THE APPLICATION OF AERIAL PHOTOGRAPHY TO THE STUDY OF A GLACIAL AREA: BREIDAMERKUR, ICELAND

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CHAPTER I

THE BREIDAMERKUR PROJECT AND A REVIEW OF PREVIOUS APPLICATIONS OF AERIAL PHOTOGRAPHY TO THE STUDY OF GLACIAL AREAS

INTRODUCTION

This thesis is concerned with the application of aerial photography to the study of a glacial area for the purpose of determining: 1) a photographic system for obtaining improved aerial photography of a glacial area for glaciological, geomorphological and ecological studies; and 2) the feasibility of using aerial photography to conduct detailed studies of glacial areas. As a result of the similar but yet diverse nature of subjects such as aerial photography, photo-interpretation and photogrammetry, it has been convenient to divide the thesis into six chapters. The first chapter deals with the background of the Breidamerkur project and contains a review of the literature on the application of aerial photography to the study of glacial areas, stressing in particular photo-interpretation and photogrammetry. In the second and third chapters the methods used in obtaining and analysing information about the Breidamerkur area are discussed, whereas the fourth chapter is concerned with an analysis of different types of aerial photography of the Breidamerkur area and the specification of a system suitable for obtaining aerial photography of a glacial area. The fifth chapter is a study of the Breidamerkur area, illustrating the use of different types of aerial photography, and emphasising the value of both photogrammetry and photo-interpretation. Finally, in the conclusion, a systematic approach to obtaining and using aerial photography for the study of a glacial area is specified, and the uses and limitations of aerial photography for the investigation of a glacial area by the glaciologist, geomorphologist, and/or ecologist, are discussed.

BACKGROUND TO THE BREIDAMERKUR PROJECT

The Breidamerkur project was first initiated in early 1964 by G. Petrie and R.J. Price of the Department of Geography, University of Glasgow, as a glacier mapping project similar to work previously carried out on the Casement Glacier, Alaska (Petrie and Price, 1966). The author, having conducted fieldwork at the Casement Glacier, and Mr. Philip Howarth, who had previously worked on Norwegian and Swiss glaciers, were invited to join the project as Ph.D. candidates.

In the early stages both Iceland and Scandinavia were considered; however, after a preliminary investigation, including a trip to Iceland and discussions with Dr. S. Thorarinsson in the summer of 1964, Breidamerkurjokull, Iceland (64°04' N Latitude 16°30' W Longitude) was selected as the area of study. Reasons for the selection included:

1. The glacier and outwash area were large enough to require more than a single investigator and could be conveniently divided into two separate areas.

2. Geomorphological features were diverse and prominent.
3. A comprehensive study of this area had never been undertaken, although major glacier fluctuations have occurred and there is historical and collateral data to support such a study (in particular the Durham University Reports, 1951, 1952).
4. Aerial photography for interpretation, measurement and mapping was available for the period 1945 - 1964.
5. The area was accessible by road from the coastal village of Hofn.
6. The Icelandic Highway Department (Vegamalastjorinn) was interested in obtaining contour maps of this area and was willing to aid in the support of the field parties.

Subsequently, the Breidamerkur area was divided into eastern and western parts on the basis of a natural river barrier, the Jokulsa, which conveniently cuts across the middle of the outwash plain in front of the glacier. This outwash plain is known as Breidamerkursandur (Figure 1.1 and maps in pocket). Based on the above division, the author became responsible for the investigation of the western area, while P. Howarth was to investigate the eastern area. The basic objective of both investigators was to produce large scale maps from aerial photography separated by a ten to twenty year period and to study the changes which had occurred during this period. In addition to this, it was possible to expand the investigation in a subject preferred by the individual investigators. Because of interest and previous experience

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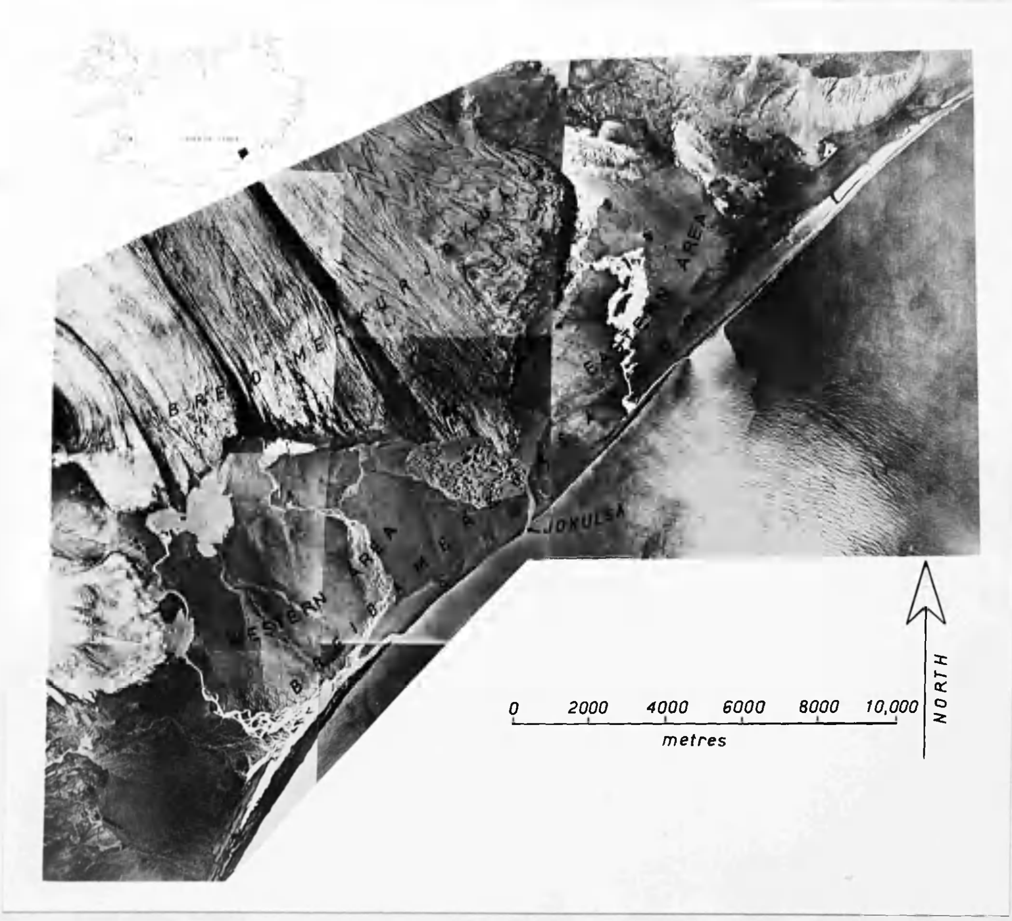

Fig. 1.1 The entire Breidamerkur Area in 1961.

in the field of aerial photography and the lack of systematic investigations into the use of aerial photography for the overall study of a glacial area, the author decided to use known and, if possible, develop new techniques which would enable studies to be carried out with a minimum amount of fieldwork. The validity of such an undertaking was enhanced by the fact that both an overall study of a relatively unknown glacier area and valuable data for future aerial photographic studies would be produced. In addition, it was believed that perhaps a contribution to glaciology and geomorphology could be made concerning the description and formation of features occurring in a glacial area.

The general outline was as follows:

September 1964 to June 1965: preparations for summer field season, including coursework in survey and photogrammetry.

June to September 1965: field season in Iceland, the major purpose being to establish a ground control network for the aerial photography.

September 1965 to June 1966: photogrammetric plotting and cartographic drafting of two large scale maps. Also personal investigations.

June and July 1966: fieldwork in Iceland concerning the photometric properties of natural objects and geomorphologic investigations.

August 1966 to October 1967: completion of work and preparation of thesis.

/REVIEW

REVIEW OF THE APPLICATIONS OF AERIAL PHOTOGRAPHY IN THE STUDY OF GLACIAL AREAS

Aerial photography has often been used in studies of glacial areas; however, for the majority of cases it is only mentioned in passing and in no instance that the author is aware of has a critical analysis been made of the potential of aerial photography for the overall study of a glacial landscape. This is undoubtedly due to two factors:

1. Major interest in aerial photography and its possible application to glacial areas has only developed since the late 1950's.
2. Most areas of the world are covered by mapping photography of one sort or another and this can be obtained very inexpensively, although scales, time of year, and photographic quality tend to preclude detailed analysis.

Today, however, with good cameras, films and aircraft more readily available, it is possible for small organisations or university groups to consider flying their own photography. Because of these increased possibilities of obtaining aerial photography, it is valuable to review work conducted by others, with thoughts as to how the information and accuracies might be improved. These studies tend to fall into two groups, those relying largely on photo-interpretation and those utilising photogrammetry.

Photo-interpretation Studies

The majority of studies in this category have centred on

/glaciological

glaciological and geomorphological investigations with the emphasis on the area being discussed rather than on methods. A synopsis of these studies and, where possible, methods, is given below with glaciological investigations being considered first.

Glaciological Investigations

The interest in photo-interpretation for the study of glaciers has been either in determining the general pattern of ice wastage over large areas containing several glaciers or in dealing with individual glaciers in detail. In the former case, La Chapelle (1962) has suggested that if maps are available, the extent of ice coverage and the positions of ice margins can be roughly determined for every year in which photography is available. In this way it is possible to assess visually the magnitude of changes and to compile a catalogue of glacier variations concerning advance, retreat, equilibrium and year-to-year changes. Thorarinsson (1956), for example, used a similar method of combining map and photographic information to determine the areal loss and maximum linear recession of three glaciers in Iceland for the period 1903 to 1945.

These methods are sufficiently accurate (to within 10 percent) for most purposes provided that: 1) the glacier is undergoing a consistent pattern of change; 2) the time interval between photography reveals changes in the glacier that are considerably larger than would be affected by small errors in locating positions on the map; and 3) the map has been compiled by accurate survey methods at a scale conducive to the ready identification and/or location of features. In regard to the photography, national photographic coverage at scales 1:40,000 to 1:50,000 combines the advantages of sufficient interpretability with large area coverage and low cost. In the future, satellite photography should prove valuable in correlating world-wide glacier variations with climate.

For more detailed studies of individual glaciers interest has been in:

1) Snow lines, mass budgets and snow depth.
2) Surface velocity, surges and ice plasticity.
3) Surface features.

Snow lines and snow depth can often be determined from an examination of mountains surrounding a glacier or by inspection of the glacier surface itself, and, for snow depth, simple measurements can be made with a parallax bar. Both of these factors can be used to deduce years of negative or positive mass budget and perhaps even to determine relative changes in mass budgets. For example, La Chapelle states (1962, p.292): "... years of strongly positive or negative mass budget in a given region stand clearly revealed from even cursory inspection of snow lines on aerial photographs. If maps are available, the ratio of snow-covered area to total glacier area at the end of each ablation season can be computed and this ratio used to deduce changes in mass budget". Another possibility mentioned is that provided sequential photography of the snow line is obtained over a single melt season, the successive values for areas of exposed ice can be combined with ground observations of surface melt rates to give successive volume melt rates. This latter method, however, would be extremely costly and instead of determining areas by interpretation it would be much more accurate to use photogrammetric methods. One photographic problem that has not been considered is that it is difficult to obtain effective images over bright areas.

For the measurement of surface velocity, one of several methods can be applied providing a boulder or some other reference object is visible on at least two sets of sequential photography. Two methods which can be used are listed below:

Method 1 - Provided adequate control exists, radial line triangulation will produce x, y positions for the objects on two sets of photography.

Method 2 - Transfer the object so that it appears in its two positions on the same photograph or on a map and then convert the distance between the object points to ground distance using the photographic or map scale.

Of course, accuracy will be affected by method used, tilt, relief, scale and reliability of available maps and rate of glacier movement; however, one of the above methods can normally be applied to derive an estimate of ice movement.

Surges and the general pattern of ice flow can also be identified by the displacement of surface features during the time interval between two sets of photography. For example, Post (1966) using aerial photographs of 1961 and 1965 determined a maximum movement of 10.1 kilometers for the Walsh Glacier. Washburn (1935, p.1881) notes that the convolutions in the banding and medial moraines of Alaskan glaciers are significant indicators of ice flow and plasticity.

Surface features visible on aerial photography may indicate the vigour and general character of a glacier. For example, a gently sloping, smooth and dark toned terminal area of a glacier indicates stagnation, whereas a steep, crevassed, white front is associated with an active or advancing glacier. For crevasse studies, Meier, Alexander and Campbell (1966) indicate that aerial photography in the blue part of the spectrum permits "seeing into" crevasse areas which are often in shadow. The use of the blue end of the spectrum, however, is impractical for most aerial photography and the author (1966) believes that colour photography, which is sensitive to the entire visible spectrum, gives just as good penetration of shadow areas and has the added advantage of higher definition and colour tones, the combination of which tends to delineate shear planes that otherwise could not be identified.

Medial moraines and dirt bands are readily identified on aerial photography. In the former case it may be possible to locate the source by tracing back along the moraine until it becomes a streak of dirt on the ice, and then continuing along this general orientation until a rock outcrop or junction of glaciers becomes visible. As Washburn (1935, p.1882) states from his studies of aerial photography of the Malaspina and tributary glaciers, "a vast number of medial moraines have been so completely buried by a layer of surface-ice that they do not reappear until ablation uncovers them, well over twenty miles below their source. This fact explains the origin of many medial moraines which slowly appear on the surface of a trunk glacier. In many cases these may be due to submerged rock masses projecting up into the ice from below, but often they can be traced several miles upstream to a junction where a medial moraine has become buried". Also, the author has found that it may be possible to identify the source of medial moraines from tones which are similar for both moraine and rock outcrops. As medial moraines often extend to the bottom of a glacier any distortions or dislocations may reveal faulting in the ice.

Dirt bands can easily be studied on aerial photography. In fact, it is likely that in most cases photography offers the only means of examination as dirt bands often occur in highly crevassed and rugged areas of a glacier. Lliboutry (1957), for instance, has been able to classify five types of dirt bands occurring on Patagonian glaciers from aerial photography taken in 1946. Surface streams, dirt cones and other features can also be detected on aerial photography, with colour followed by panchromatic photography best for general ice surface studies (Welch, 1966).

Geomorphological Investigations

As Smith (1941) and Tator (1958) point out; the validity of aerial photographs as a basis for geomorphological studies depends on two questions: 1) to what extent does surface form alone constitute an adequate basis for analysis; and 2) to what extent do aerial photographs provide an adequate picture of form? These questions have been answered by the widespread use of aerial photography in geomorphology (I.G.U., 1964) and by Sproule (1939, p.101) who mentions that: "On ground reconnaissance work, one may easily walk over well-formed eskers, drumlins, and other morainal structures, without recognising them; .... whereas the same features seen in their entirety from the air or in air photographs may be readily recognised and mapped in detail". It must be realised, therefore, that the recording of detail is often more important than metric accuracy.

The literature reveals that aerial photography for glacial geomorphological studies is normally used in one of three ways; 1) to prepare small scale physiographic maps of large areas; 2) to prepare large scale landform maps of limited areas; and 3) to support detailed studies. In the first two cases the interpreter generally has available to him some form of base map or controlled mosaic and simply transfers detail from the photographs. In the third case photographic enlargements are often used in the field and annotations placed directly on the photograph or on an overlay. The detail and annotations are then later transferred to the base map.

Small scale physiographic maps:

Vertical photographs, ranging in scales from 1:14,000 to 1:58,000, have been used to map the glacial landforms of the Labrador-

Ungava area (Hare, 1955). Detail was transferred from the photographs to standard 8-mile to the inch National Topographic sheets by the following method (Hare, 1955, p.19): "Kodatrace templates were prepared having orifices equal on the 8-mile scale (1:506,880) to the size of the standard vertical photographs on all scales encountered. The interpreter moved his template along the flight-line (which was already transcribed on to the base maps) and sketched on the base map the evidence shown by the photographs". By using every second or third photograph and alternate strips,mapping of overlap was avoided and time saved. For example, an area of 143 square miles was mapped in an hour and one-half. A similar method has been used at the University of Toronto (Dean, 1956) to map the surface characteristics of Ontario. Although this method lacks photogrammetric precision, it provides the necessary detail for small scale maps in a very short time.

Large scale landform maps:

In the preparation of large scale landform maps, topographic maps of scales larger than 1:63,360 are normally used as a base. However, if a base map does not exist it may be possible to construct one by radial triangulation (Bergstrom, 1960). Detail can then be transferred to the maps by either:

1. Sketchmaster (I.G.U., 1964, p.46),

or 2. Direct interpretation through reference to objects appearing on both map and photography (Price, 1964).

If a controlled mosaic can be constructed and relief is low, a planimetric

/map

map can be produced by tracing detail directly from the mosaic. If heights and additional planimetric detail are desired, these must then be supplied by plane table methods in the field.

A method often used, although inaccurate by photogrammetric standards, is the tracing of detail directly from the photographs. With high altitude photography over areas of low relief, the resulting errors due to relief and tilt are negligible from a geomorphological standpoint, particularly when it is the patterns and not the absolute positions of landforms that are desired. The author (1964) has used this method successfully in studies of glacial landforms in south-east Alaska and Iceland.

Support of detailed studies:

Detailed studies of glacial landforms can be divided into the following categories:

1. Glacial erosion
2. Glacial deposition
3. Fluvioglacial erosion
4. Fluvioglacial deposition.

1) Features produced by glacial erosion often reveal the direction of ice movement, and are therefore indicators of Pleistocene history. For example, Armstrong and Tipper (1948) found that it was possible to plot the orientation of groovings visible on trimetrogon coverage of north-central British Columbia and thereby determine accurately the last movement of ice in Pleistocene time. They state (p.291) that neither the great number nor parallelism of grooves "was fully realised until a

study of the trimetrogon air photographs of the area was made". A similar study has been made by H.T.U. Smith (1948) of groovings in the Mackenzie Valley.

Jenness (1952) in studies of the western islands of arctic Canada found that he could more accurately determine the location and orientation of drumlinoid landforms from aerial photographs and believes that landforms associated with continental-type glaciation "are most clearly recognisable from the air and on aerial photographs when they are located in a region of slight relief and uniform topography ....", (p.947). Svensson (1961-1962), in a more recent article, has classified glacial landforms in terms of their value as indicators of ice movement as revealed by aerial photographs. Among those forms which occur as a result of glacial erosion and appear only on air photographs, he lists (pp.142-146): roches moutonnees, rock drumlins, and striations or friction features.

2) Glacial depositional features include till, erratics, drumlins and moraines. Areas of till can often be recognised by the presence of erratics and by lineations in the direction of ice movement (Powers, 1951). Drumlins have been identified and studied on aerial photography by Sproule (1939), Thwaites (1947), Armstrong and Tipper (1948), Smith (1948), and Svensson (1961-1962). Thwaites (p.584) states that vertical photography "makes the discrimination of drumlins, which are defined in terms of their streamlined form, possible in circumstances where ground observation is not only difficult but uncertain".

Morainic deposits of all types are easily identified on air photographs. Of particular interest is the detection and identification of ice-cored moraines in which regard Ostrem states (1964, p.286): "Besides relatively large dimensions, the existence of distal snow-banks or a bright zone (indicating frequently heavy snow accumulations) gives the interpreter a good guide in deciding whether to classify a moraine ridge as being ice-cored or ice-free. In addition, the appearance of ice-cored moraines is generally reminiscent of a porridge-like compound, with a sort of rounded surface and outline, mostly with minor ridges superimposed on top of the formation, although exceptions from this rule may be found." However, factors such as climate and elevation at which the moraine occurs must influence the judgement as to whether or not a moraine is ice-cored.

Subaquatic moraines have been identified by Svensson (1963) from aerial photography of the Baltic region. He has found that in regions of elevated coasts, like the Scandinavian coast, glacial landforms such as moraines, drumlins, and eskers have been strongly eroded and levelled in the surf zone during the post-glacial elevation. However, the corresponding forms on the sea floor have been preserved and often give important information concerning the original shape and distribution of the landforms.

Fluted moraine surfaces are readily identified on aerial photography by their characteristics of linearity and parallelism in the direction of ice movement. Photographs of south-east Alaska

/(Washburn,

(Washburn, 1941; Dyson, 1952) reveal fluted moraine such as that described by Schytt (1963), and encountered by the author in Iceland. The identification of ground moraine by aerial photo-interpretation is important in the development of hydro-electric resources in Newfoundland and Labrador (Rivard, 1966) where modified or 'washed' moraine is used in road building and till has been found suitable for dyke construction.

3) Meltwater channels are the major feature produced by fluvioglacial erosion. They are indicators of glacial retreat and the location of fluvioglacial sediments. Smit (1948) found aerial photography useful for describing meltwater channels in the Alps. Jenness (1952, p.945) stated: "Aerial photographs suggest a widespread superposition of drainage and also multi-cycle drainage ....". Welch (1964) and Price (1964 and 1965) used comparative coverage to establish the sequence of establishment and abandonment of meltwater channels near the Casement Glacier, Alaska. Bergstrom (1960, p.4) states, in regard to the mapping of glacial deposits in Sweden by means of aerial photography: "Indications showing where glacifluvial sediments are to be found are given by the thousands of channels eroded by the meltwater streams from the inland ice. It is of importance to map such drainage channels also because they may give hints about the thickness of surficial deposits and about rock outcrops. As they cannot have been formed under a water surface they can give indirect information about the highest moraine limit and the distribution of glacial lakes. The bearing of this is that in areas with glacifluvial channels sediments of the type connected with such

waters will not be found".

4) Fluvioglacial depositional features include deltas, outwash plains, lake deposits, kames and kettles, and eskers. In settled areas they may be economically important for cement or road fill; however, to the glacial geomorphologist depositional forms are indicators of deglaciation and their patterns often reveal the way in which ice has retreated from an area. Normally these features consist of sand or rounded gravels and, if freshly deposited, appear in light grey tones on panchromatic aerial photographs.

Deltas and outwash plains are identified on aerial photography by their characteristic fan shape and gentle slopes (Dean, 1956). In some cases, outwash plains located by aerial photography have been considered as potential airfield sites (Pressman, 1963). Lake deposits usually occur in depressions and are indicated by a change in tone from the surrounding landscape; dark tones if moist and light if dry.

In Sweden (Bergstrom, 1960) it has been possible to identify not only lacustrine and marine sediments, but to further classify beach ridges and wave-washed deposits. If deposits of variable moisture content must be identified, colour infra-red aerial film is recommended (Winkler, 1960 and 1962).

Kames and kettles, which represent former ice-cored gravel deposits, can be identified by pock-mark patterns resulting from the melting of ice cores. Powers and Kohn (1959) and the Manual of Photo-Interpretation (1960) discuss the identification of kame and kettle areas

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Fig. 1.2 Photo-interpretation Studies of Glacial Areas

Author and Date	Area	Type of Photography (panchromatic unless otherwise specified)	Scale	Purpose
Armstrong and Tipper, 1948	Canada	Tri-metrogon		Geomorphology
Bergstrom, 1960	Sweden	Vertical	1:40,000/ 1:20,000	Mapping surficial deposits
Dean, 1956	Canada	Vertical		Mapping surficial deposits
Frost, 1953		Vertical	1:10,000/ 1:20,000	Geomorphology
Hare, 1955	Canada	Vertical	1:14,000/ 1:58,000	Mapping surficial deposits
Jenness, 1952	Canada	Vertical		Geomorphology
La Chapelle, 1962		Vertical		Glaciology
Lliboutry, 1957	S.America	Vertical	1:46,000	Glaciology
Meier, Alexander and Campbell, 1966	U.S.A.	Vertical: spectrozonal, colour infra-red, infra-red, colour, panchromatic.		Glaciology
Miller, 1957	U.S.A.	Vertical		Glaciology
Ostrem, 1964	Norway and Sweden	Vertical		Geomorphology
Post, 1966	U.S.A.	Vertical and oblique		Glaciology

/...

Fig. 1.2 (continued)

Author and Date	Area	Type of Photography (panchromatic unless otherwise specified)	Scale	Purpose
Powers, 1951	U.S.A.	Vertical		Geomorphology
Powers and Kohn, 1959	U.S.A.	Vertical		Geomorphology
Pressman, 1963	U.S.A.	Vertical	1:60,000	Mapping surficial deposits
Price, 1964	U.S.A.	Vertical	1:24,000/ 1:40,000	Geomorphology
Price, 1965	U.S.A.	Vertical	1:24,000/ 1:40,000	Geomorphology
Rivard, 1966	Canada	Vertical	1:9,600 / 1:32,000	Mapping surficial deposits
Seto, 1965	Japan	Vertical	1:20,000/ 1:25,000	Glaciology
Smit, 1948	Switzerland	Vertical	1:10,000/ 1:25,000	Geomorphology
Smith, 1941	U.S.A.	Vertical		Geomorphology
Smith, 1948	U.S.A.	Vertical		Geomorphology
Sproule, 1939	Canada	Obliques		Geomorphology
Svensson, 1961-1962	Norway and Sweden	Vertical		Geomorphology
Svensson, 1963	Norway and Sweden	Vertical	Enlargements	Geomorphology
Thwaites, 1947	U.S.A.	Vertical		Geomorphology

/...

Fig. 1.2 (continued)

Author and Date	Area	Type of Photography (panchromatic unless otherwise specified)	Scale	Purpose
Washburn, 1935	U.S.A.	Vertical and obliques		Glaciology
Washburn, 1941	U.S.A.	Vertical and obliques		Glaciology and geomorphology
Welch, 1964	U.S.A.	Vertical	1:24,000 and 1:40,000	Geomorphology
Welch, 1966	Iceland	Vertical: colour, colour infra-red, infra-red, panchromatic.	1:16,000 and 1:27,000	Geomorphology
Welch, 1967	Iceland	Vertical: colour	1:16,000	Glaciology and geomorphology
Winkler, 1960	U.S.A.	Vertical		Geomorphology
Winkler, 1962	U.S.A.	Ground		Geomorphology

on aerial photography of north-central United States.

Eskers are often associated with outwash plains or kame and kettle areas, and can be identified by their ridge form and sinuosity. For example, using aerial photography, Sproule (1939) identified and traced eskers ranging in length from a few yards to 25 miles in length in central Canada, and Armstrong and Tipper (1948) studied and traced three esker complexes in British Columbia ranging from two and one-half to 35 miles in length and with ridges of 150 feet in height. The author (1964) has determined the height of eskers in Alaska by means of parallax wedge measurements and has deduced their origin from air photo-interpretation. Figure 1.2 is a summary of some studies of glacial areas involving the use of photo-interpretation.

Photogrammetric Studies

The primary objective of photogrammetric studies of glacial areas has been to produce specialised and highly accurate maps at periodic intervals. From two or more such maps it is then possible to derive information on changes of glacier volume and height which cannot normally be obtained from less accurate and smaller scale topographic maps.

To the glaciologist, photogrammetry also offers other possibilities, including the measurement of snow depth and glacier movement and possibly the determination of glacier depth and economy. For the glacial geomorphologist, photogrammetry is of more limited value, except in areas undergoing rapid change. It then offers a quantitative means of landform measurement at successive intervals of time. By performing these measurements it is possible to establish the mode of origin or destruction of the landforms.

Glacier Mapping

In the last twenty years the traditional terrestrial photogrammetric surveys of glacial areas, initiated by S. Finsterwalder as early as 1888 (Hattersley-Smith, 1966), have been supplemented by aerial photogrammetric methods. This has been due to the advantages of covering large, rugged areas rapidly, the necessity for minimal ground work, the greater availability of aerial photogrammetric plotting equipment and the ease in plotting. It is for these reasons that aerial methods were used by the following groups to produce maps of 1:10,000 scale and larger for the International Geophysical Year (period 1956-60):

1. American Geographical Society (Case, 1958, A.G.S., 1960) for nine Alaskan glaciers.
2. Universities of British Columbia and Alberta (Konecny, 1964; Patterson, 1966) for glaciers in western Canada.
3. University of Toronto for the Salmon Glacier in western Canada (Haumann, 1960).
4. U.S.S.R. Academy of Sciences Institute of Geography for eleven glaciers in the Soviet Union (Avgevitch, 1960).
5. Comitato Glaciologico Italiano for six glaciers in the Alps (A.G.S., 1960).
6. Institut Geographique National for glaciers in the French Alps (Baussart, 1960).

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In addition to the above, glacier mapping projects using aerial and terrestrial photogrammetry were carried out in Africa by the Royal Technical College of East Africa, in Spitsbergen by a Polish group, and in Austria, Switzerland and Germany (A.G.S., 1960).

Since 1960 several other glacier mapping projects have been undertaken using aerial photogrammetry, including:

Glaciers of Axel Heiberg Island (Muller, 1963).
Byrd Glacier, Antarctica (Brandenberger, 1964).
Per Ardua Glacier, Ellesmere Island (Konecny, 1966).
Casement Glacier, Alaska (Petrie and Price, 1966).
Glaciers of Meighen Island (Arnold, 1966).
Glaciers of the Soviet Union (Avsiuk, Vinogradov and Kravtsova, 1966).

Many of these later projects are part of the International Hydrological Decade and will provide data indicating the effects of climatic variations and the present climatic trends.

Requirements for glacier mapping, which depend on the area to be mapped and the scale and contour interval selected for the final map, can be divided into 1) map accuracy; 2) aerial photography and marker size for ground control; 3) ground survey; and 4) photogrammetric equipment and procedures. As most maps are of limited areas and plotted at scales between 1:5,000 and 1:20,000 with contour intervals of 10 to 20 metres, it is possible to make fairly concrete statements about the necessary requirements.

Map accuracy:

To a large extent, map accuracy requirements depend on the time interval for which the maps are to be constructed and the slope and rate of wastage of the glacier. Contour accuracy, for example, is particularly critical as errors in the planimetric positions of contours also represent errors in height. These errors reappear in the areas derived from planimeter measurements between successive contours, which are in turn used to obtain the height and volume changes in the glacier for the period between the maps. In this regard, glaciers with steep slopes will not be affected by small height errors during contouring as these errors will not alter the planimetric positions of the contours; however, small errors in planimetric positions represent large height errors. For gently sloping glaciers the converse is true.

Of course, the significance of these errors is largely dependent on the amount of change in the glacier during the interval mapped. For example, Kick (1966, p.776) mentions that for periods of 1 to 2 years between photography, mean height errors of contours should be less than ± 0.1 metre, but for 20 years ± 1 metre will suffice. From an aerial photogrammetric standpoint even this latter accuracy is impossible to satisfy if it is considered that the spot height accuracy of most photogrammetric machines is approximately 0.02 percent (or 1/5000) of the flying height, and that 90 percent of the points tested along a carefully plotted contour will only be accurate to within two to two and a half times the spot height accuracy. Therefore, for a flying height of

5,000 metres, resulting in a scale of 1:33,000, a spot height accuracy of ± 1 metre can be expected and the contours would be accurate to approximately ± 2.5 metres. Although it is not usually possible to produce contour accuracies of less than one metre, it is feasible to increase the relative accuracy by increasing the contour interval. For example, Konecny (1964, p.71) states: "While high contouring accuracy is normally desired, it is nevertheless sufficient to use a fairly large contour interval (say 100 feet). This will cause a significant reduction in data and still not introduce significant errors, since glacial volume changes are quite regularly distributed". The relative accuracy of two maps can also be increased by basing them on the same control.

Planimetric accuracy is limited by the capabilities of the photogrammetric equipment. For example, in the graphical plotting of maps the maximum accuracy for establishing definite points of detail is ± 0.2 millimetre, although with first order equipment numerical coordinates can be read to ± 0.01 millimetre. However, even the former accuracy is difficult to obtain when large model to plot enlargement ratios are used and when the cartographic compilation must be considered. Because of these and other influencing factors an accuracy standard of 90 percent of well defined planimetric points falling within ± 0.8 millimetre (1/30 inch) of their true position has been recognised for maps at scales of 1:20,000 or larger (Manual of Photogrammetry, 1966). It should be realised, however, that the relative agreement between two maps may be much better than ± 0.8 millimetre and, also, that overall agreement and

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relative accuracy can further be improved if photographic reduction is used to produce the final maps.

Based on map accuracy requirements of ± 1 metre in spot heights and ± 0.2 millimetre in the graphical planimetric positions of well-defined points, it is possible to consider the limitations imposed by the aerial photography, ground survey and photogrammetric plotting.

Aerial photography:

Aerial photography for photogrammetric purposes automatically requires a metric camera, preferably of wide angle with a focal length of 6 inches (15 centimetres).[1] As national photographic coverage is necessarily flown with a survey camera, it meets these requirements, although it may be unsatisfactory for other reasons, such as excessive flying height, poor quality, wrong season or lack of availability to private groups. However, if aerial photography is to be flown particularly for a glacier or glacial area mapping project, it is possible to specify: 1) time of year; 2) type of film; 3) flying height, scale and overlap; and 4) location of pre-marked control points.

The best time of year for flying aerial photography of glacial areas is late in the ablation season but before the snow falls (Kasser

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[1] A metric or survey camera is one which has been calibrated and for which the distortions are known. Use of a wide angle lens (f = 6 inches) permits larger area coverage and results in better height accuracies.

and Roethlisberger, 1966). At this time snowfield areas are limited, but well defined, the glacier boundaries are evident, crevasses are visible and there is sufficient contrast to permit plotting. Of course, another problem which must be considered is that of weather. It may be dangerous to postpone a flight until late in the season when weather and cloud conditions may be so severe as to preclude aerial survey.

The type of film used in glacier surveys is hardly ever mentioned in the literature but is normally a typical panchromatic air survey film such as Kodak Double XX Aerographic or Super XX.

Flying height and scale are influenced by the map requirements, plotting machine accuracies and terrain conditions. Blachut (1961, p.486) states: "On first-order plotters and with modern 1:50,000 photography, an accuracy (mean square error) of ± 1.0 metre is possible in the x and y coordinates and a slightly better accuracy in z. The horizontal accuracy quoted above is satisfactory for maps at 1:5,000". With a six-inch lens, however, a scale of 1:50,000 is obtained with a flying height of 25,000 feet. As even first order equipment is limited to operational graphical plotting accuracies of ± 0.2 millimetre, planimetric accuracies of ± 1 metre are impossible to obtain, particularly with photograph-to-plot enlargement ratios of 10 times. In addition, even considering a first order spot height accuracy of 0.015 percent of the flying height, an accuracy of less than one metre in z is extremely optimistic. A more reasonable flying height for obtaining a one metre spot height accuracy is 5,000 metres (16,400 feet). This will also permit contouring at 5 or 10 metre intervals.

The problem of terrain in relation to flying height must also be considered. First of all, for safety, the aeroplane should fly at an altitude higher than the surrounding terrain. Secondly, if relief in the models is greater than 35 percent of the flying height, large dead areas will exist, the z range of the machine may be insufficient to allow plotting, stereoscopy is impossible, and orientation is difficult and tiresome. Thirdly, if the glacier is large, it is desirable to fly as high as possible in order that the minimum number of models are required to bridge the width of the glacier while still meeting the accuracy requirements. Furthermore, with wide angle and superwide angle cameras it is preferable to have a forward overlap of 80 percent. This allows the selection of the most favourable models, according to how the control falls, and, in the case of steep terrain, minimises dead areas and the possibility of being unable to fuse detail because of excessive radial displacement. A sidelap of 20 to 40 percent is recommended.

Pre-marking of control is also desirable and once the field locations of control points have been established, they should be marked with a material of sufficient size and colour so as to appear on the aerial photography. For example, Haumann (1960), with 1:14,000 photography, used 60 x 60 centimetre white and black markers for land and ice surfaces respectively. However, he was only able to locate the land markers. Blachut (1961) recommends marker sizes between 15 to 20 microns at image scale for land surfaces and three times that for ice surfaces. The former is about one-half the size of the floating mark of most photogrammetric machines and only slightly above the visual limitations of detection imposed by graininess in most aerial survey films. The latter would almost certainly be obscured by the effects of halation. There is no mention of these target sizes actually being employed.

In a later study Haumann (1963) found orange 50-centimetre square aluminium plates used either singly or in groups of three to four, depending on flying height, satisfactory for land surfaces. Based on this experience, he recommends a land target size of 30 microns at image scale. Again, however, this is smaller than the 40-micron diameter floating mark of many photogrammetric machines. The author (1966) used white crosses with arms five feet in width to mark control points on land surfaces and similar black crosses for ice points. As all markers were located, except one on the ice surface, the author recommends that land markers be white in colour and 50 microns to a side at image scale. For ice markers, black is the preferred colour if panchromatic film is used and orange-red if colour film is employed. For positive detection, marker size should be a minimum of 150 and 100 microns respectively.

<u>Ground survey</u>:

Control points must be established by ground survey and if aerial photography is already in existence, it is simply a case of considering the models that will be used in the plotting and establishing control for them. Control points will, of course, be natural features (or the previously discussed pre-marked points) identified on the aerial

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photographs and coordinated on the ground. Unless aerial triangulation procedures are to be used it is desirable to establish height points in the corners of each model and planimetric points in diagonally opposite corners. Preferably each height or plan point should be located so that it falls in as many models as possible, thereby minimising ground and computational work.

The accuracy of the ground survey must be such that errors in the heights and horizontal positions of control points are negligible compared with errors in the photogrammetric plotting. As flying heights of 3,000 to 5,000 metres are being considered and 0.02 percent of the flying height can be obtained with most photogrammetric machines, the height control points must be accurate to between ± 0.6 and ± 1 metre. In regard to planimetry, errors of ± 0.2 millimetre at map scale (graphical accuracy) can be tolerated. This is equivalent to a ground distance of ± 1 metre for a map scale of 1:5,000 and ± 4 metres for a map scale of 1:20,000.

In establishing a control network, then, it is necessary to determine the length of side and the accuracy to which angles must be read. For trigonometric heighting, it is possible to differentiate the trigonometric height formula (Haumann, 1960, p.97):

$$\Delta h = s\cdot\tan\alpha + i - z\ \left(\frac{1-k}{2r}\right)s$$

where: s = distance between two points

i = height of instrument

z = height of signal

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α = vertical angle

r = radius of the earth

k = refraction coefficient

to obtain:

$$d(\Delta h) = ds \cdot \tan\alpha + \frac{s(d\alpha)}{\cos^2\alpha}$$

It should be noted that possible errors in the instrument and signal heights (di and dz) and in refraction have been ignored as it is assumed in the former case that they are too small to be considered, and in the latter that the length of side is so short that errors in k are negligible. For practical purposes ds can also be ignored.

To determine the accuracy to which horizontal angles must be read, the following formula may be used:

$$d\Phi'' = \frac{m}{s} \times \rho$$

where: m = allowable error in planimetric coordinates

s = distance from station to intersection point

ρ = 206265, the number of seconds in a radian

$d\Phi''$ = angular difference in seconds.

For both the above formulas s is determined from a map or estimated.

As most glacier surveys do not cover large areas, it is possible to either break down directly from a national trig system or to use plane coordinate systems. Problems such as spherical excess and corrections

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of observations to projection directions which are encountered in higher order surveys can usually be ignored. Other elements of the survey datum, such as absolute position, orientation and elevation are similar to those encountered in normal survey work and methods of establishment can be found in survey texts (Clark, 1957; Textbook of Topographical Surveying, 1965).

Photogrammetric equipment and procedures:

Traditionally, first order or universal photogrammetric machines such as the Wild A7 (Case, 1958; 1959) or the Zeiss Stereoplanigraph (Haumann, 1963) have been recommended for glacier mapping. The reasons for this being 1) the facility for coordinate registration and aerial triangulation, and 2) greater inherent accuracy and versatility. It is interesting to note, however, that aerial triangulation is not always suitable for glacier mapping due to the inaccuracies of extending height control and, therefore, coordinate registration is of limited value. Furthermore, with the advent of electronic digitising equipment and computers, various forms of independent model triangulation are coming into use with plotters such as the Wild A8 and B8, and the Kelsh.

In regard to accuracy, machines such as the Wild A7 or Zeiss C8 are capable of heighting accuracies equivalent to 0.01 percent to 0.02 percent of the flying height and planimetric accuracies of ± 0.01 millimetre if coordinate registration is used, and of ± 0.2 millimetre for graphical plotting (Singels, 1964). However, similar accuracies can be obtained with other plotters. For instance, the Wild A8, the

/Santoni

Santoni Stereosimplex III and IIC, and the Kern PG.2 are all credited with possessing first order heighting accuracy. Furthermore, Meadows (1965) found a spot heighting accuracy of 0.021 percent for the Wild B8 and Case (1959) rated the Kelsh plotter at 0.03 percent. All of these machines will produce a graphical accuracy of ± 0.2 millimetre at moderate enlargement ratios, which is well within normal standards of map accuracy, and, in fact, is normally considered the maximum possible cartographic accuracy. Even Blachut and Muller (1966, p.752) state "... it must be realised that the limit of graphical presentation is 0.2 millimetres, ...".

In versatility, however, universal equipment has an advantage, particularly if terrestrial as well as aerial photography has to be plotted. Large z ranges permit the plotting of aerial photography in which the relief is greater than 30 percent of the flying height, and, of course, greater model to map enlargement ratios are possible.

The photogrammetric procedures used for producing glacier maps are generally dependent on the photogrammetric equipment and amount of control available. For example, if a control framework is non-existent it is possible with machines such as the C8 and A7 to establish an arbitrary framework (Case, 1959; Konecny, 1966) of high internal and relative accuracy although the absolute position and datum is unknown. As long as all maps are produced on the same framework, volume measurements will not be affected, although changes must be expressed in percents rather than absolute units. Because of the lack of position and datum, such maps have a limited value and therefore, in the author's opinion, this procedure should not be employed.

When control is limited, and, in addition to the mapping photography, small scale photography of the area to be mapped is available, control can be extended using the small scale photography and then transferring the points to the mapping photography (Haumann, 1960, 1963). Similarly, a method for extending planimetric control with non-universal equipment is by stereo-templates. If coastlines exist, they can be used for levelling (Petrie and Price, 1966). These latter methods produce accuracies sufficient for graphical plotting and, as glacial areas are usually remote, they should be considered.

