columbia, (Heath *et al*, 1978) and the geotechnical examination of rock faces, (Wickens and Barton, 1971). The working party of the Geological Society Engineering Group produced recommendations for map production, (Anon, 1972) in which terrestrial photogrammetry is discussed.

Analogue instruments rely upon mechanical and optical devices to recreate the photographic and ground relationship and so mechanical constraints are inevitable. This places two main limitations upon the type of photography that can be used for analogue measurement. Photography taken with a calibrated metric camera has to be used as systematic errors such as lens distortion and film deformation cannot be easily compensated. Secondly, only vertical aerial photographs or terrestrial photographs can be accommodated and both have to be acquired with the mechanical restrictions of the plotter as a major consideration. This is most problematical for terrestrial photographs as these have to be acquired from particular positions and with particular orientations.

Oblique photographs taken with an un-calibrated camera cannot be accommodated by an analogue instrument.

3.2.3.2 Analytical Instruments

The basis of the analytical class of instruments is that the photo-coordinates are related to their relevant ground coordinates by digital means. No stereomodel is physically recreated, although the operator is presented with a visual impression of one. The required equipment to make use of the analytical solution include an instrument capable of measuring photo-coordinates and a digital computer. A wide variety of combinations are possible; ranging from a **comparator** and a Personal Computer (PC), to a full **analytical plotter** with a super-mini host computer. The subject of analytical photogrammetry is a fundamental part of this research, a fuller discussion of the principles and instrumentation is given in Chapter 4.

The tradition of applying analytical photogrammetric techniques to solving geomorphological problems is as old as analytical photogrammetry itself. Finsterwalder used analytical photogrammetric techniques to map areas of alpine glaciers in 1888, (Finsterwalder, 1897) and provided the foundation for analytical photogrammetry (Section 4.1). In more recent applications of analytical photogrammetry, slope studies are prominent. Slope dynamics were studied in the Crimea using sequential photogrammetric surveys, (Blagovolin and Tsvetkov, 1972). Erlandson and Veress (1975) monitored a mudslide in America using close range analytical photogrammetry. Fraser (1983) carried out a stability analysis of Turtle mountain using 'free networks'. Faig (1984) used analytical photogrammetric methods to measure subsidence in mountainous regions. Faig and Armenakis (1984) also developed data processing techniques, including the measurement of grids, profiles and the determination of movement vectors. The monitoring of glaciers by analytical photogrammetry has continued, particularly in the Alps, (Stirling, 1982; Small *et al*, 1984). Unstable slopes in Nepal have been monitored by analytical close range photogrammetric techniques, (Chandler *et al*, 1987) and in southern England, (Moore, 1988).

Analytical photogrammetry has also been applied in geotechnical engineering. Veress monitored a gabion wall at the side of a US state highway by a variety of photogrammetric and geotechnical methods, (Veress and Sun, 1978; Veress and Hatzopoulos, (1981); Veress *et al*, 1981). Brandow and Karara (1976) deduced the dip and strike of rock joints in a mine using Direct Linear Transformation (DLT) (Section 4.3.1). Atkinson and Stethridge (1980) used analytical terrestrial photogrammetry to study rock slope failures in Cornwall. Bedding planes and joints within consolidated clay were also determined photogrammetrically by Moore, (1974). A review of both close range analytical photogrammetry and some applications in geotechnical engineering has been carried out by Kennie and McKay, (1987).

Micro-scale applications of analytical photogrammetry to geomorphology include slope and fluvial studies. Lo and Wong, (1973) used 35mm cameras to examine the development of rills and gullies on a small section of a weathered granite slope in Hong Kong. Collins and Moon (1979) measured stream bank erosion whilst Welch and Jordan, (1983) used a 35mm camera and digitised enlarged transparencies in order to obtain a digital terrain model (DTM) of a river channel. DTM's from each epoch were then used to compute a surface of change and to compute volumes.

All methods have limitations on accuracy, density and quality of the data which can be acquired. The literature demonstrates that analytical photogrammetric approaches are the least restrictive and offer greater flexibility than analogue methods. It was apparent that an analytical photogrammetric solution would yield the best method of acquiring spatial data from archival photographs. The technique that was eventually developed (Section 5.1) overcomes most limitations associated with photographic and ground control requirements, whilst providing accurate spatial data of known quality.

Chapter 4

Analytical Photogrammetry and Archival Photographs

4. Analytical Photogrammetry and Archival Photographs

4.1 Definitions and Development of Analytical Photogrammetry

The definition of photogrammetry (Section 1.1) encompasses both quantitative and qualitative use of photographs. The quantitative application of photogrammetry is most important in this thesis, although the qualitative aspect of air photo-interpretation is discussed in Section 8.3.2. **Metric photogrammetry** involves precise measurement to determine the size and shape of objects, (Wolf, 1983). **Analytical photogrammetry** uses measurements made on the photographs and mathematical computations to obtain such spatial data, (Ghosh, 1979). Many computations used in analytical photogrammetry involve the principle of least squares estimation. The unifying methods of least squares provide a series of algorithms for transforming measured data into derived data, taking full account of the statistical properties of the measured values. There are several texts which explain the principles and methods of least squares estimation, including Mikhail (1976) and Cooper (1987).

The term 'model' possesses several distinct meanings in analytical photogrammetry. The **stereomodel** is the three dimensional or stereoscopic impression of the object as perceived when a pair of overlapping photographs is viewed by an operator. The **mathematical model** is a widely used term which refers to two further models which should be distinguished in least squares estimation procedures. There is the **functional model**, which defines the relationships between elements that are either measured or are to be estimated. Commonly in photogrammetry, the functional model represents relations between points in the object space and their corresponding images on the photographs, (Ghosh, 1979). The second component is the **stochastic model** which expresses the statistical properties of the measured values, (Cooper, 1987).

Some of the theoretical and mathematical principles of analytical photogrammetry were established late in the 19th century and Ghosh (1979) reviews many important developments since then. Finsterwalder is credited with having provided the foundation of analytical photogrammetry between 1899 and 1932, (Ghosh, 1979). In an important address to the Academy of Sciences of Bavaria, Finsterwalder gave a concise description of the geometric relationships which govern the relative orientation of a stereopair of photographs, (Slama, 1980). Von Grüber was also an important early contributor and began development of the single point resection in 1924. Earl Church continued this work in the USA and in 1934 produced the solution for the single point resection which is still in use today.

The Second World War accelerated the development of analytical photogrammetry and this continued during the 1950's. In 1953 the Ordnance Survey developed analytical aerial triangulation. In Canada, Helava (1957) conceived the principles of the analytical plotter, (Section 4.1.1.2). In America, Schmid outlined the principles of multi-station analytical photogrammetry using the collinearity equations and introduced least squares estimation procedures. Further developments of this by Brown lead to the 'bundle adjustment' with self calibration procedures, partitioning of the design matrix and use of the stochastic properties of measurements, (Brown, 1956, 1974, 1976).

The development of analytical photogrammetry and in particular the analytical plotter has closely reflected developments in computer technology, (Torlegard, 1980). The theoretical aspects of analytical photogrammetry have always surpassed the ability to carry out some of the computations. With the increasing power of computing architectures, more complex and powerful analytical procedures have become practicable.

4.1.1 Instrumentation

A review of the instruments used for analytical photogrammetry has been carried out by Ghosh (1979). Although the commercial market is dynamic and models change, two principal types of instruments can be distinguished, the comparator and analytical plotter.

4.1.1.1 <u>The Comparator</u>

This simple instrument is used to measure the coordinates of points on a photograph in a two dimensional rectangular coordinate system. There are two types of instrument, the **mono-comparator** and the **stereo-comparator**. The latter instrument is more useful as it permits the simultaneous measurement of corresponding points on a pair of photographs. The instrument was invented by Pulfrich in 1901, (Slama, 1980) and a variety of models are still available today; for example the **Stecometer** (Zeiss-Jena) and the **Zeiss PSK2** (Zeiss-Oberkochen).

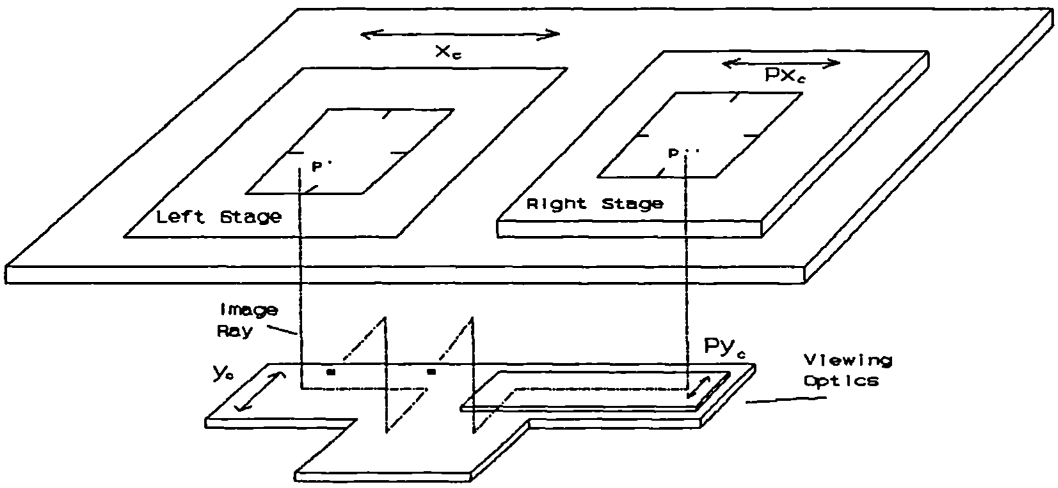


Figure 4.1 **The Stereo-comparator**

The stereo-comparator is simply constructed (Figure 4.1) and consists of two stages upon which the photographs are mounted, (Ghosh, 1979). Both stages can translate in the x and y directions and a binocular viewing system permits stereoscopic measurement of the images. The right-hand stage can effectively move independently of the left-hand stage and so differential x and y translations are possible between the photographs. Four measurements (x_c,y_c,Px,Py) are registered by linear or rotary encoders and the values either manually recorded or transmitted to a host computer. In an '**on-line**' situation the measurements are relayed to a computer, transformed into photo-coordinates and used to derive the ground coordinates of the measured point, (Krakty, 1976).

During the 1950's and 1960's the major use for the comparator was to provide photo-coordinate data for analytical aerial triangulation, (Slama, 1980). The stereo-comparator has recently experienced a new lease of life with the growth in on-line analytical photogrammetry (Torlegard, 1980).

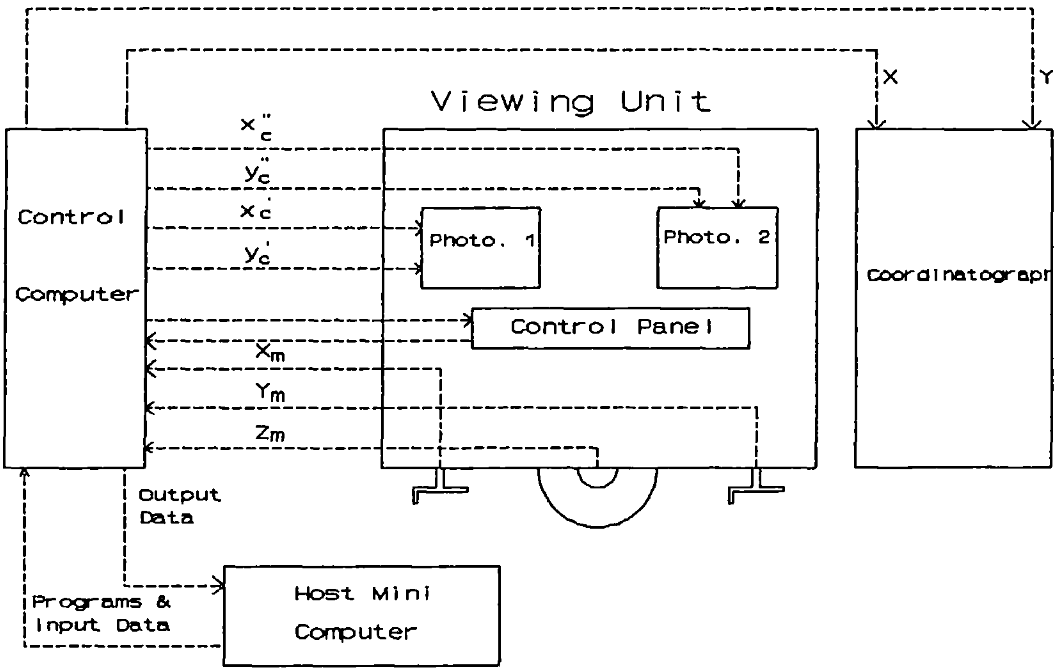
4.1.1.2 The Analytical Plotter

The analytical plotter was devised by Helava in 1957 and was patented by the US Government in 1964, (Helava, 1957; Slama, 1980). Initially the concept was received indifferently by the photogrammetric community, principally because of the reliance upon computers which were at a very early stage of development, (Slama, 1980). An agreement between Ottico Meccanica Italiani (OMI) and the Bendix computer organisation lead to the construction of the first analytical plotter, the **AP/1**, in 1961. This prototype was successful and the **AP/2** followed shortly afterwards. Further developments were slow and it was not until 1976 that OMI and Bendix had any competitors. However, at the International Society of Photogrammetry Congress in 1976, seven manufacturers exhibited commercial analytical plotters which were in late stages of development, (Slama, 1980). Since then a wide variety of models have come onto the market, each exploiting new developments in computer hardware and software. Present models include the **DSR/11** (Kern); the **BC2** (Wild); the **Planicomp** (Zeiss-Oberkochen) and the **IMA** (Intergraph). Recent developments in Personal Computers

(PC's) has lead to the introduction of cheaper, small format analytical plotters such as the **MPS-2** (CZ Scientific).

The basic configuration of the analytical plotter is obvious and deceptively simple in concept, (Slama, 1980). It is in fact a progression from the stereo-comparator where a

Figure 4.2 **The Analytical Plotter**



computer controls and can drive the stage plates to any position. There are three key components (Figure 4.2): the stereo-viewer, the central computer and an interface. The viewing system is based upon a stereo-comparator and consists of two stages which can move independently in the x and y directions. The photographs are placed upon the stages and the operator can view the photographic images through a binocular viewing system. The optics are of high quality and possess differential zoom and image rotation all controlled by the computer. The stage plates are driven by servos, receiving commands from the computer-stereoviewer interface. The actual location of the stage plates is determined by rotary or linear encoders which have a resolution of 1-2 micrometres. Two distinct tasks need to be performed by the computer. One duty is to maintain the visual impression of a stereomodel during scanning. The algorithm is based upon the collinearity equations (Equation 4.2) but corrections for a variety of systematic errors can be injected. The process must be executed continually and at sufficient speed to be undetectable by the operator, the algorithm is often known as the 'real time loop' because of these requirements. The other task of the computer is termed 'general housekeeping', this entails maintenance of files and databases and the execution of a variety of applications programs such as plotting and adjustment packages. A wide variety of host computers can be used and during the 1970's the **Digital PDP/11** was popular. A pattern that is now established is total separation of the two computing tasks. A local processor executes the real time loop and a host mini computer provides housekeeping facilities.

The analytical plotter is highly dependent upon software and the more sophisticated and developed the programs, the greater will be the potential for solving problems, (Slama, 1980). There are major problems with the development and maintenance of such a computer system and these were realised at an early stage of development, (Konecny, 1977). Despite the problems there has been a gradual acceptance of the technology, (Dubuisson, 1977) and Dowman (1977) indicates three main benefits: One advantage associated with the analytical plotter is the removal of any mechanical limits. In addition, the stereomodel can be transformed for output to either a plotting table or data bank. Finally, movement in the stereomodel can be controlled by the computer, permitting automatic movement between points for profile scanning, (Dowman, 1977).

Both the 'on line' stereo-comparator and the analytical plotter share distinct advantages over the traditional analogue approach. This is achieved as the optical and mechanical devices of the analogue instrument are replaced by a computerised functional model. This solves digitally the relationship between the photo-coordinates measured in a two dimensional photo-coordinate system and the ground coordinates in the object space. Most importantly for this thesis, the numerical solution frees photogrammetry from the mechanical and optical constraints of analogue instruments. All forms of photography: vertical, terrestrial and oblique can be accommodated, acquired with cameras of any focal length. Systematic errors can also be corrected, including lens distortion, film deformation, earth curvature and atmospheric refraction. The output is in a digital form and can allow for a variety of post processing and data analyses.

The analytical instruments are true 'universal' instruments and can theoretically relate the photo-coordinates of any sensor, photographic or digital, to any ground coordinate system.

4.1.2 Theoretical Aspects

One of the most efficient methods of storing and manipulating spatial information is within a three dimensional cartesian coordinate system. Traditionally a right handed system is used, where the Z axis is vertically upwards and aligned with the direction of gravity; the Y axis is conventionally orientated to north and the X axis to east. In photogrammetry this is often referred to as the object space coordinate system. A photo-coordinate system can be used for defining the spatial relationship between points imaged on the photographic negative. Again a right handed system is used, with the origin at the lens or perspective centre, the z axis in the direction of the camera axis and the x and y axes parallel to the plane of the negative. A point 'A_i' in the object space will have object coordinates (X_i, Y_i, Z_i). If a photograph is acquired so that the point A_i is imaged at 'a_i', (Figure 4.3, Photo 1) then 'a_i' will possess photo-coordinates of $(x_i, y_i, -c)$, where c is the principal distance or the focal length of the camera. Using strict photogrammetric terminology the principal distance is equivalent to the calibrated focal length, although in this

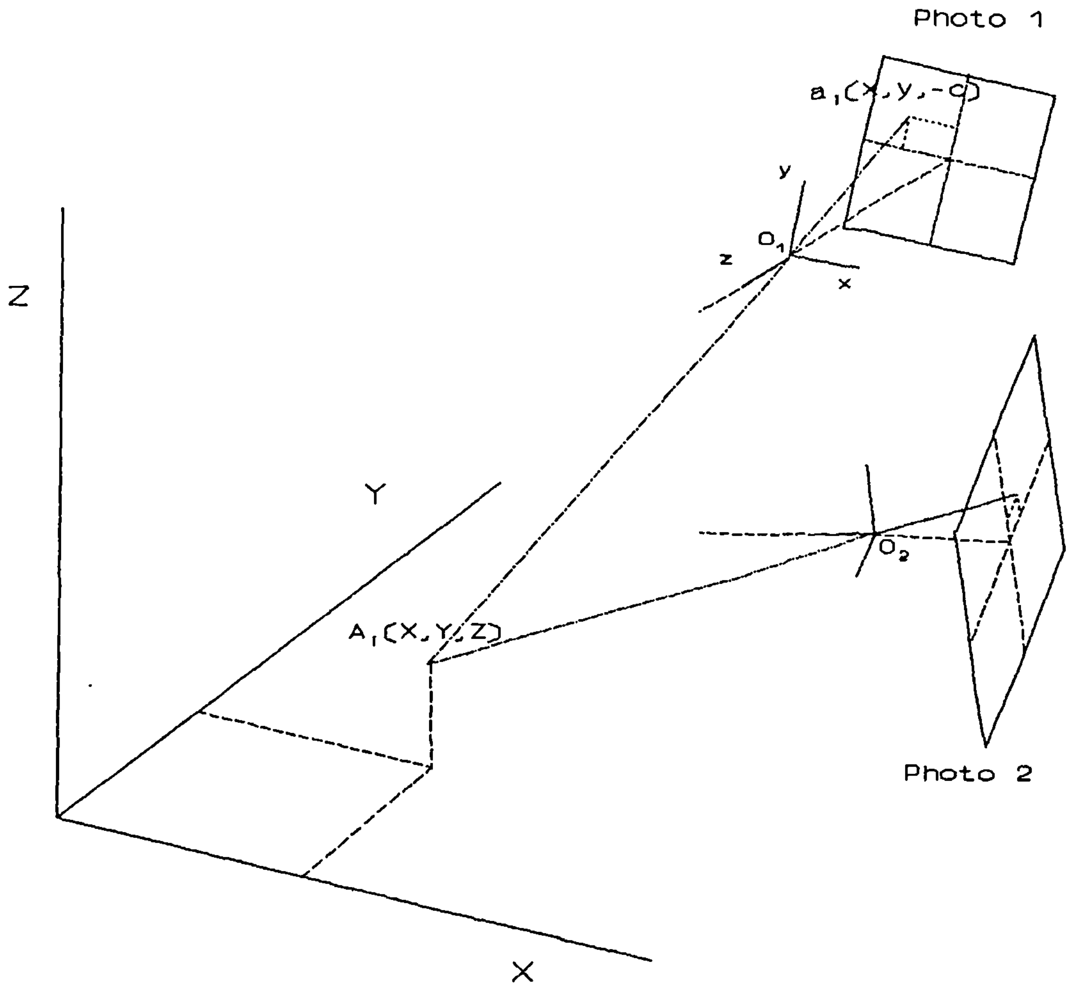


Figure 4.3 **Theoretical Aspects**

thesis the focal length and principal distance are commensurate.

The <u>general projective transformation</u> describes the relationship between two coordinate systems. A <u>central perspective projective transformation</u> is used in photogrammetry to relate object coordinates to corresponding photographic image coordinates and is defined in matrix notation as:

$$\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} + \Gamma \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ -c_i \end{bmatrix} \qquad 4.1$$

Object Space	Perspective Centre	Rotation Matrix (R)	Photo Coords.

Where:

X_0, Y_0, Z_0 are the coordinates of the perspective centre ('O'), in the object space coordinate system;

$r_{11}-r_{33}$ are the elements of the rotation matrix (R) and are functions of the orientation of the camera axis, also in the object system, (Equation 4.8); and

c is the focal length of the camera and is a constant for any one photograph.

The central perspective projective transformation is illustrated graphically in Figure 4.3 where the object point 'A_i', the perspective centre 'O' and the image point 'a_i' lie upon the same spatial line. The transformation is three dimensional, but in the special case where c is constant the transformation is from two dimensional to three dimensional space.

Elimination of the scalar 'Γ' from equation 4.1 and rearrangement produces the two collinearity equations:

$$x_i = \frac{-c(r_{11}[X_i-X_0] + r_{21}[Y_i-Y_0] + r_{31}[Z_i-Z_0])}{(r_{13}[X_i-X_0] + r_{23}[Y_i-Y_0] + r_{33}[Z_i-Z_0])} \qquad 4.2.1$$

$$y_i = \frac{-c(r_{12}[X_i-X_0] + r_{22}[Y_i-Y_0] + r_{32}[Z_i-Z_0])}{(r_{13}[X_i-X_0] + r_{23}[Y_i-Y_0] + r_{33}[Z_i-Z_0])} \qquad 4.2.2$$

These equations relate the object coordinates of a point to associated image coordinates, on a single photograph, and form the basis of analytical photogrammetry. A fuller discussion can be found in Albertz and Kreiling (1975) and Slama (1980).

In Figure 4.3, Photo 1, all points on the line aA in the object space will be imaged at a_i. It should be apparent that measuring the photo-coordinates of a point on one photograph is not enough to define the ground coordinates, as a one to one correspondence does not exist. However, if a second photograph is introduced (Photo 2) and similar measurements are made to the same point, then a solution for the ground coordinate can be obtained. The process is analogous to that of intersection in conventional field survey, although it is necessary to know the positions and orientations of the cameras or the camera parameters. The positional elements of these camera parameters are defined by X_0, Y_0 and Z_0 in the collinearity equations, whilst three independent rotational elements comprise r_{11} to r_{33}.

In the case of terrestrial photographs the camera parameters can be measured by direct field survey. A far more efficient method of determination, for both terrestrial and aerial photographs, is to perform a numerical calculation. In order to compute the camera parameters, the three dimensional coordinates of at least three well distributed 'control' points are derived using conventional survey techniques. The photo-coordinates of these control points are then measured and these data and control coordinates are used in a variety of computations such as a space resection or a bundle adjustment. The former is the simplest and consequently easiest to compute and was originally conceived by Church in 1934. The formulae are developed and given by Ghosh (1979), the Manual of Photogrammetry (Slama, 1980) and by Cooper (1987). The bundle adjustment is more flexible as measurements other than target ground coordinates and photo-coordinates can be included, (Brown, 1976; Granshaw, 1980; Wester-Ebbinghaus, 1985). This particular estimating procedure is extremely important to this thesis and is discussed in Section 4.3.2; 5.2.4. If more than three points are available for measurement then the extra or redundant measurements can be used in a least squares estimation. This computational procedure produces a more precise solution and allows the quality of the estimation to be assessed, (Section 8.2).

When the camera parameters have been determined it is possible to derive the coordinates of a new point simply by measuring the image coordinates on two photographs. These data are transformed into photo-coordinates and finally object space coordinates. The process can be repeated for other points on the site and the object coordinates stored.

To summarise, the two main steps of the measurement phase involve some form of calculation to determine the positions and orientations of the cameras. The coordinates of new points can then be determined by a series of intersections, merely by measuring the image positions on two photographs. This simple approach is flexible, although the standard collinearity equations (Equation 4.2) are only valid for photographs taken with a calibrated metric camera.

4.2 The Photogrammetric Problems associated with Archival Photographs

The purpose of the present research is to develop a technique suitable for the acquisition of spatial data from all forms of archival photography. There are many problems associated with the use of archival photographs for photogrammetric measurement and will be discussed.

1). As indicated in Chapter 2 one of the main problems with working with archival photographs is acquiring suitable imagery. The archive consists of a variety of types of photographs, including: vertical, oblique and terrestrial images, (Section 2.3). In order to use as much of the archive as possible, any developed technique must be as universal and flexible as possible and allow the use of all types of photography. An analytical solution would provide flexibility as the mechanical and optical constraints associated with the analogue approach, (Section 3.2.3.1) are not applicable. All photographs, including obliques, could be used in an analytical photogrammetric solution, providing there is some form of overlap. There is a problem of discomfort to the operator with highly convergent photographs, although this is a practical problem rather than a theoretical one.

2). Archival photography has been acquired with a variety of cameras which are not necessarily of known metric quality. Calibration data for the original camera is likely to be unavailable and so the **inner orientation** of the photographs must be treated as unknown. Faig (1976) defines a **non-metric** camera as one whose inner orientation is unknown or partially unknown and so archival photography can in general be regarded as non-metric. There are three aspects of inner orientation that need to be considered:

2a). The focal length of the camera and the position of the principal point relative to some arbitrary x y photo-coordinate system can be regarded as aspects of **primary inner orientation**.

2b). The second component is the effect of **lens distortion**. In a high quality survey camera the lens is designed to fulfil, as nearly as feasible, the condition of collinearity and this is verified by calibrating the camera. Such a lens can be regarded as distortion free because the distortion is generally less than 10 micrometres at the focal plane, (Slama, 1980). A distortion free lens cannot be presumed with non-metric or archival photography and so some form of correction must be applied. Various functional models have been used to approximate this source of systematic error, (Karara and Abdel Aziz, 1974; Fryer and Brown, 1986) but one composite function has been widely accepted in analytical photogrammetry, (Karara and Abdel Aziz, 1974). This attempts to model **radial** lens distortion using an odd powered polynomial. The smaller **tangential** component, due to the de-centring of composite lenses, is modelled with the 'Conrady' function.

2c). An additional problem associated with the inner orientation of a camera that must be considered is film deformation. This aspect is difficult to model without calibrated reference marks such as fiducials or a reseau. In general, such information will be unavailable for archival photography and so no explicit modelling for film deformation can be applied.

3). Another problem with archival photographs is the lack of surveyed control information in the object space. For most planned photogrammetric projects, full three dimensional control is provided by either direct field survey or through using control intensification procedures such as aerial triangulation, (Ackermann *et al*, 1973; Cooper, 1979; Slama, 1980). In certain cases, conventional control may be available with archival photographs, but it can be assumed that this will generally not be the case. An alternative source of control is a local large scale topographic map; planimetric data can be scaled from the map and some spot heights of a low order of planimetric quality will be available. There are several problems associated with such a source of control information. The control data will be either one or two dimensional rather than fully three dimensional. The second problem is the low order of accuracy with which planimetric data can be scaled from the plan, this accuracy depends upon the scale of the plan but deformation of the map base is a consideration. Another factor that must be taken into account is the projection that the plan is cast upon. A three dimensional cartesian system is rarely used for national mapping sheets and so the implications of this needs to be considered. A final problem arises because the date of map compilation will rarely coincide with the date of the photographs. If such a source of control is used, any selected control points must be assumed to be stable during the period between survey and photography.

4.) If positional comparisons are to be made between photographic epochs an additional problem is the definition of a common datum. A coordinate system in three-dimensional space necessitates the definition of seven datum elements: one scale element, three position elements and three rotation elements, (Cooper, 1987). These can be defined by various means and if the datum is defined differently between epochs then dissimilar coordinate systems will be used. Morphogenetic differences will then be attributable to the datum discrepancy rather than any changes due to process.

5.) An analytical plotter provides the capability for efficient acquisition of spatial data. Such an instrument had recently been acquired by the City University and so any developed technique would have to be adapted for use with this equipment.

4.3 Analytical Approaches Suitable for the Archival Photogrammetric Technique

By solving the main problems and accepting the limitations outlined in Section 4.2, it was thought that a suitable universal technique to use archival photographs for spatial measurement could be developed. A preliminary stage in this advancement was the identification and critical appraisal of photogrammetric approaches that were already established.

During the 1970's, the ability of analytical photogrammetry to correct for various systematic errors, led to the idea of using non-metric cameras as a cheaper and more flexible alternative to fully metric cameras, (Schwidefsky, 1970; Murai *et al*, 1980; Wijk and Ziemann, 1976; Hatzopoulos, 1985; Roberts and Griswold, 1986). Faig (1975) states that the calibration of a camera provides a link between metric and non-metric photography and identifies three forms of calibration: laboratory, 'on the job', and self calibration. The former requires access to the camera and is unsuitable for use with archival photographs where such access is unlikely. 'On the job' calibration permits a calibration of the camera through the use of sufficient control in the object space. An example of this approach is the Direct Linear Transformation (DLT) conceived by Abdel Aziz and Karara, (1971). Self calibration does not require object space control for a calibration as such. Techniques had been developed by Brown (1956), Kenefick *et al* (1972) and Faig (1975). Both the 'on the job' and 'self' calibration approaches appeared useful bases for the development of the archival photogrammetric technique.

4.3.1 Direct Linear Transformation (DLT)

4.3.1.1 Software development

The Direct Linear Transformation is an example of 'on-the-job' calibration and was originally devised by Abdel Aziz and Karara (1971). DLT was further extended by Karara (1972), Marzan and Karara, (1975) and Bopp and Kraus, (1976, 1978).

The novelty of the DLT approach is the establishment of a direct linear relationship between comparator coordinates of points and the corresponding object space coordinates. The method by-passes the need for photo-coordinates and consequently the requirement of the fiducial marks necessary for the definition of a photo-coordinate system. The basic DLT equations are derived by Marzan and Karara (1975) and were originally:

$$x_c + \delta x = \frac{L_1X + L_2Y + L_3Z + L_4}{L_9X + L_{10}Y + L_{11}Z + 1} \qquad 4.3.1$$

$$y_c + \delta y = \frac{L_5X + L_6Y + L_7Z + L_8}{L_9X + L_{10}Y + L_{11}Z + 1} \qquad 4.3.2$$

where:

x_c, y_c are the measured comparator coordinates of an image point,
XYZ are object space coordinates,
δx, δy are systematic errors due to lens distortion and film deformation, and
$L_1 - L_{11}$ are the eleven DLT parameters.

Although the linear components of lens distortion and film deformation are modelled by the standard DLT equations the non-linear components are ignored. In 1974 Karara and Abdel Aziz (1974) included additional parameters to model these non-linear components. The additional parameters include an odd powered polynomial to model symmetrical lens distortion and the Conrady function to model asymmetrical lens distortion. The function is of the form:

$$\delta x = x_c^c\,(K_1r^2 + K_2r^4 + K_3r^6) + P_1(r^2 + 2x_c^{c2}) + 2P_2x_c^cy_c^c \qquad 4.4.1$$

$$\delta y = y_c^c\ (K_1 r^2 + K_2 r^4 + K_3 r^6) + P_2(r^2 + 2y_c^{c2}) + 2P_1 x_c^c y_c^c \qquad 4.4.2$$

where:

x_{pc}, y_{pc}	are comparator coordinates of the principal point;
$x_c^c = x_c - x_{pc}$;	
$y_c^c = y_c - y_{pc}$;	
$r^2 = x^{c2} + y^{c2}$;	
$K_1 - K_3$	are coefficients of symmetrical lens distortion; and
P_1, P_2	are coefficients of asymmetrical lens distortion.

Marzan and Karara released a documented listing of the Fortran source code for the DLT program (Marzan and Karara, 1975) and a copy of this was obtained. After some experience with this program it was felt that there were several areas where improvements were necessary. The program was 'off-line' and not interactive and there was no facility to obtain the coordinates of points once the DLT parameters had been derived. The only form of output was the DLT parameters, the inner orientation and the fit to the control points. In order to assess the suitability of the DLT approach, it was necessary in this thesis to rectify these problems. An 'on-line' version of the program was developed, called **DLTD**.

In the course of developing and testing DLTD a further problem was found with both the standard DLT and the developed program DLTD. The basic DLT function (Equation 4.3) provides a linear solution for a non-linear problem, it makes certain approximations and is therefore non-rigorous. In the basic DLT function the eleven DLT parameters are assumed to be independent. In reality there are only nine independent parameters; three positional and three rotational elements of exterior orientation and the three elements of primary inner orientation. Bopp and Kraus (1977) developed an exact solution of the DLT equations which is referred to as the '11 parameter solution'. In this the dependencies between the eleven parameters and the nine independent parameters are stated by adding two constraint equations to the observation equations. The two constraints are:

$$(L_1^2 + L_2^2 + L_3^2) - (L_5^2 + L_6^2 + L_7^2) + ((L_5L_9 + L_6L_{10} + L_7L_{11})^2 - (L_1L_9 + L_2L_{10} + L_3L_{11})^2)\ (L_9^2 + L_{10}^2 + L_{11}^2)^{-1} = 0 \qquad 4.5.1$$

$$(L_1L_5 + L_2L_6 + L_3L_7) - (L_9^2 + L_{10}^2 + L_{11}^2)^{-1} (L_1L_9 + L_2L_{10} + L_3L_{11})\ (L_5L_9 + L_6L_{10} + L_7L_{11}) = 0 \qquad 4.5.2$$

There are two ways to apply the two sets of constraints in a least squares solution. They can be incorporated directly in the estimation by enforcing the two additional constraints between the parameters. An alternative is to consider the constraints as additional observation equations with zero variances. Bopp and Kraus chose the second approach due to the critical limitations of computer speed and memory in 1978. Modern computers are not so limiting and so it was decided to apply the constraints directly in the least squares estimation. In matrix notation, the standard observation equations are:

$v_1 = A_1x - b$ with the weight matrix Q_1^{-1},
and $0 = A_2x - d$ as additional constraints.

The least squares solution leads to:

$$\hat{x} = (A_1^TQ_1^{-1}A_1)^{-1}\ (A_1^TQ_1^{-1}b + A_2^Tk)$$

$$\text{with } k = ((A_2(A_1^TQ_1^{-1}A_1)^{-1}\ A_2^T)^{-1}\ (d - A_2(A_1^TQ_1^{-1}A_1)^{-1}\ A_1^TQb) \qquad 4.6$$

As the constraints are non-linear the function has to be linearised using Taylors theorem. A direct solution is impossible and an iterative approach is required. In an iterative solution the unknowns are corrections to the parameters requiring estimation. The computation is repeated until the corrections become zero, when the solution has **converged**.

Another problem with the standard DLT and DLTD is that a full and rigorous propagation of variance is not performed. All comparator coordinates are assumed to have been measured with equal precision and a 'global' standard deviation is applied to the comparator coordinates in the estimation. For a full propagation of variance, the variances of each point on the two photographs should be taken into account. During reprojection, necessary to deduce the coordinates of new points, the covariance matrices of both sets of DLT parameters should be used to establish the standard errors of new points. In the standard DLT the covariance matrix for the first photograph is assumed to be identical to that of the second photograph, although this expediency was understandable considering the limitations of computer memory in 1975.

In order to solve the problems with the standard DLT and DLTD the program **DLTIT** was developed. This program enforced the two constraint equations (Equation 4.5) and provided a full propagation of variance. In outward appearance the two programs are similar, the only important difference is that the DLTIT program is iterative. Such a program produces the practical problem of providing reasonable starting values for the parameters that require estimation. This particular problem was solved by computing DLT parameters from a subset of the measured control points using the standard DLT function (Equation 4.4). All measurements are then used to estimate the DLT parameters and either 1,3 or five parameters of the function necessary to model lens distortion. Following successful convergence of the solution and the determination of the DLT and lens parameters, the coordinates of a new point can be estimated by measuring the image coordinates on the photographs. A full propagation of variance computes the standard error for this new coordinate.

4.3.1.2 Application

In order to critically appraise the new DLTIT program and to assess the suitability of the DLT approach with archival photographs, a 'test field' was established.

Photography was acquired with a variety of metric and non-metric cameras and restituted by the DLTIT program.

A test field was constructed between two buildings, by placing forty small targets upon walls and a large gate. This particular site was selected because it provided positions for targets that imaged over a large proportion of the negative and also provided a wide range of camera-object distances. A survey was carried out using both a **TC1** (Wild) and an **Elta** (Carl Zeiss-Jena) self reducing tacheometer and the coordinates of all targets were estimated using a least squares variation of coordinates program. Four pairs of photographs were obtained using a **UMK 10/1318** (Carl Zeiss-Jena) metric camera; a 70mm and 50 mm **Hasselblad** small format cameras; and a **Minolta** 35mm ´amateur´ camera.

For each pair of photographs the negative image positions of all visible targets were measured using a Stecometer (Zeiss-Jena) stereo-comparator. These measurements, the coordinates of twelve well spaced control targets and the DLTIT program were then used to determine the coordinates of the other remaining targets. A program was developed that could read two files of coordinates and

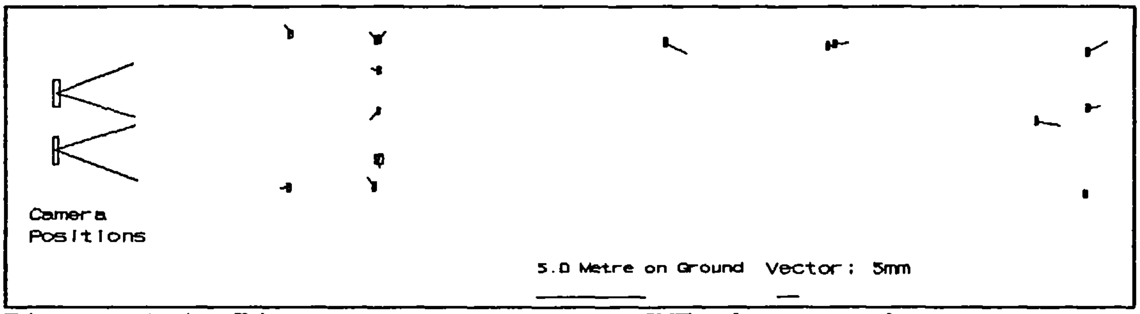


Figure 4.4 **Discrepancy vectors- UMK photography**

produce a plot illustrating the coordinate differences as vectors at an exaggerated scale. This program was used to produce a plot of discrepancy vectors using the estimated coordinates from DLTIT and those derived from the control survey, (UMK photographs, Figure 4.4). Similar plots were derived for the Hasselblad and Minolta photography (Figure

4.5). A comparison of the discrepancy vector plots produced

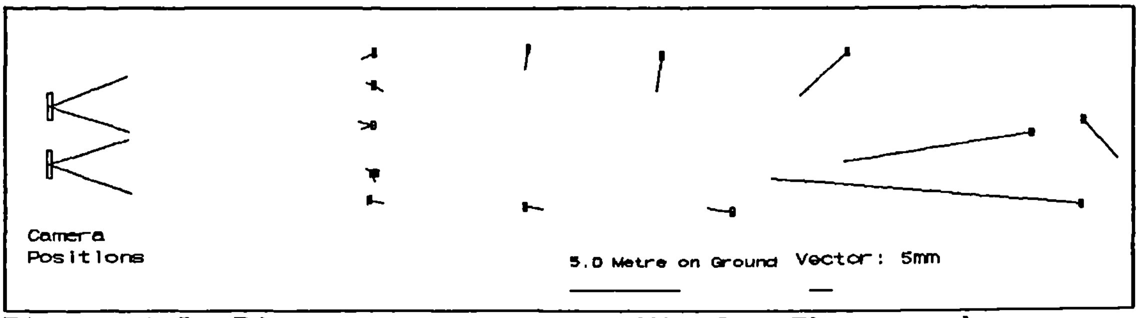


Figure 4.5 **Discrepancy vectors- Minolta Photography**

by each camera type could then yield some tentative conclusions about the DLTIT software and the DLT approach.

A comparison of the UMK results (Figure 4.4) with the Minolta plot (Figure 4.5) echo those reported by Karara and Abdel Aziz (1974) and Bopp and Kraus (1978). The cheaper 'non-metric' cameras produce results which are comparable to the metric camera, although the metric UMK camera was noticeably more accurate at the greater camera-object distances. It was found that the lens parameters were unnecessary for the metric camera, were significant in the case of Hasselblad cameras and surprisingly only just significant for the Minolta. As Karara and Abdel Aziz reported (1974) the higher parameters of the lens function were found to be irrelevant.

4.3.1.3 Discussion

Despite the success of the developments of DLT to make use of non-metric imagery, there remained a very important limitation that was apparent throughout the development and testing of the software. In order to use both DLTD and DLTIT there needs to be a minimum of six full three dimensional control points in the object space. If five lens parameters are used to model the lens, then eight control points are required. This is not a problem in close-range industrial photogrammetry, where the photogrammetry can be planned and sufficient control provided. In the case of archival photographs the photogrammetry cannot be planned and so the existence of this type of control information would be unlikely. It was decided that an alternative solution would have to be found and this became an important objective for the research programme.

4.3.2 Self Calibration Techniques

4.3.2.1 Previous developments

In addition to 'on-the-job' calibration, Faig (1975) identifies the 'self calibration' approach. This method appeared useful as, unlike DLT, an object space control field is not required to calibrate the camera. Additional control points do lead to a more precise solution, (Section 8.2.2.1) and although not necessary, are desirable. The only control requirements that are essential are the minimum necessary for definition of a datum, commonly two planimetric points and three vertical control points. For the restitution of archival photographs, a minimal amount of available control was envisaged.

Analytical self calibration techniques were first developed in America by Brown (1956) when the parameters of inner orientation were recovered simultaneously as the exterior orientation of a ballistic camera, (Kenefick *et al*, 1972). Further developments by Brown lead to the Simultaneous Multi- frame Analytical Calibration, (SMAC) which was used to calibrate aerial cameras '*in situ*'. With SMAC, *a priori* constraints of any of the exterior parameters or ground points could be applied by treating *a priori* knowledge as direct observations. Up to eight parameters were used to model aspects of the inner orientation, providing an error model for the lens inner cone, (Kenefick *et al*, 1972). The original application of self calibration methods was for simultaneous reduction of large photogrammetric blocks of vertical aerial photographs, (Ackermann *et al*, 1973; Ebner, 1976). A review of the evolution, application and potential of the method is given by Brown (1976) and the potential accuracy and reliability are discussed by Grün, (1982) and Förstner, (1985) respectively. The adjustment has subsequently become known as a **self calibrating bundle adjustment**, and has been modified and further developed by a variety of authors. Faig and Moniwa (Faig and Moniwa, 1973; Moniwa, 1976) developed the University of New Brunswick Analytical Self Calibration, called UNBASC2, (Karara, 1980). With UNBASC2, the coplanarity condition can be combined with the normal collinearity equations in situations where the geometric strength of the solution is low. Granshaw (1980) shows that multi-station convergent photography alone, can provide the geometric strength necessary for self calibration. Brown (1982) developed STARS, an all-inclusive close-range photogrammetric system combining a high quality terrestrial camera, desktop computer with an advanced self-calibrating bundle adjustment. More recent work has been carried out by Wester-Ebbinghaus (1985, 1986) who has looked at the geometric aspects of self-calibrating bundle adjustments. Important developments have also been made with the standard bundle adjustment. Wong and Elphingstone (1973); Faig and El-Hakim (1982) and Wester-Ebbinghaus (1985) discuss forms of control that are an alternative to conventional fixed coordinates, including distances and angles between points and azimuths. Fraser (1984) uses the 'free adjustment', this applies minimum constraints to define the datum and leads to a solution of optimum precision. The free adjustment has proved to be of considerable use in the detection of deformation in engineering structures, (Cooper, 1984).

4.3.2.2 Theoretical Overview

The basic theoretical aspects of self calibration methods are given by among others, Kenefick *et al*, (1972). The collinearity equations (Equations 4.2) provide the basic framework for the analytical self calibration. These are merely augmented with the functional model necessary for modelling of the cameras inner orientation. The extended collinearity equations are:

$$f_{1x}(x,l) = \frac{-c(r_{11}[X_i-X_0] + r_{21}[Y_i-Y_0] + r_{31}[Z_i-Z_0])}{(r_{13}[X_i-X_0] + r_{23}[Y_i-Y_0] + r_{33}[Z_i-Z_0])} \qquad 4.7.1$$

$$-x_i - x_p + x_i^c(K_1r^2 + K_2r^4 + K_3r^6) + P_1(r^2 + 2x_i^{c2}) + 2P_2x_i^cy_i^c = 0$$

$$f_{1y}(x,l) = \frac{-c(r_{12}[X_i-X_0] + r_{22}[Y_i-Y_0] + r_{32}[Z_i-Z_0])}{(r_{13}[X_i-X_0] + r_{23}[Y_i-Y_0] + r_{33}[Z_i-Z_0])} \qquad 4.7.2$$

$$-y_i - y_p + y_i^c(K_1r^2 + K_2r^4 + K_3r^6) + P_2(r^2 + 2y_i^{c2}) + 2P_1x_i^cy_i^c = 0$$

in which:

- x_i, y_i are the photo-coordinates of a point referred to the fiducial origin;
- x_p, y_p are the photo-coordinates of the principal point, assumed constant for all photographs;
- $x^c = x_i - x_p$,
- $y^c = y_i - y_p$,
- K_1, K_2, K_3 are correction coefficients for symmetric radial distortion, assumed constant for all photographs;
- P_1, P_2 are correction coefficients for de-centring distortion, assumed constant for all photographs; and
- c is the focal length, assumed constant for all photographs.

The Rotation Matrix R is defined by:

$$\begin{bmatrix} r_{11} & r_{21} & r_{31} \\ r_{12} & r_{22} & r_{32} \\ r_{13} & r_{23} & r_{33} \end{bmatrix} = \begin{bmatrix} \cos\phi\cos k & \cos w\sin k - \sin w\sin\phi\cos k & \sin w\sin k + \cos w\sin\phi\cos k \\ -\cos\phi\sin k & \cos w\cos k + \sin w\sin\phi\sin k & \sin w\sin k - \cos w\sin\phi\sin k \\ -\sin\phi & -\sin w\cos\phi & \cos w\cos\phi \end{bmatrix}$$

Equation 4.8

Where w, ø and k are rotations around the X,Y and Z axis.

The extended collinearity equations (Equation 4.7) can be used to estimate unknown parameters using the principles of least squares. An 'observation equation' approach can be used because measurements and parameters are separated in the function model. The function is non-linear and so it is necessary to linearise equation 4.7 using Taylors expansion, which involves deriving the partial differential coefficients of the function with respect to each parameter. If the linearised extended collinearity equations are gathered together, the collection of observation equations may be written in matrix notation as:

$$A_1 \, x \;=\; b_1 \;+ v_1 \; ; \text{ with cofactor matrix } Q_1 \qquad 4.9$$

$$\begin{bmatrix} \frac{\delta f_1}{\delta x} \end{bmatrix} \begin{bmatrix} x \end{bmatrix} \;=\; -f_1(x,l) \;+\; v \;;\quad Q_1 \qquad 4.10$$

where:

A_1 are the partial differentials of the extended collinearity equations (Equation 4.7) with respect to all estimated parameters (x);

$\frac{\delta f_1}{\delta x} = A_1$

v_1 is the vector of photo-coordinate residuals;

x vector of parameters to be estimated;

b_1 vector of the ´observed minus computed terms;´ and

Q_1 The cofactor matrix associated with all photo-coordinates.

Three groups of parameters may be distinguished in a self-calibrating bundle adjustment: the unknown exterior and interior orientation parameters; the coordinates of unknown object points; and those object points with known coordinates and standard deviations. The vector of parameters can be partitioned to represent these three groups, in the form:

$$x = \begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dddot{x} \end{bmatrix} \begin{matrix} \text{coordinates of unknown object points;} \\ \text{coordinates of object points with known standard deviations;} \\ \text{exterior and interior orientation parameters.} \end{matrix}$$

If the extended collinearity equations are considered initially, then Equation 4.9 becomes:

$$\begin{bmatrix} \dot{A}_1 & \ddot{A}_1 & \dddot{A}_1 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dddot{x} \end{bmatrix} = b_1 + v_1 ; \quad Q_1 \qquad 4.11$$

Where:

$\dot{A}_i$, $\ddot{A}_i$, $\dddot{A}_i$ are the matrices containing the partial differentials of the extended collinearity equations with respect to each group of parameters.

The coordinates and associated standard deviations of certain object points may be known from another source, as in the case of control points, (Section 5.2.4.3). A series of observation equations associated with these points can be written, of the form:

$$\ddot{x} = \ddot{b} + \ddot{v} \quad ; \quad \text{with cofactor matrix } \ddot{Q} \qquad 4.12$$

Equation 4.11 becomes:

$$\begin{bmatrix} \dot{A}_1 & \ddot{A}_1 & \dddot{A}_1 \\ 0 & I & 0 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dddot{x} \end{bmatrix} = \begin{bmatrix} b_1 \\ \ddot{b} \end{bmatrix} + \begin{bmatrix} v_1 \\ \ddot{v} \end{bmatrix} \; ; \; \begin{bmatrix} Q_1 & \\ & \ddot{Q} \end{bmatrix} \qquad 4.13$$

If survey measurements between object points have been obtained then it is possible to incorporate these into the least squares estimation, although a different set of functional models are required, (Section 5.2.4.1). The additional observation equations associated with measurements between points are of the form:

$$A_2 \, x = b_2 + v_2; \quad \text{with cofactor matrix } Q_2 \qquad 4.14$$

Equation 4.13 becomes:

$$\begin{bmatrix} \dot{A}_1 & \ddot{A}_1 & \dddot{A}_1 \\ 0 & I & 0 \\ \dot{A}_2 & \ddot{A}_2 & 0 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dddot{x} \end{bmatrix} = \begin{bmatrix} b_1 \\ \ddot{b} \\ b_2 \end{bmatrix} + \begin{bmatrix} v_1 \\ \ddot{v} \\ v_2 \end{bmatrix} \; ; \; \begin{bmatrix} Q_1 & & \\ & \ddot{Q} & \\ & & Q_2 \end{bmatrix} \qquad 4.15$$

Equation 4.15 can be represented by:

$$\bar{A}\ \bar{x} = \bar{b} + \bar{v};\ \bar{Q} \qquad 4.16$$

The normal equations are then:

$$(\bar{A}^T\ \bar{Q}^{-1}\ \bar{A})\bar{x} = (\bar{A}^T\ \bar{Q}^{-1}\ \bar{b}) \qquad 4.17$$

and the least squares estimate of the unknown parameters is:

$$\hat{\bar{x}} = (\bar{A}^T\ \bar{Q}^{-1}\ \bar{A})^{-1}\ (\bar{A}^T\ \bar{Q}^{-1}\ \bar{b}) \qquad 4.18$$

The self calibrating bundle adjustment is a flexible and powerful computational technique. The groups of parameters included above do not necessarily need to be implemented and others can be identified also. This flexibility and the limited requirement for object space control points suggested that the self-calibrating bundle adjustment could be of considerable use for the archival photogrammetric technique. For the purpose of applying this particular estimating procedure to the restitution of archival photographs the following problems were identified:

1). The functional model represented by Equation 4.7 had to tested and perhaps modified for use with archival photographs. Statistical aspects of the functional model also needed to be considered, so that a suitable stochastic model could be identified and selected. The effects of ignoring film deformation would have to be assessed.

2). The use of a large scale topographic map as a source of ground control could create problems. Methods of obtaining other control information would be required and means of employing all data to maximum benefit would need to be utilized.

3). With iterative procedures such as a self-calibrating bundle adjustment, the problem of obtaining high quality starting values for the parameters to be estimated remained an important practical restriction.

4). It was hoped to use a recently acquired analytical plotter to obtain data from archival photographs. The software that was supplied with this instrument was developed for the application of mapping from vertical aerial photographs. Consequently, it was envisaged that models consisting of convergent oblique photographs would be difficult to adapt for use with this instrument. Furthermore any spatial data that was acquired and further processed, had to be geomorphologically significant.

An overview of the archival photogrammetric technique is given in Section 5.1 and the development of all software including the self calibrating bundle adjustment is discussed in Section 5.2. Application of the technique and integration with the analytical plotter is discussed in Section 6.3 and 6.5.

Chapter 5

The Technique and its Development

5. The Technique and its Development

5.1 An Overview of the Archival Photogrammetric Technique

There are six steps associated with the archival photogrammetric technique. Although these are carried out sequentially they should not be considered independent. Figure 5.1 indicates the varying proportions of geomorphological and photogrammetric content and the approximate time and therefore cost associated with each. The most important section is photogrammetric processing and a component of this is the self-calibrating bundle adjustment. This program solves the problems associated with using archival photographs for photogrammetric measurement, discussed in Section 4.2.

Figure 5.1 The Archival Photogrammetric Technique

Time (Days)	**Activity**
31-100	Photo Acquisition
1-2	Identification and Derivation Of suitable Control
0.5	Photo Measurement
2-3	Photogrammetric Data Processing
1-5	Data Acquisition
1-30	Data Processing Data Presentation Interpretation

Photogrammetry
Geomorphology

5.1.1 Acquisition of the photographs

The initial task is to identify and obtain archival photographs from one of the sources discussed in Section 2.3. Geomorphological considerations are important at this stage as the exact area of interest and the ideal dates of the photographic epochs need defining. In addition, to indicate the minimum size of morphological change that the geomorphologist hopes to be able to identify. This may be smaller than the standard deviations of the coordinates that can be obtained with the technique, in which case either an alternative approach may be considered or the aims must be redefined.

Photogrammetric considerations are important also. A minimum of two overlapping photographs are required at any one epoch, with photographs obtained with one single camera. Additional photographs are desirable, although the geometrical arrangement defined by the photographs is an important consideration, (Section 8.2.2.1). There are two conflicting interests. For a reliable estimation of the exterior and interior orientation parameters, convergent multi-station geometry is desirable, (Granshaw, 1980). In order to determine the coordinates of a large number of points, stereoscopic measurements must be taken. If a pair of photographs is highly convergent then the operator will experience eye strain and severe discomfort. Ideally it may be possible to select a non-convergent pair of photographs from a set that are generally convergent, (Section 8.2.2.1; Figure 8.1). The choice also depends upon the style of data processing that is envisaged. If displacement vectors are required at a few key points, then a convergent multi-station approach is preferable. The more general data processing options require the acquisition of thousands of data points and so some form of stereopair is a practical necessity. Conventional vertical stereopairs are not essential, although these are comfortable to view, whilst oblique stereopairs possess additional advantages. Oblique photographs provide a more familiar perspective of the landscape, which can be useful for interpretation, (Matthews and Clayton, 1986). In addition, convergent oblique photographs often lead to object coordinates of greater homogenous precision, (Section 8.2.2.1).

Another problem associated with the selection of suitable photography is the identification of points on the photographs that will serve as control points. In general these will be points of hard detail such as corners of buildings and other man-made structures. Control points should be on stable ground so that they can be assumed to be stationary throughout the period of time defined by the relevant epochs. If necessary, the extent of the site can be increased to include sufficient control points that fulfil these objectives.

The selection of photography is often determined by availability. The user of the archival photogrammetric technique is unable to design the ideal camera-object configuration and will have to make use of whatever photography is available, at approximately the desired date. The archival photogrammetric technique provides the photogrammetric flexibility necessary to make a large part of the archive usable. The user must be flexible when deciding upon which photography is adequate for the project.

Once suitable photography has been identified, it is necessary to obtain contact diapositives from the original negatives. This is not normally a problem if the source is an established archive, but may be more difficult in the case of museums and personal collections. The whole task of photo-acquisition can take up to three months, although most of the time is spent waiting for cover-searches to be carried out and for the eventual supply of selected diapositives.

5.1.2 Identification and Derivation of Control

The object space coordinate system is generally a three dimensional right handed cartesian system and is used in photogrammetry to define three dimensional information, (Section 4.1.2, Figure 4.3). This system is entirely arbitrary and needs to be located in space by defining the seven elements of a datum. These can be defined in a variety of ways, although the simplest is to define or '**fix**' the XYZ coordinates of two points and to fix the height of a third. In photogrammetry such points are known as control points and are used both to define a datum and to form the basis of the functional relationship between the photographs and the ground coordinate system. As mentioned in Section 4.2, one of the main problems with historical photography is the lack of stable control points in the object space, which can define a datum. Control can be established by a combination of one of two methods with the archival photogrammetric technique.

Control can be provided by using a local large scale plan. In the UK this will generally take the form of the Ordnance Survey (OS) 1:2,500 or 1:1,250 series map which can be obtained unfolded from OS map dealers, (Down, 1987). This can be used to provide planimetric positions of points that are identifiable on both the photography and the map. The coordinates can be determined by measuring the positions of points relative to the national grid with careful use of a scale ruler. Spot heights and OS Bench Marks can provide vertical control points which do not necessarily have to be well defined plan points. The map will define a datum if a minimum of two planimetric points and three height points are obtained. More control points are desirable and these should be distributed over the whole site. The increased redundancy will enable the detection of any scaling errors and increase the final precision of the parameters estimated in the self-calibrating bundle adjustment. OS maps are cast upon the Transverse Mercator projection and so the definition of the datum by points coordinated from the OS plan will not strictly define a rectangular cartesian coordinate system. The systematic errors that are introduced are small and the main component is a scale error. This varies from 0.9996 to 1.0004 over the whole country and the relevant scale factor can be determined from the OS projection tables (Anon, 1950). The effects of any unknown scale factor are actually indeterminate in a self-calibrating bundle adjustment as there is a very high correlation (Section 8.2.4.3) between the scale of the object and the focal length of the camera. For this reason the scale error can be safely ignored, providing that the same scale is used for all photographic epochs. A related influence is the effect of earth curvature and this source of systematic error is examined in Section 8.2.3.4.

Control can also be provided in the form of measurements between points, (Wong and Elphingstone, 1973; Faig and El-Hakim, 1982; 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. It must then be remembered that any measured distances must be reduced to the projection, by applying the local projection scale factor.

An estimate of the standard deviation of the scaled coordinates and the measurements must be made as the stochastic properties of these data are taken into account in the self-calibrating bundle adjustment. Measurements which are reliable are weighted more highly than unreliable measurements. This allows control information derived from a variety of sources to be combined systematically in a least squares estimation procedure.

5.1.3 Photographic Measurement

With the control points identified on the photographs the next stage is to measure the image coordinates of the points. If there are sufficient scaled control points to dispense with 'natural' measurements, then the plates can be measured monoscopically. Normally natural points will be required in order to provide natural forms of control. Such points are difficult to re-identify and so stereoscopic measurement is preferred. The photography that has been acquired should be divided into 'pairs' or **stereoplets**[1], and measured with either a stereo-comparator or an analytical plotter. Each point should be measured at least three times and given some form of numeric identifier. It should be possible to measure the image coordinates to a precision of 3-5 micrometres.

The comparator will provide a file of point coordinates in an arbitrary two dimensional comparator coordinate system. In order to transform these into photo-coordinates it is necessary to measure the image positions of reference or fiducial marks. Normal vertical air photography will possess either four or eight fiducial marks which define the position of the principal point. Most other photography will not contain such fiducial marks, although large format or reconnaissance type photography can contain reference marks which may define the principal point. The uncertainty associated with the recovery of the principal point from fiducials of unknown quality is solved because the displacements of the principal point are unknown parameters in the self-calibrating bundle adjustment. All that is required are some form of reference marks which can be used to define a photo-coordinate system. The only requirement is that these marks are constant for all photographs, are readily identifiable and can be used to define a point that

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[1] The term **stereoplet** is used in this thesis to refer to a pair of photographs that was not originally acquired specifically for stereoscopic viewing, but may be used in this way.

is in a similar position to the actual principal point. The corners of the format are normally suitable, although these sometimes appear rounded under magnification. If this is the case then the edge of the format on all four sides can be defined by a series of points. These format points can be used to obtain a central point using the 'format side method', as used by Smith (1987).

5.1.4 Photogrammetric Processing

Photogrammetric processing consists of running sequentially a suite of four programs. Their function is to establish the relationship between the photographs and the ground and to determine the interior orientation of the camera. It is then possible to obtain the coordinates of new points using an intersection calculation. The theoretical aspects of these programs are considered in Section 5.2.

The first program **STEC_CON** (Section 5.2.1) transforms the comparator coordinates of the measured points into photo-coordinates. The measurements to the reference or fiducial marks are used to define the origin and orientation of this coordinate system. This program is repeated for each photograph that has been measured.

The photo-coordinates are then used in the program **COP** (Section 5.2.2) which performs a relative orientation for each stereoplet by enforcing the coplanarity condition. The left hand camera is assumed to be fixed and the right hand camera is allowed to rotate and translate until the coplanarity condition is met. Scale is defined by a b_x component of unity and an approximate focal length is required for the least squares estimation procedure. After relative orientation, the program computes **model coordinates** for all measured points and the two perspective centres of the cameras.

Program **SIM** (Section 5.2.3) then carries out a three dimensional similarity or conformal transformation, based upon the control points which now have coordinates in both the model and ground coordinate system. The derived parameters are then used to transform all model coordinates into approximate ground coordinates. The COP and SIM programs are then re-run for the remaining stereoplets, until approximate object space coordinates have been computed for all measured points and cameras.

The final program is the **block-invariant self-calibrating bundle adjustment** and is the most important, (Section 5.2.4). In this the unknown parameters are the interior and exterior orientation of the cameras and the coordinates of any unknown points. These parameters are estimated by incorporating photo-coordinates, control coordinates and any additional measurements between points into a rigorous functional model based upon the collinearity equations. The stochastic properties of all of the photo-coordinates, ground coordinates and measurements are used in the estimation so that the precision of the estimated parameters can be derived. The program uses an iterative least squares estimation procedure, in which the unknowns in the solution are corrections or increments to the relevant parameters. Such a program requires high quality starting values in order to achieve convergence and the positional parameters are provided by the programs COP and SIM. The rotational elements of exterior orientation are not computed and approximate values need to be judged, whilst the interior orientation parameters are assumed to be zero initially.

5.1.5 Data Acquisition

When a satisfactory estimation has been obtained, it is possible, using the estimated exterior and interior parameters, to extract the coordinates of new points anywhere on the site. The basic data unit for all photogrammetrically based methods is the coordinate and these can be combined in a variety of ways to provide graphical and numerical data in the form of, maps and plans, direct profiles and contours, digital terrain models (DTM) and displacement vectors. The coordinates necessary for the production of vectors can be estimated during the self-calibrating bundle adjustment, in which case no further measurement is necessary. Other forms of data require a more general approach for which additional measurement is required. This can be carried out using a stereo-comparator, but is more effective if an analytical stereoplotter is used. The City University has recently acquired the Intergraph InterMap Analytic (IMA) photogrammetric workstation, which allows for two forms of data extraction:

(1) Feature Coding- delineation of boundaries, with lines of varying colours, line-type and thicknesses.

(2) DTM collection- acquisition of a regular or grid DTM of varying size and density.

Both of these programs enable high rates of data extraction, approaching 5,000 points per day.

5.1.6 Data Processing/Presentation and Interpretation

All acquired spatial data are stored on computer file in a form that can be analysed and displayed at a graphics workstation. Geomorphological requirements become important at this stage because a wide variety of data forms can be presented:

5.1.6.1 Maps and Plans

The delineation of the boundaries between distinctive land units is a basic requirement in the production of both conventional and geomorphological maps. In geomorphology the identification and classification of morphological boundaries is an important first step in the interpretation and understanding of process.

5.1.6.2 Direct Profiles and Contours

The down slope vertical profile and cross section are commonly used in geomorphology to illustrate the mechanisms of slope failure. Profiles and sections also provide a basic framework for subsequent slope stability analyses and for the design of remedial measures. Contours are widely used to represent relief and form on most topographic maps. Photogrammetry can be used to obtain both profiles and contours directly and provide the only practical means of obtaining high quality and high density data. A single plot displaying the same profile or contour from two epochs will enable a direct and quantitative morphogenetic comparison to be made.

5.1.6.3 DTM Data Processing

The techniques mentioned in Section 5.1.6.1; 5.1.6.2 provide two dimensional representations of spatial data. Digital terrain modelling techniques use three dimensional data in order to provide either graphical or statistical forms of output. It is these techniques that exploit more fully the spatial quality of these data. Several processing options are available including the production of contour and isometric plots; surfaces of difference; slope angle maps; volume calculations; predictive evolutionary models. These techniques rely upon complex computing algorithms and require both a powerful computer system and a comprehensive DTM software package.

5.1.6.4 Computation of Displacement Vectors

The archival photogrammetric technique can be used to provide three dimensional vectors at specific points. These vectors represent movement at a point and with a network of such points, the pattern of displacements over a site.

5.2 Photogrammetric Data Processing Software

As mentioned in the overview (Section 5.1), photogrammetric processing consists of a suite of four programs. The programs are run sequentially and Figure 5.2 indicates the function of each.

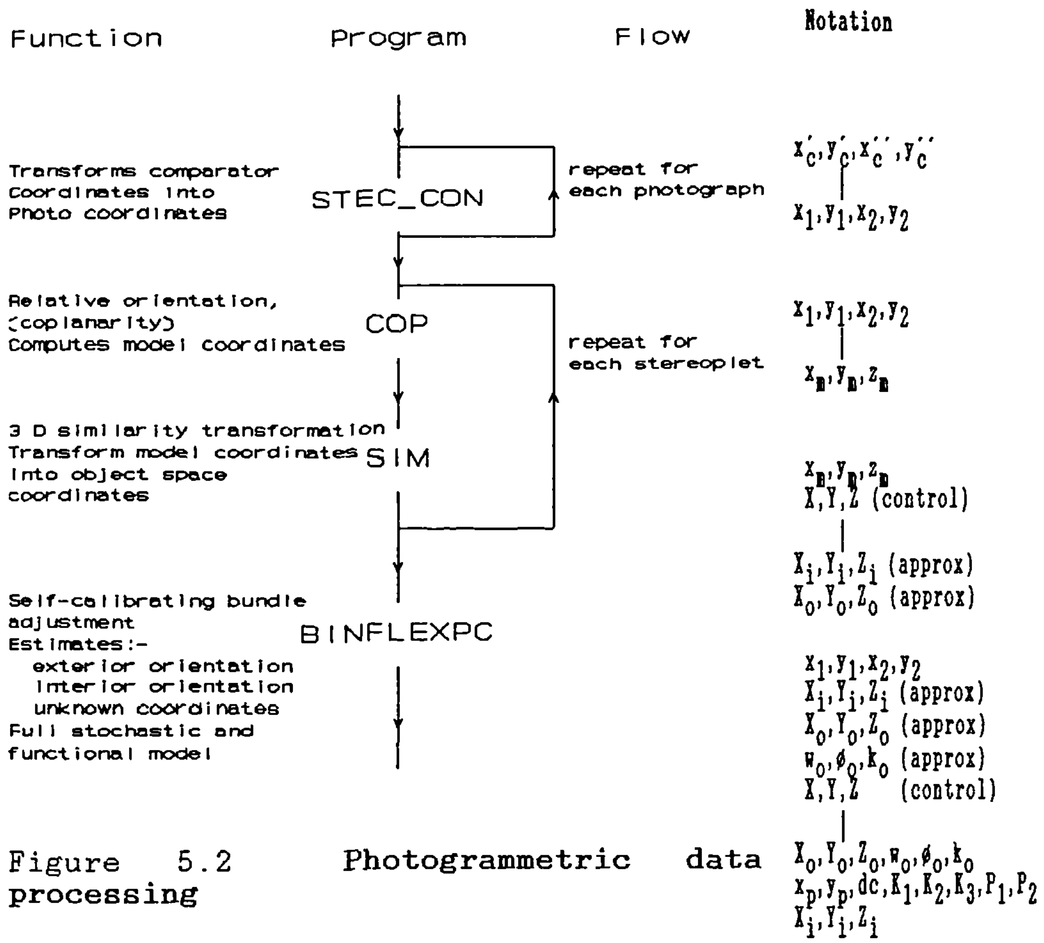


Figure 5.2 Photogrammetric data processing

It is possible to run the self-calibrating bundle adjustment directly after the photo-coordinates have been computed. There is then a practical problem of obtaining starting values for the estimated parameters that are sufficiently close to the final values. If the geometrical arrangement defined by these values is incorrect then convergence will not be achieved and the program will fail. The programs COP and SIM provide suitable starting values for the spatial coordinates associated with both measured points and cameras, although camera rotations need to be judged. The secondary benefit accrued by high quality starting values is that the number of iterations necessary before the solution converges is kept to a minimum. The two extra programs solve an important practical problem associated with bundle adjustments and can save considerable time.