A serious photogrammetric problem in the production of a glacier map is the contouring of snow or ice covered areas where lack of detail and low contrasts prevent the operator from forming a stereo image. Konecny (1964, p.131), for example, found that for snow on the glacier, with no detail visible, the standard error in heighting could exceed one percent of the flying height. However, he also concluded that contouring of crevassed or contrasting ice surfaces created no special problems. In an attempt to solve the problem of lack of contrast and detail on Norwegian glaciers, Ostrem (1966) dropped "dye bombs" from a light aircraft prior to the aerial photography. He found 3 to 5 kilograms of dye in a plastic container give the best results. The marks created by these "bombs" were visible on photography taken at an altitude of 7,300 metres. However, this method is both expensive and impractical

Fig. 1.3 Photogrammetric Data for Some Glacier Maps Produced from Aerial Photography

Author	Area	Scale of Photography	Camera/Lens	Map Scale	Contour Interval	Equipment	Aerial Triangulation
Avegevitch (1960)	U.S.S.R.			1:15,000 and smaller	10m	SD-1 Stereograph	Yes
Arnold (1966)	Meighen Island N.W.T.	1:60,000		1:50,000	10m	A8	
		1:28,000	Wild RC5 Aviogon Lens				
		1:15,000	Wild RC5 Aviogon Lens	1:25,000	5m	B8	No
Baussart (1960)	French Alps	1:25,000		1:10,000	10m		
Brandenberger (1964)	Antarctica	1:40,000	F11 Metrogon Lens			A7	Yes
Brandenberger and Bull (1966)	West United States	1:20,000–1:40,000	Metrogon Lens	1:5,000 and 1:10,000	5m	A7	
	Alaska			1:25,000	10m	A7	
Case (1958)	Alaska	1:30,000	Fairchild T11 Metrogon Lens	1:10,000	5m	A7	No
Case (1960)	West United States			1:5,400	20-40 ft.	Kelsh	
Haumann (1960)	West Canada	1:14,000–1:20,000	Fairchild 224 Metrogon Lens	1:2,500–1:10,000	10m and 20m	A7 Kelsh	Yes
Haumann (1963)	Axel Heiberg Island	1:10,000–1:30,000	Wild RC5 Aviogon Lens	1:5,000–1:25,000	5m-10m	C8 Kelsh	Yes
Kasser and Roethlisberger (1966)	Switzerland	1:17,000	Wild RC5 Aviogon Lens	1:10,000	10m		
Konecny (1966)	Alaska and West Canada	1:14,500–1:30,000		1:10,000–1:50,000	10m-30m	A5	Yes
Meier (1966)	West United States			1:6,000	3m		
				1:12,000	6m		
Kellor (1958)	Antarctica	1:20,000					
Ostrem (1967)	Norway	1:38,000 1:63,000		1:20,000	20m	B8	
Patterson (1966)	West Canada	1:12,000		1:4,800	10 ft.		
Petrie and Price (1966)	Alaska	1:29,000 1:39,000	Fairchild K17 Metrogon Lens	1:30,000	50 ft.	B8	Stereotemplate

if large areas are to be considered.

In order to compensate for any errors in plotting and cartography, the original machine plot and cartographic compilation are usually at a larger scale than the final map, which is produced by photographic reduction. Figure 1.3 lists the photogrammetric data for glacier maps mentioned in the literature and, as can be seen, scales of 1:10,000 with 10 metre contour intervals are common.

Measurements of Changes in Glacier Volumes and Heights

Volume and height changes can be accomplished by either of two methods:

1. Cartographic (graphical)
2. Formulae (numerical).

In the cartographic method (Davey, 1962) the two glacier maps are superimposed and the height change is obtained for a large number of closely spaced points over the entire glacier. Isolines are then constructed from the points to show the change in height and thickness for the whole glacier. Volume changes can be obtained by measuring the area between adjacent isolines with a planimeter and then multiplying by the mean height change. However, this method is of limited accuracy.

In the second method (Figure 1.4), originally developed by R. Finsterwalder (1954) and later modified by Hofmann (1957), the areas on both maps between successive contour lines (the corresponding contours and areas must be present on both maps) are determined by planimeter. The maps are then superimposed and the area between numerically identical

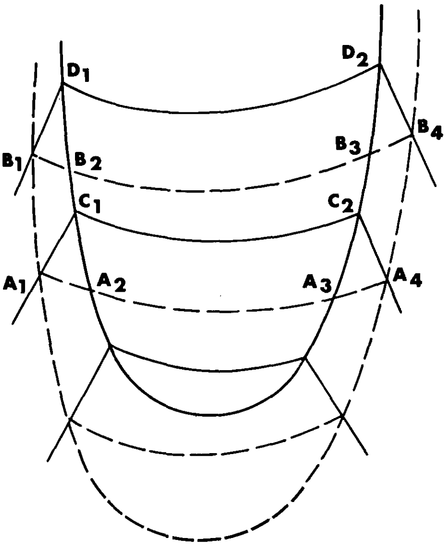

Fig. 1.4 Derivation of formulae for calculating height and volume losses.

contours is planimetered. These values may then be substituted into the following formulae:

1. Change in height for a given zone (Finsterwalder, 1954, p.308)

$$dh = \frac{dF_1 + dF_2}{F_1 + F_2} \cdot \Delta h$$

where: dh = mean decrease in height

Δh = contour interval

F_1 = $D_1D_2C_1C_2$

F_2 = $B_2B_3A_3A_2$

dF_1 = $D_1D_2B_3B_2$

dF_2 = $C_1C_2A_3A_2$

2. Change in volume for a given zone (Hofmann, 1957, p.326)

$$dv = \frac{dF_1 + dF_2 + \sqrt{dF_1 \cdot dF_2}}{3} \quad \Delta h$$

where: dv = change in volume

Volume accuracy for a height zone can be assessed by (Konecny, 1964, p.27)

$$mdv = \frac{\Delta h \cdot W \sqrt{2}}{2}$$

where: W = width of glacier

3. Change in height for one year in a given zone (Haumann, 1960, p.97)

$$\bar{dh} = \frac{dh}{n}$$

/where:

where: n = the number of years between maps

$\bar{dh}$ = the loss for one year.

Finsterwalder (p.310) also describes how the raising or lowering of the snowlines on a stationary glacier can be determined by the formula:

$$\Sigma a F = o$$

where: a = amount of accumulation minus ablation in a zone; a is positive in zones above the snowline and minus below.

F = surface area of a zone as obtained from maps.

From the formula it is possible to plot a parabolic curve (Figure 1.5) indicating variations in accumulation and ablation. Of course, this method requires field data on accumulation and ablation as well as a contour map. A simple but effective method of showing glacier changes is by means of longitudinal and transverse profiles (Baussart, 1960, p.255).

Measurement of Glacier Movement

Glacier movement is normally determined with photogrammetric methods by measuring the x, y, z coordinates (or plotting of planimetric position) for recognisable points on two or more sets of photographs. The velocity is then computed from the coordinates or plotted positions (Mellor, 1958, p.1158; Konecny, 1964, p.71). In this case pre-marked points are usually required. If photographs from two missions are of the same scale, and along the same flight lines, one photograph from

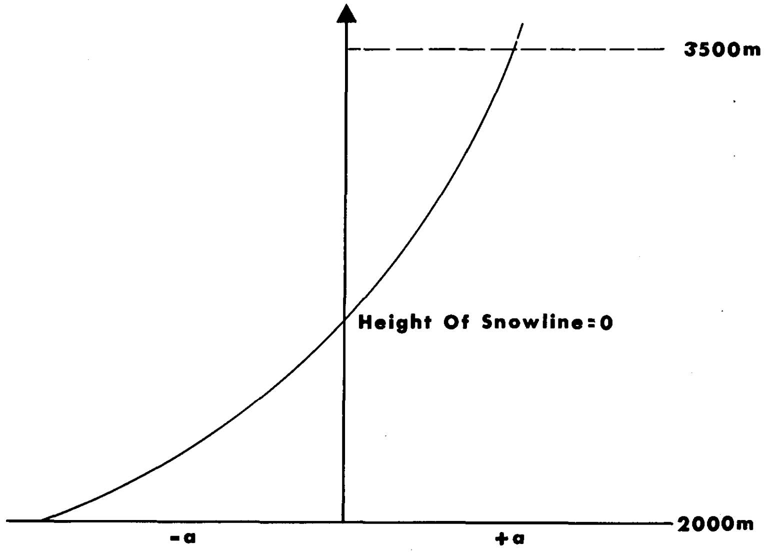

Fig. 1.5 Determination of height of snowline (Finsterwalder, 1954, p.309).

each mission can be used to form the model (Blachut, 1963, p.113) and measurement can be made directly. However, this method is unlikely to prove feasible in most cases.

The use of aerial photography for measurements of glacier movement is limited by:

1. The high cost of aerial missions
2. Weather
3. Lack of identifiable points
4. Accuracy requirements.

The first three factors are probably the most critical, although accuracy may be the limiting factor if the glacier has a slow rate of movement. For example, if the pointing accuracy at ground scale is ± 1 metre and the glacier has only moved four metres between flights, the determination of movement may be in error by as much as 50 percent. Therefore the use of aerial photogrammetry for glacier movement is best considered where yearly or longer period movement is desired, and where points, once established, can be left and identified for the duration of the study.

Determination of Glacier Depth and Economy

The determination of glacier depth, although requiring no photogrammetric measurements, can be estimated according to Lagally's formula, if the surface velocity and inclination of the glacier surface is known.

/z =

$$z = \sqrt{\frac{2uv}{p \cdot g \cdot \sin\alpha}}$$ (Hofmann, 1957, p.329)

where: z = glacier depth

u = coefficient of viscosity

p = density of glacier ice

g = gravity

α = angle of inclination of glacier surface

v = surface speed

u can be approximated by $1.0 \cdot 10^{14}$ g $\mathrm{cm}^{-1}\mathrm{sec}^{-1}$

However, this formula is limited to the centre zones of valley glaciers in which speed decreases towards the sides due to friction. The estimates obtained by this formula appear to be tentative at best.

If surface velocities are known Blachut (1963) believes it is possible to derive ablation data. For example, in Figure 1.6; Point A on the ice surface would move to position A_3 if there were no ablation; however, instead it will move along line $A - A_2$. If A_1A_2 is the horizontal displacement and Δh is the photogrammetrically measured difference in elevation, then the change in elevation caused by ablation will amount to (Blachut, 1963, p.117):

$$\mathcal{L} = \Delta H - A_1A_2 \tan\alpha$$

where: $\mathcal{L}$ = change in elevation due to ablation

α = slope angle.

In the author's opinion this method is impractical because of the necessity of sequential photography on which the same point has been

/identified

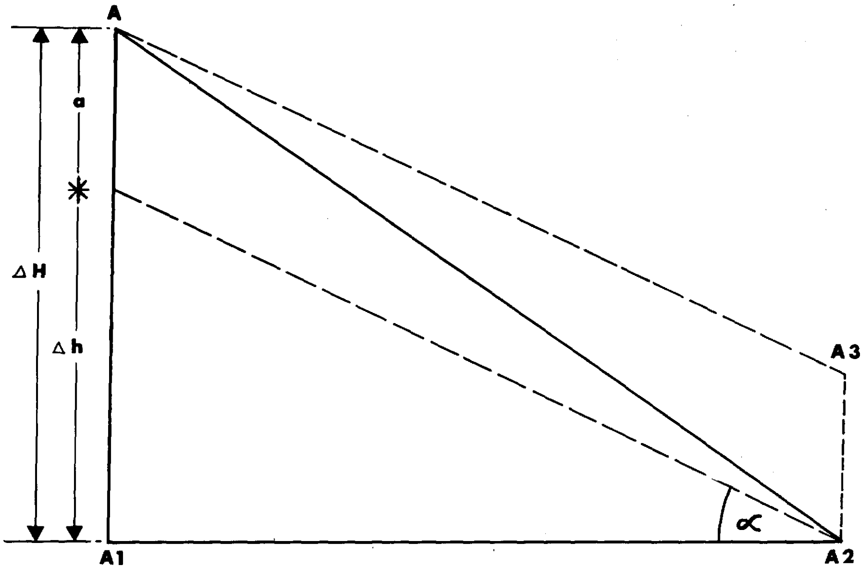

Figure 1.6   Determination of ablation (Blachut,1963, p.117).

identified and the limitations imposed by photogrammetric height accuracies. Furthermore, if sequential aerial photography is available, ablation can be determined by Finsterwalder's method. Generally, short period ablation data is best obtained by ground work using stakes placed in holes bored in the glacier.

If ablation data is established for the entire tongue below the firn line, the total accumulation can be determined. This fact has been used by Finsterwalder (1954) to derive accumulation estimates for glaciers in the Alps, Altai Pamir, Spitsbergen and Norway.

Measurement of Snow Depth

Basically there are two methods of determining snow depth by photogrammetric means:

1. By measuring relative depth between top of snow surface and bottom of snow surface at exposed sections.
2. By comparing ground elevations with snow cover elevations at the same points.

In the first instance it is only necessary to have photography during the winter months; however, in the second case photography at both periods of maximum and minimum snow cover must be available. In addition, there should be sufficient control for the accurate levelling of the stereo models. The advantage of the second method is that it is possible to determine absolute snow volumes at given periods of time (Seto, 1965) and also water volume if snow density is known (Cooper, 1965).

Glacial Geomorphological Studies

As photogrammetry is primarily of value where change is taking place, it has found only limited use in glacial geomorphological investigations. Price (1966), for example, through the use of photogrammetric measurements of an ice-cored esker complex near the Casement Glacier, Alaska, has postulated (p.123) that: "... eskers can be let down from the surface of a glacier on to the subglacial surface without being destroyed". Kravtsova (1959) in the investigation of the Mount Elburs region has used aerial photogrammetry for the production of maps illustrating the changes in surface features such as moraines and meltwater streams.

Conclusions

The overall conclusions which are reached from a review of the literature on studies of glacial areas involving the use of photo-interpretation and photogrammetry are as follows:

1. In the majority of cases vertical panchromatic photography, either representing national mapping coverage or photography flown by the military in support of the project, has been used. Subsequently, little attention has been given on how to improve photographic quality.
2. For photo-interpretation, rendition of detail is more important than metric accuracy. However, the reverse is true when photogrammetry is employed.
3. Photogrammetric methodology is much more firmly established

than either photographic or photo-interpretation techniques.

4. There has been no analysis of how to improve and employ aerial photographic methods, including photo-interpretation and photogrammetry, to the overall study of a glacial area.

Before continuing, then, it is important to make a basic distinction between the uses of photo-interpretation and photogrammetry. The value of photo-interpretation lies largely with the geomorphologist or ecologist who is interested in the description, distribution and origin of landforms or vegetative features. Therefore, these groups are more interested in photographic quality rather than high metric accuracy. For them, base maps can be constructed by radial line techniques, tracing from mosaics or photographs, or, if available, topographic maps can be employed. This is not to say that accurate base maps would be of little value - only that they are not the primary objective in the study and hence are of secondary importance.

Photogrammetry, however, is the basic tool for constructing maps and can be employed most efficiently in rugged or remote areas. Therefore, to the glaciologist, it offers a means of obtaining accurate volume and height changes of glaciers - provided photography is available over a 10 to 20 year interval. In this instance the rendition of detail is secondary to high metric accuracy. Also, although aerial photogrammetry has been considered for short-term ablation and ice movement studies, it is likely that this information can be more readily and accurately derived by ground survey or terrestrial photogrammetric

/methods.

methods. To the geomorphologist, photogrammetry offers a limited means of obtaining information on height and position changes in landforms.

It would appear from the above that both photo-interpretation and photogrammetry have much to offer in the study of a glacial area and if linked with optimum quality photography would represent a powerful means of investigation. With this in mind, the major portion of this thesis is devoted to optimising aerial photographic procedures and relating them to the overall study of a glacial area.

CHAPTER II

METHODS EMPLOYED IN THE AERIAL SURVEY AND PRODUCTION OF MAPS OF THE BREIDAMERKUR AREA

INTRODUCTION

In order to investigate the suitability of aerial photography for the study of a glacial area, it was essential to obtain both photogrammetric and interpretation photography. For photogrammetric purposes, it was desirable to have two complete sets of photography, separated by an interval of 10 to 20 years, from which it would be possible to construct accurate contour maps. These maps, of course, would provide a means of determining ice-wastage and volume changes in the glacier and also permit the detailed analysis of landform changes in front of the glacier. The only requirements of this photography were that it provide complete coverage of the Breidamerkur area, have tilts of less than 3 degrees, and be of sufficient scale to permit plotting of 1:10,000 scale maps.

The investigation into the suitability of various types of aerial photography, however, demanded that representative panchromatic, infra-red, colour, and false colour aerial films be employed, that all photography be obtained at the same scale and preferably at the same time. In addition, it was essential that certain ground preparations be carried out before and during the flight in order that the photography could be compared on a quantitative basis.

With the above considerations in mind, all previous photo-

/graphic

graphic coverage of the Breidamerkur area was determined and this is listed in Figure 2.1. As can be seen, only panchromatic photography of assorted scales existed, of which the 1945 photography alone offered the complete coverage necessary for mapping the Breidamerkur area. Unfortunately, the latter photography was held by the United States Department of Defense, and Icelandic authorisation was required for its release. As a result of two governments being involved, it took eighteen months to obtain this photography.

Although the other available photography was obtained from Landmaelingar Islands, it was considered necessary to conduct an aerial survey during the summer of 1965 in order to provide both a second set of mapping photography and the necessary panchromatic, infra-red, colour and false colour photography. Furthermore, by conducting a survey, it would be possible to specify scales, season and flight lines, to establish and pre-mark ground control, and also to lay out various markers and conduct certain ground studies which would be of value in comparing the various types of photography. This chapter, therefore, is a discussion of the aerial survey, and the associated ground survey and photogrammetric procedures used in constructing the maps. The following chapter discusses the methods employed in obtaining the data used in analysing the various types of photography.

AERIAL SURVEY

There were several different aspects to be considered in

/conducting

Fig. 2.1 Previous Photographic Coverage of the Breidamerkur Area

Type	Flown By	Date	Camera/Lens	Approximate Scale	Orientation of Flight Lines	Coverage	Source
Panchromatic	U.S.	August 1945	15 cm Metrogon	1:46,000	N-S	Complete	U.S. Department of Defense
Panchromatic	U.S.	July 1960	15 cm Metrogon	1:36,000	N-S	One strip only	Landmaelingar Islands
Panchromatic	U.S.	July 1961	15 cm Metrogon	1:37,000	N-S	Virtually complete	Landmaelingar Islands
Panchromatic	Iceland	June 1964	RC-5, 11.5 cm Aviogon	1:45,000	E-W	Sandur only	Landmaelingar Islands
Panchromatic	Iceland	September 1964	RC-5, 11.5 cm Aviogon	1:30,000	E-W	Ice margin only	Landmaelingar Islands

conducting an aerial survey. These are discussed below.

Preparations and Equipment

Once it had been decided to conduct an aerial survey, it was necessary to arrange for a suitable survey aircraft and camera. With this in mind, the author made a preliminary trip to Iceland in the spring of 1965 to discuss with Landmaelingar Islands the possibility of using the Icelandic Coast Guard DC-4 aircraft and Landmaelingar Islands' RC-5, 11.5 centimetre focal length (18 x 18 centimetre format) camera. Furthermore, it was necessary to determine whether or not Vegamalastjorinn (Icelandic Highway Department) would be willing to pay part of the costs of an aerial survey in return for maps of the Breidamerkur area. As a result of this trip, arrangements were made on the basis that a survey flight would occur on the first opportunity after August 1st and would encompass both the Breidamerkur area and the active volcanic island of Surtsey, which was being photographed at regular intervals. Vegamalastjorinn, Landmaelingar Islands and the University of Glasgow would all contribute to the cost.

Upon trying to obtain aerial films, however, it was found that single rolls of colour and false colour film could not be furnished in the 18 centimetre size. As a result, Hunting Surveys Limited were contacted and agreed to provide an RC-5A lens cone, f = 15 centimetres (23 x 23 centimetre format), and all four types of film, including separate magazines for each film. This equipment was to be air-freighted to Reykjavik on July 28th, allowing a minimum of three days for clearance,

/checking

checking and installation.

Scale of Photography and Flight Lines

For the mapping photography, a scale of 1:27,000 (H = 13,500 feet or 4,100 metres) was decided upon on the basis that only two strips oriented northeast-southwest would be required to cover the entire area, yet the maximum photogrammetric requirements of 1:10,000 scale maps and one metre spot heighting accuracy could be obtained. The interpretation photography, however, was to be flown at the larger scale of 1:16,000 (H = 8,000 feet or 2,440 metres). At this scale, three strips, also oriented northeast-southwest, were required for each type of photography. Forward overlaps were to be 80 percent for the mapping photography and 60 percent for the interpretation photography. Sidelap was 20 percent in both instances. Flight lines for the higher altitude photography are shown in Figure 2.2.

Problems in Obtaining Photography of the Breidamerkur Area

The first problem occurred during the planning of the flight lines. Because of the rapid retreat of Breidamerkurjokull since the last published map (AMS, 1945), major changes in proglacial landmarks had occurred and it was necessary to construct mosaics from the 1960-61 photography and to revise existing maps before plotting the flight lines. These mosaics and revised maps were given to the pilot and camera operator prior to the flight.

The second problem was quite unexpected and occurred at the end of July when the author and Mr. Agust Bodvarsson went to the

/Reykjavik

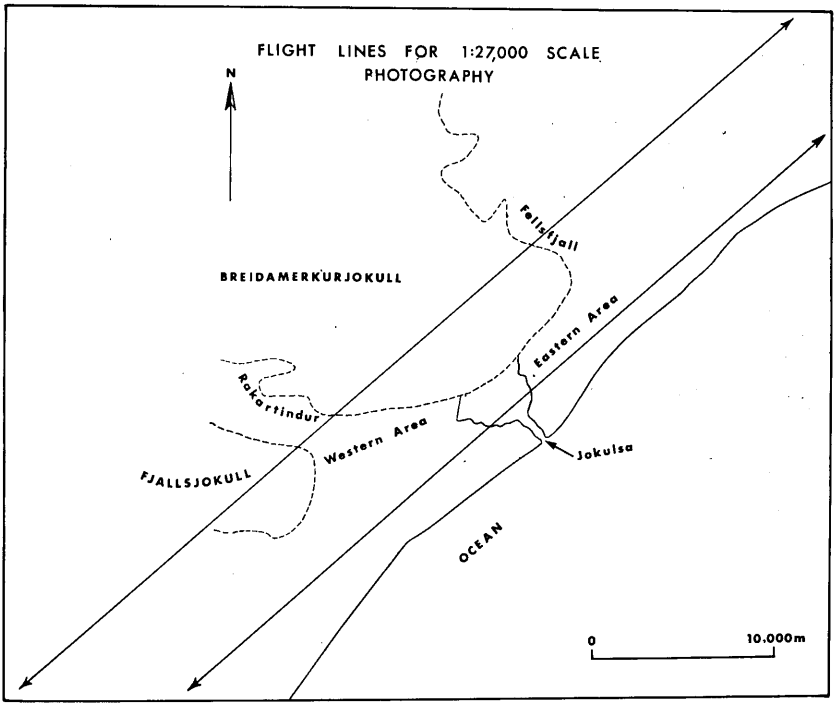

Fig. 2.2 Flight lines for the 1965 mapping photography.

Reykjavik airport to test and install the camera in the aircraft. It was learned at that time that the Icelandic Coast Guard aircrew were on vacation and would not return for two weeks. Because of the high rental cost of the camera equipment, the infrequent occurrence of suitable weather and the plans to leave Breidamerkursandur on August 28th, this was a serious blow. Fortunately, the first flight opportunity did not occur until August 24th, by which time the crew were available.

The third problem was related to the camera equipment and, in particular, the shutter speed indicator for the rotary shutter of the lens cone, and the vacuum regulator for the magazines. The operation of the former depends on a small fuse, which, in this case, was broken upon arrival. As spares were not sent with the camera, valuable time was spent in obtaining replacements from Hunting Surveys Limited. However, once a replacement was installed the speed indicator still failed to function and it was necessary to contact Hunting's for further instructions. They informed us that as the shutter speed is determined by the number of revolutions per second it was possible to perform an on-the-spot calibration using a tachometer. A tachometer subsequently arrived and a calibration was performed by placing an index mark on the shutter speed adjustment knob and then recording another mark on a piece of tape placed below the knob when the tachometer produced readings corresponding to 1/200, 1/300, and 1/400 and 1/500 second. In regard to the vacuum regulators, a stronger vacuum is required to flatten 23 x 23 centimetre film than is necessary for 18 x 18 centimetre film,

/and

and it was questionable as to whether or not the apparatus for the Icelandic magazines would operate the larger Hunting's magazines. Luckily, no difficulties were encountered.

The fourth problem was the time required to reach the Breidamerkur area once the decision to fly the photography had been made, and also the time required to complete the photographic coverage once the area had been reached. Two hours were estimated for the former and similarly two hours for the latter. This meant at least a four hour period from the time Landmaelingar Islands was contacted until the completion of the flying. As the decision to fly had to be made at Breidamerkursandur and as the local telephone exchange did not begin operating until 8.30 a.m., it was unlikely that the flying would be completed before 1.00 p.m. on the appointed day.

Weather, the fifth problem, was the most important single consideration and was linked directly to the problem of time, for once the aircraft took off from Reykjavik the success or failure of the mission hinged on the weather remaining constant for three to four hours. As a result, daily weather patterns were carefully observed throughout the month of July and during this period two important variables were noted. The first was that convection currents produced by the heating of the bare volcanic mountains on either side of the glacier caused cumulus clouds to form in late morning or early afternoon. Unless there was a strong north wind (down-glacier) these clouds would drift over the glacier and sandur. The second problem was the formation of

/sea

sea mist a mile or two off the coast. Again, if a strong north wind was blowing, this mist would remain offshore; however, if the day was sunny with light breezes, the mist would drift in over the sandur during the afternoon. Therefore, before calling Reykjavik it was necessary to have a clear, cool morning with a strong north wind. It was noted that only one such day occurred during the entire month of July.

The last major problem concerned the in- and post-flight operations. With regard to the former, this included changing filters and magazines, and determining the proper exposure for each film type. Changing filters was the most difficult task as this meant that the lens cone had to be removed from its mount and lifted from the camera compartment into the body of the aircraft between successive sets of photography. The post-flight operations included processing and transporting the various film types. Processing of the panchromatic and infra-red films was to be performed by Landmaelingar Islands immediately after the flight in order to check that the mission had been successful; however, the colour and false colour films were to be returned to Hunting Surveys Limited. This meant that the exposed films had to be cleared through Customs without the canisters being opened. With this in mind, both canisters were hand carried and fortunately no difficulties were encountered. With regard to Customs, it should also be mentioned that it was necessary to obtain special permission for entry of the aerial camera and films into Iceland.

The above problems are mentioned in the hope that by doing so

/their

their occurrence may be avoided or solved more easily by others undertaking the planning of aerial missions in glacial areas.

Flight

The photographic mission was successfully carried out on August 24th, 1965. In order to avoid fogging of the lens, the lower altitude interpretation photography was flown first and in the sequence colour, infra-red, false colour, and panchromatic. Because of the tolerance of only ± ½ stop for the false colour, two separate sets were flown at different exposures at the same altitude. The panchromatic film was exposed last in order to avoid changing filters and magazines between the interpretation and mapping photography. The total photographic flying time was three and one-half hours, the additional ninety minutes over the planned flying time being due to difficulties in removing the camera from its mount, problems in changing filters, and also jamming of the magazines. This, coupled with the fact that the aircraft did not arrive over the sandur until 1.30 p.m. because of mechanical difficulties, meant that the flight began at the time when it should have been completed. Fortunately, heavy clouds which began forming about mid-day did not obscure the area until shortly after the flight was completed. Film, filter and exposure data were as follows:

/...

Film	Filter	ASA with filter	Weston V light meter reading	f stop	Shutter speed
Ilford Hyperpan	500mμ	125	13.5	8	1/500
Kodak Infra-red Aerographic	600mμ	100	13.5	8	1/400
Kodak Ektachrome Aero, Type 8442	no filter	80	13.5	6.3	1/400
Kodak Ektachrome Infra-red Aero, Type 8443	500mμ	10	13.5	5.6	1/200 1/500

SURVEY AND PHOTOGRAMMETRIC PROCEDURES IN THE STUDY OF THE BREIDAMERKUR AREA

Ground Survey

The purpose of a ground survey in the Breidamerkur area was to establish sufficient planimetric and height control to enable the production of accurate contour maps from the aerial photography. As the plotting machines in the Department of Geography are not capable of aerial triangulation, it was necessary to plan a scheme which would provide adequate control in each model. The procedures used in planning and carrying out the survey work are discussed below.

Preparations

Because of the existence of an Iceland Trigonometric Network, based on a Lambert Conformal Conic Projection, it was possible to make use of trig. points in the Breidamerkur area. There were two reasons for preferring to break down from the Icelandic trig. system rather than

/establishing

establishing an independent network. First, if the maps were to be used by the Icelandic Highways Department, it was essential to base them on the Iceland grid: and second, as electronic distance measuring equipment was not available, it was believed a more accurate and rapid result would be obtained if the initial base were determined by resecting both end points rather than by measuring with a steel tape. With this in mind, the author obtained from Mr. Agust Bodvarsson of Landmaelingar Islands a list and description of trig.points in the area. From this list it appeared that possibly six points would be visible from the sandur. These were 11, 14, 15, 16, 1011 and 2055 (Figure 2.3). As only three points are necessary for a resection, it was decided that it would be possible to establish the initial base points by this method and other points, including the ice points, by intersection. Heights would be established by trigonometric and tacheometric methods.

The next step was to plan in advance of the aerial photography a control scheme that would provide at least three planimetric/height points for each photogrammetric model and which could be marked out on the ground. This was accomplished by constructing an overlay for the 1945 Army Map Service 1:50,000 sheet 6019 11 on which flight strips and successive model areas (60 percent overlap) for the 1:27,000 scale photography were plotted. This overlay was placed on the map sheet in its correct orientation and taped down. A second sheet of clear plastic was then placed over the first overlay and four rows of control points were marked on it so as to control as many models as possible (Figure 2.4).

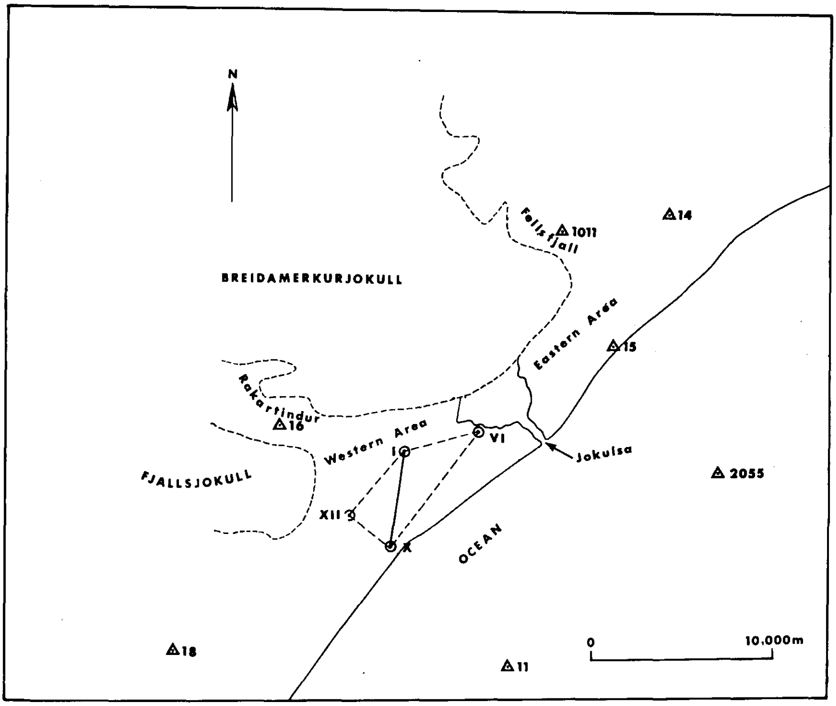

Fig. 2.3 Icelandic trig points and the initial base.

In addition to the above points, which would have both planimetric and height values, supplementary height points, to be established by tacheometric levelling, were located in the sidelap and at other locations.

Once the initial layout was complete, it was necessary to locate the proposed points on the 1964 aerial photography and to determine by stereo-observation if these locations were suitable in terms of intervisibility with other points. Adjustments were made where necessary and the points transferred back to the second control overlay. The distribution was checked by taping the second (control) overlay to the map sheet and then placing the first overlay (flight lines and models) in register and moving it along the flight lines. By doing so the control distribution could be checked in any model at any point along the flight line. From this planning it was found that for the entire 7 x 14 mile area (east and west) a total of 38 planimetric/height points and 14 supplementary height points would be required.

As it was planned to mark the control points, both for the aerial photography and ground survey, it was necessary to decide on material, and size and colour for the markers. The major requirements for the aerial markers were that they be:

1. Bright in colour and of proper shape and sufficient size to appear on the aerial photography, yet not so large as to preclude accurate pointing.
2. Of sufficient strength and durability to remain in place for several weeks.

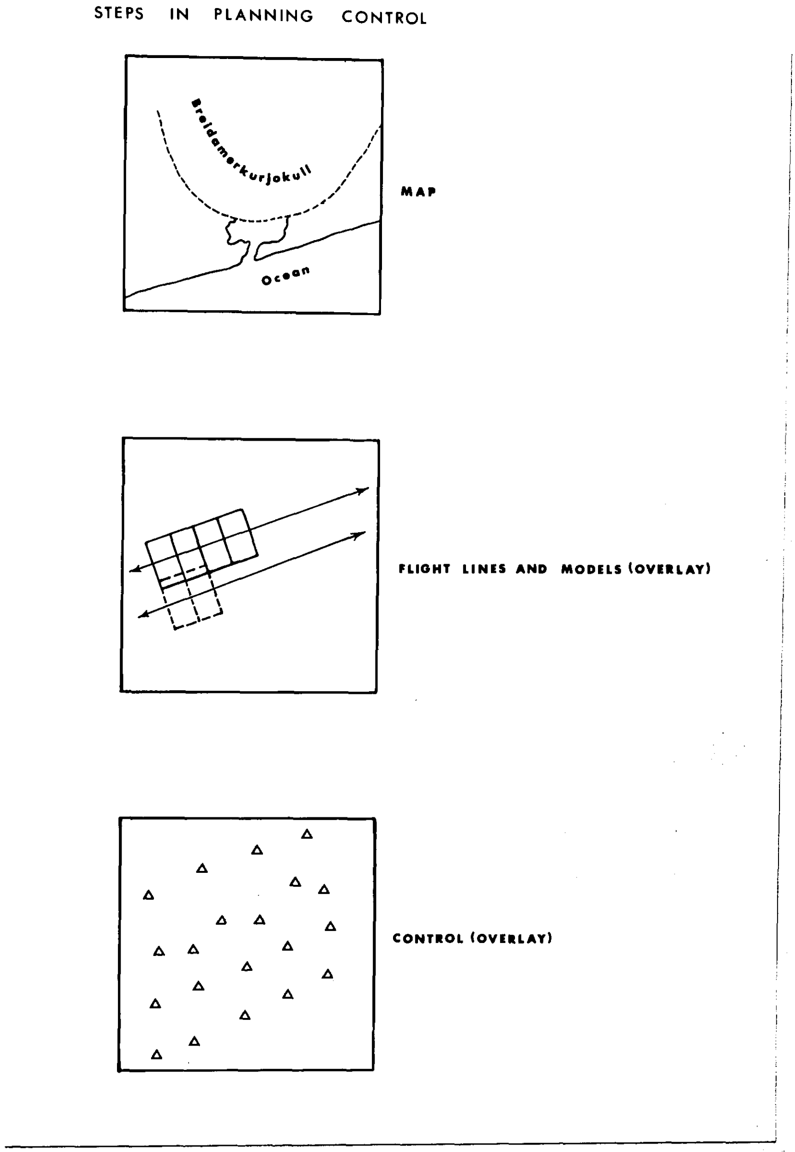

Fig. 2.4 Map and overlays used to plan the control scheme prior to the aerial photography.

3. Light, compact and portable enough to be easily carried to the most inaccessible areas.

Item 3 ruled out solid materials such as plywood and aluminium plate, and Item 2 ruled out aluminium foil or cheesecloth. As a result, it was decided to use medium weight muslin. Choice of colour was solved by placing white, gold, and dark blue pieces of cloth on white, green, brown, and black backgrounds and photographing them in the laboratory with a 35 mm camera, using a film-filter combination similar to that of the aerial photography (Figure 2.5). Based on this experiment, white and black were chosen as the most suitable colours, white for land and black for ice markers. Size was determined on the basis of tests by the United States Geological Survey (Halliday, 1963) who, for a flying height of 12,000 to 16,000 feet, recommended four separate 4 x 12 foot cross arms, or a total of 192 square feet of cloth for one marker. This size was prohibitive from an economic standpoint, and furthermore, required the handling of four separate pieces which was considered undesirable. However, it was found that by using one piece of white muslin 15 feet long and 5 feet in width, and attaching two additional pieces each 5 x 5 feet, a single cross with arms 5 feet in width and 15 feet in length could be constructed. A 3 x 3 inch hole was cut in the centre of the cross to permit centring directly over a control point.

For ground survey signals on land, it was decided to use 3 foot 6 inch staves of 2 x 2 inch timber with 10 x 14 inch yellow flags attached. These had the advantages of being available locally, and of

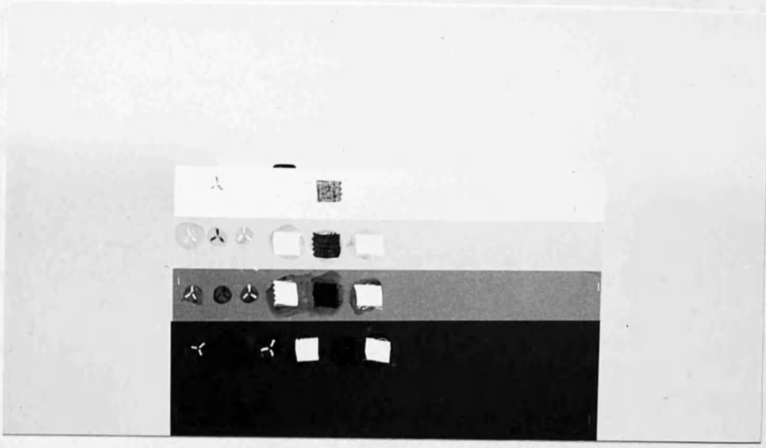

Fig. 2.5 Determination of marker colour for control points. Background colours from top to bottom are white, green, brown, and black. Marker colours (left to right) gold, blue, and white.

having sufficient size and brightness to be observable at distances up to two miles, thereby providing an accurate and definite mark for observations. Furthermore, they could be surrounded and supported by a stone cairn, and if desired, the cloth aerial marker could be slipped over the stave. Also, the tripod could be set up directly over it.

The ice points presented more difficult problems. Because of ablation, ice movement, strong glacier winds, distance from land points, and the necessity of establishing their position on the day of the aerial photography, the markers had to be secured in such a way that they could be left unattended for several days, yet be of sufficient size to be rapidly located and observed from stations in front of the glacier. It was decided, therefore, that once positions for the points were located, 6 foot deep holes would be bored in the ice and 12 foot long, 1 x 1 inch staves inserted. Next, black crosses would be slipped over the staves and anchored to the ice by rocks tied at the corners, or by stakes bored into the ice at angles. Finally, a tripod would be constructed over the stave and 12 to 15 inch wide red cloth wrapped around the top of the tripod and a similar size yellow marker attached to the centre stave.

Equipment

Because observations over distances of as great as 10 miles were expected, a Wild T2 theodolite, reading to one second of arc, was selected as the triangulation instrument. A Wild T1A, reading to 10 seconds of arc, was chosen as an alternative triangulation instrument for short distance work and was also for use in tacheometric levelling.

Accuracy Standards and Procedures

Accuracy requirements were largely determined by the flying height, photogrammetric plotting machine capabilities, and graphical accuracy. As the flying height was to be 4,100 metres (13,500 feet), and the heighting accuracy of the plotting machines to be employed was taken as 0.02 percent of the flying height, a height error of ± 0.82 metre (± 2.7 feet) would have been acceptable; however, in order to ensure all points were within these limits, it was considered desirable to set a standard of ± 30 centimetres (± 1 foot) for both the trigonometric and tacheometric heighting. Planimetric accuracy, on the other hand, is limited in the plotting machine to ± 0.2 millimetre at plotting scale, which in this case was to be a maximum of 1:10,000. Therefore, although ground positions within ± 2 to ± 3 metres (± 6.1 to ± 9.2 feet) of the true coordinates would have been acceptable, a standard of ± 1 metre was set.

In observing both horizontal and vertical angles, a minimum of four rounds were to be taken for the initial base points and two rounds for subsequent points. Accepting the reading accuracy of the T2 as ± 2 seconds of arc, an error of less than one metre could be expected at the presumed maximum distance of 23,000 metres. Because of its simplicity and ease of use in breaking down from a higher order network, the Direction Method (Textbook of Topographic Surveying, 1965) was to be used throughout.

/Fieldwork

Fieldwork

The first objective in the field survey was to locate and establish beacons at the Icelandic trig. points so that they could be used in establishing the initial base. However, of the six Icelandic trig. points that might possibly have been of use, only points 16 and 2055 were located. Point 2055, a lighthouse, was readily visible throughout the entire area and required no signalisation. Point 16, however, was reported to be at the top of Rakartindur (774 metres) and it was only with great difficulty that it was located and beaconed. Of the other points, 15 was from the survey of 1903 and had not been tied into the later triangulation, 14 and 1011 could not be accurately located, and 11 on the island of Tvisker was inaccessible. The third point required for the resection of the initial control points on the sandur was found after being described by Mr. Flosi Bjornsson of Kvisker, This was point 18 and was marked by a large stone cairn which could be observed throughout the area.

The first points established on the sandur by resection were I and X. These two points formed a base from which it was possible to intersect points XII and VI (Figure 2.3). Once these points were established the rest of the land points were observed (Figure 2.6) without great difficulty. Establishing the position of signalising and observing points on the glacier (Figure 2.6) created different problems. Because of the irregular, constantly changing ice surface, lack of identifiable small detail, and difficulties with the ice drill,

Fig. 2.6 Establishment and marking of control points.
Upper: resecting a point at the ice margin.
Lower: establishing a point on the ice surface.

it was decided that, where possible, glacier points would be established on medial moraines. In one case, however, it was essential to establish a point in the heavily crevassed area north of the Jokulsarlon. For this, a party was equipped with two-way radios and directed from a vantage point two miles in front of the glacier. In this way it was possible to both establish the approximate position of the point and also to ensure its visibility from the control points in front of the glacier.

The survey of the six glacier points was accomplished by intersection from three land points on the day of the aerial photography. As a prior test run had been carried out to obtain approximate bearings, the observations were completed over a period of approximately six hours, thereby removing the possible effects of ice movement.

Closed tacheometric traverses were used to establish the heights of a series of four points along the beach (which were marked with 5-foot white squares) and of several large rocks in the sidelap area. The 1965 map gives the final control layout for both planimetric and height points.

Computations and Accuracies of the Survey

Observations:

The accuracy of the observations is somewhat difficult to assess as fully observed triangles were rare and bearings rather than angles were used. However, after determining the orientation unknown at each point, a calculation of the difference of provisional bearings from final bearings gives a RMSE of ± 3 to ± 4 seconds of arc.

Planimetric coordinates:

The planimetric coordinates of points I and X (initial base) were adjusted relative to one another. That is, point I was established first from points 16, 18 and 2055, and as there was no way of checking the accuracy of these coordinates they had to be accepted until point X had been computed. Point X was also established from points 18, 16 and 2055; however, a bearing from I could be used as a check. As the cut from I formed an error triangle with the rays from 18, 16 and 2055 it was possible to establish a correction of + 0.09 metre in northings. However, instead of applying the entire correction to point X, the correction was distributed equally between points X and I, + 0.045, to point X and - 0.045 to point I. Once the correction was applied the coordinates were accepted as final and the bearings to points I, X, 16, 18 and 2055 were adjusted accordingly. All further bearings were influenced by the establishment of these initial bearings.