All the programs were written in FORTRAN 77 and have been developed to run on a variety of computers, including GOULD PN9005 super-mini, VAX 730 and an IBM AT personal computer. Due to the requirements of forming and inverting a large matrix in the self-calibrating bundle adjustment, processing speed can become a problem with large projects, particularly on the PC. More efficient routines to form and invert the matrix could be developed to lessen this practical problem, (Section 9.3).

5.2.1 STEC_CON

Program STEC_CON transforms the file of comparator coordinates, produced during the measurement of a photograph, into photo-coordinates. The origin and rotation of the photo-coordinate system is defined by the measured reference or fiducial marks. The program computes a mean and standard deviation for all common measured points, the latter is based upon the measurements to each point and a mean standard deviation computed for all reference marks. A file is created that stores the photo-coordinates and their standard deviations.

There are two theoretical parts of the program which are important. In a two dimensional photo-coordinate system there are three datum elements that need to be established. Scale is defined by the measurements themselves because each unit represents one micrometre. These values are derived by the encoders of the comparator, which are calibrated during routine servicing. The positional element of the datum is assigned by defining the origin of the photo-coordinate system at the intersection of two imaginary lines (**fiducial axes**) between opposite reference marks, (Figure 5.3). This

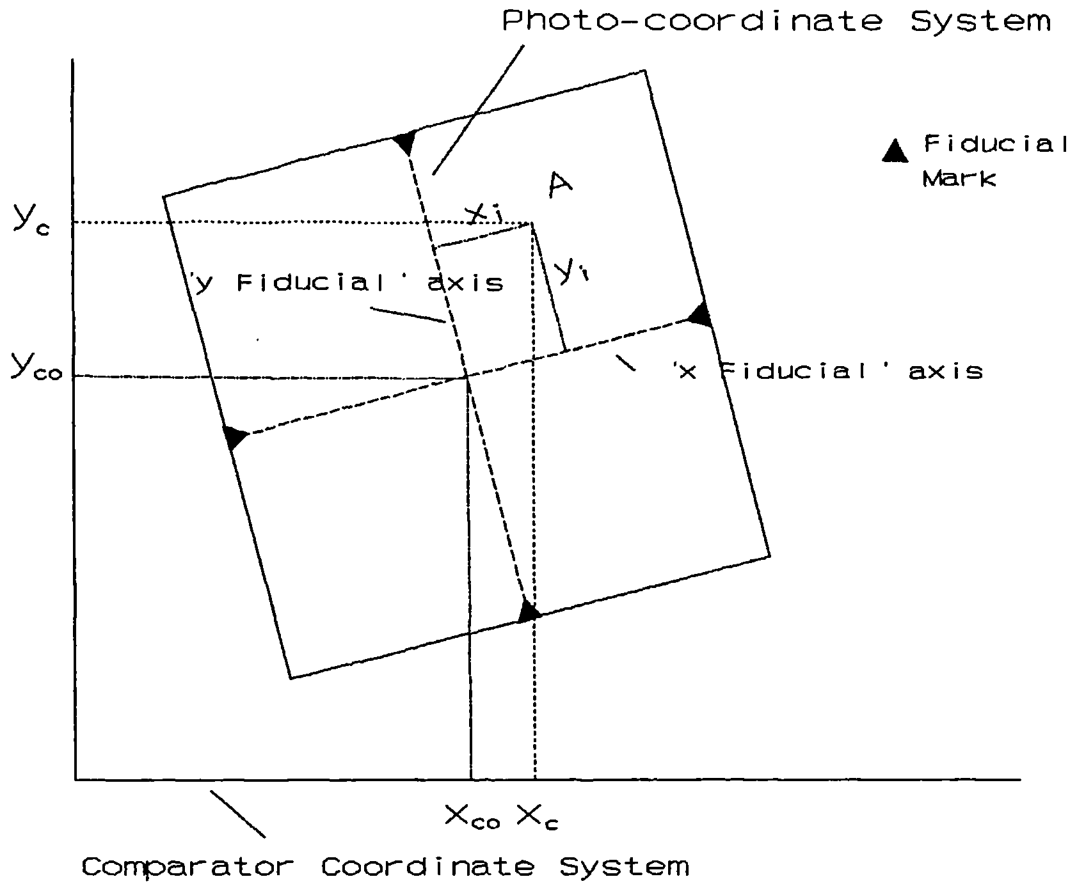


Figure 5.3 **Transformation from comparator to photo-coordinate systems**

position is determined in the comparator coordinate system by evaluating the equations of the x and y fiducial axes and computing their intersection algebraically. The third datum element is a rotation and is defined in terms of the mean gradient of the two fiducial lines.

Once a photo-coordinate system has been defined, it is possible to transform the comparator coordinates into the new photo-coordinate system. This transformation is based upon the plane coordinate transformation:

$$x_i = (x_c - x_{co}) \cos(\alpha) + (y_c - y_{co}) \sin(\alpha) \quad 5.1.1$$

$$y_i = -(x_c - x_{co}) \sin(\alpha) + (y_c - y_{co}) \cos(\alpha) \quad 5.1.2$$

Where:

x_i, y_i photo-coordinates;
x_c, y_c comparator coordinates;
x_{co}, x_{co} comparator coordinates of the intersection of fiducial axes; and

α a function of the mean gradient of fiducial lines.

The program was originally developed by J.S. Clark at City University, for use with metric photography and specifically for photography where the fiducial marks are positioned on the sides of the format. This proved to be unsuitable for non-metric photography, especially where the corners of the format were used to define the photo-coordinate system. The existing algorithm necessary to compute the rotation assumed that the x and y fiducial axes were approximately perpendicular. Ninety degrees were added to the y fiducial gradient and this value and the gradient of the x fiducial line were used to compute a mean x fiducial gradient. If corner reference marks are used with rectangular format photography, the two axes are not perpendicular and the rotation computed using the existing algorithm is incorrect. The program was therefore modified to compute a mean fiducial gradient directly from the x and y fiducial lines, without the addition of ninety degrees.

The program is run for each measured photograph and the new photo-coordinates are appended to the file '**pcds**'. This eventually contains all of the photo-coordinates in the project, with each set of coordinates distinguished by a numeric 'plate' or photo identifier. Typical output from the program may be found in the Section 10.2.1.

5.2.2 COP

The function of the program COP is to obtain a file of model coordinates for the points that have been measured in any one stereoplet. These model coordinates represent, at an arbitrary scale and orientation, the correct spatial relationships between the two cameras and the points whose image positions have been measured. The program achieves this in two stages. Firstly a numerical relative orientation is carried out, based upon the condition of coplanarity. Then a series of intersection or reprojection calculations computes model coordinates of points, using the estimated camera parameters and measured photo-coordinates. For both stages, the functional models assume that a fully metric camera has been used. For the purpose of computing high quality starting values for the self-calibrating bundle adjustment, this assumption has proved valid.

The numerical relative orientation uses the condition of coplanarity. If the coplanarity condition is enforced, the

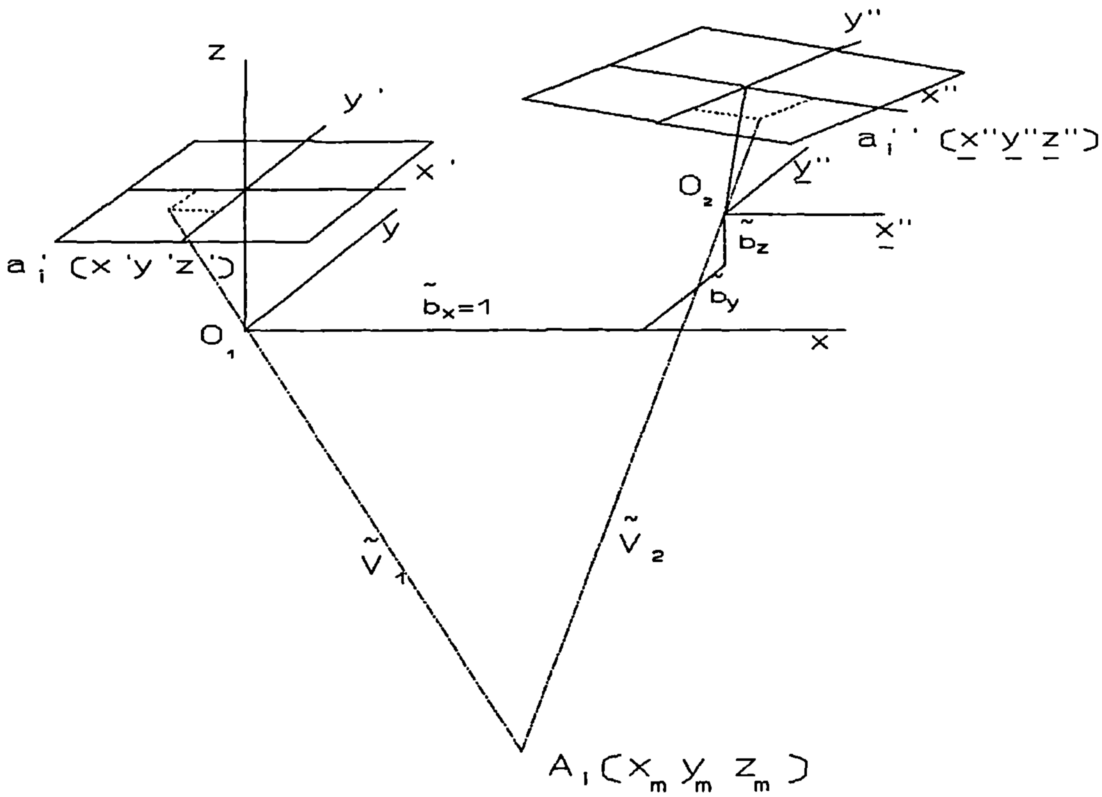


Figure 5.4 **Relative orientation using Coplanarity**

two perspective centres, any object point and the corresponding image points on a pair of photographs (Figure 5.4), must all lie in a common plane (Ghosh, 1979). When this condition is achieved the vector $\tilde{V}_1$ will intersect with the vector $\tilde{V}_2$ and these two vectors together with the photo-base vector $\tilde{b}$ will be coplanar. In such a case the triple scalar product is zero:

$$\tilde{b} \cdot \tilde{V}_1 * \tilde{V}_2 = 0 \qquad 5.2$$

where:

$$\tilde{b} = \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} \qquad \tilde{V}_1 = \Gamma_1 R_1 \begin{bmatrix} x_i' \\ y_i' \\ z_i' \end{bmatrix} \qquad \tilde{V}_2 = \Gamma_2 R_2 \begin{bmatrix} x_i'' \\ y_i'' \\ z_i'' \end{bmatrix} \qquad 5.3$$

and:

x' y' z'	are photo-coordinates of the photograph 1;
$x''y''z''$	are photo-coordinates of the photograph 2;
R_1, R_2	are the rotation matrices for the photographs 1 and 2, as defined by equation 4.8; and
Γ_1, Γ_2	are scale factors of corresponding location vectors within the camera spaces.

A datum for the model coordinate system must be defined and can be chosen to be identical to the photo-coordinate system of the left hand camera, or photograph 1. Ghosh (1979) refers to this as the **Dependent Method of Relative Orientation**. This simplifies the general case of the coplanarity condition because the matrix R_1 becomes the identity matrix. The B_x component of the photo-base $\tilde{b}$ can be assigned to be equal to unity and the two scale factors Γ_1, Γ_2 can be assumed to be equal, so defining the scale of the model coordinate system. The vectors $\tilde{V}_1$ and $\tilde{V}_2$ are then simplified:

$$\tilde{V}_1 = \begin{bmatrix} x_i' \\ y_i' \\ z_i' \end{bmatrix} \qquad 5.4$$

$$\tilde{V}_2 = \begin{bmatrix} x_i'' \\ y_i'' \\ z_i'' \end{bmatrix} = R \begin{bmatrix} x_i'' \\ y_i'' \\ z_i'' \end{bmatrix} \qquad 5.5$$

where:

z' z''	are equivalent to the focal lengths of the two cameras, (-c); and
R	is the rotation matrix of the right hand camera relative to the left hand camera.

In determinant form the triple scalar product may be written as:

$$\begin{vmatrix} 1 & x_i' & x_i'' \\ b_y & y_i' & y_i'' \\ b_z & z_i' & z_i'' \end{vmatrix} = 0 \qquad 5.6$$

The functional model is therefore:

$$f(x,l) = (y_i'z_i'' - y_i''z_i') - x_i'(b_y z_i'' - b_z y_i'') + x_i''(b_y z_i' - b_z y_i') = 0 \qquad 5.7$$

One coplanarity condition equation can be written for each pair of photo-coordinates and as the coordinates of the object point do not appear in the function, a solution can be determined without any coordinate information in the object space. The only data that are required are the photo-coordinates of images in a pair of photographs and an approximate focal length. There are five unknowns in the solution: B_y, B_z, w, ø, k and so a minimum of five pairs of well distributed photo-coordinates are required for a solution. A least squares procedure can be used if there are redundant data, as is the preferred case.

There are two approaches that can be used in the least squares estimation, a rigorous and a non-rigorous method. The standard fully rigorous solution requires the 'general case' least squares solution as both measurements and parameters appear in the functional model. This is of the form:

$$A\,x + B\,v = b$$

$$\underset{nm_p}{\left[\frac{\delta f}{\delta x} \right]}^{5}_{5} \left[x \right]^{1} + \underset{nm_p}{\left[\frac{\delta f}{\delta l} \right]}^{nm_p}_{nm_p} \left[v \right]^{1} = -f(x,l) \qquad 5.8$$

and the solution of the unknown parameters is given by:

$$\hat{x} = (A^T(BW^{-1}B^T)^{-1}A)^{-1}\, A^T(BW^{-1}B^T)^{-1}b \qquad 5.9.$$

where:

nm_p	is the number of photo-coordinates;
$\frac{\delta f}{\delta x}$	are the partial differentials of the function (5.7) withrespect to the estimated parameters B_y, B_z, w, ∅, k;
$\frac{\delta f}{\delta l}$	are the partial differentials of the function (5.7) with respect to the measurements x´,y´,x´´,y´´; and
W	is the weight matrix of the measurements.

The simpler non-rigorous method is to use an observation equation approach and ignore the stochastic model. This is of the form:

$$A\,x \;= b + v$$

$$\underset{nm_p}{\left[\;\frac{\delta f}{\delta x}\;\right]^{5}}\;\underset{5}{\left[\;x\;\right]^{1}} \;=\; -f(x,l) \;+\; v \qquad 5.10$$

and the solution is given by:

$$\hat{x} = (A^T\;W\;A)^{-1}\;A^T\;W\;b \qquad 5.11$$

A rigorous alternative is to combine these two approaches by extending the observation equation method. This can be achieved by carrying out a full propagation of variance of the photo-coordinates through the functional model. The resulting covariance matrix can then be used in place of the matrix W in equation 5.11. This will produce results identical to those of the general case solution.

The purpose of performing the numerical relative orientation is to derive model coordinates for all measured points. The relative orientation parameters (b_y,b_z,w,∅,k) are used to derive exterior orientation parameters for each camera, in the model space, (X_{0m},Y_{0m},Z_{0m},w_m,$∅_m$,k_m). These data and the photo-coordinates are then combined in a functional model based on the collinearity equations (Equation 4.2) to determine model coordinates. For each point, four observation equations are written for each of the photo-coordinates, (x´,y´,x´´,y´´). A least squares solution is then used to estimate the three unknown coordinates (x_m,y_m,z_m), in the model coordinate system.

Finally, the computed model coordinates and derived model camera parameters are used directly in the collinearity equations to establish computed photo-coordinates. These new values are subtracted from the original measured values to produce photo-coordinate residuals. These residuals indicate the degree with which the measured photo-coordinates fit the functional model. If the measurements all have large residuals then it is likely that the approximate focal length of the cameras is incorrect. This can be modified and the program can be rerun. Alternatively, one or two measurements may have high residuals, indicating poor measurement and these may be deleted cautiously from the solution. There is of course the assumption that the camera is fully metric and so some systematic errors will be expected. Despite this the photo-coordinate residuals are a useful early indicator of possible problems, they also suggest the degree to which the camera's inner orientation will require modelling in the self-calibrating bundle adjustment.

To run the program COP, the file of photo-coordinates derived by the program STEC_CON is required. If there are more than two photographs to process then the photo-coordinate file will need to be divided into a series of files, each containing the photo-coordinates of a stereoplet. Each file will require individual processing; consisting of running the program COP and SIM sequentially. The program COP requires the relevant file of photo-coordinates of a stereoplet and an estimated focal length of the left and right hand cameras. A series of iterations are performed and after convergence the unknown parameters (B_y, B_z, w, ϕ, k) of the coplanarity solution are printed, with associated standard deviations. A choice is then made either to continue and store the output into a file or to abort the program. If continued, the camera parameters deduced by the coplanarity solution are stored in a file called '**fcam**'. The model coordinates of the measured points are then computed along with the photo-coordinate residuals and these are stored in a file called '**fmod**'. The output of a typical coplanarity solution is given in Section 10.2.2.

Both rigorous and non-rigorous coplanarity solutions were originally developed. However, the simpler non-rigorous solution was eventually selected as this was perfectly adequate for the purposes of providing starting values suitable for the self-calibrating bundle adjustment. The systematic errors created by an incomplete functional model are of greater importance than an incomplete stochastic model, and are insufficiently large to prevent the determination of high quality starting values.

The second stage of the program made use of two subroutines developed by D.M. Stirling at The City University, for a space resection program. The subroutine 'proj' computes the XYZ model coordinates from known exterior orientation parameters and four measured photo-coordinates. The subroutine 'reproj' computes photo-coordinates from XYZ coordinates and the exterior orientation parameters.

5.2.3 SIM

The purpose of program SIM is to transform the model coordinates computed by the coplanarity solution into the ground or object space coordinate system. This provides the positional starting values for the self-calibrating bundle adjustment. The program achieves this by carrying out a <u>three dimensional similarity</u> or <u>conformal transformation, with over-determination</u>. There are two stages in the three dimensional similarity transformation. Firstly the transformation parameters are evaluated, using knowledge of at least three points with coordinates in both the model and ground coordinate systems. Then, using these parameters, all remaining model coordinates can be transformed into the ground coordinate system.

The theoretical aspects of a three dimensional similarity transformation are well documented in the literature, (Ghosh, 1979; Slama, 1980; Wolf, 1983 and Cooper, 1987). The approach followed in this solution is given by Albertz and Kreiling (1975). The stochastic model is ignored in the Albertz and Kreiling (1975) approach and although this is non-rigorous, the method is justified in this thesis for two reasons. Firstly, there is some suggestion that if two sets of coordinates are un-correlated, then the approach is actually rigorous (Cooper, 1987). With coordinate systems derived from different sources it can often be assumed that no such correlation is present. Second, for the purpose of computing starting values for the self-calibrating bundle adjustment a rigorous solution was not essential, especially when used in conjunction with the non-rigorous coplanarity solution. The full functional model is:

$$f(x,l) = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} - \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} + \Gamma \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \begin{bmatrix} x_M \\ y_M \\ z_M \end{bmatrix} = 0 \qquad 5.12$$

where:

x_M, y_M, z_M	are model coordinates;
X, Y, Z	are ground or object space coordinates;
X_S, Y_S, Z_S	are three translational elements;
$r_{11}-r_{33}$	are the rotational elements of the rotation matrix given by equation 4.8; and
Γ	is a scale factor.

There are seven transformation parameters that need to be determined in a three dimensional similarity transformation. These are equivalent to the seven datum elements that need to be defined in a three dimensional coordinate system. There are three translational elements (X_S, Y_S, Z_S), three rotational elements (w, ø, k) and a scale factor (Γ).

All seven elements are determined by considering the coordinates of points which are common to both the model and the ground coordinate system. The three translational elements can be determined directly from the two sets of coordinates. The four remaining parameters require a least squares solution for their determination. The solution is iterative as the function is non-linear and takes the form:

$$\underset{nm \times 4}{A} \quad \underset{4 \times 1}{x} = b + v$$

$$_{nm}\left[\frac{\delta f}{\delta x} \right]^{4} {}_{4}\left[x \right]^{1} = -f(x,l) + v \qquad 5.13$$

and the solution is given by:

$$\hat{x} = (A^T W A)^{-1} A^T W b \qquad 5.14$$

where:

nm	is the number of common ground coordinates;
$\frac{\delta f}{\delta x}$	are the partial differentials of the function 5.12; with respect to the estimated parameters w, ø, k, α; and
W	is the weight matrix, assumed to be the identity matrix.

Albertz and Kreiling (1975) identify eight software steps that are necessary to estimate the seven parameters. Firstly mean model and ground coordinates are computed from the points that are present in both systems. These are used to determine a new series of model and ground coordinates by subtracting the mean model and ground coordinates from the existing values for each point. The third step assigns the three rotations to zero and uses the new model and ground coordinates to compute an approximate scale factor using the function:

$$\Gamma = \frac{\Sigma[\sqrt{(X^2 + Y^2 + Z^2)}]}{\Sigma[\sqrt{(x_m^2 + y_m^2 + z_m^2)}]} \qquad 5.15$$

where:

X,Y,Z	ground coordinates relative to the mean ground point.
x_m, y_m, z_m	model coordinates relative to the mean model point.

$\Sigma[\sqrt{}]$ Summation of the square root of the terms contained.

The fourth step forms the rotation matrix (r_{11} - r_{33}) using the latest values for the rotations substituted into equation 4.8. The fifth step computes ground coordinates for each common point using the model coordinates and the latest values of the parameters in the functional model. These values are then used in the sixth step which forms part of the A^TA and the A^Tb matrices. The fifth and sixth steps are then repeated for each common point until the matrices are formed in their entirety. The A^TA matrix is then inverted and then post-multiplied by the A^Tb matrix, so computing corrections to the four parameters requiring estimation. Finally, in the seventh step the corrections are applied to the previous values. Steps four to seven are then repeated until the estimated corrections become zero and the solution converges.

After convergence, the model coordinates of the points used in the solution are used in the functional model with the estimated transformation parameters to compute ground coordinates. These values are subtracted from the original values to determine residuals, so indicating the degree of fit between the estimated and the original control values. The residuals are then used to determine an *a posteriori* variance factor which provides a global measure of the quality of the solution.

The second stage of the program uses the three dimensional similarity transformation to establish ground or object space coordinates for the remaining model points which have not been used in the solution. This uses the full functional model (Equation 5.12) using the parameters that have been estimated. The function can also be written:

$$X = X_s + \Gamma(r_{11}x_m + r_{12}y_m + r_{13}z_m) \qquad 5.16$$

$$Y = Y_s + \Gamma(r_{21}x_m + r_{22}y_m + r_{23}z_m) \qquad 5.17$$

$$Z = Z_s + \Gamma(r_{31}x_m + r_{32}y_m + r_{33}z_m) \qquad 5.18$$

where:

X_s, Y_s, Z_s	are the mean coordinates of the common ground points.
x_m, y_m, z_m	are the difference between the model coordinates and the mean model coordinates.
$r_{11}-r_{33}$	are elements of the rotation matrix, derived from w, ∅ and k.
Γ	is the scale factor.

The program can be used to perform a three dimensional similarity transformation between any two cartesian coordinate systems, provided that both are right handed and three dimensional. Two files are required, a file of control or ground coordinates and a file of model coordinates. With the archival photogrammetric technique, the former is derived from the large scale plan as indicated in Section 5.1. The file of model coordinates is provided by the coplanarity solution, program COP. This includes model coordinates for both the measured points and the perspective centres of the two cameras, (file: 'fmod').

The program reads the files containing control and model coordinates and selects those points with coordinates in both systems for determining the transformation parameters. A minimum of three common points are required, if there are less, the solution is indeterminate and the program stops. If there are more than three points the program performs the eight steps outlined above. After the least squares solution has converged, the residuals of the control points are printed and the option is given to continue the program and store the output, or to stop. If the residuals are acceptable the program is continued and two files are created, examples are contained in Section 10.2.3. File '**fpar**' is used to store the transformation parameters and associated standard deviations. File '**fsta**' is used to restore the original ground coordinates used in the solution and to store the transformed model coordinates. There are three index numbers which are stored with each coordinate. '1 1 1' indicates a point used during the estimation of the transformation parameters, '0 0 0' indicates a transformed coordinate. The indices are required in the self-calibrating bundle adjustment and their function is explained in Section 5.2.4.1. Two of the transformed model coordinates represent the perspective centres of the two cameras used in the coplanarity solution, in the ground coordinate system. These are appended to the file '**fcam**' originally created by the program COP, (Section 10.2.3).

During the development of the program SIM a very important practical problem was discovered. If two or more of the required rotational parameters are greater than ninety degrees, then a negative scale factor is computed and the least squares solution fails to converge. One method of solving this problem is to estimate the transformation parameters between a 'temporary' model system and the ground coordinate system. The temporary system can be defined by simply mapping the axes of the existing model system onto the axes of the ground coordinate system. For example, (Figure 5.5) the model coordinate system can be mapped onto the ground system by swapping the y and z model axis and changing the sign of the new y axis. The x axis remains unchanged in this example. The rotations required between the temporary model system and the ground coordinate system are then all less than ninety degrees and a solution is possible. This approach was developed and provided a solution to the problem, although it does introduce an extra input in which the user must be aware of the spatial relationships between the model and the ground coordinate systems. The program

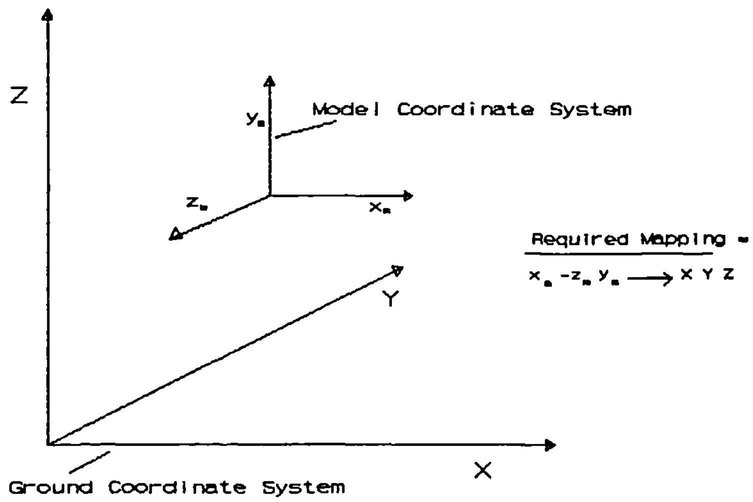


Figure 5.5 **Mapping the Model to Ground Coordinate System**

ceases to be a 'black box', although it can be argued that this is beneficial.

By operating the programs COP and SIM sequentially, starting values are provided for all positional parameters required for the self-calibrating bundle adjustment. Both programs only operate for one stereoplet and if more than one pair has been measured then programs COP and SIM must be repeated until starting values have been determined for all points and cameras, (Figure 5.2).

5.2.4 The Self-calibrating Bundle Adjustment

The self-calibrating bundle adjustment is the most important component of photogrammetric data processing. It is this program which solves most of the problems associated with archival photographs discussed in Section 4.2. The main role of the self-calibrating bundle adjustment is the estimation of interior and exterior orientation parameters for all photographs used in a solution at any one epoch. With these obtained, any pair suitable for comfortable stereo-viewing can be selected and used to determine the coordinates of new points. This is achieved merely by setting up the pair on the stereo-comparator or analytical plotter, re-measuring the positions of the reference marks and re-establishing the inner and exterior orientation using the parameters estimated from the bundle adjustment. New coordinates can then be determined by simply measuring the relative image positions of a point. The self-calibrating bundle adjustment is of crucial importance as any errors in the establishment of the inner and exterior orientations will be transmitted to those coordinates which are eventually extracted. A fully rigorous solution is therefore essential. The functional model must adequately represent the geometrical aspects of the camera and object and the relationships between them. The stochastic model must also enforce the comparative reliability between measurements and allow them to propagate through the function. This propagation will enable the quality of the estimated parameters to be assessed and allow the standard deviations of the extracted coordinates to be derived.

An historical review of the development of self-calibrating techniques is given in Section 4.3.2.1. The self-calibrating bundle adjustment that was written in this thesis developed from a standard bundle adjustment and amendments were implemented because practical application forced modifications to be made. The theoretical framework associated with the final developed program is given in Section 4.3.2.2. Early program development depended upon a series of generated data files. These test data were created from a file of station coordinates which represented an imaginary cube. By using these values and imaginary camera interior and exterior orientation parameters it was possible to compute photo-coordinates by direct use of the collinearity equations. These data were used to test the software initially and to prove that the programs were operating correctly.

The real test of the software and more importantly the functional and stochastic models contained within the bundle adjustment, was to apply the technique to archival photographs. The test site used for testing the archival photogrammetric technique was a complex of landslides in Dorset named Black Ven. The nature of this site is discussed in Section 6.1. The first test epoch consisted of two oblique photographs taken of the site in 1958 by Cambridge University, (Section 6.3.2; Plates 6.1; 6.2). Both images are of high quality and as the format is dominated by the landslide, appear to have been taken comparatively close to the feature. Points which appeared on both the photography and the Ordnance Survey 1:2,500 plan were identified and OS grid coordinates derived. The image coordinates of these points and other well defined points distributed over the site, for which no coordinates were available, were measured on a stereo-comparator, (Section 5.1; 6.3.1). Application of the archival photogrammetric technique to this test photography resulted in major modifications to the self-calibrating bundle adjustment. Each modification is associated with a different program name, the titles indicating the nature of the latest improvement. The program was originally called BUNFIX followed by BINFIX, BINFLEX and finally BINFLEXPC. Although important elements of the self-calibrating bundle adjustment were introduced in Section 4.3.2.2, it is still necessary to discuss the development of each version of the program.

In order to illustrate the significance and reasons associated with each development, a Figure showing photo-coordinate residuals and a statistical test on the quadratic form of the least squares corrections, (Cooper, 1987) accompanies each section. The data used to produce each Figure (Figures 5.6-5.9) were obtained by processing the Black Ven 1958 test data with each of the developed programs. The same data are used in each case and so the stochastic properties of the measurements remain constant. This allows both the functional and stochastic models used in each program to be compared, consequently the Figures and the statistical tests can be used to assess the efficacy of each program to restitute archival photographs.

5.2.4.1 <u>BUNFIX</u>

The self-calibrating bundle adjustment was actually developed from a standard bundle adjustment program called BUNFIX, written by J.S. Clark, a research assistant in the Department. BUNFIX was developed for fully metric photography and could estimate the exterior orientation of up to ten cameras. The program could incorporate object space coordinates which were either 'free' or 'fixed'. The former referred to object points with unknown coordinates, whilst the latter referred to known object point coordinates, although any standard deviations associated with these coordinates could not be incorporated. A minimum of seven 'fixed' points were required in order to define a datum and survey measurements between points could be included in the estimation procedure, (Section 4.3.2.2).

It was decided to develop further the existing BUNFIX program in this thesis, as it possessed several advantages. The program was coded in Fortran 77, was concisely written and was also well documented. Most importantly for archival photographs, there were two additional factors. The separation of the control coordinates into the X,Y,Z components ensured that both planimetric and height control could be used directly. It was envisaged that this form of coordinated control point would perhaps be the only type available for archival photography, (Section 4.2). Secondly, the ability to include measurements between points had been provided, which appeared a flexible additional form of control that could be important with archival photographs.

The main functional model used in the program is the standard collinearity equations, (Equation 4.2):

$$f_{1x}(x,l) = \frac{-c(r_{11}[X_i-X_0] + r_{21}[Y_i-Y_0] + r_{31}[Z_i-Z_0])}{(r_{13}[X_i-X_0] + r_{23}[Y_i-Y_0] + r_{33}[Z_i-Z_0])} - x_i = 0 \qquad 5.19.1$$

$$f_{1y}(x,l) = \frac{-c(r_{12}[X_i-X_0] + r_{22}[Y_i-Y_0] + r_{32}[Z_i-Z_0])}{(r_{13}[X_i-X_0] + r_{23}[Y_i-Y_0] + r_{33}[Z_i-Z_0])} - y_i = 0 \qquad 5.19.2$$

in which:

- x_i, y_i are the photo-coordinates of a point referred to the indicated principal point as the origin;
- c is the focal length, assumed constant for all photographs.
- r_{11}-r_{33} are the elements of the rotation matrix as defined in equation 4.8.
- X_0 Y_0 Z_0 are the position of the perspective centre of the camera in the object space coordinates system.
- X_i Y_i Z_i are the position of object points in the object space coordinates system.

An observation equation approach can be used to estimate the unknown parameters, consisting of: the exterior orientation of the cameras (X_0,Y_0,Z_0,w,ϕ,k) and any unknown coordinates (X_i,Y_i,Z_i). The solution is non-linear and so an iterative solution is required. Using the notation and framework developed in Section 4.3.2.2, Equation 4.9, the observation equations for the collinearity equations are of the form:

$$A_1\ x \;=\; b_1 + v_1\ ; \quad \text{with cofactor matrix } Q_1 \qquad 5.20$$

$$\underset{2*nm_p}{\left[\frac{\delta f_1}{\delta x}\right]^{(ni*3)+(np*6)}} \begin{bmatrix} \dot{x} \\ \dots \\ x \end{bmatrix}^{1} = -f_1(x,l) + v_1\ ; \quad Q_1 \qquad 5.21$$

where:

$\frac{\delta f_1}{\delta x}$	are the partial differentials of the function with respect to the unknown parameters;
$\dot{x}$, x	is a vector of the estimated parameters: object point coordinates and exterior orientation parameters, respectively;
v_1	is a vector of residuals;
ni	is the number of points with coordinates to be estimated;
np	is the number of photographs; and
nm_p	number of photo-coordinates.

Additional functional models are required for measurements between points:

<u>Slope distances</u>

$$f_2(x,l) = [(X_2 - X_1)^2 + (Y_2 - Y_1)^2 + (Z_2 - Z_1)^2]^{½} \quad -s = 0 \qquad 5.22$$

<u>Horizontal distances</u>

$$f_2(x,l) = [(X_2 - X_1)^2 + (Y_2 - Y_1)^2]^{½} \quad -d = 0 \qquad 5.23$$

<u>Height differences</u>

$$f_2(x,l) = (Z_2 - Z_1) \quad -h = 0 \qquad 5.24$$

<u>Horizontal Angle</u>

$$f_2(x,l) = \arctan[(X_3 - X_1)/(Y_3 - Y_1)] - \arctan[(X_2 - X_1)/(Y_2 - Y_1)] \quad -\theta = 0 \qquad 5.25$$

Vertical Angle

$$f_2(x,l) = \arccos \{(Z_2 - Z_1)/[(X_2 - X_1)^2 + (Y_2 - Y_1)^2 + (Z_2 - Z_1)^2]^{½}\} - \mu = 0 \qquad 5.26$$

where:

$X_1\ Y_1\ Z_1$ are the coordinates of point 1;
$X_2\ Y_2\ Z_2$ are the coordinates of point 2;
$X_3\ Y_3\ Z_3$ are the coordinates of point 3;
s, d, h are the measured slope, horizontal and height differences respectively; and
θ, μ are the measured horizontal and vertical angle respectively.

The additional observation equations associated with survey measurements (Section 4.3.2.2; Equation 4.14) are of the form:

$$A_2 \quad x \quad = b_2 \quad + \quad v_2; \text{ with cofactor matrix } Q_2 \qquad 5.27$$

$$\underset{nm_0}{\left[\frac{\delta f_2}{\delta x} \right]^{(ni*3)}} \left[\dot{x} \right]^1 = -f_2(x,l) + v_2 \qquad 5.28$$

where:

$\frac{\delta f_2}{\delta x}$ are the partial differentials of the survey functions with respect to the unknown object point parameters;
v_2 is a vector of survey residuals; and
nm_0 is the number of survey measurements.

Combining equations 5.21 and 5.28

$$\bar{A} \quad \bar{x} \quad = \quad \bar{b} \quad + \quad \bar{v} \ ; \quad \bar{Q} \qquad 5.29$$

The normal equations are then:

$$(\bar{A}^T \bar{Q}^{-1} \bar{A})\bar{x} \quad = \quad (\bar{A}^T \bar{Q}^{-1} \bar{b}) \qquad 5.30$$

and the least squares estimates of the parameters are:

$$\hat{\bar{x}} \quad = (\bar{A}^T \bar{Q}^{-1} \bar{A})^{-1} (\bar{A}^T \bar{Q}^{-1} \bar{b}) \qquad 5.31$$

Three or optionally four files are required by the program. One file contains the photo-coordinates that were produced from comparator measurements and processing with the program STEC_CON. A file of camera parameters contains the approximate starting values for the exterior orientations of each camera. A station coordinate file contains the coordinates of points used in the solution, each point with an associated index. Points that are regarded as known or 'fixed', possess an index of '1 1 1' and these points define the datum. The starting values of points that are to be regarded as unknowns or 'free' have an index of '0 0 0'. Any combination is possible and so for example, a point that is fixed in plan will possess an index of '1 1 0'. The final optional file contains the measurements between points. Each measurement possesses an index to indicate the nature of the measurement. For example, an index of '-1' indicates a horizontal distance, Table 5.1 gives a full list.

Table 5.1 Types of Measurements and associated Index

Measurement	Index
Horizontal distance	-1
Slope distance	0
Height difference	1
Horizontal Angle	2
Vertical Angle	3

The plot of photo-coordinate residuals produced using the Black Ven 1958 test data in association with BUNFIX is shown in Figure 5.6. The two superimposed graphs display the residuals in the x and y photo-coordinate directions and the numbers along the X axis of the graph are a selection of point identifiers. The points are ranked in order of measurement and are grouped with respect to the type of control that each represents. The first digit of each identifier indicates the nature of control that is associated with each point, (Section 5.1.2; 6.1.2; 10.2.4). A prefix of '1' symbolises an OS control point; '2' indicates a sedimentary point and '3' a point with no associated control information.

The size of the photo-coordinate residuals and the very large *a posteriori* variance factor shown in Figure 5.6

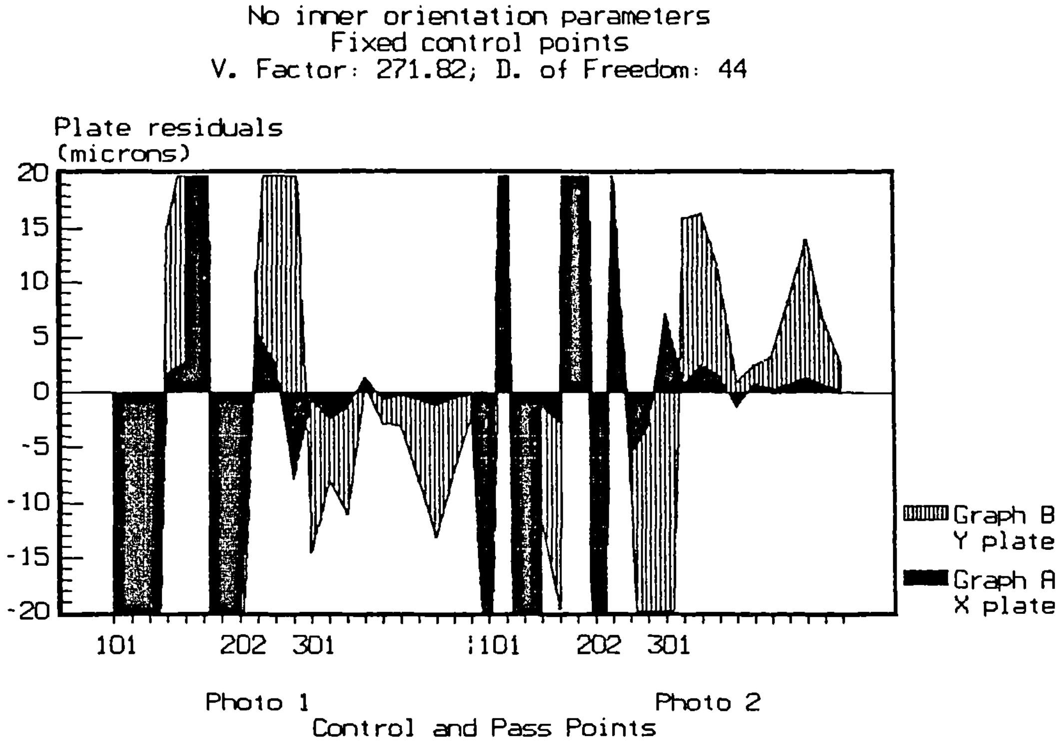


Figure 5.6 **Photo-coordinate residuals- BUNFIX**

illustrates that a standard non-self-calibrating bundle adjustment is totally inadequate for the restitution of this type of photography. The internal geometry of the camera is incorrectly assumed to be completely known and the result confirms the second requirement associated with archival photographs, (Section 4.2) that some form of camera calibration is vital.

5.2.4.2 BINFIX

The first essential development of the existing bundle program BUNFIX was to include parameters to model the inner orientation of the camera. The program could then be classified as a 'self-calibrating bundle adjustment' and this appeared to be the most important modification required for archival photography. There were two groups of inner orientation parameters that needed to be modelled. Firstly the primary inner orientation parameters, which model the displacement (x_p, y_p) of the principal point and a correction to an assumed focal length (dc). Secondly, a number of parameters to model radial and tangential lens distortion. Radial distortion was approximated by using one or three parameters of an odd powered polynomial (K_1, K_2, K_3). Tangential distortion was modelled using the Conrady function (P_1, P_2). There could be no explicit modelling for film deformation as it was envisaged that in general no calibrated fiducial or reseau data would be available.

The full functional model is:

$$f_{1x}(x,l) = \frac{-c(r_{11}[X_i-X_0] + r_{21}[Y_i-Y_0] + r_{31}[Z_i-Z_0])}{(r_{13}[X_i-X_0] + r_{23}[Y_i-Y_0] + r_{33}[Z_i-Z_0])} \quad 5.32.1$$

$$-x_i - x_p + x_i^c(K_1r^2 + K_2r^4 + K_3r^6) + P_1(r^2 + 2x_i^{c2}) + 2P_2x_i^cy_i^c = 0$$

$$f_{1y}(x,l) = \frac{-c(r_{12}[X_i-X_0] + r_{22}[Y_i-Y_0] + r_{32}[Z_i-Z_0])}{(r_{13}[X_i-X_0] + r_{23}[Y_i-Y_0] + r_{33}[Z_i-Z_0])} \quad 5.32.2$$

$$-y_i - y_p + y_i^c(K_1r^2 + K_2r^4 + K_3r^6) + P_2(r^2 + 2y_i^{c2}) + 2P_1x_i^cy_i^c = 0$$

where:

x_p, y_p are the photo-coordinates of the principal point, assumed constant for all photographs;

$x_i^c = x_i - x_p$;

$y_i^c = y_i - y_p$;

K_1, K_2, K_3 are correction coefficients for symmetric radial distortion, assumed constant for all photographs; and

P_1, P_2 are correction coefficients for de-centring distortion, assumed constant for all photographs.

The inner orientation parameters can be included in various combinations and initially it was felt that hierarchical selection would be suitable. The program was therefore coded to allow 0, 2 or 3 primary parameters and 0, 1, 3, or 5 parameters for lens distortion. The approach was that used by Karara and Abdel Aziz (1974) and does have the restriction that to estimate certain 'higher' parameters the lower parameters must also be included. For example, to incorporate the focal length as an unknown, both parameters for the displacement of the principal point require estimation.

The inner orientation parameters can be incorporated into a self-calibrating bundle adjustment in two ways. Theoretically it is possible to estimate a series of calibration parameters for each individual camera, which introduces as many as eight extra unknowns per camera. An alternative is to assume that all photographs in the estimation were obtained with a single camera and therefore only one set of inner orientation parameters apply. The former approach is a **block-variant solution**, the latter is **block-invariant**. It would appear that the block-variant solution is more useful as it allows a single bundle adjustment to be computed from photographs obtained from a variety of cameras and therefore sources. Although the program was coded for both approaches, it was clear from early tests that the block-variant solution was unsuitable for two reasons. The addition of inner orientation parameters produces a solution that is more unstable than a standard bundle adjustment because of correlation between parameters, (Section 8.2.4.3). Several sets of inner orientation parameters, necessary for a block-variant approach, were found to compound this problem because each set of parameters were themselves correlated. If the geometry defined by the photographs and the measurements (Section 8.2.2.1) is strong enough then these additional parameters can be reliably estimated. In the case study selected for this thesis, the archival photographs and available control defined geometry of insufficient strength and it is suggested that this will often be the case with historical photographs. It was also realised that a block-variant solution would seldom be required in practice. All photography must be obtained at the same time in order to be considered to represent a single photographic epoch. The chance of obtaining photographs from different sources, whilst still the same date, would be slim. The block-invariant solution appeared the most suitable and practicable approach.

The original BUNFIX program made economical use of array storage and this principle was retained in the development of the self-calibrating bundle adjustment. This was achieved by several methods. Firstly, only the upper triangular part of the $A^TQ^{-1}A$ matrix is actually stored, due to the symmetrical nature of the matrix. Also, both the $A^TQ^{-1}A$ and the $A^TQ^{-1}b$ matrices are formed directly without ever forming the A matrix in its entirety. No measurements are stored in arrays and so there is theoretically no limit to the number of photo-coordinates and survey measurements that can be incorporated into the solution. Each measurement is read and used to form the relevant elements of a row of the A matrix. In the case of photo-coordinates, two rows of the A matrix are formed and used in two routines that add the relevant elements to the $A^TQ^{-1}A$ and $A^TQ^{-1}b$ matrices.

For photo-coordinates the structure of the A_1 matrix can be illustrated by:

$$\begin{array}{c} x_1 \\ y_1 \\ \vdots \\ x_m \\ y_m \end{array}\left[\begin{array}{l} X_1\ Y_1\ Z_1\ -\ -\ X_n\ Y_n\ Z_n,\ X_{01}\ Y_{01}\ Z_{01}\ w_1\ \phi_1\ k_1,\ -\ -\ X_{0c}\ Y_{0c}\ Z_{0c}\ w_c\ \phi_c\ k_c, x_p, y_p, dc, k_1, k_2, k_3, P_1, P_2 \\ X_1\ Y_1\ Z_1\ -\ -\ X_n\ Y_n\ Z_n,\ X_{01}\ Y_{01}\ Z_{01}\ w_1\ \phi_1\ k_1,\ -\ -\ X_{0c}\ Y_{0c}\ Z_{0c}\ w_c\ \phi_c\ k_c, x_p, y_p, dc, k_1, k_2, k_3, P_2, P_1 \\ \vdots \\ X_1\ Y_1\ Z_1\ -\ -\ X_n\ Y_n\ Z_n,\ X_{01}\ Y_{01}\ Z_{01}\ w_1\ \phi_1\ k_1,\ -\ -\ X_{0c}\ Y_{0c}\ Z_{0c}\ w_c\ \phi_c\ k_c, x_p, y_p, dc, k_1, k_2, k_3, P_1, P_2 \\ X_1\ Y_1\ Z_1\ -\ -\ X_n\ Y_n\ Z_n,\ X_{01}\ Y_{01}\ Z_{01}\ w_1\ \phi_1\ k_1,\ -\ -\ X_{0c}\ Y_{0c}\ Z_{0c}\ w_c\ \phi_c\ k_c, x_p, y_p, dc, k_1, k_2, k_3, P_2, P_1 \end{array}\right] \quad 5.33$$

Unknown coordinates (n*3) ¦ Exterior orientation of cameras (c*6) ¦ Interior Orientation 0,1 or 3 Primary 0,1,3 or 5 lens

Where each element refers to the partial differential of the function with respect to the estimated parameter.
and:

n number of ground coordinates, (ni);
c number of photographs or camera stations, (np); and
m number of photo-coordinates, (nm_p).

For additional measurements between points the structure of the A_2 matrix is: (Section 4.3.2.2; 5.2.4.1)

$$
\underset{nm_0}{}\begin{bmatrix} X_1 & Y_1 & Z_1 & - & - & X_n & Y_n & Z_n \\ \multicolumn{8}{c}{\text{Unknown coordinates}} \\ \multicolumn{8}{c}{(n*3)} \\ X_1 & Y_1 & Z_1 & - & - & X_n & Y_n & Z_n \end{bmatrix}^{(ni*3)} \qquad 5.34
$$

The first test of the programs developed for the archival photogrammetric technique was made with BINFIX as the final bundle adjustment program. Initial processing of the 1958 Black Ven photography was only partially successful. The coplanarity solution was satisfactory but the three dimensional similarity transformation produced residuals of up to 5 metres on points selected as control points. These were attributed to the assumption in the earlier programs that the camera was metric. It was expected that the self-calibrating bundle adjustment would be able to accommodate these systematic errors. A solution was obtained with the self-calibrating bundle adjustment, BINFIX, but this produced disappointing results. There was a poor fit onto the control points and large photo-coordinate residuals were present, which originally contributed to an *a posteriori* variance factor of forty. In addition, the inner orientation parameters appeared very unstable. The displacement of the principal point in the y direction was estimated to be 80mm, which could not be conceived to be realistic. The only encouraging aspect of the estimation was that it verified the solution determined by the three dimensional similarity transformation.

The plot of photo-coordinate residuals (Figure 5.7) produced using the more recent revised test data illustrates that a significant improvement is gained by the inclusion of estimable inner orientation parameters. A statistical test upon the quadratic form of the least squares corrections (Cooper, 1987) was carried out:

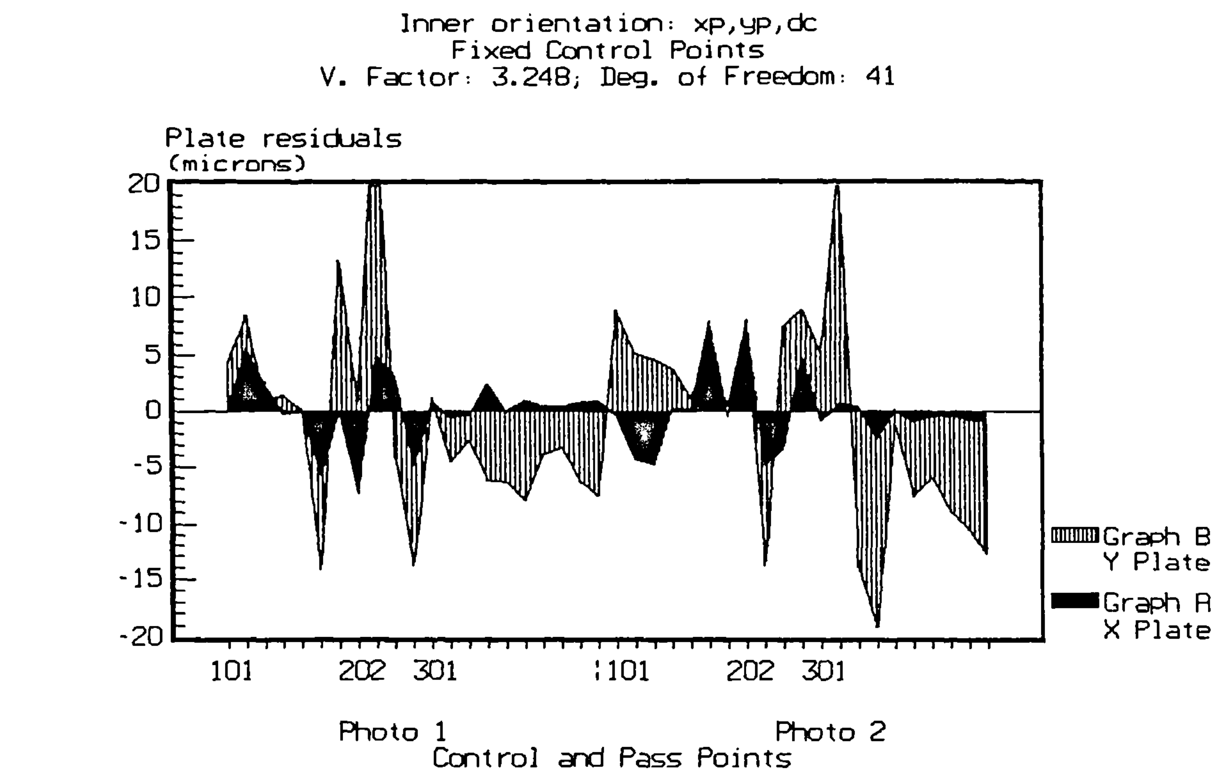


Figure 5.7 **Photo-coordinate residuals- BINFIX**

The null and alternative hypothesis are:

$$H_0 : \hat{\sigma}_0^2 = 1 \; ; \qquad H_1 : \hat{\sigma}_0^2 > 1$$

The test statistic is:

$$Y = \frac{r\ \hat{\sigma}_0^2}{\sigma_0^2} \sim \chi_r^2 \qquad 5.35$$

Where:

r	number of degrees of freedom, or redundancy;
$\hat{\sigma}_0^2$	*a posteriori* variance factor;
σ_0^2	*a priori* variance factor, (assumed equal to unity);
χ_r^2	the Chi squared distribution.

Substituting for values derived from BINFIX:

$Y = 41 * 3.248 = 133.2$

$\chi^2_{42,\,0.05} = 56$ (at the 0.05 significance level)

$133.2 > 56$; so reject H_0, accept H_1.

This statistical test shows that the *a posteriori* variance factor is significantly greater than the *a priori* value, at the 95% confidence level. Although the additional parameters have modelled the inner orientation of the camera, both the graph and the statistical test suggest that certain problems remain.

It was decided that the effect of fixing the control points was degrading the photogrammetrically measured photo-coordinates. During the derivation of the ground coordinates with a scale-rule, it was found that these could only be reliably estimated to a standard deviation of ± 1 metre. It was felt that if the stochastic nature of these measurements could be included into the overall estimation then the coordinates of points would be allowed to change or 'flex'. The degree of change would be controlled by the more precise photo-coordinates and so the photogrammetry would not be degraded by the comparatively poor control. The required modifications to BINFIX demanded a new title and so BINFLEX became the new version of the self-calibrating bundle adjustment.

5.2.4.3 BINFLEX

BINFLEX allows a standard deviation to be associated with each control coordinate and improves the stochastic model used in the self-calibrating bundle adjustment. The addition to the program may be described as an 'estimation using prior values and a cofactor matrix', although this includes only a subset of the full cofactor matrix. The terms on the leading diagonal of the cofactor matrix can only be used as it is impossible to deduce off-diagonal terms from the large scale plan used to derive the control coordinates. A standard deviation is assigned to each coordinate and so correlation between pairs of coordinates is ignored. The theoretical aspects of this approach are developed by Cooper, (1987) and are discussed in Section 4.3.2.2.

The standard observation equations associated with the collinearity equations (Equation 4.9) are:

$$A_1\, x = b_1 + v_1 \; ; \quad \text{with cofactor matrix } Q_1 \qquad 5.36$$

Suppose two points (A,B) have been previously estimated with coordinates:

$(\ddot{X}_A\ \ddot{Y}_A\ \ddot{Z}_A,\ \ddot{X}_B\ \ddot{Y}_B\ \ddot{Z}_B)$ with an associated cofactor matrix $\ddot{Q}_1$,
(theoretically of dimension 6*6)

These six coordinates give rise to six linearised observation equations, (Equation 4.12) of the form:

$$\ddot{x} = \ddot{b} + \ddot{v} \; ; \quad \text{with cofactor matrix } \ddot{Q} \qquad 5.37$$

Rearranging and including all observation equations:

$$\begin{bmatrix} \dot{A}_1 & \ddot{A}_1 \\ 0 & I \end{bmatrix} \begin{bmatrix} \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} b_1 \\ \ddot{b} \end{bmatrix} + \begin{bmatrix} v_1 \\ \ddot{v} \end{bmatrix} \; ; \quad \begin{bmatrix} Q_1 & 0 \\ 0 & \ddot{Q} \end{bmatrix} \qquad 5.38$$

where:

$\ddot{b}$ is the vector of original coordinates minus the latest values derived from the least squares estimation, (equal to zero for first iteration).

$\ddot{v}$ vector of residuals.

The normal equations are:

$$\begin{bmatrix} \dot{A}_1^T Q_1^{-1} \dot{A}_1 & \dot{A}_1^T Q_1^{-1} \ddot{A}_1 \\ \ddot{A}_1^T Q_1^{-1} \dot{A}_1 & \ddot{A}_1^T Q_1^{-1} \ddot{A}_1 + \ddot{Q}^{-1} \end{bmatrix} \begin{bmatrix} \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} \dot{A}_1^T Q_1^{-1} \dot{b} \\ \ddot{A}_1^T Q_1^{-1} \dot{b} + \ddot{Q}_1^{-1} \ddot{b} \end{bmatrix} \qquad 5.32$$

Although the constrained coordinates and free coordinates appear partitioned in the matrix notation above, there is no necessity to do this. In BINFLEX two extra subroutines make the necessary modifications to the $A^TQ^{-1}A$ and the $A^TQ^{-1}b$ matrices whilst each measurement is read and processed. The routines are called after the $A^TQ^{-1}A$ and $A^TQ^{-1}b$ matrices have been formed in the original way. One routine adds the element of the cofactor matrix of the constrained ordinate to the relevant element of $A^TQ^{-1}A$, the other adds this value multiplied by $\ddot{b}$ to $A^TQ^{-1}b$. The original structure of the program was retained and modifications to the important matrix forming routines were kept to a minimum. Much of the development necessary was associated with the addition of a ´flexing´ ordinate to the already existing ´fixed´ and ´free´ types and also modifying the form of file output.

In the station coordinate file, ´flexed´ coordinates are indicated by a negative index, the value of the index referring to the standard deviation of the relevant coordinate. An index of ´1´ remains a ´fixed´ point although an index of ´-1´ indicates a flexing point with a standard deviation of ± 1 metre. This approach ensured that data files associated with earlier versions of the program could still be processed without loss of the original intent.

The effects of this addition to the self-calibrating bundle adjustment were significant. In the 1958 test epoch used previously, the *a posteriori* variance factor was originally reduced to 2.5. The inner orientation parameters incorporated in the estimation were x_p, y_p, dc and K_1. Higher lens parameters could not be incorporated as the standard deviations associated with these parameters were greater than the parameter, indicating that they could not be reliably estimated, (Section 8.2.2.3). Figure 5.8 illustrates the improvement that was gained, although the stochastic qualities associated with the test data are different than originally used.

A statistical test on the quadratic form of the least squares corrections (Cooper, 1987; Section 5.2.4.2) was performed:

$$H_0 : \hat{\sigma}_0^2 = 1 \; ; \qquad H_1 : \hat{\sigma}_0^2 > 1$$

Substituting for values derived from BINFLEX:

$Y = 28 * 2.364 = 66.2$

$\chi^2_{28,\,0.05} = 39$ (at the 0.05 significance level)

$66.2 > 39$; so reject H_0, accept H_1.

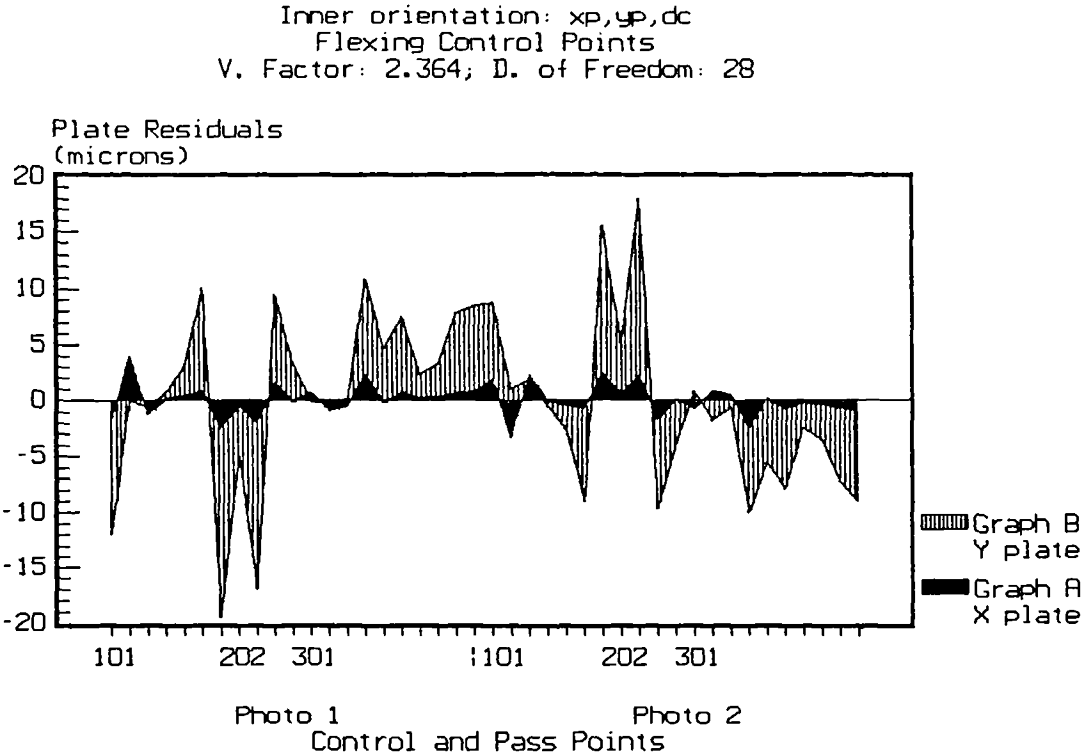


Figure 5.8 **Photo-coordinate residuals- BINFLEX**

Despite the reduction of the *a posteriori* variance factor compared with the BINFIX program, the value of this factor is still significantly greater than unity. This suggested that some systematic errors were still present which could perhaps be modelled by extending the functional model. Various possible causes were investigated, such as refraction, earth curvature and film deformation and these are investigated in Section 8.2.3. These analyses did not reveal any undetected systematic errors and so another aspect of the functional model was questioned.

One aspect of the solutions which had always caused concern had been the very large displacements of the principal point, especially in the y photo-coordinate direction. A bundle analysis program (BANAL - Section 8.2.4) was developed and one component of this was the analysis of the correlation between estimated parameters in the self-calibrating bundle adjustment. It was found that very high correlations existed between elements of interior and exterior orientation. The exact nature of these correlations depended upon the orientation of the cameras in the object space coordinate system, (Section 8.2.4). With many of the oblique photographs, such as the 1958 epoch, there was a correlation as high as 0.99 between the Omega rotation (w) and y_p, (Table 8.5). The solution for this type of problem is to drop one of the parameters from the estimating procedure, as both cannot be reliably estimated, (Ghosh, 1979; Cooper, 1987). The obvious parameter to remove was the primary inner parameter y_p but this was impossible in BINFLEX as the inner orientation parameters could only be selected in the hierarchical approach developed by Karara and Abdel Aziz (1974). If this parameter was to be dropped with the existing software, x_p and dc would also have to be removed from the solution. It was apparent that a new version of the self-calibrating bundle adjustment was required in which the inner orientation parameters could be individually selected. This was developed on a recently purchased IBM PC-AT computer and so the program was called BINFLEXPC.

5.2.4.4 BINFLEXPC

The modifications necessary to make the primary inner orientation parameters individually selective were rapidly instigated. It was felt that there was no necessity to make the lens parameters totally selective as the lens function is hierarchical. The higher parameters in the lens polynomial are smaller than the lower parameters and tangential distortion is less significant than radial distortion, (Slama, 1980).

The opportunity was also taken at this stage to make some more major changes to the program. With all the modifications that had been made the main program was approaching 900 lines of code with 250 separate lines of subroutines. It was also felt necessary to make the program more portable so that it was possible to run the program on any computer with a Fortran 77 compiler. All input-output (I/O) routines were therefore sub-programmed as these are generally machine dependent. It was also necessary to remove the coding which made use of various extensions to the Fortran 77 language and were therefore not standard for all compilers. This trimmed the main program to a more tolerable 750 lines with two subprogram libraries, one of 190 lines the other of 231 lines.

The important program modification concerned the individually selective primary inner orientation parameters and this had a satisfactory effect upon the solution. With the 1958 test epoch the y_p parameter was dropped and this had the effect of stabilising the solution to the extent that three lens parameters could be reliably recovered, rather than the one that was previously possible. The inner orientation parameters that were incorporated were therefore x_p, dc, K_1, K_2, K_3. As a direct consequence of the more refined functional model, the *a posteriori* variance factor was reduced

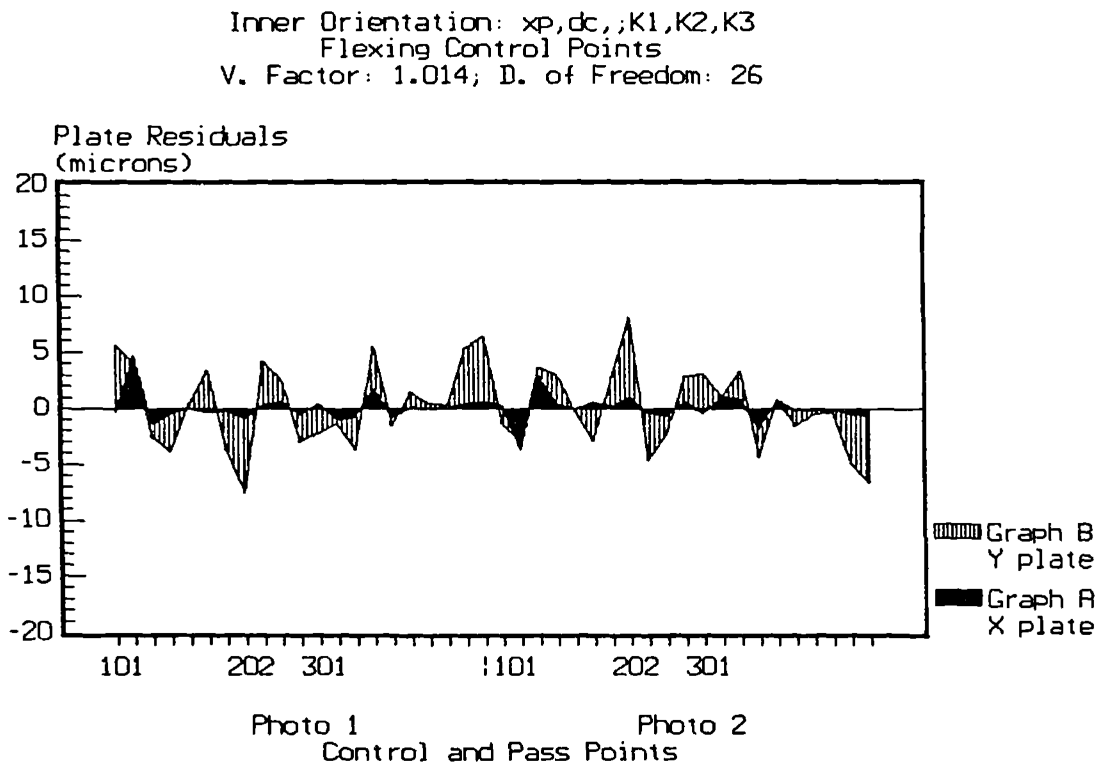


Figure 5.9 **Photo-coordinate residuals- BINFLEXPC**

to 0.75. The reduction of the *a posteriori* variance factor was so marked that it was felt justifiable to lower the standard deviations of the photo-coordinates to a realistic 5 and 7 micrometres for x and y photo-coordinates respectively. The stochastic properties of the OS control points remained unchanged as the standard deviation that was originally selected for OS points was judged acceptable. Re-computation produced the result re-produced in Section 10.2.4 and illustrated by Figure 5.9 with an *a posteriori* variance factor of 1.014. The test on the quadratic form of the least squares correction suggested that the null hypothesis should be accepted at the 95% confidence level.

$$H_0 : \hat{\sigma}_0^2 = 1 ; \qquad H_1 : \hat{\sigma}_0^2 > 1$$

Substituting for values derived from BINFLEXPC:

$Y = 26 * 1.014 = 26.4$

$\chi^2_{26,\,0.05} = 42$ (at the 0.05 significance level)

$26.4 < 42$; so reject H_1, accept H_0.

With smaller standard deviations for photo-coordinates, the whole estimation was strengthened and this reduced the standard deviations of the estimated interior and exterior orientations. The important consequence of this reduction was that the standard deviations of free points was now as low as ±1 metre. Considering that the standard deviations of the control points was only ± 1 metre, this would appear quite acceptable.

5.3 Concluding Remarks

The suite of programs that were successfully developed and examined in this Chapter can be used for the rapid restitution of archival photographs. Program STEC_CON transforms comparator coordinates into photo-coordinates, using a variety of reference marks if calibrated fiducials are unavailable. Program COP and SIM provide high quality starting values for all positional parameters and solve an important practical problem with bundle adjustments. The final version of the bundle program BINFLEXPC carries out a self-calibrating bundle adjustment with block-invariant inner orientation parameters, the primary of which are fully selective. The datum is defined by a series of previously estimated or derived coordinates which are constrained in the estimation by the diagonal terms of their cofactor matrix. This form of bundle adjustment appears adequate to enable archival photographs to be used for spatial measurement. In order to test the software more thoroughly it is necessary to apply the archival photogrammetric technique to a variety of different types of historical photographs.