It was realised at the time that while a computational check had been provided in the establishment of the initial points, there was no check on the coordinate system as a whole. With this in mind, point X was re-occupied later in the summer, and point 2056 (Ingolfshofoi lighthouse) was observed. The differences in coordinates as computed from 16, 18, 2055 and 16, 18 and 2056 were + 0.56 m in westings and + 0.57 m in northings, which is surprisingly good considering the distance of 15 miles to the lighthouse.

An approximate scale check on the system was performed by twice

/taping

taping the distance between two points. The scale error determined by comparing the mean taped distance with the computed distance was 1:2,500.

Trigonometric heights:

Point 16 (774 metres) was used as a datum for all the heights established west of the Jokulsa and vertical angles to this point were observed wherever possible. Consequently, it was possible to adjust heights not only on the basis of one another, but also independently against the datum point. To ensure against gross errors a form of closed traverse, beginning and ending at the datum, and including at least one other finalised point, was used to establish the final heights of all points. Curvature and refraction corrections were based on Clark (1963, Vol. II, p.167).

As a result of this procedure, and the fact that the largest discrepancy between provisional and final heights was 0.6 metres, it is believed that the majority of points fall within the ± 0.3 metres standard. Also, as a further check, a vertical angle from point VI to a large beacon which had been erected over the Icelandic trig. point 15 (8 metres) produced a height of 8.7 metres, which, although in error by 0.7 metre, is quite good considering that height values of the Icelandic trig. points are rounded off to the nearest whole metre and that the height of point 15 has not been re-established since 1903.

Tacheometric heights:

The tacheometric traverses were adjusted by graphical methods, and since there were no closing errors greater than 20 centimetres, it is thought that all points established by this means also have an accuracy of much less than one metre.

Photogrammetric Work

The purpose of the photogrammetric plotting was to produce two contour maps from the 1945 and 1965 aerial photography. From these maps it would be possible to compute the volume of ice wastage and to trace the evolution and development of the landforms in the Breidamerkur area.

Materials and Equipment

The materials involved were the 1965, 1:27,000 scale photography, and the 1945, 1:46,000 scale photography, both on an acetate base. In the former case, the author contact printed glass diapositives from the original negatives; however, in the latter instance, only thin-base positive transparencies of poor tonal quality had been furnished by the United States Department of Defense. Therefore, in order to use this material in the plotting machines, it was considered necessary to improve flatness and tonal quality. This was accomplished by producing intermediate negatives from the positives and then producing duplicate positives on glass plates and 0.007 inch polyester thick-base transparency material.

Equipment used in the plotting included Wild A6, Wild B8 and Santoni Stereosimplex IIC machines (Figure 2.7). All of these machines utilise mechanical projection systems and their reported accuracies are listed in Figure 2.8.

Fig. 2.7 Plotting the Breidamerkur maps on the Santoni Stereosimplex IIC (L) and Wild B8 (R).

Machine	Spot Height Accuracy	Planimetric Plotting Accuracy
Wild A6	± 0.03%[1]	± 0.2 mm
Wild B8	± 0.021%[2]	± 0.2 mm
Santoni Stereosimplex IIC	± 0.015% (estimated)	± 0.2 mm

Fig. 2.8 Photogrammetric Plotting Machine Accuracies

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[1] Blachut, T.J. (1957) "Some Results from International Mapping Experiments", <u>Photogrammetric Engineering</u>, Vol. 23, No.4, pp.767-774.

[2] Meadows, P.L. (1965) "B8 Contouring Accuracy", <u>Photogrammetric Engineering</u>, Vol. 31, No.4, pp.695-700.

General Considerations

Considerations in the production of the two maps included scale, contour interval, grid, and detail to be plotted. Instead of the previously mentioned 1:10,000 scale, 5 metre contour interval maps, a scale of 1:15,000 with a 10 metre contour interval was decided upon. The reasons for this choice are mentioned below. Although both 1:10,000 scale and 5 metre contours were possible with the 1965 photography (5 metre contours were plotted and are discussed later in the text) it was not really feasible to produce such a map from the 1:46,000 scale photography due to a necessary enlargement ratio of 1:4.6 and a calculated C factor of over 1400[1]. A combination of this enlargement factor and C factor exceeded the capabilities of two of the plotting machines available, whereas the enlargement factor of 3 and a C factor of slightly over 700 necessary for a 1:15,000 scale, 10 metre contour interval map, could be easily met by all machines. Therefore, to avoid difficulties from a purely photogrammetric standpoint, it was desirable to reduce the map scale to 1:15,000 and use a contour interval of 10 metres. Furthermore, upon calculating the outside dimensions of 1:10,000 scale maps, it was found that they would far exceed the maximum possible contact-size reproduction of 30 x 30 inches, whereas it was just possible to maintain these

/dimensions

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[1] $\text{C factor} = \dfrac{\text{flying height}}{\text{contour interval}}$. Most non-first order photogrammetric equipment has a C factor of less than 1200.

dimensions with a scale of 1:15,000. Finally, the Icelandic Highway Department, which had financed part of the photographic costs, would accept the smaller scale and contour interval. These were the principal factors influencing choice of scale and contour interval, although for the purpose of landform representation the larger scale was more suitable. This is a good example of the compromise between desired and actual map production which must often be accepted.

Before the photogrammetric plotting could begin it was necessary to prepare plot sheets on which a 10 centimetre grid and the positions of all control points were marked. For the 1965 photography these points were marked on plastic sheets using a Haag-Streit coordinatograph. Second sheets on which only the contours were to be plotted were registered with the first sheets by slotted template studs in each corner. The idea of using studs was to permit overlaying the second sheet (contours) without removing the first (planimetric detail) from the plotting table. For the 1945 photography this procedure was slightly modified in that control and transfer points on the 1965 plot sheets were transferred directly onto the 1945 plot sheets.

The instructions for plotting decided on by all members of the project were as follows:

	Subject	Colour on plot	Instructions
Planimetric detail:	moraines	red	outline base if of sufficient size, otherwise plot ridge crest

/eskers

	Subject	Colour on plot	Instructions
Planimetric detail (continued)	eskers	black	plot tops and bottoms where possible
	kame areas	black	outline and insert letter K
	channels	green	if necessary, tops and bottoms (then black for top and green for bottom)
	fluted moraine	black	outline and insert FM
	ice edge	green	
	water	blue	
	spot heights	black	
	roads	black	
Contours:	land	brown	
	ice	blue	

Plotting of 1965 Photography

Eight models were required for the plotting of the 1965 photography west of the Jokulsa. Figure 2.9 lists the machines used, the number of control points, the height residuals at control points, and the general comments for each model.

In regard to the photogrammetric operation as a whole, control distribution was generally very good in the land models, although due to errors in flight lines (resulting in less than 10 percent sidelap in

/the

Fig. 2.9 Plot Data for 1965 Photography - 1:27,000 scale
Model to Plot ratio of 1:1 used throughout[1]

Model	Machine	Control Points	Height Residuals (metres)	Comments
I October 1965	A6	I	-0.6	This model was chosen as the first because of its good control distribution. However, several difficulties were encountered with the lighting system of the A6. This resulted in the model being disturbed once, thereby necessitating re-orientation. This was also the most difficult and complex model to plot. Two weeks' delay while machine was repaired.
		II	+0.5	
		VII	0.0	
		VIII	0.0	
		3	-0.7	
		4	+0.4	
		8	+0.7	
II November 1965	A6	III	-0.4	Difficulty with lighting. Points transferred onto large medial moraine for levelling and scaling model.
		IV	0.0	
		V	-1.0	
		VI	-0.3	
		VII	0.0	
		XIX	+0.4	
		XX	+0.8	
III November 1965	IIC	I	0.0	Very high precision heighting. Optics and lighting excellent. Could see 0.5 foot white square cloth marker and could also trace telephone line across sandur. Scaling between widely spaced control points indicates ground control of sufficient accuracy.
		VIII	-0.7	
		IX	-0.8	
		XIII	+0.2	
		XVIII	+0.2	
		1	+0.1	
		7	+0.3	

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[1] All points scaled correctly.

Fig. 2.9 Plot Data for 1965 Photography (continued)

Model	Machine	Control Points	Height Residuals (metres)	Comments
IV November 1965	IIC	X	+0.5	Similar to previous model; however, big objection to Santoni is problem of having to manually control the pencil, a nuisance when there is a great deal of small detail.
		XI	-0.5	
		XII	0.0	
		XIV	0.0	
		XVIII	+0.6	
		Lake	+0.4	
		Rock	+0.2	
V December 1965	B8	II	+0.5	Wild B8 a very easy machine to use; lighting and optics very good. Big advantage is pencil lifter at finger-tips. One problem with pencil holder on pantograph is eccentricity. By revolving pencil, transscribe circle 0.5 mm in diameter. Points transferred for adjacent models.
		XXII	0.0	
		XXIII	+0.5	
		Transfer	-0.5	
		Transfer	-0.5	
VI December 1965	B8	XXIII	-0.5	Point XXIV never located. Points transferred for area east of large medial moraine.
		XXV	+0.8	
		Transfer	0.0	
		Transfer	0.0	
		Transfer	-0.5	
		Transfer	-1.5	
VII December 1965	B8	XVII	+0.7	Points transferred for Model VIII.
		XXI	+0.5	
		XXII	0.0	
		Transfer	0.0	
		Transfer	0.0	
		Transfer	+0.6	
		Transfer	-0.5	
VII January 1966	B8	XV	0.0	Relief in this model was over 700 metres. Contouring of rock cliffs difficult. Contouring took several days.
		XVI	-1.0	
		Transfer	0.0	
		Transfer	+0.5	
		Transfer	-1.0	
		Transfer	+1.5	
		Transfer	0.0	

the western part of the area) auxiliary points had to be established by photogrammetric methods and transferred to the ice models. Exposure was excellent, resulting in high definition and, of even greater importance, tilts and tips were under one degree although swing often amounted to five degrees between photographs.

In the plotting, the white land markers were readily identified and all land and medial moraine points were located. However, black crosses on the glacier surface were considerably more difficult to identify, and, in fact, one point was never located. Terrain and glacier features were easily recognised and for the most part could be plotted without difficulty, although in some instances there was some question as to the exact nature of a feature, for example fluted moraine or moraine. In order to accentuate features and for later interpretive work, intermediate five-metre contours as well as ten-metre contours were required on the land areas. This added 20 to 25 percent to the plotting time which averaged approximately 50 hours per model. As the plotting began in early October 1965, and was not completed until the end of January 1966, a total of 15 weeks was required to complete all eight models.

Plotting of 1945 Photography

Four models were required for the plotting of the 1945 photography. Figure 2.10 lists the plot data for each model.

Although the photographic quality of the 1945 photography limited definition to objects greater than five feet across, tilts were

/almost

Fig. 2.10 Plot Data for 1945 Photography - 1:46,000 scale
Model to Plot ratio of 3:5 used throughout[1]

Model	Machine	Control* Points (Heights given)	Height Residuals (metres)	General Comments
I May 1966	B8	33.0	0.0	Quality of photography better than expected. Points transferred for controlling upper model
		30.0	0.0	
		43.0	+1.0	
		26.0	+1.0	
		16.0	-2.0	
		2.0	+1.0	
		24.0	+1.0	
		25.0	+2.0	
II May 1966	B8	7.0	-1.0	Definition less than on first model. Points transferred for controlling upper models.
		25.0	+1.0	
		41.0	0.0	
		7.0	+1.0	
		2.0	0.0	
		2.0	0.0	
		34.0	+2.0	
		34.0	+1.0	
		21.0	0.0	
III June 1966	B8	42.0	0.0	Points used in scaling and levelling include ice points transferred from the area east of the Jokulsa. Points transferred to control upper part of Model IV,
		25.0	0.0	
		Transfer	0.0	
		Transfer	-2.0	
		Transfer (from east)	+1.0	
		Transfer (from east)	0.0	
		Transfer	0.0	
IV June 1966	B8	Transfer	+2.0	Considering the relief in this model and the fact that orientation is based largely on transfer points, both scaling and heights are reasonable.
		Transfer	+1.0	
		Transfer	-1.0	
		42	-3.0	
		Transfer	+1.0	
		302	0.0	
		411	0.0	
		25	+1.0	

[1] All points scaled to within 0.5 millimetre

* All control transferred from 1965 plots. No numerical designation given. Transfer refers to points transferred from one model to another.

almost non-existent, being generally less than one degree. As a result of this, and the fact that the relief in all models was less than 15 percent of the flying height, relative orientation was very rapid. Absolute orientation of the land models was facilitated somewhat by the presence of a coastline in the lower parts of the models. In the plotting of this photography only the Wild B8 was used because of:

1. The availability of distortion/altitude correction plates; this being of great importance due to the use of a Metrogon lens (up to ± 120 microns disrotion) and a flying height of 23,000 feet.
2. The greater range of enlargement ratios.
3. Ease and rapidity of orientation and plotting.

Control points on the land area were largely natural features transferred from the 1965 plot sheets, whereas those on the ice areas were transferred between models. In this latter case, and in particular the model (Model III) which was located in the centre of the glacier, it was first necessary to insert a model of the area east of the Jokulsa (which, fortuitiously, could be fully controlled because of solid land across the lower half and up the eastern side) and place points in the upper west (ice covered) corner of this model which could also be used in the levelling and scaling of Model III. Points transferred from Model III aided in controlling the upper portion of the adjacent model (Model IV). Features plotted were the same as those from the 1965 photography, although it was perhaps fortunate that much of the small detail exposed in 1965 had not yet been formed in 1945.

The time required for each model of the 1945 photography was approximately 30 hours, or only three-fifths the time required for the 1965 models. This saving in time is largely attributed to the fact that five-metre contours were not plotted. A total of five weeks was required to complete all four models.

Cartographic Work

The maps were designed by the author on the basis of previous cartographic experience. For the planning and drafting purposes both planimetric and contour plots were joined into separate but continuous sheets on the basis of the Icelandic grid. A large, clear piece of plastic on which the grid had been marked was then registered with the planimetric sheet and this arrangement placed over a light table. From this it was possible to determine the area and orientation of the final map which was limited to a 30 x 30 inch format. Because of the size limitations and to avoid half the map being covered by ocean, it was necessary to orient the grid at approximately 45 degrees to the map sheet edges.

The border, grid, and all planimetric detail were drawn first, followed by the 10-metre contours. Once the ink work was completed, photoset lettering and Zip-a-tone patterns were placed on the maps. The total time necessary to produce the first map (1965) was approximately 400 hours distributed over an eight-week period. The second map required between 200 and 300 hours. Both maps were photographed at contact scale by Cook, Hammond and Kell Limited and dyeline duplicates were produced from the positive film copies.

Comparison of Accuracies

The accuracies of the final maps were determined by the accuracies obtainable in the photogrammetric plotting and cartographic drafting. These are discussed below.

Earth curvature, refraction and distortion: Earth curvature and refraction, which cause height errors and their associated planimetric errors at the edges of the model, are determined by the flying height, From Figure 2.11, which is based on U.S. Army data, the effects of earth curvature and refraction were determined for both the 1945 and 1965 photography. However, it should be noted that as 13,000 feet (4,000 metres) altitude/distortion correction plates were used with the 1945 photography, the residual height error would be the difference between the error caused at 13,000 feet and that at the flying height of 23,000 feet. Height error data due to curvature and refraction are listed below.

	1945 23,000 feet (7,000 metres)	1965 13,500 feet (4,100 metres)
Curvature	+6.7	+2.0
Refraction	-1.0	-0.5
Total error	+5.7 feet	+1.5 feet
Correction for 13,000 feet	+1.3 feet	
Residual error in model	+4.4 feet = +1.3 metre	+1.5 feet = +0.5 metre

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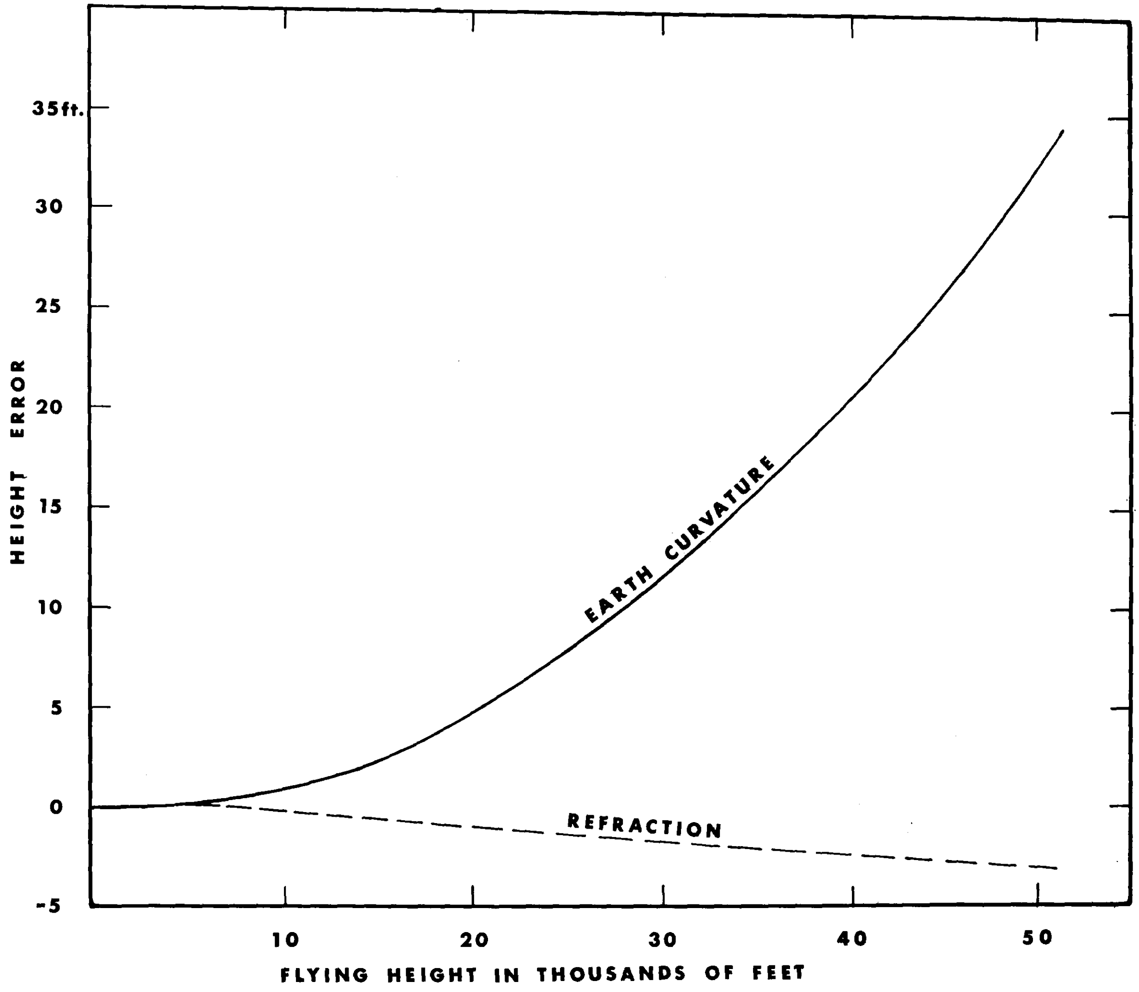

Fig. 2.11 Effects of earth curvature and refraction on photogrammetric heights.

The effects of lens distortion were also considered. In the case of the 1945 photography which was obtained with a Metrogon lens having a radial distortion curve of ± 120 microns, the effects of distortion were eliminated through the use of the previously mentioned correction plates. As the Wild Aviogon lens had a distortion of only ± 10 microns and is considered "distortion free" no corrective measures were taken for the 1965 photography. The total effects of earth curvature, refraction, and distortion for the 1965 photography would cause a maximum height error of 0.5 metre.

Spot height accuracy, and contour interval: Assuming an average operational spot height accuracy of 0.02 percent of the flying height, the machine spot heights would have a RMSE of:

1945	1965
0.02% of 7,000 m = ± 1.4 metre	0.02% of 4,000 m = ± 0.82 metre.

As both these values are greater than the errors which were caused by earth curvature and refraction, it can be assumed that the effects of these latter errors on the final height values were negligible.

For contours, if it can be assumed that the above spot height accuracies were obtained, the minimum contour interval likely to result in 90 percent of the contours within one-half the contour interval would be 7 metres for the 1945 photography and 4 metres for the 1965 photography. As a 10 metre contour interval was used the relative accuracy is much better, although the absolute accuracy remains the same.

In order to compare the contours of the two maps, the relative

/planimetric

planimetric and height differences were calculated for the 10 through 30 metre contours across the entire sandur. This was accomplished by superimposing the maps and measuring the perpendicular distances between corresponding contours at two centimetre intervals. The root-mean-square difference in planimetric positions of corresponding contours, multiplied by the tangent of the slope, gives the height differences listed below.

Contour in metres	Slope	RMS difference in planimetric position between 1945 and 1965 contours (metres)	RMS difference in height between 1945 and 1965 contours (metres)
10	23'	± 181.5 (12.1 mm)	± 1.2
20	30'	± 130.5 (8.7 mm)	± 1.1
30	50'	± 61.5 (4.1 mm)	± 0.9

It should be noted, however, that the above is for very flat ground where planimetric correspondence is likely to be poor, although height differences are quite good. Corresponding contours from the steep rock cliff area in the upper left corner of the map (Figure 2.12) confirm the high relative contour accuracy of the maps.

Final planimetric correspondence: Upon overlaying the two maps it was found that most planimetric detail coincided and that discrepancies were limited to approximately ± 0.5 millimetre in the more poorly defined features.

CHAPTER III

METHODS EMPLOYED TO OBTAIN AND ANALYSE BOTH OBJECT AND IMAGE DATA FOR THE COMPARISON OF THE BREIDAMERKUR AERIAL PHOTOGRAPHY

INTRODUCTION

In order to compare the different types of aerial photography it was necessary to establish a reference standard that would appear on all the photography and also to obtain data on the appearance and reflectance characteristics of natural objects in the Breidamerkur area. Once the photography was obtained it was essential to evaluate it on a quantitative as well as a visual basis and for this certain equipment and procedures were used. These are discussed below, whereas the results and significance of the above measurements in relation to the specification of a system suitable for obtaining aerial photography of a glacial area are considered in the following chapter.

REFERENCE STANDARDS

To compare the various film types on a quantitative basis it was necessary to establish a reference standard that would appear on all the photography. Furthermore, as colour film was to be used it was also desirable to employ a colour standard. In order to fulfil both requirements it was decided to utilise dyed cloth markers of a size sufficient to be analysed by visual and densitometric methods. Subsequently, 60 inch wide, dyed muslin cloth was obtained in the colours red-orange, magenta, yellow, green, blue-green and violet, and hand sewn

/into

into 19 x 19 foot squares. A white square was also constructed. In addition, smaller white squares of the sizes 5, 4, 3, 2, 1 and 0.5 feet were produced to be used in the analysis of definition.

All of the above cloth markers were placed on a neutral grey-gravel background near the central flight line of the interpretation photography so that they would fall within the area of best definition of the lens and photographs. Immediately after the flight was completed small patches where cut from each of the markers and carefully wrapped in black paper. The patches were subsequently sent to Perkin-Elmer Limited for spectrophotometer analysis (Figure 3.1).

REFLECTANCE MEASUREMENTS IN THE FIELD AND ASSOCIATED FIELDWORK

Reflectance Measurements

It was considered necessary to establish both the luminance and spectral reflectances of the natural objects in the Breidamerkur area[1]. This was accomplished in the second summer when the aerial photography was available for use in the field.

Luminance, which is important for determining exposure data, was measured with a Sangamo-Weston Master V light meter in the following manner. Objects identified on the photographs were located in the field

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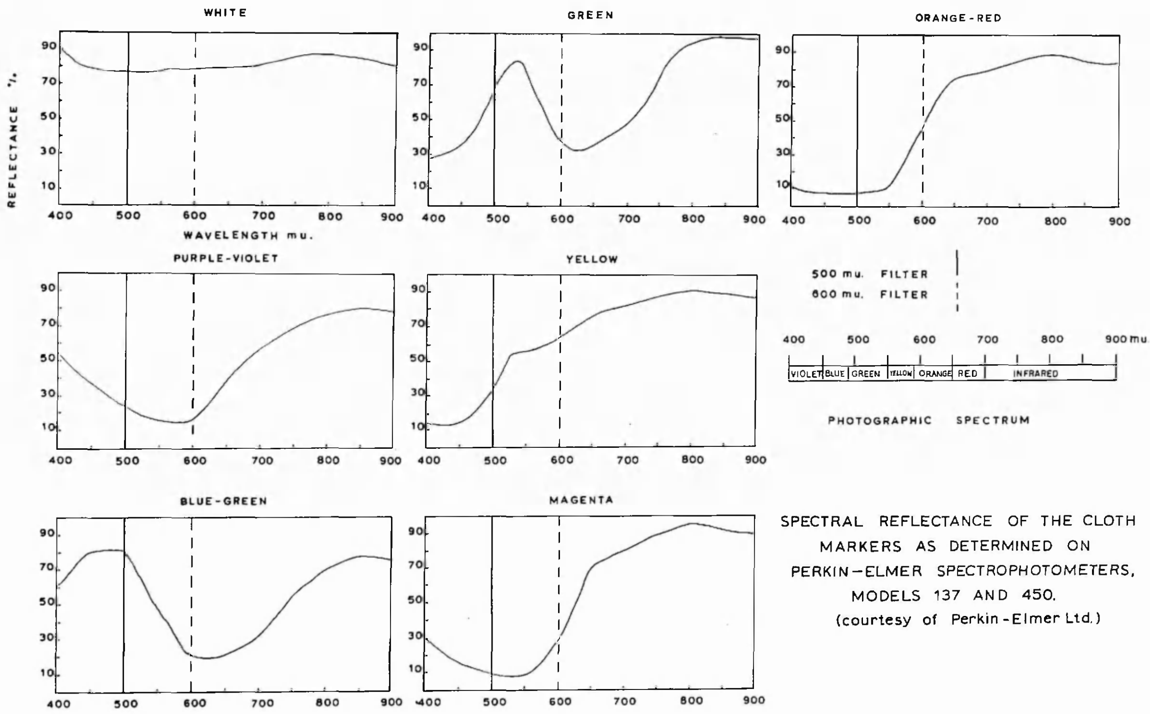
[1] Luminance (Bo) is the physical quantity of light reflected from an object and is expressed in foot-lamberts (Walsh, 1953). Spectral reflectance refers to percent reflectance in narrow bands of the spectrum.



SPECTRAL REFLECTANCE OF THE CLOTH MARKERS AS DETERMINED ON PERKIN–ELMER SPECTROPHOTOMETERS, MODELS 137 AND 450.
(courtesy of Perkin-Elmer Ltd.)

Fig.3.1 Spectral curves of the cloth markers used as reference standards.

and then with the light meter held 2.5 to 3 feet above the object, parallel to the earth's surface, the reading on the photocell was recorded. Readings were also recorded at the same time for five-foot square white and black cloth samples for which the reflection densities were known.[1] Although the angular coverage of the light meter is 55°, the recording distance of 2.5 to 3 feet was close enough to preclude the effects of what could be considered stray light. Furthermore, as the sun angle during the time of recording, 11.00 a.m. - 3.00 p.m., was approximately 45 degrees, the effects of specular reflectance were minimised (Mees and James, 1966, p.428).

The <u>spectral reflectance</u> of the natural objects in the Breidamerkur area was more difficult to measure. In recent years, investigators concerned with aerial photography have placed a great deal of emphasis on spectral reflectance, its relationship to photographic tone, and the associated possibilities of spectrozonal photography. However, most measurements have been carried out in the laboratory with specimens transported from the field (Backstrom and Welander, 1953; Keegan and Schleter, 1952-1957; Colwell/

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[1] "Reflection density is defined in general terms as the logarithm of the ratio of the evaluated portion, Po, of the radiant flux incident on the sample to the evaluated portion, Ps, of the radiant flux reflected by the sample. Thus

$$D = \log_{10} \left(\frac{Po}{Ps}\right) = \log_{10} \left(\frac{1}{R}\right)$$

where R is the reflectance of the sample." (Mees and James, 1966, p.428)

Colwell, 1960; Fischer, 1962; Rossetti and Kowaliski, 1966). Only in a few cases have measurements been made directly of undisturbed samples and with the exception of Krinov's (1947) classical data, have involved the use of a 'portable' spectrophotometer weighing several hundred pounds (Orr, Young and Welch, 1962; Olsen, 1964; Molineux, 1965; Mark Systems, 1966) with an associated generating unit. For the Breidamerkur study, laboratory measurements were ruled out because available spectrophotometers were designed for small samples (a few square centimetres) and field spectrophotometers were completely unavailable. One firm that was contacted, however, did mention they had designed, and were about to produce, a battery operated spectrophotometer, but when pressed further stated it would be a year or so before a prototype would become available.

The author then conceived the idea that it should be possible to determine the spectral curves of objects by first photographing them through a series of narrow bandpass filters and then computing the curves from the densities of the images. This idea is based on the assumption that the characteristic curve of the film employed approximates to a straight line and that the film is evenly sensitive over the spectrum utilised. Such a system would be inexpensive and portable, while the results could more easily be related to aerial photography as the method is in itself photographic. Also, by using 35 mm roll film all exposures would be on the same roll and development would be eliminated as a critical problem. Subsequently, several rolls of Ilford FP3 35 mm panchromatic film and a series of filters having peak transmissions at 20 to 50 millimicron (mμ) intervals were obtained from Ilford Limited. Similarly, 35 mm infra-red film and filters were obtained from Kodak Limited. By utilising two 35 mm cameras - one for the panchromatic film and one for the infra-red film - it was possible to cover the spectral range 400 to 900 millimicrons, which is identical to the range encompassed by the four different types of aerial photography.

It was, of course, essential to place a reference object in the field of view and for this a 10 x 14 inch white cardboard square was selected, upon which were mounted samples of the cloth markers, a Kodak grey scale, and a Kodak colour chart. In addition, it was necessary to establish the correct filter factor and, also, the exposures for varying light conditions. This was accomplished by first estimating the correct exposure for each filter (which was mounted between cardboard for convenience in handling) and then exposing a series of four photographs over the sample board at intervals of one f stop for the panchromatic film and two f stops for the slower infra-red film. The films were then developed and the negatives viewed over a light table. Based on the grey scale, it was possible to visually select the best exposure and deduce whether or not an additional correction was necessary. As the lighting conditions at the time of the test exposures were recorded on the Weston Master V light meter, it was possible to compute exposures for other lighting conditions. In this manner a chart of exposures for each film-filter combination was produced for the light meter intervals most likely to be encountered (Figure 3.2). As uniformity of exposure

/is

Fig. 3.2 Film, Filters, Filter Factors, and Exposures for the Spectral Photography with a Weston V Light Meter Reading of 13.0.

Film	Filter	Filter Factor	Aperture	Shutter Speed
Ilford FP3	601	16	10	1/8, 1/15, 1/30
	2+6	32	10	1/4, 1/8, 1/15
	623	8	10	1/15, 1/30, 1/60
	625	8	10	1/15, 1/30, 1/60
	626	8	10	1/15, 1/30, 1/60
	5+7	4	10	1/30, 1/60, 1/125
	608	100	10	1, 0.5, 1/4
Kodak Infra-red	18A+107	est. 16	5.6	1, 0.5, 1/4
	87	4	5.6	1/4, 1/8, 1/15

is imperative in this method, the computed correct exposure was used as the central exposure in a series of three photographs for the field photography. It should also be mentioned that although it is desirable to vary the aperture settings to alter exposure, this was inconvenient with the camera mounted on a tripod and, instead, the speed was varied. However, the effects of reciprocity failure have been shown to be minimal over the normal photographic range of 1 to 1/1000 second (Brock, Harvey, Kohler and Myskowski, 1966, p.34) and it is unlikely that the results were affected by this departure from normal procedure.[1]

In the field a selection of representative natural objects, including vegetation, gravels, ice, and water, were selected and located on the aerial photographs. The spectral photography was then obtained (Figure 3.3) using the following procedure:

1. The tripod was set up directly above the object to be photographed at a height of 3.5 to 4 feet and the camera attached.
2. The panoramic head of the tripod was then tilted forward until the optical axis of the camera was vertical.
3. The reference board was placed in the centre of the field of view.

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[1] Reciprocity failure refers to the fact that film exposure varied by changes in aperture does not produce exactly the same characteristic curve as exposure varied by equivalent changes in shutter speed.

Fig. 3.3 Spectral photography of moss (upper) and white ice (lower). Note sample board.

4. The light meter reading was recorded and the appropriate exposure chart selected.

5. Three exposures were made for each film-filter combination. The time required for completing a set of photographs covering the entire spectrum was approximately one hour. The photographic sequence and filter transmissions are listed in Figure 3.4.

Two variables which first caused some concern were sun azimuth and time of day. Krinov (1947) noted minor changes in spectral reflectance for the former and none for the latter. Steiner (1965) found greater differences; however, he was concerned with sun azimuths and angles of greater magnitude and variation than are found in northern latitudes and was also dealing with farm crops. In the Icelandic summer, sun azimuth changes greatly during the day but the angle does not. Furthermore, the natural objects recorded did not extend more than a few inches above the ground surface and this, coupled with the fact that the camera was mounted considerably above the object, would tend to eliminate variations in spectral reflectance.

Associated Fieldwork

Other fieldwork included the digging of stratigraphic sections, determination of rock and vegetation types, and the description and photography of all relevant ground objects. The stratigraphy of the area consists either of 1 to 2 metres of till over an indeterminate depth of gravel, as in the case of morainic deposits, or solely of gravels, as in the case of fluvioglacial materials.

Fig. 3.4 Sequence of Exposures and Filter Transmissions for the Spectral Photography.

Film, Filter and Sequence	Transmission (mμ)	Peak Transmission (mμ)	Filter Factor
Panchromatic			
Ilford 601	390-460	430	16
2 + 6	430-480	450	32
623	470-540	500	8
625	520-580	540	8
626	560-600	575	8
5 + 7	590-660	630	4
608	630-660	650	100
Infra-red			
Kodak 18A + Ilford 107	690-800	740	16
Kodak 87	above 740	800	4

The predominant rock types are basic intrusive and extrusive lavas and the major vegetative growth consists of mosses and sparse grass. Descriptions of ground features are largely discussed in Chapter V and are accompanied by illustrative photographs.

DETERMINATION OF THE REFLECTANCE VALUES

In order to obtain both luminance values and spectral reflectance curves for the natural objects, it was necessary to carry out laboratory measurements and calculations.

Luminance

For luminance, values in foot-lamberts were desired for each point on the light meter photocell scale. In addition, it was considered essential to determine the spectral response of the photocell. As this data was not available from the manufacturers, the light meter, accompanied by the white and black cloth samples, was sent to the National Physical Laboratory for calibration. Although conditions for the calibration were specified in accordance to the actual use in the field, this was rendered impossible because of equipment limitations and certain compromises were necessary. Basically, the luminance calibration was performed by placing the light meter in front of an opal diffusing plate illuminated from behind by a tungsten light (Standard Illuminant A at 2854°K). Intensity was altered by varying the distance of the light from the opal plate and luminances on the diffusing side were measured with an illuminometer calibrated at 2854°K. As the illuminometer values corresponding to the scale of the light meter photocell were furnished

/in

in candelas per square metre, it was necessary to apply a <u>conversion</u> factor to obtain foot-lamberts. This conversion is carried out in the following manner:

$$\begin{aligned} 1 \text{ candela/metre}^2 &= 0.0929 \text{ candelas/foot}^2 \\ &= 0.0929 \times \pi \text{ lumen/foot}^2 \\ &= 0.2919 \text{ foot-lamberts} \end{aligned}$$

$$(1 \text{ foot-lambert} = 1 \text{ lumen/foot}^2)$$

In addition, a <u>correction factor</u> (F) for an energy source approximating daylight (6000°K) was required because of the non-uniform spectral response of the photocell (Figure 3.5). Therefore, Standard Illuminant C (6500°K) was chosen for which the spectral power distribution is available in Wright (1964, p.267). The correction factor (F), by which the values in foot-lamberts obtained for Standard Illuminant A must be multiplied, was derived from the responsivity curve and the data from Wright by the following formula:

$$F = \frac{\int E_{2\lambda} \; V_\lambda \; d_\lambda}{\int E_{1\lambda} \; V_\lambda \; d_\lambda} \times \frac{\int E_{1\lambda} \; S_\lambda \; d_\lambda}{\int E_{2\lambda} \; S_\lambda \; d_\lambda}$$

where: $E_{1\lambda}$ and $E_{2\lambda}$ = the relative spectral power distribution of the light sources under consideration (Standard Illuminants A and C).

S_λ = the relative spectral responsivity of the photocell.

V_λ = the relative spectral sensitivity of the eye.

In this case $E_{1\lambda}$ and $E_{2\lambda}$ are already weighted for V_λ and the first term drops out leaving:

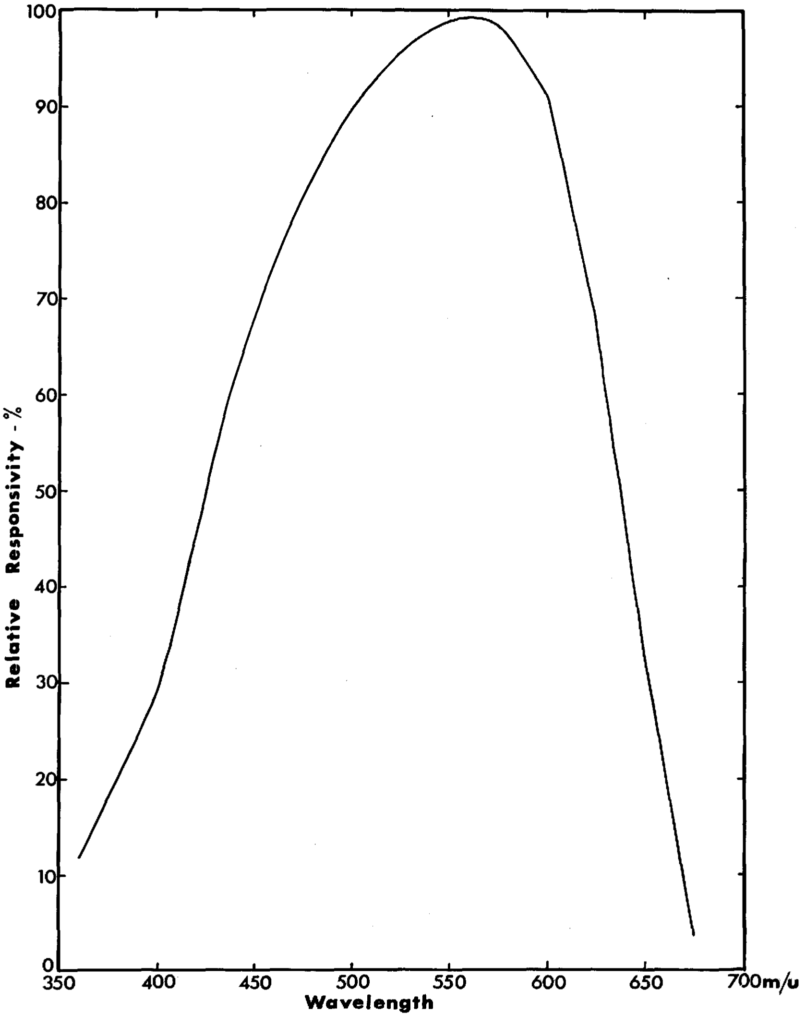

Fig. 3.5 Spectral response of the photocell.

$$F = \frac{\int E_{1\lambda} S_\lambda d_\lambda}{\int E_{2\lambda} S_\lambda d_\lambda}$$

This integration was performed by the author and the factor, F, was found to be 0.83. Its value was later confirmed by measurements at the National Physical Laboratory.

The luminance scale of the light meter based on the calibration data is listed in Figure 3.6. A continuous graph plot has been derived from these values and is shown in Figure 3.7. Based on the known reflection densities of the black and white cloth samples and their average light meter readings, it has also been possible to establish an equivalent percent luminance scale (see Figure 3.6). Furthermore, as 100 percent luminance in foot-lamberts is equal to illumination in foot-candles, the illumination has been determined as equal to 5700 foot-candles.[1] This figure agrees fairly well with the figure of 6000 foot-candles computed by Brown (1952) for the months of June and July at 64 degrees north latitude ± 3 hours from local apparent noon.

Something should also be said of the accuracies of the luminance measurements and the relationship of the non-uniform sensitivity of the photocell to the reflectance characteristics of natural objects. In regard to the former, the National Physical Laboratory indicates an uncertainty of ± 5 to ± 10 percent. The latter has not been determined;

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[1] The foot-candle is a photometric unit of <u>illumination</u>

Fig. 3.6 Luminance Values Based on the Weston V Light Meter

Meter Reading	True Luminance (Candelas/ metre^2)	Foot-Lamberts for 2854° K (candelas/ metre^2 x 0.2919)	Foot-Lamberts for 6500° K (Foot-Lamberts for 2854° K x 0.83)	Equivalent Percent Luminance 100% = 5700 Foot-Lamberts
15.97	21,000	6,159	5,112	90
14.99	8,390	2,449	2,033	36
14.00	3,970	1,159	962	17
13.00	2,020	590	490	9
12.00	1,000	292	242	4
11.00	513	150	125	2
10.00	277	81	67	1

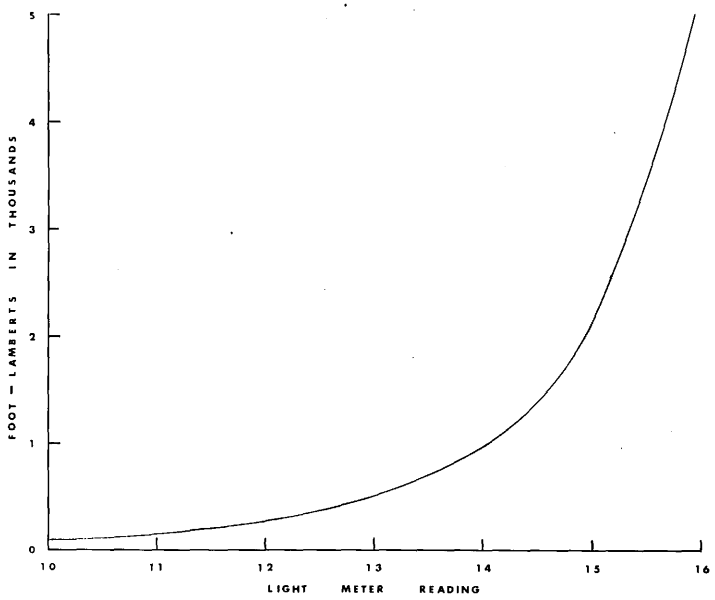

Fig. 3.7 Luminance values for the Weston V light meter; **graphical representation of Fig.3.6**

however, as most natural objects have very low colour saturations (Penndorf, 1956) and low reflectances in general, the non-uniform response of the photocell is not thought to significantly affect the measurements.

Spectral Reflectance

In order to derive spectral reflectance curves for the natural objects, several separate operations were required. The first was the development of the films, which was carried out under carefully controlled conditions to ensure both uniformity over an entire roll and between rolls. Next, density measurements using an EEL Universal densitometer were performed on 22 rolls of negatives, using the following procedure for each exposure:

1. Densities of each of the eight cloth samples on the reference board were measured.
2. Four to six density measurements were then made of the natural object and the average density recorded.

In all, a total of nearly 7000 density measurements were performed.

From the recorded density measurements of the black and white cloth samples, it was possible to select one negative from each series of three exposures which matched a standard (determined after preliminary analysis and experimentation). An example of eight exposures selected on a roll of panchromatic film is shown below.

/...

Ilford Filter No.	Filter Colour	Density (units) White	Density (units) Black
None	-	1.27	0.44
601	Blue	1.24	0.44
2 + 6		1.24	0.44
623		1.29	0.44
625	Green	1.33	0.42
626		1.36	0.42
5 + 7		1.27	0.42
608	Red	1.24	0.38

Once the exposures had been selected, adjustment was carried out for each exposure independently using the method outlined below. The actual example discussed is shown in Figure 3.8 and is based on a panchromatic film-red filter combination exposed over an area of fluted moraine.

1. Cloth samples listed.
2. Density of the film base plus fog recorded (Clear or Cl). Note that the decimal point in the density measurement has been dropped to simplify computational procedures.
3. Density of each coloured cloth sample (C) is recorded and also the density of the natural object under study.
4. Clear (Cl) density subtracted from the density of the cloth samples and natural object (C-Cl).
5. Next, a correction factor is established on the basis that density units can represent percent reflectance provided reflectance is known for the cloth samples. In this case

Fig. 3.8 Example of the Method Used to Determine the Spectral Reflectance of Natural Objects. Note this example is for Fluted Moraine at the Wavelength of 630 Millimicrons.

Cloth Samples/ Natural Object	Clear (C1)	Colour (C)	C-C1	Correction Factor	Provisional %	Trace %	Difference	Correction	Final
White	35	124	89	79/89 = .89	79	79	0		
Red	"	111	76	"	68	68	0		
Magenta	"	98	63	"	56	62	-6		
Yellow	"	124	89	"	79	70	+9		
Green	"	64	29	"	26	33	-7		
Blue-green	"	59	24	"	21	20	+1		
Violet	"	64	29	"	26	24	+2		
Black	"	40	5	"	4	2	+2	-1	3
Fluted moraine	"	51	16	"	14			-1	13

a reflectance of 79 percent for the white cloth sample has been determined from the Perkin-Elmer spectral traces and the white-clear value obtained in step 4 is used to obtain provisional reflectances. For example, if white reflected 79 percent and white-clear (C-Cl) = 89 density units, then the correction factor equals 79/89 = 0.89.

6. The C-Cl values for all the other colours were then multiplied by this factor to give a provisional percent value (%). Both steps 5 and 6 are conveniently performed by slide rule.

7. The provisional percent values were next compared with the Perkin-Elmer spectral reflectance (Trace) values at peak filter transmission points for the cloth samples. Based on the difference between the provisional percents and the trace percents an additional correction was applied to obtain the final value (Final) for the natural object, which in this case is fluted moraine. As can be seen, this last correction is based primarily on those markers whose density values are closest to that of the natural object, in this case blue-green, violet and black.

An example for a panchromatic film-blue filter combination with maximum transmission at 430 millimicrons is shown in relation to the characteristic curve in Figure 3.9.

The accuracy of the method depends on several factors, including:

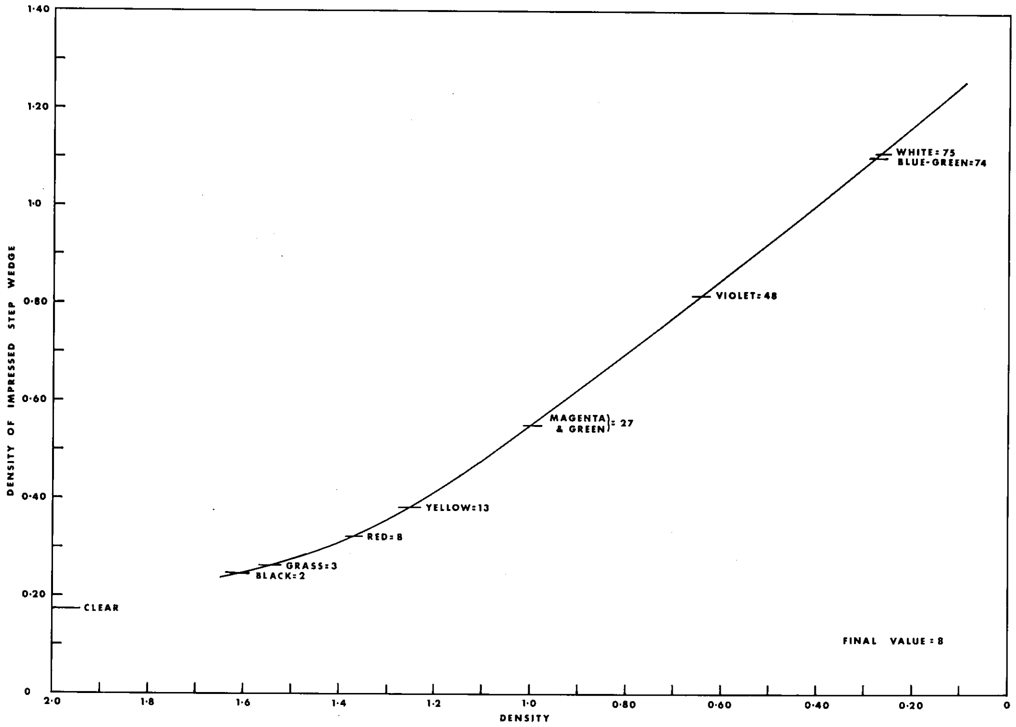

Fig. 3.9 Characteristic curve of a spectral photograph taken through a 430 mμ filter.

1. The accuracy and gradient of the reference spectral trace in the zone of the spectrum under consideration.
2. The accuracy of the filter transmission curves.
3. The wavelength interval between filters and the amount of overlap between transmission curves.
4. The evenness of sensitivity of the film employed and the spectral transmission of the camera lens.
5. The linearity of the characteristic curve and the accuracy of density measurements.

Of the above items, 4 and 5 appear to be the factors which are most difficult to establish and control. In regard to item 4, it would be possible to integrate the spectral sensitivity and transmission curves of the film and lens with the spectral trace to determine the effective spectral trace from which the final correction would be determined; however, this would only appear to be necessary if either the film sensitivity varied considerably over the spectral range being used or if highly saturated objects were being photographed. For low saturations, such as exhibited by most natural objects in the visible spectrum, determination of the correct filter factor appears to compensate adequately for variations in the sensitivity of the film and the transmission characteristics of the lens.

The largest source of error, of course, lies with the sensitometric characteristics of the film employed. Ideally, a film employed for this type of work should have a short toe, a long straight line portion

/and

and a gamma, which under normal processing conditions, is near unity. In this instance the density of the black cloth fell on the toe and most of the natural objects just at the bottom of the straight line portion. By giving more weight to values in the low densities for the final correction it has been possible to obtain an estimated ± 3 percent accuracy in the visible spectrum and ± 5 percent in the infra-red spectrum. Precision is much better and has been found to be ± 1 and ± 3 percent in the visible and infra-red spectrums respectively. The reason for the lower accuracy in the infra-red is largely due to the fact that all of the markers exhibit high infra-red reflectance and it is only possible to obtain approximate correction factors. On the whole the spectral traces derived for the natural objects agree quite well with those obtained by Krinov for similar objects.

EQUIPMENT USED IN THE ANALYSIS OF THE PHOTOGRAPHY

Equipment can be divided into the following categories, including: photographic materials, viewing equipment, and analysing equipment.

Photographic Materials

With the exception of the false colour, which was used as a reversal film, it was necessary to produce positives from negatives. Although paper prints are preferable for fieldwork, positive film transparencies are necessary for a quantitative analysis of definition and tone. In regard to definition, the transparent base minimises multiple internal reflection of light between the base and emulsion

/surface

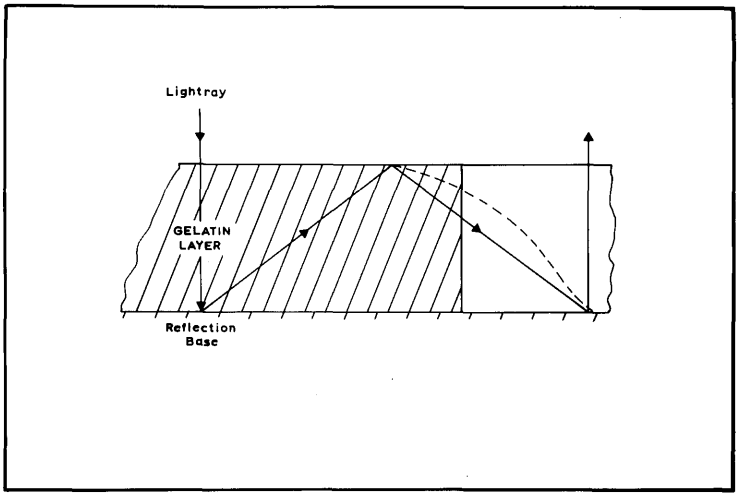

Fig. 3.10 Loss of edge sharpness due to internal reflections between the base of a paper print and the surface of the emulsion layer.

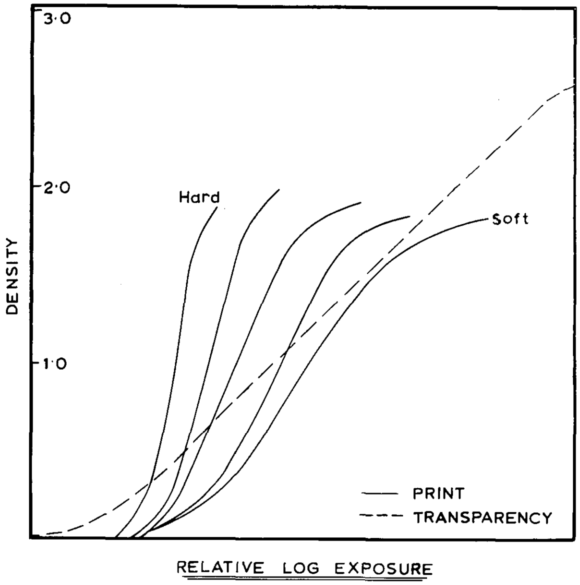

Fig. 3.11 Characteristic curves of representative paper print and film transparency material, also called D-log E curves.

surface (Figure 3.10), thereby increasing edge sharpness and thus improving definition (Stapleton, 1964). On paper prints small tonal differences will be obscured by loss of edge sharpness and also the more limited brightness range (Figure 3.11) may be insufficient for recording the total brightness range in the negative (Corten, 1960; Mullins, 1966). In addition, most analysing equipment, such as densitometers and spectrophotometers, is designed to accept transparent materials. For these reasons, positive film transparencies were produced from the colour, panchromatic, and infra-red negatives.

Viewing Equipment

For the visual analysis of the transparencies it was necessary to construct a special light table that would produce white light of sufficient intensity to illuminate colour transparencies viewed through filters. The light table is shown in Figure 3.12 and consists of 12 Philips 40W colour matching tubes (6500°K), dimmer units, and a small exhaust fan. A mask, made from cardboard, was designed to prevent stray light from reducing visual contrasts when viewing either single or pairs of transparencies. According to Colwell (1954, 1966) perhaps 200 steps on the grey scale can be detected by using variable intensity, rear illumination.

As it was desired to view the colour transparencies through coloured filters in order to enhance the images by means of spectral filtering (O'Neil and Nagel, 1957), it was necessary to obtain transparent

/materials

Fig. 3.12 Light table used for the visual interpretation.
Note the mask, fan, and dimmers.

materials for which the spectral transmission curves were known. After considerable investigation, gelatin filters used in theatrical lighting were obtained from Strand Electric Limited, London. These filters, which come in sheets measuring 24½ x 21 inches, cost only a few shillings each, yet are of high quality and standard transmission curves are furnished. The filters were placed either beneath or above the transparencies during the analysis. Their position in relation to the viewer is not critical (Judd, 1955).

Optical equipment used in the visual analysis included Hilger and Watts, Wild, and Hensoldt monocular magnifiers of 5 to 40 times magnification, and Wild, Toko, and Old Delft stereoscopes of 1.5 to 4.5 times magnification. Generally, an approximation of the necessary visual magnification for maximum detection possibilities is equal to the resolution in lines per millimetre x 0.8 (Selwyn, 1948); however, in most practical work the factor $\frac{\text{lens-film resolution}}{\text{eye resolution}}$, where eye resolution is taken as 5 lines per millimetre, will give a good indication of the magnification most suited for general viewing and interpretation.

Analysing Equipment

In order to measure the brightness or densities of images on the various films and also to check the spectral transmission of various filters, the following equipment was used.

/...

Type	Characteristics	Purpose
Hilger and Watts microphotometer	Light transmission only.	To determine image brightness of cloth markers.
EEL Universal densitometer	White light, 1, 2, and 4 mm apertures, red, green and blue filters. Density readings direct.	Determination of densities for spectral reflectance computations, and also of the images of natural features on the aerial photography.
Joyce, Loebl Mark IIIC recording microdensitometer	White light, graph plots, gear ratios of 1:1 to 200:1, slit widths of less than 1 micron.	Definition studies.
Perkin-Elmer spectrophotometers	Visible spectrum recording spectrophotometers for small transparent samples.	Analysis of filters to check transmission curves.

Of the above instruments, the Hilger and Watts microphotometer was found to be extremely susceptible to stray light and of little practical use other than to measure the brightness (light transmission) of the images of the coloured cloth markers on the aerial films. The EEL Universal densitometer was excellent for measuring the transmission densities of image areas larger than two millimetres square on aerial and ground photographs; however, its usefulness is limited due to the restricted aperture range of 1 to 4 millimetres. The Joyce, Loebl microdensitometer is well suited for measuring the transmission densities of image areas down to a few microns in diameter. In addition, its excellent gear ratios and continuous graphical plot capability permit edge traces of

/targets

targets imaged on the film to be obtained. As discussed below, these traces can be used to evaluate the definition capabilities of the photographic system. The spectrophotometers, while useful for checking the spectral transmission of some of the filters, were designed for liquid chemical analysis and could not be adapted for image-evaluation studies.

PROCEDURES IN THE QUANTITATIVE EVALUATION OF DEFINITION

Definition, which is usually taken to mean the clarity with which detail is reproduced (Higgins and Perrin, 1958, p.66), is associated with good modulation transfer function, low granularity and high resolving power (Brock, Harvey, Kohler and Myskowski, 1966, p.42). For many years definition has been judged on the basis of resolving power which is expressed in terms of lines per millimetre. In photographic terminology (which must be distinguished from television) a line of resolution is equal to the combined width of a light line and its associated dark space (Brock, 1952), both being of equal width. Therefore, if resolution is equal to 10 lines per millimetre, each light and dark component has a width of 0.05 millimetre or 50 microns. In recent years, however, it has been realised that more than resolving power is necessary for good definition and during the period 1948 to present numerous papers have been published on the factors affecting definition (e.g. Selwyn, 1948; Kardas, 1955; Higgins, Wolfe and Lamberts, 1956; Barrows, 1957; Lamberts, 1959; Perrin, 1960, 1961; Campbell, 1962; Fleming, 1963; Mikhaylova, 1965).

Perhaps the least well understood concept now being applied to image evaluation is that of modulation transfer function (MTF). In its original form MTF is based on the fact that a sinusoidal distribution remains sinusoidal after imagery, regardless of the image forming system (Selwyn, 1948, 1959). However, because perfect lenses are still diffraction limited (due to the aperture), and because films will diffuse the image somewhat, due to internal reflections[1], the amplitude of the sinusoidal distribution in the object will be reduced in the image as its frequency is increased. This attenuation of amplitude with increasing frequency is known as the modulation transfer function, where modulation is normally expressed as:

$$M = \frac{I\ max - I\ min}{I\ max + I\ min}$$

where: I is expressed in relative linear units, such as transmission.

(This is another method of expressing contrast, hence the term contrast transfer function is sometimes used.) In simpler terms, as the lines per millimetre are increased the edges become closer together and because of diffusion will eventually overlap, finally taking the form of a solid image of uniform density.

Although the theory of the MTF is based on sinusoidal targets, sharp square edges, such as those encountered in resolution bar targets,

/or

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[1] That is, both lens and emulsions have spread functions.

or isolated objects such as single bars, edges of pavement, or overhanging roofs, etc. can, for practical photographic purposes, be assumed to represent a sinusoidal distribution (Brock, 1961). By scanning the image of such an edge with a microdensitometer having a long narrow slit, aligned parallel to the edge being measured, the amount of diffusion due to combined spread functions of lens and emulsion is automatically integrated to give an edge trace which can be represented by I (x) (Figure 3.13). I(x) is, in fact, the summation of a series of line spread functions and is therefore an intensity distribution.

$$I(x_o) = \int_{-\infty}^{x_o} A(x)dx$$

where: $A(x)$ = line spread function

x_o refers to bar width (microns).

The visual impression of edge sharpness that is rendered is dependent on the density distribution across the edge. As previously mentioned, edges in photographic images approximate to a sinusoidal distribution and because spread functions, edge traces and MTF are all interconvertible (Mees and James, 1966), it is possible to determine the MTF of a system from edge trace data. That is, it is possible to determine the frequency response or contrast for any resolution over the bandwidth (range of resolution) reproduced by the system for a given target contrast. When edge traces of single bars are the basis for this calculation, the result is more properly termed the <u>single-bar response function</u>. Mathematically the single-bar response function

/(Ix_o)

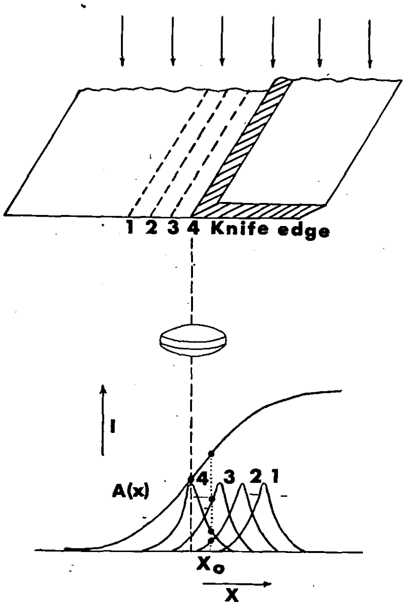

Fig. 3.13 Formation of edge trace I(x) as summation of elementary line spread-functions A(x). The summation of four elements is indicated for the position x_o.

(Mees and James, 1966, p.502)

(Lx_o) is equal to:

$$L(x_o) = 2E(2x)$$

Where: $E(x)$ is the normalised exposure edge response function and is derived from $I(x)$ and the characteristic curve.

The single-bar response function has been computed for the colour, panchromatic and infra-red photography using the following method (Itek No. 7, 1964, p.24). See Figure 3.14.

1. Edges of the white (medium contrast target) and purple (low contrast target) cloth squares were traced using the Joyce, Loebl microdensitometer. Slit size was 3 x 200 microns and a gear ratio of 200:1 was used throughout (1 millimetre in the image was enlarged to 200 millimetres on the plot; similarly, 1 millimetre on the graph was equal to 5 microns in the image).
2. Step wedges impressed on the transparencies at the time of printing were also recorded.
3. A plot of image distance to density was constructed for the smoothed edge trace.
4. The characteristic curve of the transparency was determined by plotting known densities of the step wedge against the densities of the impressed step wedge. The densities of the former were then converted to log relative exposure.
5. Using the characteristic curve determined in step 4 and the plot obtained in step 3, a third plot was constructed of

/image

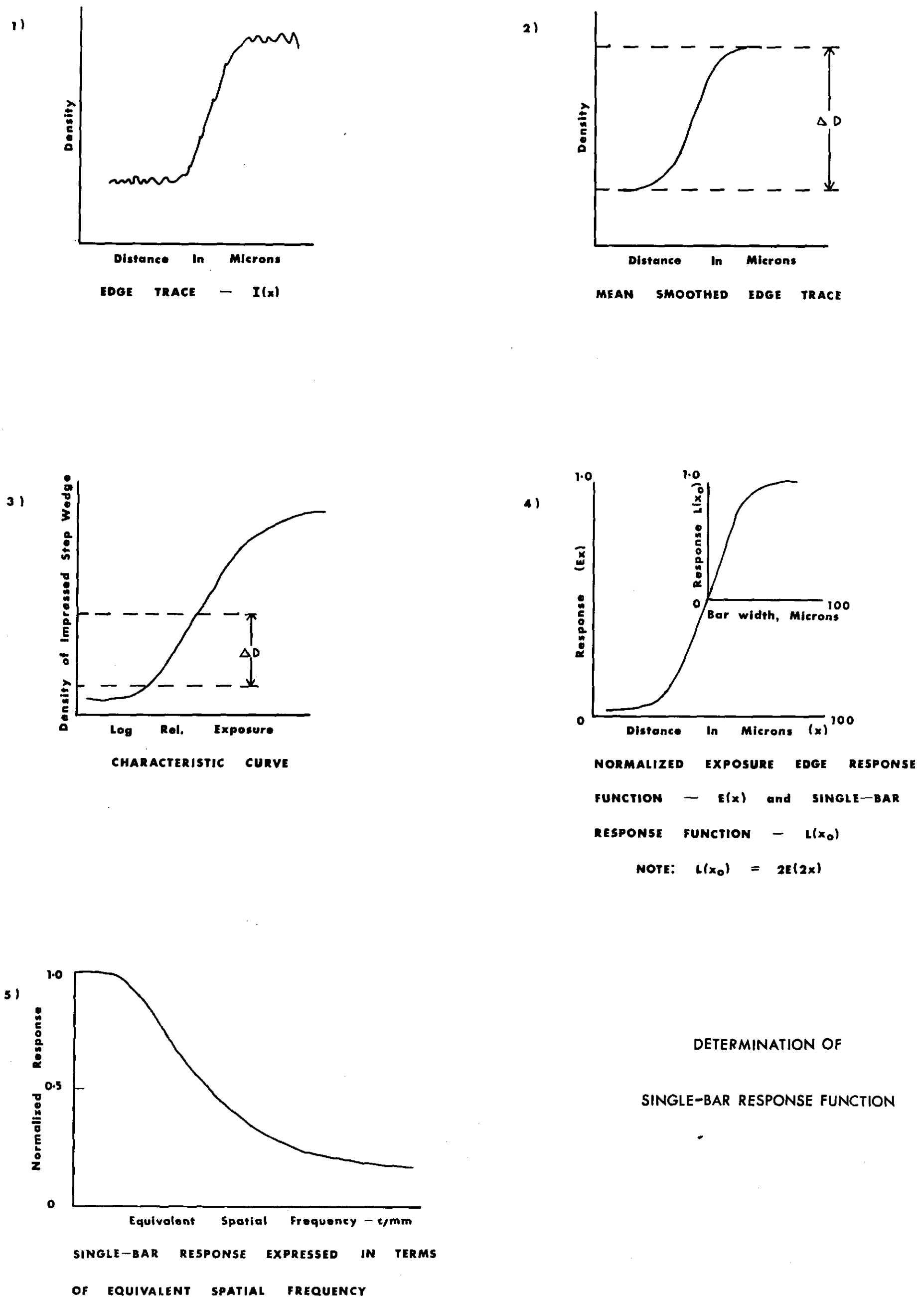

Fig. 3.14 Determination of the single-bar response function from edge trace data.

image distance, x, against relative exposure (Ex) which represents response.

6. The mid-point of the exposure edge response function was visually selected and a new set of coordinate axes drawn.

7. The ordinate of these axes becomes the normalised single-bar response (Lx_o) and the abscissa becomes the bar width (x_o) with increments along both axes having twice the values of those used in the exposure edge function.

To obtain the single bar response as a function of spatial frequency, or what for practical purposes can be called the MTF system, it is necessary to convert the bar width to cycles per millimetre (or, in alternative terminology, lines per millimetre) by:

$$\frac{1000}{2x_o}$$

The resulting plot then appears as in 5 of Figure 3.14. It should be noted that this is a simplified graphical method based on the assumption that the edge spread functions are symmetrical and, strictly speaking, symmetry is only likely to occur on-axis; however, as it is thought that the accuracy of this method is sufficient for the analysis of present day high acuity aerial photographic systems, it should be satisfactory for lower acuity systems such as the one being discussed.[1]

/Also

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[1] High acuity systems include long focal length panoramic camera-fine-grain film combinations which produce resolutions well above those of ordinary survey camera-film combinations.

Also, although it would have been desirable to compute the single-bar response function of the false colour photography, it was not possible to impress a step wedge on the reversal film prior to development. It should further be mentioned that while extensive testing of MTF procedures has been accomplished under laboratory conditions using test cameras (Itek, 1962-1964), only Welander (1962, 1966) mentions operational data for more conventional survey cameras. Furthermore, although badly needed, little work has been done on the relationship of quantitative data to qualitative analysis. This aspect in regard to a glacial area is fully discussed in the following chapter.

PROCEDURES USED IN THE OBJECTIVE SPECIFICATION AND MEASUREMENT OF TONE AND CONTRAST

Tone and contrast, like definition, can be regulated in the photographic process providing the characteristics of the environment and photographic system are known. Similarly, it is possible, although to a lesser degree, to evaluate the benefits of tone and contrast through quantitative measurements of the images of objects. However, before discussing these factors the concepts of colour, tone and contrast will be reviewed.

Colour is usually thought to consist of three components or dimensions: hue, saturation, and brightness. Hue refers to a scale of perceptions ranging from blue through red; saturation represents a colour's degree of departure from an achromatic colour (one lacking a

/distinguishable

distinguishable hue) of the same brightness; and brightness is that dimension referring to a series of achromatic colours ranging from dark to light (Burnham, Hanes and Bartleson, 1963, pp.13-14). From a photographic interpretation viewpoint, the advantage of colour aerial photography over black-and-white is that the combination of hue plus saturation (chromaticity) is added to brightness (tone). For discussion purposes, however, tone will refer to the cumulative psychological impression of hue, saturation and brightness when discussing colour or false colour aerial photography, but only to brightness differences in black-and-white photography. In photographic terminology, brightness of the object is usually expressed as log brightness or, more correctly, log luminance. In the photograph, the object luminances become image densities.

The term 'contrast' is used both to imply tonal differences in the scene or image and the capacity of a photographic material to produce differences among tones in the photographic image (Todd and Zakia, 1967). Because of the various aspects of contrast and its numerical expression, it is best considered in terms of subject and photographic contrast.

Subject contrast is usually expressed as the logarithm of luminance ratios. For example, if the highlight luminance of a scene is 2000 foot-lamberts and the darkest shadow represents a luminance of 100 foot-lamberts, then the luminance ratio is 20:1 and the log luminance ratio is 1:3.

The contrast of photographic materials is determined from

/sensitometric

sensitometric data and may be expressed as:

1. Gamma (γ), the slope of the straight line portion of the Density vs log Exposure curve (D - log E or characteristic curve).
2. A density difference which $= \log \left(\frac{I \max}{I \min}\right)$
3. A log E interval between two points. The log E interval is inversely related to contrast.

In tone reproduction, if log luminances of the scene are plotted against transmission densities of a negative or transparency and the result is a straight line with a slope of 1.00 (45 degrees), then exact reproduction has been obtained and luminance differences are equal to density differences (Mees and James, 1966, p.465). If the gamma is raised, the density differences or contrasts are greater than the luminance differences in the scene. Similarly, if the gamma is reduced, contrast is also reduced.

The <u>relationship of contrast to the human eye</u> has been largely investigated in terms of contrast thresholds. Middleton (1935), for example, found that the eye could distinguish a luminance difference of two percent when viewing <u>distant objects</u> and Selwyn (1948) established that the contrast threshold of resolution in the black-and-white <u>photographic image</u> is about 0.02 to 0.04 density units. With colour photographs, Mikhailov (1961) found that density differences of 0.07 were required before changes in brightness were noted; however, the eye's sensitivity to changes in hue is of the order of two millimicrons change

/in

in wavelength. With this brief introduction in mind, a quantitative approach to obtaining good tone reproduction of features in glacial areas will be discussed.

Factors Affecting Tone and Contrast

Factors which will influence tone and contrast reproduction in the aerial photograph include illumination, reflectance characteristics of the natural objects, atmosphere and camera flare, illumination fall-off, filter, exposure and the film and processing conditions. If all the above parameters can be determined, it is possible to specify an entire photographic procedure prior to the aerial mission and to predict what the tone and contrast relationships are likely to be. This can be accomplished through formulae and tone reproduction diagrams.

Illumination and Reflectance

For vertical aerial photography it is desirable to consider the earth as a horizontal plane and illumination as a function of solar altitude. Illumination is then referred to as solar horizontal plane illumination (Brock, 1961) and can be represented by (Is). It is usually expressed in foot-candles or metre-candles.

The luminance reflectance of natural objects in units such as foot-lamberts can be derived from direct measurement (Jones and Condit, 1941) with calibrated instruments (e.g. the light meter) or, provided both solar horizontal plane illumination in foot-candles and the reflectance factor (percent reflectance) of the object are known, foot-lamberts can be derived from:

foot-lamberts = foot-candles x reflectance factor.

Therefore the luminance of ground objects can be represented by (Bo) or by (Is·Rg) where Rg equals the reflectance factor.

Atmosphere

The overall effect of the atmosphere is to reduce contrast with the amount of reduction determined by the size and number of light scattering particles in the atmosphere at the time of photography. Basically there are two types of scattering (Brock, 1952, p.160):

1) that caused by gas molecules to create a "Rayleigh" atmosphere; and

2) that due to particles in the air which create a "Mie" atmosphere.

In a Rayleigh atmosphere, which exists largely between 15,000 and 40,000 feet, scattering is inversely related to the fourth power of wavelength.[1] According to Middleton (1950, p.671), Rayleigh atmospheres are characterised by a hue of about 475mμ thus accounting for the visually blue skies on clear days. Below 15,000 feet, Mie particles, such as dust, smoke or pollen, or water droplets, cause scattering which is less distinctly related to wavelength. That is, as the number or size of particles increases, non-wavelength dependent scattering also increases (Bullock, 1956) resulting in a de-saturation of colours (Bogachkov, 1962) and hence loss of contrast. For this reason aerial photography is best carried out in clear skies and bright sunlight (Aschenbrenner, 1954).

/Because

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[1] Scattering is non-existent at altitudes above 40,000 feet (Bousky, 1960).

Because of scattering, the atmosphere both reduces the transmission of object reflectance and adds a luminance of its own. For example, data by Mazurowski and Walker (1962) indicate that the transmission of the atmosphere in the normal direction for clear weather conditions is approximately 0.5 in the blue, 0.7 in the green, and 0.8 in the red and near infra-red regions of the spectrum. Other data (Brock, Harvey, Kohler and Myskowski, 1966) indicate that for hyper-altitude photography (above 30,000 feet), atmospheric luminances of 575 to 725 foot-lamberts can be expected for solar altitudes of 30 to 50 degrees. The effects of both atmospheric attenuation and luminance are summed up in the following formulae:

$$B_{o_A} = Bo \cdot Ta + Ba$$

and $$C_a = \frac{Bh \cdot Ta + Ba}{B_1 \cdot Ta + Ba}$$ (Brock, Harvey, Kohler and Myskowski, 1966, p.16).

where: Bo_A = the luminance of the object as viewed from the air (foot-lamberts)

Ca = aerial contrast

Bh = highlight luminance of a ground scene (foot-lamberts)

B_1 = lowlight luminance of a ground scene (foot-lamberts)

Ta = atmospheric transmission (%)

Ba = atmospheric luminance plus camera flare (foot-lamberts)

Bo = luminance of the ground object (foot-lamberts).

Effects of the Atmosphere and Camera

When the effects of the atmosphere plus camera flare are added to illumination fall-off, filter factor and exposure time, there are likely to be further changes in tone and contrast (Tupper and Nelson, 1955; Tupper, 1956; SPSE, 1966). Considering only on-axis illumination in the image plane, it is possible to compute a graphical plot of the relation between these factors. For example:

$$I = \frac{B_{o_A} T_L}{4(f/no)^2 F}$$

(Kingslake, 1963, p.109)
(Brock, Harvey, Kohler and Myskowski, 1966, p.85)

where: I = illumination in the image plane in foot-candles

T_L = lens transmission (%)

f/no = relative aperture

F = filter factor

B_{o_A} = luminance of the aerial object in foot-lamberts.

Substituting the previously mentioned equation for B_{o_A} into the above and considering exposure time, the following formula is obtained:

$$E = \frac{t(Bo \cdot Ta + Ba)\, T_L}{4(f/no)^2 F}$$

where: E = exposure in foot-candles-seconds

t = shutter speed in seconds.

Multiplying by 10.76 to obtain metre-candle-seconds (sensitometric data is usually expressed in metre-candle-seconds):

$$E = \frac{2.7t\ (Bo \cdot Ta + Ba)T_L}{(f/no)^2\ F}$$

Using this formula Figure 3.15 has been derived. This curve can be called the atmosphere and camera curve.

The combined effects of atmosphere, camera and exposure can be seen to severely compress the luminance range of the ground scene, particularly in the lowlight region.

Determination of Exposure and its Relation to the Film

Because of compression of the ground scene luminance range even before the film is considered, it is usually desirable to employ aerial films with a gamma of greater than 1.0 so as to increase contrasts in the developed image. In order to do this, however, the camera exposure must be such that both the lowlights and highlights are recorded on the straight line portion of the characteristic curve (Harris, 1957). For negative films the lowlights must be recorded at the bottom of the curve and for reversal films, the highlights. Normally, the camera exposure is chosen so that the lowlight (or highlight) luminance produces a density of 0.3 to 0.5 above base plus fog. To calculate the exposure the following formula is used:

$$t = \frac{E_1\ (f/no)^2\ F}{2.7\ (Bo \cdot Ta + Ba)\ T_L}$$

where: E_1 is the lowlight film exposure in metre-candle-seconds required to produce a density of 0.3 to 0.5 above base plus fog and is obtained from sensitometric data (Figure 3.16).

/Tone

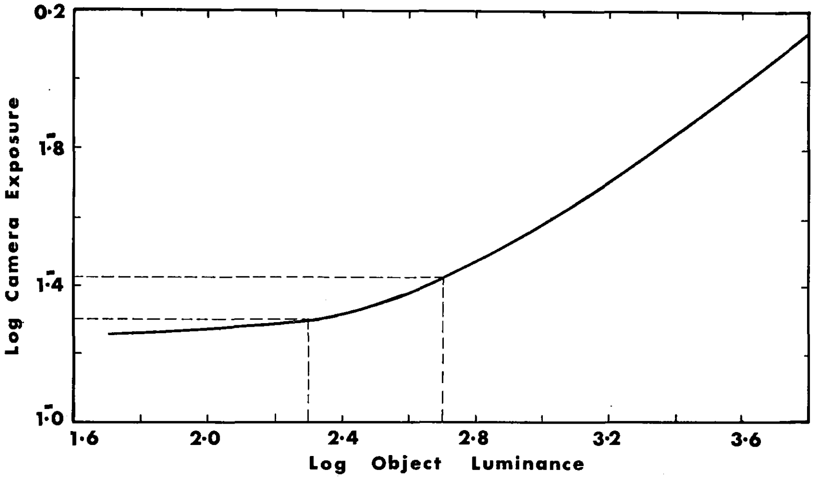


Fig. 3.15 Atmosphere and camera curve. Note the severe compression in the lowlight region due to atmospheric luminance and camera flare (Brock, Harvey, Kohler and Myskowski, 1966, p.85).

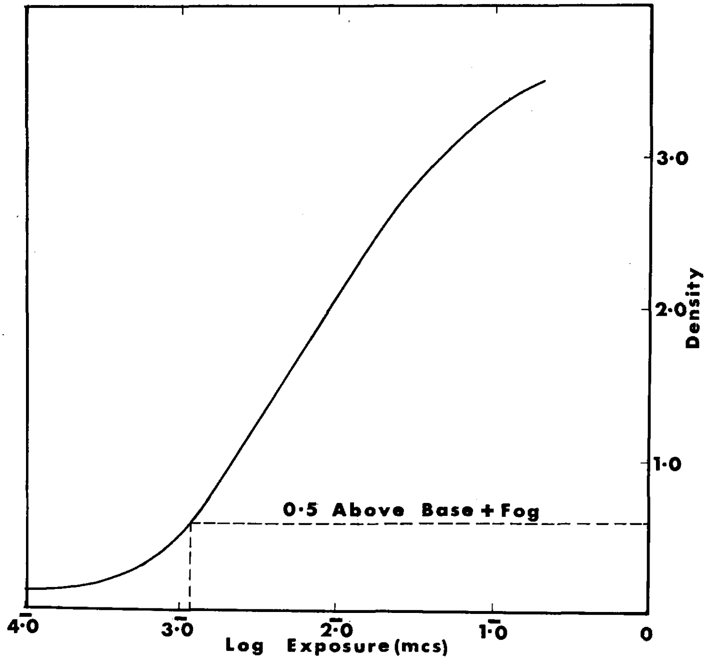


Fig. 3.16 Sensitometric data is used to determine shutter speed so that most objects are recorded on the straight line portion of the characteristic curve.

Tone Reproduction

All the essential parameters necessary for determining tone reproduction have now been discussed and it is possible to illustrate by graphical means how the entire photographic cycle can be planned in advance through the construction of a tone reproduction diagram (Figure 3.17).

Steps:

1. Determine camera exposure using:

$$t = \frac{E_1 (f/no)^2 F}{2.7\ (Bo \cdot Ta + Ba) T_L}$$

where: E_1 is expressed in m.c.s. as obtained from sensitometric data.

2. Determine the atmosphere and camera curve for the above exposure using:

$$E = \frac{2.7t\ (Bo \cdot Ta + Ba) T_1}{(f/no)^2\ F}$$

where: Bo is assumed for enough objects to plot the atmosphere plus camera curve.

3. Plot the D-log E curve of the negative based on the sensitometric data.

4. Plot the D-log E curve of the positive material using sensitometric data. Exposure will be determined by testing.

5. Compare the actual reproduction with perfect reproduction. Perfect reproduction line extends at an angle of 45 degrees from the lowlight intersections in the upper right quadrant.

/From

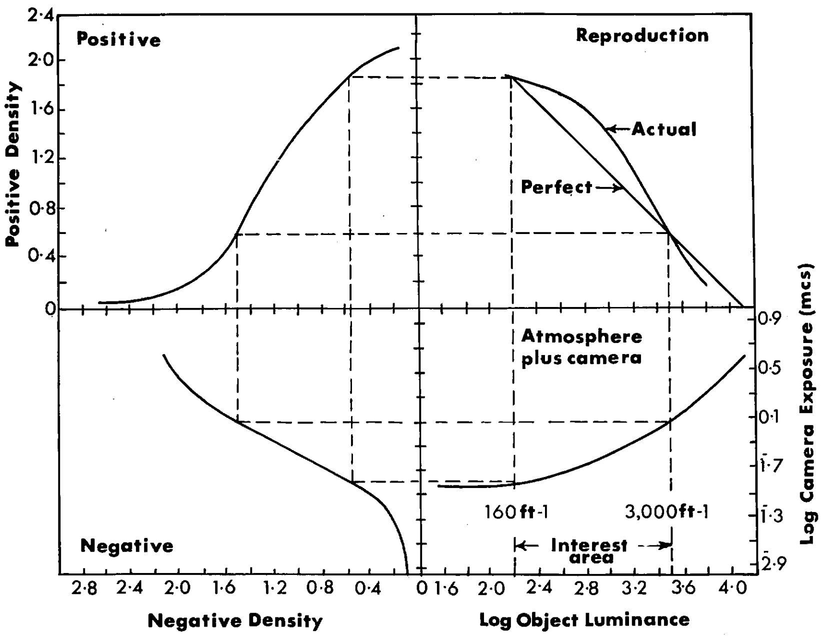


Fig. 3.17 Example of a tone reproduction diagram. (Brock, Harvey, Kohler and Myskowski, 1966, p.86)

From the above, it can be seen that the entire tone reproduction cycle can be planned provided all the necessary parameters are known. Furthermore, it is evident that provided something is known about the environmental parameters and imaging system, it should be possible to determine the effectiveness of the system by density measurements of objects of known reflectance. These aspects in regard to the Breidamerkur area and photography are discussed in the following chapter.

CHAPTER IV

AN ANALYSIS OF THE BREIDAMERKUR PHOTOGRAPHY AND THE SPECIFICATION OF PHOTOGRAPHIC SYSTEMS FOR OBTAINING PHOTOGRAPHY OF A GLACIAL AREA

INTRODUCTION

In order to evaluate or specify a photographic system it is necessary to consider all the parameters affecting image quality. In this chapter these parameters are discussed for both the Breidamerkur photography and area under the headings of Lens-Film Characteristics, Definition and Tone and Contrast, which, unlike shape, pattern, and texture, can be controlled in the photographic process by careful consideration of aberrations, shutter speeds, apertures, granularity, sensitometric characteristics and environmental factors. Therefore, before attempting to specify suitable photographic systems for obtaining aerial photography of a glacial area, it is essential to analyse the comparative photography of the Breidamerkur area and to determine and relate the above parameters to the quality of this photography. Once this has been accomplished, it is possible to consider how the photography can be improved and the type of system that should be employed to obtain optimum quality photography of a glacial area.

To perform this analysis both visual and quantitative methods have been employed. For example, in the evaluation of definition, it is essential to determine not only which types of photography permit the detection of small objects, but also the influence of abberations, object contrast, image motion, granularity and resolution. In order to do this it is necessary to employ quantitative methods such as the single-bar response function.

Similarly, for tone and contrast, it is quite possible to determine visually which type of photography offers the greatest fund of information; however, if tone and contrast are to be improved upon in future photography it is essential to evaluate each influencing factor. These include illumination, reflectance characteristics of the object, atmosphere and camera, and film type. From the measurements in the field, the environmental factors are known and both camera and film data are available. Therefore it is possible to reconstruct a hypothetical set of photography through the use of tone reproduction diagrams. This gives an insight into what tones and contrasts can be expected and the problems of tone reproduction with reference to the photography of a glacial area. From density measurements and the visual evaluation of the Breidamerkur photography, it is then possible to determine if the hypothetical tone reproduction diagrams are valid and what types of photography are likely to produce optimum tone and contrast for the study of a glacial area.

Once both definition and tonal requirements have been outlined, it is possible to consider the cameras, film types, filters, and flying heights, and these are discussed in the last part of the chapter.