Chapter 6

Practical Applications

6. Practical Applications

6.1 The Black Ven Landslide

All new techniques must be applied in practice, in order to modify and validate the methodology. For the archival photogrammetric technique, such a case study must provide photography that can be regarded as typical, in order to produce results that are relevant to other applications. The case study chosen for validation is the Black Ven landslide in Dorset and was selected for a variety of reasons. First, it was known that historical aerial photographs of the landslide were available as examples appear in two publications (Brunsden, 1969; Conway, 1974). These papers contain both vertical and more importantly oblique aerial photographs dated between 1946 and 1966. Work carried out on the adjacent cliffs at Stonebarrow (Brunsden, 1974; Brunsden and Jones 1976; Brunsden and Jones, 1980) also refer to similar aerial photographs and demonstrate that the Black Ven photographs are not unusual. Second, the Black Ven landslide is the most active complex of mudslides in the British Isles (Brunsden and Goudie, 1981). Changes of form have been exceptionally large in the last fifty years and many of these have been recorded qualitatively by geologists and geomorphologists in the past (Lang, 1927; Arber, 1941; Lang, 1955, 1959; Brunsden, 1969; Denness, 1972; Arber, 1973 and Conway, 1974). It was felt that to detect and quantify these changes in four dimensions, would be of distinct geomorphological importance and provide a very powerful illustration of the archival photogrammetric technique.

The Black Ven landslide is situated between Lyme Regis and Charmouth on the Dorset coast. There are three distinct active landslide sub-systems (Figure 6.1), although one sub-system (Black Ven 3) is a recent development which will not be considered in this thesis. The two eastern sub-systems (Black Ven 1,2) possess the classic morphology of mudslides: a source region, a track and a lobe or accumulation zone. The source region which appears as a great amphitheatre shaped

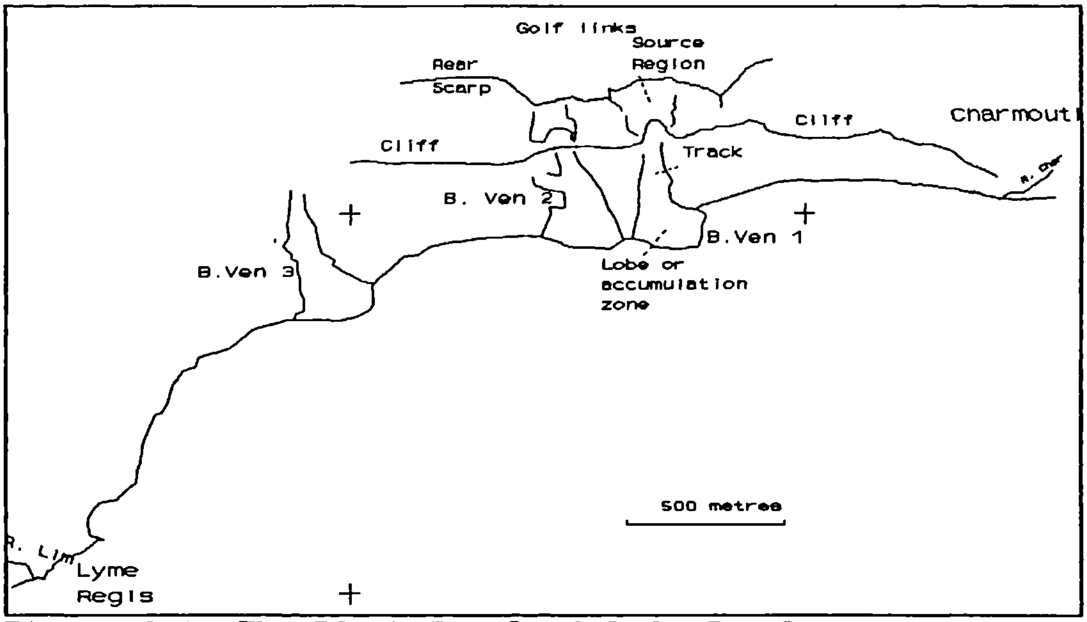


Figure 6.1 **The Black Ven Landslide Complex**

hollow on Black Ven 1 (OS Grid Ref: 357932) is Black Ven *sensu stricto*. However, following Lang (1927) the whole section of cliffs between Charmouth and the Church Cliffs at Lyme Regis are commonly referred to as Black Ven. The name originates from the Dorset and Devon word ´ven´ which refers to ´fen´ or bog, (Arber, 1941).

6.1.1 The Geology

The cliff sections have always provided an important study area for geologists because the landslides frequently reveal fossil specimens. Lang (1927) gives a detailed account of the stratigraphical succession, whilst more recent geological work is contained within the Geological Survey Memoir, sheets 312 and 327, (Wilson *et al*, 1958). The geology is also summarised by Denness *et al* (1975) and Conway (1974). 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 summarised in Figures 6.2 and 6.3.

Figure 6.2 Geological Formation of Black Ven (from Conway, 1974)

Period	Unit	Thickness (m)
Quaternary	**Head** Angular Chert in sandy clay matrix	3
Cretaceous (Upper Greensand)	**Chert Beds** Broken Chert beds in a firm coarse sandy clay matrix with some iron oxide cementation in lower part	7
	Foxmould Fine silty sand, lower 15m shows patches of soft calcareous sandstone (cowstone)	35
	Gault Soft, silty micaceous clay with some fine sand	7
	Unconformity	
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

The character of the sediments provides an important factor in controlling the general morphology of the site. The section (Figure 6.3) illustrates several well developed terraces (Plate 6.1), which are at the base of the Upper Greensand, the Belemnite Marl and within the Black Ven Marls. The terraces are caused by the existence of resistant horizons within the Liassic sediments; the upper terrace by the Belemnite Marl, whilst the lower terraces are the consequence of thin limestone bands. The Belemnite Marl and the mudstones in the Lias are also impermeable and impede the free passage of water. Pore water pressures can be very high in sediments above these horizons and these high pore pressures are a factor in promoting failure. The Upper Greensand in the top forty metres 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).

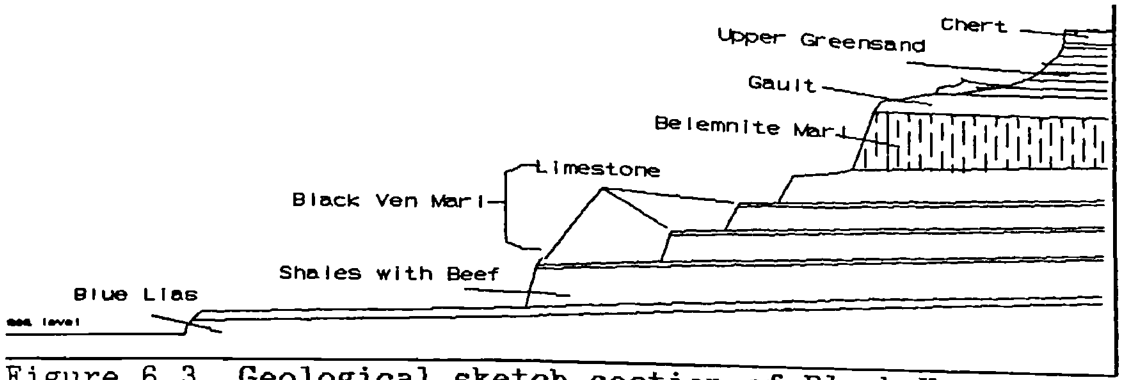


Figure 6.3 **Geological sketch section of Black Ven**

The geological structure is also a major controlling factor upon morphology and the potential for change. The Liassic beds dip approximately 2-3° in the direction of SE/ESE, although the presence of gentle folds distort 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, (Cooke and Doornkamp, 1974).

6.1.2 The Landslides - A literature review

The landslides at Black Ven have attracted considerable interest over the last century. Arber (1941) summarises events from as early as the beginning of the 19th century and includes a short history of the ill fated coast road which ran between Lyme Regis and Charmouth. The coast road was eventually closed in 1924 due to the landslides, although it could be followed on foot until 1938. The two ends of the old road can still be seen today, severed by a gap of 600 metres. In 1973, Arber (1973) updated the history of Black Ven and other landslides near Lyme Regis.

The development of the landslide complex is graphically illustrated by Brunsden (1969) who uses three vertical photographs to show the appearance of the landslide in 1946, 1948 and 1958. Small differences are noticeable between the 1946 and 1948 photographic epochs, but in the 1958 photographs the changes are much larger. The photographs are used to compile a geomorphological sketch map.

During the early 1970's the Institute of Geological Sciences carried out some work in the area and attempted to explain some of the mechanisms behind the movements. Denness, of the Institute, (1972) uses Black Ven to illustrate the 'reservoir principle of mass movement.' It is defined as:

> *'that overall failure mechanism governing all types of landslide complex that degenerate more rapidly from their initial stages of failure in a relatively solid state to a more viscous or liquid state than would be present if they were supplied only by run-off.'*

The geological conditions necessary are a permeable stratum overlying an impermeable and relatively soft stratum. Such conditions are present at Black Ven, between the Cretaceous and Liassic sediments and it is suggested that this mechanism is primarily responsible for the repeated failures of the slope. The presence of a partially eroded syncline within the cliff complex also serves to localise the discharge of groundwater and concentrates seepage erosion at that point, (Black Ven 1). The loss of material at the base of the Cretaceous over steepens the rear scarp and stresses are generated which exceed the resistance provided by the low cohesion of the Foxmould and Chert beds. Large failures consisting of sliding and rotating Chert are characteristic of this upper zone.

Conway (1974), also of the Institute of Geological Sciences, extended the reservoir principle. He introduces the term 'secondary reservoirs' which occur in debris accretions developed on degrading slopes. If such debris accumulates rapidly then it is possible to generate excess pore pressure which promotes instability by decreasing the strength of the material. The process is also referred to as the 'undrained-loading hypothesis', (Hutchinson and Bhandari, 1971). At Black Ven there are several secondary reservoirs or areas of undrained loading, where material and debris cascade from one terrace or one landslide unit to the next. At each stage the material becomes increasingly mixed, entrains additional material and becomes weaker as the material reaches residual strength. Conway (1974) also compiled a comprehensive geomorphological map of the site and established a series of symbols to represent different morphological units and features, (Section 6.5.2).

From the literature it is possible to identify periods when morphological change has been greater than average. During the winter of 1957/1958 a series of extensive failures occurred, one of which was graphically reported by Mr J.F. Jackson, who wrote in *The Proceedings of the Dorset Natural History and Archaeological Society:*

> *'I saw a great mass of Upper Greensand, densely covered with bushes and trees slowly crawling downwards from the highest terrace, while below a river of liquid mud was slipping over the low cliff above the beach',* (Lang 1959).

The failures of 1958 resulted in two lobes of material extending 122 metres into the sea, (Brunsden, 1969). The remnants of these two lobes still remain (1988), 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; 1988). During this period Arber (1973) reports the loss of several cliff paths and a wire fence enclosing the cliff top golf links.

6.1.3 An Evolutionary Model

Although not directly concerned with the Black Ven landslide some important related work was carried out on adjacent landslides at Stonebarrow, on cliffs east of Charmouth, (Brunsden, 1974; Brunsden and Jones 1976; Brunsden and Jones, 1980). An 'evolutionary model' was developed for this landslide complex, (Brunsden and Jones, 1976) and as the two sites are similar this can be used to develop an evolutionary model for Black Ven.

Although the material in the landslide system moves downslope, a 'zone of aggression' can be imagined which moves inland and up the slope. This is because a primary cause for continued activity is the removal of material out of the system by marine erosion of the mudslide toe. This loss prevents the development of a low aggradation slope which would have a stabilising effect. The gradient is kept steep and so the rate of debris transport across the track and toe of the mudslide is maintained. Removal of material gradually undermines the hard limestone band responsible for the first cliff. This eventually fails, introducing new material into the system, both from the cliff and from the terrace immediately above. The gradient of this upper terrace is steepened so increasing the rate of debris transport and in turn undermining the next limestone band. This pattern is repeated until the zone of aggression reaches the uppermost terrace, within the Upper Greensand. Here the character of the failures change due to differences in geology. Saturated blocks of Upper Greensand and Chert move slowly towards the Belemnite cliff edge. Again this has the effect of steepening the gradient of the upper terrace which continues until stresses in the undercliff exceed the strength of the Upper Greensand and Chert, when the cliff fails. Rotational and translational failures are characteristic of this upper section, these tend to be infrequent but substantial and introduce large quantities of new material into the landslide system.

Superimposed on this model are a series of processes associated with the transport of debris and material down through the system. The flow of water is a fundamental factor in the degree of activity and is associated with many of these processes. Immediately above the impermeable Belemnite Marls there is an important line of springs, which drain a large area of ground behind the undercliff. Water and detritus pour over the cliffs creating deep gullies which erode the cliff edge. Once the water and material falls onto the terrace below, Liassic mudstones and Cretaceous sands are mixed with copious quantities of water. The geological conditions necessary for the development of mudslides are present and if the pore water pressures are high enough the material slides downslope, entraining more material in the process. The mud is funnelled into various tracks and cascades over the smaller limestone cliffs beneath. The mud and material eventually spills out onto the beach in a series of broad lobes. The debris cascade may itself generate very rapid movement. If material descends over a terrace edge very quickly it will load the material on the lower terrace. If the system cannot drain easily then very high pore pressures can be created by the process of undrained loading (Hutchinson and Bhandari, 1971). The resulting movement is often in the form of a surge.

Activity on the landslide operates at several time scales. There is a great seasonal variation which is in response to changes in the groundwater conditions. Winter precipitation increases pore-water pressures and the most active period is between January and April, although seasons do vary. Longer time scales are important also. It has been suggested that these landslide complexes operate in cycles, with a return period of 100 years, (Cambers, 1976; Brunsden and Jones, 1980).

6.1.4 The Geomorphological Problems

It is essential to establish the type of geomorphological problems that can be solved by extracting precise three dimensional data of Black Ven, from archival photographs.

1. Although some work has been done regarding the morphological changes of the site (Brunsden, 1969), this has used non-rigorous techniques. Precise and <u>rigorous, dated plans</u> will enable precise morphogenetic comparisons to be made. This will allow the effects of the processes to be

quantified and help greatly in assessing the rate of operation of certain processes.

2. Precise dated plans would only provide planimetric information and could be extended to include a three dimensional study of the site. A variety of digital terrain modelling techniques could be used to illustrate and quantify morphology and it's attributes and to quantify the results of process.

3. No quantitative assessment has been made of the volume of material that has passed through the Black Ven landslide system. Such a study may be able to include volumes of material transferred between sub-systems and units. It may also be possible to obtain displacement vectors which would quantify movement at certain specific points.

4. Various trends and patterns of processes could perhaps be discovered by analyzing digital terrain models of the site and other patterns may be discovered using statistical procedures. It may be possible to predict the location and extent of future active areas or even predict the future form of the site.

These four groups of geomorphological problems were examined using data derived from archival photographs in conjunction with various processing methods. This work is discussed in detail in Chapter 7 and re-appraised in Section 7.4.

6.2 Acquisition of Photography of Black Ven

As mentioned in Section 2.1, one of the most important practical problems is the acquisition of photography at a pertinent epoch, which is suitable for photogrammetric measurement. In the case of the Black Ven landslide the desire to obtain an optimum sequence ensured that the search for suitable photographs continued for fourteen months.

Request for cover-searches were originally made to larger and obvious photographic archives on May 1st, 1987. Government influenced sources included the Central Register of Aerial Photographs of England (CRAPE), Royal Commission on the Historic Monuments of England (RCHME), Joint Air Reconnaissance and Interpretation Centre (JARIC) and the University of Cambridge Committee for Aerial Photography, (Section 2.3.1). In the commercial sector, Aerofilms and Cartographical Services Ltd were also contacted, (Section 2.3.2). The latter is based in Salisbury and represented the local commercial organisation.

CRAPE traced two sorties, one dated 1972 at a scale of 1:7,500, the other dated 1977 at 1:10,000. RCHME traced a series of recent vertical photographs, whilst JARIC required a fee of £5.00 before a search could be organised. Aerofilms and Cartographic Services both sent details of recent vertical photography, dated 1978 and 1986 respectively. The University of Cambridge Committee for Aerial Photography sent photocopies of oblique and vertical coverage, dated 1948, 1958, 1966, 1969 and 1972 which were the type of photographs that were envisaged for use with the archival photogrammetric technique. The Cambridge University Collection was visited so that exact requirements could be decided upon, after viewing prints. An order was placed for contact diapositives to be reproduced from the 1948, 1958, 1966 obliques and the 1969 large scale verticals.

With the exception of the Cambridge University Collection, the replies were disappointing because all photographs consisted of comparatively recent verticals. It was felt that such photography would be of little use in validating the archival photogrammetric technique. A further letter was sent to CRAPE, Aerofilms and Cartographic Services, asking specifically for historical and oblique photographs. This proved unsuccessful, although alternative sources were suggested.

Other commercial air survey companies were later contacted, including J.A. Story and Partners, B.K.S. Surveys Ltd and Clyde Surveys. In addition, Airviews, West Air Photography and Chorley and Handford Aerial Surveys Ltd were approached, who specialise in obtaining oblique photographs. All of these sources proved unproductive.

Additional sources that were approached included Dorset County Council, Nature Conservancy Council, Times Picture Library, Royal Photographic Society, Science Museum Library, Geological Society and the Air Photo Library at the University of Keele. These all proved to be ineffectual, although they often helped by suggesting additional archives.

Other sources were the libraries and museums (Section 2.3.3) in the vicinity of Black Ven. Letters were written to these sources and visits were made to the Philpott museum in Lyme Regis, the Heritage Coast Centre at Charmouth and the Dorset County Museum in Dorchester. The latter visit was the most successful because access was provided to some very old terrestrial photographs taken as early as 1880. A pair of photographs was actually found of the Black Ven landslide taken in 1890. Unfortunately the original negatives had been mislaid and both the photo-scale and the photo-base were too small to be considered for measurement, (Section 8.2.2.1). Contact was also made with Miss M. Arber who has been interested in the landslides at Black Ven for over fifty years. Her publications (Arber, 1941; 1973) contain several terrestrial photographs of the site. It was hoped that these photographs and perhaps others would be suitable, but correspondence suggested that this was not the case.

Despite the failure in managing to trace additional material, the photography obtained from the University of Cambridge Committee for Aerial Photography appeared very useful and so practical application of the archival photogrammetric technique could begin. The search for photography was continued, specifically for photographs prior to 1948 and to obtain a chronological sequence. By chance, the photographs obtained from the Cambridge University Collection appeared to fall at approximately ten year intervals, with key epochs in 1948, 1958 and 1969. It was felt that to obtain as full a sequence as possible with such a ten year interval would be most beneficial from a geomorphological viewpoint.

An obvious way to extend the sequence was to obtain recent photography. Although the conventional archive sources could have been contacted for this, it was decided to acquire the photography personally, for a variety of reasons. It was felt that the developed procedures and analytical techniques could be tested more fully if high quality spatial control coordinates could be provided in the object space. Full command of the acquisition of the photographs and of the installation of targeted points would enable requirements to be met fully and cheaply. It was also believed that the use of a hand-held large format camera from a cheap platform such as a light aircraft, in conjunction with analytical photogrammetric techniques, could provide a cost effective way of obtaining high quality spatial data, (Chandler and Moore, 1989). It was felt that this was not fully appreciated by geomorphologists and to some extent surveyors and photogrammetrists.

Contact had been made with the Chief Flying Instructor at Exeter flying club and he was in agreement to carrying out such a sortie over the Black Ven landslides. A Rolleimetric 6006 large format 'semi-metric' camera was borrowed from a Rolleimetric distributor and this camera appeared suitable for the purpose. The term semi-metric is used as although of cheaper construction than a metric aerial camera the Rolleimetric 6006 had been calibrated. The focal length of the camera was known and so a comparison between this value and that estimated in the self-calibrating bundle adjustment would be of interest. The camera also contained a calibrated reseau plate which could enable the effects of film deformation to be assessed, (Chandler *et al*, 1989). An investigation into the significance of these effects was important as it was impossible to correct for this type of systematic error explicitly with the archival photogrammetric technique, (Section 8.2.3.1).

The most active period of landsliding in the area is between January and March, (Brunsden, 1974). Two sorties were eventually flown, one in January 1988 the second in June 1988, so that the effects of a season of process at the Black Ven landslide could perhaps be assessed. At each sortie a series of targets was positioned on and around the landslides, which were large enough to be identified on the photography. A local datum was defined by the installation of two reference pegs that could be relocated at each epoch. A control survey was carried out using a Wild TC1 tacheometer and the coordinates of the targets were established on the local datum using a ´three dimensional variation of coordinates´ estimation program.

Although the sequence of photography that had now been obtained covered a period of forty years there was an important gap during the late 1970´s. Some of the replies from earlier correspondence to holders of the archive revealed several possibilities and these were investigated further. Eventually an order was placed for three diapositives taken in 1976 by the Ordnance Survey, at a scale of 1:7,500. The date of these photographs was not exactly midway between the 1969 and 1988 epochs but were chosen because the photographs could be regarded as typical of the vertical archive.

Throughout the period spent searching and acquiring photographs it was hoped that an epoch prior to 1948 could be found. In addition, although the 1948 photographs from the Cambridge University Collection could be restituted in a self-calibrating bundle adjustment, only a limited amount of three dimensional data could be extracted, (Section 6.3.2; 8.2.2.1). Following a meeting with J. Henry of Ove Arup and Partners, London, it was decided to trace high altitude vertical RAF photography taken shortly after the war. The ability to extract positional data from these photographs was important, particularly to Mr Henry, as these represented the first complete national photographic coverage of England and Wales, (Section 2.2). The relevant photographs were traced by visiting the National Library of Air Photographs at the Royal Commission for Historical Monuments of England. Unfortunately the quality of these was low due to atmospheric haze but an order was placed with the Joint Air Reconnaissance and Interpretation Centre (JARIC) who held the original negatives. The scale of the photographs was 1:10,000 with an approximate flying altitude of 5,000 metres.

A summary concerning the geometrical characteristics of the photographs eventually selected and employed for the Black Ven case study is contained in Table 6.1, Section 6.3.2. Full size prints of the photographs are illustrated in Plates 6.1- 6.12, also in Section 6.3.2.

6.3 Photogrammetric Processing

6.3.1 Measurement Points

Before any diapositives could be measured and processed it was necessary to identify points of detail suitable to measure, two types of points were distinguished. A '**control point**' was one for which some aspect of spatial position was known, generally either its planimetric position or its height. A '**pass point**' was a point whose coordinate was totally unknown, but could be estimated in the self-calibrating bundle adjustment. These two types of point had to fulfil a variety of functions. Of main concern was the identification of control points that could be used to define the datum. This had to be defined in such a way that a single datum could be used at all epochs, so ensuring that any differences were attributable to geomorphological process and not to differences in the datum, (Section 4.2). All selected points were also going to be used in the self-calibrating bundle adjustment to establish both the exterior and interior orientations of the cameras. The disposition of these points was important, (Section 8.2.2.1). To enable a reliable recovery of the exterior and interior orientation parameters, control points were required to be positioned around and within the area of interest. In the case of the estimation of the parameters necessary for the modelling of lens distortion, control or pass points needed to be distributed over the whole format of the diapositives. There were several problems. Coordinated control points were obviously unavailable within the landslides and what was available tended to be distributed behind the back-scar, some distance from the landslides. It was also impossible to pick pass points which appeared over the whole format. There was generally a band of sea, and with the oblique photographs a similar band of sky, across large portions of the format, (Plates 6.4, 6.8).

A series of well defined control points was identified on the OS 1:2,500 plan of the site, and Figure 6.4 shows the

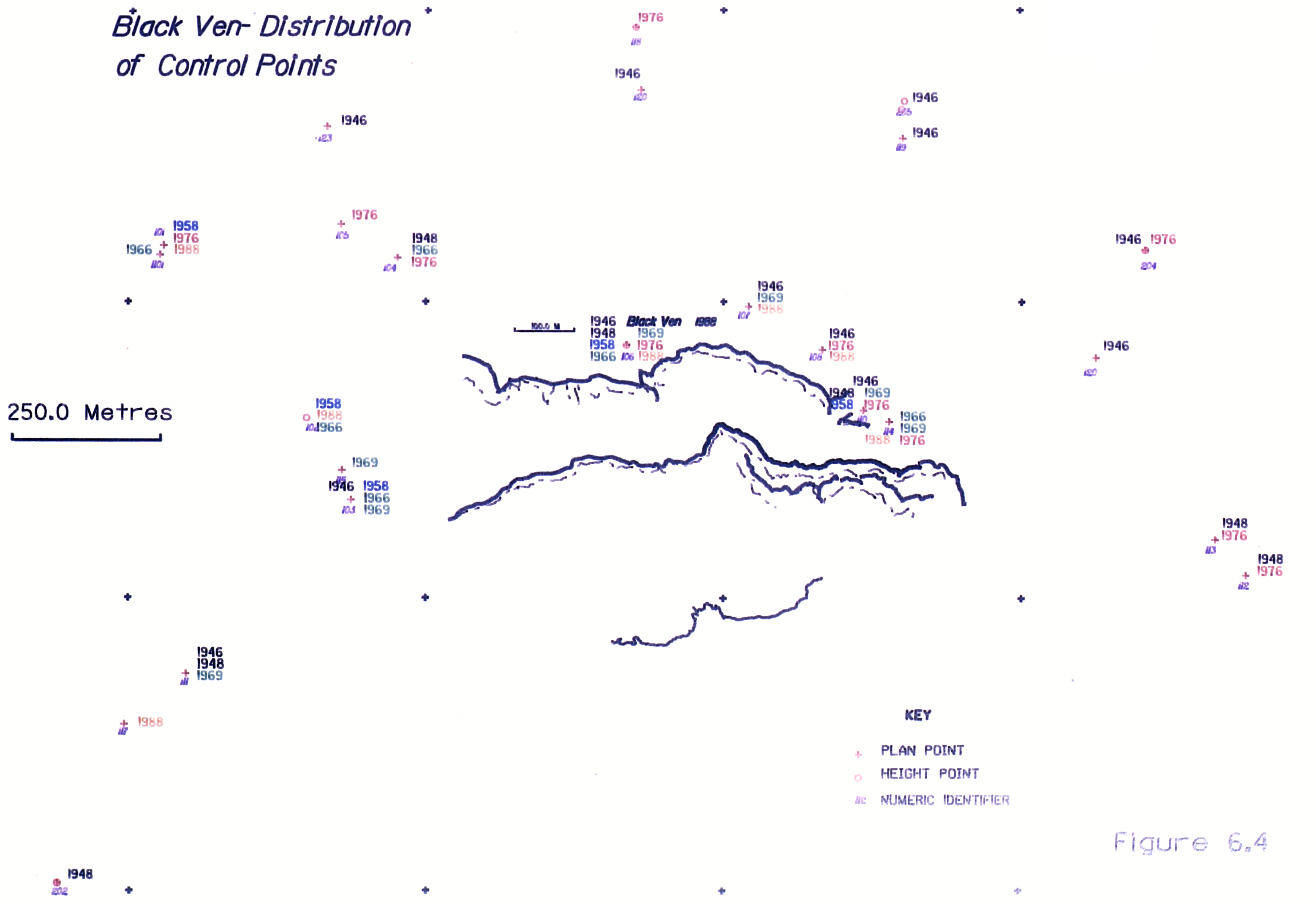

Black Ven- Distribution of Control Points
250.0 Metres
100.0 M
Black Ven 1988
KEY
PLAN POINT
HEIGHT POINT
NUMERIC IDENTIFIER

Figure 6.4

distribution of control points used at each epoch. The planimetric control coordinates were measured from the plan using a scale rule. The heights of the vertical control points were taken from data printed on the OS map. There was a shortage of clearly defined plan points in the immediate vicinity of the slip and some poorly defined points had to be selected. The most problematical were those distinguished by the intersection of hedges. Although well defined upon the OS map, these tended to be large features on the photography, especially under magnification and with the obliquity of view given by some of the photographs. There were only two height control points in the immediate locality of the landslide and one of these was obscured by vegetation.

Despite these problems it was realised that a series of pass points could be used to define three natural forms of control. It was mentioned in Section 5.1.2 that a series of points defining a water boundary would be at the same height. The interface between the sea and the beach at Black Ven could be used, although it was found that a thin line of debris deposited by the most recent high tide was more suitable. A height difference of zero between these 'beach points' could be included in the self-calibrating bundle adjustment as an additional measurement. A standard deviation could be associated with the value, representing the confidence with which the boundary had been measured and this form of control proved to be important.

The significance of some of these beach points had to be further increased as only one usable height control point was provided by the OS plan. In order to define a datum, a minimum of three points are required to be fixed in altitude. Three beach points were assigned a height of either 0.5 or 1.0 metre, depending upon the position of the point relative to the water line. A standard deviation of ± 0.5 metre was assigned to each of these beach points. This stochastic attribute was judged reasonable because sea-level could be estimated from the position of the sea relative to a rock bench and the mean tidal range at Lyme Regis is 2.1 metre, as defined by tide tables (Fowler, 1988). The actual sea level at the time of photography could have been established by recourse to the tide tables, providing the time and date of photography was known but although the date was known, the time of the photography was not. The provision of additional height points using these assumptions was non-rigorous but the expediency was justified as no alternatives were possible. Additional ground survey work was carried out at a later date and this enabled the difference in height between one of the planimetric control points and mean sea-level to be deduced. This provided an additional height for a control point upon the cliff top and confirmed the tidal range deduced from the tide tables. The survey suggested that the assumptions that had been made were acceptable, at the level of precision of these archival photogrammetric surveys.

The most important area of geomorphological interest was within the landslides themselves. All measurement points discussed so far were distributed around the periphery of the landslide site, rather than within it. The third form of natural control redressed this balance as it involved a series of pass points which were within some of the most active areas of the landslides. The sedimentary bands are very distinct on aerial photographs of Black Ven (Plate 6.4). The dip and strike of both the Liassic and Cretaceous sediments were known from publications by Conway (1974) and Denness *et al* (1975). It was thought that if it were possible to deduce the horizontal distance between two pass points positioned on different parts of the same sedimentary band, then using the known dip and strike it would be possible to calculate the theoretical difference in height between them. These height differences could then be used as additional measurements between points, in the self-calibrating bundle adjustment. The problem of obtaining the horizontal distance between a series of such 'sedimentary points' was overcome by running an initial bundle adjustment with the coordinates of these points as unknown parameters. A program was developed which created a file of computed height differences from a known dip and strike and the coordinates computed in the bundle adjustment. Included in the output (Section 10.2.5) was the height difference as defined by the original coordinates, comparison between these and the theoretical computed values enabled poor measurements to be deleted. The self-calibrating bundle adjustment could then be re-estimated using a series of additional height differences between these sedimentary pass points.

The main problem with the method is the assumption that the dip and strike is uniform. It is known from the publications by Denness *et al* (1975) that faults and minor folds are embodied within the general dip and strike of the sediments, (Section 6.1.1). Despite this, the method did appear valid between points which were less than twenty metres apart and the additional measurements improved the spatial precision of points within the landslide. The sedimentary points also tended to be distributed in the centres of the format, which helped in providing a more even distribution of points. This was essential for the reliable estimation of the parameters used to model lens distortion, (Section 8.2.2.2).

In the case of the 1988 photography, additional measurement points were available because a series of targets had been positioned in the object space. The three dimensional coordinates of these points had been computed, in a local reference system, and would provide the high quality of control necessary to analyse certain aspects of the self-calibrating bundle adjustment, (Section 8.2.3.1, 8.2.5).

6.3.2 The Self-calibrating Bundle Adjustments

The photography that was eventually obtained from the archive produced camera/object relationships that were very different from each other. A summary of these and other pertinent data are found in Table 6.1. Figure 8.1a also illustrates the spatial relationships between the archival photographs and the Black Ven landslide.

Table 6.1. Camera/Object Relationships

Date	Source	Photo No.	Plate No.	Nature	Format (mm)	Focal (mm)	Distance (m)	Photo Scale
1946	RAF	4319		Vertical	210 x	550.00		
		4318	6.12		175	550.00	5,527	1:10,049
		4317				550.00		
1948	CU	AS2	6.5	Oblique	130 x	206.55	1,454	1:7,040
		AS1	6.6		130	206.55	1,983	1:9,602
		AS3	6.7			206.55	1,286	1:6,230
1958	CU	WX6	6.1	Oblique	130 x	201.94	1,319	1:6,533
		WX7	6.2		130	201.94	1,386	1:6,863
1966	CU	ANQ91		Oblique	130 x	209.74	910	1:4,341
		ANQ92			130	209.74	950	1:4,532
		ANQ90	6.3			209.74	1,066	1:5,086
		ANQ93	6.4			209.74	1,186	1:5,656
1969	CU	K17-012		Vertical	230 x	166.03		
		K17-013	6.8		230	166.03	670	1:4,041
		K17-014				166.03		
1976	OS	76 073		Vertical	230 x	305.04		
		76 074	6.11		230	305.04	2,278	1:7,468
		76 075				305.04		
1988	Personally			Oblique	60 x	50.83	1,013	1:19,940
Jan					60	50.83	959	1:18,874
			6.9			50.83	903	1:17,779
			6.10			50.83	935	1:18,412
						50.83	1,414	1:27,832
						50.83	1,283	1:25,251

Sources: RAF: JARIC, RAF Brampton
OS: Ordnance Survey
CU: Cambridge University Committee for Aerial Photographs

Note: The camera/object distances are based upon a point in the middle of the landslide.

The 1958 photography taken by the University of Cambridge Committee for Aerial Photography were the first photographs measured and processed. The photographs (Plates 6.1, 6.2) consisted of a pair of obliques, (one stereoplet) which were of high image quality and were acquired with a Williamson F-24 reconnaissance camera, (Darrell, 1988). As many of the Ordnance survey planimetric control points as possible were measured on a stereo-comparator (Section 4.1.1.1; 5.1.2). Other measured points included a series of beach and sedimentary points, (Section 6.3.1). These raw comparator coordinates were then processed according to the principles outlined in Section 5.1.4. Initial self-calibrating bundle adjustments highlighted problems with the software and lead to the developments discussed in Section 5.2.4. A satisfactory adjustment was eventually computed (Section, 10.2.4) and the photographs could then be used to extract the coordinates of new points. The inner orientation parameters that were found to be most significant (Section 8.2.2.3) were x_p, dc, K_1, K_2, and K_3.

The second set of photographs that were selected for measurement and computation consisted of four oblique photographs taken in 1966 by the University of Cambridge Committee for Aerial Photography. The two stereoplets provided coverage of both Black Ven 1,2 (Example: Plates 6.3, 6.4) and what was to become Black Ven 3. The camera used was the Williamson F-24 and although image quality appeared high, under magnification the pair of Black Ven 1,2 were blurred. Despite this, control and pass points were identified and measured on the stereo-comparator. Self-calibrating bundle adjustments were computed for each pair initially, but these were later combined in one estimation. Similar inner orientation parameters to those from the 1958 estimation were found to be significant, (Section 8.2.2.3).

Plates 6.1, 6.2 **1958, Cambridge University Collection- WX6, WX7**

Plates 6.3, 6.4 1966, Cambridge University Collection-
ANQ90, ANQ93

Plates 6.5, 6.6 1948, Cambridge University Collection- AS2, AS1

The photography taken in 1948 by the University of Cambridge Committee for Aerial Photography was measured and processed according to the techniques discussed in Section 5.1. Three oblique photographs were available (Plates 6.5-6.7), but these proved to be far from ideal. Although plates

Plate 6.7 **1948, Cambridge University Collection- AS3**

6.5 and 6.6 could be regarded as a stereoplet the top of the landslide was only visible on one of the photographs. The photo-scale was very small. The third photograph provided excellent coverage of the landslide but could not be used with either of the other photographs because of the very great convergence, (Section 5.1.1; 8.2.2.1). It was obvious that the amount of coordinate data that could be extracted from this photography was limited. Despite this, the epoch was used to test further the self-calibrating bundle adjustment. It was found that the combination of all three photographs provided very great geometric strength and despite the small photo-scales the standard deviations of some of the points were as low as ±0.9 metre.

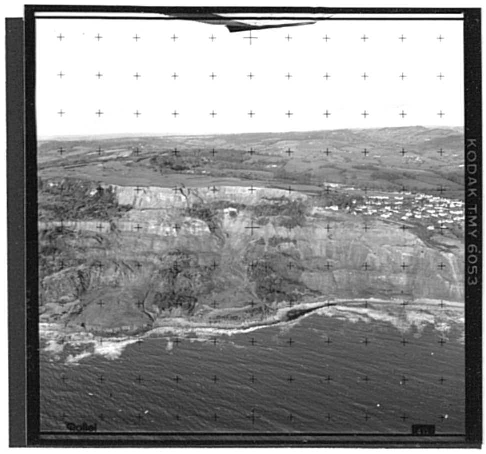
The photographs provided by the University of Cambridge Committee for Aerial Photography taken in 1969, were different from those already processed, (Example: Plate 6.8). The photographs had been acquired using a vertically mounted Fairchild K17B air survey camera, (Darrell, 1988). Three photographs were available, but only a limited number of the OS control points were imaged because the photo-scale was very large (Table 6.1) and the format was dominated by the landslides. An additional problem was the large camera-bases (400 metres) which made stereoscopic viewing difficult because the images were very different. This problem was compounded by the large photo-scale which also made it difficult to assess the location of the measuring mark within the landslides. Despite these problems a suitable self-calibrating bundle adjustment was computed using a different set of inner orientation parameters used in previous epochs. No primary inner orientation parameters were estimated as x_p and y_p proved to be insignificant and the calibrated focal length of the camera was obtained from the University of Cambridge Committee for Aerial Photography. Three radial lens distortion parameters were found to be significant.

The 1988 photography was uncharacteristic of the archival photographs for three reasons. First, thirty six photographs were taken both in January and June and so an optimum configuration could be selected at each epoch. Second, the three dimensional control targets that were placed in the object space could be incorporated into a self-calibrating bundle adjustment in a variety of ways. Finally, the calibrated reseau images provided the option to compensate for film deformation, (Chandler *et al*, 1989).

Six photographs were chosen from the January sortie (Examples: Plates 6.9, 6.10). Selection based upon coverage, photo-scale, image quality and geometry. Ordnance survey (OS)

Plate 6.8 1969, Cambridge University Collection- K17-O 13

control points, targeted control points, beach, sediment points and the image positions of 121 reseau crosses were measured. Three of the OS control points had disappeared due to redevelopment of buildings, but additional points were identified and measured from the OS plan. In order to assess the effects of film deformation it was decided to carry out two self-calibrating bundle adjustments. In one, some form of correction using the calibrated reseau coordinates would be made, whilst in the other no correction would be applied. The difference between these two estimations would then indicate the relevance of such a systematic error, (Section 8.2.3.1). Initially the effects of film deformation were ignored and so photogrammetric processing followed the established pattern.



Plates 6.9, 6.10 **January 1988, Personally acquired**

During the self-calibrating bundle adjustment the problem of how to incorporate the coordinated targets was met. It was impossible to use the coordinates directly because a local datum unrelated to the National Grid had been used for the estimation. The coordinates could have been transformed to the OS reference system, if sufficient field survey measurements to local OS control points had been taken. Access to the nearest OS triangulation pillar was refused by the secretary of the local golf club and it was impracticable to use any other OS control point. It was also impossible to use the original survey measurements because the position of the tacheometer was not visible on the photography. Initially it was decided to transform the coordinates of the targets into distances between points, which would be independent of positional datum elements. The additional measurements could then be incorporated into the self-calibrating bundle adjustment with the positional datum elements defined by OS control points, as in previous epochs. A program was written to transform a file of three dimensional coordinates into either the horizontal, vertical or slope components, between all points. The program included a full propagation of variance; from the standard deviations of the coordinates through to the standard deviations of the derived distances.

The January 1988 self-calibrating bundle adjustment was computed with additional measurements between targeted points and their associated standard deviations. An analysis of the solution revealed large residuals on some of the OS control point coordinates. Originally it was thought that this was due to a discrepancy of scale between the local reference system and the OS grid system. After examination, no scale error was traced and because there had been some problems with the definition of an identical datum at all epochs (Section 6.4) it was decided to re-compute using only the control information that was available for the historical epochs. The additional measurements between the targeted points were removed and the definition of control was identical to the approach used for the archival photographs.

Both the 1988 January and June photographs were used in self-calibrating bundle adjustments with the datum defined by the coordinates of the targets in the local system. The June photography was used to compare the estimated inner orientation parameters with those defined by the camera calibration certificate, (Section 8.2.5) and to assess the effects of film deformation (Section 8.2.3.1). By comparing both sets of 1988 photography, the effects of one season of process could be analysed. Such a study was not carried out because one of the main aims of this thesis was the application of archival photographs to geomorphology.

The 1976 photography consisted of three vertical photographs taken by the Ordnance Survey at a scale of 1:7,500 (Example: Plate 6.11) using a Zeiss RMK A 30/23 air survey camera, (Sims, 1988). Coverage was extensive due to the smaller photo-scale and sufficient OS control points were available, including three height control points. Photogrammetric processing followed the standard procedures, although it was found that the focal length of the camera could not be reliably estimated due to the correlation with camera height, (Section 5.1.2). The calibrated focal length had been procured from the OS (Sims, 1988) and was used in the final bundle adjustment. Lens parameters were found to be insignificant.

The final set of photographs that were processed were dated 1946. The quality of this photography was poor due to a combination of small photo-scale (1:10,000) and atmospheric haze. Three photographs were available (Example: Plate 6.12) and these were obtained from the RAF at JARIC. Abundant OS control was available due to the extensive coverage provided by the photographs. No camera calibration data were available from JARIC although it was known that an F52 camera had been used with a nominal focal length of 20 inches, (Longhurst, 1988). Estimation of the focal length proved unreliable due to correlation with flying height (Section 8.2.4.3). One radial lens parameter was found to be significant and spatial precision was better than expected, particularly in plan. The standard deviations of typical object points was approximately ±0.6 metre in plan and ±1.6 metre in elevation. The lower precision obtainable in elevation is due to a combination of the high flying height, long focal length and low image quality, (Section 8.2.2).

Plate 6.11 1976, Ordnance Survey- 76 074

Plate 6.12 1946, RAF- 4318

6.4 The Datum Problem

To ensure that all morphological differences were attributable to process and not to differences in the coordinate reference system, a datum had to be defined and subsequently used at all epochs. The Ordnance Survey national grid provided a suitable standard coordinate system through the use of the OS 1:2,500 map to supply planimetric and altimetric data for the control points. These points were used to provide the necessary link between the reference system and the photography and defined the datum used at each epoch. Due to the uneven distribution of control points that were measurable at each epoch (Section 6.3.1; Figure 6.4), the datum definition was not always ideal. (The optimum spatial relationship between control points and photographs is discussed in Section 8.2.2.1).

A datum can be defined by establishing the seven datum elements; three positional, three rotational and one scale. The simplest method of datum definition is to identify three control points that can be measured at all epochs. Two points must be fixed in all three dimensions, whilst the third must be fixed in height. In the case of archival photogrammetric surveys such a ´minimally constrained´ least squares estimation causes two problems. First, the identification of three such well defined coordinated points at all epochs will be rarely possible. In the case of Black Ven, an examination of Figure 6.4 reveals that only one point (Point Id: 106) appeared on photographs at all epochs. In addition, for the reliable estimation of the coordinates of new points it is preferable that more than the minimum amount of control information necessary to define a datum should be available, (Faig, 1975). The increased rigidity of the object space coordinate system provided by an evenly distributed set of three dimensional coordinates enables a more reliable recovery of the elements of the interior orientation parameters, especially the focal length, (Wester-Ebbinghaus, 1986).

The reliable estimation of the inner orientation of the camera was obviously an important aim of the self-calibrating bundle adjustments and as many OS control points were measured at each epoch, as possible.

Initial application of the self-calibrating bundle adjustments were associated with testing the developed software and obtaining solutions that could be described as 'acceptable.' An acceptable solution appeared to depend upon several factors:

1. Low control point residuals. ⎫ Variance factor=1.0
2. Low photo-coordinate residuals ⎭
3. Low standard deviations of estimated coordinates of points, located in the centre of the landslide.

It was found difficult to maintain a balance between these factors as to an extent these were mutually exclusive. It was felt that small standard deviations for points in the centre of the landslide were important as these represented the precision with which new points could be coordinated. In retrospect this factor was over-stressed and led to several incorrect practices. First, during estimations it was very difficult to decide upon the relative importance of photo-coordinate and control coordinate measurements and measurements between points. It was tempting to remove or increase the standard deviations of measurements which produced large residuals and to reduce the standard deviations of those measurements that fitted the functional model. The second step appeared necessary in order to keep the standard deviations of estimated points low. Second, there was a shortage of height control data at some epochs, especially with the 1969 photographs. The initial solution to this problem was to transfer control data from one epoch to another, but this created additional difficulties.

The result of both practices was a series of individually acceptable bundle adjustments, which had become based upon slightly different datums. Differences could now be attributable to differences in datum rather than geomorphological processes. The 1969 epoch was the most problematical and appeared to have a four metre height displacement compared with the other epochs. The lack of OS control points was the main cause of these difficulties, but the procedures outlined above compounded the problems.

It became apparent that it would be necessary to re-compute all of the self-calibrating bundle adjustments using one single datum so that true differences could be reliably detected. Several methods were identified:

1. Assemble the coordinates of all the control points estimated in the self-calibrating bundle adjustments and compute the means and standard deviations of them. Then re-compute all of the bundles upon this refined coordinate system.
2. Re-compute the bundle adjustments in one large estimation procedure. The 'total solution.'
3. Re-compute each epoch using a 'standardised datum.'

The first option was not attempted because the standard deviations of control point coordinates transferred from other epochs would become overstated. In addition, this approach would only be valid if no new epochs were to be processed and additional photography was envisaged.

The second option was attempted but there were three problems. The array definitions in the program that had been developed had to be extended to accommodate a maximum of 40 cameras and 150 coordinates. This extension lead to a major practical problem of processing speed. The solution that was attempted incorporated the 1948, 1958, 1966 and 1969 epochs, and included 12 cameras and 140 points. These data created an $A^TQ^{-1}A$ matrix which contained 121,032 stored elements. This large array required approximately one hour of actual CPU time to form and invert and with seven iterations before convergence was achieved, required overnight or weekend processing. Other quicker methods of inverting the $A^TQ^{-1}A$ matrix are available but were not developed as other problems suggested that the total approach was not practicable. The self-calibrating bundle adjustment had assumed block-invariancy for the reasons stated in Section 5.2.4.2, clearly the assumption that the same camera had been used at all epochs was erroneous in the case of the 'total solution.' The problem was appreciated and the effects reduced to a minimum by using a non-self-calibrating bundle adjustment with inner orientation parameters established by previous self-calibrating adjustments. This approach could only provide a partial solution because the inner orientation would require re-estimation. The final problem with the total solution was more subtle. Although some common points were measured at several epochs, it was realised that due to differences of perspective, it was probable that the points actually measured at different epochs were slightly different. In single epoch estimations this discrepancy would be removed by the ability of the control coordinates to adjust, controlled by the assigned standard deviations, (Section 5.2.4.3). In the total solution, large photo-coordinate residuals were probably the result of the inability of the coordinates of a point to flex in several directions. Despite all of these problems a solution was eventually obtained with a variance factor of 8.6. A statistical test on the quadratic form of the least squares corrections, (Section 5.2.4.2) indicated that this variance factor was still significantly large and although the total solution was of interest, the datum it defined was not used.

The third possible method of solving the datum problem was eventually selected. This involved specifying the way in which the control data were used to define a datum, including all stochastic properties, and then using these at each epoch. The datum was established by the following definitions:

1. **OS Control Plan points**, coordinates scaled from OS 1:2,500 plan. Standard deviations +/- 1.0 metre.
2. **OS Control Height points**, values obtained from OS 1:2,500 plan. Standard deviations +/- 0.2 metre.
3. **Beach Points**, height estimated (0.0, 0.5, 1.0 metre). Standard deviations +/- 0.5 metre.

4. **Sediment Points**, height differences determined from known dip and strike of Liassic sediments. (SE/ESE 2.5°) Standard deviations +/- 0.5 metre.

5. **Point '106'** height determined by ground survey above mean sea-level (151.8 metre).
Standard deviation +/- 0.4 metre.

With this standardised approach, it was felt that the datums used at each epoch, although not theoretically identical, would be sufficiently similar to permit meaningful comparisons. In order to establish acceptable estimations the term 'acceptable' used in association with a self-calibrating bundle adjustment was redefined as:

1. Low control point residuals. ⎫ Variance factor=1.0
2. Low photo-coordinate residuals ⎭
3. Comparisons between epochs of the elevations of common plan control points, with elevation as an estimated parameter.

Table 6.2 indicates a comparison between the estimated heights of common planimetric control points and it is possible to see that the differences are mainly lower than the standard deviations of those points.

Table 6.2 Datum comparison- Elevations of Common points and Their Standard Deviations

Date	Pt: 101	103	107	108	110	111	114
			(Standard Deviation)				
1946			139.46 (0.94)	131.05 (1.17)	107.21 (1.22)		
1948					110.94 (0.63)	80.61 (0.51)	
1958	170.41 (0.64)	121.20 (0.34)			110.87 (0.55)		
1966	170.98 (0.55)	120.60 (0.26)					101.74 (0.68)
1969		119.76 (0.79)	139.99 (0.58)		100.47 (9.21)	82.03 (2.82)	100.85 (5.61)
1976	167.08 (0.77)			133.80 (0.25)	111.05 (0.29)		102.51 (0.32)
1988 (Jan)	170.90 (0.76)		141.44 (0.60)	133.06 (0.66)	111.01 (0.69)		102.49 (0.73)

6.5 Integration with an Analytical Plotter

The photo-coordinates necessary for an acceptable self-calibrating bundle adjustment were measured using a stereo-comparator (Stecometer, Zeiss-Jena). The next stage was the extraction of spatial data from the archival photographs using the estimated interior and exterior orientation parameters and new photographic measurements. This procedure could be carried out using the stereo-comparator but would be more effective if an analytical plotter is used. Such an instrument creates and maintains a stereomodel at the position of the floating mark, which greatly eases the scanning and tracing of detail, (Section 4.1.1.2).

The City University has recently acquired the Intergraph 'Inter-Map Analytic' (IMA) analytical plotter and this provides additional features which help both with data extraction and further data processing and presentation. The IMA possesses two graphics screens, one of which can be viewed through the left hand eye-piece. This allows data, such as line strings that have been digitised, to be superimposed upon the left-hand photographic image. The feature is known as 'superimposition' and helps the operator to avoid duplication and to classify features consistently. The IMA software package is comprised of four principal modules:

1. **Project management**- used to enter and edit data associated with a particular photogrammetric project.
2. **Orientations**- which 'sets up' pairs of photographs so that measurements can be made from a stereomodel. These measurements are then transformed into three dimensional coordinates.
3. **Feature Coding**- allows lines of detail to be coordinated and classified according to a user defined feature table.
4. **DTM Data collection**- allows a grid type digital terrain model to be measured.

In addition to operating as an analytical plotter the IMA can also function as a full three dimensional graphics workstation. This enables data that have been acquired from photographs to be analysed and viewed from any perspective and at any scale. A VAX 730 host computer provides storage for data files and further processing opportunities, the most important of which for this thesis was the Digital Terrain Modelling software package, (Section 8.4). Other options include the ability to obtain plots on an A0 plotter.

6.5.1 Restitution of a Stereomodel

The analytical plotter is theoretically extremely flexible, although computer programs are necessary to exploit these capabilities. The software that was initially obtained with the IMA was developed for mapping from conventional vertical aerial photographs. Initial tests revealed that the standard software was not able to accommodate convergent oblique photography directly. The IMA possesses five processors, all of which need to be controlled in order to provide interaction between operator, hardware and graphics. The complex nature of the IMA system precluded the option of developing 'in-house' software, at that stage. It was hoped that although some problems would be experienced with the IMA software, these would be overcome.

Several stages are necessary in order to be able to extract data from a pair of photographs with the IMA. First, details regarding a particular 'project' need to be entered into the IMA database. Camera calibration details included the focal length of the camera and the position of the principal point with respect to the photo-coordinate system. These values had been deduced from the self-calibrating bundle adjustment and were entered into the database. Other calibration details included lens distortion parameters and the calibrated positions of the fiducial marks. The calibrated position of the fiducial marks were unavailable and so the measured positions had to be used.

The second stage is to establish the geometric relationships between the comparator system of the analytical plotter, the photo-coordinate and the ground coordinate system. The 'Orientations' software is used and this comprises two procedures. The first, called IO, carries out the 'inner orientation' of the photographs. This entails placing the photographs on the stage plates of the analytical plotter and measuring the four positions of the fiducials on each photograph. Either a two dimensional affine or a similarity transformation is carried out, which establishes the relationship between the comparator coordinate and the photo-coordinate system. The second procedure, known as SO, carries out a space resection to compute the cameras exterior orientation, based upon photo-coordinate measurements of object space control points.

The SO procedure was theoretically unnecessary in the case of the archival photographs as these parameters had been estimated in the self-calibrating bundle adjustment. However, it was impossible to avoid this step as until the SO had been computed and accepted it was impossible to extract data in either Feature-Coding or DTM Data Collection. If the SO software was used to re-establish the exterior orientation parameters, the program failed. The software had been developed for conventional vertical photographs and it was believed that certain assumptions had been made in the algorithms. The difficulties were resolved by re-entering the exterior orientation parameters into the database with very small standard deviations. Then, after a series of measurements to some of the control points, it was possible to enforce re-computation of the previously estimated exterior orientation parameters. These values could be accepted and stored in the relevant part of the database. A stereo-model could then be perceived at the position of the floating mark and both the Feature Coding and DTM data collection software accessed. Once the SO software had been successfully completed for any particular model, future measurement of the photo-pair could be achieved by simply down-loading the SO parameters from the database. If the photographs had been removed from the stage plates the two dimensional transformation parameters had to be re-established using the IO option of Orientations.

6.5.2 Feature Coding

Important aspects of extracting geomorphological data from archival photographs are the recognition, classification and co-ordination of geomorphological boundaries, (Section 7.2.1). The IMA provides the ability to acquire both three dimensional coordinates rapidly and to classify the boundaries according to a user defined coding system. The Feature Coding software allows the operator to code linear features using different line styles, colours and thicknesses by selection from a series of pull down menus.

The default feature codes provided by the IMA are of limited use from a geomorphological viewpoint as they have been developed for aerial mapping applications. The facility to create user defined codes was used for geomorphological applications, with an emphasis on coastal landslides. The coding system was based upon that developed by Conway (1974) for a geomorphological plan of Black Ven. The menu system is hierarchical and four categories were defined; morphological form, morphological features, morphological failures and system boundaries. Table 6.3 illustrates the full feature code table.

There is a facility which enables 'cells' to be defined and placed at desired points. A cell is simply a collection of graphical elements that can be placed into an Intergraph graphical 'design' file, at any selected point. It was hoped to create a series of cells that could represent the series of line-styles used for annotating morphological maps, (Savigear, 1965). It was found impossible to develop a line feature which was composed of a series of associated cells and so the coding system had to rely upon differences in colour, weight and line-types. A series of

Feature Table- Geomorphology of Coastal Landslides

KEY

MORPHOLOGICAL FORM

ROCK SLOPES. TOP > 40°
ROCK SLOPES BOTTOM
ANGULAR CONVEX BREAKS OF SLOPE, < 40°
ANGULAR CONCAVE BREAKS OF SLOPE
SMOOTH CONVEX BREAKS OF SLOPE
SMOOTH CONCAVE BREAKS OF SLOPE
SEA CLIFF
OTHER MORPHOLOGICAL BOUNDARIES

MORPHOLOGICAL FEATURES

TENSION CRACKS
SHEAR PLANES
GULLY
COMPRESSIVE RIDGE
SCRUB
PONDS AND MARSH

MORPHOLOGICAL FAILURES

MUD SLIDE
DEGRADED MUD FLOW
SAND RUN
ROTATIONAL SLIDE BLOCK
DEGRADED ROTATIONAL SLIDE BLOCK
ROCK FALL
BOULDER ARC

SYSTEM BOUNDARIES

SYSTEM
SUB-SYSTEM
UNIT
SUB-UNIT

Table 6.3

geomorphological symbols was created but were only of limited use because it was impossible to place a 'three dimensional' cell whilst using the IMA. Use of cells had to be restricted to small two dimensional symbols, such as those used to represent areas of 'scrub' and 'ponds and marsh', (Table 6.3; Example: Figure 8.3).

With the establishment of the feature table, each linear feature that was identified could be categorized during measurement. These data were stored in the Intergraph design file at various graphical 'levels'. The differing levels permitted selective display of the data at the graphics workstation.

The procedures and software developed for use with archival photography were successfully applied to a variety of historical photographs of the Black Ven case study. Furthermore, procedures were instigated which enabled an analytical plotter to obtain historical spatial data. The next important phase of the research was to acquire historical data of the Black Ven landslides and to develop methods of data processing which were of geomorphological relevance.

Chapter 7

Data Acquisition and Processing

7. Data Acquisition and Processing

The final stages (Figure 5.1) associated with the archival photogrammetric technique are:

1. Data acquisition;
2. Data processing;
3. Data presentation and
4. Interpretation.

As discussed in Section 5.1, these stages require a greater proportion of geomorphological expertise and photogrammetric considerations become less important. During the final interpretative stages, it is only an understanding of the quality (Section 8.2) of the coordinates that requires photogrammetric expertise.

The areas of Black Ven selected for particular investigation were the two large eastern mudslide systems of Black Ven 1 and 2 (Figure 6.1). These were chosen because the archival photographic coverage concentrated upon this area, and the sites are the subject of geological and geomorphological studies by previous workers, (Lang, 1927, Arber, 1941; Lang, 1955, 1959; Brunsden, 1969; Denness, 1972; Arber, 1973 and Conway, 1974).

7.1 Data Acquisition

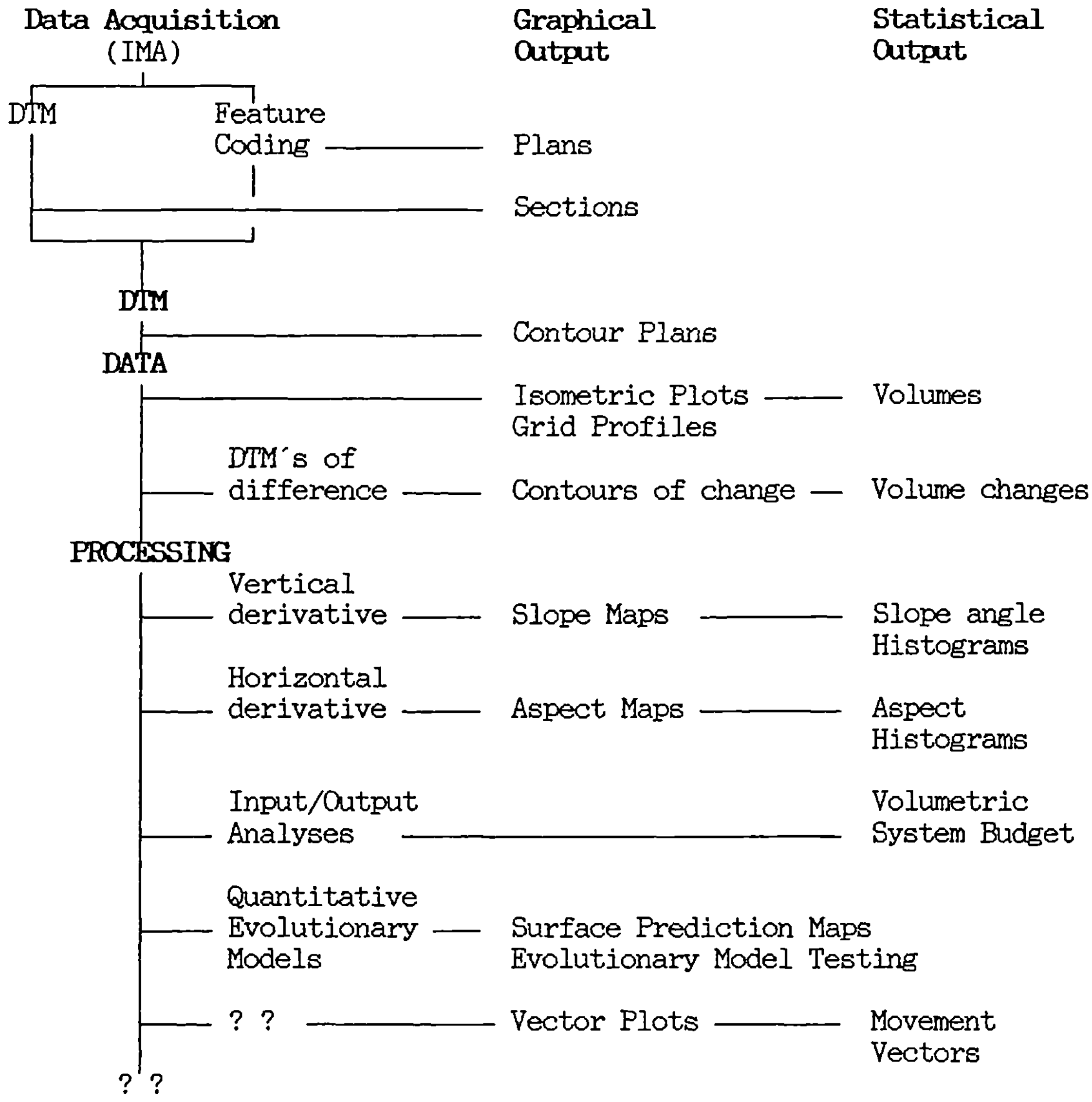
In the case of the Black Ven landslide the re-measurement of the photographs necessary to acquire new three dimensional coordinates was carried out using the InterMap Analytic (IMA) analytical plotter. This instrument provided several advantages, principally high rates of data extraction and superimposition of digitised data, (Section 6.5). Two distinct phases of data acquisition could be identified: feature coding and DTM data collection. The former entailed identification of important morphological boundaries and classification according to the coding system that had been developed, (Section 6.5.2). Following identification, each feature was traced and a series of three dimensional coordinates digitised which represented the feature. The identification of relevant boundaries required understanding of geomorphological processes, the problems associated with identification and interpretation are discussed in Section 8.3.2. The second phase of data acquisition made use of the DTM Data Collection software (Section 6.5) which provided the ability to obtain both a regular grid DTM or to measure directly any profile. No interpretive skills were required during DTM measurement, although some understanding was necessary for selection of relevant profiles.

The photographs from all archival epochs were measured in a consistent way, so that similar data were acquired at each epoch. Some differences were inevitable, due to varying image quality and geometry (Section 8.2.2). The Feature Coding software was used initially, with delineation of major morphological boundaries, followed by the smaller morphological features and slope failures. The features that were identified required approximately 8,000 detail points to record at each epoch. The DTM that was subsequently measured consisted of a 10 x 15 metre grid, which required 3,000 points to cover the area under particular investigation. Even with the rapidity of measurement provided by the IMA, the whole phase of data acquisition required a minimum of 15 hours of instrument time for each epoch.

7.2 Data Processing for Geomorphology

The basic data unit that was acquired during Feature Coding and DTM 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 geomorphological benefit. Several processing options were investigated and it was found that these can be used to provide the geomorphologist with a selection of graphical and numerical data. The options are summarised in Figure 7.1 and include basic planimetry, direct profiles, DTM data processing, quantitative evolutionary models and movement vectors.

Figure 7.1 Geomorphic Data Processing



Key ? ? Other possibilities

The data that were acquired from the five historical epochs of Black Ven were used in the development of the processing techniques summarised in Figure 7.1. The feature coded data were used for the basic graphical methods of data presentation and interpretation (Section 7.2.1). Profile data were acquired directly within the DTM Data Collection software package (Section 7.2.2). Both feature coded data and regular DTM data were combined and used in the more advanced DTM data processing and interpretation methods (Section 7.2.3).

In the course of developing the various techniques and applying these to the case study, results were interpreted which are of particular significance both to the Black Ven landslide and to geomorphology. These important results are discussed in greater detail in Section 7.3.

7.2.1 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 categorisation of morphological boundaries is an important first step in the interpretation and understanding of form and process. A variety of geomorphological maps and coding systems are available (Cooke and Doornkamp, 1974) and important systems have been developed at the International Institute for Aerospace Survey and Earth Sciences (ITC) (Van Zuidam, 1986) and also by Savigear (1965). The coding system that was developed for use in Feature Coding (Section 6.5.2) was based upon a system utilised by the Institute of Geological Sciences, (Conway, 1974) in a study of the Black Ven landslides.

Traditionally, geomorphological maps have been compiled by sketching detail onto a conventional large scale base map, (Savigear, 1965; Van Zuidam, 1986). The precise definition and coding of geomorphological boundaries by rigorous photogrammetric techniques combines the benefits of geomorphological interpretation with positional relevance. Five geomorphological maps were produced, (Figures 7.2- 7.6) 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.