LENS-FILM CHARACTERISTICS

Lens and Filters

The lens used for the 1965 aerial photography was a Wild Aviogon

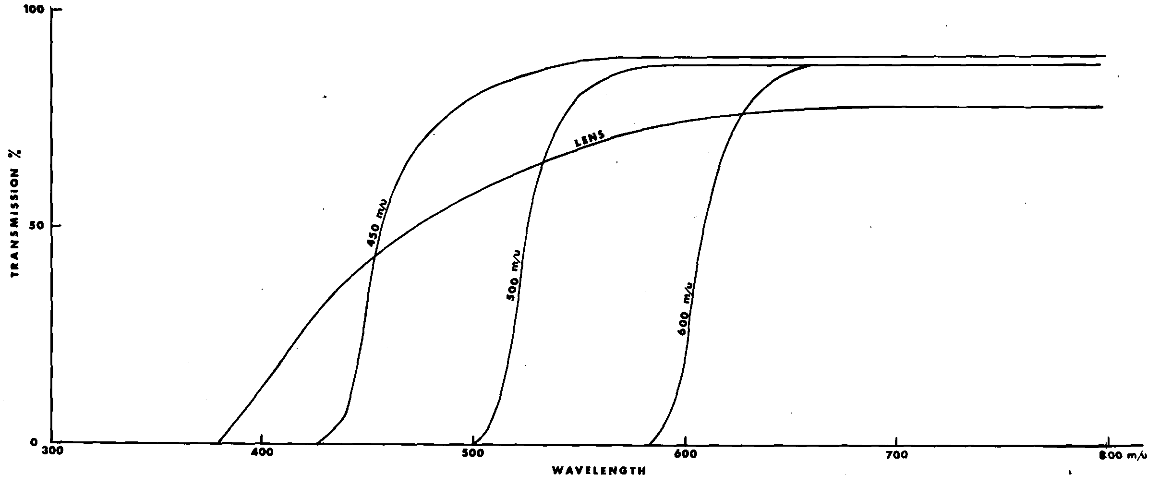


Fig. 4.1 Wild Aviogon lens and filter transmissions (Courtesy of Wild Heerbrugg).

(No. 12), f = 6 inches, having a maximum aperture of 5.6 and shutter speeds from 1/100 to 1/700 second. According to Duddek (1967), chromatic aberrations in the Aviogon lens are corrected for the range 450 to 650 millimicrons, and transmission is approximately 0.65 between 400 and 650 millimicrons and 0.78 for 500 to 800 millimicrons (Figure 4.1). The maximum high contrast resolution capability of the lens combined with a fine grain panchromatic film is 55 lines per millimetre and occurs at between 5 and 10 degrees off-axis (Wild-Heerbrugg, personal communication). Filters normally used include 2x yellow (minus-blue) and 4x red optical flats with spectral cutoffs of 500 and 600 millimicrons respectively (Figure 4.1). For the Breidamerkur photography the 500 millimicron filter was used with the panchromatic and false colour films, whereas the 600 millimicron filter was employed with the infra-red film.

Film Characteristics

The characteristic curves and film sensitivities of each film employed are shown in Figures 4.2 and 4.3. Their characteristics and qualities are further discussed below.

Ilford Hyperpan

This is a fast, wide latitude, panchromatic air survey film (now discontinued) which is fairly evenly sensitive over the photographic spectrum of 500 to 670 millimicrons. According to Kardas (1955), the optimum density for peak resolving power in panchromatic films occurs at 0.6 to 0.8 units above base plus fog; however, as is characteristic of most high speed emulsions, the resolution and recordability of very

/low

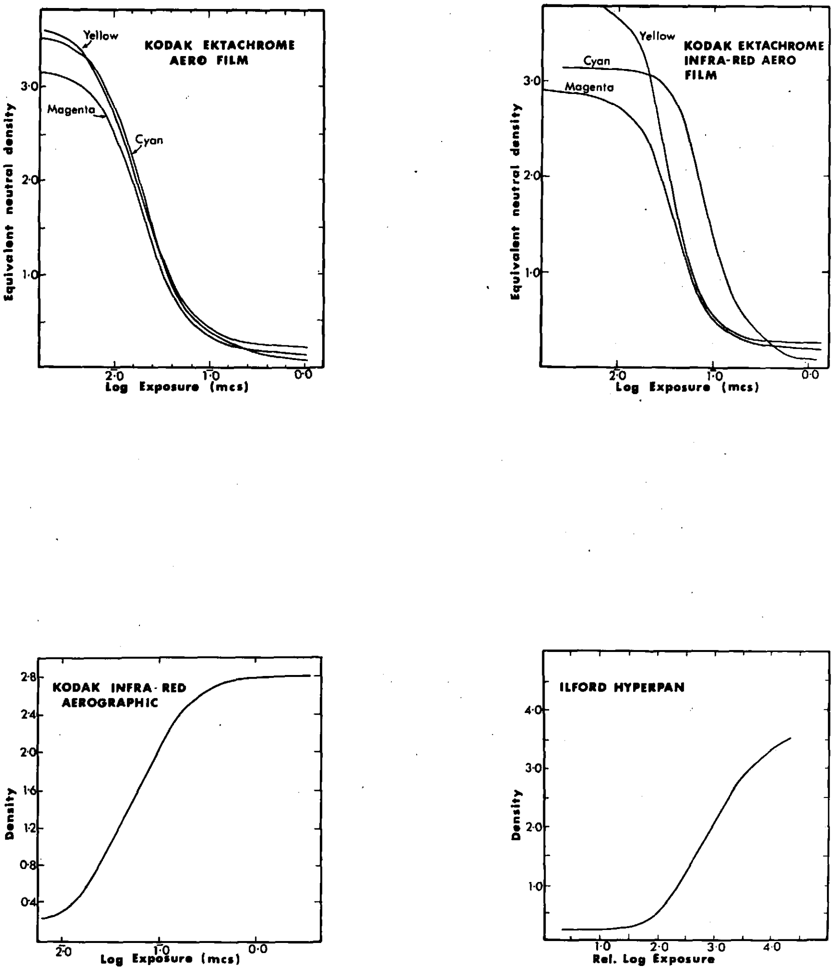
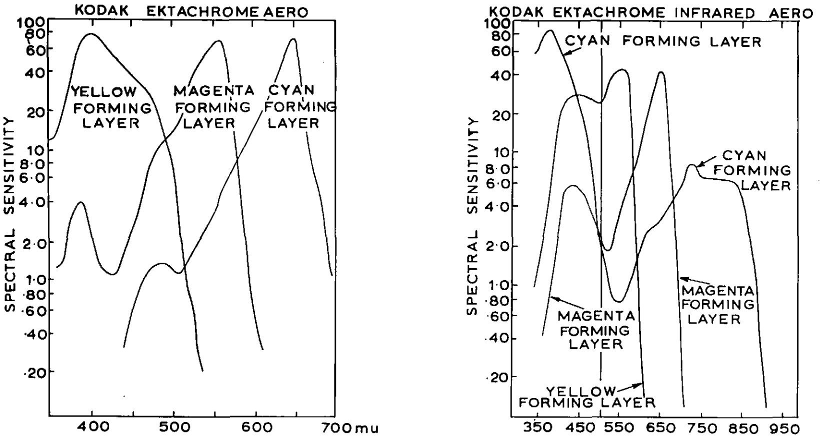


Fig. 4.2 Characteristic curves of the films.

FILM SENSITIVITIES



BLUE SENSITIVE	YELLOW FORMING LAYER
FILTER	FILTER
GREEN SENSITIVE	MAGENTA FORMING LAYER
RED SENSITIVE	CYAN FORMING LAYER
BASE	BASE

INFRARED SENSITIVE	CYAN FORMING LAYER
GREEN SENSITIVE	YELLOW FORMING LAYER
RED SENSITIVE	MAGENTA FORMING LAYER
BASE	BASE

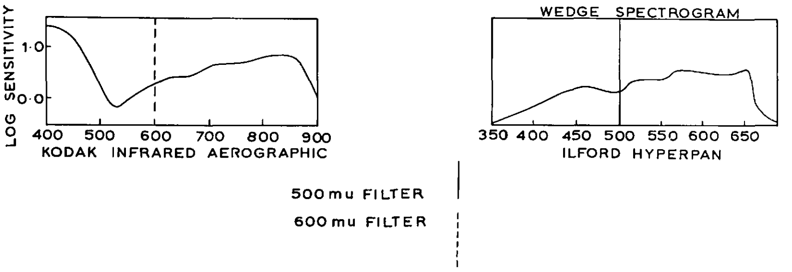


Fig. 4.3 Manufacturers' data for film sensitivities.

low contrast detail suffers due to granularity and image spread. In this regard, Kardas ranked Hyperpan's overall information capacity (as a function of target contrast, exposure, and resolving power) as lying between the well-known Kodak Super XX and Tri X films. In the case of the Breidamerkur photography, the exposure was excellent, resulting in maximum definition.

Kodak Infra-red Aerographic, Type 5424

As can be seen, this film is primarily sensitive to the blue and infra-red wavelengths of light; however, it is normally used with a yellow, red or infra-red filter which eliminates blue light. Because of its sensitivity to longer wavelengths of light, infra-red photography has been reported to have superior haze penetrating capabilities (Colwell, 1960). However, it has been shown (Middleton, 1950) that as haze particles increase in size scattering becomes less dependent on wavelength and, in fact, with the exception of industrial or dry haze (IGN, 1959; Zarzycki, 1963), infra-red photography does not offer much advantage in haze penetration over minus-blue panchromatic photography. Brock (1952, p.250) states that the impression of haze penetration is largely due to the greater contrasts such as between vegetation, which reflects over 40 percent in the infra-red, and clear water, which totally absorbs infra-red reflectance. These contrasts are further increased by a relatively high gamma.

Several problems are immediately encountered if the use of infra-red photography is contemplated, including storage, exposure and

/chromatic

chromatic correction. In regard to storage, it is recommended that infra-red film be used within six months of manufacture to avoid decreased sensitivity and associated increased fog levels due to decomposition of the sensitising dyes (Glafkides, 1960; Meier, 1962). Correct exposure is difficult to determine as neither the eye nor light meter photocells are sensitive to infra-red radiation, and therefore it is essential to know the reflectance properties of the landscape being photographed. For example, a densely vegetated area may require 2 to 3 times less exposure than a bare rock area.

The problem of chromatic aberration is perhaps the most serious where high definition is required. In order to correct for this problem with lenses such as the Aviogon (as opposed to the Universal Aviogon which is corrected for infra-red, colour, and panchromatic photography) it is necessary to either: 1) physically extend the focal distance by 1/200 to 1/400th of the focal length (Maruyasu and Nishio, 1960, p.3); 2) to employ a version of the Aviogon specially computed for infra-red - the Infragon; or 3) to use a meniscus ground filter in place of an optical flat. As the above alternatives were not possible, only the 600 millimicron optical flat was used for the Breidamerkur infra-red photography. This resulted in poorer definition than might otherwise have been obtained and must be taken into account in the following comparison of the photography.

Kodak Ektachrome Aero, Type 8442

This is a high contrast, colour reversal film designed for

/medium

medium to high altitude aerial photography. Like most colour aerial films, it consists of three separate layers sensitive to the blue, green and red portions of the visible spectrum respectively and has a yellow filter sandwiched between the blue and green sensitive layers. Used as a reversal film, a complementary coloured dye is produced in each layer in an amount roughly inversely proportional to the logarithm of the exposure of the given layer (Sorem, 1967). If employed as a reversal colour film processed to a negative stage with a modified C22 process, the dye quantities produced are approximately proportional to the log exposure and layer colours in the negative are the same as those of the original scene. The principal advantage of using Type 8442 as a negative film is an increase in exposure latitude from $\pm \frac{1}{2}$ f stop to one stop under to two stops over exposure (English, 1965). However, by using Type 8442 as a negative film, instead of as a reversal film, the equivalent ASA speed drops from over 200 to 80. As anti-vignetting filters should be employed to reduce illumination fall-off in the plane of the negative, the exposure index is reduced still further. In addition to the above, definition suffers because of the added printing stage, and costly positive print or transparency materials are necessary.

A general problem often encountered with colour photography obtained with an Aviogon lens is the formation of a purple spot (on the positive) in the centre of the photograph (Woodrow, 1967; Duddek, 1967). This is attributed to internal reflections from the diaphragm and to some extent can be avoided by using the maximum aperture and controlling exposure by shutter speed.

For the Breidamerkur photography, Type 8442 was used as a negative film without a filter. Because of the clear atmospheres encountered in glacial areas, the lens cutoff of 400 millimicrons appears to be sufficient to eliminate haze for altitudes below 8,000 feet; however, an anti-vignetting filter would likely improve colour balance and picture quality, simplify the printing stage, and reduce the purple spot which appears on the colour transparencies.

Kodak Ektachrome Infra-red Aero, Type 8443

Often referred to as the camouflage detection or false colour film, this three layer reversal film is sensitive to the green, red, and infra-red portions of the spectrum and for objects reflecting in these regions, the corresponding positive images are blue, green, and red (Figure 4.4), hence the name false colour. The term 'camouflage detection' is derived from the principle that healthy, green vegetation reflecting strongly in the infra-red will image red-magenta, whereas camouflage, green paint, or dead vegetation (which appear visually similar but reflect weakly in the infra-red portion of the spectrum) will image purple or blue-green. However, in order to obtain a differentiation between most natural objects which reflect 10 to 15 percent in the visible region from those reflecting 40 to 60 percent in the near infra-red (healthy vegetation), it has been necessary to reduce the sensitivity of the infra-red sensitive layer in relation to the red and green sensitive layers. As a result, low luminance neutral objects appear

/blue-

EKTACHROME INFRARED

Object	WHITE	INFRARED	RED	GREEN	BLUE	BLACK	
Filter					▨		
Transparency			CYAN	CYAN	CYAN	CYAN	infrared sensitive layer
		YELLOW	YELLOW		YELLOW	YELLOW	green " "
		MAGENTA		MAGENTA	MAGENTA	MAGENTA	red " "
Image	WHITE	RED	GREEN	BLUE	BLACK	BLACK	

Fig. 4.4 Relationship of object, filter, transparency, and visual image for Kodak Ektachrome Infra-red Aero film. The cyan layer acts to exclude red light, and similarly yellow to exclude blue, and magenta to exclude green.

blue-green rather than grey (personal communication with W.E. Shea, Eastman Kodak Company, 1966). This point has also been stressed by Fritz (1967) in his paper "The Optimum Methods of Using Infrared Sensitive Color Film" which deals exclusively with the characteristics of Type 8443. It should also be noted that a 500 millimicron filter is always used with this film to protect the infra-red sensitive layer from the blue light to which it is also sensitive. Furthermore, because effective image formation deals largely with the visible spectrum it is unnecessary to correct for chromatic aberrations by extending the focal distance. Storage properties are superior to infra-red film.

For the Breidamerkur photography, Type 8443 was used on the advice of Hunting Surveys Limited as a reversal film at an equivalent ASA of 10. Normally, however, this film will be employed at a speed of ASA 65 or, if desired, an equivalent ASA of 200 can be obtained without loss of definition by extending the development time (personal communication with Mr. House, Ordnance Survey, 1967).

DEFINITION

Definition in the various types of photography has been assessed by both visual and quantitative methods. For example, the visual study is based on the ability to detect various objects and features, whereas the quantitative analysis is discussed in relation to defined parameters, such as the single-bar response function, object contrast, image motion, image position in relation to the optical axis, granularity, and film resolution.

Visual Evaluation of Definition

For the visual study, corresponding transparencies for each type of photography were analysed under 3 times stereo and 5, 10, and 40 times monocular magnification. The basis for judgement can be separated into two categories: 1) the detection of largely artificial objects of known size at known locations; and 2) the detection and identification of natural features at both known and unknown positions, or what could be termed "practical definition".

In the first category the targets were the graded-size white cloth markers of 5, 4, 3, 2, 1 and 0.5 feet square, circular ventilators on the roof of a hut, boxes and boards. From an examination of these objects by several interpreters (Figure 4.5) the photography was given the following ranking:

1. Panchromatic
2. False colour
3. Colour
4. Infra-red

and certain subjective judgements made. For example, it can be conclusively stated that the panchromatic photography gave the best definition in terms of the smallest detectable object and, in fact, even smaller white squares could have been detected. The false colour and colour films were similar to each other; however, it was usually possible to detect smaller objects at known locations with the false colour in spite of a slight smearing in the direction of flight attributed to image motion.

/A

Fig. 4.5 Visual Evaluation of Definition Based on Objects of Known Size

Film	Smallest detectable white square		Estimated size of box, ventilator, or purple or grey square required for detection
	with 10 x magnification	without magnification	
Ilford Hyperpan	0.5 ft. (0.15 m)	2 ft. (0.60 m)	1 ft. (0.30 m)
Kodak Infra-red Aerographic	1 ft. (0.30 m)[1]	2 ft. (0.60 m)	2.5 ft. (0.75 m)
Kodak Ektachrome Aero	1 ft. (0.30 m)[2]	1 ft. (0.30 m)	1-1.5 ft. (0.30-0.45 m)
Kodak Ektachrome Infra-red Aero	0.5 ft. (0.15 m)	2 ft. (0.60 m)	1-1.5 ft. (0.30-0.45 m)

[1] It should be noted that as the graded white squares were placed on a grass instead of a gravel background, the high infra-red reflectance of the grass reduced the contrast ratio for the infra-red photography. The estimate is based on a gravel background.

[2] An 0.5 foot white square was thought to have been detected on one transparency.

A fault noticed on some colour and false colour transparencies was the tendency for the edges of images, regardless of orientation, to appear slightly diffused under greater than 10x magnification. This is thought to be caused by dye diffusion and did not affect interpretation. As expected, the infra-red photography produced the worst definition due to lack of correction for chromatic aberrations. These appear to have caused a diffusion visible at edges of most images.

In terms of practical definition the photography must be ranked quite differently:

1. Colour
2. Panchromatic
3. False colour
4. Infra-red.

In this instance it is also possible to make concrete statements. First of all, in terms of detecting small objects at unknown locations, the colour photography was by far superior to the other types. In addition, a greater variety of natural objects could be instantly recognised and delineated. This must be attributed to colour contrasts through the addition of hue and saturation (chromaticity) to brightness. The other films were best for detecting or recognising certain classes of objects; however, this is discussed later. The important aspect about this latter ranking is the consideration of tone.

Generally, it was thought that the most effective viewing magnification for all the photography was approximately 8 to 10 times.

Furthermore, it was concluded from comparing the 1:16,000 photography with the 1:27,000 mapping photography, on which the 0.5 foot white square was just detectable, and from the plotting of the various sets of photography, that the detection of low contrast objects of 1 to 2 feet in diameter (such as the roof ventilators) is indicative of high definition photography suitable for the interpretation of a glacial area.

Quantitative Evaulation of Definition

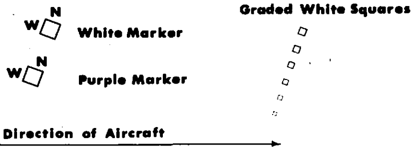
Based on known quantities such as the single-bar response function, object and image contrast, image motion, image position in relation to the optical axis, granularity, and film resolution, it has been possible to evaluate definition in an objective manner. These factors and their significance are discussed below (see Figure 4.6).

Single-Bar Response Function

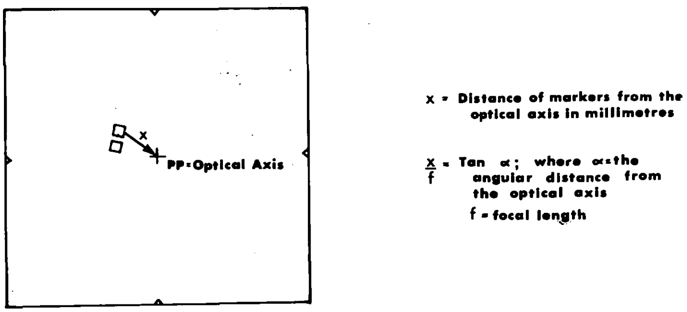
Several edge traces (as discussed in Chapter III) were made for both the white (medium contrast target) and purple (low contrast target) square markers using a 3 x 200 micron slit in the Joyce, Loebl microdensitometer. Although exposure calibration was maintained by step wedges impressed on the transparencies, the transfer function of the microdensitometer was not determined. However, as the fequencies (range of lines per millimetre or cycles per millimetre imaged by the system) being studied are low and there are certain inaccuracies in the graphical method employed (e.g. in determining a mean smoothed edge trace), it is unlikely that this factor had a significant bearing on the final results. Relative accuracy should be reasonable in any case,

/for

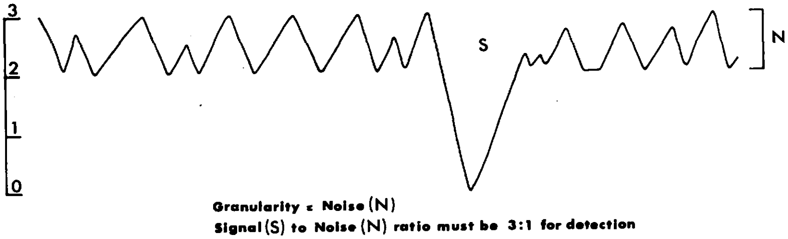
1. MARKERS AND EDGES



2. POSITION OF MARKERS IN RELATION TO THE OPTICAL AXIS



3. GRANULARITY



4. ADJACENCY EFFECTS

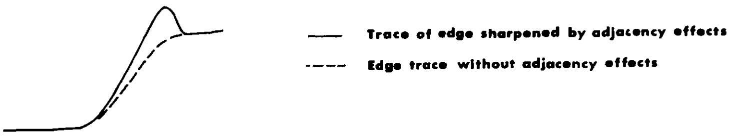


Fig. 4.6 Some factors influencing definition.

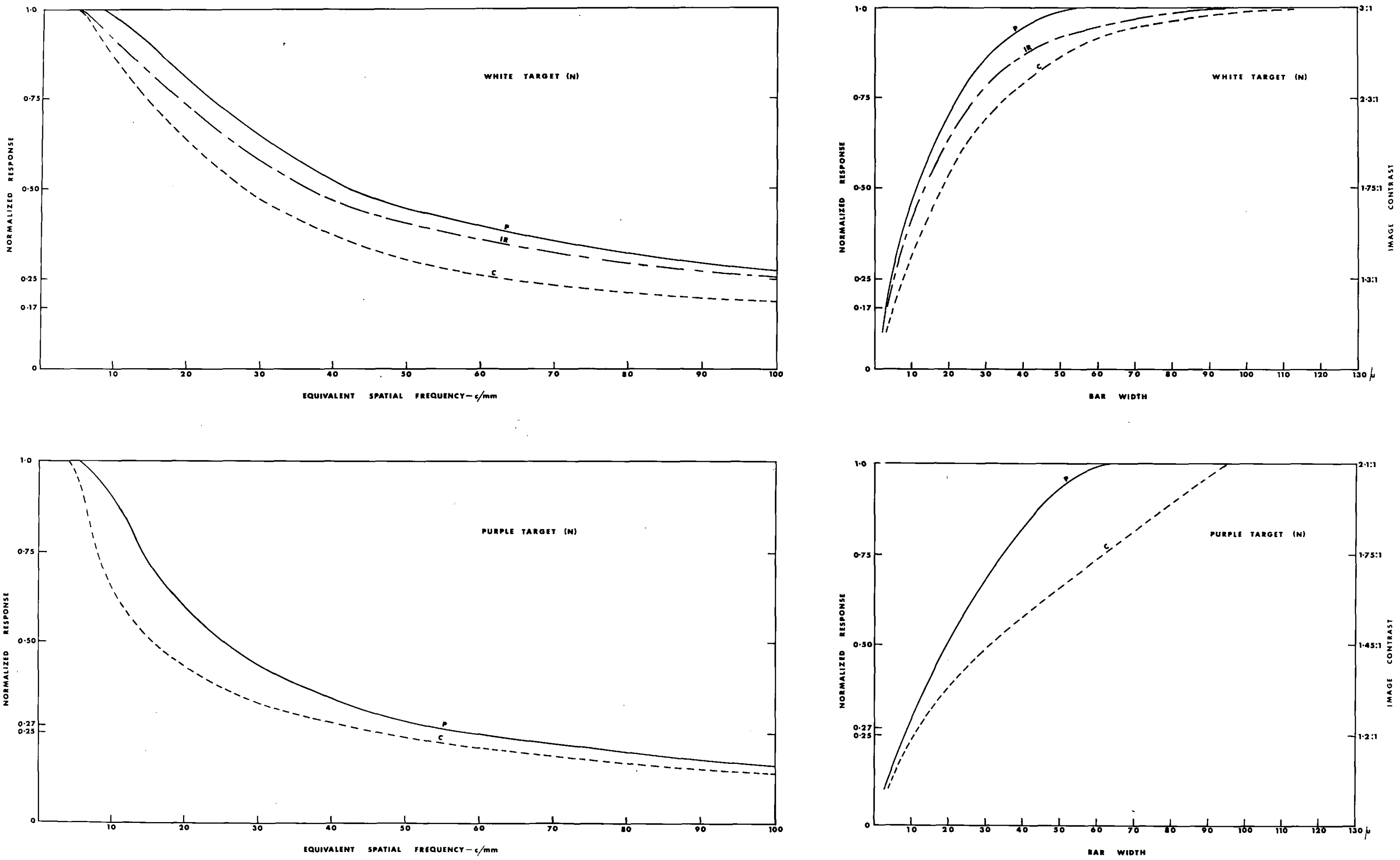


Fig. 4.7 Single-bar response functions for the north edges of the cloth markers.

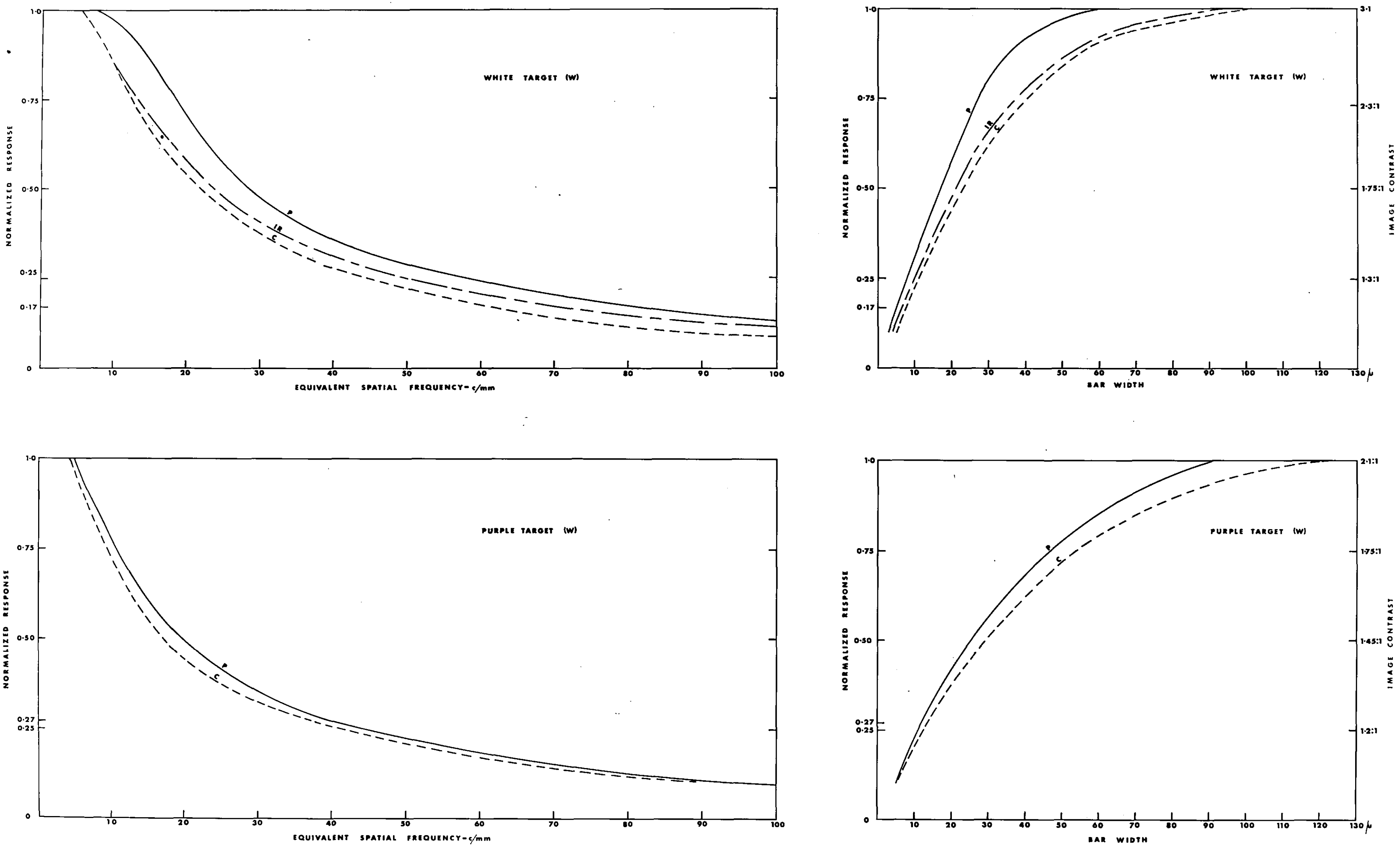


Fig. 4.8 Single-bar response functions for the west edges of the cloth markers.

for the same operating conditions and edges were used throughout. As will be noted, single-bar response has been plotted both as a function of spatial frequency and bar width (Figures 4.7 and 4.8).

Object and Image Contrast

Object contrast has been determined by comparing the areas under the spectral traces for the markers and gravel over the effective wavelengths employed in each type of photography. Image contrasts of each edge used in the calculation of the single-bar response functions were determined from the microdensitometer traces. Contrast and density differences are listed in Figure 4.9. As will be noted, purple marker contrast data has not been recorded for the infra-red photography. This is due to its high reflectance in the infra-red, therefore producing an image contrast approximately the same as that of the white marker. As previously mentioned, single-bar response functions could not be calculated for the false colour photography due to the lack of a step wedge on the reversal positive. The contrast can, however, be noted from traces of the graded squares shown in Figures 4.10 to 4.13.

Image Motion

As the aircraft's ground speed was approximately 220 m.p.h., the translational effects of image motion have been determined for each image edge (Figure 4.14, column 1). As can be seen they are most serious for the west edges of the cloth markers, which are oriented more nearly perpendicular to the flight line. As translational (linear) image motion is likely to be the motion causing image degradation in

Fig. 4.9 Contrast and Density Difference for Cloth Markers in both Object and Image Space. The West Edges were Approximately Perpendicular to the Direction of Flight and the North Edges Parallel

	Object White target/ gravel	Object Purple target/ gravel-Pan	Object Purple target/ gravel-Colour	Image-Pan West Edge		Image-Pan North Edge		Image-Colour West Edge		Image-Colour North Edge		Image IR West Edge	Image IR North Edge
				White	Purple	White	Purple	White	Purple	White	Purple	White	White
Contrast	5.6:1	1.25:1	1.6:1	2.7:1	2.1:1	3.3:1	2.2:1	3.1:1	1.7:1	3:1	2.2:1	3.2:1	3.3:1
Density Difference	0.75	0.1	0.20	0.43	0.35	0.52	0.35	0.49	0.24	0.48	0.35	0.51	0.52

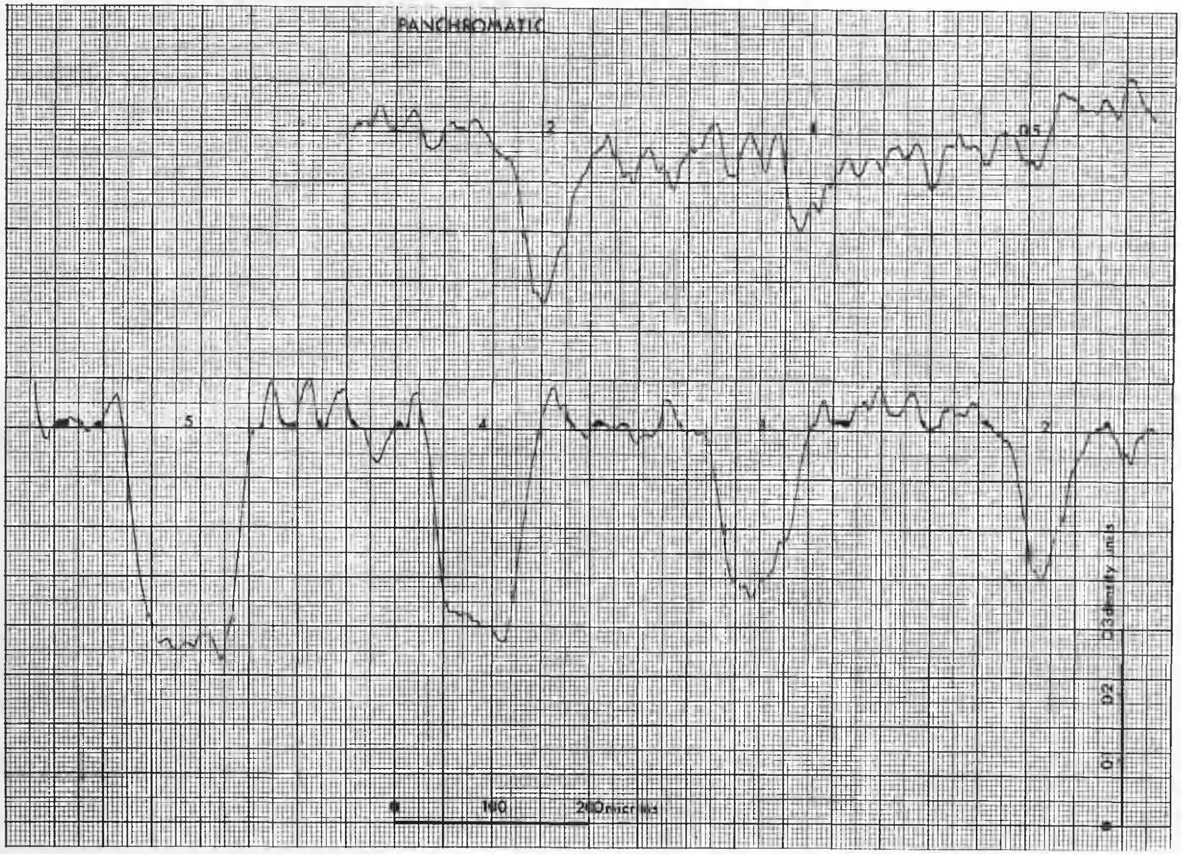


Fig. 4.10 Microdensitometer trace of the graded marker squares on the panchromatic photography.

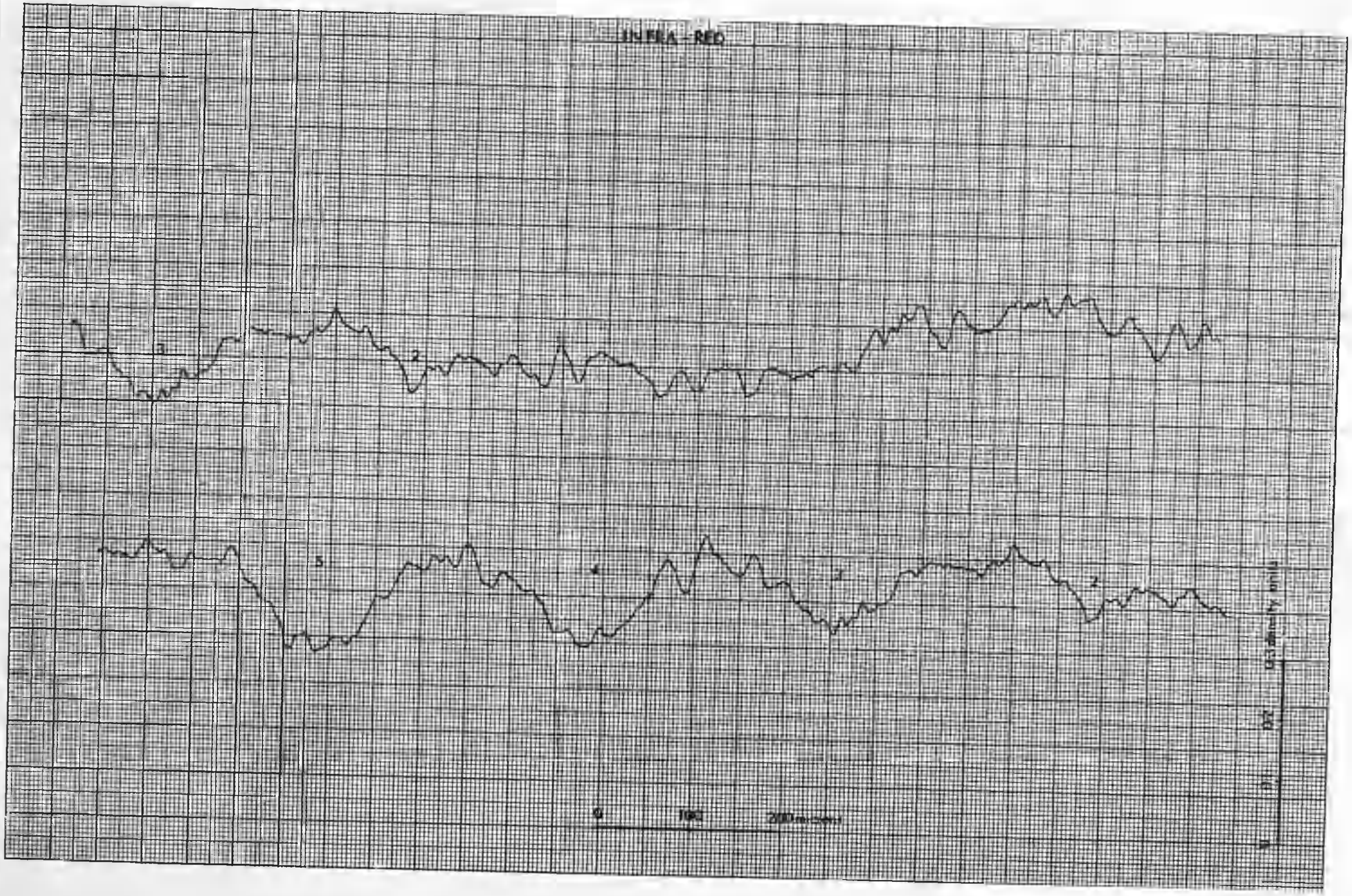


Fig. 4.11 Microdensitometer trace of the graded marker squares on the infra-red photography.

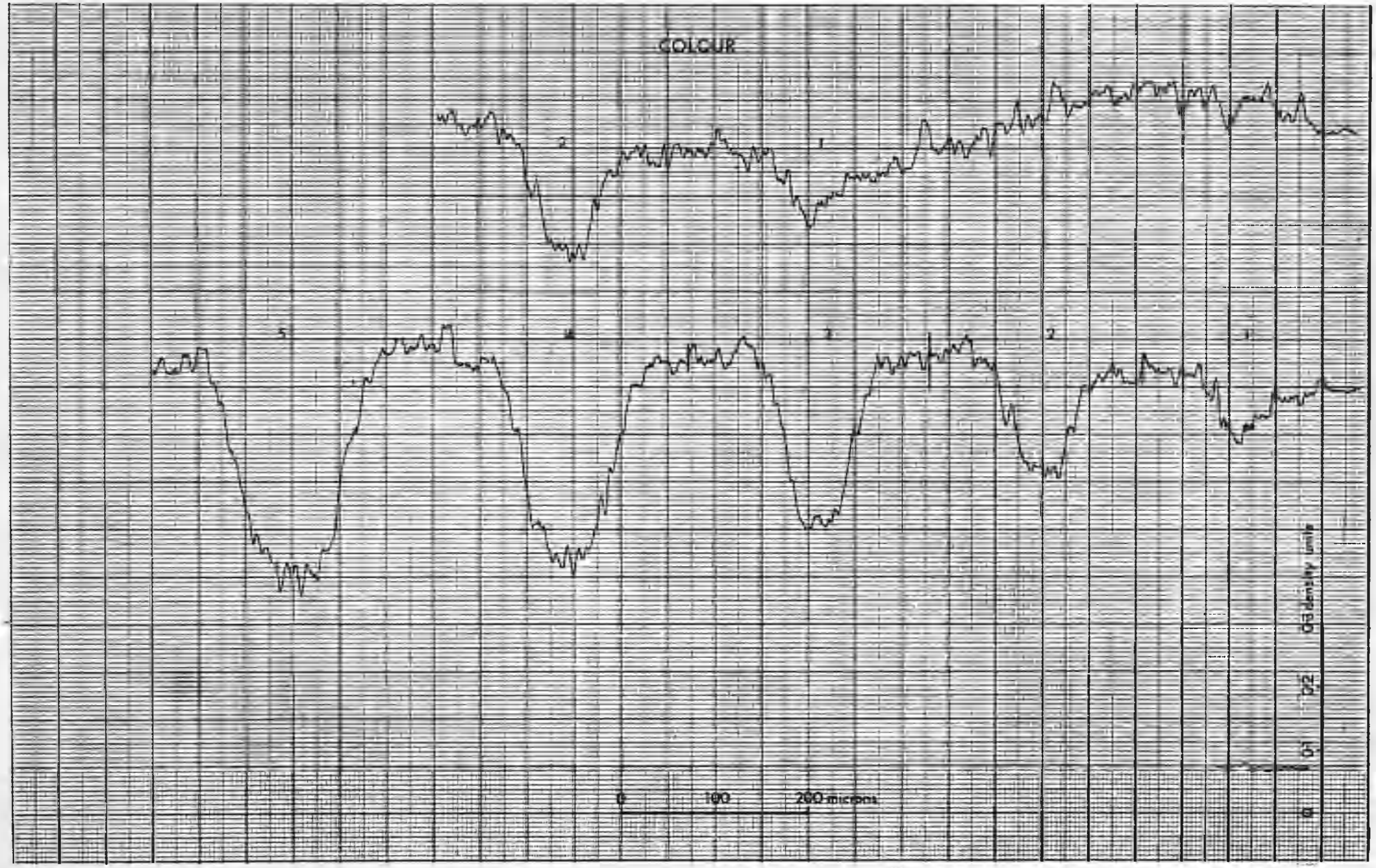


Fig. 4.12 Microdensitometer trace of the graded marker squares on the colour photography.

survey photography (Macdonald, 1952) and as it must equal approximately one-half line of resolution before serious degradation in resolution begins (Carman and Carruthers, 1951; and Trott, 1960), it has been possible to compute the maximum possible resolution for bar targets oriented similarly to the cloth squares (Figure 4.14, column 2). It should be noted that as the aircraft approached the targets from the same direction for each type of photography the edges were affected in the same manner.

Image Position in Relation to the Optical Axis

Resolution also varies with angular distance from the optical axis and as lens-film high contrast resolution data was available for the Aviogon lens used in combination with a fine-grain panchromatic film, it has been possible to determine the percentage difference from the point of maximum resolution (lines per millimetre at 5 to 10 degrees off axis) at known distances from the optical axis (Figure 4.14, column 3). It should also be mentioned that off-axis image positions can result in asymmetrical edge spread functions (Rosenau, 1966; Washer, 1966) and therefore responses may differ according to the orientation of the edge in the image plane (Brown, 1967).

Film Resolution

Although both high and low contrast film resolution figures are available (Figure 4.14, column 5), neither is a complete indicator of the definition capabilities of the film in terms of visual examination (Macdonald, 1951, 1956, 1958; Higgins, Wolfe and Lamberts, 1956; Barrows, 1957). Of the two, however, low contrast figures are more representative of the aerial image and have been found to correspond reasonably with detection (Itek, No.4, 1963; Molnar, 1963). Where lens resolution is greater than three times the film resolution on the basis of the Rayleigh criterion its contribution to image degradation is negligible (Perrin and Altman, 1951). Therefore, in the case of the Breidamerkur photography, the effects of the lens on the photographic resolution near the axis are minimal.

Granularity

Granularity or 'noise' has been listed from manufacturers' data (Figure 4.14, column 6) and determined from traces of the impressed step wedges and cloth markers (Figure 4.14, column 7). The relationship of granularity to detection has been established by tracing the graded white squares using the same slit size as that used for tracing the step wedges and also for the edge traces, that is, 3 x 200 microns. Based on the traces of the graded white squares (Figures 4.10 to 4.13) it was found that a 3:1 signal-to-noise ratio is necessary for microdensitometer detection of an object (Figure 4.14, column 8). This corresponds to the estimate given by Higgins and Perrin (1958, p.74).

Discussion

From the above factors and their interrelationship as shown in Figure 4.14, it is apparent that in terms of resolution, image motion (columns 2 and 4) is a limiting factor for high contrast targets, whereas film resolution (column 5) is the limiting factor for low contrast targets. Therefore, one would expect that the west edges of the white

/markers

Fig. 4.14 The Effects of Image Motion, Lens, Film, and Granularity on Definition

Film	1		2		3		4		5		6	7	8
	Computed Image Motion[1] (Microns in the plane of the negative)		Maximum Resolution with Image Motion in lines/mm $\left(\frac{1000}{\text{Image Motion} \times 2}\right)$		Percent Difference in Resolution from Maximum Resolution as determined by position of targets in relation to the optical axis		Maximum Resolution with Image Motion and Percent Difference combined to give maximum resolution in lines/mm		Film Resolution lines/mm		Listed[2] Granularity (Kodak) (density units)	Noise (density units)	3:1 Signal-to-noise ratio = density difference of:
	West Edge	North Edge	West	North	West	North	West	North	Target Contrast 1000:1	1.6:1			
Ilford Hyperpan	10	5	50	100	1	2	49	98	75 est.	45	0.105 est.	0.05	0.1
Kodak Infra-red Aerographic	13	7	38	72	12	15	33	54	89	28	0.115	0.04	0.08
Kodak Ektachrome Aero	13	7	38	72	0	1	38	71	56	28	0.080	0.06	0.12
Kodak Ektachrome Infra-red Aero	26 31	16 19	19 16	31 26	8	19	17 15	25 21	71	36	0.058	0.02	0.04

[1] Ten microns equals a ground distance of 16 centimetres or 6 inches at 1:16,000 scale

[2] Root-mean-square granularity values obtained from scanning a uniformly exposed and developed sample with a densitometer having an aperture 24 μ in diameter (Kodak Tech Bits, 1965, No.2, p.10)

markers would produce lower response curves than those obtained from the north edge and this is borne out in Figures 4.7 and 4.8. Correspondingly, it could be expected that generally the response curves derived from edge traces of the purple markers would agree and this is confirmed by these Figures.

In regard to the response curves derived from the white markers, it is interesting to note the anomaly of the infra-red response. Although a response similar to that of the panchromatic film might be expected on the basis of target contrast and film resolution, chromatic aberrations would almost certainly reduce edge sharpness unless there were compensating measures of some sort. In this case adjacency effects[1] appear to have sharpened the edge between the transparent positive image of the white marker and the much denser surrounding gravel areas which were, in fact, under-exposed on the negative. This explanation is confirmed by an examination of the steep edge traces of the white marker and also of the traces of the graded white squares (Figure 4.11) which were located on a sparse grass covered background. In the latter case, exposure and development between target and background are much more even, thereby minimising adjacency effects. From this trace it is apparent that the chromatic aberrations have caused diffusion of the image to a much greater

/extent

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[1] Edges between heavily and lightly exposed areas are sharpened in the development process by the interchange of exhausted developer in the heavily exposed area with relatively fresh developer in the lightly (or under-exposed) area. See No. 4 in Figure 4.6.

extent than is indicated by the response curves and that the infra-red photography, in the circumstances of this test, is inferior in definition to the other types of photography including the false colour. Although it was not possible to derive a response curve for the false colour, the microdensitometer trace of the graded squares (Figure 4.13) indicates that it would rank below the colour and above the infra-red photography.

The effects of granularity are also noticeable. Granularity limits the density difference, ΔD, that will be detected by the microdensitometer. As can be seen from the traces, this is about 0.07 to 0.10 units which roughly corresponds to a 3:1 signal-to-noise ratio. As the total density difference between the gravel background and the cloth marker is known, it has been possible to derive the percent response that is equivalent to ΔD, or stated differently, the percent response required for microdensitometer detection. For the white marker ΔD averages about 17 percent response and for the purple about 27 percent. This in turn means that a larger purple square is required for detection, and this can be seen from the response functions on which the 17 and 27 percent limits have been indicated (Figures 4.7 and 4.8). It is interesting to note upon comparing the west and north edge responses that the granularity has a much greater effect on the medium contrast target than on the low contrast target. This further indicates that low contrast resolution targets are less likely to be distorted than high contrast targets, and therefore to better represent the operational capabilities of the photographic system (see Stapleton, 1960). Also, it can be seen that low contrast resolution, while more closely related to detection, is not equivalent. For example, from the west edge response curves it would appear that at the cutoff point a resolution of 36 lines per millimetre is being recorded for colour and 40 for the panchromatic photography. This, of course, is impossible for the colour photography if low contrast film resolution is 28 lines per millimetre. The panchromatic figure, while more reasonable, is also thought to be too high as resolutions above 30 lines per millimetre are seldom obtained in practice with this lens-film combination (personal communication with D. Cook, Ordnance Survey).

Based on the quantitative evaluation the photography must be ranked as follows:

1. Panchromatic
2. Colour
3. False colour
4. Infra-red.

Comparison of the Visual and Quantitative Evaluations of Definition

It is apparent from the preceding discussions that quantitative definition does not altogether correspond to visual definition. For example, in terms of object size, it is evident from the data listed below that smaller white squares are detected by visual rather than by microdensitometric methods and that even smaller white squares could have been detected. It is unlikely that the estimated figures are in error by more than an inch or two.

/...

	Smallest white square detected visually (10x)	Smallest white square detected by microdensitometer (20x)	Estimated smallest white square which could be detected visually
Panchromatic	0.5 ft. (0.15m)	0.5 ft. (0.15m)	0.33 ft. (0.10m)
Colour	1 ft. (0.30m)	1 ft. (0.30m)	0.66 ft. (0.20m)
False Colour	0.5 ft. (0.15m)	2 ft. (0.61,)	0.33 ft. (0.10m)
Infra-red	1 ft. (0.30m)	2 ft. (0.61m)	0.66 ft. (0.20m)

Furthermore, from traces made of a five-foot square piece of black cloth, it would appear that the eye is able to detect smaller low contrast objects than the microdensitometer.

The reasons for the difference between the analyses must be viewed in regard to the various operational parameters, such as film resolution, granularity, exposure, image motion, and also the fact that the quantitative assessment is based largely on density differences and does not take into account shape or colour tone. For example, with reference to shape, the microdensitometer must use a relatively long slit to reduce the effects of granularity (Figure 4.15). For bars longer than the slit and oriented perpendicular to the direction of scan, the detection capability of the microdensitometer approaches that of the eye; however, for squares or other small objects which do not entirely fill the slit, the density differences are obscured by granularity. The same also applies to large objects which do not have sufficient contrast to exceed the 3:1 signal to noise ratio, that is density differences above 0.1 density units. For example, the image of a jeep track across the sandur is easily visible on the photography and was

/thought

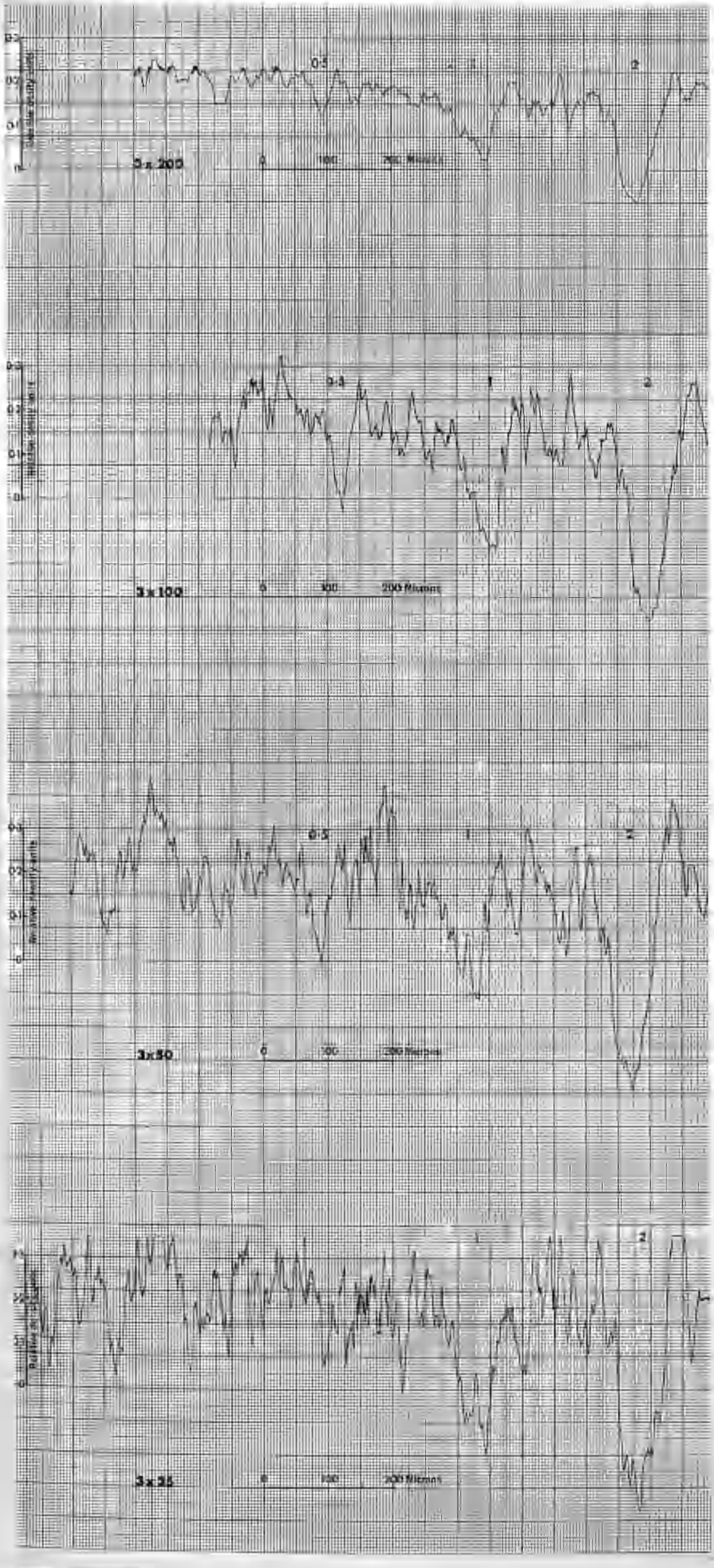

Fig.4.15 Microdensitometer trace of the graded marker squares on the panchromatic photography utilising different slit lengths. Granularity limits the effective slit size to approximately 3x100 microns.

thought to represent a good low contrast edge, yet a trace across the jeep track revealed no noticeable change in density. This seems to be a good example of the ability of the eye to assimilate an image from several points which by themselves are indistinguishable (Salzman, 1949); something the microdensitometer does not seem to be capable of performing with relatively grainy films.

Density differences are also obscured due to image motion or aberrations. For example, aberrations have diffused the graded white squares on the infra-red photography to the point where it is impossible to separate signal from noise for even the two-foot square, although the one-foot square is clearly visible. Image motion also tends to diffuse the edges as is evidenced by the lower responses for the west edge and from the traces of the graded cloth squares on the false colour photography. In this latter case the low granularity combines with colour tone differences to permit the visible detection of the smallest square, indicating that it is possible to partially offset degrading factors such as image motion through low granularity and colour tone. Colour tone is of particular interest as it does not necessarily imply a density difference. This example also indicates that resolution is not completely indicative of the system's capability to record small detail (Macdonald, 1958) and that image motion and granularity must be considered (also see Mikhaylova, 1965). These factors are particularly significant in view of the capabilities of survey cameras (f = 6 inches) which are limited to lens-film resolutions of about 35 lines per millimetre for low contrast targets, regardless of the film used (Brock, 1961; Welander, 1962, 1966; Meier, 1966; personal communication with G. Bushnell, 1967). Therefore, to improve definition over the Breidamerkur photography, it is possible to obtain a slightly better system resolution by employing higher resolution films; however, any significant improvement must be accomplished through the consideration of granularity, colour tone, and image motion, and the correction for aberrations, all of which influence the sharpness of edges either through density differences or colour differences.

Of the above factors, it is possible to separate image motion on a visual basis. For example, from viewing the graded-squares on both the 1:16,000 scale and 1:27,000 scale panchromatic photography and also on the 1:16,000 scale colour photography, it can be said that the threshold of detection in each case was due to granularity or dye diffusion. As all sets of photography were taken from an aircraft with a ground speed of approximately 220 m.p.h., and as shutter speeds of 1/500 second were used for the panchromatic photography and 1/400 for the colour photography, it is apparent that image motions of the order of 10 to 15 microns will not seriously impair definition with a six-inch focal length lens used under similar conditions. However, as is indicated by the false colour photography, shutter speeds resulting in uncompensated image motions of greater than 20 microns will result in a worsening of definition. The single-bar response function for the purple marker tends to confirm the visual evaluation and indicates that for low contrast

/objects

objects, image motion is unlikely to have a serious effect unless it exceeds the low contrast resolution capability of the film.

Conclusions on Definition for the Study of a Glacial Area

Based on the visual evaluation of the Breidamerkur photography, it is thought that the detection of low contrast objects of 1 to 2 feet in diameter is indicative of photography suitable for the study of a glacial area, and that ease and rapidity of detection is facilitated by colour tones. From the visual evaluation it has been possible to construct a "detectability" graph which relates scale, object contrast and detection (Figure 4.16) and is representative for the Breidamerkur colour and panchromatic photography.

The quantitative evaluation, on the other hand, tells us little about the size of object required for visual detection and does not differentiate colour and panchromatic photography except on the basis of density differences. As such its usefulness is limited. However, it does bring out the relative importance of factors such as aberrations, granularity, image motion, object and image contrast, and resolution. These, when linked with the known parameters such as film resolution, aircraft speed, etc., provide valuable indications as to the type of cameras and films required for obtaining photography that will meet the definition requirements in terms of smallest detectable objects.

From the combined visual and quantitative analysis the following general specifications as to camera, film, and exposure can be made:

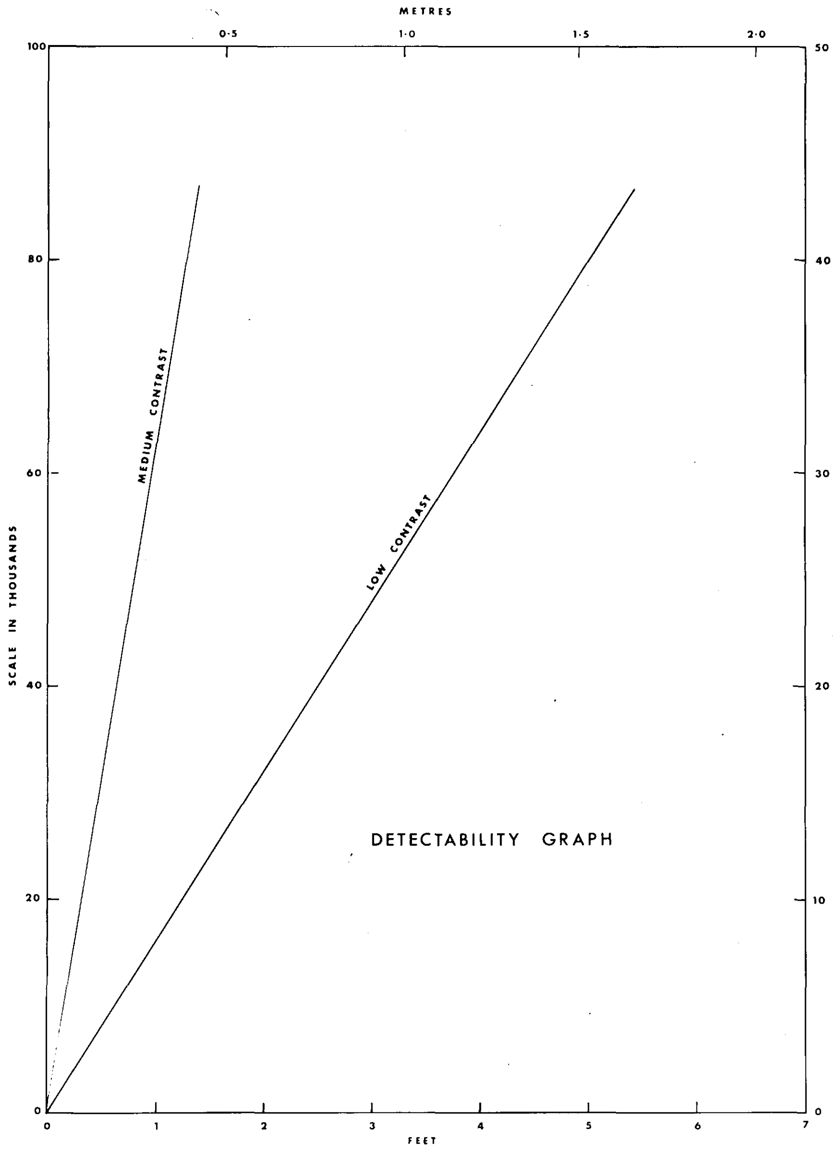

Fig. 4.16 Detectability graph for medium and low contrast objects based on the Breidamerkur panchromatic and colour photography taken with a Wild Aviogon lens, f = 6 inches. It should be noted that the lines are extrapolated for flying heights above 13,500 feet (4,100 metres).

1. <u>Camera</u> - the lens must be corrected for chromatic aberrations over the sensitivity range of the film employed and, if possible, a 'Universal' lens which is corrected for chromatic aberrations between 400 and 900 millimicrons should be used.

2. <u>Film</u> - colour film is preferred on the basis that it is easier to detect and differentiate small low contrast objects and natural features. However, granularity or dye diffusion, rather than lens-film resolution or image motion, is likely to prevent the detection of small objects. Therefore fine-grain films are to be preferred. This is particularly significant in view of the fact that six-inch focal length lens-film combinations are unlikely to produce operational resolutions much above 35 lines per millimetre.

3. <u>Exposure</u> - apertures are of secondary importance to image motion in obtaining good definition. Therefore exposure should be regulated primarily by shutter speeds. In regard to the influence of image motion, it was found for film resolutions below 45 lines per millimetre, aircraft ground speeds of 200 to 250 m.p.h., six-inch focal length cameras, and altitudes above 8,000 feet, that shutter speeds of 1/400 second or greater will preclude the effects of translational aircraft motion from seriously degrading definition.

THE RELATIONSHIP OF TONE AND CONTRAST TO THE STUDY OF A GLACIAL LANDSCAPE

In order to evaluate the importance of tone and contrast in relation to a glacial environment, it has been necessary to again conduct both a visual (qualitative) and a quantitative analysis. From the visual analysis it is possible to determine which type of photography provides the best tonal relationships. The quantitative analysis, on the other hand, indicates the importance of factors such as illumination, reflectance characteristics of natural objects, and the effects of the atmosphere and camera. These are discussed in relation to the Breidamerkur area and, when used to construct hypothetical tone reproduction diagrams, indicate the major problems of tone reproduction in aerial photography of a glacial area. Quantitative measurements on the Breidamerkur photography itself further point out the influence of various parameters such as the atmosphere and camera, and permit conclusions to be drawn as to the importance of film, camera, and flying height. By linking the visual and quantitative assessments, it is possible to state both the importance and methods of obtaining good tone and contrast on various types of aerial photography of a glacial area.

Visual Evaluation of Image Tone and Contrast for Natural Features in the Breidamerkur Area

As discussed by the author (see enclosed publication), tone and contrast are important in the interpretation of the following categories of natural features in a glacial area:

1. Vegetation
2. Water
3. Bedrock, gravels, soils
4. Landforms
5. Glacier surface.

Vegetation (Figures 9 and 10 in the enclosed publication)

Basically there are three categories of vegetation which are prominent enough in the Breidamerkur area to be distinguished on the aerial photography. These are:

1. Grass (*Festuca sp.* and *Agrostis sp.*)
2. Rushes (*Juncus balticus*)
3. Moss (*Rhacomitrium sp.*)

In addition to the above,it is also possible to include the outwash plain or sandur in this section as it is covered by thin mixtures of vegetation. However, because of the sparseness and low height of the vegetation, it might be expected that the underlying gravels would alter its tonal rendition (Orr, Young and Welch, 1962). This is the case on the false colour film where yellows tend to indicate moss and sandur, whereas the red-magenta tones are produced by the grass and rush areas, which are particularly evident in the vicinity of small streams or moist areas. In these latter areas there is sufficient water to maintain plant vigour until late in the autumn. To some extent the same pattern is evident on the infra-red photography where vegetation is rendered in very light shades of grey as compared to the considerably

/darker

darker toned gravels; however, the extreme contrasts, with vegetation too light and the gravels too dark, preclude good definition.

On the colour photography, vegetation appears in tones of green, green-brown, and green-yellow and while it is possible to outline areas of vegetation, it is not feasible to distinguish between the various types. Differentiation might be improved, however, if the photographic scale were increased through a reduction in flying height, or if Type 8442 were used as a reversal film where gamma and, therefore, colour saturation is increased. Vegetation cannot be delineated on the panchromatic photography as its tone corresponds closely to that of the gravels.

Water (Figures 8, 9, and 10 in the enclosed publication)

Water features in the Breidamerkur area range from very clear water bodies, such as ponds caused by the melting of buried ice in kettle holes, rain filled depressions, or small streams on the sandur, to very heavily silted or muddied streams and lakes which are visually milky or chocolate-brown in appearance.

The colour photography has proven particularly valuable for the separation and identification of water features. Clear water images blue-black and silted water in brown tones. Intermediate colour tones of light blue, blue-green, and green are also recorded, corresponding to increases in the reflectance of longer wavelength light due to suspended matter in the water. The panchromatic photography renders water features similarly to the colour, except that shades of grey replace colours and consequently silted ponds are difficult to distinguish from gravels.

/Gradations

Gradations of suspended matter in the water are also less evident on the panchromatic photography.

In regard to the infra-red sensitive films, the false colour photography has proven excellent for the tracing of small stream courses. Clear water, for example, images deep-blue, although becoming blue-green with increasing cloudiness. Streams on the sandur are surrounded by vegetation (which images in red-magenta tones) and are quite easily defined as red and blue-green represent the two colours of maximum contrast (Judd, 1955). Depth penetration in clear water was measured on the Santoni IIC stereoplotter and found to be from 10 to 15 feet. The infra-red photography images clear water in black tones with little or no depth penetration; however, like the rest of the photography, increasing cloudiness of the water due to suspended matter produces lighter images.

Bedrock, gravels and soils (Figures 8 and 10 in the enclosed publication)

Bedded basaltic lavas and basalt gravels are perhaps the predominate features in the Breidamerkur area. In the former case reddish-brown is the most common visual colour and in the latter light grey. Soil development is limited to the older moraines and to vegetated areas on the sandur.

The colour photography, again because of small colour-tone variations, proved most suitable for identifying bedrock and individual lava beds of the bedrock. It has also been excellent for distinguishing between recently deposited or exposed gravels and those that have been subjected to weathering for a number of years. For instance, this attribute has been a significant factor in distinguishing between recently abandoned meltwater channels which image in cream or light brown colour tones and the older channels which appear in brown and dark brown tones. It should also be mentioned that most older channels and gravel deposits have moss or grass growing in or on them and this also aids in distinguishing their relative ages. On the panchromatic photography both bedrock and gravels image in medium to light grey tones and while it is possible to differentiate between these two subjects, small alterations in tone (indicated by colour changes on the colour photography) are often obscured.

Both bedrock and gravels image blue-green on the false colour and medium to dark grey on the infra-red. Consequently, small tonal changes are not easily detected. One advantage of the false colour, however, was that moist soil areas imaged dark blue or blue-green and could readily be delineated (Winkler, 1962, also found this to be the case). For example, wet sand areas representing the limits of wave action along the beach were easily detected.

Landforms (Figures 8 and 10 in the enclosed publication)

Landforms of particular interest in the Breidamerkur area include fluvioglacial gravel deposits, such as kames and eskers, and glacial deposition features, such as moraines and medial moraines. For the detection, recognition, and interpretation of both groups of features, colour photography proved superior to the other types for two reasons. First, small patches of ice buried beneath fluvioglacial deposits could be readily detected due to the colour contrasts between the light cream-colour of gravels and the dark brown spot caused by exposed patches of stagnant ice or the moisture from the slowly melting ice. Second, rock types of different colour tone could be detected in morainic deposits, indicating both their type and origin. This was particularly noted in the case of the three adjacent medial moraines of Mavabyggdarond which were known to have originated from different sources. In both the above instances the other film types were less satisfactory as contrasts were slight, although the panchromatic photography, due to the light grey tones of gravels, was superior to either the false colour or infra-red photography.

Two important properties of both colour and false colour photography attributed to tone and contrast were:

1. Increased awareness of landform patterns due to the colour contrasts of gravel, vegetation, and water.
2. Apparent increased stereoscopic acuity.

In the latter case the red-magenta and blue-green tones on the false colour film represent opposing parts of the spectrum and it may be that small differential parallaxes, due to wavelength differences, exist either (or both) in the transparencies and in the retinal image (Anson, 1959, 1967).

<u>Glacier surface</u> (Figures 8 and 10 in the enclosed publication)

The surface of Breidamerkurjokull varies from a dazzling white, through shades of grey caused by banding, to black stagnant ice

/along

along the front margin. In addition, crevasses, surface streams, and dirt cones of various blues, browns and blacks are common.

Colour photography not only records these small tonal variations, which give emphasis to the character and roughness of the ice surface, but permits the accurate delimitation of the glacier snout due to the colour contrast between brown gravels and black ice. The panchromatic film also produced good contrasts; however, tone and contrast rendition on both the false colour and the infra-red photography was considered poor for interpretation purposes. In the former case, all but the whitest ice tended to image in even blue-green tones unsuited for ice-surface studies. In the latter, the dark grey tones of supraglacial debris and shadow areas contrasted too highly with white ice.

Conclusions

Tone and contrast rendition is best on colour photography which, in this instance, recorded and emphasised small colour changes that are impossible to detect on the other types of photography. False colour is particularly good for distinguishing between vegetation types and between vegetation, gravel, and water which image red-magenta, blue-green, and blue respectively. Its tonal properties, however, do not lend itself to ice-surface or landform studies. Panchromatic photography permits the easy distinction between dark-toned clear water, light-grey gravels, and ice-surface features, but is less satisfactory for differentiating between gravels and vegetation which image in similar grey tones. Infra-red photography, as used in this study, is unsatisfactory because the contrast range between vegetation, which is too light, and some gravel areas, which are too dark, precludes good definition. Figure 4.17 is a summary of the visual tone and contrast properties of the various features.

Factors Influencing Tone and Contrast in the Breidamerkur Area

In order to evaluate tone and contrast in an objective manner it is necessary to consider all influencing factors. These are discussed below.

Illumination

Based on average clear weather conditions, latitudes of 60 to 70 degrees, and solar altitudes of 30 to 45 degrees (such as would be encountered in the course of the day during the months of June, July, and August), the solar horizontal plane illumination will vary from 4000 to 7000 foot-candles (Brown, 1952; Brock, Harvey, Kohler and Myskowski, 1966). Therefore, the figure of 5700 foot-candles as derived from the calibrated light meter data is taken as representative of the illumination of the Breidamerkur area.

Characteristics of Natural Objects in the Breidamerkur Area

Natural objects influence tone both by their shape and texture, and by their reflectance characteristics. As the previously mentioned methods of reflectance measurements tended to integrate the effects of texture, slope, etc., these factors will not be considered separately. It should also be noted in regard to the foregoing measurements that, strictly speaking, foot-lamberts only refer to the visible spectrum from

Fig. 4.17 Visual Evaluation of Tone and Contrast for the Breidamerkur Photography

Type of Photography	Tone					Major Contrasts
	Vegetation	Water	Bedrock, Gravels, and Soils	Landforms	Glacier Surface	
Panchromatic	Medium grey	Dark grey for clear water to light grey for silted water	Medium to light grey	Medium to light grey	very light for white ice to dark grey	Clear water, gravels, and white ice
Infra-red	Very light grey	Black to medium grey	Medium to dark grey	Medium to dark grey	White to black	Vegetation, clear water, and white ice
Colour	Green, green-brown, green-yellow	Black, blue, blue-green, green, brown	Brown, tan, cream	Brown, tan, cream	White, blue, brown, black	Vegetation, water, gravels and landforms, and ice surface
False Colour	Red-magenta to yellow	Blue to blue-green	Blue-green except for moist soils which image dark blue.	Blue-green	White and blue-green	Vegetation, water, moist soils and white ice

400 to 700 millimicrons and if the infra-red is considered radiometric units should be used. However, as reflectance factors in the infra-red were measured by means of a photographic receptor rather than a photocell, and were adjusted on the basis of percentage reflectance, it is convenient for tone reproduction considerations to use what could be termed equivalent foot-lamberts.

Spectral reflectance refers to percent reflectance in narrow zones of the spectrum rather than over the entire visible or photographic spectrum and is important if the use of narrow bandpass filters is contemplated (as in spectrozonal photography). In this regard, there is one factor which tends to be overlooked by photo-interpreters and that is, reflectance in narrow zones of the spectrum can be considered as luminances or luminance differences with values in foot-lamberts. This relationship becomes apparent when spectral curves of filters and natural objects are superimposed and is helpful when considering whether or not the use of narrow bandpass filters is justified (also see Langley, 1962).

Figure 4.18 lists luminance values based on several hundred light meter readings of representative features (Figures 4.19 and 4.20) in the Breidamerkur area. As can be seen, based on mean luminances, the luminance ratio of a common dark object such as clear water at 240 foot-lamberts and white ice at 4900 foot-lamberts is 20:1, or a log luminance ratio of 1.3 units. The average light meter reading for the entire area is approximately 13.0 or equivalent to 490 foot-lamberts. It is interesting to note that luminance variations of ± 150 foot-lamberts within a

Fig. 4.18 Luminance Values for Natural Objects in the Breidamerkur Area as Derived from the Light Meter Readings.

Subject	Colour	Mean Light Meter Reading	Mean Luminance in Foot-Lamberts	Luminance Range in Foot-Lamberts	
				Max.	Min.
Wet sand	Black/dark grey	11.9	240	250	210
Dry sand	Black to grey	13.2(grey) 12.6(black)	550 370	650	330
Fine gravel	Grey {brown red green grey	13.3	600	700	490
Medium gravel	Grey {brown red green grey	13.5	700	960	490
Coarse gravel	Grey {brown red green grey	13.7	800	1400	490
Medial moraine	Brown-grey	13.5	700	750	650
Fluted and ground moraine	Grey-dark grey	13.5	700	1070	490
Grass	Brown-green	12.9	450	490	420
Rushes	Dark green	11.9	240	310	240
Moss	Yellow-green	12.7	400	550	250
Dead moss	Green-brown	12.7	400	420	350
Sandur	Brown-green	12.6	370	400	350
Wet mud	Grey-brown brown dark brown	13.0	490	800	370
Dry mud	Light grey-brown to dark brown	13.3	600	960	350
Clear water	Dark	11.9	240	330	90
Silted water	Light blue to brown	13.5	700	1070	370
White ice	White	15.9	4900	5700	960
Black ice and buried ice	Black	12.3	310	350	250
Dirt cone	Black	11.4	170	180	160

Fig.4.19 Panchromatic (upper) and infra-red (lower) photographs of ground moraine (foreground); and vegetation, bedrock, and ice (background).

Fig. 4.20 Panchromatic (upper) and infra-red (lower) photographs of grass, rushes, moss, and a small stream course.

given subject are not uncommon due to variations in texture, moisture content, and relation to sun and slope.

Spectral reflectance curves of representative natural features based on the photographic records are given in Figure 4.21 and have been grouped to illustrate the three main categories of spectral reflectance curves for natural objects (Krinov, 1947; Goldman, 1960).

1. Soils, gravels, rocks, silted water: near neutral reflectance with gradual increase from approximately 8 percent in the blue to 17 percent in the red. A decline in the infra-red for features such as medial moraine, silted water, and ground moraine with some moisture content.
2. Vegetation: very little reflectance from 400 to 500 millimicrons. Peak of 10 to 15 percent near 550 millimicrons. A secondary minimum between 630 and 680 millimicrons - the zone of maximum absorbance of chlorophyll. A sharp rise to between 25 and 45 percent reflectance in the infra-red. Note the lower infra-red reflectance of moss and the influence of moss and gravels on the reflectance curve for the sandur.
3. White ice and clear water: a decline from the blue through the infra-red. The clear water has a generally low reflectance from the green portion of the spectrum onwards.

In addition to the graphical representation, a tabulation of percent reflectance by wavelength and filter is given in Figure 4.22.

It should be noted that although the light meter and photographic

/data

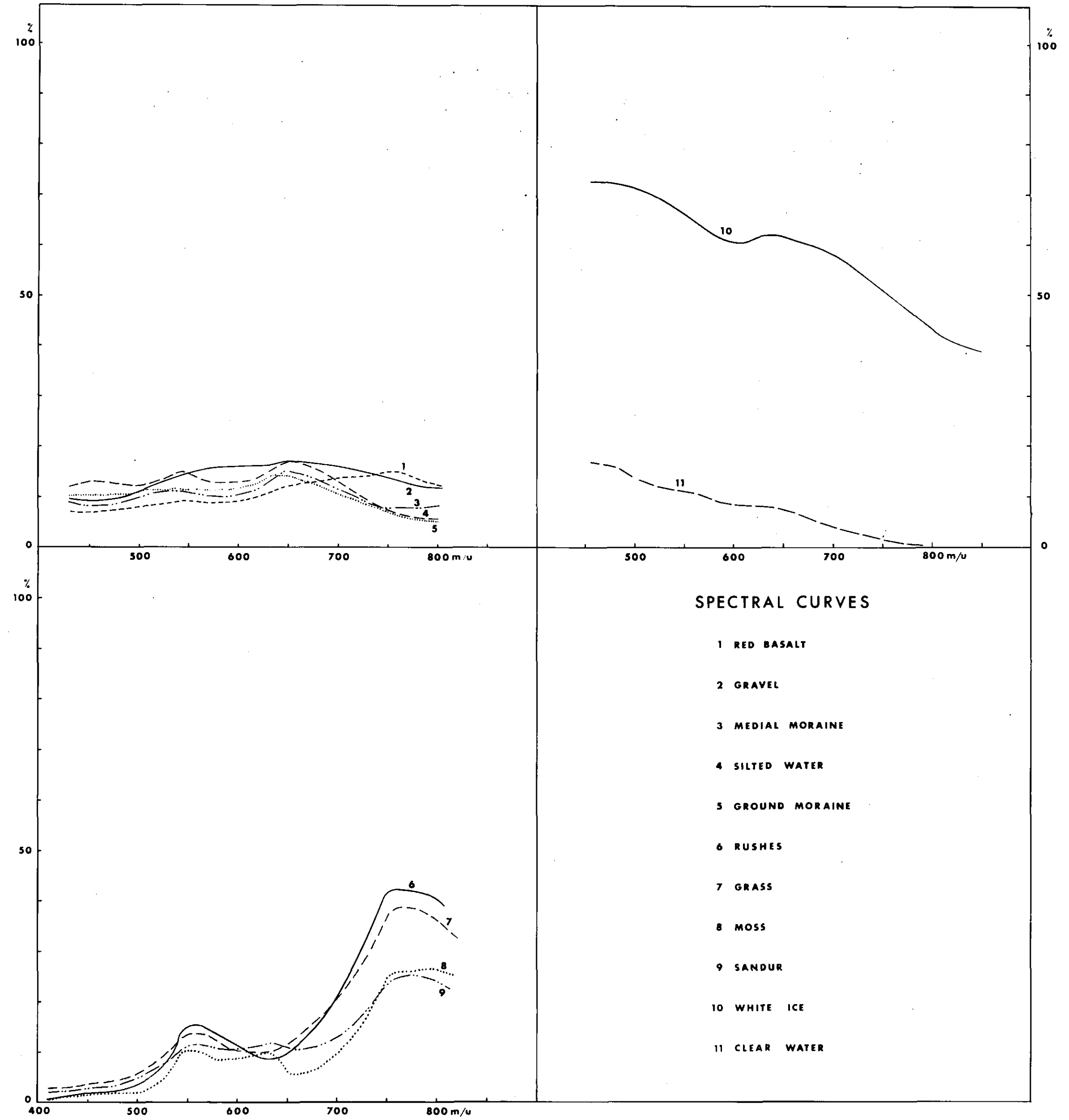

Fig. 4.21 Spectral reflectance curves of natural objects in the Breidamerkur area.

Fig. 4.22 Percent Reflectance by Filter and Wavelength ($m\mu$)

Filter No.[1]	601 (P)	2+6 (P)	623 (P)	625 (P)	626 (P)	5+7 (P)	608 (P)	18A+107 (IR)	87 (IR)
Subject / Wave-[2] length $m\mu$	390-460 (430)	430-480 (450)	470-540 (500)	520-580 (540)	560-600 (575)	590-660 (630)	630-660 (650)	710-800 (740)	760-900 (800)
Moss	1	2	2	9	9	10	6	25	26
Gravel	12	13	12	15	13	15	17	14	12
Grass	3	4	6	12	12	10	12	37	36
White Ice	72	71	66	61	62	60	58	45	39
Medial Moraine	9	8	10	11	10	13	15	8	8
Mud	11	11	11	11	13	15	14	8	9
Silted Water	10	9	11	14	16	16	17	8	6
Clear Water	16	14	11	9	8	5	4	0	0
Red Basalt Rock	8	7	8	9	9	11	12	15	12
Rushes	1	2	4	13	13	9	10	42	40
Fluted and Ground Moraine	10	10	11	11	11	14	14	8	5

[1] P = panchromatic film IR = infra-red film

[2] Peak Transmission (430)

data do not correspond exactly because of differences in the receptors and variations between objects, the agreement is sufficiently accurate for either visual or objective studies.

Effects of the Atmosphere

As glacial areas are normally characterised by extremely clear atmospheres, it could be presumed that a condition approaching a Rayleigh atmosphere exists in sunny weather. This has been largely borne out from data accumulated during the aerial survey. For example, comparing the light meter readings of 13.5 obtained at an altitude of 8,000 feet (2,440 metres) with the mean ground light meter reading of 13.0, there is a difference of 210 foot-lamberts, indicating an atmospheric luminance of approximately 210 foot-lamberts existed at the time of photography. Based on: 1) the fact that camera flare is unlikely to be more than one percent and on data from Molnar (1963) which indicates a near linear increase in atmospheric luminance until an altitude of 13,000 feet is reached; 2) the previously mentioned figures of 575 and 725 foot-lamberts for hyperaltitudes (which can be taken as above 30,000 feet); and 3) an approximate value of 400 foot-lamberts for 13,000 feet (4,100 metres) obtained from a comparison of sensitometrically processed positives from both the 8,000 and 13,500 foot panchromatic photography, it has been possible to construct what is thought to be a representative plot of atmospheric luminance plus camera flare as a function of flying height for a glacial area. This plot is for solar altitudes between 35 and 50 degrees and is shown in Figure 4.23.

/Effects

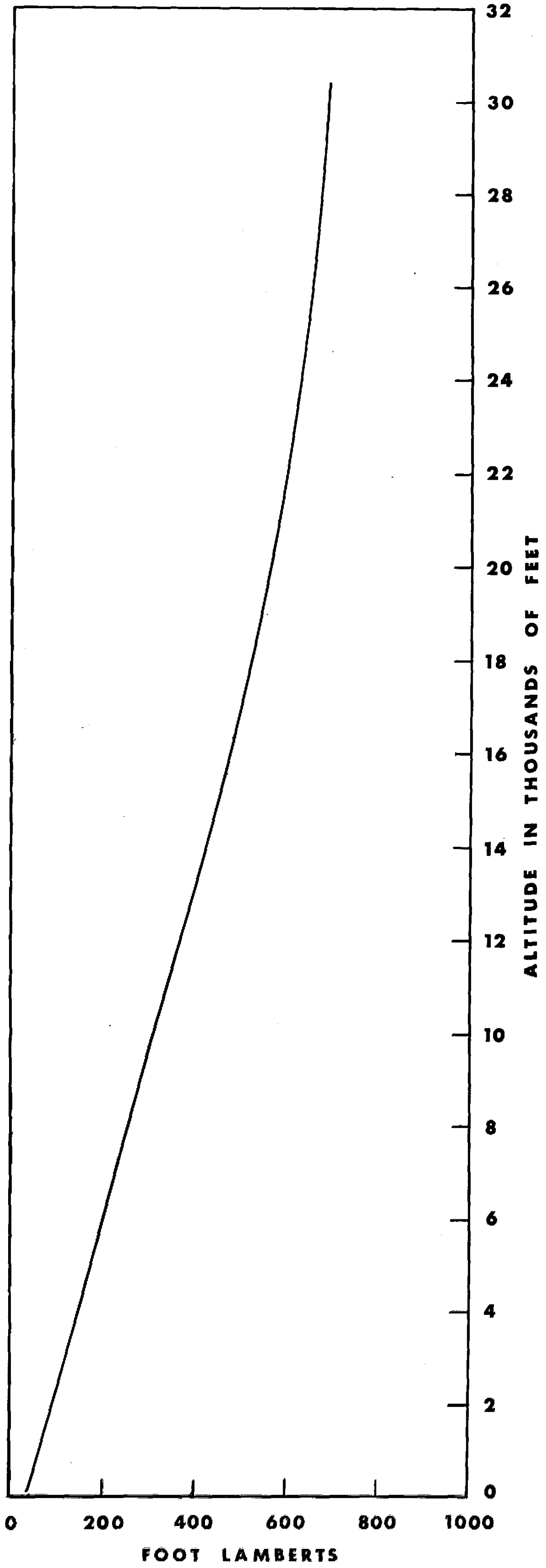

Fig. 4.23 Atmospheric luminance plus camera flare for clear weather conditions.

Effects of the Atmosphere plus Camera

When the effects of the Aviogon lens transmission, filter, and aperture, together with those resulting from the exposure for normal minus-blue panchromatic photography, are added to the atmosphere, the previously derived ground luminance ratio of 1.3 log units for ice:clear water is reduced to approximately 0.93 log units (or a contrast of 8.5:1) for a 300 foot-lambert atmosphere and 0.72 log units (or 5.2:1) for 600 foot-lamberts (Figure 4.24). Of particular significance, however, is the compression in the lower and middle tones, where the log luminance difference of 0.4 between log object luminances of 2.5 to 2.9 - the log luminance range of the visible spectrum in which most objects in a glacial landscape fall - has been compressed to approximately 0.22 and 0.17 units respectively, indicating that identification of most objects based on tone and contrast will be tenuous. This matter is further complicated when it is realised that illumination fall-off in the Aviogon lens can cause the addition of as much as 0.55 density units in the extreme corners of the photograph (Figure 4.25).

It should also be noted that the log difference in exposure between the two curves in the lowlight region is approximately 0.2 units or one-half f stop. The shape of the curves will remain constant for a given atmospheric luminance as long as Ta and T_L are not altered radically; however, the curves will shift vertically in relation to the log E axis as f stop and t are varied.