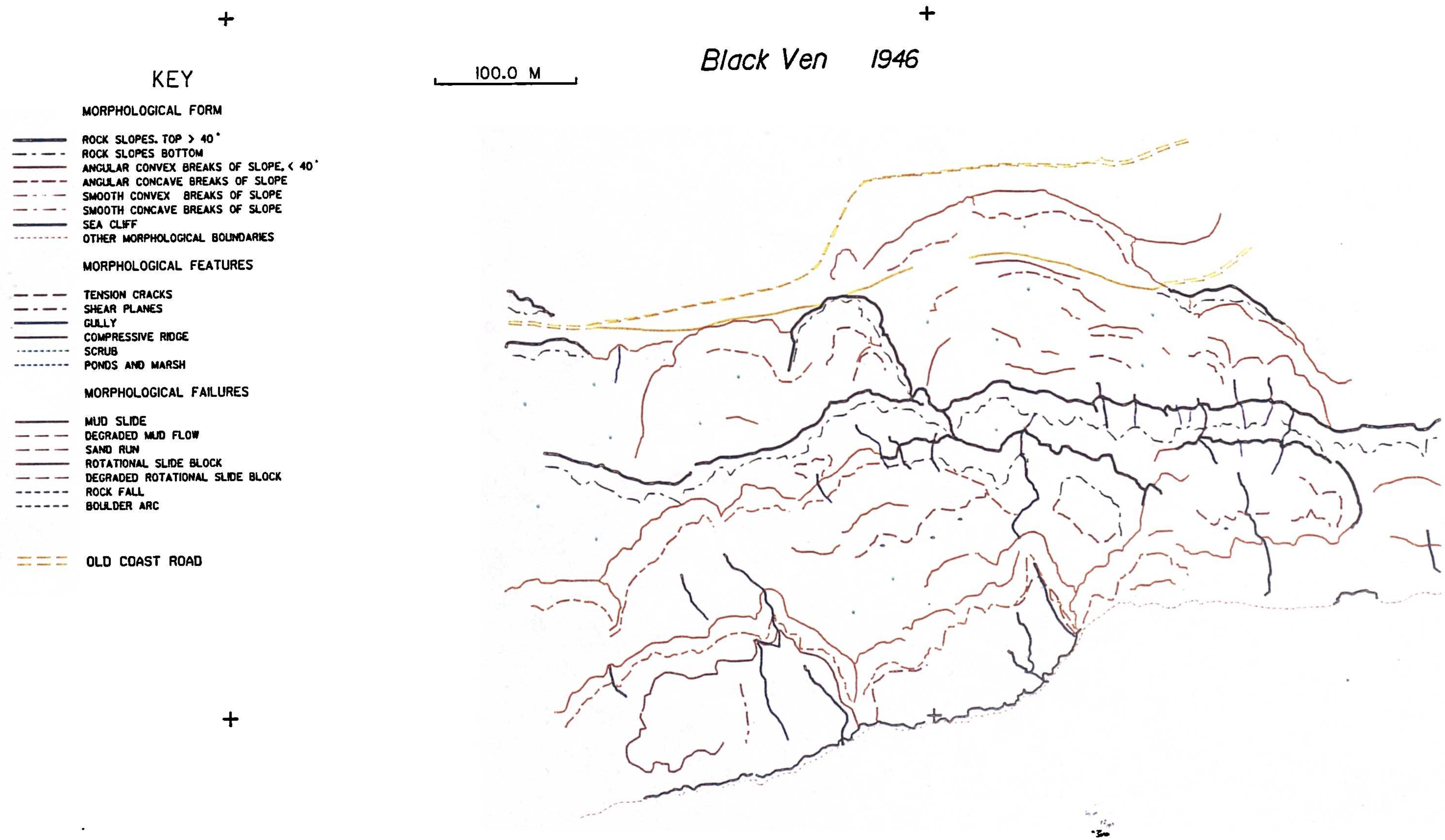

Black Ven 1946
100.0 M
KEY
MORPHOLOGICAL FORM
ROCK SLOPES. TOP > 40°
ROCK SLOPES BOTTOM
ANGULAR CONVEX BREAKS OF SLOPE, < 40°
ANGULAR CONCAVE BREAKS OF SLOPE
SMOOTH CONVEX BREAKS OF SLOPE
SMOOTH CONCAVE BREAKS OF SLOPE
SEA CLIFF
OTHER MORPHOLOGICAL BOUNDARIES
MORPHOLOGICAL FEATURES
TENSION CRACKS
SHEAR PLANES
GULLY
COMPRESSIVE RIDGE
SCRUB
PONDS AND MARSH
MORPHOLOGICAL FAILURES
MUD SLIDE
DEGRADED MUD FLOW
SAND RUN
ROTATIONAL SLIDE BLOCK
DEGRADED ROTATIONAL SLIDE BLOCK
ROCK FALL
BOULDER ARC
OLD COAST ROAD

Figure 7.2

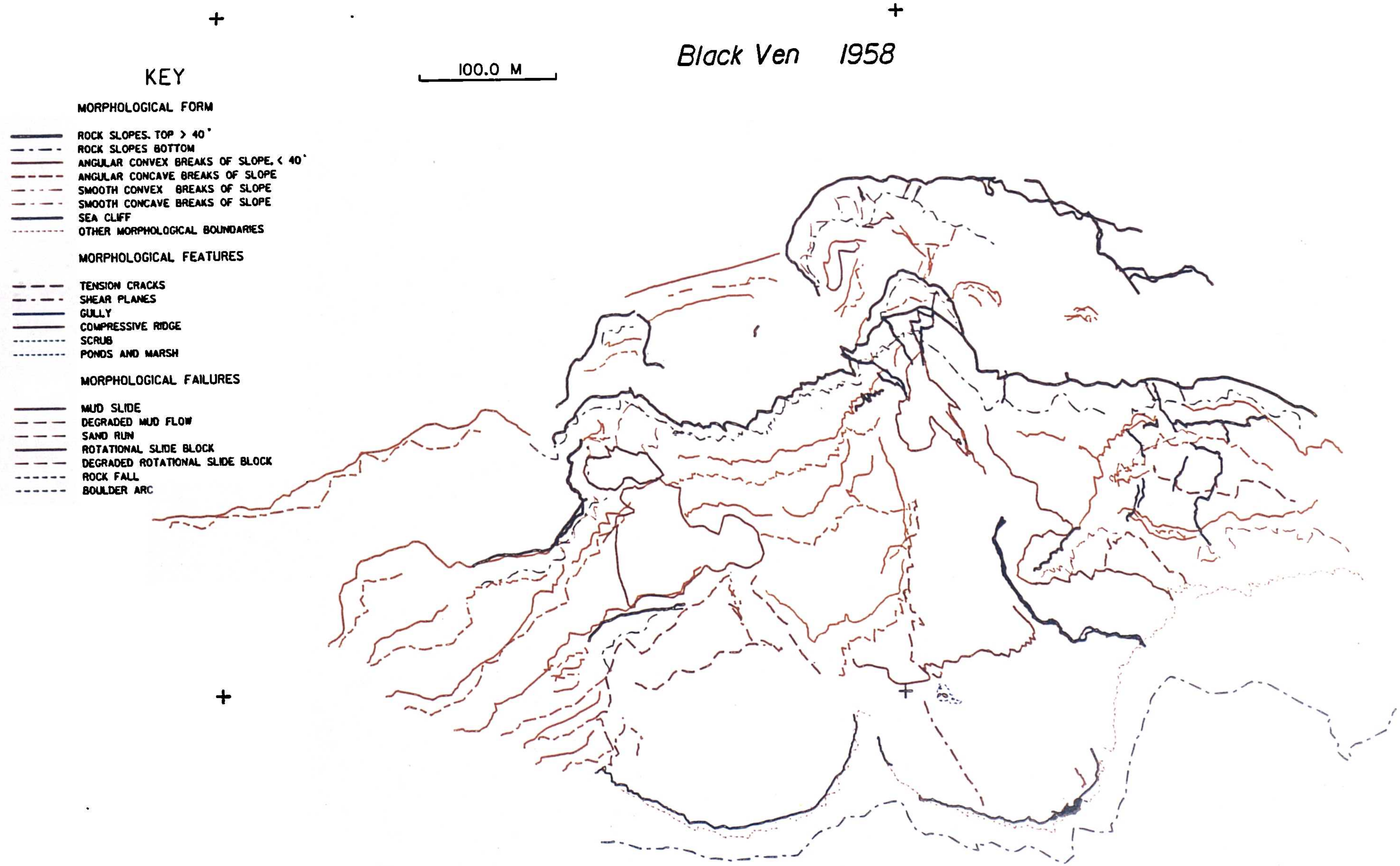

Black Ven 1958
100.0 M
KEY
MORPHOLOGICAL FORM
ROCK SLOPES. TOP > 40°
ROCK SLOPES BOTTOM
ANGULAR CONVEX BREAKS OF SLOPE. < 40°
ANGULAR CONCAVE BREAKS OF SLOPE
SMOOTH CONVEX BREAKS OF SLOPE
SMOOTH CONCAVE BREAKS OF SLOPE
SEA CLIFF
OTHER MORPHOLOGICAL BOUNDARIES
MORPHOLOGICAL FEATURES
TENSION CRACKS
SHEAR PLANES
GULLY
COMPRESSIVE RIDGE
SCRUB
PONDS AND MARSH
MORPHOLOGICAL FAILURES
MUD SLIDE
DEGRADED MUD FLOW
SAND RUN
ROTATIONAL SLIDE BLOCK
DEGRADED ROTATIONAL SLIDE BLOCK
ROCK FALL
BOULDER ARC

Figure 7.3

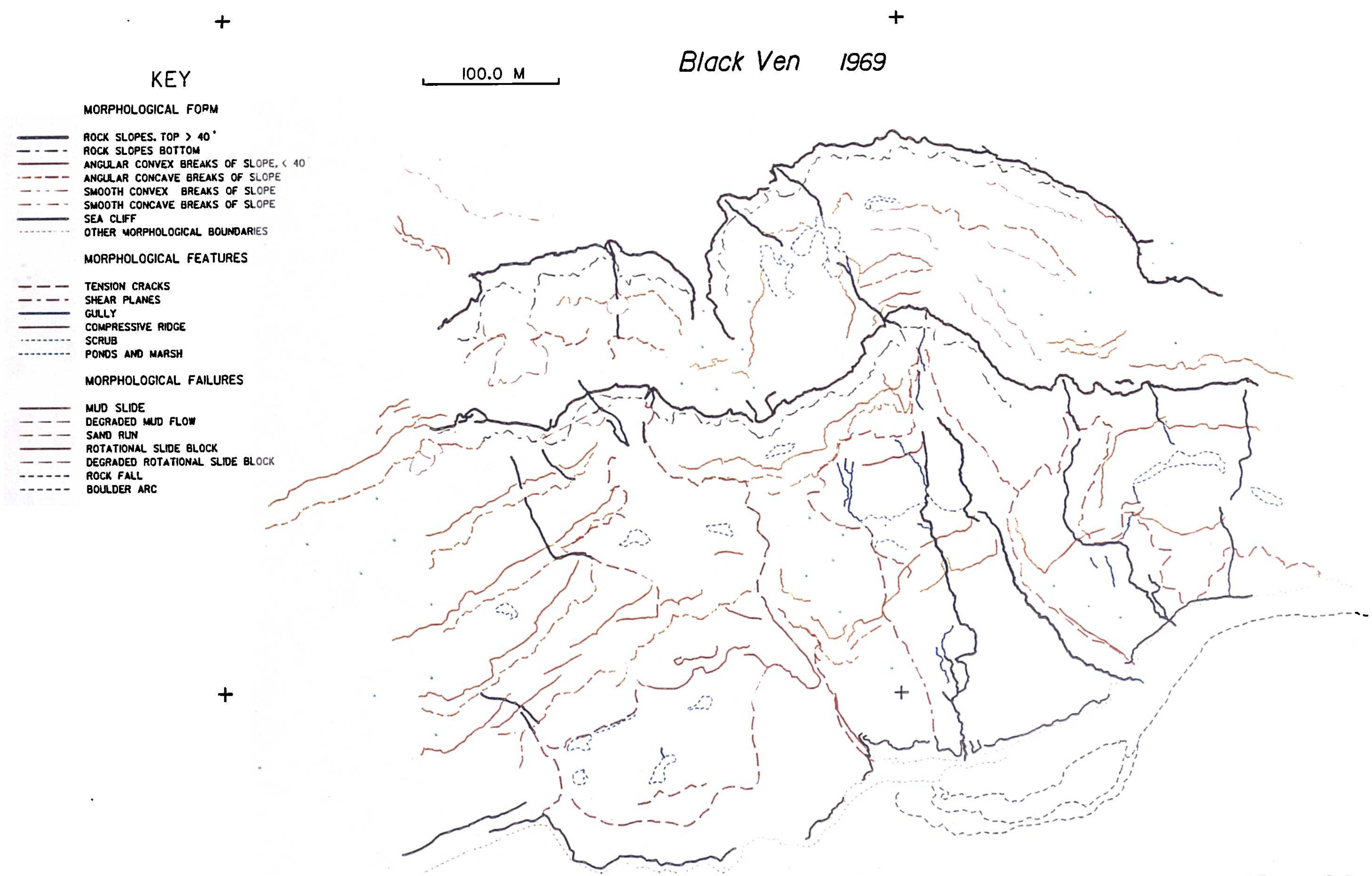
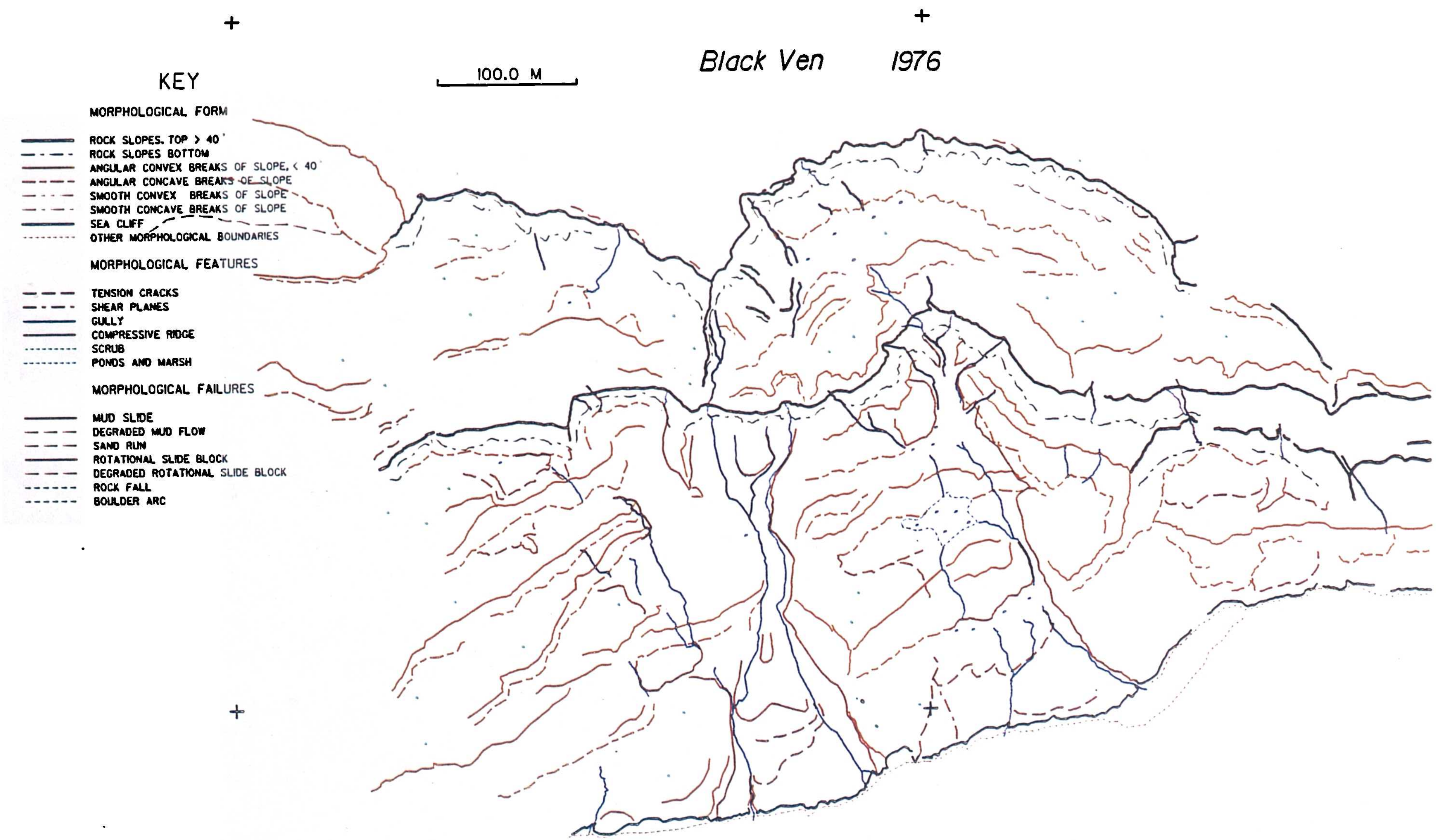

Black Ven 1969
100.0 M
KEY
MORPHOLOGICAL FORM
ROCK SLOPES. TOP > 40°
ROCK SLOPES BOTTOM
ANGULAR CONVEX BREAKS OF SLOPE, < 40
ANGULAR CONCAVE BREAKS OF SLOPE
SMOOTH CONVEX BREAKS OF SLOPE
SMOOTH CONCAVE BREAKS OF SLOPE
SEA CLIFF
OTHER MORPHOLOGICAL BOUNDARIES
MORPHOLOGICAL FEATURES
TENSION CRACKS
SHEAR PLANES
GULLY
COMPRESSIVE RIDGE
SCRUB
PONDS AND MARSH
MORPHOLOGICAL FAILURES
MUD SLIDE
DEGRADED MUD FLOW
SAND RUN
ROTATIONAL SLIDE BLOCK
DEGRADED ROTATIONAL SLIDE BLOCK
ROCK FALL
BOULDER ARC

Figure 7.4



Black Ven 1976
100.0 M
KEY
MORPHOLOGICAL FORM
ROCK SLOPES. TOP > 40°
ROCK SLOPES BOTTOM
ANGULAR CONVEX BREAKS OF SLOPE, < 40°
ANGULAR CONCAVE BREAKS OF SLOPE
SMOOTH CONVEX BREAKS OF SLOPE
SMOOTH CONCAVE BREAKS OF SLOPE
SEA CLIFF
OTHER MORPHOLOGICAL BOUNDARIES
MORPHOLOGICAL FEATURES
TENSION CRACKS
SHEAR PLANES
GULLY
COMPRESSIVE RIDGE
SCRUB
PONDS AND MARSH
MORPHOLOGICAL FAILURES
MUD SLIDE
DEGRADED MUD FLOW
SAND RUN
ROTATIONAL SLIDE BLOCK
DEGRADED ROTATIONAL SLIDE BLOCK
ROCK FALL
BOULDER ARC

Figure 7.5

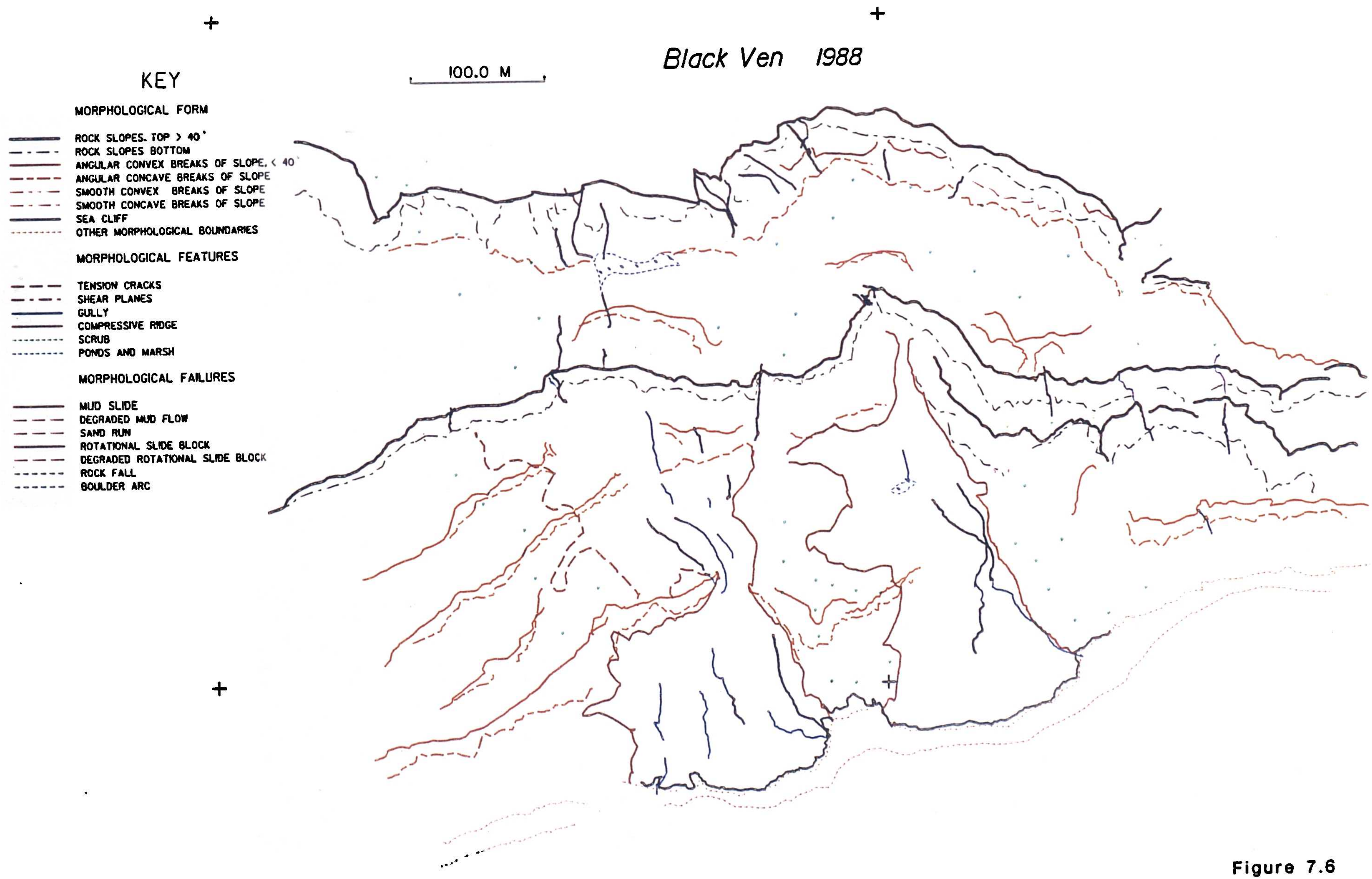

Black Ven 1988
100.0 M
KEY
MORPHOLOGICAL FORM
ROCK SLOPES. TOP > 40°
ROCK SLOPES BOTTOM
ANGULAR CONVEX BREAKS OF SLOPE. < 40°
ANGULAR CONCAVE BREAKS OF SLOPE
SMOOTH CONVEX BREAKS OF SLOPE
SMOOTH CONCAVE BREAKS OF SLOPE
SEA CLIFF
OTHER MORPHOLOGICAL BOUNDARIES
MORPHOLOGICAL FEATURES
TENSION CRACKS
SHEAR PLANES
GULLY
COMPRESSIVE RIDGE
SCRUB
PONDS AND MARSH
MORPHOLOGICAL FAILURES
MUD SLIDE
DEGRADED MUD FLOW
SAND RUN
ROTATIONAL SLIDE BLOCK
DEGRADED ROTATIONAL SLIDE BLOCK
ROCK FALL
BOULDER ARC

Figure 7.6

The size and extent of the two mudslides at each epoch were derived from the geomorphological maps of Black Ven, the dimensions are summarised in Table 7.1, (Standard deviations derived from Table 8.1).

Table 7.1 Morphometric Data- Extent of Main mudslides

	Black Ven 1				**Black Ven 2**			
Date	Max. Length (L) (m)	Active lobe (W) Width (m)	S.Dev. L.& W	L/W	Max Length (L) (m)	Active lobe (W) Width (m)	S.Dev. L.& W	L/W
1946	194.	145.	2.3	1.4	194.	162.	2.3	1.2
1958	366.	234.	1.7	1.6	317.	184.	1.7	1.7
1969	305.	151.	1.4	2.0	342.	240.	1.4	1.4
1976	285.	160.	0.8	1.8	294.	117.	0.8	2.5
1988	308.	145.	2.4	2.1	302.	154.	2.4	2.0

The standard deviations associated with these measurements are derived from the standard deviations of the coordinates of 'sediment points' used in the self-calibrating bundle adjustment. These standard deviations are perhaps understated because the selection of relevant morphometric measurements is arbitrary and different workers will identify different mudslide boundaries, (Section 8.3.2.1). Despite this problem, the dimensions in Table 7.1 reveal the variability of size of the main mudslides and that periods of major activity are marked both by an extension of the mudslide and an increase in width. These increases occurred in 1958 on Black Ven 1 and in 1969 on Black Ven 2, with very similar final dimensions. Following this, both mudslides contracted and the active width was approximately reduced by a factor of two.

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, (Figure 7.7). Such a morphogenetic study can be quantified by measuring the horizontal displacements of important morphological boundaries through time.

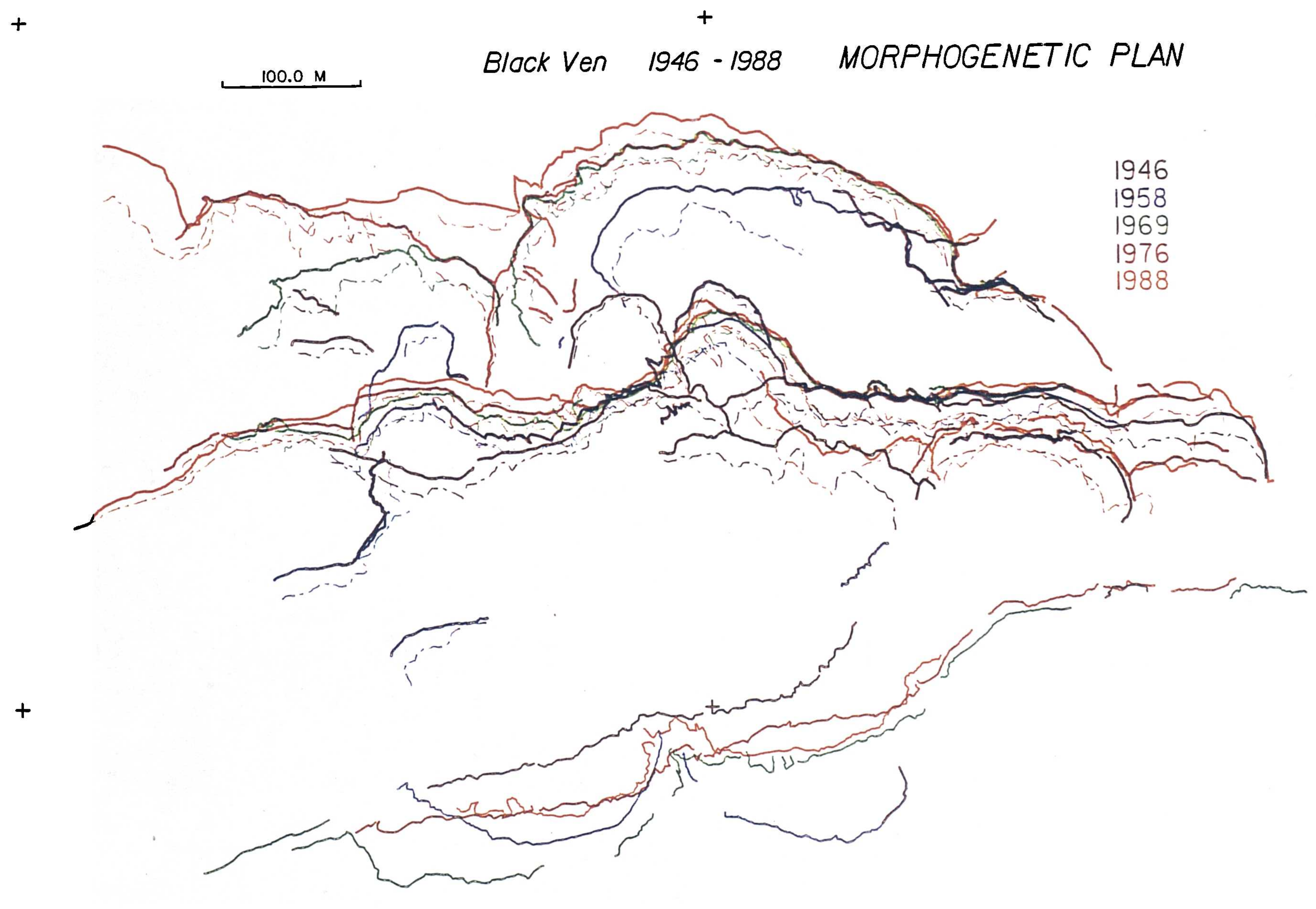

Black Ven 1946 - 1988 MORPHOGENETIC PLAN
100.0 M
1946
1958
1969
1976
1988

Figure 7.7

This type of **morphogenetic analysis** was carried out for the Black Ven landslide in order to establish process rates and is discussed further in Section 7.3.1.

7.2.2 Direct Profiles

The down-slope vertical profile and cross section are commonly used in geomorphology to illustrate the mechanisms of slope failure and to design remedial measures. Profiles have become important because they are comparatively easy to acquire, analyse and interpret. Two main methods have been used in geomorphology to acquire the relevant data. For small scale profiles, the erosion pin has been the simplest, most precise, but laborious method, (Young, 1960; Haigh, 1977). Direct field survey techniques have also been used (Savigear, 1952; Blong, 1972; Gilg, 1973), especially for larger scale features such as hill slopes. More recently, photogrammetric methods have been developed, (Stirling, 1982) and applied (Small *et al*, 1984; Chandler *et al*, 1987; Chandler and Moore, 1989) and these provide the most practical means of obtaining high quality and high density data. A variety of techniques to analyse slope profiles have been used, (Young, 1961; Demirmen, 1975); including 'Best Units Analysis', (Young, 1971) although such analyses require careful interpretation (Gerrard, 1978). Several two dimensional slope models have also been produced and tested, (Scheidegger, 1961; Culling, 1963; Ahnert, 1970; Kirkby, 1984; 1987; Kirkby *et al*, 1987) which attempt to model the development of slope profiles, (Section 7.2.3.7).

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; 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 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

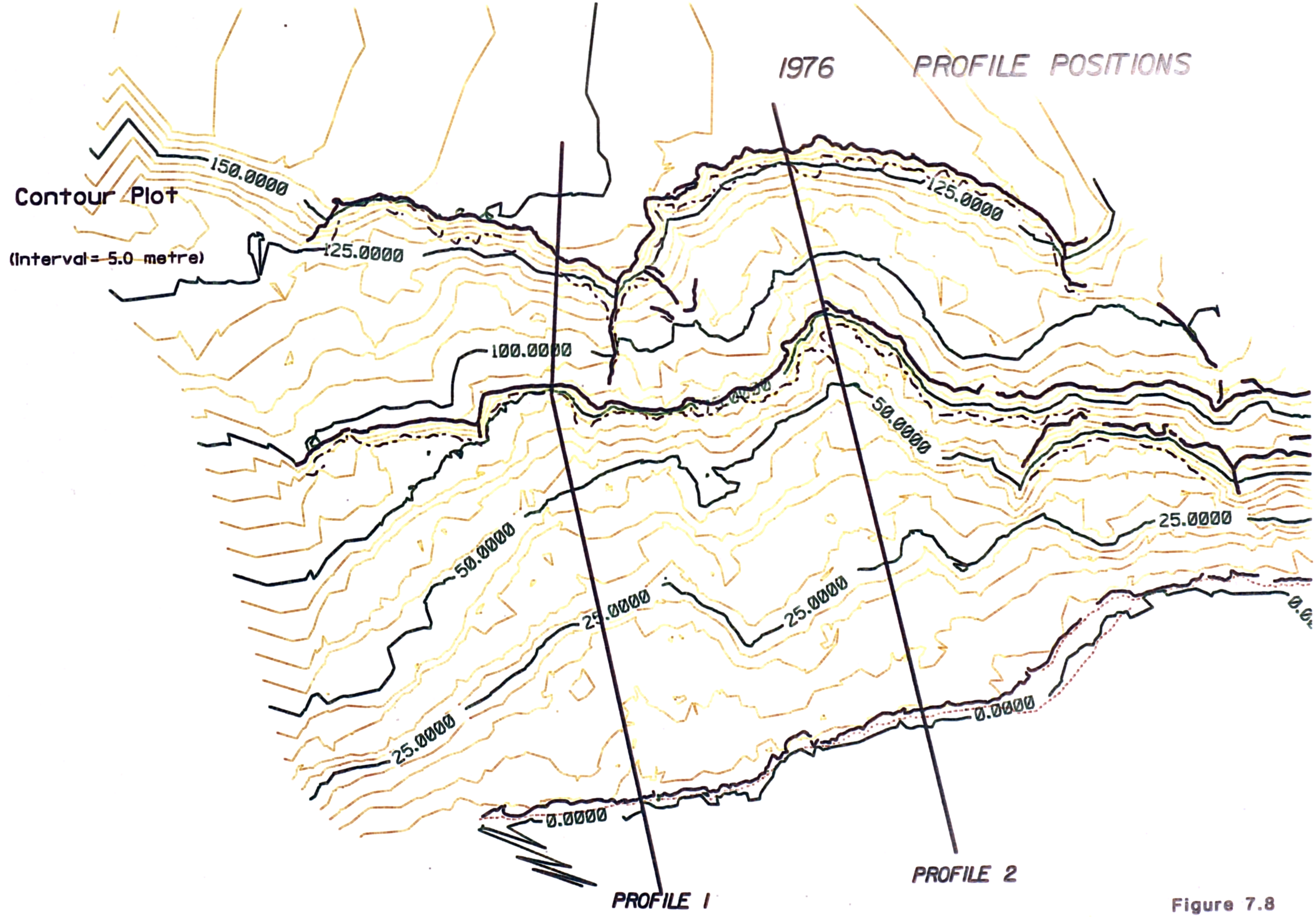

1976 PROFILE POSITIONS
Contour Plot
(Interval = 5.0 metre)
150.0000
125.0000
125.0000
100.0000
50.0000
50.0000
25.0000
25.0000
25.0000
25.0000
0.0000
0.0000
PROFILE 1
PROFILE 2

Figure 7.8

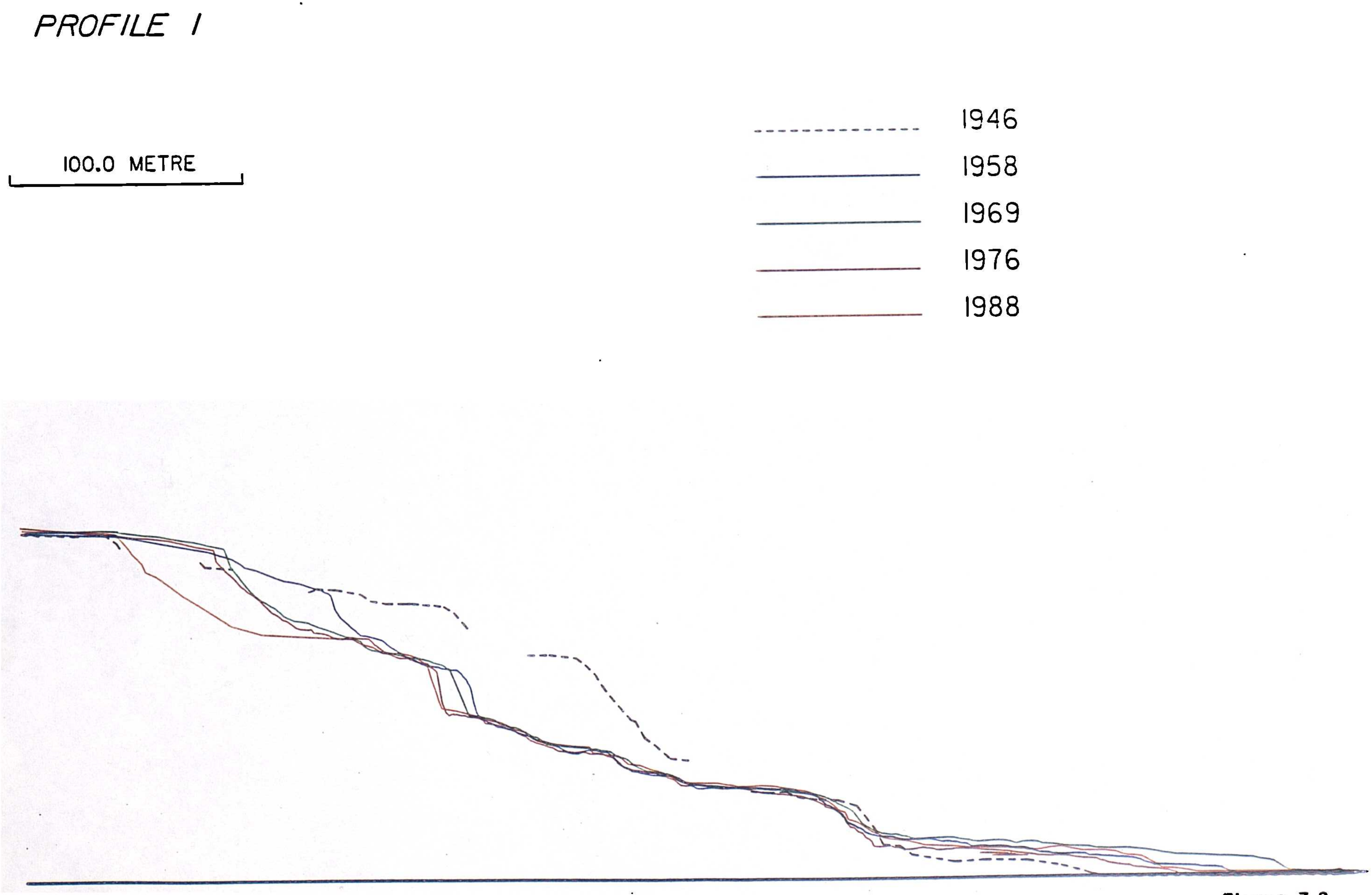


Figure 7.9

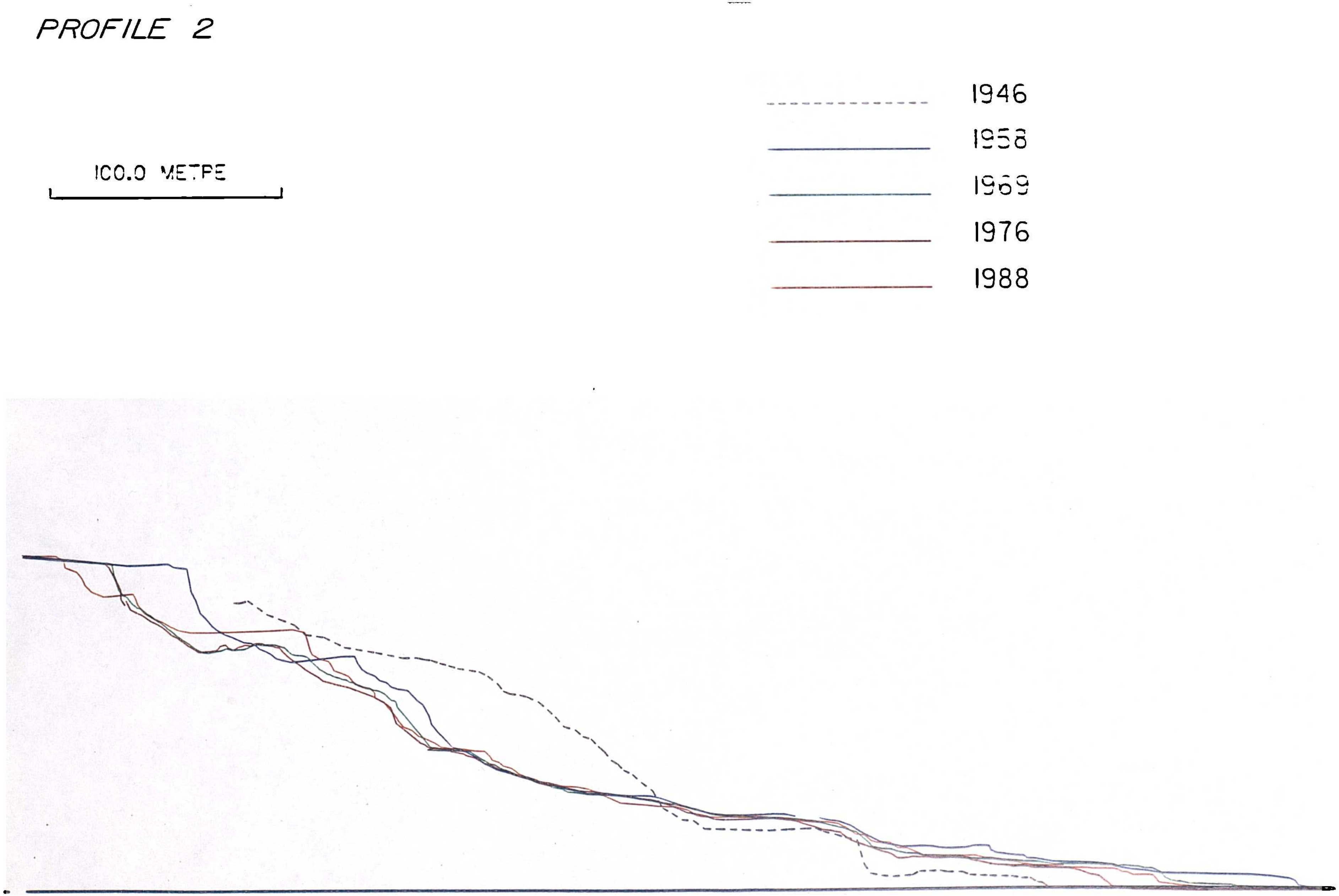


Figure 7.10

of the ground surface along the plane of interest can be displayed. The observation procedure can be repeated for the same plane, but using photography from a different epoch. This enables quantitative morphogenetic comparisons to be made.

Two vertical profiles were measured at each epoch and the contour plan (Figure 7.8) denotes the positions of Profiles 1 and 2. The profiles themselves (Figure 7.9- 7.10) echo the morphogenetic displacements discussed in Section 7.3.1, although precise displacements only indicate the change along the line of each profile. The historical profiles give an indication of the form of the slopes, which cannot be presented with the morphogenetic plan (Figure 7.7). Some of the geological factors controlling the development of form can be clearly seen, particularly the resistant horizons within the Liassic sediments. The precision of the two profiles acquired from the 1946 photographs is comparatively unreliable and the profiles are illustrated by pecked lines. The lower precision is associated with the difficulties of setting the floating mark on the ground surface due to the unfavourable base:distance ratio, (Section 6.3.2, 8.2.2.1).

The measurement of profiles was found to be a rapid and direct method of monitoring change in the plane of the selected profile. The data processing requirements are small so that results can be rapidly displayed. One major problem with the method is that the measured profile should follow the line of 'maximum energy.' This is equivalent to a line of maximum gradient and although theoretically possible to achieve during measurement, would require the development of a special program within the IMA environment which could interact with a previously created DTM. The alternative is to approximate the line of maximum energy into a series of short line sections. Different sections would be required at each epoch and as each needs to be projected orthogonally onto the plane of view, the display of these data would be problematical. The practical solution is to accept the limitations of the method and to select planes that are as close to the ´maximum energy line´ as possible. In the case of Black Ven this did not prove to be difficult, (Figure 7.8).

7.2.3 DTM Data Processing/ Geomorphometry

The techniques discussed in Section 7.2.1, 7.2.2 can all be regarded as two dimensional. Digital terrain modelling techniques use three dimensional data in order to provide either graphical or statistical forms of output. It is these techniques that really exploit the spatial quality of the photogrammetrically acquired data. A review of the theoretical aspects and some of the available packages is given by Petrie and Kennie (1987). The various geomorphometric parameters that can potentially be derived are discussed by Evans (1972).

Several processing techniques are available, but as these rely upon complex computing algorithms, both a powerful computer and a comprehensive DTM software package are required. Fortunately such a package was associated with the IMA and once understood provided important capabilities. One of the main problems with terrain modelling is the acquisition of sufficient data to model accurately the landform. This is a sampling problem in which the total population can never be known, but can be represented, at a particular level of significance, provided sufficient number of points are obtained, (Section 8.4). The type of DTM that is procured affects this problem greatly. The distribution of points acquired for a regular grid-based DTM are not related to the characteristics of the terrain itself, (Petrie and Kennie, 1987). DTM´s comprising a series of points which depict breaks of slope are more related to the landform but provide no data between line strings. In the case of Black Ven, a composite DTM was produced by combining data acquired in Feature Coding with a regular grid DTM acquired within DTM Data Collection.

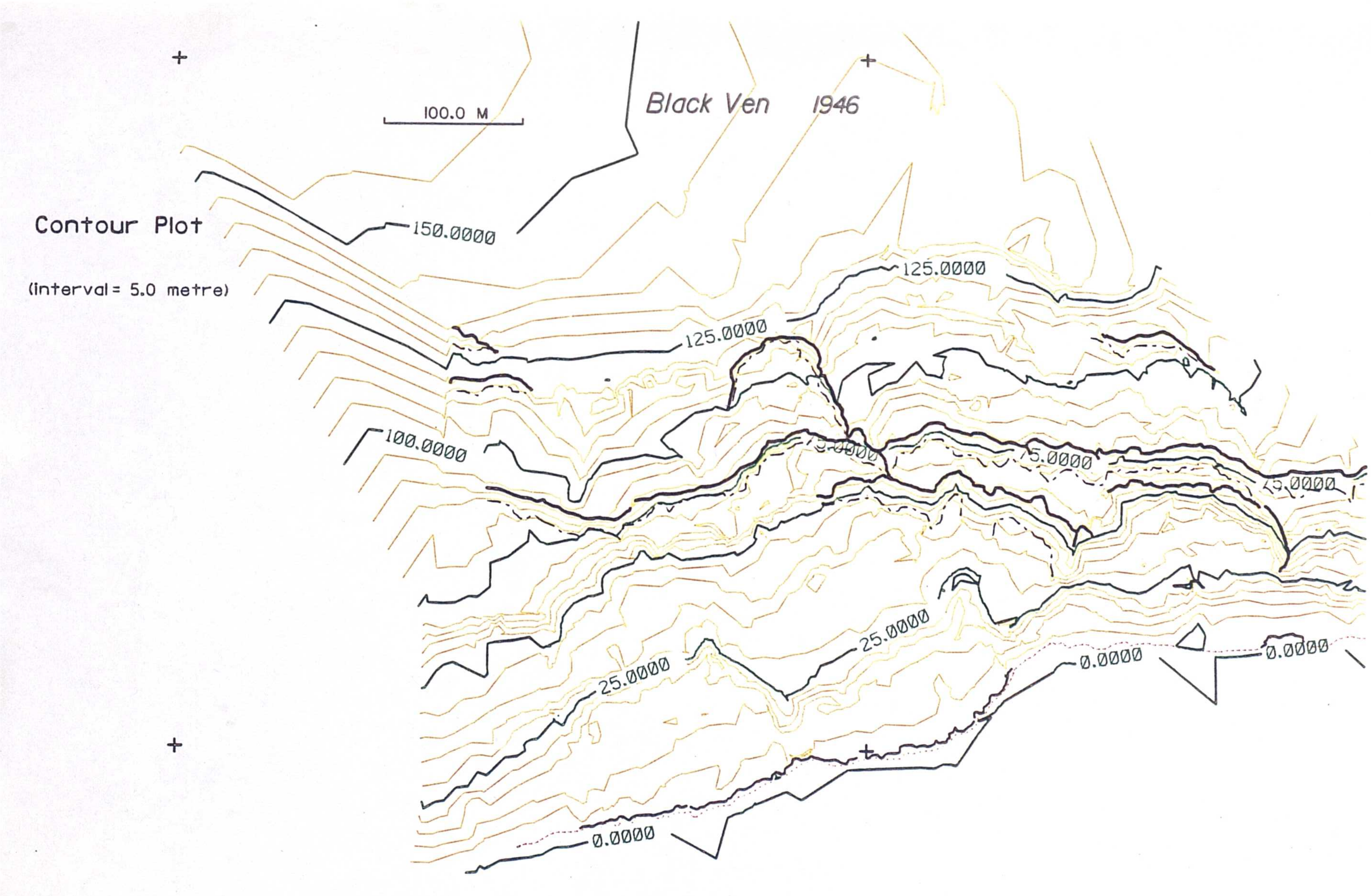

Black Ven 1946
100.0 M
Contour Plot
(interval= 5.0 metre)
150.0000
125.0000
125.0000
100.0000
25.0000
25.0000
0.0000
0.0000
0.0000

Figure 7.11

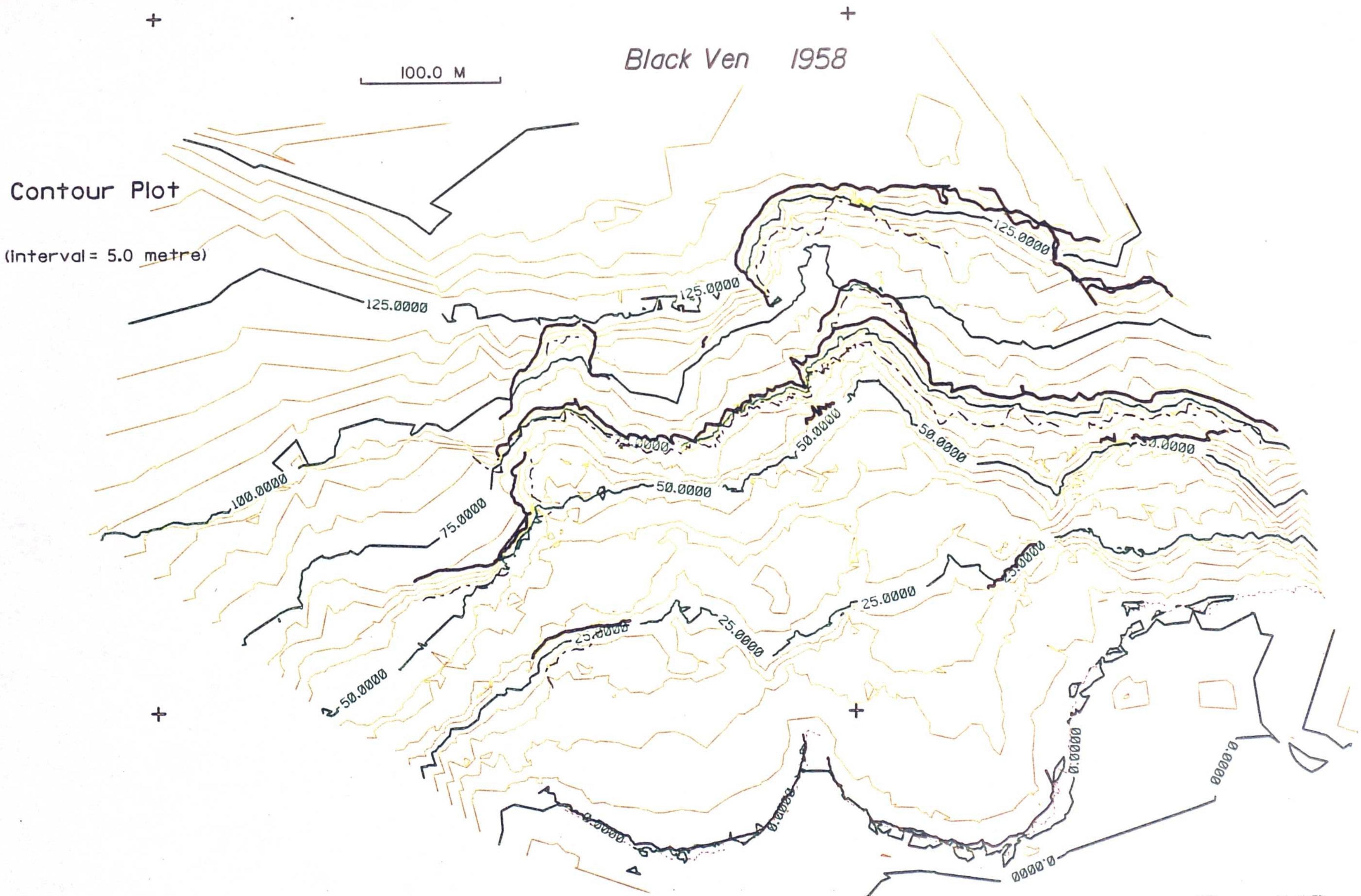

Black Ven 1958
100.0 M
Contour Plot
(interval= 5.0 metre)
125.0000
100.0000
75.0000
50.0000
25.0000
0.0000

Figure 7.12

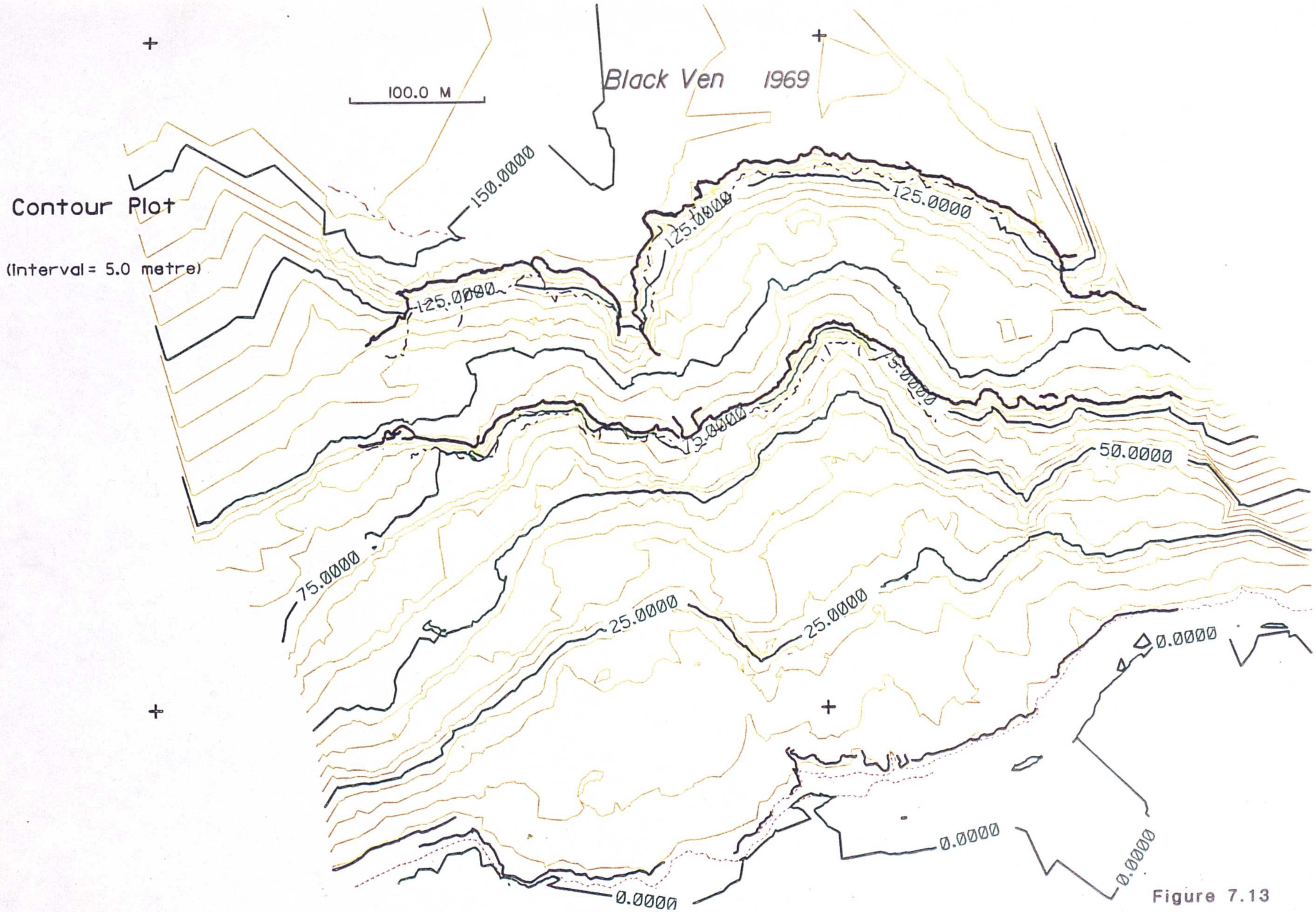

Contour Plot
(Interval= 5.0 metre)
100.0 M
Black Ven 1969
150.0000
125.0000
125.0000
125.0000
75.0000
75.0000
75.0000
50.0000
25.0000
25.0000
0.0000
0.0000
0.0000
0.0000

Figure 7.13

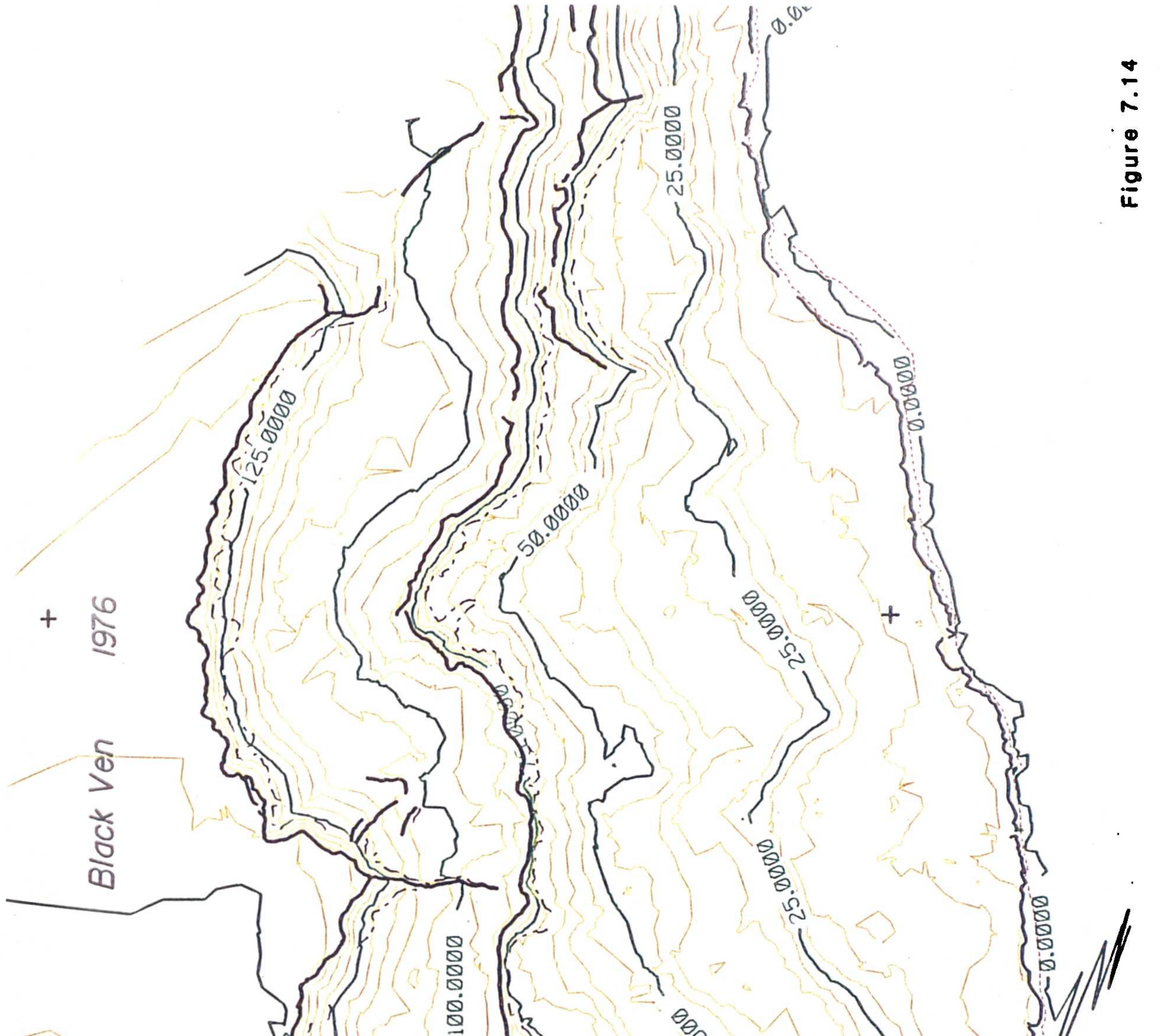
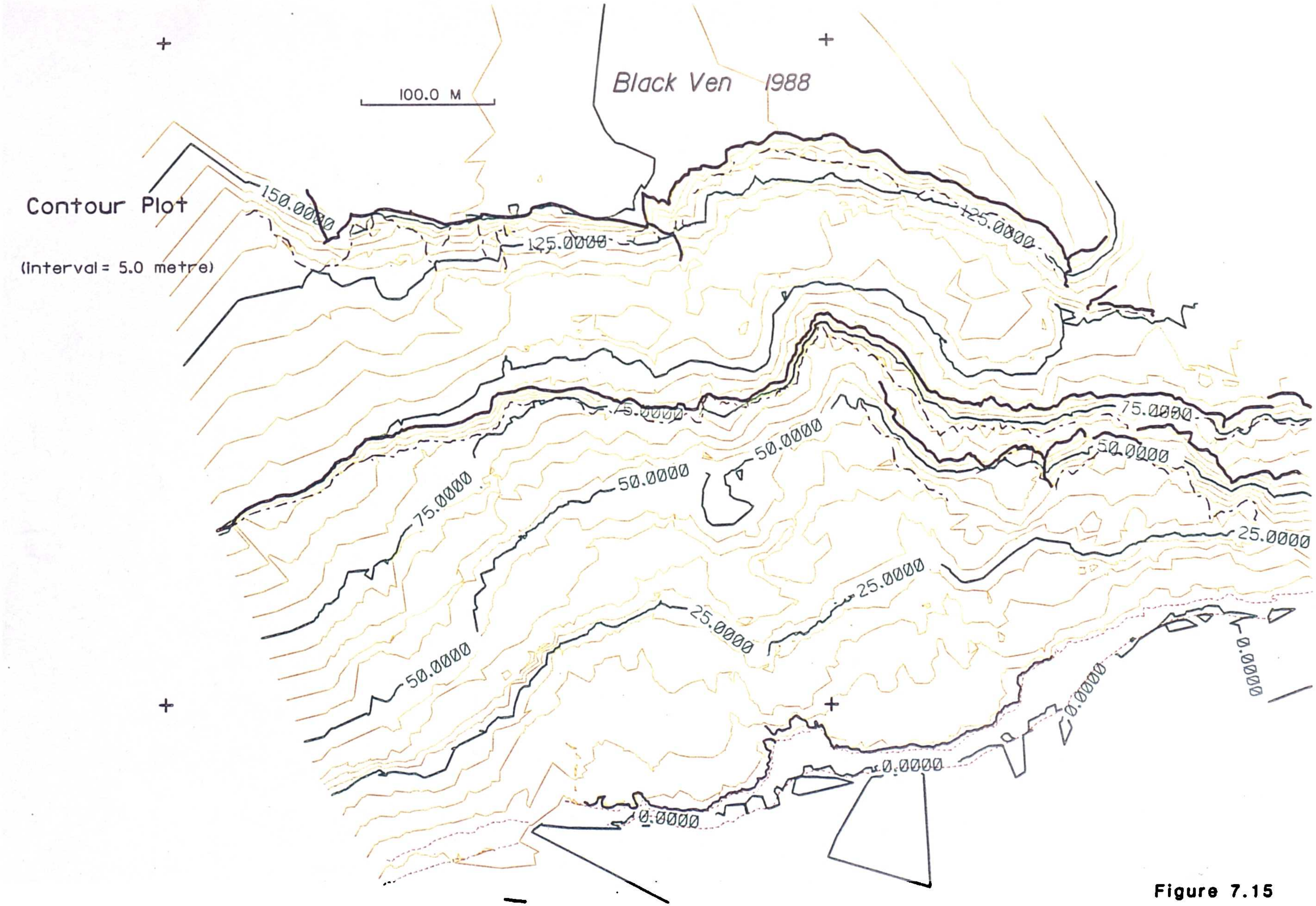

Black Ven 1976
Contour Plot
(Interval=5.0 metre)
100.0 M
150.0000
125.0000
125.0000
100.0000
50.0000
50.0000
25.0000
25.0000
25.0000
25.0000
0.0000
0.0000

Figure 7.14



Contour Plot
(Interval = 5.0 metre)
100.0 M
Black Ven 1988
150.0000
125.0000
125.0000
75.0000
75.0000
50.0000
50.0000
50.0000
75.0000
50.0000
25.0000
25.0000
25.0000
0.0000
0.0000
0.0000
0.0000

Figure 7.15

The former defined important breaks of slope, whilst the latter provided information between these lines. This combination produced a DTM with approximately 11,000 data points at each epoch. For the area under consideration, the mean data density was 1 point per. 28 m^2.

There are a variety of DTM data processing options, (Figure 7.1). Each of these will be discussed and illustrated by the Black Ven case study. Results of special significance are examined further in Section 7.3.

7.2.3.1 Contour Plots

Contour plots can be produced by triangulating the DTM coordinates, so forming a faceted surface. For Black Ven, contour plots were produced at each epoch and these were overlain with important morphological boundaries (Figures 7.11- 7.15). The contoured plots give a reasonable representation of site morphology, indicating steep areas and breaks of slope.

Pitty (1982) states:

> *'For the geomorphologist, the contour map is the basic indispensable description of their subject matter, portraying the vertical dimension precisely and outlining vividly the dimension and breadth of landforms.'*

The addition of the major morphological boundaries was found to be important because this provides strong visual clues, essential to help identify particular locations.

7.2.3.2 Isometric Views/ Grid Profiles

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. A comparison between the isometric plots of Black Ven produced from a 5 metre grid, (Figures 7.16- 7.20) illustrate the changes that have occurred on the landslide site, particularly recession of the rear scarp and development of the lobes (Section 7.3.1). What is also apparent is the density of detail that has been recorded by the 11,000 DTM data points.