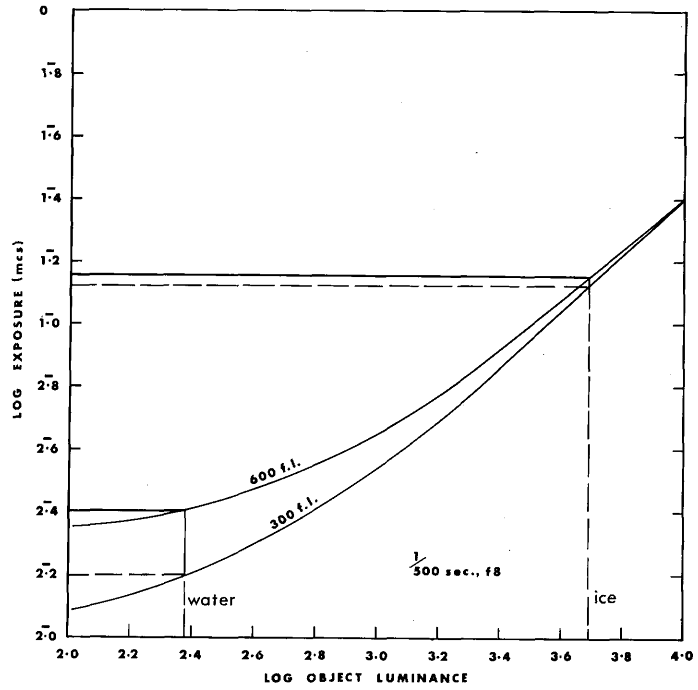

Fig. 4.24 Atmosphere and camera curve for a Wild Aviogon lens and atmospheric luminances of 300 and 600 foot-lamberts. Note the compression of the log object luminance ratio for clear water:white ice.

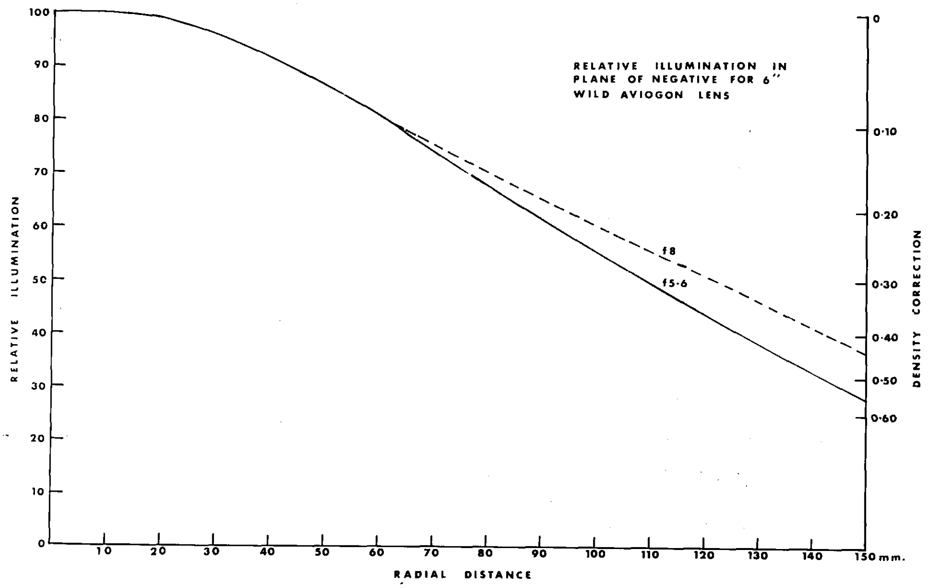

Fig. 4.25 Illumination in the plane of the negative.

Tone Reproduction Considerations for the Study of a Glacial Area

Based on the aforementioned object measurements, hypothetical tone reproduction diagrams (Figures 4.26 to 4.29) have been constructed utilising the same films, with the exception of Kodak Super XX (which is similar to Ilford Hyperpan), as those employed for the Breidamerkur photography. It should be noted, however, that the exposure and processing conditions discussed below are for minimum exposure and maximum contrast (as is typical of most air survey work)and do not necessarily correspond to the conditions used in obtaining and processing the Breidamerkur photography. This is particularly true of Type 8442, which is considered as a reversal film exposed and developed to manufacturer's specifications rather than a negative colour film used under modified conditions. Although discrepancies between the theoretical and actual conditions exist, an insight can be gained into the problems and value of tone reproduction diagrams and, as will be seen later, their relationship to the quantitative measurements of the images in the Breidamerkur photography can be assessed. Figure 4.30 lists the parameters used in constructing the tone reproduction diagrams.

An analysis of each of the tone reproduction diagrams brings out the following conclusions.

Panchromatic (Figure 4.26)

Very little tonal differentiation between gravels and vegetation can be expected. It is very difficult to record the luminance range when white ice is included, and final reproduction is far from perfect

/although

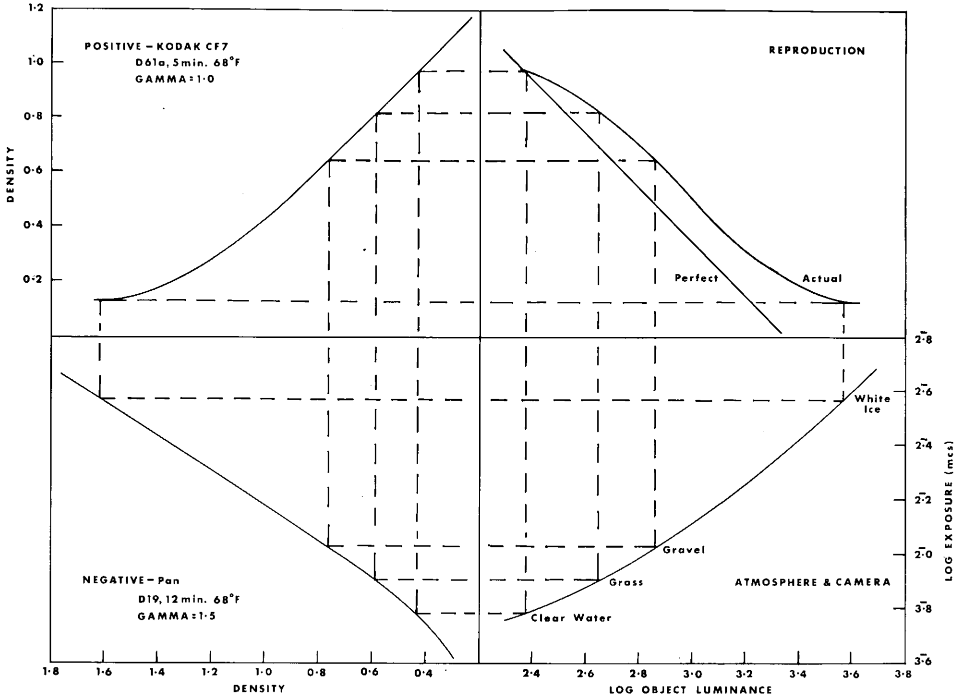

Fig. 4.26 Tone reproduction diagram for Kodak Super XX.

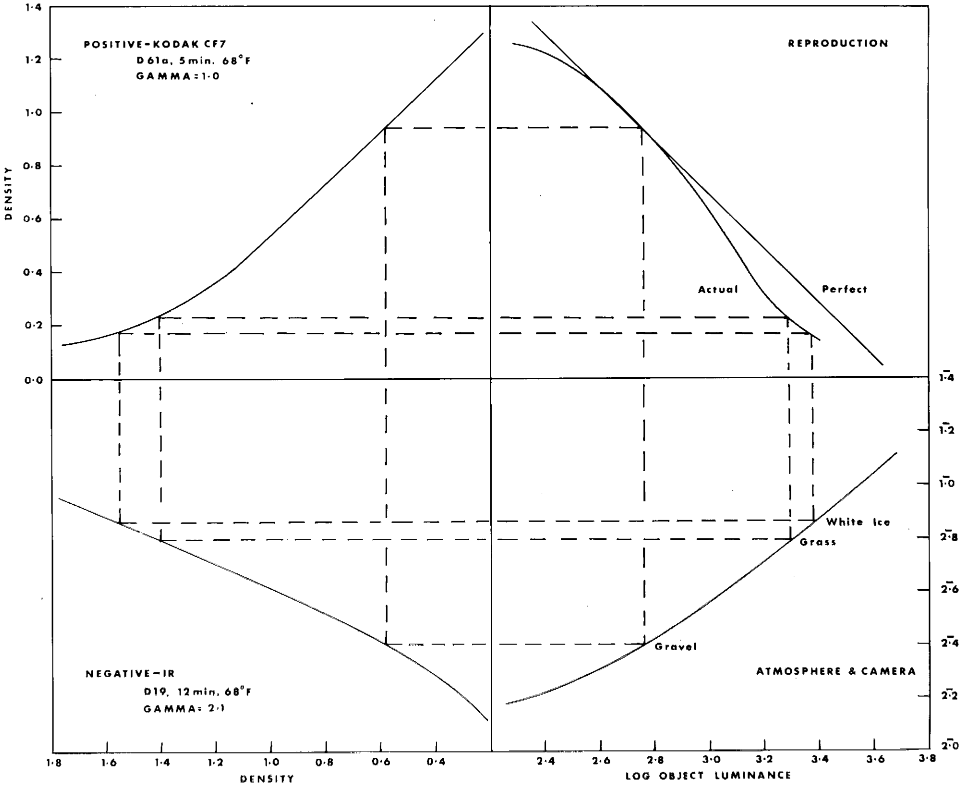

Fig. 4.27 Tone reproduction diagram for Kodak Infra-red Aerographic.

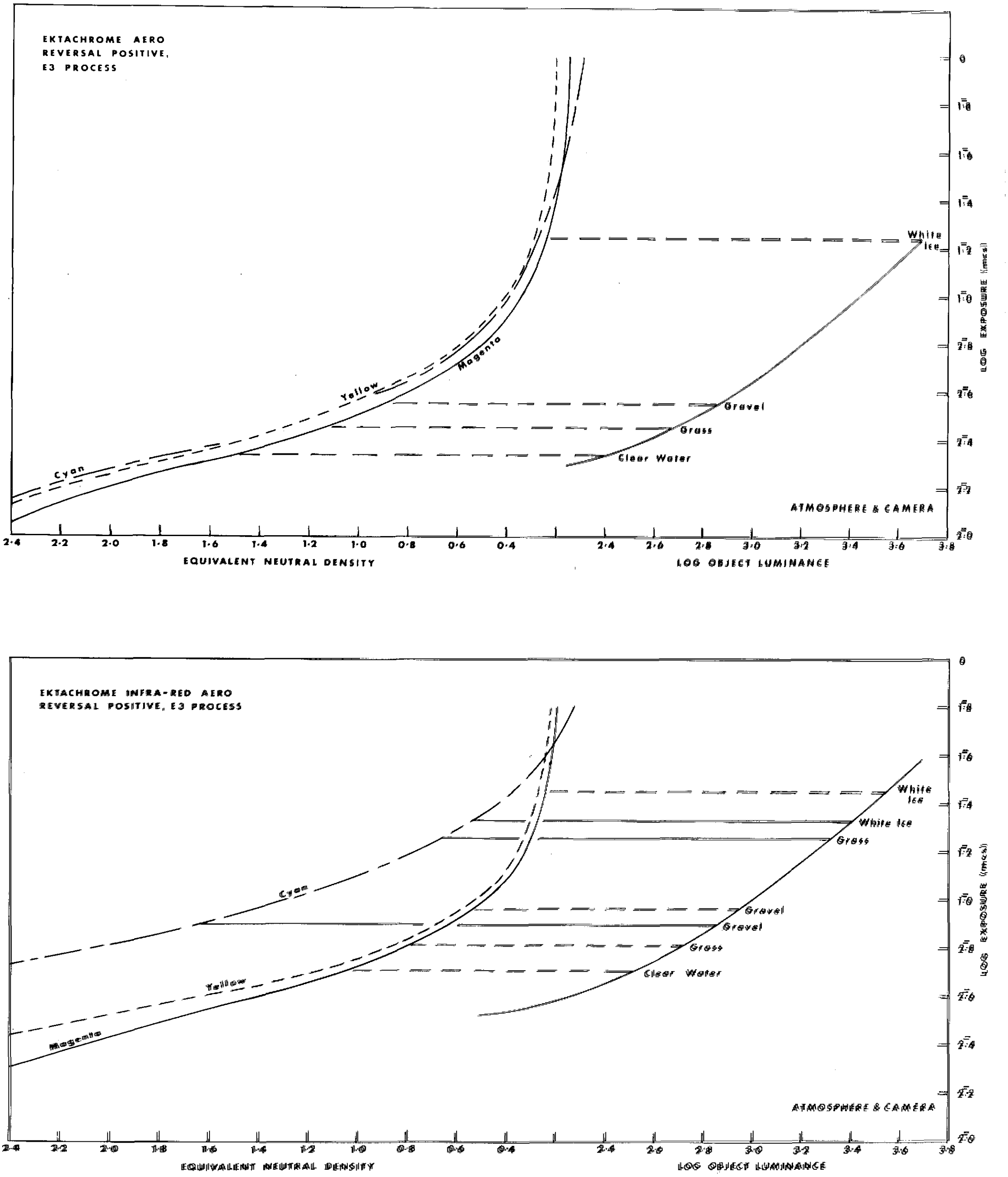

Fig. 4.28 (upper) and Fig. 4.29 (lower) Tone reproduction diagrams for Kodak colour (4.28) and false colour (4.29) films.

Fig. 4.30 Factors used in Constructing the Hypothetical Tone Reproduction Diagrams

Film	Filter and Filter Factor	Wild Aviogon Lens (T_L)	Atmospheric Luminance in Foot-Lamberts	Atmospheric Transmission (Ta)	Luminance of Object (Bo) in Foot-Lamberts	Required Density above Base (Density Units)	Exposure Time (t)/Aperture
Kodak Super XX	500mμ 2	0.78	300	0.75	240	0.40	1/700 sec./f 11
Kodak Infra-red Aerographic	600mμ 2	0.78	300	0.80	510	0.50	1/500 sec./f 8
Kodak Ektachrome Aero	Anti-vignetting 1.4	0.65	300	0.70	4900	0.30	1/700 sec./f 6.3
Kodak Ektachrome Infra-red Aero	500mμ 1.5	0.78	300	0.75	4900	0.30	1/500 sec./f 5.6

although visually satisfactory.

Infra-red (Figure 4.27)

Very high contrasts can be expected between vegetation and gravels. In fact, it is impossible to satisfactorily record either because of the differences in infra-red reflectance and the high gamma of the negative material. Reducing the gamma of the positive material does not materially alter this relationship. One advantage is that the white ice, because ot its lower reflectance in the infra-red, is recorded lower on the D-log E curve; however, with both ice and vegetation at one end and gravels at the other, contrasts are high and definition will be poor. Generally, it can be stated that contrasts in the middle tones have been expanded with compression in the shadow area.

Colour (Figure 4.28)

Because of the high gamma when used as a reversal film, attempts to place white ice at densities of 0.4 to 0.5 result in densities of 1.0 and greater for other subjects. Therefore, it is necessary to compromise and place ice at 0.3. In this case, colour saturation should be very good for gravels and vegetation, although requiring a very bright light source for viewing. The most serious problem that will be encountered in using this film at altitudes below 10,000 feet, will be exposure latitude. However, at altitudes above 15,000 feet compression of the luminance range will allow good placement on the D-log E curve.

False colour (Figure 4.29

The effect of the slower infra-red sensitive layer becomes immediately evident. Gravels and water with low infra-red reflectance are not exposed in this layer, although they are strongly exposed in the red and green sensitive layers to create a blue-green visual image. Rushes and grass, however, which reflect about four times more radiation in the infra-red than in the visible spectrum, strongly expose the infra-red sensitive layer, creating a red-magenta image. Moss and sandur with infra-red reflectances about two to three times as high as their visible reflectance produce a yellow visual image.

Conclusion

The basic problem in tone reproduction for the interpretation of a glacial area, therefore, is to separate vegetation, water, gravels, and ice into distinct density or colour bands, yet compress the overall luminance range so that it can be encompassed in the optimum recordability range of the negative or reversal emulsion. To accomplish this it is necessary to consider landscape characteristics, the atmosphere, camera, filters, exposure, illumination fall-off, negative and reversal materials, and, of course, the positive material. In the following section quantitative measurements of the images of objects in the Breidamerkur area are performed on the Breidamerkur photography.

Quantitative Evaluation of the Breidamerkur Photography

The quantitative relationship of ground objects to images has been determined by measuring the image densities on positive transparencies of objects for which luminances and/or spectral reflectance were measured on the ground. In the case of the panchromatic and infra-red photography,

/transparencies

transparencies have been adjusted to a common gamma by means of step wedges impressed on the positive materials at the time of printing. The false colour transparencies are automatically the result of a reversal film and it is assumed that exposure and processing have been consistent. As the colour positives were produced from negatives using different filter combinations and exposures there is no systematic relationship between them in terms of filter densities[1]. Estimated and known gammas of all negatives and positives are listed below:

	Gamma		
	Negative	Positive	Total (Negative x Positive)
Ilford Hyperpan	1.3	1.0	1.3
Kodak Infra-red Aerographic	2.0	1.0	2.0
Kodak Ektachrome Aero	1.0	1.8	1.8
Kodak Ektachrome Infra-red Aero	-	2.2	2.2

The effects of illumination fall-off have been approximately compensated for by measuring the radial distance of the image object from the principal point and then applying a density correction based on the known illumination fall-off.

/Figure

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[1] Filter densities refer to density measurements of colour or false colour films through red, green, and blue filters with transmissions corresponding to the sensitivities or absorbtions of the three layers (Evans, 1952).

Figure 4.31 illustrates the corrected densities of the image objects for each type of photography as determined by densitometer measurements utilising white light approximating to daylight. Figures 4.32 and 4.33 give the red, green, and blue filter densities for the colour and false colour photography. An analysis of these charts reveals the following major points.

Panchromatic

Clear water and white ice represent the extremes with the density of white ice equivalent to the film base (that is, there is not an effective image), and clear water at a density of just over 1.0. The mean difference in densities between gravels and vegetation is approximately 0.10. Gravels would not be accurately distinguished from vegetation on the basis of quantitative measurements of tone.

Infra-red

Clear water at a density of just over 1.0 and white ice again representing clear film represent the extremes. Grass vegetation has only slightly higher densities than ice, with mixed vegetation considerably greater. Other subjects fall into a common grouping in the middle tones.

Colour

White light density measurements again place ice and clear water at the extremes; however, differences between other groups of subjects are slight, the main distinction being gravels, vegetation, and silted water. Of the filter densities, those using green and red light

/most

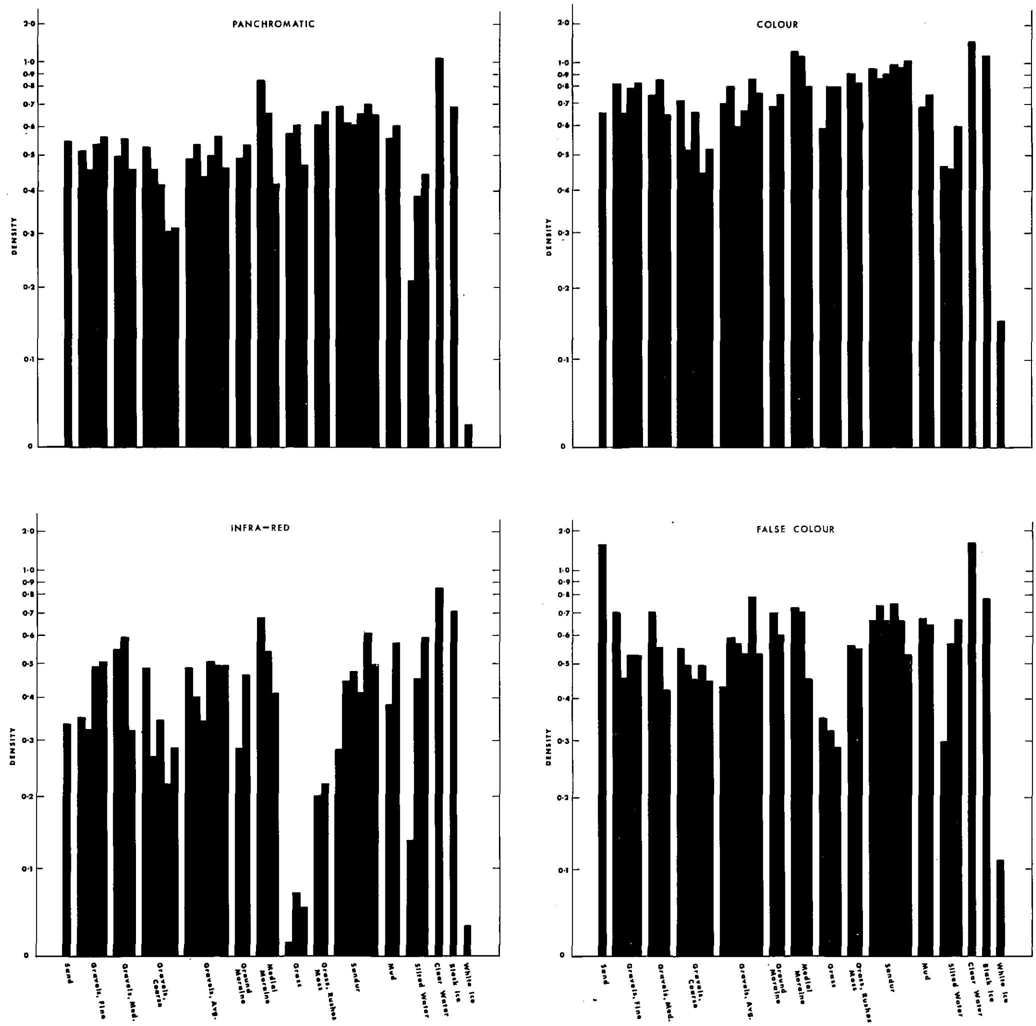

Fig. 4.31 White light density measurements of the images of representative ground objects in the Breidamerkur area.

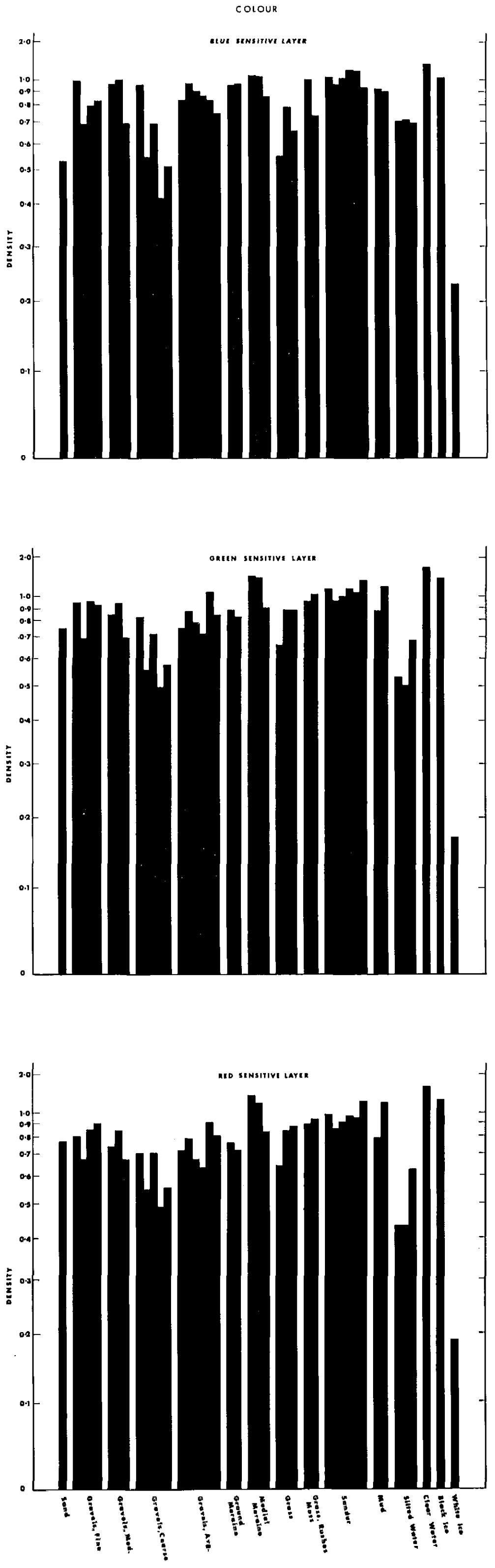

Fig. 4.32 Filter densities for the colour photography.

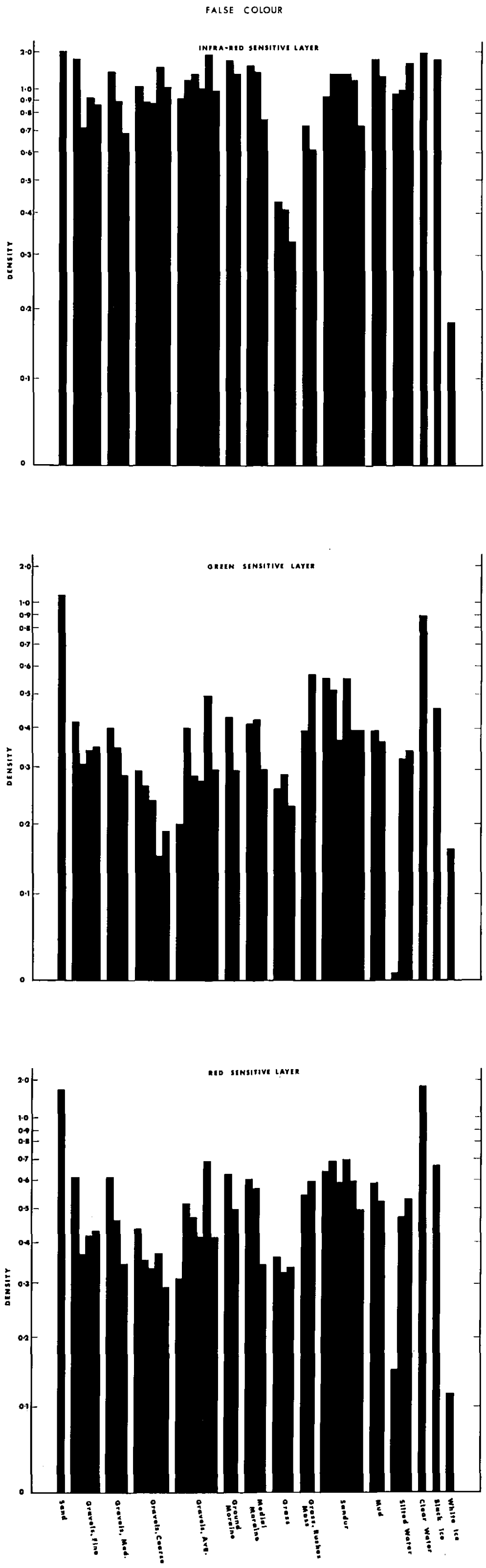

Fig. 4.33 Filter densities for the false colour photography.

most closely correspond to the white light measurements, indicating major image formation in the green and red sensitive layers. The primary role of the blue sensitive layer is to add colour balance.

False Colour

Again, for white light measurements, white ice and clear water represent the luminance range; however, moist sand also registers very darkly, indicating the sensitivity of this film to moist areas. Variations in density are considerable and it is unlikely that with the exception of vegetation, white ice and clear water, any meaningful differentiation could be obtained on the basis of tone alone. In terms of filter densities, green and blue light are most indicative of image formation and also of image colour with red light only denoting vegetation.

Conclusions

The overall conclusions that emerge from the density measurements of the Breidamerkur photography are as follows:

1. Differentiation between objects on the basis of quantitative measurements of image densities is limited to major groups - the groups depending on the type of photography - and then only a statistically probable distinction is likely.
2. The blue zone of the spectrum is not particularly useful for image formation. Atmospheric luminance and attenuation tend to cause even exposure of the blue sensitive layers.
3. Variations in density within groups of objects are considerable and will increase with gamma. This, coupled with the fact

/that

that only the green, red, and, to a limited extent, infra-red zones of the spectrum are useful in image formation, indicates that narrow bandpass filters, in combination with black-and-white films, are unlikely to produce any better results than normal panchromatic minus-blue or modified infra-red photography.

4. If all groups of objects, i.e. ice, vegetation, water, and gravels, are to be distinguished by tone on black-and-white photography, the infra-red portion of the spectrum must be considered, otherwise colour photography must be used.

The above measurements also substantiate the aerial telephotometer[1] data compiled by Carman and Carruthers (1951), who found that log luminance differences of small adjacent objects in the ground scene (when viewed from the air) are likely to have contrasts averaging about 0.08 log units with extremes of 0.02 and 0.18 units. In addition, the measurements largely confirm the previous theoretical consideration of tone reproduction.

Overall Conclusions from the Visual and Quantitative Evaluation of Tone and Contrast

The quantitative assessment of tone and contrast indicated the value of density differences, whereas the visual evaluation emphasised the importance of colour differences. Both density and colour differences serve the same purpose, that is to bring out the patterns of major

/groups

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[1] A telephotometer measures luminances over a narrow angular field.

groups of objects - ice, water, gravels, and vegetation. With black-and-white films this is only possible provided the infra-red portion of the spectrum is considered, regardless of the film-filter combinations used. However, both the visual and quantitative study indicated that infra-red photography poses certain difficulties, both in definition and tone and contrast, which must be overcome if suitable photography is to be obtained of a glacial area. Panchromatic photography, on the other hand, is limited by the inability to satisfactorily record the slight tonal differences between sparse vegetation and gravels, although it poses fewer photographic problems.

Colour and false colour photography permit the separation of groups of objects on the basis of colour tone rather than density and as the eye is much more sensitive to colour differences than to density or brightness differences (Figure 4.34) and as colour differences are less likely to be affected by illumination fall-off in the plane of the negative, these films provide a much greater potential for detecting and identifying objects than the black-and-white films[1]. In addition, subtle changes in colour tone often indicate different types of rocks or soil, or species of vegetation. As such they extend the potential for the investigation of a glacial area through the use of aerial photography.

/With

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[1] That is, density is a logarithmic expression and corresponds fairly well to the response of the human eye. As such, the separation of objects becomes increasingly difficult as densities increase. Colour differences, on the other hand, are more independent of increases in density.

Fig. 4.34 Differentiation of Coloured Marker Images, by both Quantitative and Visual Means

Film	Marker colour in order of brightness	Brightness (light transmission in arbitrary units)	Visual impression of the order of brightness - based on the impressions of three interpreters	Visual impression of colour
Ilford Hyperpan	White	22.5	White	Impossible to determine colours of markers
	Yellow	20.8	Yellow	
	Red-orange	17.8	Red-orange	
	Magenta	17.6	Magenta	
	Green	15.8	Green	
	Blue-green	14.4	Blue-green	
	Purple-violet	11.7	Purple-violet	
Kodak Infra-red Aerographic	White	17.5	White	Impossible to determine colours of markers
	Red-orange	17.1	Red-orange	
	Yellow	17.0	Yellow) similar	
	Magenta	16.3	Magenta)	
	Purple-violet	11.8	Purple-violet	
	Green	8.3	Green	
	Blue-green	7.4	Blue-green	
Kodak Ektachrome Aero	White	17.4	White	White
	Yellow	15.0	Yellow	Yellow
	Blue-green	9.8	Blue-green)	Blue-green
	Red-orange	9.4	Red-orange) similar	Red-orange
	Green	9.2	Green)	Green
	Magenta	9.0	Magenta)	Magenta
	Purple-violet	6.2	Purple-violet	Purple-violet
Kodak Ektachrome Infra-red Aero[1]	Magenta	19.6	Red-orange	Yellow
	Red-orange	19.5	Magenta	Yellow
	White	19.0	Purple-violet)	Yellow
	Yellow	18.5	White) similar	Yellow
	Purple-violet	18.3	Yellow)	Yellow
	Green	15.8	Green) similar	Purple
	Blue-green	15.1	Blue-green)	Purple

[1] As most of the markers have high reflectance in the red and infra-red, they tend to image yellow.

With the various advantages and disadvantages of each type of photography known and the parameters of the Breidamerkur area determined, it is now possible to consider the link between definition, and tone and contrast, and to specify systems suitable for obtaining aerial photography of a glacial area.

SPECIFICATION OF PHOTOGRAPHIC SYSTEMS FOR GLACIAL AREAS

Good definition depends on good tone and contrast as the terms modulation transfer or contrast transfer function denote. The important link, however, is the fact that in these studies the detection of an object by either mechanical or visual means requires a minimum density difference between objects of approximately 0.1. Therefore in the specification of a black-and-white system, it will be necessary to separate major categories of objects in the tone reproduction cycle by differences of 0.1 density units, while retaining the possibilities of recording small objects. The problem, then, is to specify what is important for the interpretation of a glacial area. In the author's opinion, the detection of very small objects is secondary to good tone reproduction for the interpretation of natural landscapes. In the case of a glacial area, this means that the recording of objects one to two feet in diameter is sufficient for most interpretation requirements whether it be for ecological, geomorphological or glaciological purposes and, for this discussion, it will be assumed that the photography must satisfy all three fields.

/Cameras

Cameras

For cameras, a conventional wide angle, six-inch focal length camera (23 x 23 centimetre format) such as the Zeiss RMK A15/23 with a Pleogon lens, a Wild RC8 equipped with a Universal Aviogon, or the Fairchild KC series equipped with Geocon lenses (Norton, 1967) should be considered. These cameras are suitable for all types of photography, including the infra-red, and have shutters permitting exposure control through shutter speed rather than apertures. Maximum aperture is f 5.6. In addition, their large formats permit good area coverage and if desired the photography can be used for photogrammetric purposes.

Films

Low granularity, a low contrast resolution capability exceeding 35 lines per millimetre, sufficient speeds to permit short exposures, and a sensitivity range which will permit the separation of objects on the basis of reflectance are the main criteria. Other considerations include the preference for colour films, regulation of processing conditions, and the production of positives.

Of the black-and-white films currently available, Kodak Infra-red Aerographic, Type 5424, and Kodak Special Panatomic-X Aerial (Estar Base), Type SO-136 should be considered. Type 5424 has the desired infra-red sensitivity and is of sufficient speed to permit short exposures with all types of filters. Furthermore, both gamma and speed can be altered in processing to compensate for errors in exposure. Unfortunately,

/disadvantages

disadvantages include a low contrast resolution of 28 lines per millimetre and a comparatively high granularity.

Kodak SO-136 is a special order panchromatic film. It has the combined advantages of extended red sensitivity, therefore permitting the use of red filters without large filter factors, a low contrast resolution of 65 lines per millimetre, and a granularity half that of the infra-red film or of more conventional survey films such as Kodak Super XX or Ilford Hyperpan. Furthermore, its dyed backing will reduce internal reflections and because ot its high gamma of 2.3, it is well suited for high altitude (above 20,000 feet) photography. The polyester base provides good dimensional stability. Disadvantages include the fact that regardless of its extended red sensitivity and high gamma, it is unlikely to differentiate between gravels and sparse grass vegetation on the basis of tone. In addition, exposure latitude is limited and gamma cannot be significantly altered in the development process, although by changing the development time speed may be altered. A practical consideration is the fact that as a special order film, a minimum order of several rolls may be required.

In regard to colour and false colour films, Kodak Ektachrome MS Aerographic (Estar Base), Type SO-151 and Ektachrome Infra-red Aero, Type 8443 or similar products should be considered. Both these films have the advantage of colour and the latter, of course, is sensitive to the near infra-red portion of the spectrum. Because Type 8443 has already been discussed, only a few additional comments will be made.

/Because

Because of a low contrast resolution of 36 lines per millimetre, a granularity of one-half that of the other films and the contrasts provided by the red-magenta tones of vegetation and the blue and blue-green of gravels and water, it is suitable for high altitude photography of a glacial area. However, it should be used at speeds compatible with the recommended manufacturers' aerial exposure index of 25.

Kodak SO-151 is a new medium speed colour film, which offers several advantages over Type 8442. These are an increased exposure latitude, a polyester base, a low contrast resolution of 40 lines per millimetre (as compared to 28 lines per millimetre for Type 8442), and a granularity of less than half that of either Type 8442 or conventional black-and-white survey films. In addition, it is easily processed to either a reversal positive or negative. Based on conversations with members of the Air Survey Branch of the Ordnance Survey, SO-151 used as a reversal film with 420 millimicron haze and 1.4 or 2.2 anti-vignetting filters produces photography equal in definition to the best panchromatic photography. These factors, plus the advantage of colour and the possibility of using the stable polyester base reversal positive for either interpretation or photogrammetric purposes (Woodrow, 1967; Umbach, 1967), recommend it for studies of glacial areas.

The greatest disadvantage of this film is its relatively low speed (aerial exposure index of 6), thereby necessitating shutter speeds of the order of 1/200 to 1/400 second. For this reason it should not be used at low altitudes. Another practical consideration is the relatively high cost of the film and a length of only 125 feet.

Filters

The quantitative measurements of the Breidamerkur photography revealed that several narrow bandpass filters employed with black-and-white film are unlikely to provide additional information over normal minus-blue panchromatic or infra-red photography. To substantiate these results and to determine which type of filter should be used, vertical ground photography utilising both panchromatic and infra-red films was obtained through yellow (500 millimicron), orange-red (590 millimicron), and deep red (630 millimicron) filters. In order to compare the combinations effectively, density measurements were made of the major groups of objects and gamma normalised to 1.0 so that density differences were equivalent to luminance differences. The results are shown in Figure 4.35. As can be seen, neither yellow nor orange-red filters, in combination with normal panchromatic film (sensitive from 400 to 670 millimicrons), are likely to produce significant differences between gravels and vegetation. The infra-red photography, on the other hand, does differentiate between the groups of objects. However, as with the Breidamerkur photography, infra-red aerial films are usually employed with red (or infra-red) filters and developed to gammas considerably in excess of 1.0, resulting in clear water at one end of the characteristic curve and vegetation and ice at the other. In order to partially avoid this problem, yellow (500 millimicron) filters are recommended resulting in modified infra-red photography. A filter factor of 1.5x is adequate.

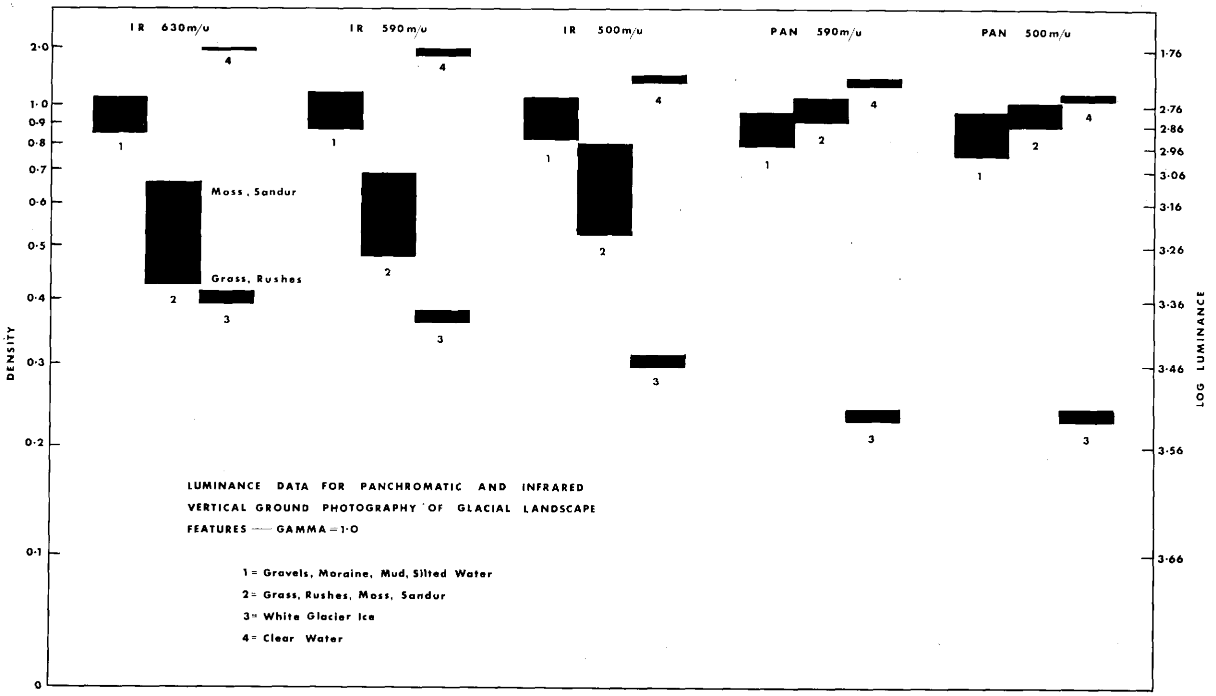

Fig. 4.35 Determination of filters for aerial photography by means of vertical ground photography. Note the excellent separation of groups of objects provided by the infra-red film used with a 500 mμ filter.

With extended red panchromatic films, a red filter (600 millimicron) will provide maximum contrasts without severely increasing the exposure over the normal minus-blue panchromatic photography. For SO-136 a filter factor of 3x is recommended.

False colour films are normally used with a 500 millimicron filter to exclude the blue portion of the spectrum. The Kodak aerial exposure index of 25 takes into account the use of such a filter.

For colour aerial photography it is desirable to employ a light haze filter (420 millimicron) for altitudes above 8,000 feet (2,440 metres). In addition, a 1.4x or 2.2x anti-vignetting filter is recommended to provide evenness of exposure and good colour balance in the negative or reversal positive.

Exposure and Processing

Based on the Breidamerkur photography, it is recommended that exposure times of 1/400 second or greater be used for aircraft ground speeds of 200 to 250 m.p.h., and altitudes of 8,000 feet (2,440 metres) or above. If flying height is decreased, or focal length or aircraft speed is increased, the shutter speed should be proportionately increased (Attwell, 1959). If choice of aperture is possible, f 8 provides the best definition in the Wild Aviogon (Molnar, 1963) and is also likely to do so with the other camera lenses. Smaller apertures, however, tend to reduce definition (Mikhaylova, 1965) and with colour films increase the possibility of "flare" spots in the centre of the photographs (Uspenskiy, 1958).

In determining exposure, luminance data, guides such as the Kodak Aerial Exposure Computer (1966), or light meters can be used. The latter two are probably best if reversal colour films are to be used and processed under manufacturers' specifications. For black-and-white films, however, the use of luminance data permits the entire photographic cycle to be linked through tone reproduction diagrams. Figures 4.36 and 4.37 indicate the potential of tone reproduction diagrams for infra-red and panchromatic photography of a glacial area. In the former, which is based on an atmospheric luminance of 300 foot-lamberts (or an altitude of approximately 10,000 feet), near perfect tone reproduction with adequate separation of all major groups of objects is possible. In the latter, which is based on an atmospheric luminance of 600 foot-lamberts (or an altitude of approximately 20,000 feet), the extended red sensitivity may permit the separation of gravels and vegetation. Reproduction is not perfect but should be visually satisfactory.

Processing should be carried out according to the pre-determined conditions of the tone reproduction diagram or according to the manufacturer's recommendations. Before processing the film, however, test exposures made at the beginning or end of the flight should be processed and inspected in case alterations in development time are required to correct for errors in exposure.