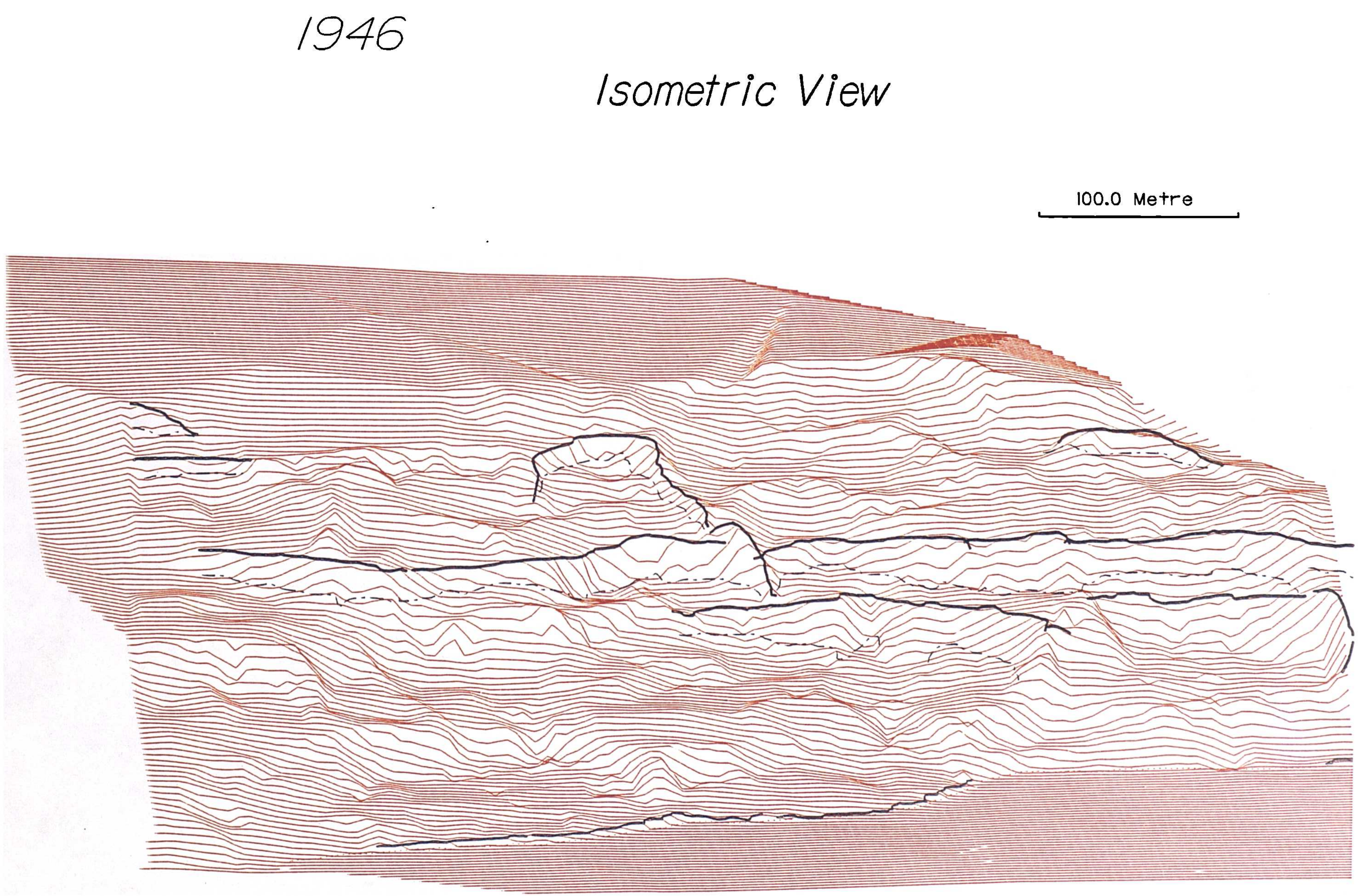


Figure 7.16

1958 Isometric View

Figure 7.17

1969 Isometric View

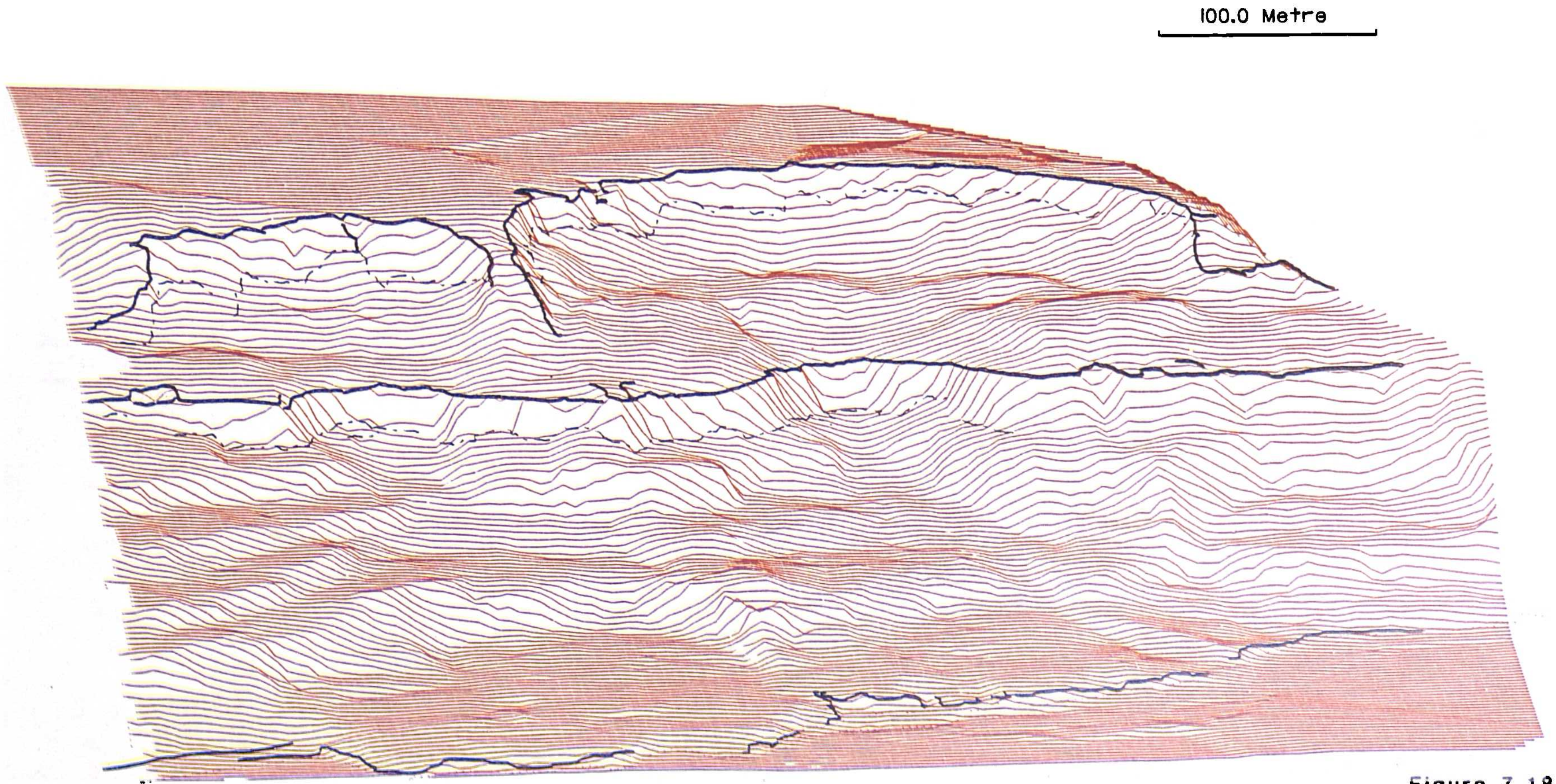


Figure 7.18

1976

Isometric View

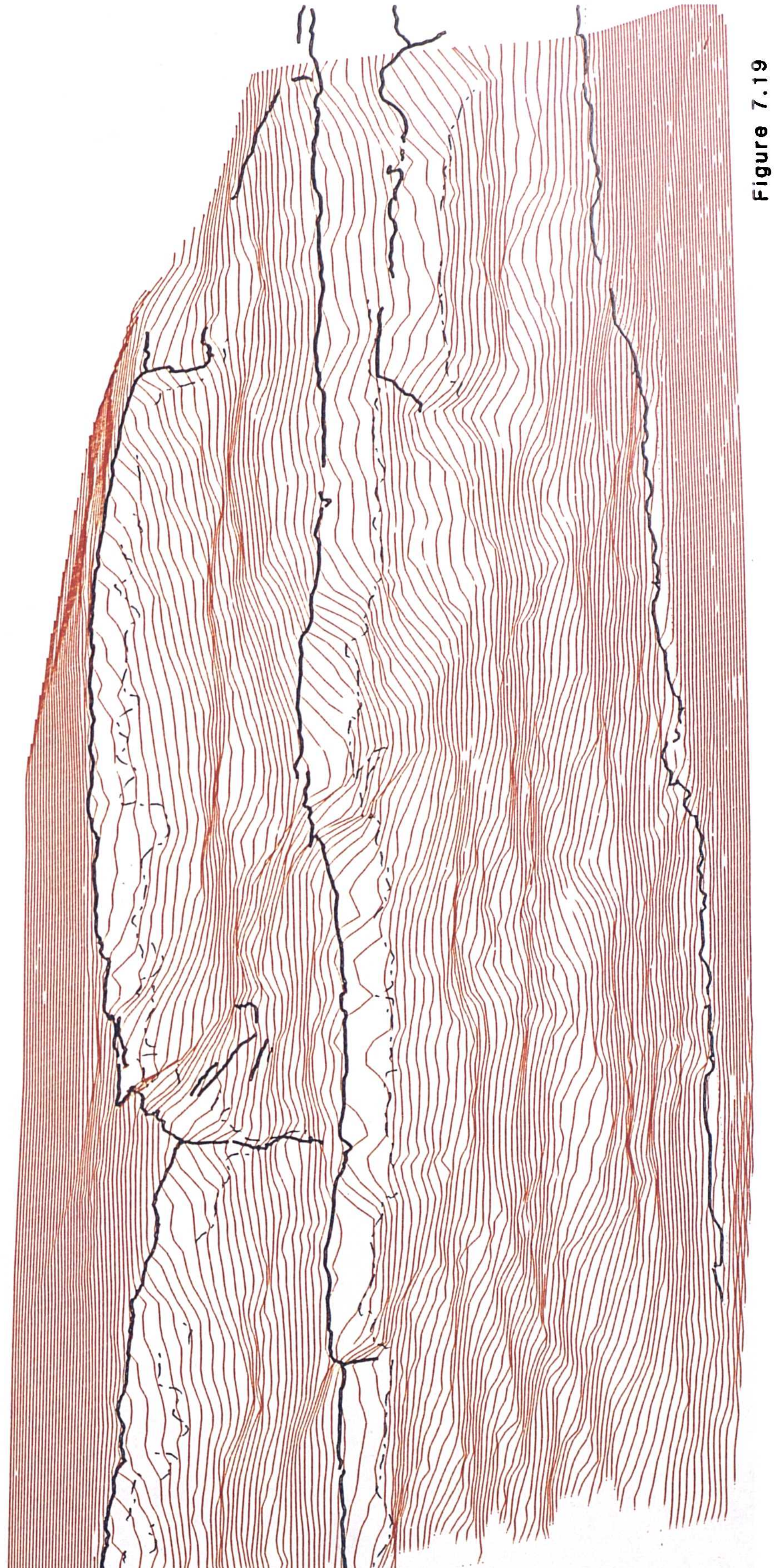


Figure 7.19

1988

Isometric View

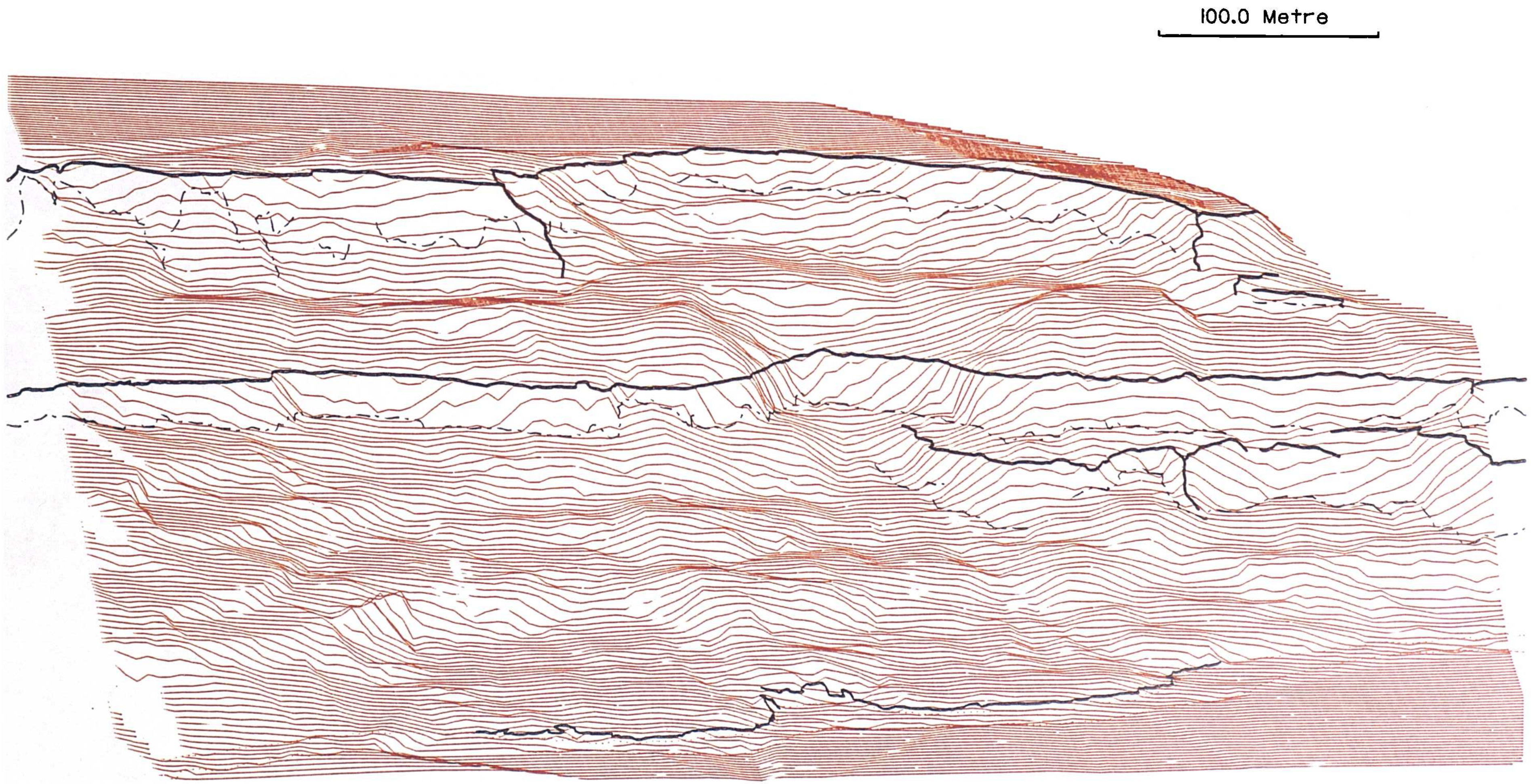


Figure 7.20

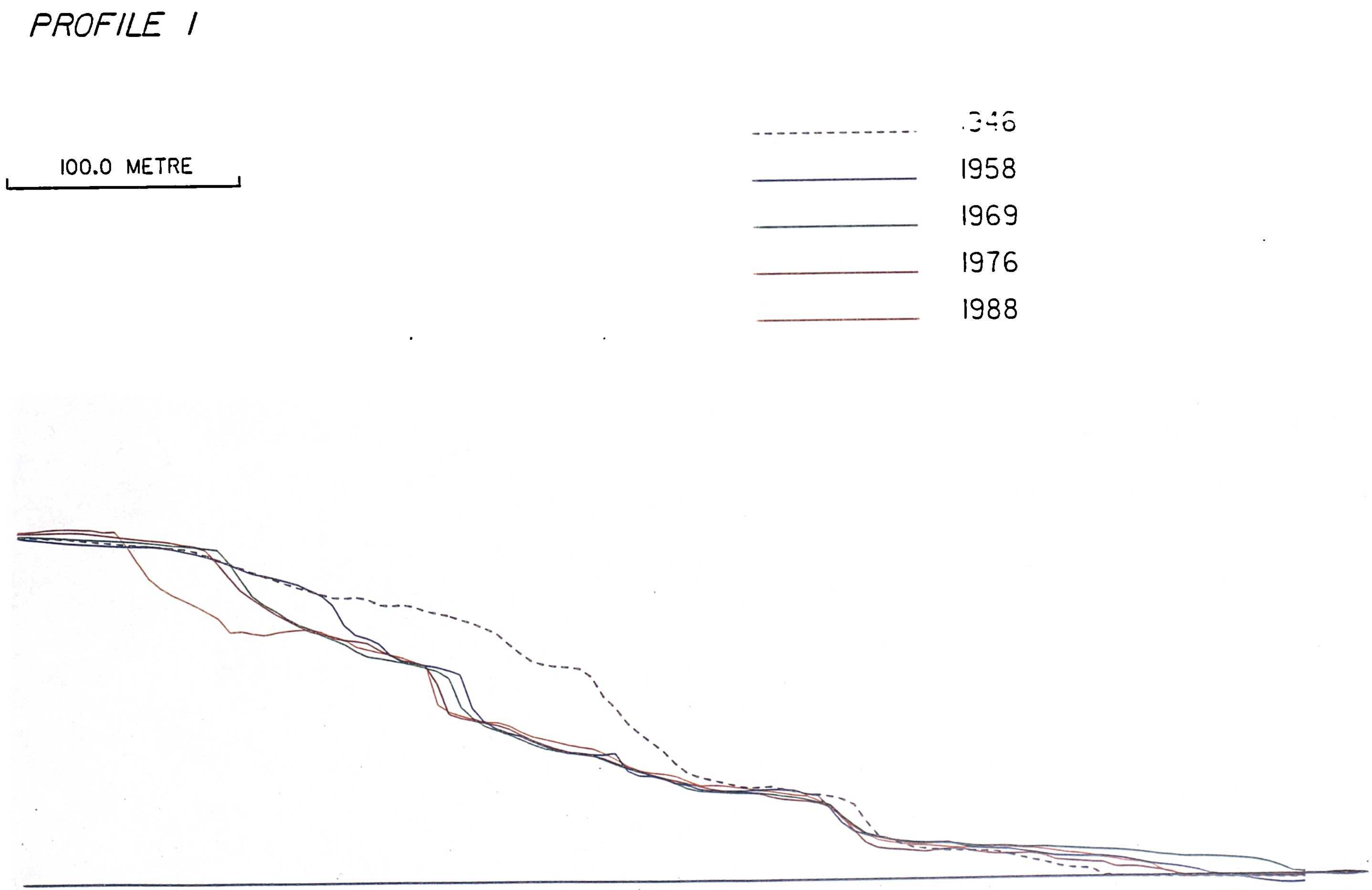


Figure 7.21

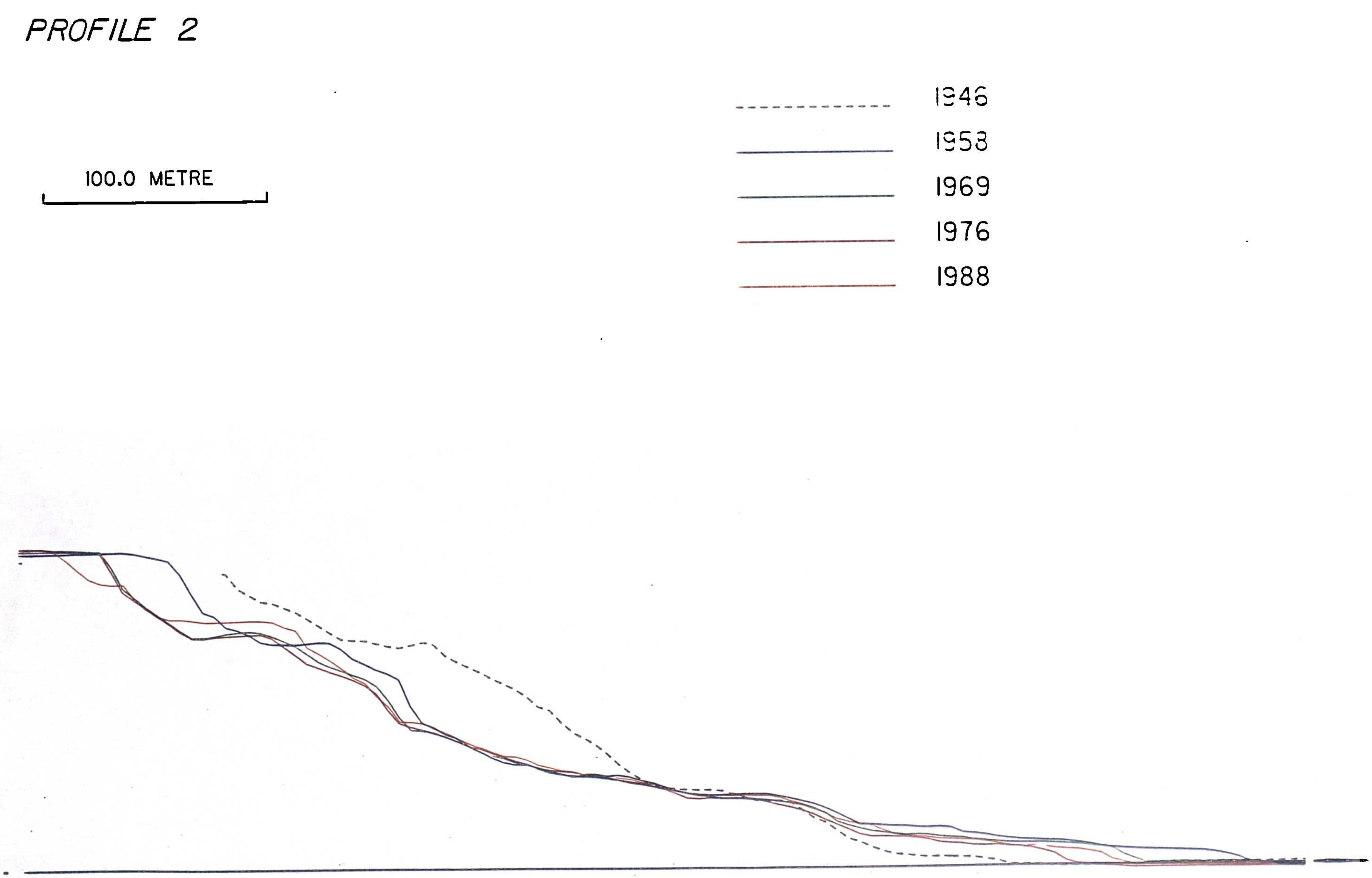


Figure 7.22

The isometric plot can be useful if the site is unfamiliar, as the surface can be viewed from any direction in space and at any scale. Although the isometric plot is by definition at a constant scale, spatial data can only be measured from it if one of the spatial planes is known and fixed. In general, the isometric view can only be of pictorial or qualitative interest.

The grid file can be used to provide cross sections and profiles anywhere on the site. This can be useful for the rapid quantitative recognition of areas which have experienced most change. It should be remembered that these sections can only be as accurate as the DTM itself, so a major factor is the density of the constituent DTM points. The most accurate representation can be obtained by observing a profile or section directly, as indicated in Section 7.2.2.

Two profiles were created from the grid files at each epoch, (Figures 7.21- 7.22) using the same profile lines as used for the direct measurement of profiles (Section 7.2.2). This procedure enabled the DTM profiles to be compared with those measured directly, (Figures 7.9- 7.10). Some minor differences are apparent, particularly in respect of the 1946 epoch, which is associated with the poor geometry defined by the 1946 photographs (Section 6.3.2, 7.2.2, 8.2.2.1). Under close examination, the DTM profiles consist of a series of straight line sections, which indicate the density of the grid used for their formation. More data points are used to represent the directly measured profiles, which produces a more natural impression.

7.2.3.3 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

DTM OF DIFFERENCE

KEY

ISOLINES OF SURFACE DIFFERENCE
(INTERVAL: 5.0M)

red line	MATERIAL LOSS
green line	NO CHANGE IN SURFACE LEVEL
blue line	MATERIAL GAIN

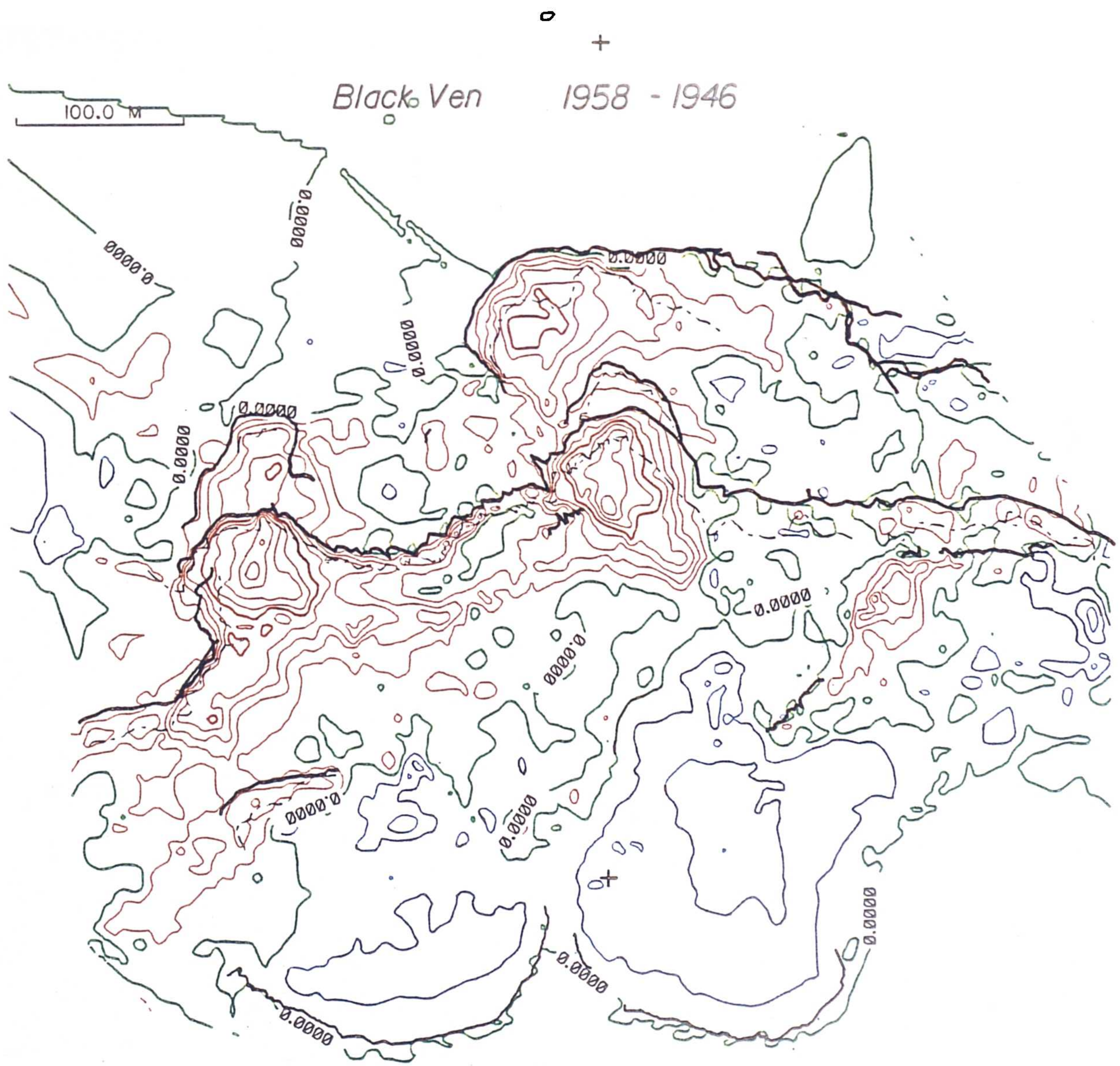


Figure 7.23

DTM OF DIFFERENCE

KEY

ISOLINES OF SURFACE DIFFERENCE
(INTERVAL: 5.0M)

- MATERIAL LOSS
- NO CHANGE IN SURFACE LEVEL
- MATERIAL GAIN

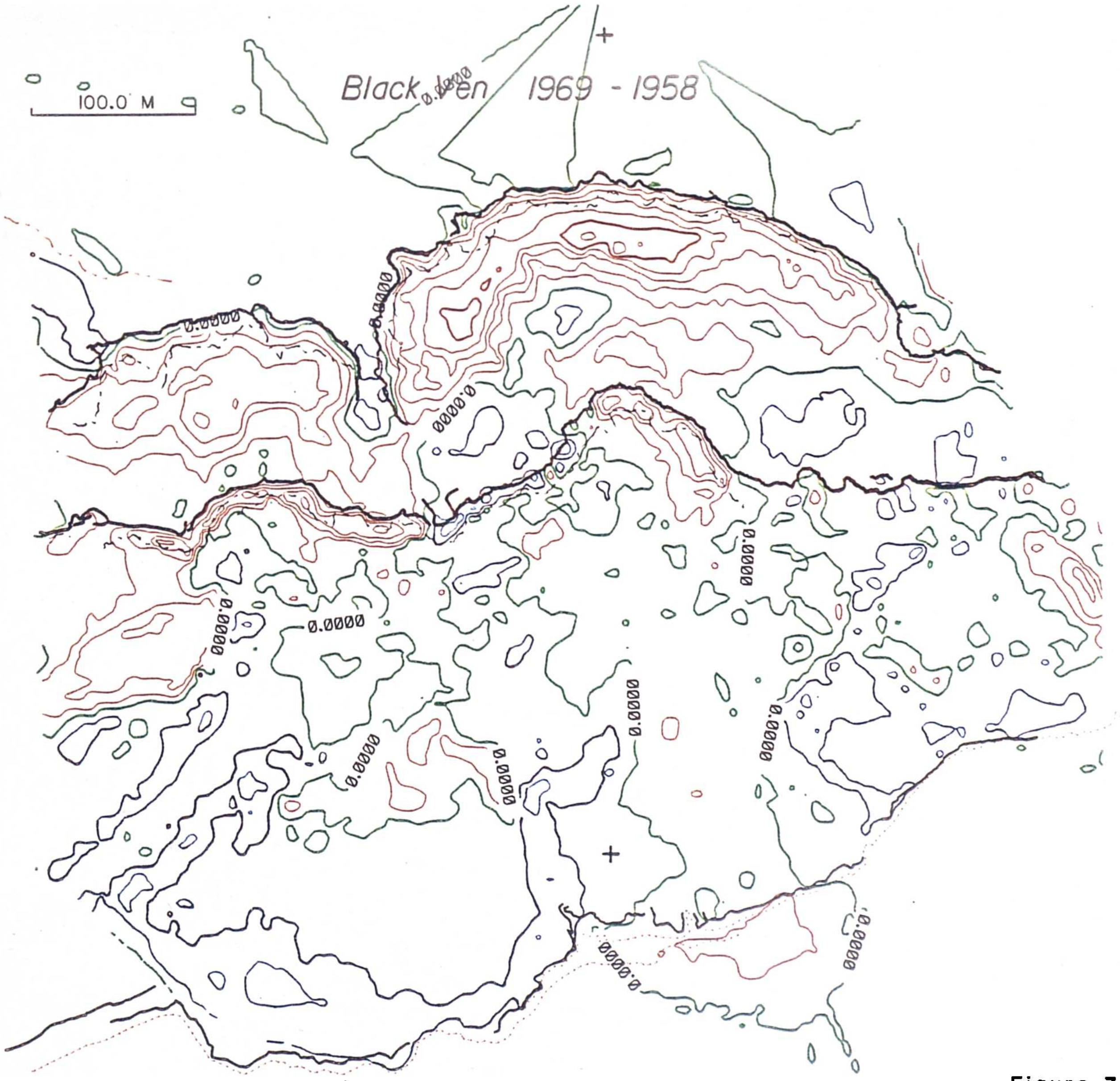


Figure 7.24

DTM OF DIFFERENCE

KEY

ISOLINES OF SURFACE DIFFERENCE
(INTERVAL: 5.0M)

- MATERIAL LOSS
- NO CHANGE IN SURFACE LEVEL
- MATERIAL GAIN

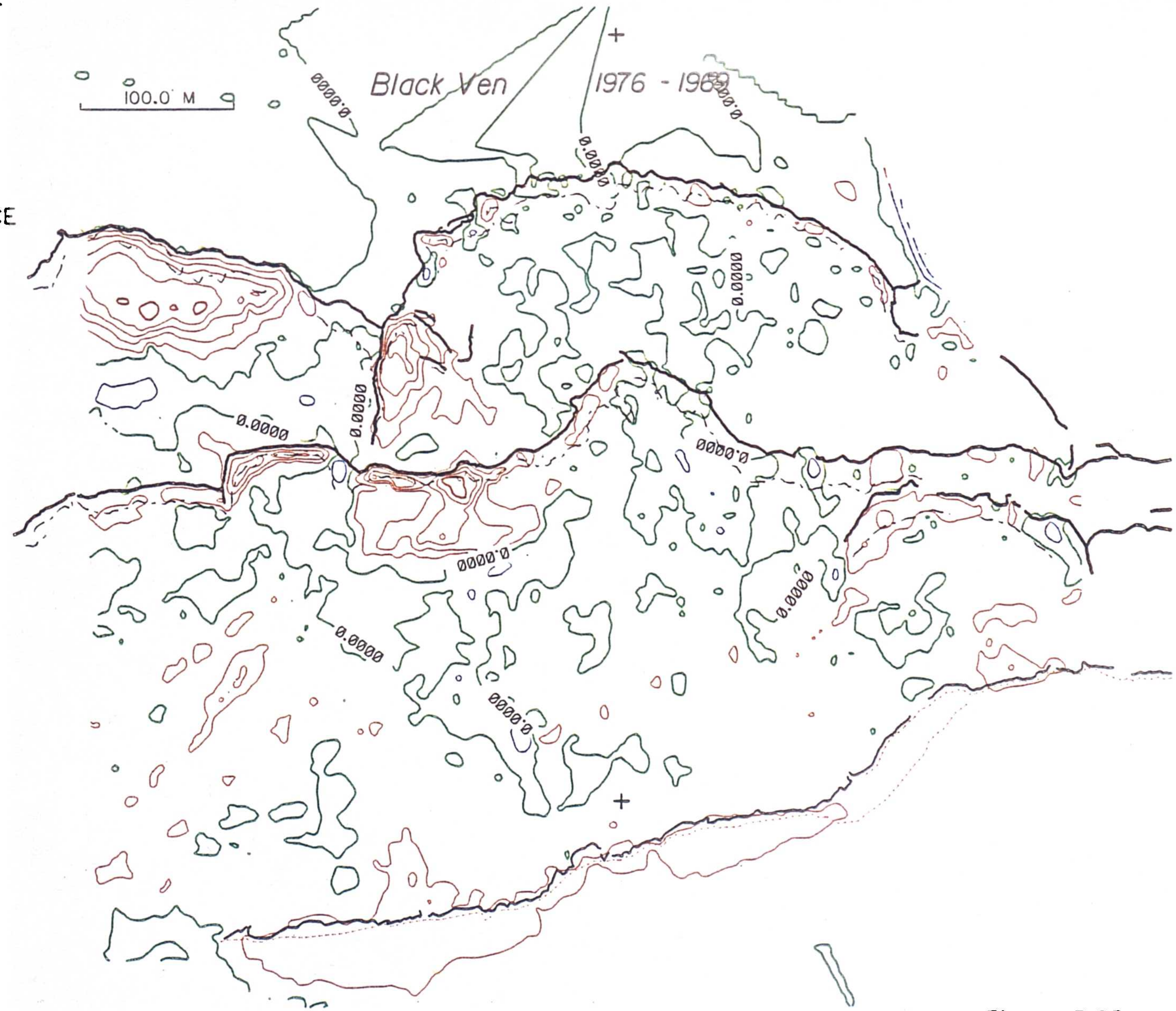


Figure 7.25

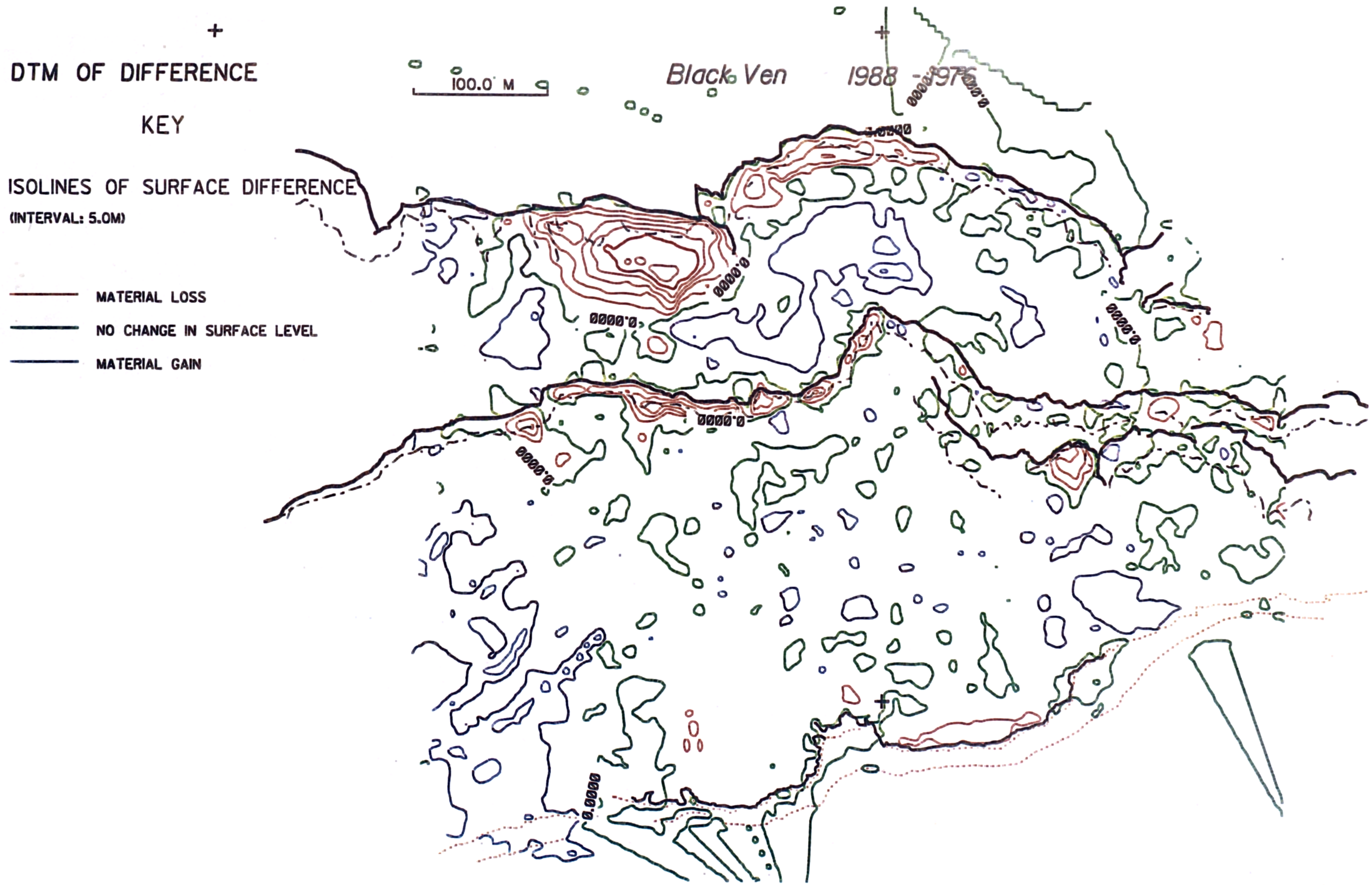

DTM OF DIFFERENCE
KEY
ISOLINES OF SURFACE DIFFERENCE
(INTERVAL: 5.0M)
MATERIAL LOSS
NO CHANGE IN SURFACE LEVEL
MATERIAL GAIN
100.0 M
Black Ven
1988 - 1976
0.0000

Figure 7.26

period defined by the photographs and was used on a small scale by Welch and Jordan (1983). The surface of change or '**DTM of difference**' can be contoured and will quantify the effects of geomorphological processes. 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 exercise caution because areas which appear to exhibit no change are not necessarily inactive regions. They can be 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.

By comparing DTM's of difference, derived from several successive photographic epochs, it is possible to see the change in the distribution of geomorphic activity through time. Four DTM's of difference were created from the 1946, 1958, 1969, 1976 and 1988 epochs, (Figures 7.23- 7.24). From an analysis of these plots it is possible to see directly the areas that have experienced most change, and more importantly to quantify in terms of an elevation difference, (Section 7.3.2).

7.2.3.4 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). This slope grid file can be used to produce a variety of slope maps and these were examined using the Black Ven case study with grids at both 5 and 10 metre density. The simplest type (Figure 7.27) can be produced by contouring the slope 'surface,' but this is difficult to interpret. A more familiar type of map is a slope shaded map (Figure 7.28) in which the area between the slope contour lines are colour coded according to a user-defined colour table. The third approach is to produce a slope vector map in which each slope facet within the grid is used to derive a small line symbol, (Figure 7.29). The length of this line indicates the slope angle and is <u>inversely</u>

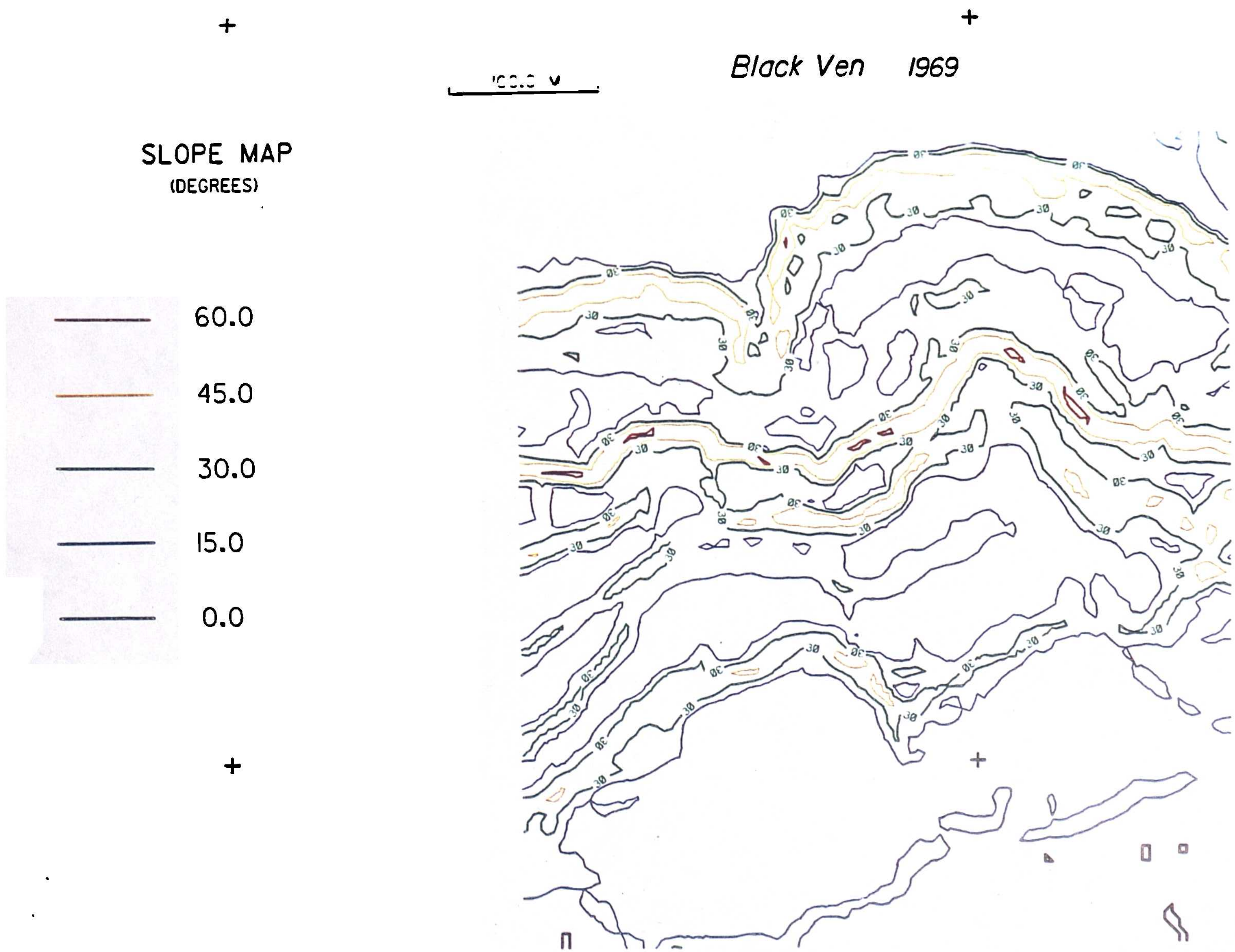
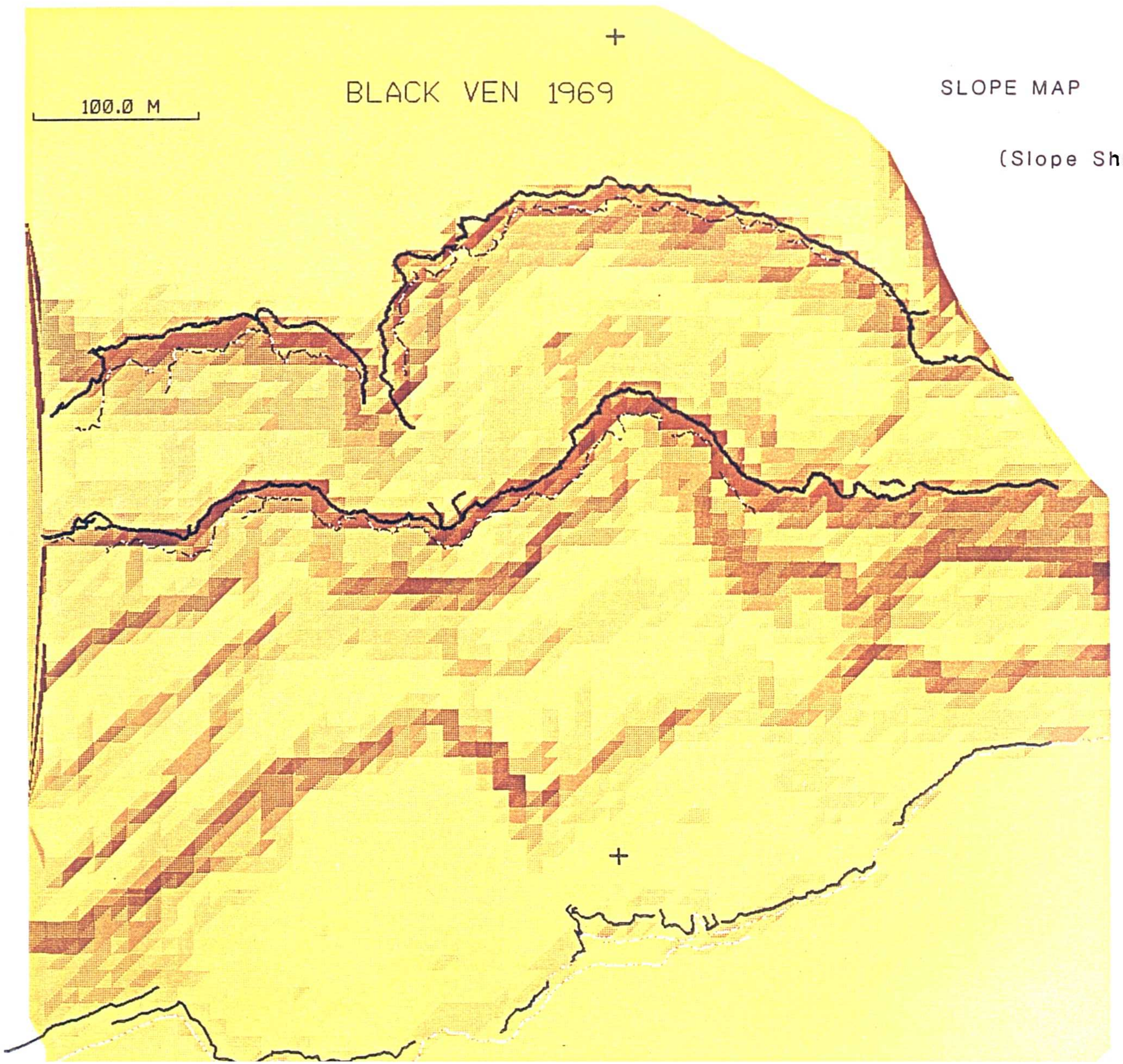


Figure 7.27



SLOPE MAP

(Slope Shading)

Figure 7.28

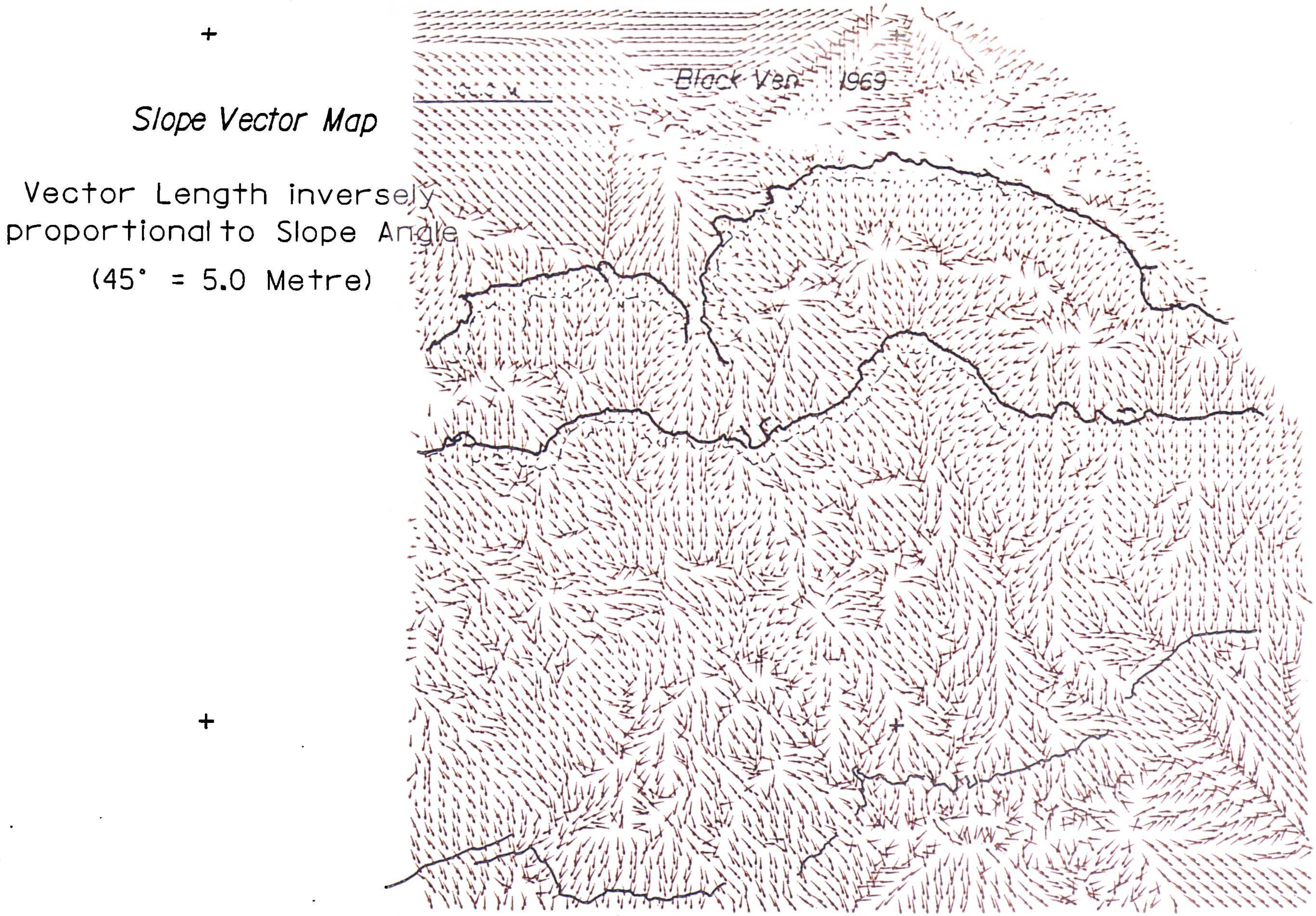

Slope Vector Map
Vector Length inversely
proportional to Slope Angle
(45° = 5.0 Metre)
Black Ven 1969

Figure 7.29

proportional to slope angle. Perhaps more importantly, the vectors are orientated according to the aspect of each facet and such a map appears to yield more information regarding slope orientation, (Section 7.2.3.5). The slope vector map can be used to indicate the maximum energy line and would assist in the selection of suitable vertical profiles, (Section 7.2.2). This type of plot could be useful for identifying the boundaries between different sub-systems (Section 7.2.3.6). Finally, the slope vector map suggests patterns of flow, particularly within the two main mudslides, although these are not true flow vectors, (Section 7.2.4).

The facilities to produce the slope shaded map (Figure 7.28) and slope vector map (Figure 7.29) were not available at City University. The plots were obtained using a more advanced DTM software package, kindly made available by YRM, a firm of architectural designers, (Section 7.3.4).

The slope grid can also be used to provide statistical forms of output, which proved to be especially valuable. The slope grid can be used to derive reliable histograms representing the distribution of slope angle. Carson and Petley (1970) use slope histograms to identify characteristic slope distributions for weathered slope debris of differing lithological origin. The variations of slope distribution are explained in terms of a relationship with the mechanical characteristics of weathered debris, under a set of process assumptions. The hypothesized mechanism of breakdown of debris through time, finally leads to a scheme of slope development through time, (Thornes and Brunsden, 1977). The latter stage associated with this study (Carson and Petley, 1970) provides an illustration of a 'location-for-time substitution,' (Section 1.2).

There 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 large 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. The distributions are illustrated by Figures 7.30a- 7.30e.

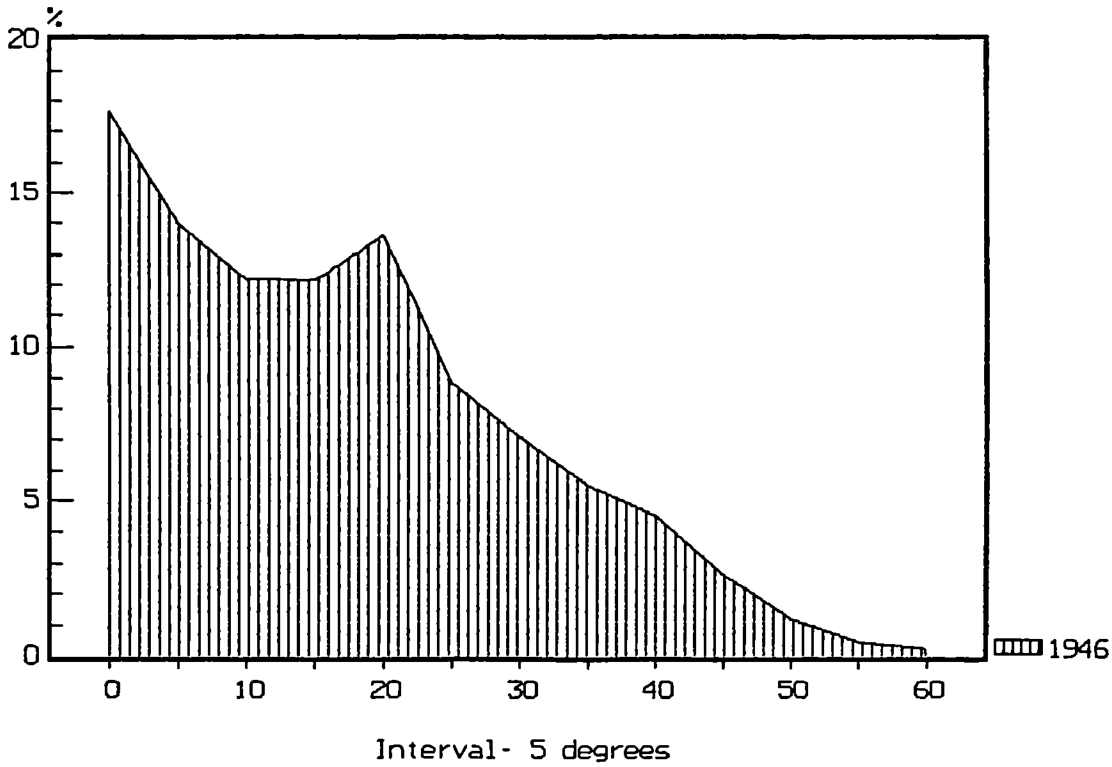


Figure 7.30a **Distribution of slope angle- 1946**

A comparison between the five histograms reveals that with the exception of the 1946 epoch, the distributions have not changed significantly. This would appear remarkable because since 1958 sections of the rear scarp have recessed by 94 metres, (Section 7.3.1). This has wider implications than just the Black Ven landslide and these are examined in Section 7.3.3.

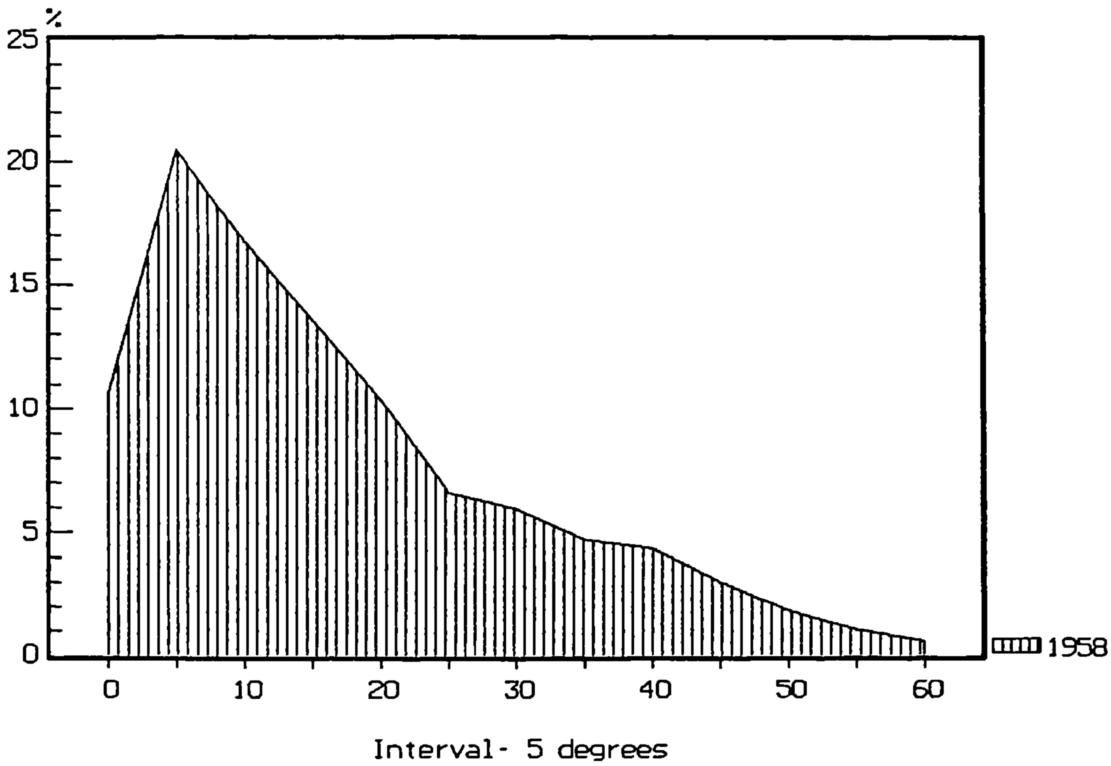


Figure 7.30b **Distribution of slope angle- 1958**

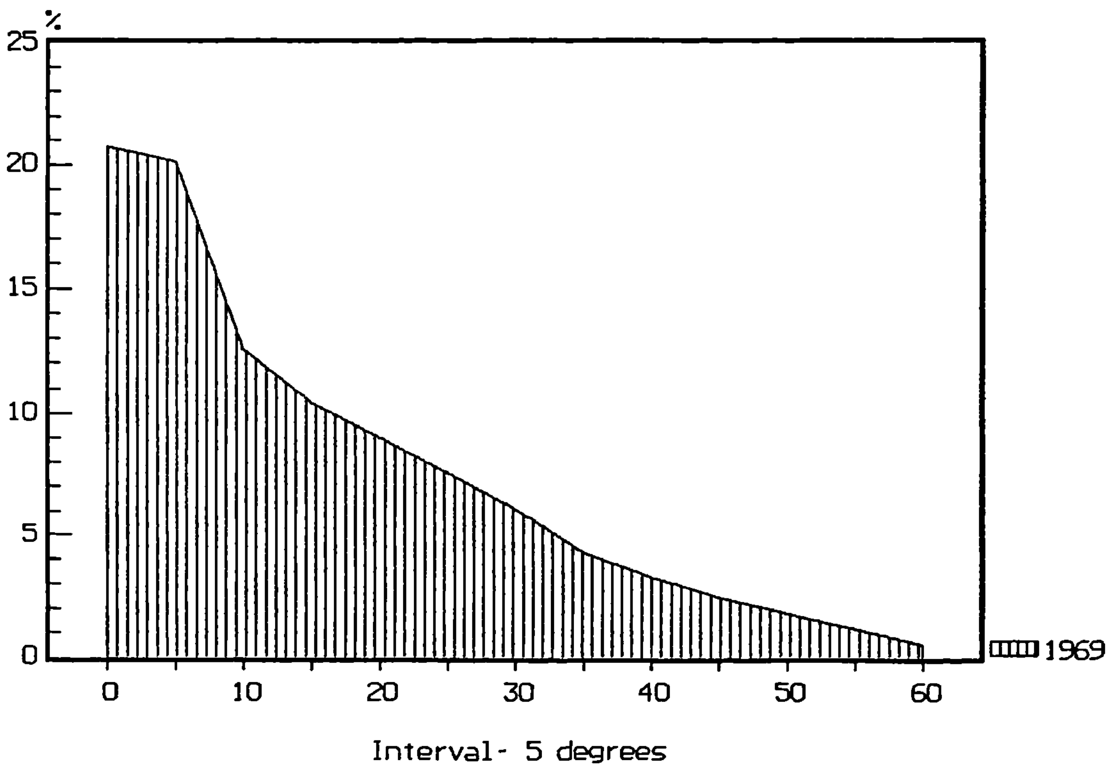


Figure 7.30c **Distribution of slope angle- 1969**

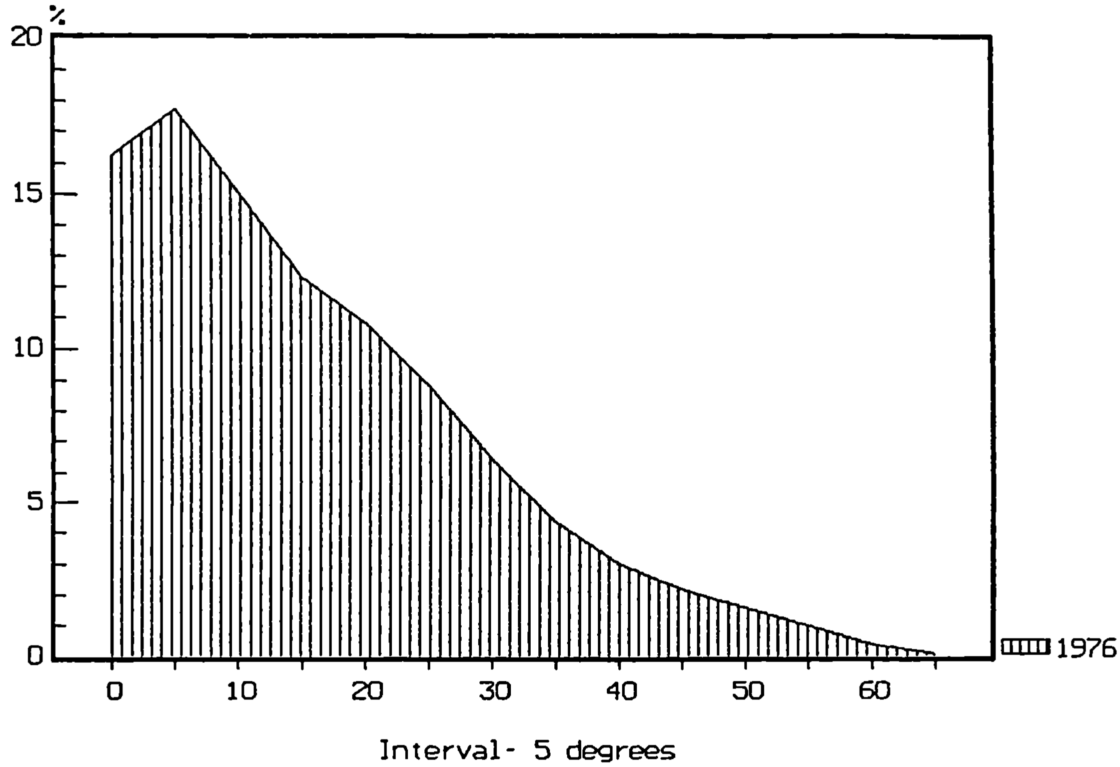


Figure 7.30d **Distribution of slope angle- 1976**

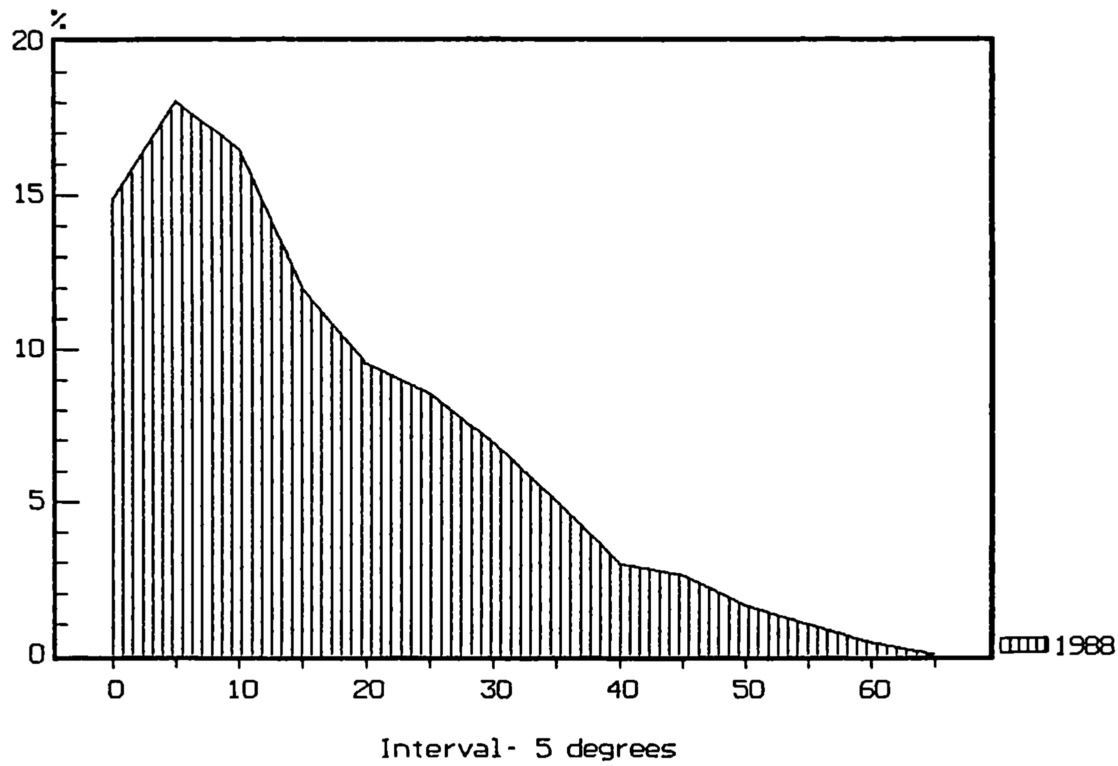


Figure 7.30e **Distribution of slope angle- 1988**

The real advantage of a DTM software package is the ability to produce information that in some way summarises the whole data set. The determination of mean slope angle for the site at each epoch is one example and these are tabulated in Table 7.2, with an associated standard deviation. The mean slope angle has fluctuated between 18.85° and 17.04°, with perhaps a gradual reduction overall. This fluctuation is possibly associated with cycles of activity.

Table 7.2 Mean slope angle, 1946-1988

Date	Mean slope Angle (°)	Standard Deviation (°)
1946	18.490	0.006
1958	18.846	0.005
1969	17.040	0.005
1976	17.693	0.005
1988	18.063	0.005

Figure 7.30f provides a graphic illustration of Table 7.2 and this portrays some form of cyclic behaviour. More time is required before the full 100 year cycle suggested by Cambers (1976) and Brunsden and Jones (1980) can be identified and confirmed. If such a cycle was proven then Figure 7.30f

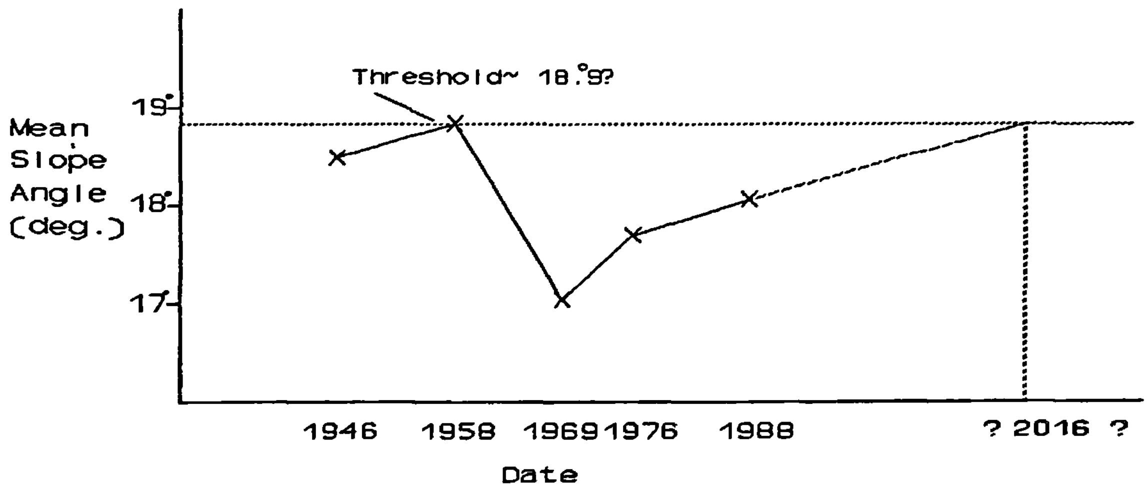


Figure 7.30f **Activity threshold**

could illustrate a threshold of 18.90°, after which a major phase of landsliding occurs. If such a threshold exists, then it could be used to project into the future and to predict the next main phase of activity. There are several problems associated with such a forecast. The overall variation of mean slope angle is only 1.8°, which is very small and should not be over-interpreted. The existence of the threshold of 18.90° is certainly not proven, particularly when it is realised that the 1958 photography was attained after the main period of failure. Also, it is difficult to identify a pattern as the statistics combine the effects of two mudslide systems. Finally, it is also impossible to predict other events, both natural and man-made which may have an important effect on the development of the landslide complex.

Despite the reservations indicated above, the approach is of merit and does provide some tentative quantitative information regarding the cyclic behaviour of the landslides. Such information has not previously been available and could only be obtained by applying the archival photogrammetric technique to historical photographs.

7.2.3.5 Aspect Maps/Histograms

The standard grid file can also be used to produce aspect maps and slope orientation distributions because slope aspect is the first horizontal derivative of the altitude surface, (Evans, 1972). The shaded aspect map appears difficult to interpret (Figure 7.31) but may be useful in the compilation of a **hazard map**. The slope orientation distributions (Figure 7.32) are also difficult to interpret as no clear pattern can be distinguished. During the five historical epochs the mean aspect was generally between 169° and 175°, although in 1976 this pattern was disturbed by a positive deviation of 5° to 180°. This inexplicable variation may be insignificant but is possibly associated with the development of the two dominant axis of the two mudslide systems since 1958. The strike of the Cretaceous sediments is S/SSW (191.24°) and the Lias SE/ESE (123.75°), (Conway, 1974). Although the strike of the two sedimentary groups is possibly a factor controlling the distribution of slope aspect it is difficult to identify any clear relationships. It is possible that a notable shift in

SHADED ASPECT MAP

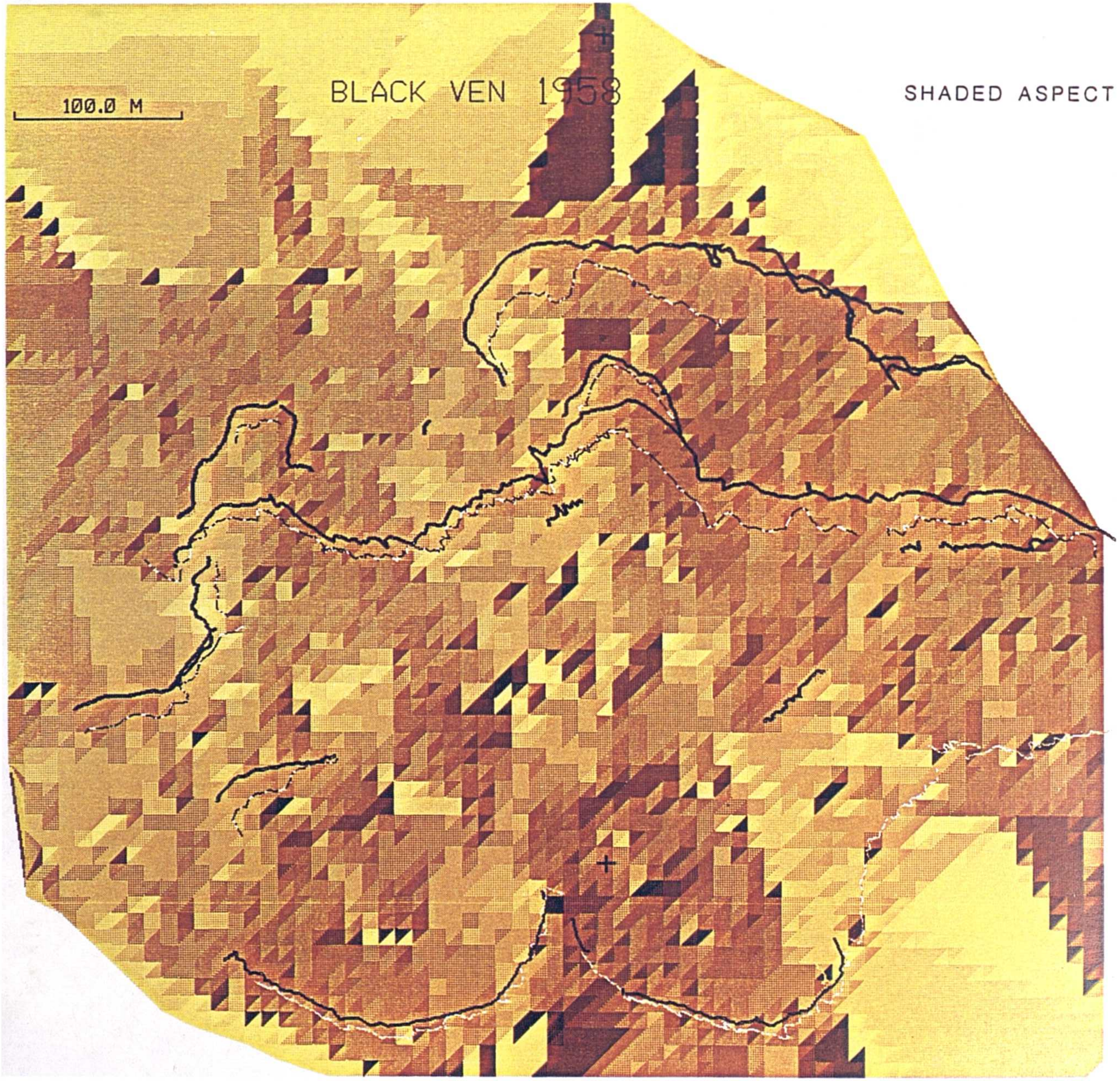


Figure 7.31

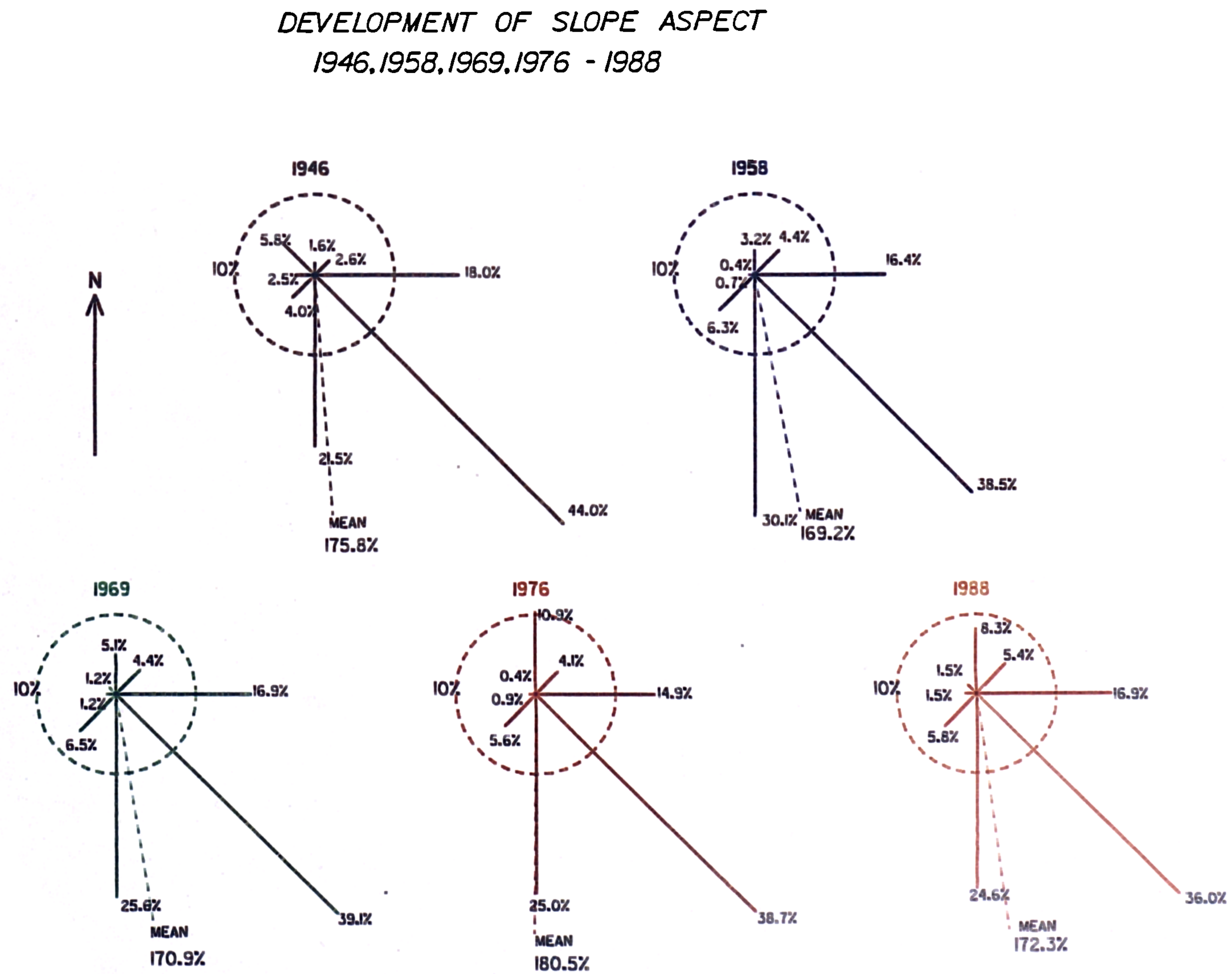

DEVELOPMENT OF SLOPE ASPECT
1946,1958,1969,1976 - 1988
N
1946
10%
5.8%
1.6%
2.6%
2.5%
4.0%
18.0%
21.5%
44.0%
MEAN
175.8%
1958
10%
3.2%
4.4%
0.4%
0.7%
6.3%
16.4%
38.5%
30.1%
MEAN
169.2%
1969
10%
5.1%
4.4%
1.2%
1.2%
6.5%
16.9%
25.6%
39.1%
MEAN
170.9%
1976
10%
10.9%
0.4%
4.1%
0.9%
5.6%
14.9%
25.0%
38.7%
MEAN
180.5%
1988
10%
8.3%
5.4%
1.5%
1.5%
5.8%
16.9%
24.6%
36.0%
MEAN
172.3%

Figure 7.32

the distribution of slope aspect can indicate a change in the direction of activity and may be useful for the identification of future areas of degradation.

7.2.3.6 Volume calculations/ Input - Output analyses

One of the benefits of a digital terrain model of difference, is that it can be used to calculate volume changes within areas contained by the grid file. The proper use of analytical photogrammetry with historical photographs enables a standard deviation to be associated with the computed volume change. This is important when assessing the significance of a detected volumetric change. The calculation of change of volume is based upon the summation of a series of changes computed within individual grid cells.

$$vl = \frac{l_g^2}{4}(h_1 + h_2 + h_3 + h_4) \qquad 7.1$$

The stochastic properties can be derived by propagation of variance:

$$\sigma_{vl}^2 = \frac{l_g^4\ \sigma_h^2}{4} \qquad \text{(assuming } \sigma_{lg} = 0;\ \sigma_{h1},\ \sigma_{h2} \text{ etc } = \sigma_h) \qquad 7.2$$

The volume change contained within an area consisting of many grid cells is:

$$Vl = \Sigma\ vl \qquad 7.3$$

with

$$\sigma_{Vl}^2 = \Sigma\ \sigma_{vl}^2 \qquad 7.4$$

where:

vl	change of volume contained within one grid cell;
l_g	Dimension of a grid cell, (assumed square);
h_1 to h_4	Elevation at four grid cell corners of DTM of difference;
h	Mean elevation;
σ	Standard deviation of an element, (vl, l, h);
Ar	Total area under examination; and
Vl	Total volume contained within area Ar.

In order to evaluate volumetric changes occurring on the landslide complex, Black Ven 1 and 2 were considered as two sub-systems within the whole landslide system. One of the main problems with the evaluation of the volume of material that had been lost from the area within the sub-systems, was the identification of sub-system boundaries. The two mudslide sub-systems were extremely dynamic and so boundaries changed between epochs. One solution to the problem was to divide the computed volume change (Vl) by the total area (Ar) used in the computation. This yielded a mean change in elevation (El) between the epochs for a particular area and enabled more meaningful comparisons between epochs and locations to be made.

Continuing:

$$El = \frac{Vl}{Ar} \qquad 7.5$$

and by propagation of variance:

$$\sigma_{El}^2 = \frac{\sigma_{Vl}^2}{Ar^2} \qquad \text{(assuming } \sigma_{Ar} = 0\text{)} \qquad 7.6$$

substituting for σ_{Vl}^2 from equation 7.2

$$\sigma_{El}^2 = \frac{n \; l_g^4 \; \sigma_h^2}{4 \; Ar^2} \qquad 7.7$$

Where:
- El Mean elevation change
- n Number of grid cells within total area Ar.

Each sub-system on the Black Ven landslide was further divided into two units at each epoch, and volume changes were computed for each. The units that were represented were the catchment regions and lobes for both Black Ven 1 and 2, (Figures 7.33- 7.36). Areas were defined by joining boundaries coordinated during feature coding (Section 6.5.2, 7.2.1) with short straight line sections. The identification of the relevant boundaries was assisted by consulting the morphological and contour plans (Figures 7.2- 7.6, 7.11- 7.15). The boundaries then had to be joined to form an enclosed 'shape' at the graphics workstation and the area of each shape determined using one of the workstation's graphics functions.

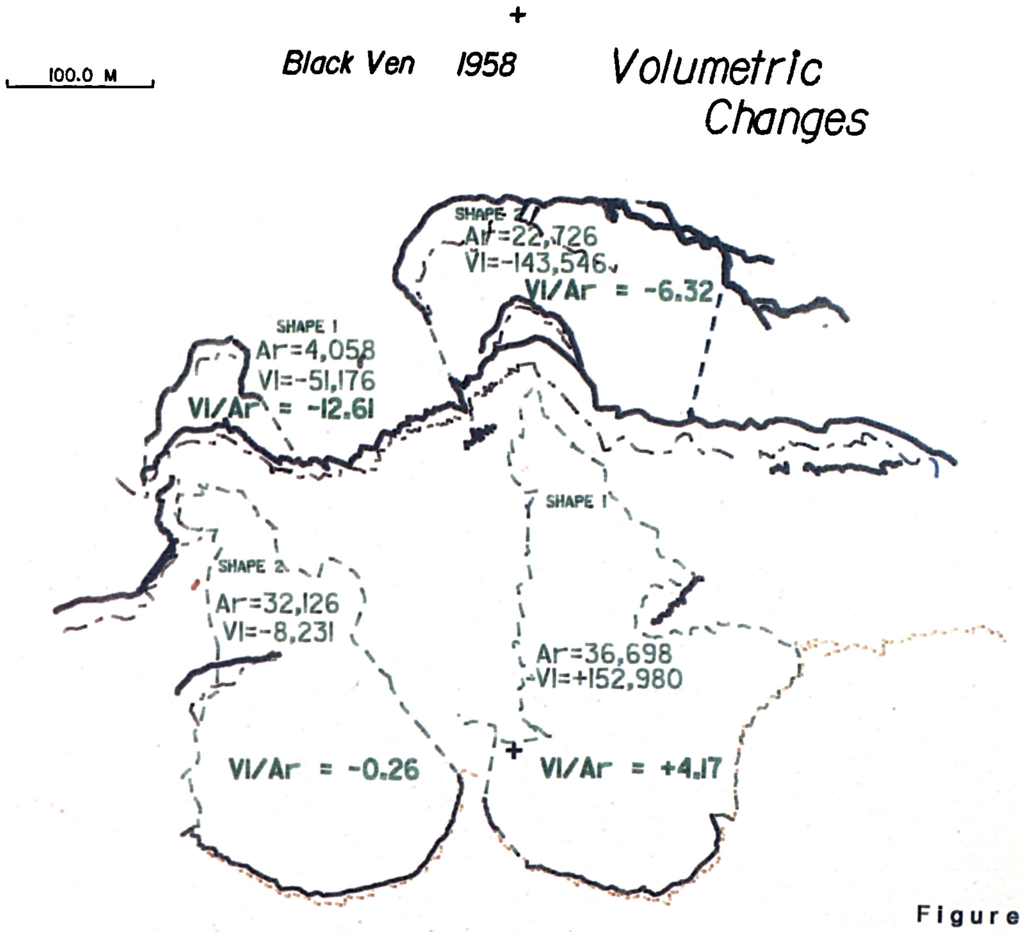


Figure 7.33

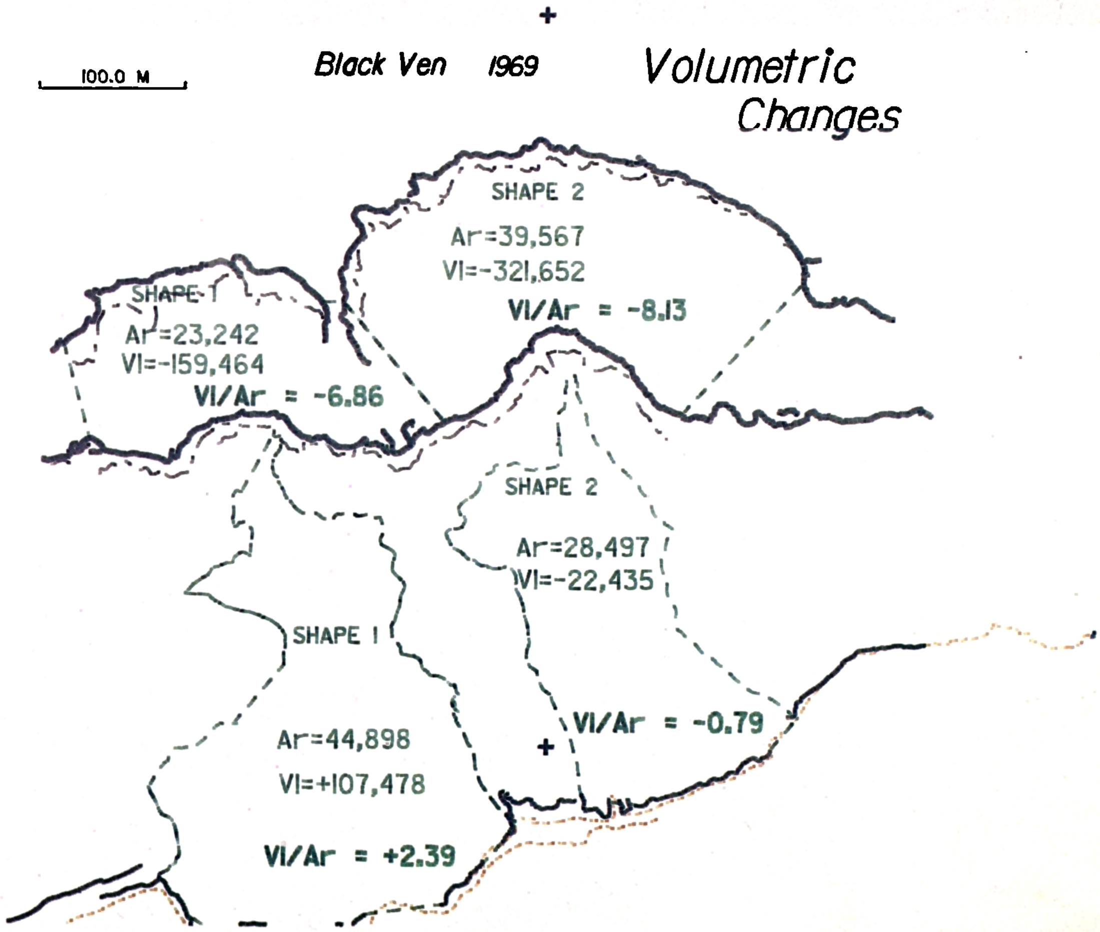


Figure 7.34

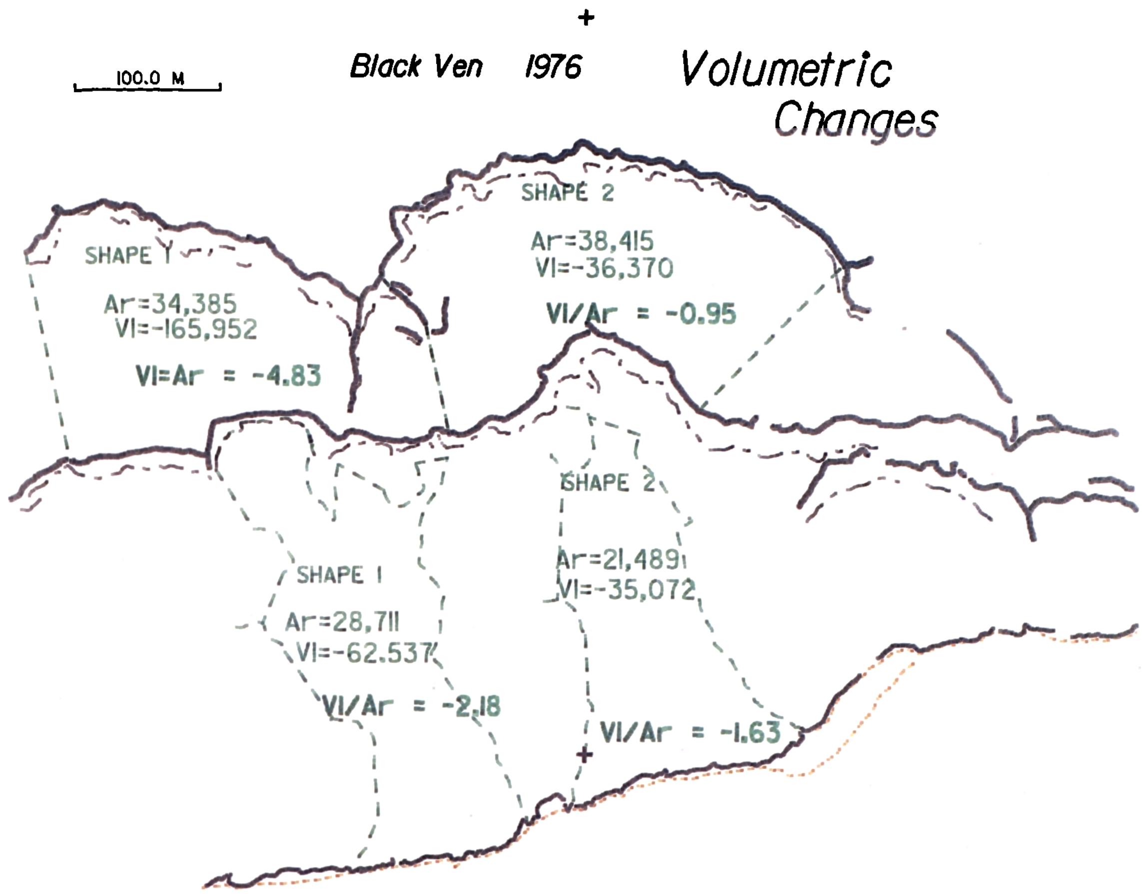


Figure 7.35

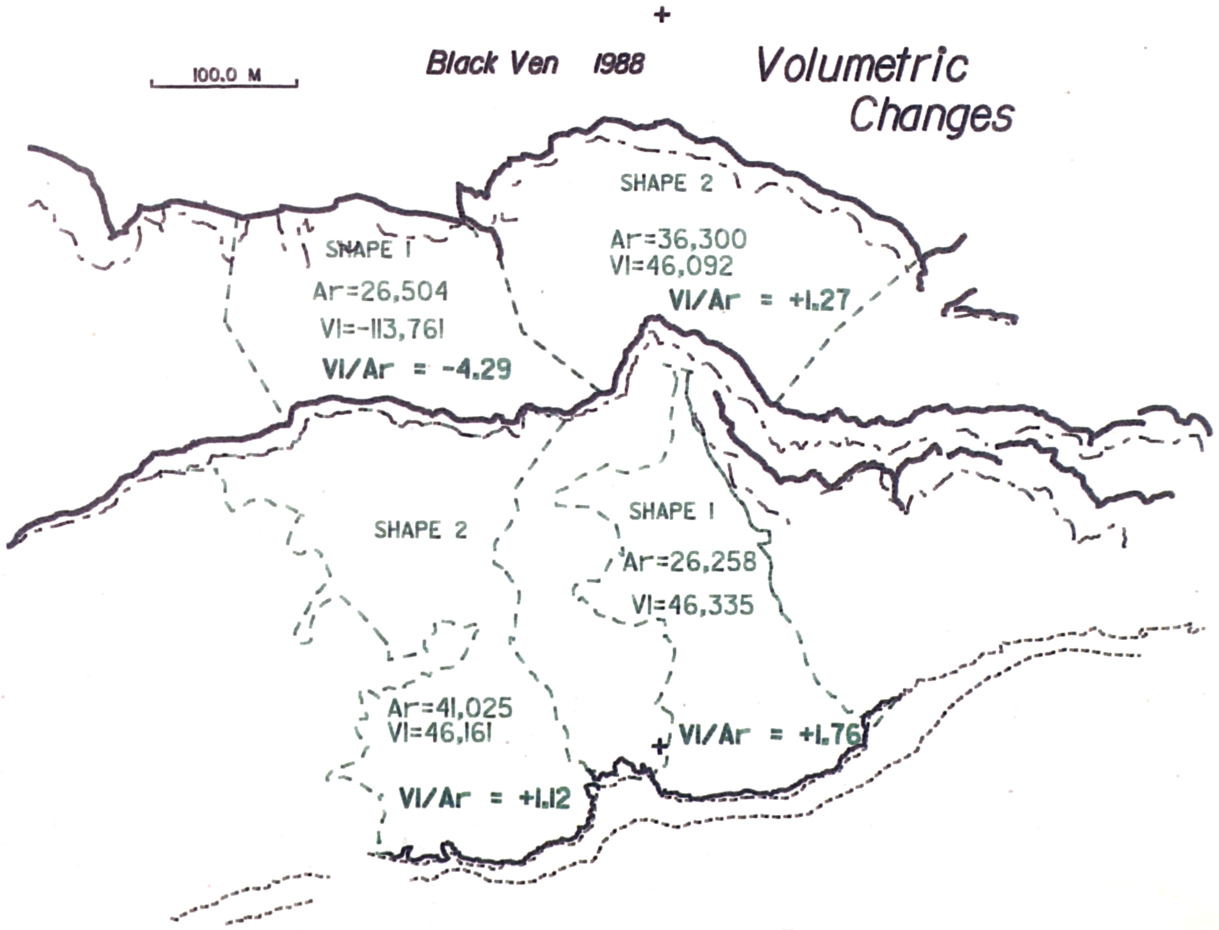


Figure 7.36

A volume of change was then computed by using a 5 metre grid, representing a 'DTM of difference' in the calculation. A mean elevation change was finally computed by dividing the computed volume by the surface area of the shape. The results are summarised in Table 7.3, (standard deviations derived from Table 8.1 and Equation 7.7).

<u>Table 7.3 Mean Surface Changes- Catchment area</u>

	Black Ven 1		**Black Ven 2**	
Date	Elevation Change (m)	S.Dev. (m)	Elevation Change (m)	S.Dev. σ_{El} (m)
1946				
	-6.32	0.017	-12.61	0.040
1958				
	-8.13	0.006	-6.86	0.008
1969				
	-0.95	0.007	-4.83	0.007
1976				
	(+1.27)	(0.007)	-4.29	0.008
1988				

The mean elevation changes quantify the changes that have occurred on the two sites during the last forty two years. The active periods on both Black Ven 1,2 are well represented and significant losses of material are apparent. The small gain experienced on Black Ven 1 between 1976 and 1988 is spurious and is associated with a lack of coordinated points in this area due to vegetation cover. The oblique aerial photographs taken in January 1988 were taken at too low an altitude to be able to measure detail points within this highly vegetated area. This problem was not experienced with the 1958 epoch as the vegetation was less during this active period.

The changes experienced on the lobe units of the two mudslides are less variable than those in the catchment areas, (Table 7.4). The maximum mean elevation change was +4.17 although changes of approximately ±2 metres are more representative of the later epochs. The lower variability is expected for mudslides, which show little change in elevation and are able to change in size and position, (Section 7.2.1).

These small adjustments are in response to the loads that are supplied by material originating from the catchment area and the Belemnite cliffs.

Table 7.4 Mean Surface Changes- Lobes

Date	Black Ven 1 Elevation Change (m)	S.Dev. σ (m)	Black Ven 2 Elevation Change (m)	S.Dev. σ_{gl} (m)
1946				
	+4.17	0.013	-0.26	0.014
1958				
	-0.79	0.008	+2.39	0.006
1969				
	-1.63	0.009	-2.18	0.008
1976				
	+1.12	0.008	+1.76	0.007
1988				

The problems associated with boundary definition at a dynamic site such as Black Ven prevented a more detailed volumetric examination because boundaries changed radically between epochs. Such a quantitative volumetric analysis of the system components is potentially valuable and is known as a system budget. Theoretically, by knowing the volumetric inputs and outputs occurring between each unit and sub-unit, the geomorphologist can begin to understand the complex inter-relationships and feedbacks between components within the subsystem and system as a whole. Such a **systems** approach has proved to be useful to geomorphology in the past, although these have tended to be qualitative, (Brunsden, 1973). Using the archival photogrammetric technique a systems approach can now be quantitative, furthermore measures of quality can be associated with all volumetric inputs and outputs that are derived.

7.2.3.7 **Quantitative Evolutionary Models**

An alternative avenue of investigation that also suggested potential was the development of a quantitative evolutionary model. Such an evolutionary model should be defined by functions such as the **universal soil loss equation**, (Gerrard, 1981) or the **mass balance** or **continuity equation** (Kirkby, 1987). A simple application of the mass balance equation to a landslide site would be to consider the development of a single slope profile. A suitable evolutionary model would consist of a 'linear multiple store model' such as that proposed by Kirkby *et al*, (1987). For any of the stores, the mass balance equation may be written:

$$(S_i - S_0)Dt = Dz\ Dx \qquad 7.8$$

where:

S_i sediment input from upslope;
S_0 sediment output to next store downslope;
Dt time increment;
Dz increase in storage (ie. elevation); and
Dx distance increment (ie. distance between stores.

Flows of sediment can then be computed according to a series of equations which attempt to model each identified process. In order to produce an adequate evolutionary model it is necessary to solve two problems. First, in order to fully represent the processes controlling landform evolution, the process models need to be extremely complicated and sophisticated. In addition, the simplified two dimensional model indicated above, needs to be extended to the third dimension, possibly following the approach of Armstrong (1976). Once a suitable evolutionary model is established, and proven, it can be used for tentative prediction and is potentially of great value.

One approach that is attempted in this thesis to produce a simplified quantitative evolutionary model is to predict the future form of the Black Ven landslide, based upon morphological changes occurring during the preceding years. This approach is discussed in Section 7.3.4.

7.2.4 Computation of Displacement Vectors

Analytical photogrammetry and historical photographs can be used to provide three dimensional displacement vectors at discrete points. With a network of such points, the pattern of movement can be derived for the whole site. It should be remembered that a single photogrammetric survey can only provide the spatial positions of points, at any one instant, in some arbitrary three dimensional coordinate system. In order to monitor movement, a minimum of two surveys are required; the dimension of time being the period between surveys or epochs. Vectors or distances moved may be calculated simply by subtracting the three dimensional coordinate of a point at the first epoch, from the coordinate of the same identifiable point at the subsequent epoch. This may be repeated for any number of points distributed over the whole site, so providing three dimensional vectors of displacement which are in their correct spatial relationship to each other. If these vectors are divided by the time between surveys, then additional vectors can be produced which represent the rate of movement at each selected point.

With historical photography, points such as boulders, pieces of vegetation and prominent features on buildings must be used as targets. The main problem with these 'natural' targets is one of identifying accurately the selected points, not only on all photographs at one epoch but also on all photographs at the other epochs. The intervals between surveys and the rates of processes are extremely important in this respect. One boulder can look very similar to another, especially if changes have been large. The retrospective quality of photogrammetry can help greatly with this problem. All photogrammetric measurement can be delayed until all of the historical photography has been acquired and only carried out if sufficient points are identifiable on all sets of photographs.

In the case of the Black Ven case study there were no man-made features that could serve as high quality targets.

Natural targets were also unusable because large changes had occurred and the intervals between the historical photographic epochs had been too long to re-identify points with any certainty. It had been hoped to carry out this type of analyses with the January and June 1988 photography. After examination of these recent photographs under magnification, it was found that even during this short period, activity had been sufficiently great to preclude the reliable re-identification of any natural targets. Some form of pre-marked target would have to be used on this particularly active site.

7.3. Results of Special Geomorphological Significance

7.3.1 Morphogenetic Study of Black Ven

A morphogenetic analysis (Section 7.2.1) was carried out for the Black Ven landslide and yielded important information regarding the combined rates of geomorphological processes. Measurements were scaled from a single large scale plan, (Figure 7.7) showing the positions of the rear scarp, the prominent cliff line of the Belemnite Marl and the frontal lobe of the mudslides in 1946, 1958, 1969, 1976 and 1988. Each measurement was associated with a standard deviation, which enabled the significance of any change to be assessed. The aim was to obtain a mean rate of recession for the cliffs and to compare these values with those obtained on the adjacent cliffs at Stonebarrow, (Brunsden and Jones, 1976; 1980). Measurements taken of the position of the mudslide lobes would also provide information regarding the cyclical behaviour of the slides. Tables 7.5-7.8 summarises the measurements, (standard deviations are derived from Table 8.1).

Table 7.5 Morphogenetic Displacements- Rear Scarp

Date	Black Ven 1 Displacement (m)	σ	Mean Rate (m/ann.)	σ	Black Ven 2 Displacement (m)	σ	Mean Rate (m/ann.)	σ
1958								
	-30.9	1.4	-2.81	0.13	-54.7	1.4	-4.97	0.13
1969								
	-2.4	0.8	-0.34	0.11	-9.1	0.8	-1.30	0.11
1976								
	-6.7	1.7	-0.56	0.14	-30.3	1.7	-2.50	0.14
1988								
	-40.0	1.8	-1.33	0.06	-94.1	1.8	-3.14	0.06

The position of the rear scarp retreated very significantly in the 30 year period defined by the photographs, 40 metres at Black Ven 1 and 94 metres at Black Ven 2. The earlier epoch was not included as the source regions of the two systems were not fully established in 1946. The rate of retreat varied, with very active periods between 1958 and 1969 (2.81 ±0.13 m/ann and 4.97 ±0.13 m/ann) and lower rates between 1969 and 1976 (0.34 ±0.11 m/ann and 1.30 ±0.11 m/ann). Overall rates conceal the short term variability and are significantly higher than the mean rates found on the adjacent cliffs of Stonebarrow (0.29 m/ann - 0.71 m/ann, Brunsden and Jones, 1976, 1980). It is interesting that during the period 1969 - 1976 Black Ven 1 was known to be in a slow degradation state and was not actively mudsliding, (Brunsden, 1988). The scar degradation of 0.34 ±0.11 m/ann by small scale adjustment process is insignificantly different from the lower scale figure for Stonebarrow of 0.29 m/ann.

The Belemnite cliff was sub-divided into three sections because it was found that rates of recession were substantially higher along the axes of the two main mudslides. The mean rates of recession along the two axes were 0.52 ±0.06 m/ann and 1.25 ±0.04 m/ann, whilst the comparatively inactive cliff sections between each axis receded at a mean rate of 0.23 ±0.04 m/ann. The rates vary with time for the general cliff section but interestingly the rate is relatively constant on the more active axis.

Table 7.6 Morphogenetic Displacements- Belemnite Cliff

Date	General Cliff Displ. (m)	S.Dev. σ	Rate (m/ann)	σ
1946				
	-3.5	1.6	-0.29	0.13
1958				
	-0.2	1.4	-0.02	0.13
1969				
	-3.1	0.8	-0.44	0.11
1976				
	-2.8	1.7	-0.23	0.14
1988				
	-9.6	1.5	-0.23	0.04

Between 1958 and 1988 on Black Ven 2 the mean rate was approximately 0.9 m/ann between four successive epochs. An overall mean rate of 0.66 ±0.05 m/ann was derived from all three zones and this agrees quite closely with the value ascertained by Brunsden and Jones (1976) of between 0.4 and 0.5 m/ann. It should be realised that although the basal removal processes were efficient at both Black Ven and Stonebarrow, at Black Ven the process was mudslide removal, whilst at Stonebarrow the process was direct coastal erosion by the sea.

Table 7.7 Morphogenetic Displacements- Belemnite Cliff

Date	Black Ven 1 Axis Displ. (m)	S.Dev σ	Rate (m/ann.)		Black Ven 2 Axis Displ. (m)	S.Dev. σ	Rate (m/ann.)	σ
1946								
					-26.2	1.6	-2.18	0.13
1958								
	-2.9	1.4	-0.26	0.13	-9.8	1.4	-0.89	0.13
1969								
	-2.4	0.8	-0.34	0.11	-6.0	0.8	-0.86	0.11
1976								
	-10.3	1.7	-0.86	0.14	-10.6	1.7	-0.88	0.14
1988								
	-15.6	1.8	-0.52	0.06	-52.6	1.5	-1.25	0.04

Table 7.8 Morphogenetic Displacements- Mudslide Lobes

Date	Black Ven 1 Displacement (m)	σ	Mean Rate (m/ann)	σ	Black Ven 2 Displacement (m)	σ	Mean Rate (m/ann)	σ
1946								
	+104.3	1.6	+8.69	0.13	+54.0	1.6	+4.50	0.13
1958								
	-54.5	1.6	-4.95	0.13	+20.7	1.6	+1.88	0.13
1969								
	-24.5	1.2	-3.50	0.11	-39.0	1.2	-5.57	0.11
1976								
	+17.9	1.9	+1.49	0.14	+5.0	1.9	+0.42	0.14
1988								

The position of the mudslide lobe is a good indicator of the degree of recent activity as the lobe extends seaward during active periods and then gradually recedes as material is removed by marine processes. The large failures of 1958 (Section 6.1.2) are well represented with both lobes indicating massive extensions of 104.3 metres and 54.0 metres. Other important advances occurred between 1958 and 1969 on Black Ven 2, and on both lobes since 1976. The rates of advance are probably irrelevant statistics as the advances tend to occur within one season, (Brunsden, 1969). The rates of retreat are more important as these indicate the rate of marine denudation. A value of 4.7 ±0.15 m/ann is perhaps representative of this process, but this may be distorted because between photographic epochs each lobe may have both extended and shown signs of loss. This illustrates some of the problems associated with discontinuous records such as photographs taken infrequently and arbitrarily in relation to the time scales associated with geomorphological processes. The mudslide lobes are not a feature of the Stonebarrow landslide complex and so no comparative figures are available.

7.3.2 DTM´s of difference

The technique associated with the subtraction of a grid surface at one epoch from a grid at an earlier epoch to produce a DTM of difference was found to be especially valuable. Four DTM´s of difference were created from the 1946, 1958, 1969, 1976 and 1988 epochs, (Figures 7.23-7.26). The first DTM of difference, between 1958 and 1946, is dominated by the extreme events of 1958 (Section 6.1.2). Both mudslide systems exhibited great activity, with each showing massive recession of both the rear scarp and the Belemnite Cliff. This period also saw the development of the two source regions which are indistinct in the 1946 epoch. Between 1969 and 1958 this pattern continued with the rear scarp of Black Ven 1 being the most active area. During later epochs this area remained almost unchanged between 1976 and 1969, but has since shown signs of reactivation. The rear scarp of Black Ven 2 has remained highly active throughout the whole period, with increased activity since 1969. This general pattern is reflected by the morphogenetic developments of the rear scarp discussed in Section 7.3.1. Other patterns can be distinguished at the toes of the two mudslides. The 1958 and 1946 plot shows the advance of lobes associated with the massive failure of February 1958, (Section 6.1.2). Between 1969 and 1958 the lobe of Black Ven 2 continued to advance, whilst that of Black Ven 1 retreated slightly. Between 1976 and 1969 both showed signs of loss and between 1988 and 1976 Black Ven 1 has shown clear signs of advance.

It is clear that this particular technique is illuminating and with careful interpretation provides a very powerful computational procedure. It should be stated that there is a danger of over-interpretation because an incidental recording of the site is a small fraction of a site´s history. Many features experience cyclical patterns of activity, both short-term or seasonal and long-term. If for example two of the photographic epochs are dated at different times of the year, then seasonal differences will be recorded and should not be interpreted as long term trends.

7.3.3 The Model of Dynamic Equilibrium

The most important results associated with the application of these techniques to the Black Ven case study, were derived from the histograms of the distribution of slope angle, (Figure 7.30a- 7.30e). These histograms were derived from the 5 metre density grid representing slope angle in 1946, 1958, 1969, 1976 and 1988, (Section 7.2.3.4). The slope grids were themselves derived from approximately 11,000 spatial data points, acquired at each epoch. If these distributions are combined in one histogram (Figure 7.37) then inter-epoch comparisons can be made. The 1946 histogram appears quite different from later distributions, particularly with respect to the high incidence of slope angles between 0-5° and 15-25°. If the histogram derived from the 1946 data is ignored, over the thirty year period during which the landslides have exhibited great activity, the distribution has changed remarkably little. The only pattern that may be distinguished since 1958 is between 1958 and 1969 there was a reduction in the percentage of slope angles 5-20°, and subsequently the percentage of slope angles in this range gradually increased. Overall, the differences are small and so it is possible to conclude that slope morphology has remained stable, despite radical changes in the position of the slope boundaries. This is an example of **dynamic equilibrium**, an important qualitative temporal model in geomorphology, (Thornes and Brunsden, 1977).

The dynamic equilibrium model is accredited to Gilbert (1877) who introduced the concept of 'steady state,' (Pitty, 1982). In this, work done and imposed loads are approximately in balance, outflows equal inflows, form remains unchanged and consequently slope form is **time independent**. Hack (1960) revived the model to explain the 'ridge-ravine' topography of the Appalachian Mountains. Hack suggests that once a dynamic equilibrium form has become

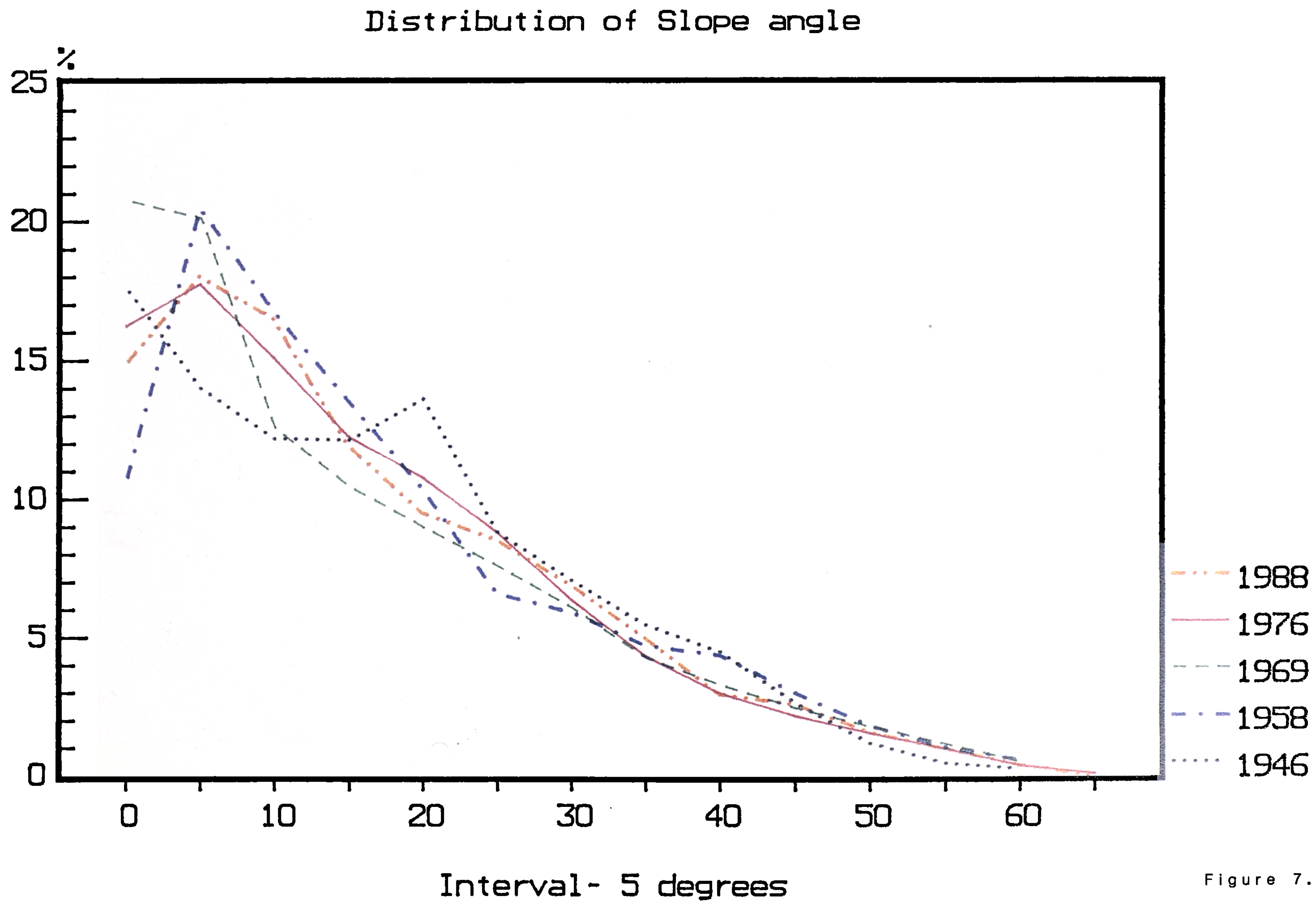

Distribution of Slope angle
%
25
20
15
10
5
0
0
10
20
30
40
50
60
Interval- 5 degrees
1988
1976
1969
1958
1946

Figure 7.37

established, it will remain essentially unchanged in character as long as the external conditions remain constant, (Thornes and Brunsden, 1977). Some work has been carried out to validate the model but these have operated at either small scale (Brunsden and Kesel, 1973) or have made use of 'location for time' substitutions (Welch, 1970) which create other uncertainties, (Section 1.2). The development of the distribution of slope angle since 1958 described here, suggests that the dynamic equilibrium model fits the events of the Black Ven landslide. This implies that the model of dynamic equilibrium is valid in certain situations and does have potential for further application in geomorphology.

7.3.4 Evolutionary Model based on changes of Form

An attempt was made to develop a quantitative evolutionary model (Section 7.2.3.7) based upon morphological change. Initially it was envisaged that a grid surface representing the 'mean annual rate of change' could be derived from the grid surfaces representing each epoch. Such an annual rate of change surface could be produced from each DTM of difference, by dividing by the number of years between each epoch. This could be repeated for the other DTM's of difference, so producing annual rate of change surfaces for each inter-epoch period. By meaning these annual rate of change surfaces, a mean annual rate of change surface could finally be derived. This surface could then be used to predict future form, by multiplying the mean rate of change surface by the required number of years and adding the result to a grid surface representing morphology at a particular epoch.

There was a major problem. The data used to represent morphological form were simply an array of elevation values organised in the form of a regular grid. The prediction of future form based upon changes in these elevations would have been insufficient to model the results of processes operating on the Black Ven landslide. It was apparent that the Belemnite cliff retreated parallel to itself (Section 7.3.1) and because Black Ven appeared to obey the model of dynamic equilibrium (Section 7.3.3) a more suitable framework would have been 'parallel retreat.' In order to build this type of rule into the evolutionary model and so enforcing cliff recession, it was decided to rotate all grid files by 90°. Fortuitously, the coordinate reference system was aligned with the Y axis in the desired direction of parallel retreat and so the required rotation could be accomplished simply by switching the coordinates of the Y and Z axis. The 'elevation' stored within the rotated grid files would become the Y coordinate of any point. Any numerical modification of these rotated files, based upon previous rotated morphological changes, would modify the Y coordinates of points. When a predicted rotated grid surface was finally orientated back to the original position, any change in Y value would result in either an advance or recession of the ground surface.

Extensive data processing was required to achieve the 90 degree rotation because there was no facility to rotate a grid within the DTM software. In order to obtain data in a form that could be altered by a computer program, these grid data had to be translated into a variety of internal DTM formats. The 1958, 1969, 1976 and 1988 epochs were used to obtain a 'mean annual rotated surface', it was decided not to incorporate the 1946 epoch because the state of dynamic equilibrium was not established in 1946, (Section 7.3.3). Two predicted surfaces were derived using this form based evolutionary model. The first surface represented Black Ven in 1988 and was derived by multiplying the mean annual rotated surface by 12 years, adding this to the 1976 rotated surface and finally rotating this back to the normal position. This surface was derived in order to evaluate the accuracy of the method prior to a longer future term prediction.

A DTM of difference between the 1988 computed and the 1988 measured surfaces was derived, so that areas which had not been accurately predicted would become immediately

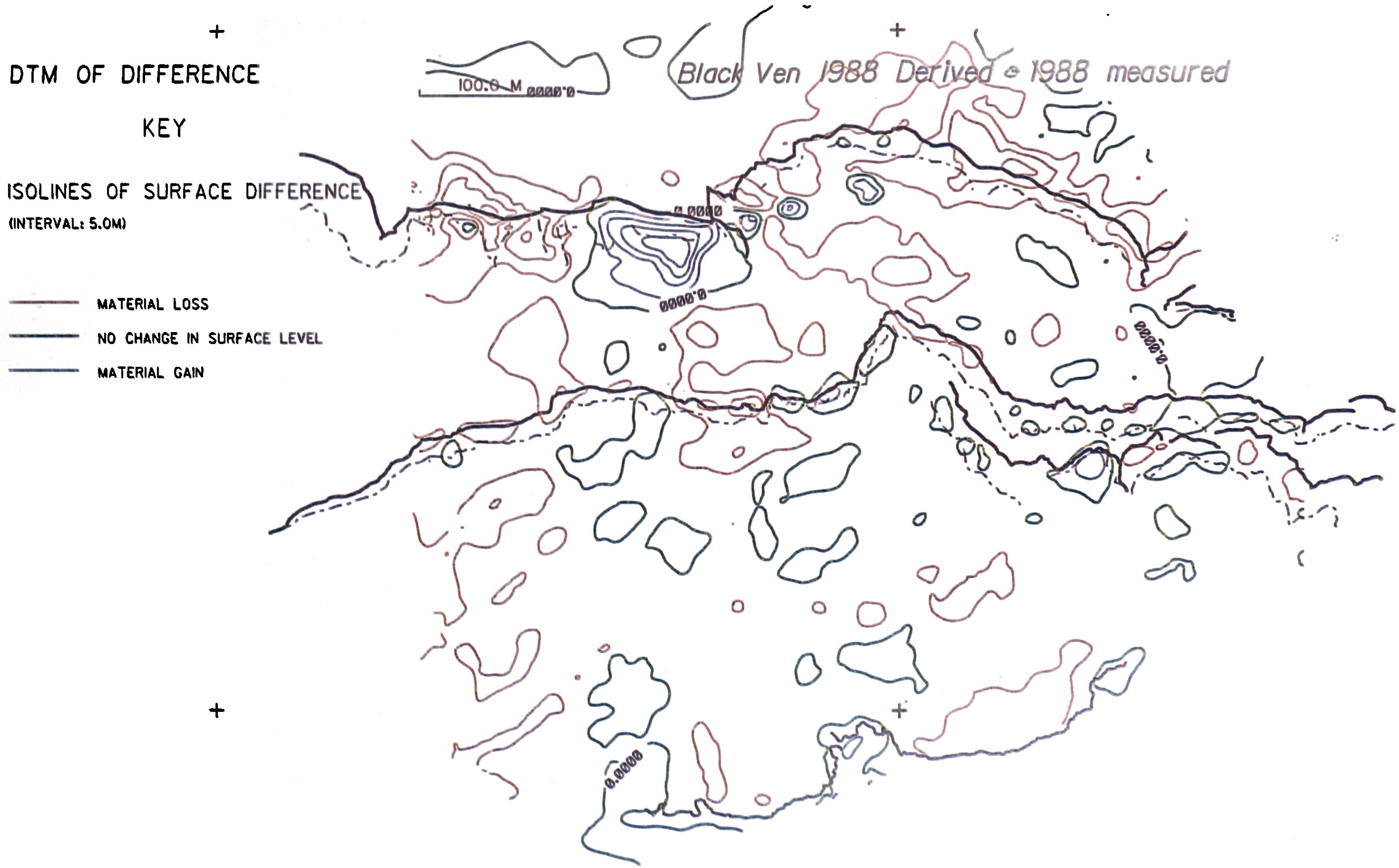

DTM OF DIFFERENCE
KEY
ISOLINES OF SURFACE DIFFERENCE
(INTERVAL: 5.0M)
MATERIAL LOSS
NO CHANGE IN SURFACE LEVEL
MATERIAL GAIN
100.0 M
Black Ven 1988 Derived - 1988 measured
0.0000

Figure 7.38

apparent. It was found necessary to apply a convolution filter to the predicted surface which smoothed the derived surface, (Figure 7.38). With the exception of a few spurious points and an area of rear scarp, which experienced very rapid recession between 1976 and 1988, the prediction is quite accurate. Further analysis of the 1988 prediction was achieved by producing a histogram of the distribution of elevation difference between the un-smoothed 1988 computed and 1988 measured surface, (Figure 7.39). This suggests that 68.8% of the derived surface is within 3 metres of the actual measured surface. There is a danger of circularity of argument because the actual measured difference between 1976 and 1988 was used, but in conjunction with other data, to derive the mean annual rotated rate. All data were used because the main aim was to derive a predictive model that was as accurate as possible.

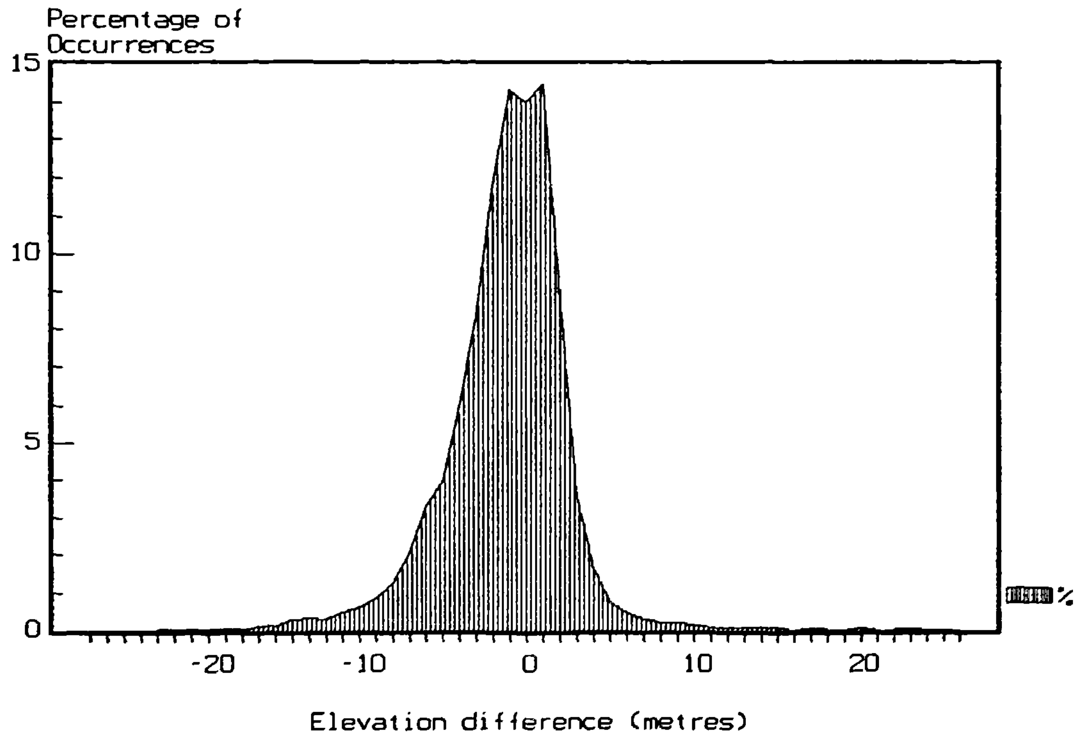


Figure 7.39 Histogram: Elevation difference, 1988 derived - 1988 measured

Black Ven Predicted Isometric view
Year 2000

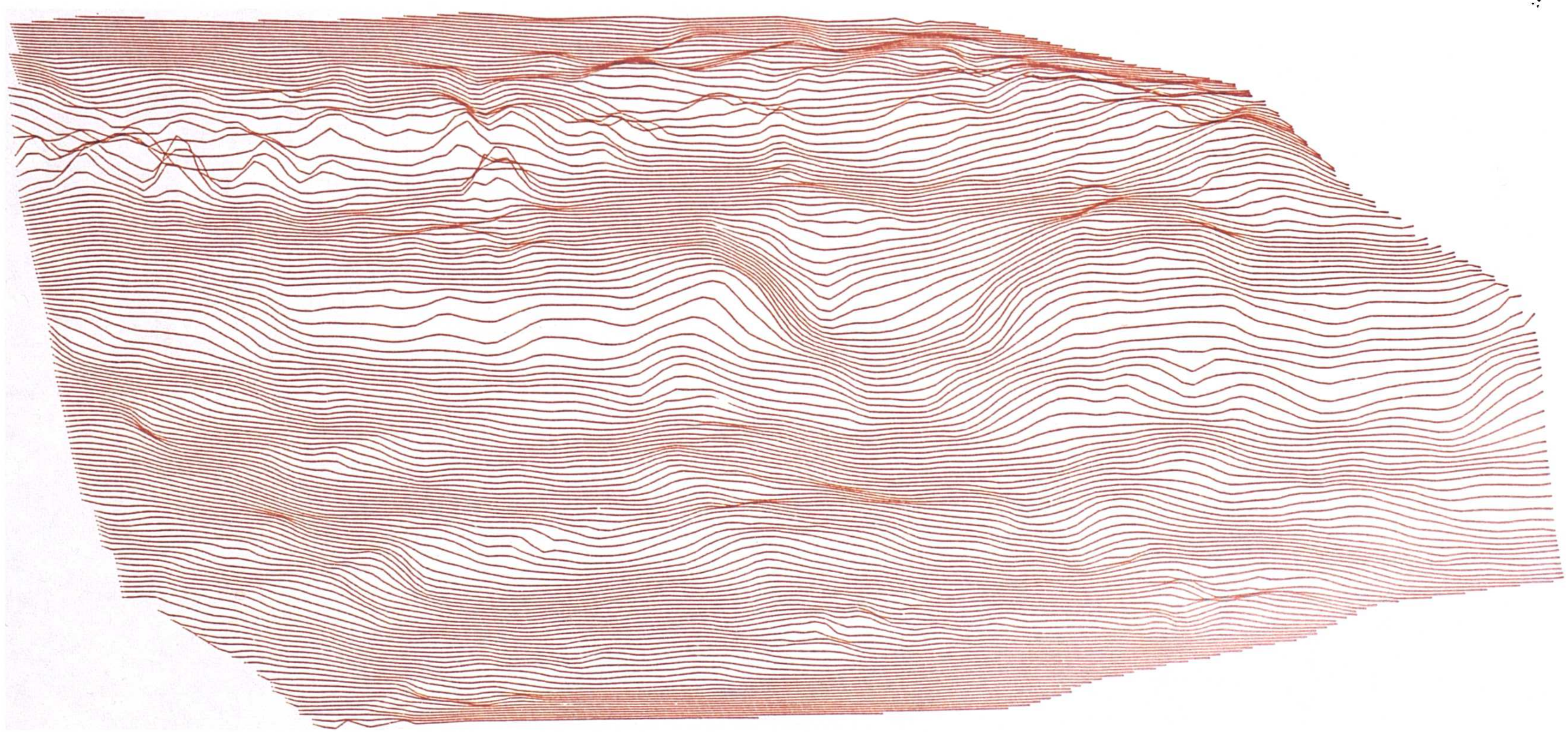


Figure 7.40

Figure 7.40 illustrates a prediction of the form of the Black Ven landslide in the year 2000, based upon mean rotated morphological change since 1958. A DTM of difference between the year 2000 and the 1988 measured surfaces was also derived, (Figure 7.41) and illustrates the changes in elevation which the evolutionary model predicts. The main morphological boundaries measured from the 1988 photographs are included in Figure 7.41 and enable the rate of recession of the Belemnite cliff and rear scarp to be estimated. The Belemnite cliff appears to have retreated by between 6 and 14 metres, which relates closely to the rates obtained in Section 7.3.1. The rear scarp has receded, although not as neatly as the Belemnite cliff. Several high points appear in front of the rear scarp; these are probably associated with the 90° break of slope at the top of the rear scarp, the 90° rotations that have been applied and small errors in the original data. Despite these minor problems the method appears to be successful and possibly represents an optimum with which future morphology can be predicted, based upon morphological change derived from the past alone.

A more reliable predictive model could be developed if the continuity equation and realistic process equations could be combined, (Section 7.2.3.7). For these developments, the grid cells require topological intelligence, in which each grid cell can recognise the value held in any adjacent cell. If additional grids, containing slope angles, slope aspect and stratigraphical data are superimposed upon a grid representing elevation, then material could be moved mathematically from one cell to another according to a pre-defined process equation. The movement of material will modify the morphology of the surface, requiring re-computation of the slope and aspect grids and perhaps reselection of suitable process equations. Following this re-evaluation the evolutionary model can be re-run to predict a new surface. Using this concept and a series of iterations a true quantitative evolutionary model can be built. Related work has been carried out (Armstrong, 1976; Kirkby, 1987) and with the growth in computer assisted methods, (Kirkby *et al*,

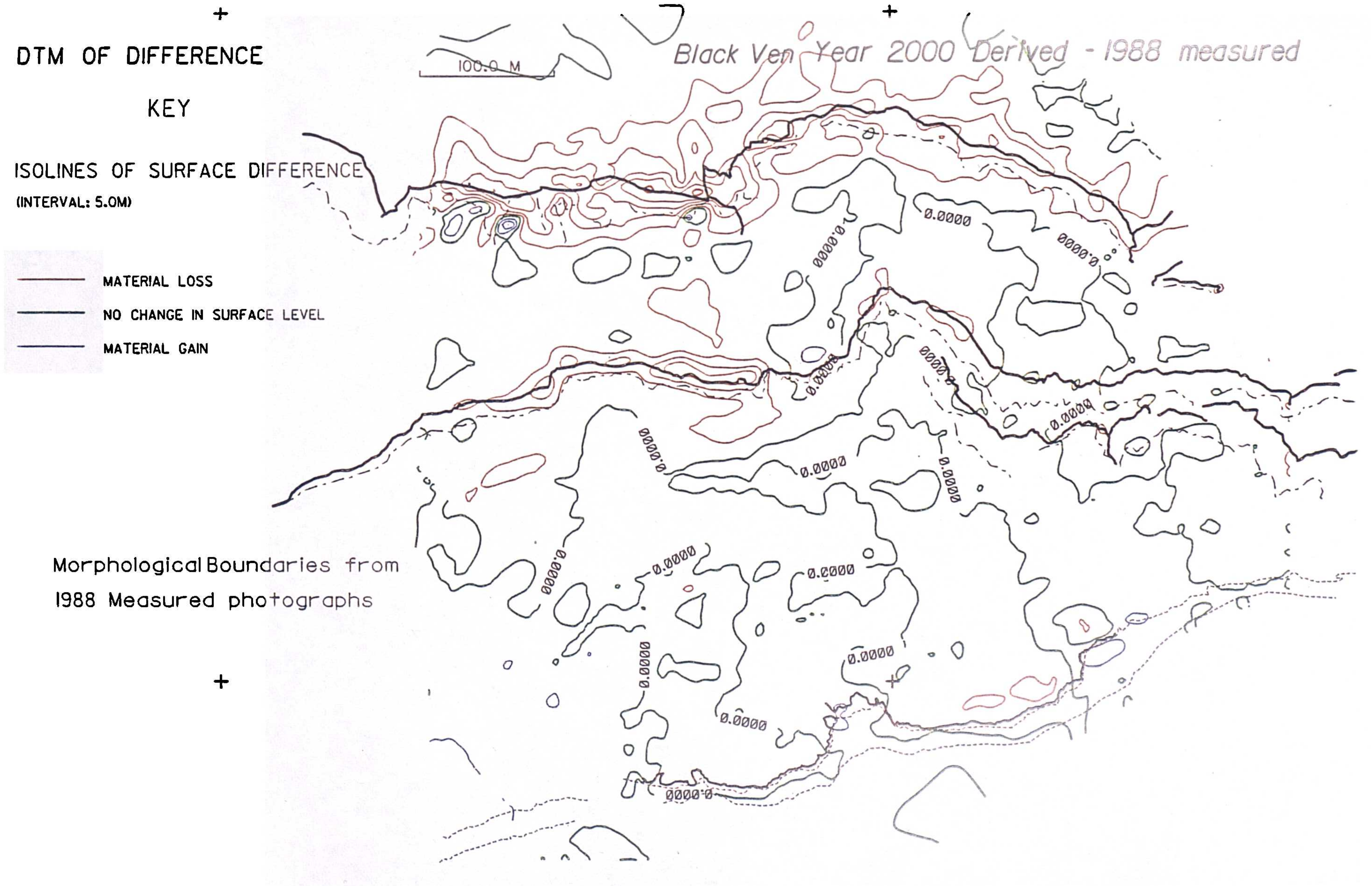

DTM OF DIFFERENCE
KEY
ISOLINES OF SURFACE DIFFERENCE
(INTERVAL: 5.0M)
MATERIAL LOSS
NO CHANGE IN SURFACE LEVEL
MATERIAL GAIN
100.0 M
Black Ven Year 2000 Derived - 1988 measured
Morphological Boundaries from
1988 Measured photographs
0.0000

Figure 7.41

1987) analytical process models are becoming more practicable. The important role for the archival photogrammetric technique could be to test these evolutionary models. Realistic trials could be established by comparing surfaces derived analytically with those derived from archival photographs.

7.3.5 Animation

The slope and aspect maps (Figures 7.28, 7.29, 7.31) were produced using a more advanced DTM software package than available at the City University. Access to this 'ESP' (Engineering Site Package) software was provided by a London based firm of architects who were interested in the research that was being carried out. During the production of the slope and aspect maps, it became apparent that an additional form of data presentation was available. This additional facility was the production of a sequence of images on the graphics screen, so that they appeared as an 'animated sequence'.

The ability to create an animated sequence representing the development of the Black Ven landslide since 1946, appeared useful. Any type of screen image could have been used, but in order to create a realistic image, a three dimensional slope shaded map (Figure 7.28) was used to provide a base. Isometric views of the slope shade map were created from data representing Black Ven in 1946, 1958, 1969, 1976, 1988 and the images were stored on disc. A computer package then recalled each of these images and combined them to form a short animated sequence. The sequence could not be reproduced on the computer system at City University and so a video of the sequence was made using a small portable video camera. Initially each image is recalled from disc storage and loaded into an area of computer screen memory. When each frame has been loaded, the screen images are rapidly swapped sequentially, so giving the impression of an animated film. This two phase procedure is useful because the slope map from each epoch can be individually studied, prior to animation.

The animation is especially valuable because the changes in landslide morphology are displayed in a new dynamic way. The evolution of the mudslide lobes and the recession of the rear scarp is especially striking, particularly the manner with which the area of rear scarp along the main landslide axes recesses initially, followed by the area of scarp between. Similar animated sequences were created by selecting different viewpoints and these all provide an important fresh dynamic method of viewing the evolution of the Black Ven landslide.

7.4 Concluding Remarks

Several geomorphic data processing options have been developed, investigated and tested on the Black Ven landslide. Most of these have been successful and there is clearly potential for important further developments. In Section 6.1.4 a series of geomorphological problems were identified, which could possibly be resolved by attaining historical three dimensional data from a site such as Black Ven. It is pertinent to investigate the extent to which these problems have been resolved.

1. Precise planimetric data, of known quality (Section 8.2) can be provided and these basic data can be used to produce a basic **description** of a feature under investigation. The ´planimetric approaches´ are typified by the production of geomorphological maps (Section 7.2.1) and sectional profiles (Section 7.2.2). Furthermore, by comparing precise dated plans, **process rates** can be estimated with known precision, (Section 7.3.1).

2. The addition of the third dimension by the production of contour plots (Section 7.2.3.1) and isometric grid plots (Section 7.2.3.2) further enhances depiction of a feature. Techniques associated with the **monitoring**, and quantitative assessment of morphological change are rewarding, particularly the DTM´s of difference, (Section 7.3.2). These

provide an insight into process rates and the **distribution** of activity.

3. An analysis of volume and volume changes is certainly possible with archival photographs, although the identification of boundaries at dynamic sites such as Black Ven remain a problem. The determination of mean elevation changes (Section 7.2.3.6) provided a partial solution but this was insufficient to allow a systems type of analyses.

4. The ability to produce statistical data that summarise the site at a particular epoch are important, especially the slope distributions and mean slope angle (Section 7.3.4). The histogram of the distribution of slope angle suggest that the model of **dynamic equilibrium** is indeed valid in certain cases. More advanced processing techniques associated with **quantitative evolutionary models** (Section 7.3.4) show great potential and it has been shown that future form can be predicted. The creation of **animated sequences** (Section 7.3.5) provides fresh insight into the evolution of the Black Ven landslide.

Chapter 8

Data Quality

8. Data Quality

8.1 Introduction

The Collins English Dictionary defines 'quality' as *'the degree or standard of excellence'*, (Hanks, 1986). There is a problem with the usage of the term quality in geomorphology and photogrammetry, as each science has a different interpretation. To the photogrammetrist, quality refers to the precision, reliability and accuracy of measured data and the photogrammetric restitution. In geomorphology the term has a wider application. Traditional elements of geomorphology are interpretation and classification, and it is the quality of these which is an important factor in understanding geomorphological phenomena. Since the shift in emphasis towards process studies and quantification, measurement of variables has become increasingly important in geomorphology. These data are both spatial and non-spatial in character and the precision, reliability and accuracy of these measurements has become relevant.

In an assessment of data quality, for a subject that encompasses both photogrammetry and geomorphology, it is necessary to examine both photogrammetric and geomorphological data quality.

8.2 Photogrammetric Data Quality

8.2.1 Theoretical Aspects

In photogrammetry, some elements of a functional model are measured and used to estimate values of other elements, often referred to as parameters. The measured elements generally include comparator coordinates of relevant images and the coordinates of control points. The estimated parameters consist of ground coordinates and interior and exterior orientation parameters, (Section 5.1). The measurement of elements of the functional model is important and classical theory of measurement errors, divides errors into three groups: random, gross and systematic. It is the combined effect of all three types of error that controls the quality of derived data, such as the ground coordinates of points, (Torlegard, 1980).

Measurements regarded as random variables, (Cooper, 1987), are subject to the laws of statistics and so variations of measured values made under the same conditions are said to have random errors, (Cooper, 1974). This statistical or stochastic characteristic enables the stochastic properties of measurements to propagate through the functional model and permits an assessment of the stochastic properties of derived data. Gross errors are blunders or mistakes made by observers or malfunctioning equipment (Torlegard, 1980). This type of error can generally be traced and removed using various 'data snooping' procedures, (Section 8.2.4.1). Systematic errors arise from the selection of incorrect or incomplete functional models and it is often difficult to detect the presence of such an error.

Precision, reliability and accuracy are three terms that can be used to describe quality with respect to the three types of error. Unfortunately confusion has arisen over the use of these terms, not least because accuracy and precision are used interchangeably in the English language, (Hanks, 1986). The photogrammetric literature is also inconsistent because several authors regard accuracy as a measure of all three types of error, (Torlegard, 1980; Hottier, 1976).

In this thesis, precision and reliability are used to describe the quality of a data set with respect to random and gross errors respectively, (Cooper and Cross, 1988). Also following Cooper and Cross (1988) the term accuracy will be used to describe quality with respect to systematic errors. A consideration of all three measures of quality is necessary to describe fully the quality of measurements and derived data. In order to make a quantitative assessment of quality it is necessary to have some form of measure of precision, reliability and accuracy.

Measures of precision are based upon **cofactor matrices** which are essential components of a least squares estimation, (Equation 5.31). In the case of the self-calibrating bundle adjustment, (Section 5.2.4) where an observation equation approach is used, the cofactor matrix of the estimated parameters is:

$$Q_{\hat{x}} = (A^T Q_l^{-1} A)^{-1} \qquad 8.1$$

where:

- A is the design matrix A, in which elements are the partial differential coefficients of the function with respect to the estimated parameters;
- Q_l is the cofactor matrix of the measurements, (equivalent to the weight matrix W); and
- $Q_{\hat{x}}$ is the cofactor matrix of the estimated parameters, $(\hat{x})$.

The cofactor matrix can be used to derive various measures of precision, including the standard deviations of estimated parameters, standard ellipses, eigen values and eigen vectors. The standard deviations of all estimated parameters in the 1958 self-calibrating bundle adjustment are contained in Section 10.2.4.

Reliability is the ability to describe or detect gross errors in the measurements, called **outliers**. Both internal and external reliability are recognised. The former is a measure of the size of the marginally detectable gross error, (Cooper and Cross, 1988). The latter is the effect of an undetected gross error on the estimated parameters or on some function of them. Several measures are available to describe both internal and external reliability. These are discussed in Section 8.2.4.2.

There are no clear methods of assessing or measuring accuracy. The only possible approach is to extend the functional model until it becomes over-parametised. If parameters can be reliably estimated, then it is possible to state that the parameter is accurate with respect to a particular set of systematic errors, (Cooper and Cross, 1988).

8.2.2 Factors Affecting Quality

There are a range of internal and external factors which will affect the quality of photogrammetric restitution. These will be examined in the context of the archival photogrammetric technique and illustrated by the Black Ven case study. There is a particular emphasis on the quality of object coordinates that can be derived.

8.2.2.1 Precision

One important factor affecting precision is the geometry provided by the photographs. A three dimensional network can be envisaged in which the photographs are related to the object by bundles of rays. The rigidity of this network is controlled by the spatial or geometrical positions of the cameras and ray bundles relative to the object. Two photographs with a small base:distance ratio (B:D) provide weak geometry. This geometry gives rise to object coordinates that are less precise and have less homogeneous precision than in a situation when convergent multi-station photographs are available, (Granshaw, 1980). The orientation of the photo-base is also important and for optimum precision should be perpendicular to an imaginary line drawn between the centre of the object and the midpoint of the photo-base. An additional practical consideration is the inability of the human brain to perceive a three dimensional model if the photographs are too convergent, (Section 5.1.1). The ideal configuration between camera positions and the object is illustrated by Figure 8.1 and consists of two pairs of photographs, each pair taken from different directions. This optimum configuration would provide strong geometry, yielding precise homogeneous coordinates, but the photographs would also be comfortable to view stereoscopically. Note also the provision of perhaps ten well displaced, clearly identifiable control points, (see below).

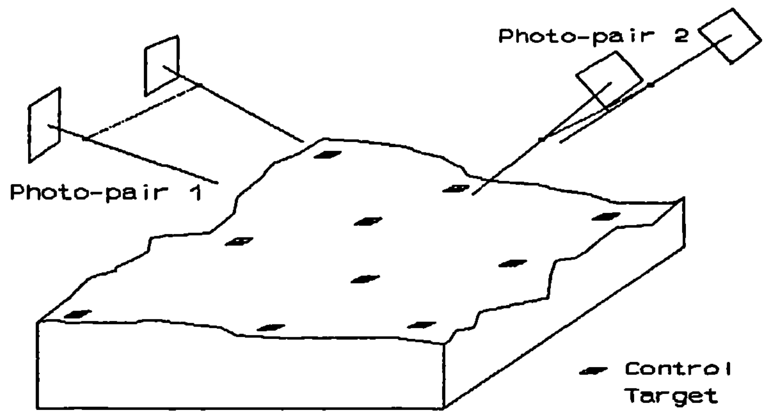


Figure 8.1 **The ideal camera-object configuration**

Some of these geometrical factors are illustrated by the 1948 photographs of Black Ven, (Figure 8.1a). Two of the photographs (Plates 6.5, 6.6) were taken at a distance of 1400 and 1900 metres from the site, (Table 6.1). Photo-scales were different, but with differential zoom a model was formed that was comfortable to view stereoscopically. The B:D ratio was quite high (1:2.5) but as the base was not aligned perpendicular to either of the camera axes, the effective B:D ratio was lower. With this geometry the precision of points on the object was only ±2 metre. With the addition of the third photograph (Plate 6.7), the geometry was significantly improved and the obtainable precision of points in the object was as high as ±0.8 metre. This third photograph was taken from quite a different position and orientation from the other two and was impossible to use for stereoscopic measurement in conjunction with either of the other photographs.

If a limited number of well identified points are required to be coordinated, perhaps for the derivation of movement vectors, (Section 7.2.4) then convergent geometry would be an advantage. The general data acquisition techniques (Section 7.2) require stereoscopic measurement and

BLACK VEN-CAMERA POSITIONS AND APPROXIMATE ORIENTATIONS

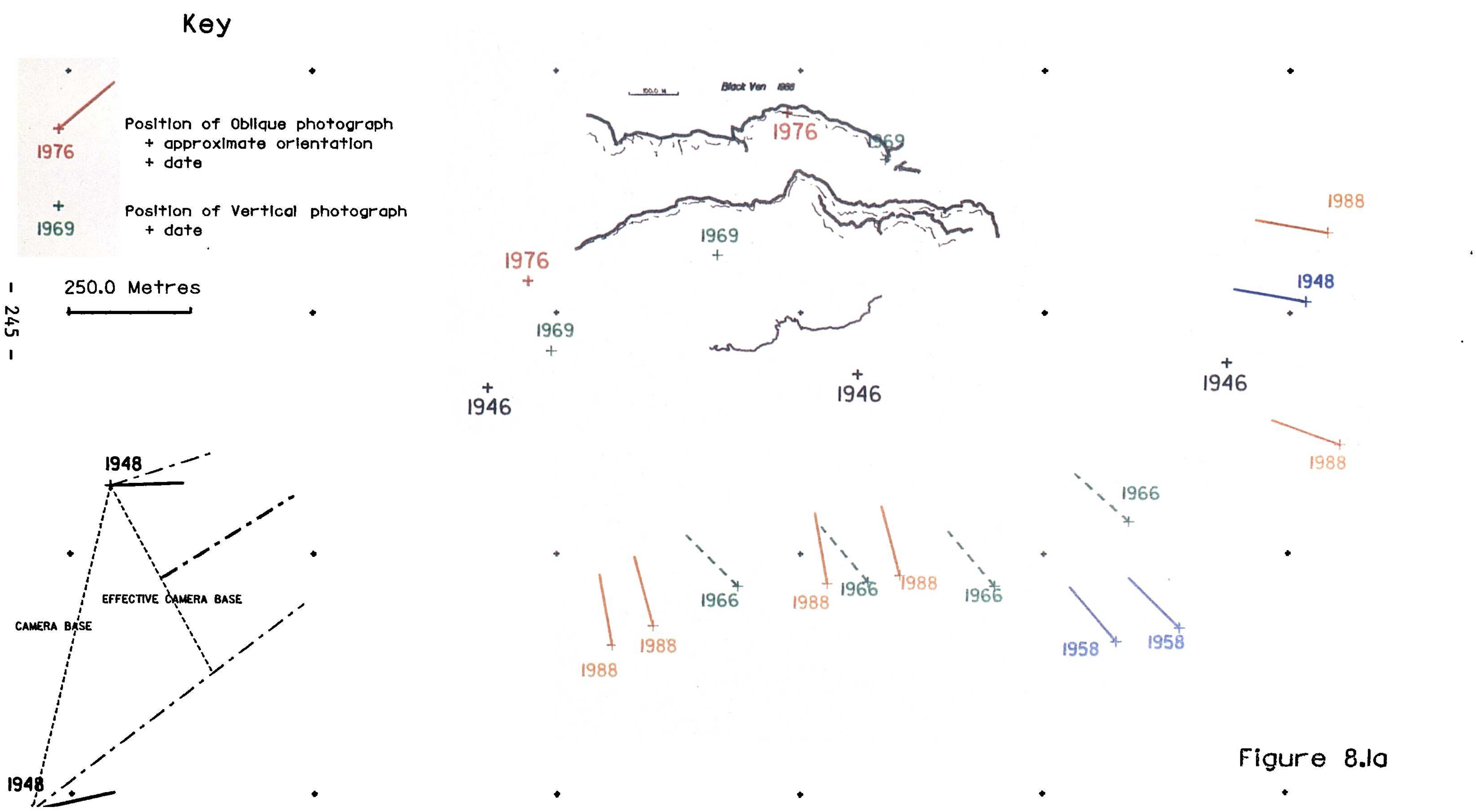


Figure 8.1a

so smaller B:D ratios are necessary. A balance is required between high theoretical precision associated with strong geometry, with lower precision but comfort of stereoscopic viewing. The 1958 epoch perhaps represents such a compromise, (Figure 8.1a) with the photo-base aligned parallel to the object and with a B:D ratio of 1:10. Unfortunately with historical photographs the photogrammetric network can never be designed. The user of the archival photogrammetric technique will often be unable to obtain even a close approximation to the ideal configuration, illustrated by Figure 8.1.

Another factor associated with geometry is the nature of the camera that was originally used to acquire the photographs. Metric survey cameras possess a large image format (230 x 230mm) compared with the smaller format sizes associated with reconnaissance photography (130 x 130mm) and small format photography (60 x 60mm). For a constant ground area, the survey format camera provides photographs which possess a larger photo-scale compared to the smaller format cameras. With large scale photographs the image size of objects are larger and can be measured more precisely. For the Black Ven case study a variety of format sizes were used (Section 6.3.2) and it can be seen that with the exception of the 1946 photography, large format cameras tended to produce photography with a large photo-scale, (Table 6.1 and 8.1). This large photo-scale appears to be a major controlling factor upon the precision of object points, (Table 8.1).

Table 8.1 Photo-scale and standard deviations of typical object points- Black Ven

Date	Pt.Id.	Format Size (mm)	Photo-Scale (S)	σ_X (metres)	σ_Y (metres)	σ_Z (metres)
1946	403	210 x 175	10,049	0.51	0.52	0.96
1948	413	130 x 130	9,600	0.90	0.50	0.33
1958	306	130 x 130	6,600	0.90	0.88	0.37
1966	427	130 x 130	5,000	1.05	0.77	0.35
1969	406	230 x 230	4,041	0.43	0.46	0.36
1976	403	230 x 230	7,468	0.32	0.32	0.39
1988 jan	403	60 x 60	18,000	0.98	0.96	0.39

There are other factors associated with these theoretical values, but the trend is quite clear.

The instrument used to measure the image positions on the diapositives is important also. Important factors are the resolution of the encoders, the degree of magnification of the viewing optics, the size of the measuring mark, quality of the optics, and the overall design and construction of the instrument. Most instruments are tested and calibrated so that the precision of any measurements can be assessed. Two types of instrument were used for measuring diapositives for the Black Ven case study. The stereo-comparator used for the initial measurement (Section 5.1.3; 6.3.1) was the Stecometer (Zeiss-Jena), which has a precision of ±2 micrometres (Slama, 1980). The data acquisition phase (Section 5.1.5; 6.5) was carried out using the IMA. This particular analytical plotter has a precision of ±3 micrometres. Some comparators and particularly small format analytical plotters have a precision of ±20 micrometres and provide less precise measurements.

A factor which is often overlooked is image quality and this is particularly important with archival photographs. The film base and the silver crystals that make up the image have a finite life, although this can be extended with proper storage, (Section 2.4). Developments in the chemistry of photographic emulsions over the last fifty years have radically reduced the size of the crystals that make up the image. The resolution is now greater so magnification of the image can be increased, which permits more precise measurements. Aerial films used in the early 1950's such as Ilford FP3 and Kodak Super XX had a resolution of approximately 20 lines/mm, (Fish, 1953). The resolution of Ilford FP3 increased to 40 lines/mm during the 1960's, (Arnold *et al*, 1971). Recent developments in 'T- grain' technology have increased resolution still further. TMAX 400 ASA film has a resolving power of 50 lines/mm, (Kodak Publications, 1987), although it is not available yet for survey format cameras. A good illustration of these improvements is a comparison between the 1946 vertical photography (Plate 6.12) compared with the small format obliques (Plates 6.9, 6.10, 8.1, 8.2) obtained in January and June of 1988 using T-Max 400 ASA film. The T-Max emulsion yields an exceptionally sharp image in which the silver grains can only be seen if the negative is magnified 40 X. In contrast the 1946 imagery is extremely grainy, even un-magnified.

The image can also be blurred due to image motion or due to the use of a focal plane shutter, (Section 8.2.3.3), which will reduce the precision of the measurements. Significant blurring was present in two of the 1966 photographs, (Section 6.3.2). This was imperceptible on the photographic print but was a problem with the magnified diapositive.

Other factors are the number, distribution, precision and design of the control coordinates that are used to restitute the archival photographs, (Section 5.1.2; 6.3.1). The greater the number of control coordinates the more precise will be the estimation of both ground coordinates and interior and exterior orientation parameters. The 1969 epoch provided strong geometry due to the large photo-scale (1:4,041) and large photo-base, but due to the limited coverage of the site only a few OS control points were available. The precision of coordinated object points was therefore lower than that obtained in 1976, (Table 8.1). The 1976 photography was also taken with a survey format camera but the smaller scale permitted the identification and utilisation of a larger number of O.S. control points.

The precision of the control coordinates is a major controlling factor on the final precision of all estimated parameters. The OS control points were assigned standard deviations of ±1 metre (Section 6.3.1) on the basis of the scale of the OS 1:2,500 map and the use of a scale rule to derive coordinates. If an OS 1:1,250 map had been available then the overall precision of points would have been significantly increased because the measurements derived by the scale rule would be more precise.

The design or definition of the control points is also important. Poorly defined control targets will present a poor image and will lead to less precise measurements. During the Black Ven case study, due to a lack of well defined control points like corners of buildings, recourse was made to poorly defined points such as hedge intersections, (Section 6.3.1). This form of control proved to be unfavourable because no single well defined point was available, (Section 6.3.1). For this particular case study the fences also proved to be transient features, two fences were completely removed in order to extend a golf course. It is thought that this type of difficulty could be typical of the sort of problems associated with the use of archival photographs for photogrammetric measurement.

8.2.2.2 Reliability

The reliability of the photogrammetric restitution can only be improved by increased redundancy of the measurements, (Hottier, 1976). Hottier (1976) identifies three methods to increase measurement redundancy, to which a fourth can be added:

1. increasing the number of image measurements;
2. increasing the number of targets defining each object point;
3. increasing the number of frames at each camera station, and
4. increasing the number of camera stations.

If a new photogrammetric project is being designed then these four methods can be incorporated, although increasing the number of frames is not practicable in dynamic situations such as aerial photography.

With archival photography altering the configuration of cameras and targets is impossible and so increasing the number of measurements is the only certain method of increasing reliability. There are two methods which can be implemented: increasing the number of image points and increasing the number of measurements to each point.

Although natural targets have to be used with the archival photogrammetric technique, there is no theoretical limit to the number of targets that can be measured and used in the self-calibrating bundle adjustment. Increasing the number of points will increase redundancy, although it appears that after approximately fifty well distributed points have been incorporated, no further benefits are accrued. (The types and merit of each category of point is examined in Section 5.1.2 and 6.3.1.).

The alternative method of increasing redundancy is to increase the number of measurements to each point. The technique is also related to precision because multiple pointings increase the precision of measurement and improve geometry. Hottier (1976) discovered that increasing the number of pointings from 1-3 resulted in a 30% gain in accuracy (reliability!; Section 8.2.1). All photo-coordinates used in the self-calibrating bundle adjustments of Black Ven were derived from four measurements to each point. This approach is not suitable for the 'on-line' determination of the coordinates of new points, and it is perhaps reasonable to state that the object coordinates of detail points are approximately 30% less reliable than those coordinates determined in a self-calibrating bundle adjustment.

Although in the case of archival photographs the number and configuration of photographs available will be fixed, the selection of suitable photographs is critical. Increasing the number of photographs of the object increases redundancy and therefore reliability. Multi-station techniques also improve geometry and consequently increase precision, (Section 8.2.2.1.).

8.2.2.3 Accuracy

The functional model that is used to restitute the measured data is the most important regulator of accuracy.

There is a major problem associated with the definition of a suitable functional model necessary to relate image measurements to ground coordinates. In certain situations the selected functional model is known to be erroneous and therefore non-rigorous. Steps can then be taken to make the functional model supposedly rigorous; a good example of this is the development of the DLT equations discussed in Section 4.3.1. The problem arises because it is impossible to state absolutely that the functional model is complete. This is especially true with regards to the functional model used in the archival photogrammetric technique. The cameras that were originally used have unknown geometric qualities, which can only be approximated. The effects of film deformation are unknown, as are the effects of a focal plane shutter and atmospheric refraction. (These systematic errors are discussed individually in Section 8.2.3.) All of these additional systematic errors have an effect, although often sufficiently small to be insignificant. The various systematic effects can be modelled using suitable mathematical functions, such as the polynomial used to model lens distortion. It is difficult to assess how effective these models and their parameters are in removing the various systematic errors. A further complication is high correlation between estimated parameters, and correlation was found between the inner and exterior orientation of the camera, (Section 5.2.4.3; 8.2.4.3). Correlation can prevent the reliable determination of many of these additional parameters and so they have to be dropped from the solution, (Granshaw, 1980). In practice this does not create a problem because the remaining systematic errors are compensated by parameters used to fulfil other components of the functional model.

Fortunately the analytical photogrammetric solution used in the archival photogrammetric technique permits certain assessments to be made of accuracy.

The parameters that are included in the estimation procedure to model a particular type of systematic error can be tested for significance. The proper method involves applying a statistical test (Cooper, 1987) based upon the standard deviation of any particular parameter.

The null and alternative hypothesis are:

$$H_0 : p_0 = 0; \qquad H_1 : p_0 \neq 0$$

The test statistic is:

$$t = \frac{(\hat{p} - p_0)}{\sigma_{\hat{p}}} = \frac{\hat{p}}{\sigma_{\hat{p}}} \sim t_{m-1} \tag{8.2}$$

Where:

- p_0 true value of a parameter;
- $\hat{p}$ estimated value of a parameter;
- $\sigma_{\hat{p}}$ is the diagonal element of the cofactor matrix $Q_{\hat{x}}$, (Equation 8.1);
- m is the number of observation equations which contain the parameter; and
- α significance level of the statistical test.

Critical values are derived from statistical tables and if:

$$t_{m-1,1-\alpha/2} < t < t_{m-1,\alpha/2} \tag{8.3}$$

then H_1 is rejected and H_0 accepted. If this is the case, then the particular additional parameter cannot be reliably estimated at the selected significance level, (typically α equals either 0.01, 0.05 or 0.10).

A quicker alternative method of assessing the significance of an additional parameter is to compare the estimated value with its standard deviation. If the estimate of the additional parameter is less than its standard deviation then the estimated parameter is insignificantly greater than zero and should be removed from the estimation. This alternative procedure is quick and useful but is not based upon rigorous statistical principles.

If any parameter can be reliably estimated, or judged significant, then the parameter can be regarded as being accurate with respect to a particular set of systematic errors, (Cooper and Cross, 1988). In the case of the Black Ven photographs, these tests were used to assess the relevance of additional parameters necessary to model the inner orientation of the camera, (Section 5.2.4.2; 6.3.2).

Other measures of accuracy depend upon the residuals of both photo-coordinates and ground coordinates. A residual is the difference between the measured value of an element and that derived using the functional model and the estimated parameters. Measurements are assumed to possess the properties of random variables (Cooper, 1987) and so the residuals should be small and randomly distributed. If there are any trends, then it is likely, assuming that there are no gross errors, that the selected functional model is either erroneous or incomplete. The residuals can be tested for normality by performing a Chi squared test, (Section 8.2.3.3) although graphs are useful to indicate trends. Graphs of photo-coordinate residuals are utilized to illustrate the effectiveness of various functional models used during the development of the self-calibrating bundle adjustment, (Figures 5.6- 5.9). A simple global comparative measure of accuracy is the ***a posteriori* variance factor**. This is derived from both photo-coordinate and ground coordinate residuals and the standard deviations that are associated with these measurements.

$$\hat{\sigma}_0^2 = \frac{(\hat{v}^T Q_l^{-1} \hat{v})}{(nm - nu)} \qquad 8.4$$

Where:

$\hat{\sigma}_0^2$	The *a posteriori* variance factor;
nm	number of measurements;
nu	number of parameters to be estimated;
$\hat{v}$	vector of residuals; and
Q_l^{-1}	is the inverse cofactor matrix of the original measurements.

If the variance factor is significantly greater than unity then, assuming no gross errors, either the stochastic model assigned *a priori* is erroneous or certain systematic errors remain un-compensated, or both. The variance factor can be statistically tested, at a certain level of significance, using either a Chi squared test (Section 5.2.4.2) or the more general F test, (Cooper, 1987). In an F test the two hypotheses are:

$$H_0: \hat{\sigma}_0^2 = \hat{\sigma}_*^2 \qquad H_1: \hat{\sigma}_0^2 > \hat{\sigma}_*^2$$

The test statistic is:

$$F = \frac{\hat{\sigma}_0^2}{\hat{\sigma}_*^2} \sim F_{r-1,\, r_0-1} \qquad 8.5$$

Where:

$\hat{\sigma}_*^2$	is the *a priori* variance factor;
$\hat{\sigma}_0^2$	is the *a posteriori* variance factor;
r	number of degrees of freedom associated with the *a priori* variance factor; and
r_0	number of degrees of freedom associated with the *a posteriori* variance factor.

If the *a priori* variance factor is assumed to have been obtained from an infinitely large sample, the *a priori* variance factor is normally made unity. The *a posteriori* variance factor becomes the test statistic and is compared with a critical value deduced from statistical tables of the F distribution, for a selected level of significance. Table 8.2 tabulates the variance factors for each of the epochs at Black Ven, with an F test of the ratio of variances at the 0.01 and 0.05 levels of significance.

Table 8.2 Variance factors, 1946-1988

Date	a posteriori V. Factor	Redundancy	F Test Statistic	Critical Value 0.01(α)	Critical Value 0.05	Accept H_0/H_1
1946	1.4938	58	1.4938	1.49	1.32	H_0/H_1
1948	1.2992	20	1.2992	1.88	1.57	H_0
1958	1.0136	26	1.0136	1.76	1.50	H_0
1966	2.9626	48	2.9626	1.53	1.36	H_1
1969	1.0642	57	1.0642	1.48	1.33	H_0
1976	1.0743	66	1.0743	1.44	1.30	H_0
1988 jan	1.2962	77	1.2962	1.41	1.28	H_0

The value of the variance factor depends upon the stochastic properties of the measurements and so it is always possible to derive an acceptable variance factor by increasing the standard deviations of the measurements. The standard deviations of all OS control points used at all epochs was ± 1.0 metre (Section 6.3.1) and the standard deviations of photo-coordinates varied between 5- 10 micrometres. It was accepted that these values represented the stochastic properties of photo-coordinates and control coordinates that were available. An analysis of the *a posteriori* variance factors summarised in Table 8.2 indicate that acceptable and accurate solutions have been derived for all photographic epochs except 1966. The photography associated with this epoch was blurred (Section 6.5.1) and was not used for data acquisition. Variance component analysis can also be carried out to assess local measures of accuracy but this was not performed for the Black Ven case study.

8.2.3 Systematic Errors

The importance of, and problems associated with the selection of suitable functional models were discussed in the preceding section. Four systematic errors were ignored in the final functional model, (Section 5.2.4.4) for a variety of reasons, and it was felt necessary to investigate the significance of these individually.

8.2.3.1 <u>Film deformation</u>

It was decided that it was impossible to compensate for film deformation explicitly using the archival photogrammetric technique as calibrated fiducial and reseau data would, in general, be unavailable. The consequence of ignoring this systematic error was not known, so an investigation into the effects was necessary.

To compensate for film deformation explicitly it is necessary to use **reseau** photography, which is obtained with a reseau camera. A reseau camera is designed to produce a series of crosses which are imaged onto the negative at the instant of exposure. By knowing the calibrated positions of these crosses and comparing them with the positions of their images during measurement, it is possible to compensate for two components of deformation: out of plane deformations, due to departures of the film from the format plane; and in-plane deformations caused by dimensional changes in the film subsequent to exposure, (Ziemann, 1972). There are a variety of computational techniques used to compensate for the systematic errors associated with film deformation:

1. A mathematical treatment applied to all reseau image points at the same time. The x and y corrections to each observed point can be computed from a **second order polynomial**.
2. Use of the four local reseau crosses surrounding the image point which is to be corrected. A **bilinear** equation can be applied in both x and y, giving a unique fit, since for each imaged point there are four parameters and four observations.
3. **Linear least squares interpolation** involving the use of a pair of empirically derived covariance functions for the x and y distortion components. This method of interpolation is based on the theory of stationary random functions, (Yaglom, 1962). An assumption that the deformations in x and y are mutually independent can be made to simplify the computation. (Kraus, 1971; Schut, 1974; Hardy, 1977).

These three approaches produce three different sets of refined photo coordinates, any one of which can then be processed in a bundle adjustment program.

The June 1988 photography appeared to provide material suitable for a practical examination of the effects of film deformation, (Chandler *et al*, 1989). The photographs were obtained using a hand held Rollei 6006 semi-metric camera, with reseau. Nine targets had been distributed around the object space and a control survey carried out using a Wild TC1 tacheometer. The coordinates of these targets were established on a local coordinate system using a three dimensional variation of coordinates estimation program. The standard deviations of the object control points were less than ±0.01 metre.

Four photographs were selected for measurement

Plate 8.1, 8.2 **June 1988, Personally acquired**

(Examples: Plate 8.1, 8.2) in which seven coordinated targets appeared on at least two photographs. An additional stage was required for photogrammetric data processing, (Section 5.1.4) associated with the optional refinement of photo-coordinates for film deformation. Software to implement three techniques of compensating for film deformation had been developed by a research student at City University. Both a standard and self-calibrating bundle adjustment were then used in order to assess the effectiveness of the self calibration technique. To enable meaningful comparisons, each option was processed with the same set of photo-coordinates and control coordinates. The stochastic properties of both photographic measurements and control coordinates also remained constant. Three different methods of compensating for film deformation were investigated, so including the raw un-processed data there were four basic sets of photo-coordinates.

In order to summarise and examine results it was necessary to identify a single comparative measure. An identical stochastic model had been used for all permutations and so the *a posteriori* variance factor could indicate crudely the presence of un-compensated systematic errors, (Table 8.3).

Table 8.3 Variance Factors- with/without Reseau Corrections

photo-coords.	*A posteriori* variance factor (Self Calib.) (dc, K_1, K_2, K_3)
raw	1.72
2nd Order	1.89
Interpolation	0.64
Bi-linear	0.63

It is clear from this table that film deformation corrections are relevant, provided a suitable functional model can be selected. Of the three methods of compensating for film deformation either the bilinear or interpolation function appear to lower the variance factor significantly. The second order correction appears to be unfavourable but it is thought that this is mainly due to localised areas of film un-flatness.

Despite this conclusion the variance factor derived from the raw photo-coordinates is not large and this suggests that the effects of film deformation are not as significant as was originally feared. It is thought that the parameters used to model the lens are also removing a significant proportion of the distortions associated with film deformation. In the case of archival photographs, where it would be impossible to correct for film deformation explicitly, it would appear that the effects of ignoring this particular source of systematic error are not significant.

8.2.3.2 Atmospheric refraction

In the original development of the self-calibrating bundle adjustment, atmospheric refraction was ignored because of correlation with rotational elements of exterior orientation. It was thought that any systematic errors associated with atmospheric refraction would be compensated by a small camera rotation, in the vertical plane. This would be the case with oblique aerial photographs in which points on the object are equidistant from the cameras. Clearly the camera-object distances varied and so a reappraisal of the assumption was necessary.

A variety of refractive models have been used in photogrammetry, (Bertram, 1966; Schut, 1969; Scarpace and Wolf, 1973). The model that is used in this analysis is the simple model derived by Saastamoinen (1974), valid for flying heights up to 9 kilometres.

$$10^6 Rf = 13(H - h)[1 - 0.02(2H + h)] \qquad 8.6$$

where:

H is flying height, (km); and

h is average ground elevation, (km).

The model deduces photogrammetric refraction (Rf) in micro-radians, for rays at angles of 45° to the image plane. The model can be adapted for use with oblique imagery by regarding flying height as distance between camera and object point and ignoring average ground elevation. The size of the systematic error for points at maximum and minimum distances from the camera are tabulated in Table 8.4. The distances were obtained from the 1948 Black Ven epoch, and focal length was based on the camera used, (206mm).

Table 8.4 Photo-coordinate Corrections- Refraction

Slope Distance (Km)	Angular Correction Rf (μradians)	Photo-coordinate correction (micrometres)
0.386	4.9	1.0
1.684	20.4	4.2

These data suggest that in the case of the 1948 self-calibrating bundle adjustment a systematic error of a maximum of 4.2 micrometres should be present. To investigate this

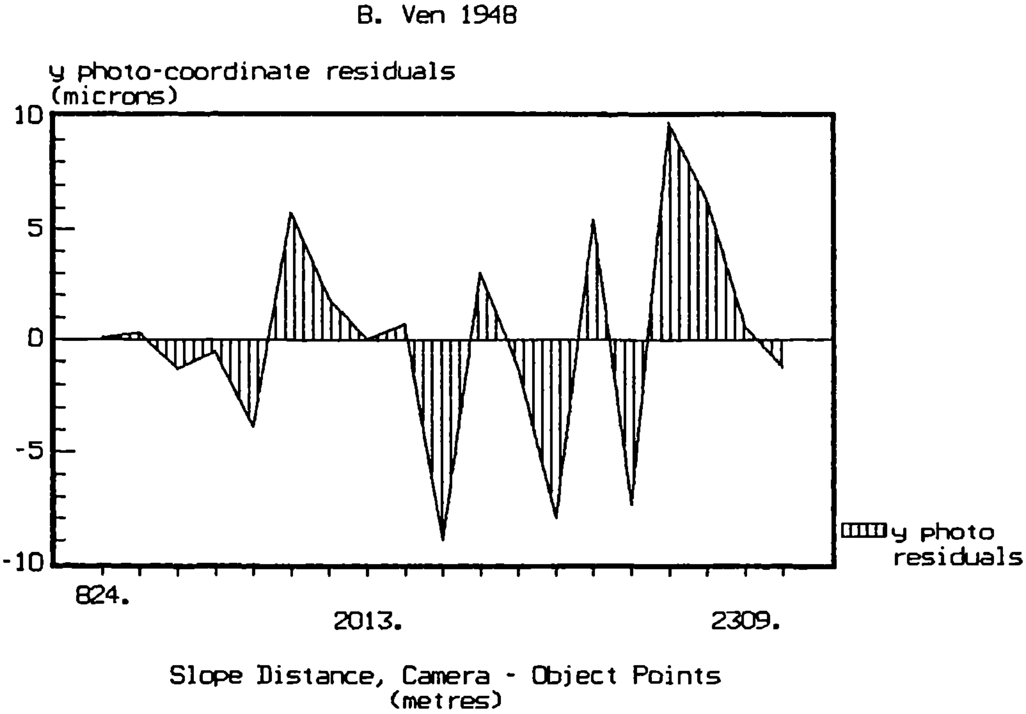


Figure 8.2 Relationship between camera-object distance with y photo-residuals

systematic error further it was decided to assess the relationship between camera-object distance and magnitude and direction of the y photo-coordinate residuals. Figure 8.2 shows that although some trend may just be discernible, it is small.

An explicit correction for atmospheric refraction appears unnecessary for two reasons. First, the size of such a systematic error is much lower than the random errors associated with measurement, (Section 8.2.2.1) and that perhaps the most significant component of atmospheric refraction is compensated by the exterior orientation parameters. Second, an explicit correction could only ever be approximate because data summarising atmospheric conditions at the time of photography would be very difficult to obtain.

8.2.3.3 Focal-Plane Shutters

The photography originally obtained in 1948, 1958 and 1966 of Black Ven was attained with a Williamson F24 Reconnaissance camera, (Darrell, 1988). This type of camera uses a focal plane shutter which produces a systematic error, (Aldred, 1968) which is ignored in the present self-calibrating bundle adjustment. The error is associated with motion of the image due to movement of the aircraft during exposure. The focal plane shutter produces an image which is equivalent to an infinite number of line photographs with respect to a constantly changing perspective centre, (Ghosh, 1979).

Theoretically the collinearity equations are invalid unless they are extended to include this systematic effect. El Hassan, (1982) developed the functional models for vertical aerial photographs, where the shutter is moving in the direction of flight.

$$dx_i = \frac{\pm u \; t_e \; x_i}{S \; l_s} \qquad 8.7$$

where:

u	velocity of aircraft;
S	photo-scale number;
t_e	exposure time;
l_s	width of slit; and
x_i	x photo-coordinate.

This model was extended for use with oblique aerial photographs by Smith (1987) and described as **dynamic image compensation**. Neither of these models was incorporated into the functional model used with the archival photogrammetric technique for two reasons. In tests carried out by using both image compensation and a standard bundle adjustment, Smith (1987) concludes that:

> *'From an examination of object space coordinates only one model showed a really significant improvement by using the dynamic solution.'*

It appeared that dynamic compensation was only just significant when used in conjunction with oblique aerial photographs acquired with a calibrated Vinten camera. It was felt that a self-calibrating bundle adjustment would be unable to estimate reliably the additional parameters necessary to model a focal plane shutter, in addition to parameters already used to model other aspects of inner orientation.

Smith (1987) also states:

'The dynamic solution can cause a deterioration in the results in comparison to the static solution, especially with small amounts of control.'

The derivation of sufficient control is a problem associated with the archival photogrammetric technique, (Section 5.1.2) amply demonstrated by the Black Ven case study, (Section 6.3.1; 6.4). It was felt that the addition of the functional model used for dynamic image compensation would exacerbate the problems of acquiring sufficient ground control.

The third justification for ignoring the focal plane shutter error source was based upon the results that were achieved. If such a systematic error had been important then the photo-coordinate residuals would reflect this omission. The graph of photo-coordinate residuals derived from the final functional model used in the self-calibrating bundle adjustment, (Figure 5.9) shows that the distribution appears random. Further analysis of the residuals included a Chi squared test to check for normality. The Chi squared statistic was evaluated using the 'Minitab' statistical analysis package and suggested, at the 0.05 level of significance, that the photo-coordinate residuals were normally distributed.

Both the graph (Figure 5.9) and the Chi squared test suggest that the effect of ignoring systematic errors associated with a focal plane shutter, is insignificant with the Black Ven photography. It is thought that the errors may be more appreciable in the case of photographs of a scale greater than 1:5,000 taken from a rapidly moving platform.

8.2.3.4 Earth Curvature

It is necessary to accommodate earth curvature in a national mapping system and the OS national grid uses a Transverse Mercator projection based upon the Airy 1830 ellipsoid, (Cooper, 1987; Harley, 1975). The collinearity equations are formulated for use within a right handed three dimensional cartesian coordinate system, (Section 4.1.2). The use of coordinates derived directly from the OS grid within a self-calibrating bundle adjustment is theoretically erroneous as the OS coordinates are not true three dimensional cartesian coordinates. This systematic error introduces a small apparent image distortion, caused by curvature of the earth, (Ghosh, 1979). The displacement is small and can be approximated by:

$$ds = \frac{H\ s^3}{2\ Rd\ c^2} \qquad 8.8$$

where:

H	flying height;
Rd	is radius of earth, (Approx. 6.4 E^6 metre);
s	is radial distance of an image point; and
c	focal length of camera.

In the case of the 1946 photographs in which the flying height was 5,600 metres, focal length of 550mm and for an image point with a radial distance of 140mm, the radial displacement is approximately -3.9 micrometres. It is suggested that this correction is small compared to other systematic errors and can be ignored in most situations.

8.2.4 Program BANAL

In section 8.2.1 quality with respect to random, gross and systematic errors was introduced and measures of precision, reliability and accuracy were mentioned. All of these measurements assume that both an adequate functional and stochastic model has been defined, (Cooper and Cross, 1988) and that all gross errors have been removed from the solution. In order to assist in the derivation of an adequate set of measurements and to permit an assessment of certain aspects of quality, the program BANAL (Bundle ANALysis) was developed.

There were three main objectives of the program. First, to carry out some form of 'data snooping' in order to obtain an adequate set of measurements; second to determine measures of internal reliability which would assist in the detection of gross errors; and finally, to look at correlation between estimated parameters in order to define an optimum functional model, (Section 8.2.2.3). It was felt unnecessary to determine any additional measures of precision because the developed self-calibrating bundle adjustment determines the standard deviations for all estimated parameters, (Section 10.2.4). The problems associated with measures of accuracy are discussed in Section 8.2.1; 8.2.2.3.

The existing bundle program could have been modified to derive these additional measures after successful convergence. This approach would have been simpler because most of the necessary matrices are derived in the self-calibrating bundle adjustment. A more convenient and manageable alternative was to develop a separate program which used data derived by the bundle program.

There are five matrices that are required and in an observation equation approach, (Cooper and Cross, 1988) such as a self-calibrating bundle adjustment, they are:

$$\hat{x} = (A^T Q_l^{-1} A)^{-1} . A^T Q_l^{-1} b \qquad 8.9$$

$$\hat{v} = (A\hat{x} - b) \qquad 8.10$$

$$Q_{\hat{x}} = (A^T Q_l^{-1} A)^{-1} \qquad 8.11$$

$$Q_{\hat{l}} = A (A^T Q_l^{-1} A)^{-1} A^T \qquad 8.12$$

$$Q_{\hat{v}} = Q_l - Q_{\hat{l}} \qquad 8.13$$

where:

x matrix of estimated parameters,

A	design matrix;
Q_l	is the cofactor matrix of the original measurements;
b	matrix of observed - computed terms;
v	matrix of estimated residuals; and
$Q_{\hat{x}}, Q_{\hat{l}}, Q_{\hat{v}}$	Cofactor matrices of estimated parameters, measurements and residuals.

The data derived in equations 8.9, 8.10 and 8.11 are determined within the self-calibrating bundle adjustment. The estimated parameters (Equation 8.9) are stored on file and could readily be recreated in an off-line program. Similarly, the cofactor matrix of the estimated parameters (Equation 8.11) could be recreated, although this required modifying the bundle program to store this file. The matrix of estimated residuals (Equation 8.10) could be recreated using the original measurements, the estimated parameters and the functional model.

It was decided to ignore correlation between measurements and to compute only the diagonal elements of the cofactor matrix of the estimated measurements (Equation 8.12). This is justifiable for the purposes of data snooping (Section 8.2.4.1) because it is generally accepted that measurements are un-correlated, (Cooper, 1987) and permitted some important simplifications to the necessary algorithms. The entire design matrix (A) is not required and each measurement can be processed individually. As it is unnecessary to store the entire A matrix there are no limits to the number of measurements that can be processed. This follows the strategy used in the self-calibrating bundle adjustment, (Section 5.2.4.2). The diagonal elements of the cofactor matrix of the estimated residuals could also be similarly derived, (Equation 8.13).

8.2.4.1 Data Snooping

One problem associated with least squares estimation procedures is the derivation of an accepted set of measurements in which all blunders or gross errors have been eliminated. Certain algorithms have been developed to help the detection of gross errors or outliers, and are known as 'data snooping' procedures. The data snooping technique developed by Baarda (1968) was implemented in the BANAL program and relies upon the computation of the tau test statistic:

$$w_i = \frac{\hat{v}_i}{(\mathrm{diag}\{Q_{\hat{v}}\})^{\frac{1}{2}}} \qquad 8.14$$

The value of the tau statistic is compared with a critical value derived from the probability distribution, either at 0.01, 0.05 or 0.10 levels of significance. If the computed value is greater than the selected critical value then it is possible that the measurement is a blunder and the cause of the problem should be investigated and rectified. During program execution such a problematical measurement is flagged by some form of symbol. The results of a typical data snooping procedure are illustrated in Section 10.3.2.

8.2.4.2 Internal Reliability

Two measures of internal reliability can be determined, tau factor (τ) and roe (J). These are both given by Cooper (1987) but accredited to Pelzer (1979) and Ashkenazi (1980) respectively. The tau factor is defined as:

$$\tau_i = \frac{\sigma_{li}}{(\sigma_{\hat{l}i}^2 - \sigma_{li}^2)^{\frac{1}{2}}} \qquad 8.15$$

From which:

$$\Omega_i^u = \delta_i^u \, \tau_i \, \sigma_{li} \qquad 8.16$$

where:

Ω_i^u upper bound of the measurement error which will not be detected;

$\sigma_{\hat{l}i}^2$, σ_{li}^2 variances of measurements and their estimates;

δ_i^u factor depending upon significance level (α) and power ($1 - \beta$) of the test.

Values at a specific significance level and for a test of a particular power can be deduced from statistical tables and used to evaluate δ_i^u. This can then be used to derive the upper bound of measurement error. It is then possible to make the following type of statement:

> *statistical testing with a significance of α, there is a β% chance of a gross error of ∇_i^{ll} remaining undetected in this particular measurement.*

The BANAL program implemented the computation of the tau factor and the upper bound of measurement error, associated with each measurement and results derived from the 1958 photography are given in Section 10.3.3.

The individual tau factors can also be used to carry out a global test on the reliability of the measurements. The redundancy number should equal the sum of the reciprocals of the squares of each tau factor, or:

$$r = \Sigma \, 1/\tau_i^2$$

This test was carried out for the 1958 self-calibrating bundle adjustment, (Section 10.3.3).

The roe statistic (J) provides an alternative measure of internal reliability, although this is slightly less sensitive than the tau factor.

$$J = \frac{\sigma_{\hat{l}i}}{\sigma_{li}} \qquad 8.17$$

For a completely reliable measurement roe equals zero, conversely roe equals unity if the measurement is completely unreliable. This measure of internal reliability was evaluated for each self-calibrating bundle adjustment associated with the Black Ven case study. The results for the 1958 photography are illustrated in Section 10.3.3.

8.2.4.3 Correlation Between Estimated Parameters

Another problem associated with least square estimation procedures is correlation between estimated parameters. The problem is particularly important in self-calibrating bundle adjustments where many additional parameters can be selected, (Section 5.2.4.3; 8.2.2.3). The problem is discussed by several authors, (El Hassan, 1982; Granshaw, 1980).

To solve problems associated with correlation it is first necessary to detect which estimated parameters are correlated. This can be achieved by deriving coefficients of correlation (ρ_{xy}) between parameters (xy) from the cofactor matrix. Those parameters which possess high correlations can then be excluded from the functional model, (El Hassan, 1982) and the remaining parameters re-estimated. The function necessary to determine the coefficient of correlation is given by Cooper, (1987).

$$\rho_{xy} = \frac{\sigma_{xy}}{\sigma_x \ \sigma_y} \qquad 8.18$$

For the photography acquired for the Black Ven case study, it was obviously necessary to investigate correlation. It was envisaged that high correlation could pose a problem, principally between the additional parameters necessary to model the inner orientation of the camera and the exterior orientation parameters. A facility to derive correlation coefficients between any parameter and a range of other parameters was developed within the BANAL program. Examples of the output are contained in Section 10.3.4.

The facility to derive correlation coefficients between estimated parameters proved crucial to the successful development of the self-calibrating bundle adjustment, (Section 5.2.4.3; 5.2.4.4). The BANAL program was developed and tested at the time when the program BINFLEX was the latest version of the self-calibrating bundle adjustment. This version (Section 5.2.4.3) could only permit a hierarchical selection of the inner orientation parameters. In order to include the focal length (dc) as an additional parameter it was necessary to include both displacements of the principal point (x_p, y_p). A series of correlation coefficients was computed between the inner and exterior orientation parameters for all photographs. Table 8.5 contains the results derived from the 1958 photographs of Black Ven, using the BINFLEX program, (Section 5.2.4.3).

Table 8.5 Correlation Coefficients BINFLEX- Inner and Rotational Exterior Orientation Parameters (Black Ven 1958)

Parameter	Cam.	x_p	y_p	dc
Omega	1	+0.94	+0.99	+0.88
	2	+0.94	+0.99	+0.88
Phi	1	+0.62	+0.85	+0.84
	2	+0.68	+0.89	+0.86
Kappa	1	-0.94	-1.00	-0.88
	2	-0.94	-1.00	-0.88

This table shows that very significant correlations were present, particularly between the displacement of the principal point in the y direction (y_p) and omega and kappa where there was almost a functional relationship. To avoid this correlation the additional parameter (y_p) had to be removed and the solution re-estimated. This was not possible with the existing BINFLEX program and lead to the development of BINFLEXPC, the final version, with selectable inner orientation parameters. Re-computation of the 1958 epoch with y_p removed made a very significant improvement to the solution, (Section 5.2.4.4). The solution was stronger, required fewer iterations to achieve convergence and enabled three lens parameters to be reliably estimated. The additional lens parameters significantly reduced the residuals of the photo and ground coordinates, and improved the accuracy of the solution and the precision of estimated ground coordinates. Similar improvements were gained with the Black Ven photographs from other epochs.

The analysis of correlation coefficients was repeated for the solution derived using the BINFLEXPC program, (Section 5.2.4.4). The results are contained in Table 8.6.

Table 8.6 Correlation Coefficients BINFLEXPC- Inner and Rotational Exterior Orientation Parameters (Black Ven 1958)

Parameter	Cam.	x_p	y_p	dc	K_1	K_2	K_3
Omega	1	+0.69	-	+0.32	-0.04	+0.05	-0.06
	2	+0.72	-	+0.30	-0.02	+0.03	-0.05
Phi	1	-0.85	-	+0.48	-0.28	+0.14	-0.09
	2	-0.88	-	+0.45	-0.27	+0.13	-0.08
Kappa	1	-0.91	-	+0.03	-0.26	+0.13	-0.06
	2	-0.92	-	+0.02	-0.25	+0.13	-0.06

Table 8.6 shows that correlation coefficients are reduced by the removal of the y_p inner parameter, accounting for the improved geometrical strength and increased precision.

Further analysis of correlation was associated with the parameter used to estimate a correction to the camera focal length (dc). Two aspects were examined:

It was thought that some correlation would be present between the estimated correction to the camera focal length and the parameters used to model lens distortion. The relevant correlation coefficients were determined for the 1958 photographs of Black Ven and are tabulated in Table 8.7.

Table 8.7 Correlation Coefficients BINFLEXPC- Inner Orientation Parameters (Black Ven 1958)

Parameter	K_1	K_2	K_3
Focal Length	-0.50	+0.38	-0.32

The correlation coefficients illustrated in Table 8.7 suggest that correlation between the estimated correction to the camera focal length and the parameters used to model lens distortion is small and can be ignored.

Correlation between the focal length and elevation of the camera was also examined. During application of the self-calibrating bundle adjustment to the vertical air photographs of Black Ven, it was found that the focal length could not be estimated reliably, (Section 6.3.2). It was thought that this was due to correlation between the estimated correction to the camera focal length and flying height. Suitable correlation coefficients were derived from all self-calibrating bundle adjustments used with the Black Ven case study and tabulated (Table 8.8).

Table 8.8 Correlation between focal length and flying height

Camera Id:	1946 v	1948 o	1958 o	1966 o	1969 v	1976 v	1988 o	v= vertical o= oblique
1	1.000	0.044	0.166	-0.015	0.998	0.997	0.515	
2	1.000	0.127	0.197	0.067	0.999	0.998	0.541	
3	1.000	-0.111		0.480	0.998	0.997	0.637	
4				0.465			0.646	
							0.606	
							0.634	

In the case of vertical photographs there are significant correlations between the estimated correction to the camera focal length and flying height. This correlation is associated with the lack of depth in the object for vertical photographs, whereas object depth can be very great in the case of oblique photography. The functional relationship between focal length correction and flying height can only be eliminated by removing the additional parameter used to correct the approximate focal length. It would appear that for vertical air photographs, providing that the estimated correction to the approximate camera focal length is small, that any errors in the selection of focal length will be compensated by a subsequent change in flying height.

8.2.5 Comparison between Estimated and Calibrated Inner Orientation parameters

All archive sources had been contacted in order to establish the camera calibration data for the cameras used for the acquisition of the Black Ven photographs. A comparison between certain elements of estimated inner orientation parameters and those defined by the calibration certificates would test the efficacy to which the cameras inner orientation was modelled by the self-calibrating bundle adjustment. In the case of the 1969, 1976 and 1988 photographs the calibrated focal lengths of the cameras were obtained, (Darrell, 1988; Sims, 1988; Kafetz, 1988). No detailed calibration data were available for the 1946 RAF (Longhurst, 1988) and the 1948, 1958 and 1966 (Darrell, 1988) photographs from the Cambridge University Collection.

The only form of comparison that was possible was associated with the estimation of the focal length of the cameras used. Table 8.9 summarises the findings.

Table 8.9 Calibrated and Estimated focal lengths

Date	Calibration information	SI Units (mm)	Estimated focal length	S.Dev σ_{dc} (mm)
1946	20 in	508	513.62	16.74
1948	8 in	203	206.55	0.34
1958	8 in	203	201.94	1.68
1966	8 in	203	209.74	1.81
1969	153.2 mm	153.2	166.03	3.83
1976	305.04 mm	305.04	304.59	2.30
1988(jan)	51.02 mm	51.02	50.83	0.19
1988(june)	51.02 mm	51.02	51.23	0.21-local datum

The table illustrates that the self-calibrating bundle adjustment derived estimates for camera focal length which are close to the best calibration data available. The standard deviations of these estimated values are considerably lower in the case of oblique aerial photographs, where correlation between the correction to the focal length and flying height is low, (Section 8.4.3).

8.3 Geomorphological Data Quality

The quality of geomorphological data has a wider understanding than in photogrammetry. Precision, reliability and accuracy are significant elements, particularly with respect to the measurement of field parameters such as soil strength and pore water pressure. Two other important factors are interpretative quality and quality of classification and these are integral aspects of air photo-interpretation (API). One of the prime roles of the applied geomorphologist is to map geomorphological phenomena (Goudie, 1987) which requires identifying relevant points, features and boundaries using API and classifying them to create some form of map or plan. API has been an important aspect of engineering geology and geomorphology, (Fezer, 1971; Norman 1969, 1970; Norman and Huntingdon, 1974; Norman *et al*, 1975; Lo, 1976; Beaumont, 1977; Speight, 1977; Matthews and Clayton 1986).

8.3.1 Morphological and Geomorphological Maps

Geomorphologists distinguish between two styles of map: morphological and geomorphological. Morphological maps represent discontinuities in the ground surface and define some aspect of ground geometry, (Savigear, 1965). The aim of geomorphological maps is the identification and exact description of landforms, indicating position, arrangement and genesis, (Verstappen, 1983). Morphological maps are general and require no interpretation of the landscape, whilst geomorphological maps are specific and adapted to explain or illustrate particular aspects of landform. Verstappen, (1983) distinguishes between morpho-genetic, morpho-dynamic, morpho-metric and morpho-chronological geomorphological maps. Morpho-genetic and morpho-dynamic maps indicate the origin and development of landforms, (Section 7.2.1, Figure 7.7). Morphometric maps are similar to morphological maps but are concerned with form rather than slope facets, (Section 7.2.1; Figures 7.2- 7.6). Morpho-chronological maps attempt to indicate the relative age of landform features. The two styles of map are not necessarily mutually exclusive, Savigear, (1965) states:

> *'Morphological maps can form an essential base map when an interpretation is to be made of the relations of surface forms to the distributions of other physical and cultural phenomena.'*

More simply, the morphological map can serve as a base upon which other applications can be constructed.

The maps of the Black Ven landslides compiled in this thesis, (Figures 7.2- 7.6) were constructed on this twofold basis. The base or morphological map comprises the boundaries between the different slope facets, according to the feature coding sub-heading of Morphological form, (Section 6.5.2; Table 6.3). Superimposed upon these data are the boundaries of morphological features and morphological failures (Table 6.3) which required an element of interpretation to identify. The classification is based upon the system used by Conway (1974), (Section 6.1.2).

8.3.2 Air Photo-Interpretation (API)

Air photo-interpretation has been defined as:

> *'The act of examining photographic images for the purpose of identifying objects and judging their significance'*, (Colwell, 1960).

This definition implies that there are three stages to air photo-interpretation: examination, identification and evaluation or classification, (Lo, 1976). Vink (1964) recognises the importance of the human interpreter and the associated level of significance which controls the quality of API. This level of significance, or 'reference level' (Tait, 1970), is the general knowledge of the phenomena and processes which are in the mind of the interpreter. Higher reference levels will lead to a larger number of features that will be recognised and this will be reflected in the degree of map completion.

The initial stages of API (examination and identification) depend upon the abilities of the interpreter to recognise relevant features on the basis of several key visual elements. These elements (shape, tone, texture, colour, size and pattern) are discussed in detail by Colwell (1960); Lo (1976); Matthews and Clayton (1986). After a series of elements have been identified the third stage is to evaluate and classify. This entails grouping the various elements according to a pre-defined system, generally designed to illustrate some particular aspect of the landscape.

There are a variety of external factors which affect the quality of API. These include the orientation of the camera axis, film and filter combinations, photo-scale, timing of the photography, image medium and characteristics, (Matthews and Clayton, 1986). These factors have been investigated specifically in the context of detecting slope instability by Norman *et al*, (1975). For the user of the archival photogrammetric technique the most relevant external factors are the orientation of the camera, photo-scale and timing of the photographs. Colour and false colour infra-red emulsions are comparatively rare and most archival photographs consist of black and white (panchromatic) images, (Section 2.3; 10.1). Oblique aerial photographs create certain problems for API, associated with the varying photo-scale over the image and the amount of ground hidden by features such as buildings and hills, ('dead ground'). Obliques do provide the user with a more familiar perspective, and this can be important for the less experienced interpreter. Timing of the photography refers to both the season and the time of day in which the photographs are acquired. The identification of small topographic variations possible with low sun angles has been well exploited (Matthews and Clayton, 1986), particularly by archaeologists, (St Joseph, 1966; Hampton, 1975).

8.3.2.1 Identification of Boundaries

One of the main problems associated with interpretation is the identification of the exact position of features, particularly boundaries. This was one of the problems that was experienced during the original development of morphological mapping techniques in the UK, by the British Universities Geomorphological Research Group, (later called The British Geomorphological Research Group or BGRG). It was felt that no two people are likely to agree on the exact location of the boundaries of slope elements, (Anon, 1959). Practical field tests were conducted in which an area of 5km x 2km was mapped by three different workers, using approximate ground survey techniques. Peel (1960) reports that: *75% of the detail was perceptibly different- not only in position but even in kind* (ie. different classifications). Other factors contributed to this high percentage but Peel (1960) concludes: *to a significant degree three experienced surveyors produced markedly different interpretations.* Savigear, (1965) contradicts these findings by attributing such differences to inexperience.

The identification of boundaries in the Black Ven case study suggested that problems of the nature reported by Peel (1960) exist. Deciding what was the exact boundary between morphological units was in some cases difficult. This problem was even more apparent when identifying geomorphological boundaries such as the extent of mudslides. These difficulties are reviewed and analysed further in Section 8.3.4.

8.3.2.2 Aspects of Classification

One of the most important advantages of the aerial photograph is that the photographs are capable of being interpreted with specific themes in mind, (Lo, 1976). Different systems of classification will produce very different types of maps, each useful for different purposes. Aerial photographs can be used to create morphological, morphogenetic or morpho- chronological maps (Section 8.3.2) and indeed any type of map which is not necessarily related to geomorphology.

It is difficult to classify digitised features consistently. A boundary may be classified with one code in one area and a different code applied to a continuation of the same feature, in another section of the site. Photogrammetric methods are particularly prone to this problem because magnified photographic images are used for measurement, (Section 8.3.4). Superimposition of measured data within the IMA (Section 6.5) reduces this problem because coordinated features from any epoch are superimposed onto the left-hand photographic image. Another difficulty associated with classification is that several boundaries possess multiple classifications. For example, a mudslide boundary often represents a break of slope. This problem was solved by using a hierarchical system of classification in which geomorphological boundaries took priority over morphological ones. In the example just cited, the boundary would be classified as a mudslide. The variability of classification due to differing operators is discussed in Section 8.3.4.

8.3.3 Recommended Approach to Air Photo-interpretation/Digitisation

If the archival photogrammetric technique is applied to geomorphological studies there are perhaps three stages of air photo-interpretation and digitisation.

8.3.3.1 Examination

Photographs produced from the images that are to be measured, must first undergo a detailed, but overall examination. An attempt must be made to gain understanding and to recognise, interpret and perhaps classify the important boundaries. Major morphological boundaries are the easiest to identify as these are dependent solely upon form, (Section 8.3.1). Monoscopic appraisal is perhaps adequate, although occasional stereoscopic appreciation is useful. The images should not be magnified at this stage.

8.3.3.2 Digitisation/Classification

This requires the use of the final measuring device, either an analytical plotter or a stereo-comparator, (Section 4.1.1). This stage entails the digitisation of the boundaries and features that were recognised in stage one. The IMA used for the Black Ven case study required these data to be classified at the time of digitisation. This is the quickest and most efficient method but can result in mis-classification. The digitisation procedure is comparatively slow and requires concentrated examination of small sections of the site. This often results in the identification of additional features, unrecognised in section 8.3.3.1, but can lead to varying degrees of incompleteness, unless a methodical system is applied. In the case of Black Ven it was found useful to digitise the major morphological boundaries first. Boundaries such as the rear scarp, the Belemnite cliff and sea cliff dominated the whole site and were easy to identify. The second set of features digitised tended to be the morphological features such as gullies, ponds, and perhaps shear planes and tension cracks. The final phase was the most difficult and entailed the digitisation of morphological failures and system boundaries. This required a fuller understanding of process and required interpretation. It was at this stage that it became apparent that different operators may produce different results, (Section 8.3.4.).

8.3.3.3 Editing/Checking

The final stage requires a basic check upon the measured data so that all required areas are evenly represented and classified consistently. If possible, reference should be made to material produced at other epochs, so that classification is consistent between epochs. Some editing will be necessary and is achieved most conveniently using a graphics workstation.

8.3.4 Measurement/Interpretation/Classification Trial

It was apparent that slight differences in interpretation and classification would produce geomorphological maps that were quite different. These problems are minimised if only one person is responsible for the phase of data acquisition, but in commercial environments this is often neither feasible or desirable. The reduction of quality of the final geomorphological maps and other derived parameters (Section 8.4) could be significant and so further tests were arranged in order to assess the extent of this particular problem.

A small area of the Black Ven landslide was delimited and two assistants were asked to identify and classify the features that they perceived using the geomorphological feature table, (Section 6.5.2; Table 6.3). The area selected (Figure 8.3) was approximately 150 x 200 metres in size and contained both a large section of mudslide (Black Ven 1) and the Belemnite cliff. The 1976 vertical photographs (Section 6.2; 6.3.2) were selected because they were of high image quality and produced a model that was comfortable to view.

The two chosen assistants could be positioned at opposite ends of a continuum, based upon photogrammetric and geomorphological knowledge. One was a photogrammetric operator who used the IMA daily, but only understood a limited amount of geomorphology. The other assistant was a geomorphological research student at Kings College, who was studying the mechanics of the Black Ven landslide, but knew little photogrammetry. Both the ´photogrammetrist´ and ´geomorphologist´ were given approximately four hours to digitise the test area, using the IMA and asked to comment upon the task. No help was given to either assistant, although the geomorphologist was provided with two hours instrument tuition because he had not used the instrument previously. A different pair of photographs, unrelated to the Black Ven landslide, was used for this tutorial.

The geomorphological maps that were produced by each operator are illustrated in Figures 8.4, 8.5. The coding system used for boundary classification is discussed in Section 6.5.2, 7.2.1 and illustrated by Table 6.3 and Figures 7.2- 7.6. The geomorphologist made certain modifications to the original classification and these alterations are indicated on Figure 8.5.

The geomorphological maps do appear quite different, in ways that could have been predicted. The data acquired by the photogrammetrist are denser, appear smoother and are more complete than the geomorphologist's map. This is related to the relative experience of using the IMA. Both assistants identified and classified the most important morphological boundaries, although the geomorphologist used the 'greater than 40° slope', (Table 6.3) boundary for all concave breaks of slope. After the test the geomorphologist realised this mistake and had mis-judged vertical exaggeration of the stereomodel. Both workers identified and classified gully features, although the photogrammetrist digitised a greater number.

The boundaries of geomorphological significance produced more diverse results. The photogrammetrist only identified three geomorphological failures, namely three superficial mudslides. These features were more correctly identified by the geomorphologist as sediment accumulation zones, where the fines had been washed out from the chert. The geomorphologist also identified the main mudslide and identified the boundary as non-active. Some shear planes were also symbolised. The photogrammetrist missed all other geomorphological features and spent the remaining period of the test mapping vegetation. The geomorphologist did not have sufficient time to digitise these features.

After the test, each operator was asked to make any comments about the study. The photogrammetrist found difficulties with classifying the boundaries even though it was felt that most had been identified.

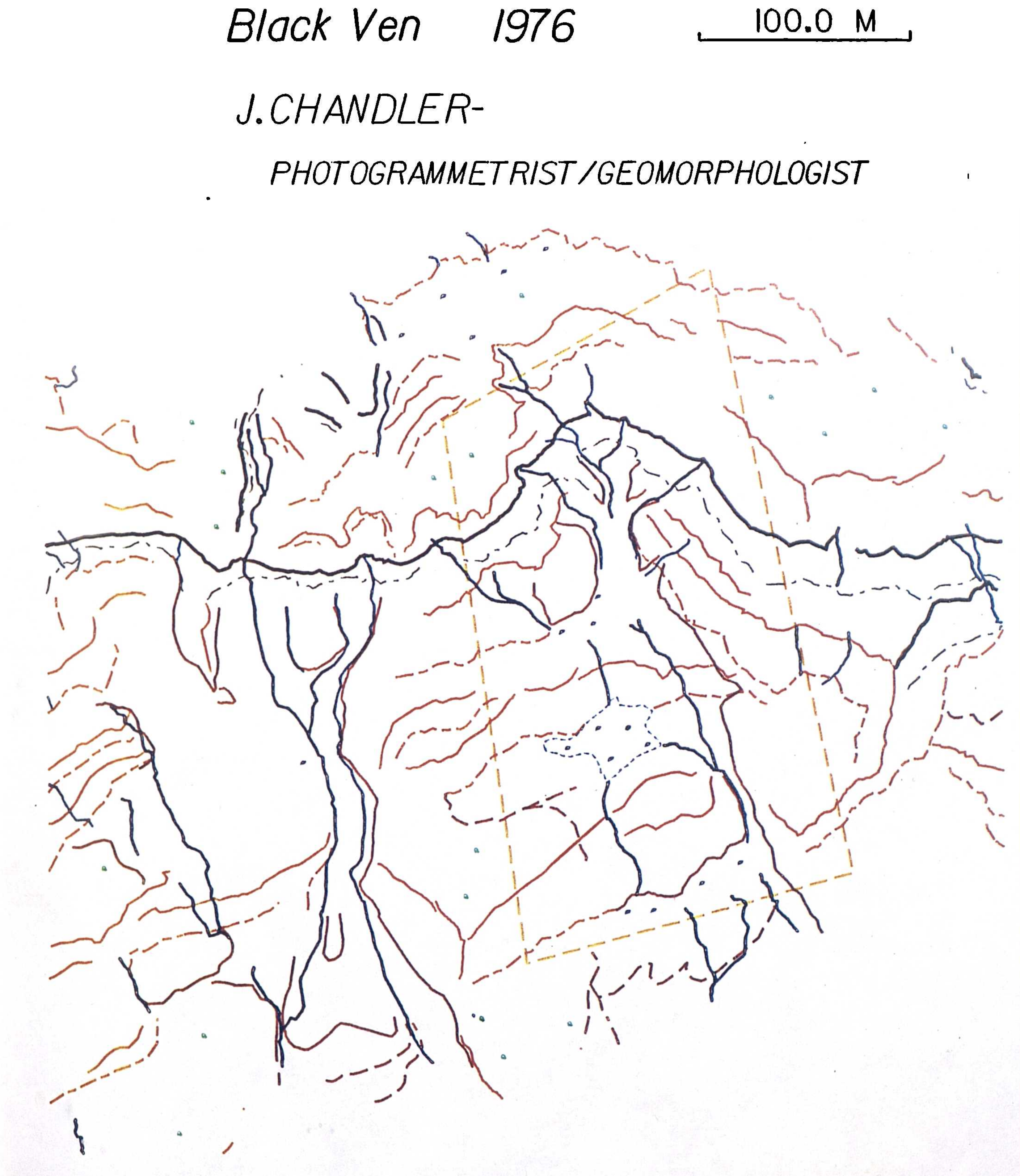

Black Ven 1976
100.0 M
J.CHANDLER-
PHOTOGRAMMETRIST/GEOMORPHOLOGIST

Figure 8.3

Black Ven 1976

100.0 M

JOHN TARLETON PHOTOGRAMMETRIST

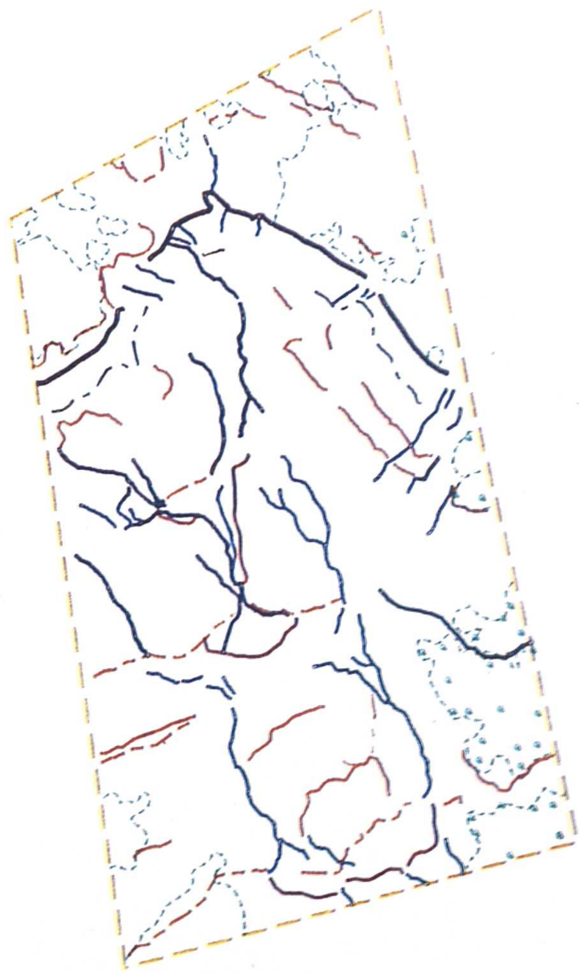
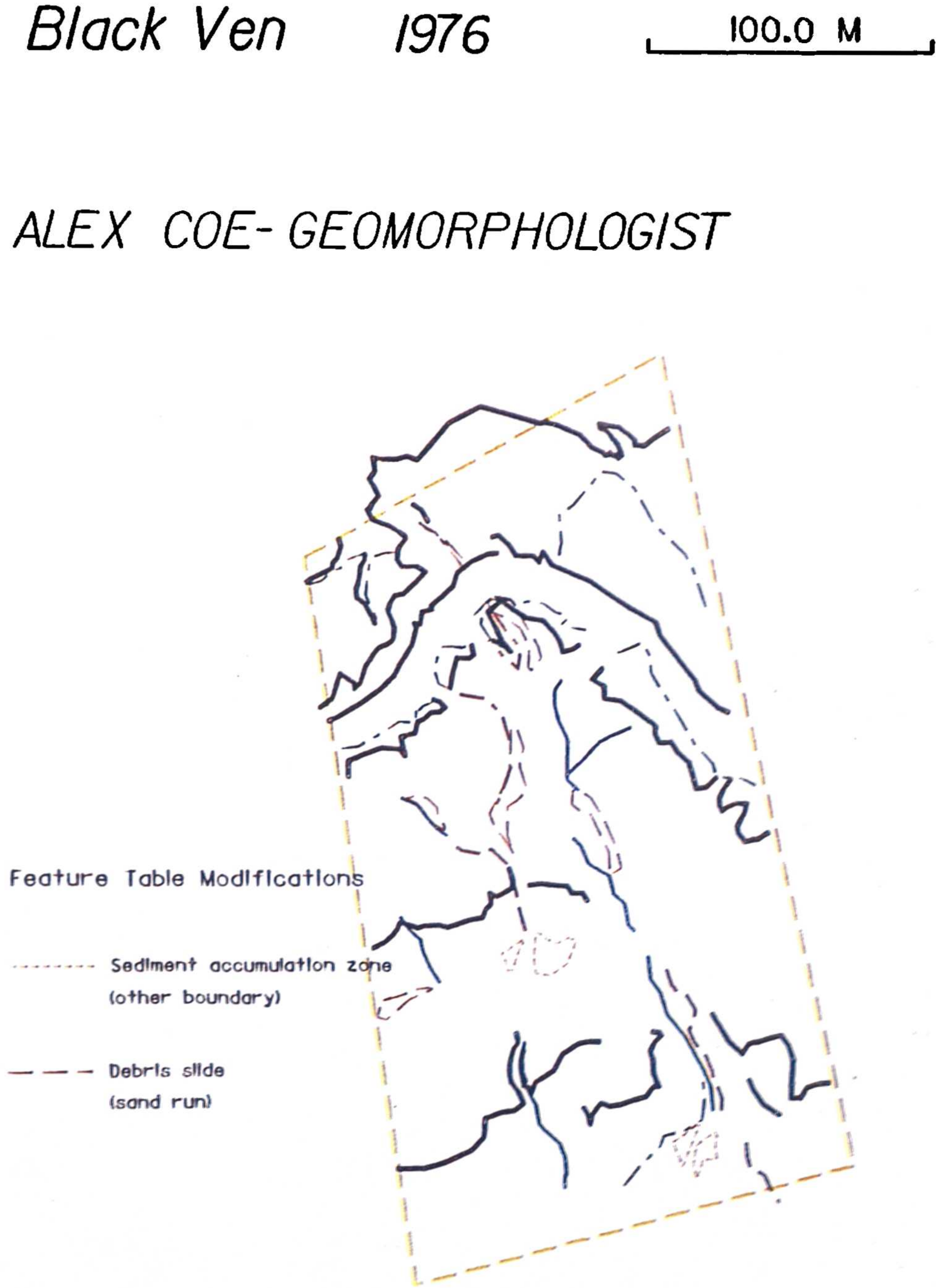


Figure 8.4

+

Black Ven *1976*



+

Figure 8.5

The geomorphologist found that the large scale of the photography was a major problem, particularly relating detail viewed under magnification within context of the whole site. It is thought that this compounded the confusion associated with vertical exaggeration of the stereomodel. It was suggested that a visual examination of standard photographic prints would have been useful, prior to the phase of data acquisition.

If the results are compared with the plan produced by the author, (Figures 8.3; 7.2- 7.6) it is apparent that optimum results are achieved by an operator with an understanding of both photogrammetry and geomorphology. This supports the findings that were deduced from earlier research on Nepalese hillslopes, (Chandler *et al*, 1987) in which photogrammetric techniques were used to monitor slope processes. There are some differences in the classification of some of the geomorphological features, especially those associated with the mudslides. It is recommended that where possible one individual should be responsible for data extraction at all epochs.

8.4 Digital Terrain Modelling

As discussed in Section 7.1; 7.2 (Figure 7.1) the production of geomorphological maps and plans is just one possible form of data output that can be of geomorphological significance, (Section 7.2.1). Most of the advanced data processing techniques used in the archival photogrammetric technique (Section 7.2.3) rely upon digital terrain modelling techniques. The conceptual basis of a digital terrain model (DTM) or a digital elevation model (DEM) is accredited to Miller and Laflamme, (1958). A DTM can be regarded as a statistical representation of the continuous surface of the ground by a large number of selected points with known XYZ coordinates, (Lo, 1976).

The quality of the DTM is an important controlling factor upon the quality of all graphical and statistical data that are derived, using the techniques discussed in Section 7.2.3. There are several factors that control the quality of a DTM.

The XYZ coordinates that are used to represent each terrain point must be of sufficient quality for the purposes of any subsequent analyses. The precision, reliability and accuracy of point co-ordination (Section 8.2.2) controls the quality of coordinated points used to form a DTM. The position of each point possesses stochastic properties which summarise the quality of the point with respect to random, gross and systematic errors, (Section 8.2.1). The stochastic nature of these coordinates should be remembered, although in most packages these properties are ignored.

Another important factor is the number or density of points that are used to form the DTM. Ackermann (1978) reports that there seems to be a simple, in first approximation, linear relationship between contour accuracy and average density of recorded terrain points.

The distribution of terrain points is also an important factor and surprisingly a uniform distribution is not ideal, (Ackermann, 1978). In photogrammetry, the distribution of terrain points depends upon the method of data acquisition. If a regular grid based DTM is acquired then the density must be high enough to portray accurately the smallest terrain features that are required to be modelled. If this is done then the overall density will be too high and will lead to embarrassing and unnecessary data redundancy, (Petrie and Kennie, 1987). This problem has lead to the development of progressive sampling techniques (Makarovic, 1973; 1977) in which the density of the DTM is determined by the topography. An alternative method of data acquisition is to acquire a series of line strings (McCullagh, 1988). These can represent important morphological boundaries or other breaks of slope and provide the positional data necessary for the representation of important areas. A problem arises for regions between line strings, because unless data are acquired for these zones then no information is provided which will reduce the quality of the DTM. The difficulties associated with selection of the exact position of a boundary (Section 8.3.2.1.) is also a problem which will affect the quality of the DTM that is eventually produced.

It was found in the case of Black Ven (Section 7.2.3) that a combination of both types of DTM fulfilled the requirement stated by Ackermann, (1978) that the density of terrain points should be effectively adapted to the terrain features. The coordinates derived for the representation of morphological and geomorphological boundaries depicted all major breaks of slope, whilst the areas between were represented by the regular grid based DTM, (Section 7.2.3).

There are several digital terrain modelling packages available and these use two software approaches: random to grid interpolation and triangulation based methods, (Petrie and Kennie, 1987). The former require the fitting of some form of mathematical surface to the acquired data, using either the whole data set at once or sub-sets of it and then combining. Typical functions include high order polynomials and these vary depending upon the actual package used. Triangulation based packages create a surface using a series of triangles, the vertices of which are defined by the terrain points. Two triangulation routines have been developed, the Delaunay, (Delaunay, 1934) and the radial sweep algorithm, (Mirante and Weingarten, 1982). Each attempt to produce a unique series of triangles that are as equilateral as possible and with minimum side lengths. It was recognised that the triangulation based methods were superior (Mark, 1975) as all data points are honoured and breaks of slope can be readily incorporated into the surface. The approach was not originally favoured as the processing speed was slow and it appeared impossible to generate the same set of triangles from the same set of data, independent of the starting point of the triangulation routine, (McCullagh, 1988). These early problems have now been resolved and a fuller review of the various approaches is given by Petrie and Kennie, (1987) and McCullagh, (1988).

Some DTM packages provide the ability to triangulate the initial data and then to create a grid based DTM from this triangulated surface. This combines the efficiency of data storage provided by a grid based approach with the full honouring of all data points and the inclusion of breaks of slope associated with triangulation. This combination is provided by the Intergraph DTM and ESP packages, (Section 7.2.3; 7.3.5) and Panacea, (McCullagh, 1988).

An awareness of the various processing algorithms is useful when assessing the sensibility of final output. This is particularly true for the more advanced forms of DTM data processing. The selection of the class interval during the derivation of slope angle distribution at each epoch, (Section 7.2.3.4) will alter the appearance of the final graph and requires careful consideration.

8.5 Concluding Remarks

The quality of data that are acquired using the archival photogrammetric technique depends upon a range of factors.

The precision of the photogrammetric restitution depends upon the geometrical arrangement defined by the available photographs and the camera that was originally used; the control data that is available and the instrument used to measure the photo-images. Reliability can be improved by increasing data redundancy and accuracy by selection of the optimum functional model.

Geomorphological factors which affect the overall quality include the air photo-interpretation abilities possessed by the operator and the desired form of data output. Geomorphological maps require a significant degree of geomorphological expertise in order to obtain consistent and reliable maps. The digital terrain modelling techniques require less geomorphological understanding during data acquisition but do require such training for full interpretation. The stochastic nature and the methods that have been used to acquire and process a DTM should always be remembered.

Chapter 9

Conclusion

9. Conclusion

The archival photogrammetric technique enables historical photographs to be measured photogrammetrically and to provide spatial data of known quality. This ability represents an important new development, particularly when applied to geomorphology. The geomorphologists's main problem is that usually there is insufficient time to observe how landscapes evolve, (Paine, 1985; Section 1.2). Using the methods devised in this thesis, the period of time can be extended to the date of the earliest photographs that are available and suitable. Ergodic transformations and other methods of circumventing the geomorphologist's problem are avoided (Section 1.2) and the effects of geomorphological processes can be measured directly and comparably for the same point in space. Other earth scientists, historians, lawyers, planners and engineers will find the technique of value. The small increase in demand for historical photographs will perhaps provide some additional revenue, necessary for the maintenance of UK photographic archives.

9.1 The Technique

The archival photogrammetric technique is based around computerised analytical procedures, primarily a <u>self-calibrating bundle adjustment</u>, (Section 5.2.4). This computational procedure establishes numerically, the relationship between the photographs and a ground coordinate system. The replacement of the analogue stereoplotter with such a mathematical model is flexible and well established, (Ghosh, 1979) but such techniques have not been previously applied to archival photographs. Photo pairs are still required, but these do not have to fulfil the tight rotational and positional requirements demanded by analogue instruments. The only photo requirement is some degree of overlap and a base:distance ratio greater than 1:12.

The whole technique can be sub-divided into several distinct sections, which are carried out sequentially, (Section 5.1, Figure 5.1).

Photo Acquisition- A suitable sequence of contact diapositives must be acquired from one of the archives, (Section 2.3; 5.1.1). Many of these sources are now installing computerised registers, so searches are becoming quicker.

Identification and derivation of Control- Surveyed and coordinated points will generally be unavailable, but control can be scaled from a local large scale plan, (Section 5.1.2). Additional control can be provided by measurements between points. These can include 'natural' measurements, for example; zero height differences between points defining water boundaries. The stochastic properties of all coordinates and measurements should be judged, as the measurements are weighted in the final adjustment. If inter-epoch comparisons are required then a standard datum should be defined, (Section 6.4).

Photo measurement- The image positions of control and pass points are measured using a stereo-comparator, (Section 5.1.3). These measurements must be transformed to a photo-coordinate system and reference points such as corners of the format can be used if suitable fiducial marks are not available. If the corners appear rounded, then an alternative is to apply the 'format side' method, as used by Smith (1987).

Photogrammetric Processing- consists of a suite of four programs, (Section 5.1.4, Figure 5.2). The first program transforms the image coordinates of points from the comparator coordinate system into a photo-coordinate system. This transformation is defined by the comparator coordinates of the fiducial or reference marks, (Section 5.2.1). A coplanarity solution (Section 5.2.2), followed by a three dimensional similarity transformation (Section 5.2.3), is then used to derive object space coordinates for the cameras and all measured points. This step is not essential, but provision of high quality starting values solves an important practical problem associated with the fourth program, the least squares self-calibrating bundle adjustment, (Section 5.2.4). This final program estimates the exterior orientation parameters of the cameras and the coordinates of unknown object points. Elements of interior orientation, which model the internal geometry of the camera, are also estimated. Two groups can be identified:

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

No explicit modelling for film deformation is included for two reasons: it is improbable that calibrated fiducial data are available; also an examination of the effects of ignoring film deformation, (Section 8.2.3.1) suggest that the omission is in practice expedient.

The internal parameters can be included in various combinations, so that inestimable parameters can be dropped if there is high correlation between the internal and external parameters, (Section 5.2.4.4; 8.2.4.3). Other important aspects of the program are the ability to include measurements between points, which enables unconventional control to be included, (Section 6.3.1). The stochastic nature of coordinates and measurements are taken into account and so data of various precision can be used. The self-calibrating bundle adjustment overcomes rigorously many of the problems associated with historical photography.

Data Acquisition- When a satisfactory solution has been obtained, it is possible, using the estimated exterior and interior parameters, to acquire the coordinates of new points anywhere on the site. This procedure can be carried out using a stereo-comparator, but is more effective if an analytical plotter is used, (Section 6.5). The 'InterMap Analytic' analytical plotter, at the City University, allows for two forms of data extraction:

1. Feature Coding- delineation of boundaries, with lines of varying colours, line-types and thicknesses, (Section 6.5.2).
2. DTM collection- extraction of a grid DTM of any size and density.

Each of these programs enables high rates of data extraction, approaching 5,000 points per day.

Data Processing/Presentation and Interpretation- All these data are stored on computer file in a form that can be analysed and processed at a graphics workstation. The basic unit for all photogrammetrically based methods is the coordinate. It is this unit which can be obtained with a density and efficiency which is unobtainable by other techniques. Data extraction is greater, denser and with subsequent data processing, more powerful and flexible.

The coordinate can be used to provide geomorphologists with a variety of graphical and numerical data. These include basic planimetry (Section 7.2.1); direct profiles (Section 7.2.2); DTM data processing (Section 7.2.3); movement vectors, (Section 7.2.4); quantitative evolutionary models (Section 7.3.4) and animated sequences (Section 7.3.5). The DTM data processing options are particularly useful in geomorphological studies. These options rely upon complex algorithms and it is necessary to have access to both a powerful computer and a comprehensive DTM modelling package, (Section 7.2.3).

9.2 Achievements of Research

In the course of carrying out this research programme the following general, photogrammetric and geomorphological achievements have been attained.

1. The various sources of archival photographs of England were identified, classified and an estimate of the total number of archival photographs was made, (Section 2.1). The major organised collections were visited or contacted and assessments made of the type, quantity and age range of the photographs that each kept, (Section 2.3). Such a review should assist users of the archival photogrammetric technique to obtain suitable historical photography.

9.2.1 Photogrammetric

2. The problems that archival photographs present when used for photogrammetric measurement were identified, (Section 4.2). This lead to the recognition that a self-calibrating bundle adjustment would provide a suitable analytical photogrammetric method for the restitution of archival photographs. This procedure, which was originally developed for analytical aerial triangulation, (Brown, 1956; Ackermann *et al.*, 1973; Ebner, 1976) had not previously been used to restitute historical photographs. Furthermore, it was realised that the flexibility provided by an analytical solution could allow all forms of photography to be used, including terrestrial, vertical and oblique aerial photographs. This flexibility would enable a significantly greater proportion of the archive to be of photogrammetric relevance, particularly those oblique collections which were apparently only of qualitative significance (Section 2.3) to the geomorphologist or earth scientist.

3. A self-calibrating bundle adjustment was implemented (Section 5.2.4) and two developments of the functional and stochastic models were found to be essential, if archival photographs were to be used successfully.

First, it was found that the stochastic properties of the control coordinates had to be incorporated into the solution, (Section 5.2.4.3). The only object control coordinates generally available with archival photographs are those derived from a large scale plan. If the precision of these are over-stated then measured photo-coordinates are forced to fit the control data and the photographic measurements are degraded. By assigning appropriate standard deviations to the coordinates of scaled control points this problem can be avoided. This refinement to the stochastic model used within the self-calibrating bundle adjustment allows scaled control points to provide sufficient control data for successful restitution.

Second, correlation between exterior and interior orientation parameters, as described by Granshaw (1980) and El Hassan (1982), was confirmed (Section 8.2.4.3). The self-calibrating bundle adjustment had to be modified so that certain inner orientation parameters could be removed from the functional model, if significant correlation was present, (Section 5.2.4.4).

4. A program to analyse the data derived from the self-calibrating bundle adjustment was written, (Section 8.2.4). This development provided the ability to assess correlation between parameters and to derive various measures of quality associated with the self-calibrating bundle adjustment, (Section 8.2).

5. The low precision inherent with control data derived from a large scale plan, necessitated the development of additional forms of control data. Other less conventional forms of object space information were identified (Section 5.1.2) and applied (Section 6.3.1). These forms of control consist of 'natural' measurements between points which can be incorporated into the self-calibrating bundle adjustment. The most important of these, particularly for coastal sites, was a zero height difference between a series of points positioned on the high water mark, (Section 6.3.1). Another

form of control was a computed height difference between points on the same sedimentary deposit, based upon the known dip and strike of the sediments. These forms of additional control are not essential for restitution but do increase the precision of points coordinated in the object space.

6. The use of two additional pre-processing programs, the coplanarity solution and the 3D similarity transformation, solved an important practical problem associated with least squares estimation procedures such as the bundle adjustment, (Section 5.2.2; 5.2.3). The derivation of high quality starting values for all of the positional parameters ensures convergence of the self-calibrating bundle adjustment, with a minimum number of iterations. The methods can be applied to all forms of bundle adjustment.

7. A detailed re-examination of the functional model used in the self-calibrating bundle adjustment showed that the systematic errors that were ignored, for a variety of reasons, were not significant, (Section 8.2.3). The effects of film deformation cannot be corrected explicitly, but fortuitously appear correlated with the parameters used to model the lens. The effects of a focal plane-shutter can normally be ignored, confirming the findings of Smith, (1987).

8. A sequence of archival photographs was acquired of the test site, dated: 1946, 1948, 1958, 1966, 1969, 1976. The sequence was completed by acquiring personally, oblique aerial photographs using a hand held small format camera, in January and June 1988. The full sequence of photographs represent a wide variety of archival and contemporary photography. The 1946 near vertical photographs are representative of the first photographs that were acquired systematically, of the whole of England and Wales, (Section 2.2; 6.2). The 1948, 1958, 1966 oblique photographs are typical of those acquired with a reconnaissance type camera, (Section 6.2). The 1969 photographs are not conventional vertical photographs, suitable for mapping, because of the

very long camera base. In contrast, the 1976 vertical photographs could be regarded as typical of those acquired for mapping purposes. The 1988 sorties represent a cost effective method of acquiring aerial photographs and spatial data, using the latest camera and film technology. All this photography was restituted successfully using the archival photogrammetric technique. On the basis of these results it would appear that the technique can be applied to a wide range of oblique and vertical archival photographs, provided that certain basic requirements are fulfilled. A minimum of two overlapping photographs are required, with a base:distance ratio greater than 1:12. More photographs are preferable but 100% overlap is not essential.

9.2.2 Geomorphological

9. During application of the technique to a sequence of vertical and oblique aerial photography of the Black Ven case study, dense and comprehensive three dimensional data were acquired. These unique data represent the morphology of the Black Ven landslide in 1946, 1958, 1969, 1976 and 1988.

10. The three dimensional data that were acquired at each epoch was further processed to compile various conventional plots that are original for the Black Ven landslide.

a) Geomorphological maps (Section 7.2.1, Figures 7.2- 7.6) were produced, although an investigation into the quality of interpretation (Section 8.3.4) confirmed the fears of Peel (1960) that morphological mapping is to an extent operator dependant, (Figures 8.3- 8.5). The geomorphological maps were combined to produce a morpho-genetic map (Figure 7.7) which was used to derive estimates of the rate of change of the rear scarp, the Belemnite cliff and the mudslide lobes, (Section 7.3.1, Tables 7.5- 7.8). The mean rate of recession derived for the Belemnite cliff corresponds with that derived for the adjacent Stonebarrow landslide, by Brunsden and Jones (1976, 1980). The rate derived for the rear scarp is significantly greater than that derived on Stonebarrow, (Section 7.3.1).

b) A composite DTM (Section 7.2.3; 8.4) was formed by combining line strings representing morphological boundaries with a grid measured DTM. This yields a high quality surface with a minimum number of measured points and once formed, DTM processing was found to be particularly useful, (Section 7.2.3). Contour plots, isometric views, slope and aspect maps could all be produced and these provide a full description of the morphology of the site, at each epoch.

c) Two vertical profiles were derived at all epochs by both direct photogrammetric measurement (Section 7.2.2, Figures 7.8- 7.10) and by interrogation of a DTM, (Section 7.2.3.2, Figures 7.21, 7.22). The former approach yields a more accurate profile but is slow to measure compared with the DTM derived profile. A DTM profile is useful for the rapid quantitative determination of active areas, (Section 7.2.3.2.).

11. In addition to the conventional forms of graphical output, several additional methods of processing these data were developed and found to be particularly important.

The subtraction of two surfaces at different epochs derived a surface of difference that could be contoured and further processed. These DTM's of difference (Section 7.3.2, Figures 7.23- 7.26) indicate and quantify the most active areas of the site. It was found that the positions of the most active zones varied between epochs and were related to the various cycles of activity associated with the two mudslide systems.

Statistical processing methods were found to be important. Slope angle distributions were evaluated at each epoch and combined to illustrate the change in distribution of slope angle through time, (Section 7.3.3, Figure 7.37). This shows that the morphology of the Black Ven landslide has been stable since 1958, despite rear scarp recession of 94 metres. It is thought that this is the first major quantitative illustration of **dynamic equilibrium**, a landform evolutionary model first proposed by Gilbert (1877) and later revived by Hack (1960),(Section 7.3.3). In a geomorphological sense this illustration is thought by the author to be particularly noteworthy.

Volume calculations were also carried out in an attempt to quantify volumetric changes between units within the two mudslide systems. It was found that unit boundaries changed radically between epochs and so the computed volumes were transformed into mean elevation changes, (Section 7.2.3.6).

Attempts were also made to predict the morphology of the landslide system based upon the changes that have occurred in the past, (Section 7.3.4, Figures 7.38, 7.40, 7.41). This evolutionary model was used to predict two surfaces at different epochs. The first epoch, 1988 was selected so that a comparison could be made between the predicted surface in 1988 with the measured surface. Analysis of the predicted surface revealed that 68.8% of the surface was within ±3.0 metre of the measured surface, (Figure 7.39). The second derived surface represented the form of the Black Ven landslides in the year 2000, (Figure 7.40) and was also compared with the 1988 measured surface, (Figure 7.41).

The framework necessary for the development of a quantitative evolutionary model, based upon simulated geomorphological processes was identified. The crucial role of the archival photogrammetric technique could be to test and refine such models. Realistic trials could be established in which surfaces derived analytically are compared with those derived from archival photographs.

Animated sequences were developed for the Black Ven landslides, including the 1946, 1958, 1969, 1976 and 1988 epochs. These provided a novel method of viewing the evolution of the landslides in which forty two years of process are reduced to three seconds. The method provides fresh insight into the Black Ven landslides and their evolution.

9.3 Possibilities for Future Research

The archival photogrammetric technique should be applied to other case studies for three reasons. First, one of the main problems of the Black Ven case study was the shortage of OS control points, which lead to a problem of datum definition (Section 6.4). Other case studies are likely to possess more identifiable control points, will lead to a more precise solution and allow a fuller analysis of the self-calibrating bundle adjustment. Second, it is apparent that one of the reasons for the success of the technique, is the extreme dynamic nature of the Black Ven landslides analysed in the case study. Dynamic sites are comparatively rare and so for the technique to become accepted it should also be applied successfully to other less active sites. Finally, the patterns and rate of operation of geomorphological processes associated with another site could be compared with those derived from Black Ven. Similarities may become apparent and this would permit greater understanding of geomorphological processes and their inter-relationships.

From a photogrammetric viewpoint it would be useful to examine the effects of altering the functional model used to model the inner orientation of the camera, on the estimated object coordinates. Possible alterations could include removing the displacement of the principal point, or using a different order polynomial to model the lens. Such an examination must be carried out with a variety of photographs which define different geometric relationships between object and photographs. It would be also be useful to examine the correlation between the inner and exterior orientation parameters in greater detail.

Some additions could be made to the self-calibrating bundle adjustment program in order to improve efficiency.

Although the program can accommodate 150 unknown coordinates and up to 20 cameras the time required to form the matrices and to invert the $A^{T}Q^{-1}A$ matrix can become prohibitively long. This practical problem is obviously dependant upon the hardware that is available, but is particularly acute with the IBM PC-AT. There are more efficient routines available, which identify and invert a series of sub-matrices derived from the whole $A^{T}Q^{-1}A$ matrix, (Ghosh, 1979). If this type of algorithm was implemented, processing speed would be increased.

The data that have already been acquired for the Black Ven case study could be further processed and analysed. A quantitative evolutionary model based upon simulated geomorphological processes could be constructed. This would lead to a more reliable predictive model than the one based upon previous changes in form used in Section 7.2.3.7. The model could be tested and refined by applying it to the Black Ven landslide and comparing predicted form with measured form. A smoother animated sequence could be derived by adding additional computed epochs. Ultimately, this animated sequence could be extended into the future, possibly to predict the date of the next massive failure.

Section 10

Appendices

Appendix

10.1.1 The Aerial Photographic Archive of England

Organisation/Address	collections	type	Media	Approx. Numbers
The Central Register of Aerial Photographs of England (CRAPE)				
The Ordnance Survey	National	Vertical	Negatives	1,200,000
Room N1524	1950-todate	1:7,500		
Romsey Rd		1:25,000		
Southampton S09 4DH		1:50,000		
The Royal Commission on the Historical Monuments of England (RCHME)				
Air Photography Unit	'Specialist'	Obliques	Negatives	500,000
Fortress House	1950-todate			
23 Saville Row				
LONDON W1X 1AB	'Crawford'	Obliques	Prints/Negs.	
	prior 1945			
	'RAF'	Verticals	Prints	2,500,000
	1945-1964	1:2,500 -	1:60,000	
	'OS'	Verticals	Prints	500,000
	1952-1984	1:7,500		
	'Meridian'	Verticals	Prints/Negs.	500,000
	1965-	1:2,400 -	1:6,000	
Joint Air Reconnaissance and Interpretation Centre (JARIC)				
RAF Brampton	'National'	Verticals	Negatives	3,000,000
Huntingdon	1948	1:28,000		(unknown)
Cambridgeshire PE18 8QL				
	'National'	Verticals	Negatives	
	1969	1:60,000		
	'National'	Verticals	Negatives	
	1980/1981	1:50,000		
Cambridge University Collection				
The Mond Building	1948- Todate	Obliques	Negatives	400,000
Free School Lane				
Cambridge CB2 3RF				
Ministry of Agriculture Fisheries and Food (MAFF)	1965- Todate	Vertical	Negatives	200,000
Government Building, Block B		1:2,000 -	1:25,000	
Brooklands Ave.				
Cambridge CB2 2DR				

Appendix

Aerofilms Gate Studios Station Rd Boreham Wood HERTS WD6 1EJ	Aerofilms 1919-todate	Obliques	Negatives	500,000
	Huntings 1945-1986	Verticals	Negatives	
Clyde Surveys formerly Fairey Surveys Reform Rd Maidenhead	'Commercial' 1946-todate	Vertical	Negatives	290,000
J.A. Story and Partners 92-94 Church Rd Mitcham Surrey	'Commercial'	Vertical	Negatives (mainly colour)	250,000
Cartographic Services Ltd Landford Manor Salisbury Wiltshire	'Commercial'	Vertical	Negatives	500,000 (unknown)
BKS Surveys Ltd Ballycrain Rd Coleraine BT51 3HZ	'Commercial'	Vertical	Negatives	
Engineering Surveys Ltd West Byfleet Surrey	'Commercial'	Vertical	Negatives	
Airviews (M/C) Ltd Byroe House 27 Ashley Rd Altingham Cheshire WA14 2DP	'Aerial' 1947- todate	Obliques	Negatives	75,000
West Air Photography 23 Cecil Rd Weston-super-Mare Somerset	'Aerial' 1969- todate	Obliques	Negatives	45,000
Chorley and Handford, Wallington Photography House South Park Hill Rd CROYDON CR2 7BY	'Aerial'	Obliques	Negatives	Unknown

10.1.2 Photogrammetric Archives in the UK –Questionnaire

Y|N

1. **DO YOU HOLD ANY PHOTOGRAMMETRIC ARCHIVAL DATA?**
   If NO please go to question 11
   If YES

	UK data	....
	other countries	....

2. **TYPE OF PHYSICAL DATA STORED**

2.1	Photography	metric cameras	....
		" pos	....
		" neg	....
		" B/W	....
		" colour	....
2.2	Photography	non-metric cameras	....
		" pos	....
		" neg	....
		" B/W	....
		" colour	....
2.3	Digital sensed data	on magnetic tape	....
	eg MSS, SPOT etc	on film pos	....
		" neg	....
		" B/W	....
		" colour	....

2.4	Approximate size of Archive	mag tapes	< 100 .
			100 – 500 .
			500 -1000 .
			1000 < .
		rolls of aerial film	< 100 .
			100 – 500 .
			500 -1000 .
			1000 -5000 .
			5000 -10000.
			10000 < .
		sheet/plate film exposures	< 1000.
			1000 – 5000.
			5000 -10000.
			50000 < .

2.5 Do you hold photographic prints for which you have no negatives ?
If YES estimated quantity . ...

2.6 Percentage rate of increase in items per year
- tapes . ...
- film . ...
- prints . ...

3. TYPE OF CAMERA/SENSOR USED TO GENERATE MATERIALS HELD

3.1 Metric aerial camera — focal length
- - 85mm . ¦
- -152mm . ¦
- -210mm . ¦
- -305mm . ¦
- others .

3.2 Metric close range cameras — focal lengths ....

3.3 Non- metric cameras — format size
- 35mm . ¦
- 70mm . ¦
- others .

3.4 Multispectral
- SPOT . ¦
- TM . ¦
- LANDSAT . ¦
- others-specify..................

4. SUPPORTING DATA/MATERIALS HELD

- Camera/Sensor calibration data — full . ¦ / partial . ¦
- Sortie cover data . ¦
- Photo control information . ¦
- Record cards . ¦
- Microfilm/microfiche . ¦
- Seperate computerised records — full . ¦ / partial . ¦

5. DATA MANAGEMENT

5.1 Storage location (items from paras 2-4)
- ad hoc . ¦
- specially designed . ¦

5.2 Information management/retrieval methods
- manual . ¦
- part computerised . ¦
- fully " . ¦

system name (or in-house) ....

If manual only are there any plans to automate? ¦

6. **DO YOU HAVE ANY FACILITIES FOR REPRODUCING YOUR DATA FOR OTHERS?** ¦

7. **CHARGES FOR RESEARCH AND SUPPLY OF INFORMATION AND/OR MATERIALS**

7.1 Information
- no charge . ¦
- search fees . ¦
- other.........

7.2 Materials - prints, films, documents etc
- nominal . ¦
- materials only . ¦
- self financing . ¦
- quantity discounts . ¦
- royalty charges . ¦

8. **DO YOU ADVERTISE YOUR ARCHIVE ?**

If yes how?
- professional journals . ¦
- periodicals . ¦
- newsletters . ¦
- trade literature hand-outs . ¦
- direct mailing . ¦
- others . ¦

9. **STATISTICAL DATA KNOWN ON LEVEL OF USAGE OF DATA**
- in-house only . ¦
- nos of external enquires/year or range . ¦
- nos of items/transactions processed/year . ¦

10 **DO YOU FORWARD DETAILS OF NEWLY ACQUIRED PHOTOGRAPHIC/SENSOR INFORMATION TO A CENTRAL REGISTER ?** . ¦

If NO would you be prepared to do so in the future? . ¦

11 **Any further relevant comments you wish to make ?**

10.1.3 Photogrammetric Archives in the UK - Results

Question	Yes	No	N/R
1. Do you hold any photogrammetric archival data?	53	2	0
UK Data?	51	2	0
Other countries?	16	4	33
2. Type of physical data stored			
2.1 Metric photography?	26	5	22
" positives	35	3	15
" negatives	22	12	19
" B/W	37	3	13
" colour	24	10	19
2.2 Non-metric photography?	15	11	27
" positives	21	11	21
" negatives	17	13	23
" B/W	25	9	19
" colour	16	13	24
2.3 Digital sensed data?			
on magnetic tape	12	21	20
Film positives	12	18	23
" negatives	10	20	23
" B/W	11	19	23
" colour	10	20	23

2.4 Approximate size of archive?	Range	
Magnetic tapes	< 100	11
	100 - 500	2
	500 - 1000	0
	1000 <	3
Rolls of aerial film	< 100	10
	100 - 500	5
	500 - 1000	3
	1000 - 5000	3
	5000 - 10000	3
	10000 <	3
Sheet/plate exposures	< 1000	13
	1000 - 5000	8
	5000 - 10000	3
	10000 <	5

2.5 Do you hold any photographic prints for which you hold no negatives?

Estimate quantity

< 500	6
500 - 1000	2
1000 - 2000	4
2000 - 5000	9
5000 - 10000	9
10000 - 50000	2

2.6 Percentage rate of increase in items per year?

Range	Tapes	Films	Prints
0%	6	5	5
1% - 5%	1	7	8
6% - 10%	1	8	5
11% - 20%	3	0	1
20% <	4	2	1

3. Type of Camera/Sensor used to generate Materials Held

3.1 Focal Length of metric aerial camera

	Yes	No	N/R
85mm	11	22	20
152mm	27	7	19
210mm	7	25	21
305mm	10	25	18
Other	12	23	18

3.2 Format size of non-metric camera

35mm	16	13	24
75mm	17	13	23
Other	10	16	27

3.3 Multi-spectral

SPOT	13	17	25
TM	14	16	25
LANDSAT	16	14	25

4. Supporting data/materials held?

Full camera calibration	14	19	20
Partial " "	8	21	24
Sortie cover data	33	4	16
Photo control information	20	12	21
Record cards	18	15	20
Microfilm/microfiche	5	24	24
Fully computerised records	1	28	24
Partially " "	6	22	25

7. <u>Charges for research and supply of information and/or materials</u>

7.1	Information			
	No charge	35	4	14
	Fees	8	20	25
	Other	2	4	47
7.2	Materials- prints, etc..			
	Nominal	7	13	33
	materials only	7	14	22
	self financing	17	5	31
	quantity discounts	14	6	33
	royalty charges	21	6	26

8. Do you advertise your archive?	Yes	No	N/R
professional journals	7	9	37
periodicals	5	11	37
newsletters	7	11	35
trade literature	12	11	31
direct mailing	6	10	37
others	7	0	45

10. <u>Do you forward details of newly acquired photographic/sensor information to a Central Register?</u>

Currently	16	28	9
Future	24	3	26

Results printed courtesy of the Photogrammetric Society.

10.2 Photogrammetric Processing-Output Files

10.2.1 STEC_CON

File 'pcds' containing photo-coordinates computed from raw comparator measurements.

Photo No.	Pt. Id.	x Photo (mm)	y Photo (mm)	S.E. x (micrometres)	S.E. y (micrometres)	No. of meas.
1	101	-33.6830	48.8412	4.15	11.04	4
1	102	-44.3221	40.2028	6.18	5.02	4
1	103	-53.4629	35.8545	4.50	8.37	4
1	104	-5.8318	42.7514	4.98	5.89	4
1	105	-9.3943	44.9253	4.98	5.75	4
1	106	18.3102	29.7085	4.51	6.10	4
1	110	63.1344	5.5554	4.47	5.85	4
1	201	-50.4495	0.4276	10.00	15.00	2
1	202	-47.6479	-0.4382	10.00	15.00	2
1	212	8.0729	-23.5907	10.00	15.00	2
1	218	54.9253	-34.4302	10.00	15.00	2
1	219	61.3680	-37.1477	10.00	15.00	2
1	301	-14.3605	20.5386	10.00	10.00	2
1	302	-7.4662	18.6395	10.00	15.00	2
1	303	6.3300	13.5138	10.00	15.00	2
1	304	13.5637	11.8568	10.00	15.00	2
2	101	-28.0979	47.8595	4.11	5.69	4
2	102	-40.2152	40.0606	5.27	5.04	4
2	103	-49.7444	36.1947	6.14	6.79	4
2	104	-3.2298	42.4716	4.42	5.10	4
2	105	-6.0018	44.4123	4.98	5.12	4
2	106	16.7301	30.6646	4.69	5.69	4
2	110	55.2274	8.4973	4.43	5.04	4
2	201	-51.1390	4.2846	4.84	5.42	2
2	202	-48.6979	3.4818	10.00	15.00	2
2	212	-1.3769	-17.4318	10.00	15.00	2
2	218	41.5164	-28.0675	10.00	15.00	2
2	219	47.1585	-30.5844	10.00	15.00	2
2	301	-15.5619	22.2772	10.00	15.00	2
2	302	-9.2746	20.5009	10.00	15.00	2
2	303	2.8150	15.8270	10.00	15.00	2
2	304	9.3783	14.2791	10.00	15.00	2

10.2.2 COP

Results of the coplanarity solution, after processing the file 'pcds' above.

The relative Orientation, file **'fcam'**

Camera	B_x	B_y (Metre)	B_z	w	ø (Degrees)	k	focal (c) (mm)
1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	200.00000
2	1.00000	-0.30636	0.50030	0.76319	4.33698	0.65201	200.00000

S. Errors 0.00510 0.00568 0.01851270 0.06207498 0.01733177

model coordinates, file **'fmod'**

Pt. Id.	x_m (Model coordinates)	y_m (Metre)	z_m	rxl (Photo-coordinate residuals)	ryl (microns)	rxl	rxr
101	-2.781205	4.033910	-16.515017	-2.074	-10.213	1.939	9.750
102	-3.027776	2.746746	-13.662923	-1.043	-4.493	0.987	4.240
103	-3.348569	2.245724	-12.526725	-0.106	-0.426	0.101	0.399
104	-0.422865	3.099753	-14.501589	0.175	0.865	-0.165	-0.830
105	-0.715978	3.423549	-15.241970	0.523	2.640	-0.491	-2.536
106	1.073552	1.741474	-11.727692	2.208	10.005	-2.111	-9.605
110	2.890940	0.254964	-9.157571	-3.292	-12.980	3.220	12.501
201	-2.429899	0.020600	-9.633003	-0.033	-0.096	0.033	0.088
202	-2.281711	-0.021143	-9.577153	1.157	3.320	-1.131	-3.070
212	0.317191	-0.925951	-7.854060	-4.233	-11.786	4.183	10.993
218	2.037447	-1.277468	-7.419267	2.175	6.313	-2.171	-5.970
219	2.232378	-1.351377	-7.275437	0.460	1.330	-0.460	-1.259
301	-0.785036	1.122749	-10.933213	0.075	0.285	-0.073	-0.269
302	-0.403913	1.008135	-10.818740	0.705	2.668	-0.682	-2.525
303	0.324898	0.693571	-10.266268	0.575	2.145	-0.559	-2.035
304	0.684998	0.598418	-10.102387	2.594	9.731	-2.524	-9.249
999	0.000000	0.000000	0.000000				
1	0.000000	0.000000	0.000000- Model coordinates of LH camera				
2	1.000000	-0.306357	0.500299- Model coordinates of RH camera				

10.2.3 SIM

The three dimensional similarity transformation produces two output files. The transformation parameters with their associated standard deviations, in file 'fpar'

Omega	Phi (Degrees)	Kappa	Scale Factor (Γ)
-11.96220068	-17.41300270	38.94641946	119.87231893
0.32550151	0.13973863	0.12357533	2.23692473

X_s	Y_s (Metres)	Z_s
5029.901	3393.278	139.375

The transformed model coordinates, now in the object space coordinate system, in file 'fsta'

Pt. Id.	X	Y (Metres)	Z	Index			
101	4561.5000	3595.0000	165.0000	1	1	1	ie 'fixed'
102	4801.5000	3304.0000	135.9000	1	1	1	
103	4876.0000	3164.5000	120.0000	1	1	1	
105	4859.0000	3631.0000	168.0000	1	1	1	
106	5339.0000	3427.0000	151.8000	1	1	1	
110	5736.5000	3317.0000	110.0000	1	1	1	
101	4568.0297	3594.3212	163.0473	0	0	0	ie 'free'
102	4797.3289	3297.4115	134.1689	0	0	0	
103	4868.4555	3161.7158	121.3806	0	0	0	
104	4956.0907	3585.4338	169.3768	0	0	0	
105	4865.1693	3633.8739	171.5465	0	0	0	
106	5337.3687	3432.1674	149.6557	0	0	0	
110	5737.1480	3319.0102	110.9010	0	0	0	
201	5238.0504	2931.6014	2.8768	0	0	0	
202	5256.7455	2937.5596	2.2475	0	0	0	
212	5644.2788	2973.6148	2.6547	0	0	0	
218	5841.1770	3064.4142	1.4001	0	0	0	
219	5871.5098	3065.7128	1.3581	0	0	0	
301	5251.3521	3200.9999	91.6006	0	0	0	
302	5297.5973	3218.6756	87.9631	0	0	0	
303	5413.4354	3221.3511	84.1372	0	0	0	
304	5460.6647	3233.5415	84.4764	0	0	0	

The file 'fcam' with camera parameters in model coordinate system, (Section 10.2.2)

Camera	B_x	B_y (Metre)	B_z	w	ø (Degrees)	k	focal (mm)
1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	200.00000
2	1.00000	-0.30636	0.50030	0.76319	4.33698	0.65201	200.00000
S. Errors		0.00510	0.00568	0.01851270	0.06207498	0.01733177	

appended by the postional elements of the camera parameters, now in the object coordinate system.

	X	Y (Metres)	Z			
1	6147.5360	2290.7341	427.5840	0	0	0
2	6283.4525	2319.6774	425.6838	0	0	0

10.2.4 Self-calibrating Bundle Adjustment- BINFLEXPC

The self-calibrating bundle adjustment produces four principal output files.

The camera parameters are stored in file 'fort.10'

Camera	X	Y	Z	omega	phi	kappa	focal
		(metres)			(degrees)		(mm)
1	6160.6265	2310.2295	397.0665	66.0644	37.3044	21.5309	201.688
2	6291.8806	2338.3214	395.1717	64.9223	41.4804	22.9023	201.688

Int. O.	dXp	dYp	dc	(mm)
	2.5611	0.0000	1.6882	

Int. O.	k1(m-2)	k2(m-4)	k3(m-6)	P1(m-1)	P2(m-1)
	0.5494E+01	-0.2028E+04	0.1902E+06		

File of standard deviations of estimated parameters, file 'fort.11'

Target	X-S.E.	Y-S.E.	Z-S.E.	Index (S.errors)		
101	0.9194	0.8655	0.6369	-1.00	-1.00	0.00
102	1.1211	0.8939	0.0997	0.00	0.00	-0.10
103	0.9450	0.8502	0.3356	-1.00	-1.00	0.00
104	1.4734	1.3249	0.5606	0.00	0.00	0.00
106	0.7930	0.6951	0.3811	-1.00	-1.00	-0.40
110	0.8116	0.8668	0.5548	-1.00	-1.00	0.00
105	1.6703	1.5095	0.6524	0.00	0.00	0.00
202	1.7906	1.3703	0.5995	0.00	0.00	-1.00
212	1.5751	1.5343	0.5985	0.00	0.00	-1.00
218	1.5531	1.3518	0.5729	0.00	0.00	-1.00
219	1.6768	1.5065	0.5774	0.00	0.00	-1.00
301	1.2148	0.8381	0.3321	0.00	0.00	0.00
302	1.1036	0.8342	0.3523	0.00	0.00	0.00
303	1.0025	0.9006	0.4037	0.00	0.00	0.00
304	0.9655	0.9071	0.3955	0.00	0.00	0.00
305	0.9060	0.8803	0.3736	0.00	0.00	0.00
306	0.9432	1.0318	0.4212	0.00	0.00	0.00
307	0.9653	1.0825	0.4807	0.00	0.00	0.00
320	1.4741	0.9749	0.3961	0.00	0.00	0.00
321	1.3523	0.9239	0.3705	0.00	0.00	0.00
322	1.2319	0.8692	0.3452	0.00	0.00	0.00

1	6.5243	6.1742	2.9182	0.2085	0.2859	0.1376
2	7.0166	6.2362	2.9294	0.2230	0.2849	0.1604

1.0796	0.0000	1.6649
0.1904E+01	0.5254E+03	0.5184E+05

Variance factor (Sigma-nought-squared) = 1.0136
(Degrees of Freedom) = 26

File 'fort.8' contains the measurements and their residuals

First the photo-coordinates.

Camera	Target	x-plate (mm)	y-plate (mm)	Std. Errors x (micrometres)	Std. Errors y (micrometres)	(Com. - Obs.) x (micrometres)	(Com. - Obs.) y (micrometres)
1	101	33.683	-48.841	4.150	7.040	-0.255	3.258
1	102	44.322	-40.203	6.180	5.020	4.611	-1.050
1	103	53.463	-35.855	4.500	8.370	-1.468	-1.152
1	104	5.832	-42.751	4.980	5.890	-0.508	-3.519
1	105	9.394	-44.925	4.980	5.750	-0.005	-0.034
1	106	-18.310	-29.709	4.510	6.100	-0.371	4.091
1	110	-63.134	-5.555	4.470	5.850	-0.220	-3.559
1	202	47.648	0.438	5.000	8.000	-0.933	-6.512
1	212	-8.073	23.591	5.000	8.000	0.332	3.594
1	218	-54.925	34.430	5.000	8.000	0.666	1.996
1	219	-61.368	37.148	5.000	8.000	-0.583	-2.372
1	301	14.361	-20.539	5.000	8.000	0.460	-2.531
1	302	7.466	-18.640	5.000	5.000	-1.036	-0.300
1	303	-6.330	-13.514	5.000	8.000	-0.792	-2.785
1	304	-13.564	-11.857	5.000	8.000	1.817	3.719
1	305	-18.951	-11.443	5.000	8.000	-0.795	-0.681
1	306	-33.367	-4.856	5.000	8.000	0.136	1.287
1	307	-42.119	-1.988	5.000	8.000	0.038	0.354
1	320	28.317	-15.783	5.000	8.000	0.046	0.412
1	321	20.912	-15.467	5.000	8.650	0.471	4.994
1	322	15.932	-16.166	5.000	8.000	0.627	5.798
2	101	28.098	-47.859	4.110	5.690	0.245	-2.226
2	102	40.215	-40.061	5.270	5.040	-3.628	1.130
2	103	49.744	-36.195	6.140	6.790	2.948	0.825
2	104	3.230	-42.472	4.420	5.100	0.410	2.750
2	105	6.002	-44.412	4.980	5.120	0.005	0.028
2	106	-16.730	-30.665	4.690	5.690	0.555	-3.703
2	110	-55.227	-8.497	4.430	5.040	0.175	2.740
2	202	48.698	-3.482	5.000	8.000	1.050	6.934
2	212	1.377	17.432	5.000	8.000	-0.388	-3.949
2	218	-41.516	28.067	5.000	8.000	-0.693	-1.750
2	219	-47.159	30.584	5.000	8.000	0.615	2.256
2	301	15.562	-22.277	5.000	8.000	-0.457	3.365
2	302	9.275	-20.501	5.000	8.000	1.061	-0.118
2	303	-2.815	-15.827	5.000	8.000	0.820	2.432
2	304	-9.378	-14.279	5.000	8.000	-1.853	-2.473
2	305	-14.701	-13.812	5.000	8.000	0.800	-0.012
2	306	-26.600	-7.937	5.000	8.000	-0.146	-1.346
2	307	-34.309	-5.328	5.000	8.000	-0.040	-0.369
2	320	29.255	-18.013	5.000	8.000	-0.051	-0.437
2	321	22.288	-17.650	5.000	8.000	-0.514	-4.518
2	322	17.230	-18.172	5.000	8.000	-0.680	-6.116

Followed by the measurements between points.

Index	Points			Measurement (Metre)	S.Error (mm)	Ht. Inst. (m)	Tgt. Ht. (m)	Residual (mm)
-1	101	102	0	378.000	1500.000	0.000	0.000	-2157.3837
-1	101	103	0	535.800	1500.000	0.000	0.000	2157.8985
-1	110	106	0	414.000	1000.000	0.000	0.000	576.0423
1	218	219	0	0.000	300.000	0.000	0.000	88.2645
1	301	302	0	-1.582	1000.000	0.000	0.000	1644.3270
1	302	303	0	-4.595	1000.000	0.000	0.000	-576.7829
1	303	304	0	-1.650	1000.000	0.000	0.000	-1829.2060
1	304	305	0	-0.258	1000.000	0.000	0.000	1867.5844

Finally, the control coordinates

Pt.	Coordinate (m)	S.Error (m)	Residual (m)
101	4561.5000	1.0000	0.1570
101	3595.0000	1.0000	-0.0005
102	135.9000	0.1000	-0.0012
103	4876.0000	1.0000	-0.1277
103	3164.5000	1.0000	0.4107
106	5339.0000	1.0000	0.2431
106	3427.0000	1.0000	-1.1137
106	151.8000	0.4000	-0.0029
110	5736.5000	1.0000	-0.2724
110	3317.0000	1.0000	0.7035
202	1.0000	1.0000	0.0804
212	1.0000	1.0000	0.4461
218	0.5000	1.0000	-0.2365
219	0.5000	1.0000	-0.1482

File 'fort.9' contains the estimated coordinates of all points

Target	X	Y (Metres)	Z	Index (S.errors)		
101	4561.3430	3595.0005	170.4096	-1.00	-1.00	0.00
102	4800.2987	3299.3321	135.9012	0.00	0.00	-0.10
103	4876.1277	3164.0893	121.1960	-1.00	-1.00	0.00
104	4956.2998	3580.1252	175.1941	0.00	0.00	0.00
106	5338.7569	3428.1137	151.8029	-1.00	-1.00	-0.40
110	5736.7724	3316.2965	110.8675	-1.00	-1.00	0.00
105	4864.0709	3628.6539	178.5095	0.00	0.00	0.00
202	5270.7827	2944.2692	0.9196	0.00	0.00	-1.00
212	5651.2381	2979.3514	0.5539	0.00	0.00	-1.00
218	5843.4488	3067.0303	0.7365	0.00	0.00	-1.00
219	5873.4487	3068.1551	0.6482	0.00	0.00	-1.00
301	5259.1707	3200.7833	91.9492	0.00	0.00	0.00
302	5304.7242	3217.8564	88.7228	0.00	0.00	0.00
303	5419.2750	3220.4111	84.7046	0.00	0.00	0.00
304	5465.3614	3232.7898	84.8838	0.00	0.00	0.00
305	5482.6819	3263.1798	82.7582	0.00	0.00	0.00
306	5611.1308	3224.1037	85.3138	0.00	0.00	0.00
307	5666.7780	3223.1531	85.8601	0.00	0.00	0.00
320	5240.1299	3103.7471	67.3256	0.00	0.00	0.00
321	5268.9514	3138.3087	68.4682	0.00	0.00	0.00
322	5268.0226	3181.2469	67.5966	0.00	0.00	0.00

10.2.5 Sedimentary Points

Index	Points			Measurement (Metre)	S.Error (mm)	Ht.Inst/Tgt. (m)		Nature	Height Diff. (metre)
1	301	302	0	-1.582	1000.0	0.0	0.0	Sediments	-3.274
1	302	303	0	-4.595	1000.0	0.0	0.0	Sediments	-4.078
1	303	304	0	-1.650	1000.0	0.0	0.0	Sediments	0.106
1	304	305	0	-0.258	1000.0	0.0	0.0	Sediments	-1.795

10.3 Bundle Analysis

10.3.1 Standard Errors of the Estimated Measurements

Cam.	Target	S.Err. (meas) x (micrometres)	S.Err. (meas) y	(Com. - Obs.) x (micrometres)	(Com. - Obs.) y	S.Err.(Estimated meas.) x (micrometres)	S.Err.(Estimated meas.) y
1	101	4.15	7.04	-0.19	3.24	4.09	6.14
1	102	6.18	5.02	4.70	-1.05	5.62	4.21
1	103	4.50	8.37	-1.35	-1.17	4.35	6.38
1	104	4.98	5.89	-0.50	-3.45	4.95	4.67
1	105	4.98	5.75	0.00	0.02	4.95	4.66
1	106	4.51	6.10	-0.35	4.19	4.43	5.06
1	110	4.47	5.85	-0.32	-3.46	4.46	5.43
1	202	5.00	8.00	-0.88	-6.45	4.95	6.96
1	212	5.00	8.00	0.37	3.66	4.96	7.09
1	218	5.00	8.00	0.60	2.16	4.91	6.99
1	219	5.00	8.00	-0.67	-2.19	4.92	7.02
1	301	5.00	8.00	0.47	-2.45	4.95	6.10
1	302	5.00	5.00	-1.03	-0.20	4.92	4.40
1	303	5.00	8.00	-0.78	-2.69	4.94	6.03
1	304	5.00	8.00	1.84	3.82	4.94	6.13
1	305	5.00	8.00	-0.76	-0.58	4.96	6.20
1	306	5.00	8.00	0.17	1.37	4.98	6.62
1	307	5.00	8.00	0.06	0.44	4.98	6.56
1	320	5.00	8.00	0.04	0.49	4.97	6.21
1	321	5.00	8.65	0.47	5.08	4.97	6.39
1	322	5.00	8.00	0.62	5.89	4.97	6.05
2	101	4.11	5.69	0.20	-2.11	4.03	5.18
2	102	5.27	5.04	-3.66	1.25	4.87	4.10
2	103	6.14	6.79	2.95	0.93	5.66	5.63
2	104	4.42	5.10	0.32	2.92	4.40	4.26
2	105	4.98	5.12	-0.08	0.19	4.95	4.30
2	106	4.69	5.69	0.48	-3.52	4.58	4.77
2	110	4.43	5.04	0.01	2.90	4.41	4.76
2	202	5.00	8.00	1.00	7.10	4.94	6.79
2	212	5.00	8.00	-0.47	-3.79	4.95	6.98
2	218	5.00	8.00	-0.81	-1.56	4.90	7.06
2	219	5.00	8.00	0.46	2.48	4.91	7.08
2	301	5.00	8.00	-0.55	3.55	4.95	5.84
2	302	5.00	8.00	0.97	0.08	4.91	4.77
2	303	5.00	8.00	0.73	2.62	4.93	5.79
2	304	5.00	8.00	-1.93	-2.28	4.94	5.90
2	305	5.00	8.00	0.73	0.18	4.95	5.99
2	306	5.00	8.00	-0.22	-1.18	4.97	6.48

2	307	5.00	8.00	-0.11	-0.20	4.97	6.41
2	320	5.00	8.00	-0.15	-0.25	4.96	5.95
2	321	5.00	8.00	-0.61	-4.33	4.96	6.02
2	322	5.00	8.00	-0.78	-5.93	4.96	5.79

Type	From	At	To	S.Err(Meas) (mm)	Resid. (mm)	S.Err(Estimated) (mm)
-1	101	102	0	1500.000	-2157.374	1056.957
-1	101	103	0	1500.000	2157.920	914.985
-1	110	106	0	1000.000	575.975	807.250
1	218	219	0	300.000	88.300	273.061
1	301	302	0	1000.000	1644.400	196.270
1	302	303	0	1000.000	-576.800	197.172
1	303	304	0	1000.000	-1829.200	176.569
1	304	305	0	1000.000	1867.600	187.994

Target	S.Err(Meas) (Metre)	Resid. (Metre)	S.Err(Estimated) (Metre)
101	1.00	0.16	0.92
101	1.00	0.00	0.87
102	0.10	0.00	0.10
103	1.00	-0.13	0.95
103	1.00	0.41	0.85
106	1.00	0.24	0.79
106	1.00	-1.11	0.70
106	0.40	0.00	0.38
110	1.00	-0.27	0.81
110	1.00	0.70	0.87
202	1.00	0.08	0.60
212	1.00	0.45	0.60
218	1.00	-0.24	0.57
219	1.00	-0.15	0.58

10.3.2 Data Snooping

At the 5% level of significance, Test statistic = 1.960

Cam.	Target	X	Flag	Y	Flag
1	101	0.26		-0.94	
1	102	-1.83		0.39	
1	103	1.16		0.22	
1	104	0.97		0.96	
1	105	0.00		-0.01	
1	106	0.42		-1.23	
1	110	0.93		1.60	
1	202	1.28		1.64	
1	212	-0.60		-0.99	
1	218	-0.65		-0.56	
1	219	0.75		0.57	
1	301	-0.67		0.47	
1	302	1.17		0.08	
1	303	0.99		0.51	
1	304	-2.40	*	-0.74	
1	305	1.17		0.11	
1	306	-0.36		-0.31	

1	307	-0.12		-0.10
1	320	-0.08		-0.10
1	321	-0.86		-0.87
1	322	-1.10		-1.12
2	101	-0.25		0.90
2	102	1.82		-0.43
2	103	-1.23		-0.25
2	104	-0.77		-1.04
2	105	0.16		-0.07
2	106	-0.47		1.13
2	110	-0.03		-1.75
2	202	-1.31		-1.68
2	212	0.68		0.97
2	218	0.83		0.41
2	219	-0.48		-0.67
2	301	0.75		-0.65
2	302	-1.05		-0.01
2	303	-0.89		-0.47
2	304	2.42	*	0.42
2	305	-1.08		-0.03
2	306	0.42		0.25
2	307	0.21		0.04
2	320	0.24		0.05
2	321	1.03		0.82
2	322	1.28		1.07

Type	From	At	To	Test Statistic	Flag
-1	101	102	0	-2.03	*
-1	101	103	0	1.82	
-1	110	106	0	0.98	
1	218	219	0	0.71	
1	301	302	0	1.68	
1	302	303	0	-0.59	
1	303	304	0	-1.86	
1	304	305	0	1.90	

Target	Test Statistic	Flag
101	0.40	
101	0.00	
102	-0.15	
103	-0.39	
103	0.78	
106	0.40	
106	-1.55	
106	-0.02	
110	-0.47	
110	1.41	
202	0.10	
212	0.56	
218	-0.29	
219	-0.18	

10.3.3 Reliability

At the 5% level of significance (α)= 1.96
Power of test of 0.9, then ($1-\beta$)= 1.28

Target Cam.		X- Plate Tau Factor	Test Stat.	Roe	Y- Plate Tau Factor	Test Stat.	Roe
1	101	5.86	78.96	0.99	2.04	46.65	0.87
1	102	2.40	48.19	0.91	1.83	29.87	0.84
1	103	3.88	56.64	0.97	1.54	41.92	0.76
1	104	9.59	154.97	0.99	1.64	31.31	0.79
1	105	9.93	160.52	0.99	1.71	31.82	0.81
1	106	5.39	78.92	0.98	1.79	35.41	0.83
1	110	13.11	190.22	1.00	2.70	51.18	0.93
1	202	7.24	117.45	0.99	2.03	52.70	0.87
1	212	8.00	129.79	0.99	2.16	56.12	0.89
1	218	5.42	88.00	0.98	2.06	53.42	0.87
1	219	5.57	90.40	0.98	2.08	54.02	0.88
1	301	7.20	116.81	0.99	1.55	40.12	0.76
1	302	5.69	92.29	0.98	2.10	34.09	0.88
1	303	6.33	102.63	0.99	1.52	39.55	0.75
1	304	6.51	105.58	0.99	1.56	40.41	0.77
1	305	7.73	125.40	0.99	1.58	41.04	0.77
1	306	10.51	170.45	1.00	1.78	46.29	0.83
1	307	10.25	166.37	1.00	1.75	45.36	0.82
1	320	8.83	143.23	0.99	1.59	41.17	0.78
1	321	9.09	147.41	0.99	1.48	41.66	0.74
1	322	8.82	143.15	0.99	1.53	39.66	0.76
2	101	5.19	69.21	0.98	2.41	44.52	0.91
2	102	2.62	44.76	0.92	1.72	28.15	0.81
2	103	2.57	51.19	0.92	1.79	39.40	0.83
2	104	10.56	151.46	1.00	1.82	30.04	0.83
2	105	9.74	157.36	0.99	1.84	30.54	0.84
2	106	4.65	70.70	0.98	1.83	33.79	0.84
2	110	11.91	171.19	1.00	3.03	49.53	0.94
2	202	6.56	106.44	0.99	1.89	49.13	0.85
2	212	7.29	118.21	0.99	2.04	53.08	0.87
2	218	5.13	83.31	0.98	2.12	55.13	0.88
2	219	5.27	85.57	0.98	2.15	55.81	0.89
2	301	6.82	110.58	0.99	1.46	38.00	0.73
2	302	5.42	87.98	0.98	1.25	32.34	0.60
2	303	6.06	98.39	0.99	1.45	37.59	0.72
2	304	6.26	101.55	0.99	1.48	38.47	0.74
2	305	7.39	119.92	0.99	1.51	39.13	0.75
2	306	9.80	159.01	0.99	1.71	44.27	0.81
2	307	9.57	155.29	0.99	1.67	43.45	0.80
2	320	8.07	130.88	0.99	1.50	38.82	0.74
2	321	8.34	135.32	0.99	1.52	39.38	0.75
2	322	8.14	132.09	0.99	1.45	37.60	0.72

Type	From	At	To	Tau Factor	Test Stat.	Roe
-1	101	102	0	1.41	6.86	0.70
-1	101	103	0	1.26	6.14	0.61
-1	110	106	0	1.69	5.50	0.81
1	218	219	0	2.41	2.35	0.91
1	301	302	0	1.02	3.31	0.20

1	302	303	0	1.02	3.31	0.20
1	303	304	0	1.02	3.30	0.18
1	304	305	0	1.02	3.30	0.19

Target	Tau Factor	Test Stat.	Roe
101	2.54	8.25	0.92
101	2.00	6.48	0.87
102	12.67	4.11	1.00
103	3.06	9.92	0.95
103	1.90	6.16	0.85
106	1.64	5.33	0.79
106	1.39	4.51	0.70
106	3.29	4.28	0.95
110	1.71	5.55	0.81
110	2.01	6.51	0.87
202	1.25	4.05	0.60
212	1.25	4.05	0.60
218	1.22	3.96	0.57
219	1.22	3.97	0.58

Global test on Internal Reliability

r should equal $\Sigma\ 1/\tau_i^2$

where:
r redundancy number;
τ_i tau factor associated with measurement i.

$r = 26$ $\qquad \Sigma\ 1/\tau_i^2 = 25.98$

10.3.4 Correlation between Parameter x and Parameter(s) y

Init.	Param. x	S.Err		Param(s). y	S.Err	Correlation Coefficient
67	66.064	0.0036				
			76	2.561	0.0011	0.6895
			77	0.000	0.0017	0.3233
			78	5.494	1.9041	-.0399
			79	-2028.000	5.25E+02	0.0470
			80	190200.000	5.18E+04	-.0627

11. Glossary

11.1 Photogrammetric

Aerial triangulation- The process for the extension of horizontal and/or vertical control whereby the measurements of angles and/or distances on overlapping photographs are related in spatial solution using the perspective principles of the photographs, (Slama, 1980).

Anaglyph- A stereogram in which the two views are printed or projected superimposed in complementary colours, usually red or green. By viewing through filter spectacles of corresponding colours, a stereoscopic image is formed. (Slama, 1980).

Analytical plotter- a photogrammetric plotting system which solves mathematically the relationship between photographic image coordinates measured in the two dimensional photographic reference system and the ground coordinate system, (Slama, 1980).

Bundle adjustment- The bundle adjustment estimates the exterior orientation parameters of the cameras as a result of one simultaneous least squares solution of all photographs. (Ghosh, 1979). Such an adjustment can combine photogrammetric bundles and additional geodetic information such as object coordinates, distances, height differences and directions, (Kotowski et al, 1988).

Calibration- The act or process of determining certain specific measurements in a camera. Such a calibration is used in correcting or compensating for such errors, or for purposes of record. In close-range photogrammetry, calibration may be performed directly, (laboratory) or indirectly ('on the job' or self-calibration), (Slama, 1980).

Camera lucida- A monocular instrument using a half-silvered mirror, which permits superimposition of a virtual image of an object onto a plane, (Slama, 1980).

Close-range photogrammetry- A branch of photogrammetry wherein object-to-camera distances are not more than 300 metres, (Slama, 1980).

Collinearity- The basic projective transformation describing the relationship between two mutually associated three-dimensional systems of coordinates, (Ghosh, 1979).

Comparator- An optical instrument, usually precise, for measuring rectangular or polar coordinates of points on any plane surface, such as a photographic plate, (Slama, 1980).

Control- A system of points with established positions or elevations, or both, which are used as fixed references in positioning and correlating map features, (Slama, 1980).

Coplanarity- The condition of exposure of a pair of photographs in which any object point, the two perspective centres and the corresponding image points on the two photographs all lie in a common plane, (Ghosh, 1979).

Degrees of freedom- Term used in least squares estimation procedures and is equivalent to 'redundancy'. Defined by:

$$r = m - n$$

where:

- m is the number of distinct elements necessary to define the mathematical model uniquely.
- n the number of measurements, (Cooper, 1987).

Diapositive- A positive photograph on a transparent medium, usually polyester or glass, (Slama, 1980).

Exterior orientation- The position of the camera station and the attitude of the taking camera at the instant of exposure, (Slama, 1980).

Fiducial axes- The lines joining opposite fiducial marks on a photograph, (Slama, 1980).

Fiducial marks- Index marks which are rigidly connected with the camera lens which form images on the negative and usually define the principal point of the photographs, (Slama, 1980).

Focal Plane- The plane perpendicular to the axis of the lens, in which images of points in the object field are focused, (Slama, 1980).

Functional model- set of equations expressing the relationships between elements in abstract space. These elements consist of measurements and parameters that require estimation, (Cooper, 1987).

Inner orientation- The determining of the interior perspective of the photograph at the instant of exposure. Elements of interior orientation are the calibrated focal length, location of the principal point, and the calibrated lens distortion, (Slama, 1980).

Least squares- a series of algorithms for transforming observed data and their covariance matrix into derived data and their covariance matrix, (Cooper, 1987).

Metric camera- A camera whose interior orientation is known, stable and reproducible, (Slama, 1980).

Non-metric camera- A camera whose interior orientation is completely or partially unknown and frequently unstable (Slama, 1980).

Parallax- The apparent displacement of the position of a body, with respect to a reference point or system, caused by a shift in the point of observation, (Slama, 1980).

Perspective centre- The point of origin or termination of bundles of perspective rays, (Slama, 1980).

Photogrammetry- the art, science and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring and interpreting photographic images and patterns of electro-magnetic radiant energy and other phenomena', (Slama, 1980).

Photo-mosaic- An assembly of aerial photographs whose edges usually have been torn, or cut, and matched to form a continuous photographic representation of portions of the earth's surface, (Slama, 1980)

Principal point- The foot of the perpendicular from the interior perspective centre to the plane of the photograph, (Slama, 1980).

Projection- Mathematical functions used to transform ellipsoidal coordinates into plane rectangular coordinates. The Transverse mercator projection is a series of formulae are used by the Ordnance Survey for defining the national grid.

Redundancy- See 'degrees of freedom'.

Relative orientation- The determining of the position and attitude of one of a pair of photographs with respect to the other photograph, (Slama, 1980).

Resection- The determination of the position and attitude of a camera, with respect to the exterior coordinate system, (Slama, 1980).

Residual error- The difference between any value or quantity in a series of observations, (corrected for known systematic errors) and the quantity obtained from the combination or adjustment of that series. Also called residuals, (Slama, 1980).

Restitution- The determination of the true position of objects or points; the image of which appears distorted or displaced on aerial photographs. Restitution corrects for distortions resulting from both relief and tilt displacement, (Slama, 1980).

Rigorous- making the validity of the successive steps completely explicit, (Hanks, 1986). In association with least squares estimation procedures, the term is used to describe the completeness of the stochastic model and the adequacy of the functional model used for restitution.

Standard deviation- Measure of the precision of a single observation or a derived parameter. Its square is termed the variance.

Stereomodel- The three dimensional model formed by the intersecting homologous rays of an overlapping pair of photographs, (Slama, 1980).

Stereopair- Two photographs of the same area taken from different camera stations so as to afford stereoscopic viewing, (Slama, 1980). In this thesis a distinction is made between a conventional stereopair and a stereoplet. The former refers to a stereopair which was originally acquired for stereoscopic viewing/measurement. A stereoplet refers to a pair of photographs that were not acquired specifically for stereoscopic viewing but can be used in this way.

Stereoplotter- An instrument for plotting a map or obtaining spatial solutions by observation of a stereoscopic models formed by stereopairs of photographs, (Slama, 1980).

Stereo-viewer- An optical system designed to allow the perception of a stereomodel when a stereopair of photographs is viewed, (Slama, 1980).

Stochastic model- The statistical properties of the measured elements, (Cooper, 1987).

Subtense measurement- A ground survey technique used to establish the horizontal distance between two points. The technique is based upon the measurement of the horizontal angle subtended by a short base of known length, commonly a two metre 'subtense bar.'

Systematic error- An error arising from the inability to mathematically correct for a particular physical effect, (Slama, 1980).

Terrestrial photograph- A photograph taken by a camera located on the ground, (Slama, 1980).

Three dimensional similarity transformation- Transformation from one coordinate system to another in which shape remains constant but position, scale and rotation can all alter. Also known as a conformal transformation.

11.2 Geomorphological

Accumulation zone- area in receipt of sediment from any transportation process. In the context of mudslides the zone consists of single or overlapping lobes of debris, delivered from mudslide tracks, (Brunsden, 1984).

Active area- region of mudslide which is currently experiencing movement.

Aggradation slope- The building upwards of a slope by accumulation of material by various geomorphological agencies, (Goudie, 1985)

Best Units analysis- The method used for slope profile examination whereby the profile is divided into segments and elements such that the respective coefficients of variation of slope angle do not exceed specified values, (Goudie, 1985)

Boulder arc- A curved line of boulders deposited by an advancing mudslide lobe. The boulders remain for long periods because they are too large to be transported by marine processes.

Catchment- source region of a mudslide system, (See 'Source region').

Cohesion- The attraction of particles to each other (usually clay minerals in soils) which is not governed by a friction law (ie. it is independent of stress) but does provide a measure of the strength of the material. (Goudie, 1985)

Compressive ridge- The surface expression of an area of a mudslide which has experienced compressive flow.

Ergodic transformation- Ergodic theory was originally developed to provide a firm theoretical link between statistical and exact mechanics, but has since been applied to geomorphology. The unifying principle of ergodic reasoning is that the ensemble average is quantitatively substituted for the time average. In geomorphology the 'ensembles' are replaced by sets of spatial points or areas. For example: consider a region in which there are a variety of different types of river reach, of which 3% have a sinuosity of 1.2. If ergodic conditions apply, it can be predicted that the average river in the region will have that sinuosity for 3% of its lifetime, (Paine, 1985). See also 'location-for-time substitution.'

Erosion pin- A large pin inserted into the ground surface and used to gauge the changes of position of the ground surface by physical measurement. The technique has been used widely to monitor the movement of soil on slopes, particulary through surface wash processes.

Gabion- A wire framed box filled with large boulders. Gabions are used to build retaining walls where movement is expected because small displacements can be accommodated.

Geomorphological processes- The mechanical methods by which material erodes, weathers, is transported and deposited.

Geomorphological map- A generalised term covering a wide variety of special purpose maps used in geomorphology and environmental management. Require varying degrees of interpretation for their compilation.

Landslide- The movement down-slope under the influence of gravity of a mass of rock or earth, (Goudie, 1985)

Lobe- See 'Accumulation zone'

Location-for-time Substitution/ Space-time analogue- In geomorphology many so called 'space-for-time' substitutions have been employed, which are not strictly ergodic, (See 'Ergodic transformation'). Unless space is quantitatively substituted for time using a frequency distribution, then the terms 'location-for-time substitution' or a 'space-time analogue' are preferable.

Morphology- The shape of the ground surface

Morphological map- displays only the shape or morphology of the ground surface, with breaks of slope and gradients indicated, (Goudie, 1985). No subjective interpretation is required to compile such a map.

Morpho-chronological map- distinguish between landform according to their time of initiation, (Cooke and Doornkamp, 1974)

Morpho-dynamic map- indicate the nature and extent of surface movement.

Morpho-genetic map- defines the origin and development of landform. Form and material composition should also be shown because of the close link with processes, (Cooke and Doornkamp, 1974)

Morpho-metric map- supplies information about the dimensions of landform. Morphometric information includes data on such things as slope steepness and shape, (Cooke and Doornkamp, 1974)

Mudslide- a form of mass movement in which masses of softened argillaceous, silty or very fine sandy debris advance chiefly by sliding on discrete boundary shear surfaces in relatively slow moving, lobate or elongate forms, (Brunsden, 1984).

Pore pressure- The pressure exerted by water in pores of a soil or other sediment. Pressure is positive when below the water table and negative when above it, (Goudie, 1985)

Rills- A small channel that changes location with every runoff and that can be obliterated easily, (Goudie, 1985).

Rotational failure- The name given to failure, normally in clays although also in weak rocks, where the shape of the slip surface, which forms the boundary between the stable ground and the mass which has moved, is curved, (Goudie, 1985)

Shear plane- the boundary between stable ground and a mass of material which has moved by mass movement.

Slope stability analyses- The procedure for examining the likelihood of failure of a soil or rock slope. Generally requires knowledge of the cohesion and friction properties of the slope material and slope geometry, (Goudie, 1985)

Source region- In the context of mudslides the term refers to the location where a mudslide originates. It consists of failure scars, disturbed slumps, rotational slips or translational failures, debris slopes and complex depositional areas of softened, weathered and fissured debris with confused groundwater distributions, (Brunsden, 1984).

Space-time analogue- See 'location-for-time' substitution.

Tension crack- a fracture in the ground surface resulting from stresses which cannot be accommodated by the ground material. Appear within material that is actively mudsliding and in areas prior to rotational failure.

Track- the track of a mudslide is usually steep, straight or gently concave channel or series of channels through which mudslide material passes from the accumulation zone or source region, (Brunsden, 1984).

Undrained loading- Situation where an accumulation zone receives material at such a rapid rate that pore water pressures increase. If the pore water pressure reaches a critical point then extensive mass movement will be initiated.

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