Flying Height

Flying heights for recording the detail of the features of a glacial landscape can be determined on the basis of: 1) detection of low-

/contrast

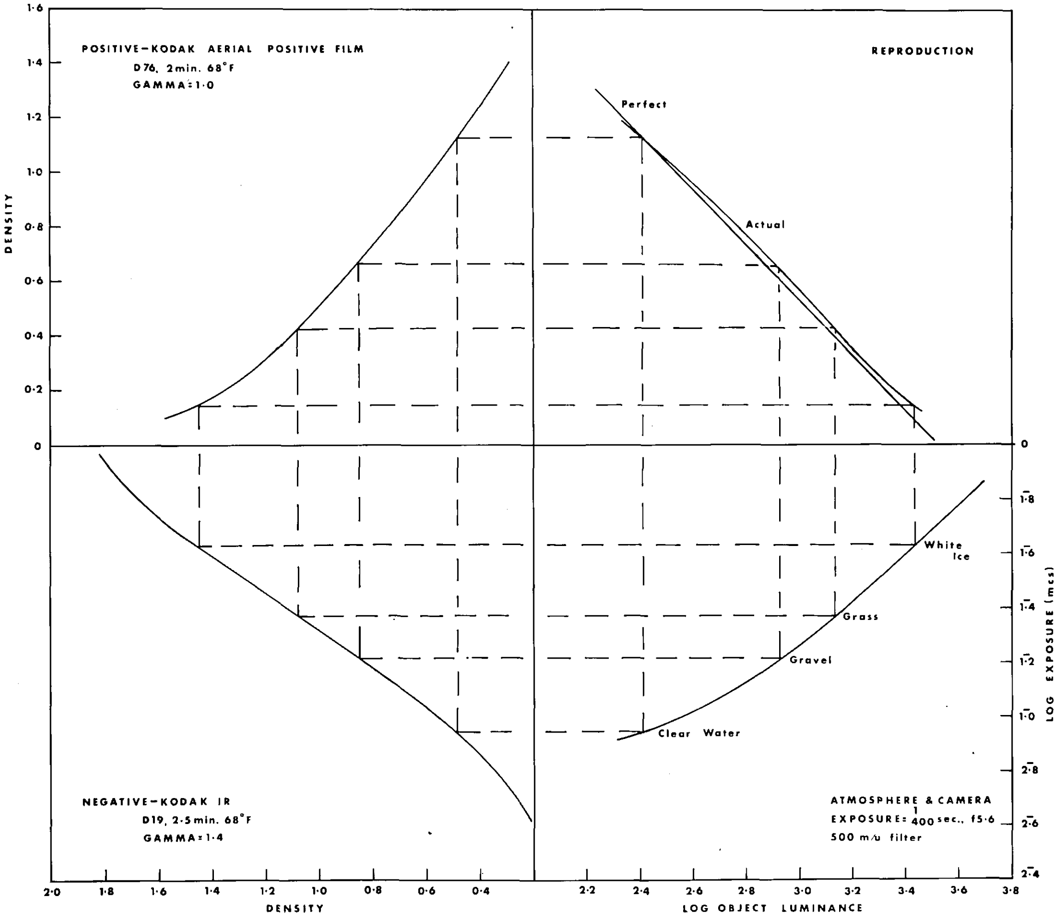

Fig. 4.36 All major groups of objects can be recorded at suitable density intervals on infra-red film by careful regulation of filter, exposure, and processing conditions.

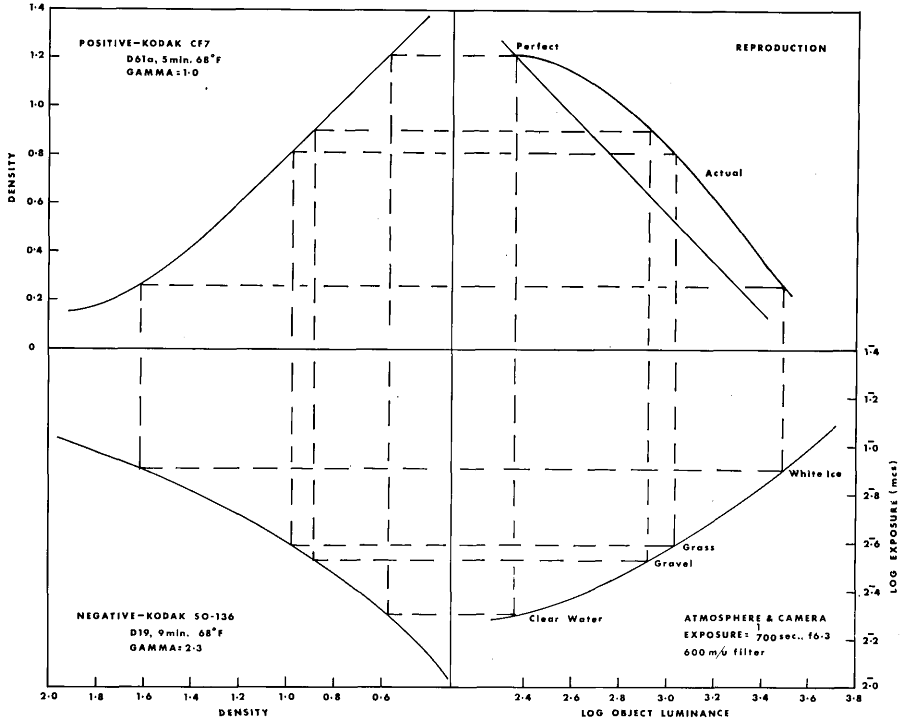

Fig. 4.37 Tone reproduction diagram for Kodak SO-136. Note that separation of all major groups of objects is unlikely.

contrast objects one to two feet in diameter; and 2) the ability of the film to record objects with sufficient density or colour differences at the flying height being considered.

For Kodak Infra-red Aerographic Type 5424, which has a granularity factor and low contrast resolution similar to Type 8442, and since cameras employing lenses corrected for chromatic aberrations are to be employed, definition similar to that obtained with the Breidamerkur colour photography can be expected. As such the detectability graph (Figure 4.16) can be used. An examination of this graph indicates that flying heights to 15,000 feet (4,600 metres) will provide the necessary definition. The previously discussed tone reproduction diagram indicates that, providing exposure and processing conditions can be controlled, all major groups of objects will be recorded at density differences greater than 0.1 units at a flying height of 10,000 feet (3,000 metres). Extending the flying height to 15,000 feet is unlikely to significantly alter the tonal relationships. In the case of Types SO-136, SO-151, and 8443, granularities are approximately one-half that of the infra-red film (or the Ilford Hyperpan film used for the Breidamerkur photography) and low contrast resolutions are higher. As data from Macdonald and Watson (1956) and Macdonald (1958) indicate a gain factor of approximately two in detectability if granularity is halved, while keeping factors such as scale and resolution constant, it is possible to construct a detectability graph for these films (Figure 4.38). As can be seen, it should be possible to obtain adequate definition from flying heights

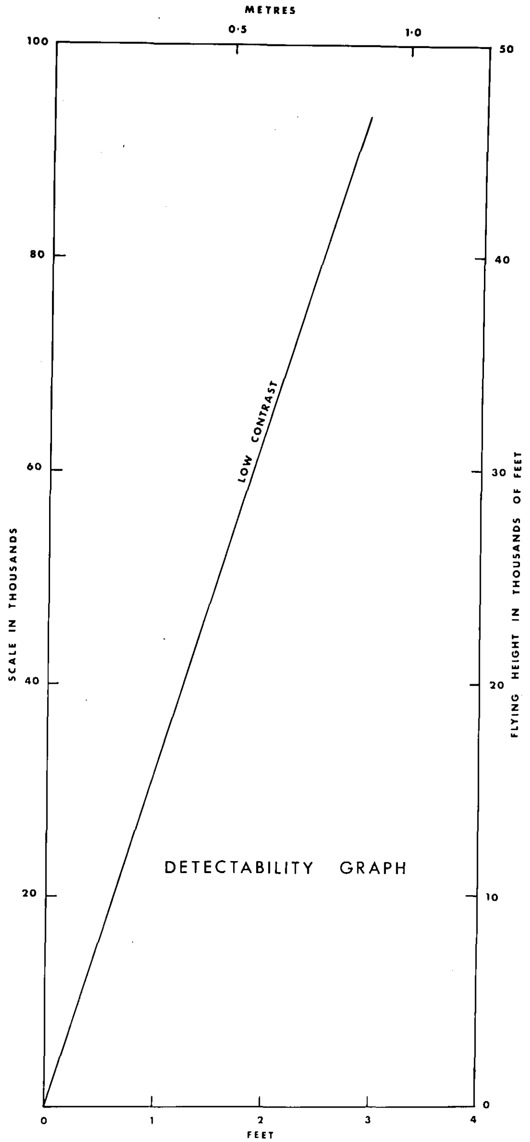

Fig. 4.38 Estimated detectability for 6 inch lens and SO-136, SO-151, and Type 8443

of 20,000 to 30,000 feet resulting in scales of 1:40,000 to 1:60,000.

In terms of contrast, flying height will make little difference for the separation of vegetation and gravels on the panchromatic photography. As has already been mentioned, the infra-red sensitivity and colour contrasts of false colour make it particularly well suited for high altitude photography. Although colour film has often been considered unsuitable for high altitude photography because of a layer sensitive to blue light, it is now known that through careful consideration of film and filter, excellent colour photography can be obtained from any altitude (Howell, 1958; Smith, 1963; Swanson, 1964; Lowman, 1966).

CONCLUSION

From the preceding discussion, it is evident that through careful consideration of the environmental and photographic parameters, it is possible to specify a system which will result in optimum photography for the study of a glacial area. In this regard, colour photography appears to provide the best differentiation of objects, yet maintains good definition through low granularity. However, in order to fully assess the value of the various types of aerial photography, to determine the relationship of shape, pattern, texture, and position to scale, and to evaluate photo-interpretation and photogrammetric methods for the study of a glacial area, it has been necessary to conduct a detailed investigation of the Breidamerkur area using the various sets of photography, the two 1:15,000 scale maps, and collateral information. This study is discussed in the following chapter.

CHAPTER V

AERIAL PHOTOGRAPHY APPLIED TO THE STUDY OF THE BREIDAMERKUR AREA

INTRODUCTION

In the preceding chapter, the photographic considerations in obtaining aerial photography of a glacial area were discussed. However, to determine the effectiveness of aerial photography, it is essential to consider the value of both photogrammetric and photo-interpretation techniques in relation to a glacial area, and to consider the uses and limitations of each for the glaciologist, geomorphologist, and ecologist. In addition, it is important to determine the importance of factors such as scale, tone, slope, pattern, texture, and relative position in combination.

This chapter, then, is an analysis of the western part of the Breidamerkur area illustrating the uses of both photogrammetric and photo-interpretation methods as supported by the literature, personal communications, maps, and limited ground observations. In order to provide an introduction to the study, the general history and characteristics of the Breidamerkur area are discussed first.

History of Breidamerkurjokull

Breidamerkurjokull, one of the largest outlet glaciers of the Vatnajokull ice-cap, is approximately 15 kilometres across at the terminus and although now removed from the sea by two to five kilometres and in a period of continual retreat, has had a long history of fluctuations.

During the Ice Age, more than 6,000 years ago, it is thought that the sea was 100 to 200 metres lower than at the present time (Thorarinsson, 1937, p.166), and that ice and fluvial erosion carved out large fiords which now extend beneath the sea. In the warm period following the Ice Age, the sea rose to 50 or 60 metres higher than present and Vatnajokull and its outlet glaciers retreated, filling the fiords with gravels to create the sandurs that are visible today. As a result of this transgression of the sea and of fluvioglacial deposition, it is concluded that much of Breidamerkurjokull now rests on a marine foundation (Ahlmann and Thorarinsson, 1937, p.182). Subsequent to the warm period which ended approximately 2,500 years ago (Eythorsson, 1960, p.62), the climate became cooler and the glaciers began to re-form; however, it was not until approximately 1600 that Breidamerkurjokull reached its present size. At this time the climate became markedly severe (Schell, 1961, p.355) and the glacier began a rapid advance. By 1698 the last remains of settlement had disappeared from Breidamerkursandur (Jonsson, 1957, p.179). Since 1700 the fluctuations of Breidamerkurjokull have been documented and summarised as follows (Thorarinsson, 1943, pp.28-29):

1702: Glacier front was about 1000 m behind 1903-1904 position.
1702-1756: Slight advance.
1756-1793: Recession.
1793-1839: Advance to approximately 1903-1904 position.
1839-1894: Several rapid advances and recessions. Maximum

/advance

advance in historical times ended in 1880-1894.

1894-present: Recession at rate of 20-50 m per year.

It is interesting to note that the maximum advance of the glacier occurred about 1880, forming the last end moraine on the sandur (F. Bjornsson, 1966, personal communication). Furthermore, there is no record of the glacier ever reaching the sea. This is confirmed to some extent by recognisable maps of the area produced as early as 1500 (Nørlund, 1944).

Thickness of Breidamerkurjokull

The thickness of the glacier was approximately established by seismic soundings during the French-Icelandic expedition of 1951 (Bauer, 1951; Eythorsson, 1952; Cailleux, 1958). According to Eythorsson (1952, p.4), a large subglacial valley termed Breidamork extends about ten kilometres back from the glacier's edge (an estimated 15 kilometres back from the mouth of the Jokulsa), beyond which the subglacial land rises gradually to a maximum elevation of 830 metres. A longitudinal cross section of Vatnajokull based on these soundings revealed that the ice covering Breidamork is 100 to 500 metres thick, whereas that of Vatnajokull reaches 600 to 800 metres in thickness. As the land under Vatnajokull does not exceed 1000 metres (Eythorsson, 1960, p.28) in altitude and the present limit of glaciation is 1100 metres above sea level, Vatnajokull could not exist if it were not for the presence of the 600 to 800 metres of ice already covering the land surface.

Snow Lines, Accumulation and Ablation

/According

According to Ahlmann and Thorarinsson (1939), the firn line on Breidamerkurjokull occurs at an elevation of approximately 1100 metres, with accumulation increasing at a rate of 26 to 28 centimetres per 100 metres of altitude. This rate is fairly constant despite yearly variations in precipitation and accumulation. Eythorsson (1960, p.29) further states that: "According to surveys that have been made (from 1936 and 1951) the winter snow in Nordlingalaegd (a north-south orientated surface depression on Breidamerkurjokull) seems to be 450 - 500 centimetres, and its water value 250 - 300 centimetres. Some of this snow melts away in the course of the summer, while 250 - 300 centimetres usually remain till the following winter ..... ."

Ablation is primarily influenced by warm maritime winds from the south and east. Thorarinsson and Ahlmann (1938, p.230) mention that ablation continues for twelve months of the year in areas 80 metres or less above sea level, and for ten to eleven months to as high as 200 metres. As elevation increases, ablation becomes increasingly limited to the summer period and is less influenced by meteorological factors.

Surface Features of Breidamerkurjokull

Major ice surface features include several medial moraines and dirt bands. The largest medial moraine, Esjufjallarond, extends from Esjufjall to Jokulsarlon and is formed by the merging of four medial moraines in the vicinity of the Esjufjall mountain range (Eythorsson, 1960, p.28). Similarly, Mavabyggdarond can be traced to a small nunatak at about 600 metres elevation.

The prominent banding on Breidamerkurjokull is presumably caused by dust and by ash from volcanic eruptions, such as those of Katla in 1918 and Grimsvotn in 1934, being deposited in the snowfields. The ash is carried to accumulation areas by a predominant south-west/north-east upper air flow (Thorarinsson, 1944, p.10).

Landforms of the Breidamerkur Area

The dominant landforms of the Breidamerkur area include: 1) the mountain ridges of Rakartindur (795 metres) and Fellsfjall (803 metres) on the west and east margins of Breidamerkurjokull; and 2) the gently sloping Breidamerkursandur which extends between the outer end moraines and the sea (Figure 5.1, and the maps in the rear pocket). Along the ice margins several lakes have been formed and from west to east are named Fjallsarlon, Breidarlon, Jokulsarlon, and Stemmarlon (eastern area). The largest is the 5 x 2 kilometre, 110 metre deep Jokulsarlon (Kjartansson, 1957), which is connected to the sea by the Jokulsa. As the Jokulsa could only be crossed by ferry at the time of the survey, it effectively separated the eastern and western parts of the Breidamerkur area.

In the western area, the predominant landforms are a series of parallel moraine ridges marking successive positions of the glacier terminus (Thorarinsson, 1953; Eythorsson, 1960) and numerous fluvioglacial features developed in the last twenty years. Although the sandur is criss-crossed with abandoned stream courses, present drainage is limited to Breida, Fjallsa, and frontal drainage eastward into Jokulsarlon. The

/former

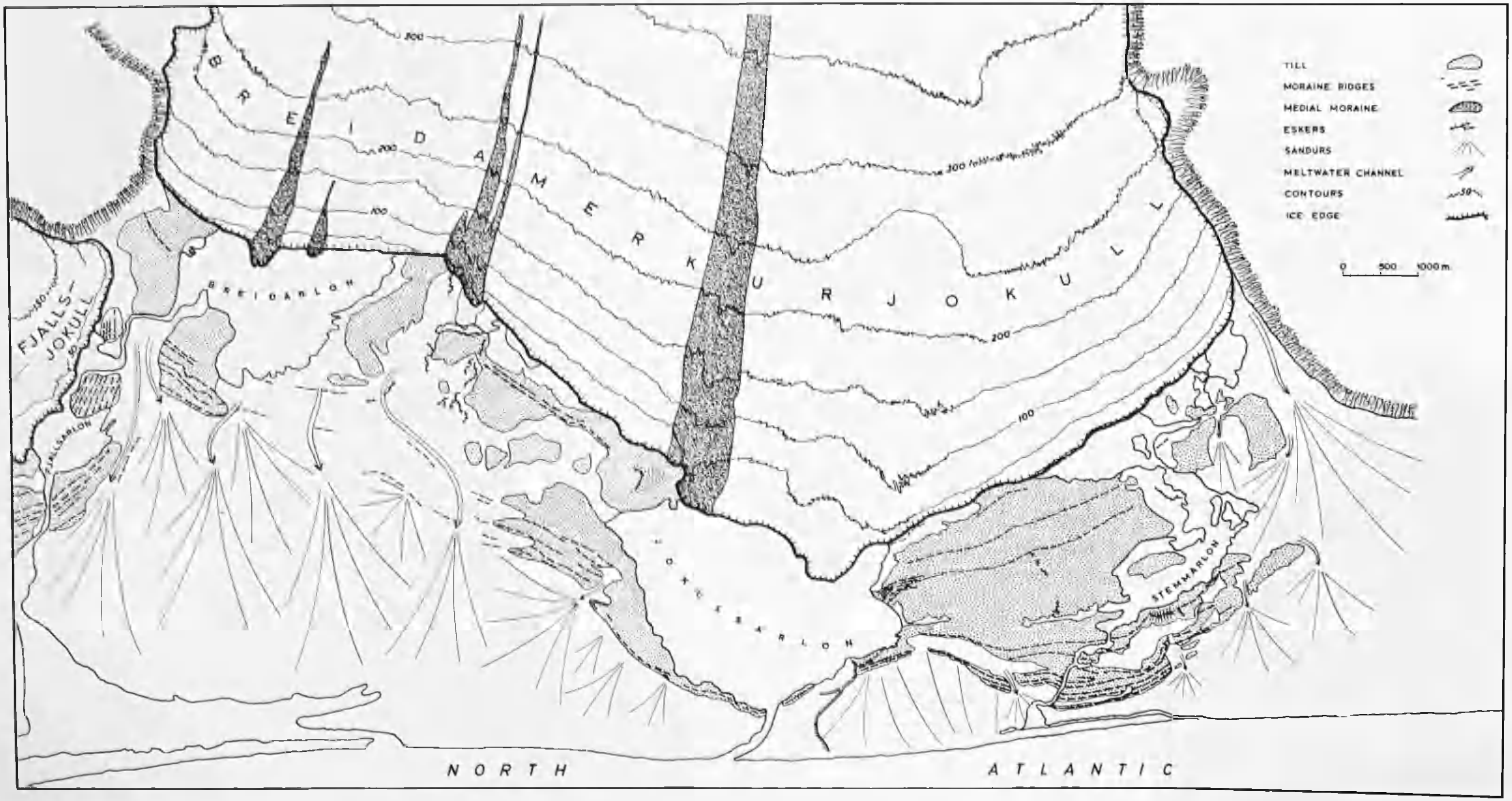

Fig. 5.1 Landforms of the Breidamerkur area.

former two streams are part of a continuous drainage system which connects Breidarlon and Fjallsarlon to the sea. The formation of a sandbar along the coast has resulted in the Fjallsa being diverted eastward before emptying into the sea. At the western margin of the glacier, an ice-dammed lake has been formed north of Rakartindur (795 metres).

Geology of the Breidamerkur Area

Based on geologic formations, Iceland is divided into a north-east/south-west orientated central zone of late Tertiary to Pleistocene age rocks collectively termed the Palagonite Formation, and bordering zones of Tertiary basalts (Thorarinsson, Einarsson and Kjartansson, 1959, p.139). The major difference between the formations is the greater variety of rock types of the younger series, including basalts, tuffs, fluvioglacial deposits, and palagonite breccias. Although the Palagonite Formation is reported to meet the Tertiary basalts at Breidamerkursandur (Jonsson, 1954, p.148; Thorarinsson, Einarsson and Kjartansson, 1959, p.139) the mountain ridges of Rakartindur and Fellsfjall appear to consist largely of 8 to 12 metre thick beds of reddish-brown and grey basalts typical of the Tertiary group (Jonsson, 1954, p.148). Differences in colouring are probably due to weathering (Hatch, Wells and Wells, 1952, p.298). For example the British Naval Intelligence Handbook on Iceland mentions (1942, p.4) that the beds of red and brown rock are weathered lavas containing a high proportion of the oxides of aluminium and iron, and were probably formed in a much warmer climate than at present.

Fifty rock samples from each of fourteen sites on western

Breidamerkursandur and the medial moraines produced the following distribution.[1]

Dolerite (microgabbro)	> 60 percent
Gabbro	10 to 20 percent
Microgranite, felsite, conglomerate, andesite, and tuff.	5 percent or less

The three medial moraines of Mavabyggdarond, which from west to east appear visually to be dark grey, red-brown, and grey-green in colour, consist respectively of 100 percent basalt; 80 percent basalt plus granophyre, felsite and andesite; and 60 percent basalt plus fine and medium-grained grey tuff. The above distributions show that the predominant rock types are basic intrusive and extrusive lavas.

Climate of the Breidamerkur Area

The climate of the Breidamerkur area is strongly influenced by the high ice plateau of Vatnajokull and the warm south-eastward flowing Irminger current. The warm current and onshore winds keep the January-February temperatures from dropping much below 0°C. and those of July from rising above 11°C. Moisture laden air masses, when forced to rise, are cooled by Vatnajokull and produce copious amounts of precipitation distributed through the year.

In order to establish the climate trends and characteristics of the Breidamerkur area in the last 100 years, data on temperature and /precipitation

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[1] Collected by Dr. R.J. Price and field assistants, and identified by Dr. Holdgate, Department of Geology, University of Glasgow.

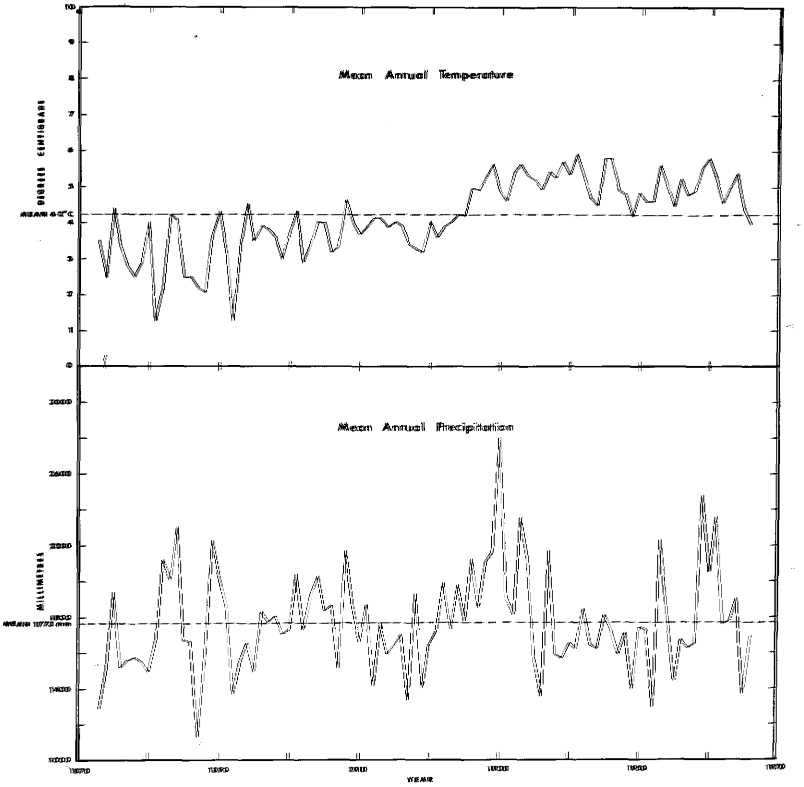

Fig. 5.2 Temperature and precipitation data for the Breidamerkur area.

precipitation for Fagurholsmyri and Teigarhorn, stations in the Breidamerkur area, were obtained from Vedurstofa Islands (Iceland Meteorological Centre). At Fagurholsmyri, eight miles southwest of Breidamerkursandur, temperatures have been recorded since 1903 and precipitation since 1922. Teigarhorn, however, which is approximately forty miles northwest of Breidamerkursandur, has had both temperature and precipitation recorded since 1873. From a comparison of the Fagurholsmyri and Teigarhorn data in common years it was possible to determine constants of + 0.3°C. for temperature and + 568 millimetres in precipitation, which when applied to the Teigarhorn data give an indication of climate conditions at Fagurholsmyri from 1873 onwards. Figure 5.2 indicates the annual temperature and precipitation trends for Fagurholsmyri during the period 1873 to 1966. The mean annual temperature and precipitation over the 94-year period is 42°C. and 1,773 millimetres respectively. The interesting point in regard to this climatic data is that since 1925 the mean annual temperature has been approximately 1.5°C. higher than in the previous 52-year period, but annual precipitation has remained fairly constant. This indicates that temperature rather than precipitation is responsible for the retreat of the glacier.

Vegetation of the Breidamerkur Area

Information on the vegetation of Breidamerkursandur is limited. The Durham University Expedition of 1952 reported moss (species unknown), sheep's sorrel (*Rumex acetosella*), bent grass (*Agrostis stolonifera*), and viviparous sheep's fescue (*Festuca vivipara*) as the most common species,

/with

with sheep's sorrel and the grasses appearing first on the outwash in front of the glacier.[1] They suggest (p.29) that this indicates mosses are not the primary colonisers. However, Lindroth (1965, pp.44-46) in a study of the Skaftafell area observed a total of 68 species of grasses and 26 mosses. In areas deglaciated more than three, but less than thirty years, all but two of the mosses were present whereas 20 species of grasses had still not appeared.

On western Breidamerkursandur Mr. Flosi Bjornsson of Kvisker, at the author's request, collected and identified the predominant species of vegetation. The grasses are sheep's fescue (Festuca ovina L) and bent grass (Agrostis alba L), although some narrow false oat (Trisetum spicatum L) is also to be found. Other common species of vegetation are Baltic rush (Juncus balticus Willd), common sedge (Carex goodenowii), and moss (Rhacomitrium sp.). Flowering plants include thrift (Armeria vulgaris Willd), moss campion (Silene acaulis L), purple saxifrage (Saxifraga oppositifolis L), grass of parnassus (Parnassia palustris L), and mountain rock cress (Arabis petrea L).

THE USE OF PHOTOGRAMMETRY

This section discusses the value of photogrammetry in obtaining

/information

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[1] Common names supplied by H. McAllister, Department of Botany, University of Glasgow.

information about the Breidamerkur area. The production of the two 1:15,000 scale base maps has already been discussed, and of course this has been the principal use of photogrammetry. However the information on ice-wastage, as derived from the two maps, and also from other photogrammetric measurements, has not yet been mentioned and this is considered below. In addition, photogrammetry has proven extremely useful in obtaining data on other glaciological and geomorphological features, including marginal lakes and eskers.

Equipment

Equipment included the previously described Wild B8 and Santoni Stereosimplex IIC plotting machines, and positive transparencies or glass diapositives from all available panchromatic photography. As this photography was obtained from flying heights ranging from 8,000 feet (2,440 metres) to 23,000 feet (7,000 metres) it provides a good indication as to the required scales and flying heights for photogrammetric purposes.

Glaciology

Glaciological data has been derived from profiles, area and volume changes, and from spot heights. Profiles are considered first.

Profiles (Figure 5.3)

From careful examination of the available photography it was possible to select photogrammetric models which covered the same ice margin area for the years 1960 and 1961. Using these models, twenty metre contours were plotted on gridded sheets and these sheets were superimposed on the 1945 and 1965 maps. From the combination of sheet overlays and maps, it was possible to select a line extending through the 394500N 416000E and 399000N 417500E grid marks which was common to all plots and roughly perpendicular to the ice margin. Profiles were constructed along this line (A-A') with 0 at the 394500N 416000E grid mark (see Figures 5.3 and 5.5). In addition, by photographically reducing the 1945 map to 1:100,000 scale (Figure 5.4), it was possible to superimpose it on the 1903 Danish map and contruct a profile for 1903. As the 1:25,000 scale Durham University Map of 1951 was available, a profile was also constructed for that year.

From the above profiles it was evident that the general configuration of the glacier surface had not changed appreciably over the period 1903 to 1965, and as the positions of the ice margin were known for 1880 and 1937, profiles were estimated for these dates as well. Based on the profiles, the downwastage at the snout of the glacier was as follows:

Period	Total Downwastage	Per Year
1880-1937	105 m	1.8 m
1937-1945	140 m	17.5 m
1945-1965	148 m	7.4 m

As can be seen, the downwastage correlates well with the warming trend in the climate of the Breidamerkur area.

Area, Height, and Volume Changes, 1945 to 1965

From the 1945 and 1965 maps it has been possible to determine the area, height, and volume changes for the glacier west of Esjufjallarond using the methods of Finsterwalder (1954), Hofmann (1957), Haumann (1960),

/and

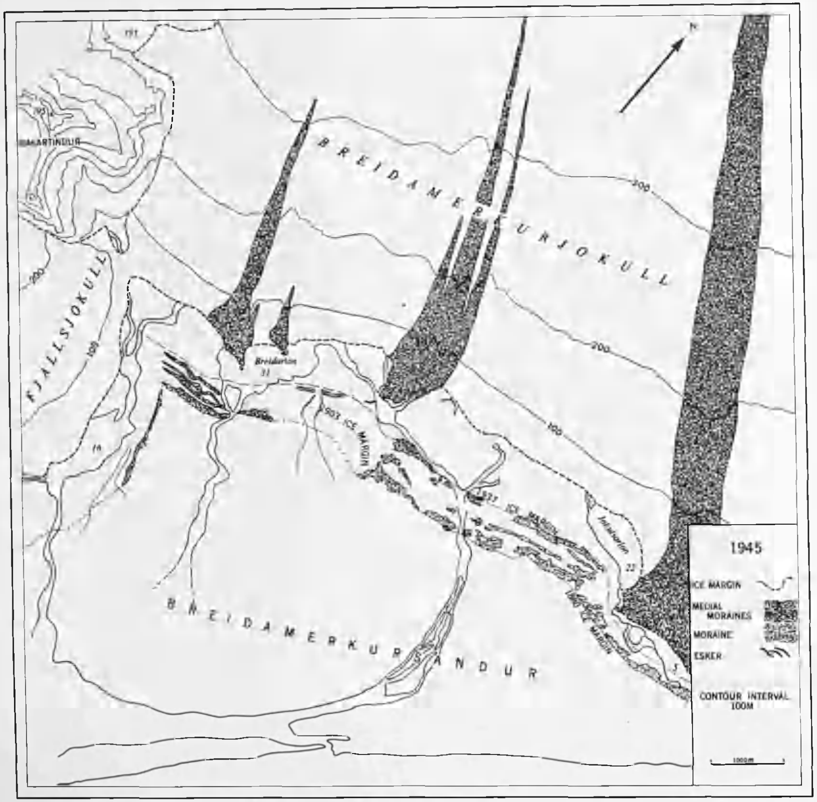


Fig. 5.4 1:100,000 scale map of the Breidamerkur area in 1945. Positions of earlier ice margins are also indicated.

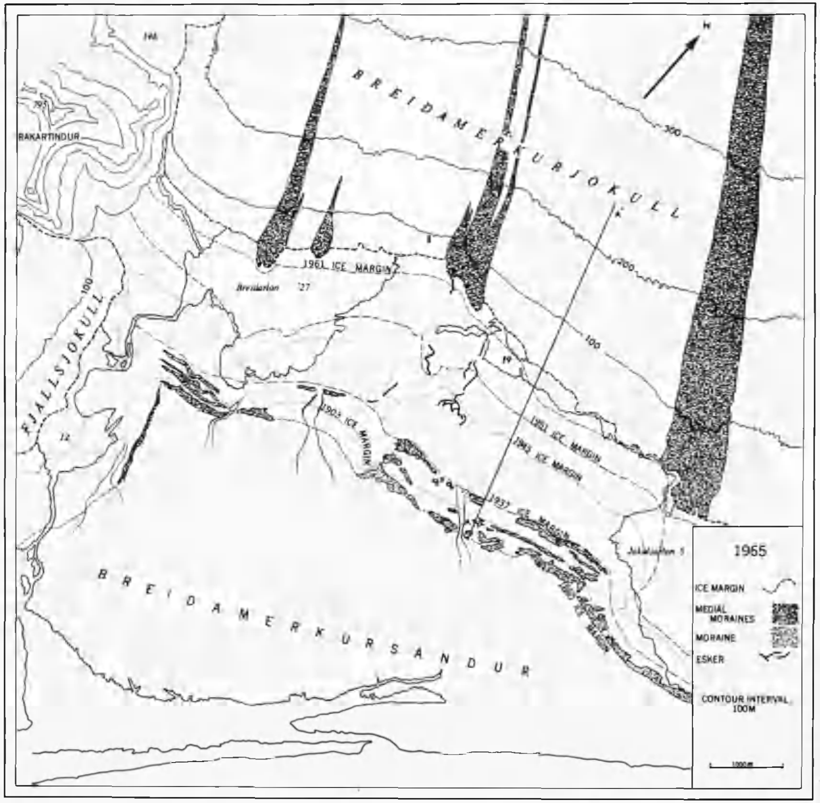


Fig. 5.5 1:100,000 scale map of the Breidamerkur area in 1965. The line A-A' along which the profiles in Fig. 5.3 were taken is also indicated.

and Konecny (1964). These methods, which are outlined in the first chapter, entail planimetering between successive contours on each map and then on the two maps superimposed. The area values obtained are then substituted into the formulae. Figure 5.6 is a listing of the data based on the planimeter measurements.

Although the planimeter measurements provided accurate data for the terminal portion of the glacier, comments about their value, the photographic scale, heighting accuracies and contour intervals are in order. As the area and volume data are limited to the snout of the glacier, it is not possible to relate accumulation and ablation, and although height changes have been obtained, these can be reasonably estimated from profiles which are constructed in a few minutes (as compared to the several weeks required for planimeter measurements and computations). Also, from an examination of the ablation values, it is evident that 20 metre contours, instead of 10, would have given a better indication of the relation of ablation to altitude. Furthermore, 20 metre contours would have reduced the photogrammetric and planimeter work and would have resulted in more accurate volume measurements, as the errors in position and height of the contours are reduced relative to the contour interval. From this experience, it is believed that had only glaciological data been desired, it would have been better to have sacrificed some accuracy for greater area coverage. That is, higher flying heights resulting in scales of 1:40,000 to 1:50,000 would have permitted the entire ablation area to have been plotted at 1:15,000 scale

Fig. 5.6 Area, Height, and Volume Changes in the Terminal Portion of Western Breidamerkurjokull, 1945 to 1965.

Contours	F_1(1945) (m^2 x 10^2)	F_2(1965) (m^2 x 10^2)	dF_1 dF_2 (m^2 x 10^2)	dh	dv (m^3 x 10^2)	dh/n
130			16020			
	760	2020		122	169470	6.1
140			17920			
	1560	2490		132	261750	6.6
150			35500			
	2700	5240		111	436470	5.5
160			52420			
	4110	6720		142	980780	7.1
170			101490			
	7220	11220		113	1037340	5.6
180			106040			
	9400	11330		103	1069030	5.1
190			107820			
	11330	11110		96	1076520	4.8
200			107550			
	14450	11410		77	988130	3.8
210			90400			
	11380	10060		84	896630	4.2
220			89020			
	10940	10750		82	888480	4.1
230			88760			
	13290	12420		69	880550	3.4
240			85890			
	14670	13760		61	866240	3
250			85890			
	14770	15990		56	867540	2.8
260			87170			
	14010	16020		59	879400	2.9
270			88780			
	13840	15430		61	893130	3
280			89950			
	14000	14000		64	898311	3.2
290			89790			

F_1F_2 = areas in square metres

dF_1dF_2 = areas in square metres between the same contours over the 20-year period

dh = total height loss in metres

dv = volume loss in cubic metres

$\frac{dh}{n}$ = height loss/year in metres

Formula:

$$dh = \frac{dF_1+dF_2}{F_1+F_2} \cdot \Delta h$$

$$dv = \frac{dF_1+dF_2+\sqrt{dF_1 \cdot dF_2}}{3} \cdot \Delta h$$

without increasing the number of models. Contour intervals of either 20 or 40 metres would have reduced the photogrammetric, cartographic, and planimeter work. An alternative possibility would have been the use of a superwide angle camera (f = 3.5 inches) at approximately the same flying height. However, photographs taken with superwide angle cameras in mountainous terrain have large, dead areas due to excessive relief displacement, and both definition and illumination fall off rapidly towards the corners of the photograph.

Marginal Lakes

Several marginal lakes have developed in the western portion of the Breidamerkur area, including Fjallsarlon, Breidarlon, Jokulsarlon, and an ice-dammed lake on the western margin of the glacier north of Rakartindur (1945 and 1965 maps). The former three lakes all became evident as the ice margins retreated from the backslopes of ridges in the 1930's, thus exposing or causing a lake to develop between the backslope of the ridge and the ice margin. The ice-dammed lake is shown on the 1903 map and has probably been in existence during most of historical time.

As these lakes have been responsible for both the formation of and changes in the landforms of the Breidamerkur area, and as they may be useful indicators of future glacier movement or changes, photogrammetric heights were measured on all available photography. These, coupled with depths obtained by soundings (F. Bjornsson, 1966, personal communication; Kjartansson, 1957; and Price, 1966, personal communication), should prove useful in future studies and will be referred to in the

Fig. 5.7 Heights of Major Lakes as Determined by Photogrammetric Measurements.

Lake and Date		Height in Metres	Comments
Jokulsarlon	Origin 1930's	?	Appears to have remained at approximately the same level since it began to form. Reported depth of 110 metres.
30 August	1945	5	
19 July	1960	5	
24 August	1965	5.5	
Breidarlon	Origin early 1930's		Level dropped in the late 1940's or early 1950's as the ice front retreated. Depth of 84 metres.
30 August	1945	31	
4 July	1961	27	
8 September	1964	28	
24 August	1965	27.5	
Fjallsarlon	Origin early 1930's		Lake level dropped as the ice margin retreated. Once continuous drainage along the margin of Fjallsjokull was established in 1964 both the upper and lower lakes were united and obtained the same level of 12.5 metres. Depth of the lake is 58 metres.
30 August	1945	16	
4 July	1961	19 upper lake	
		14 lower lake	
8 September	1964	12.5 upper lake	
		12.5 lower lake	
24 August	1965	12.5 upper lake	
		12.5 lower lake	
Ice-dammed lake	1903 map	220	This lake drains periodically, creating a small outburst once or twice a summer (Bjornsson, 1962). Water pressure must be a factor as icebergs stranded on the walls above the water-line (in some cases) indicate drainage occurs when the water reaches a certain level and continues until there is insufficient pressure. Late in season, however, ice tunnels may be open regardless of pressure and drainage is straight through. Maximum depth of this lake is thought to be between 50 and 75 metres.
30 August	1945	151	
4 July	1961	167	
8 September	1964	83	
24 August	1965	146	

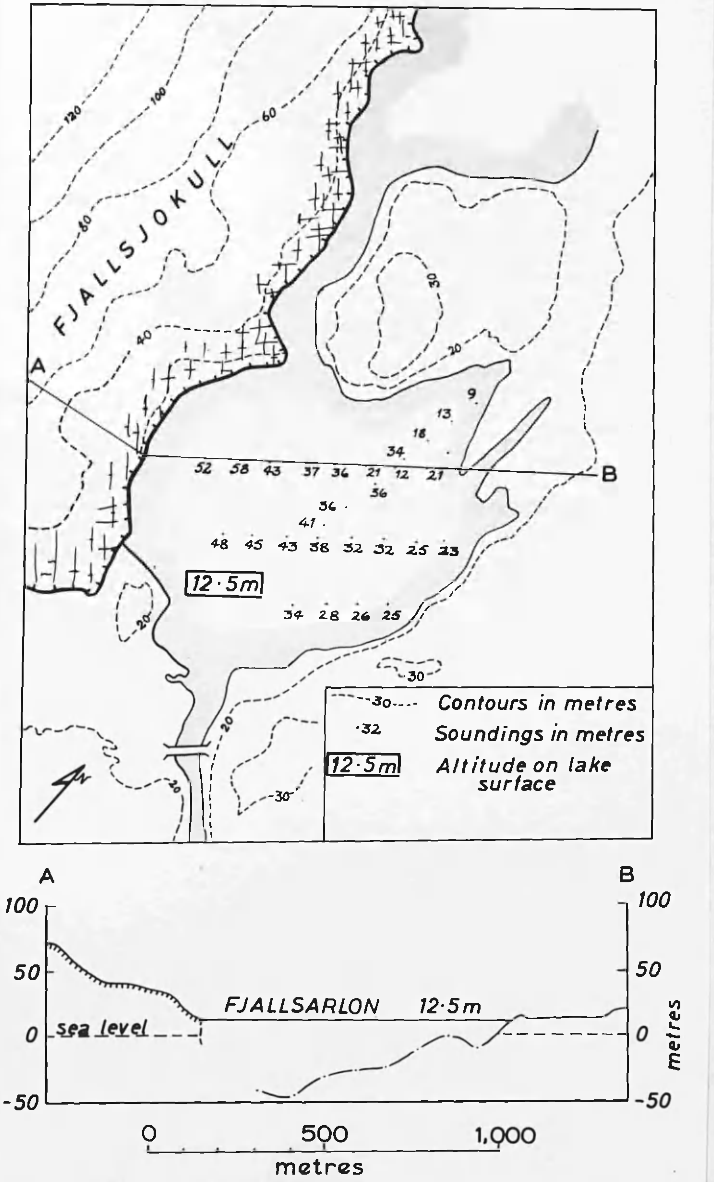


Fig. 5.8 Soundings of Fjallsarlon combined with photogrammetric data.

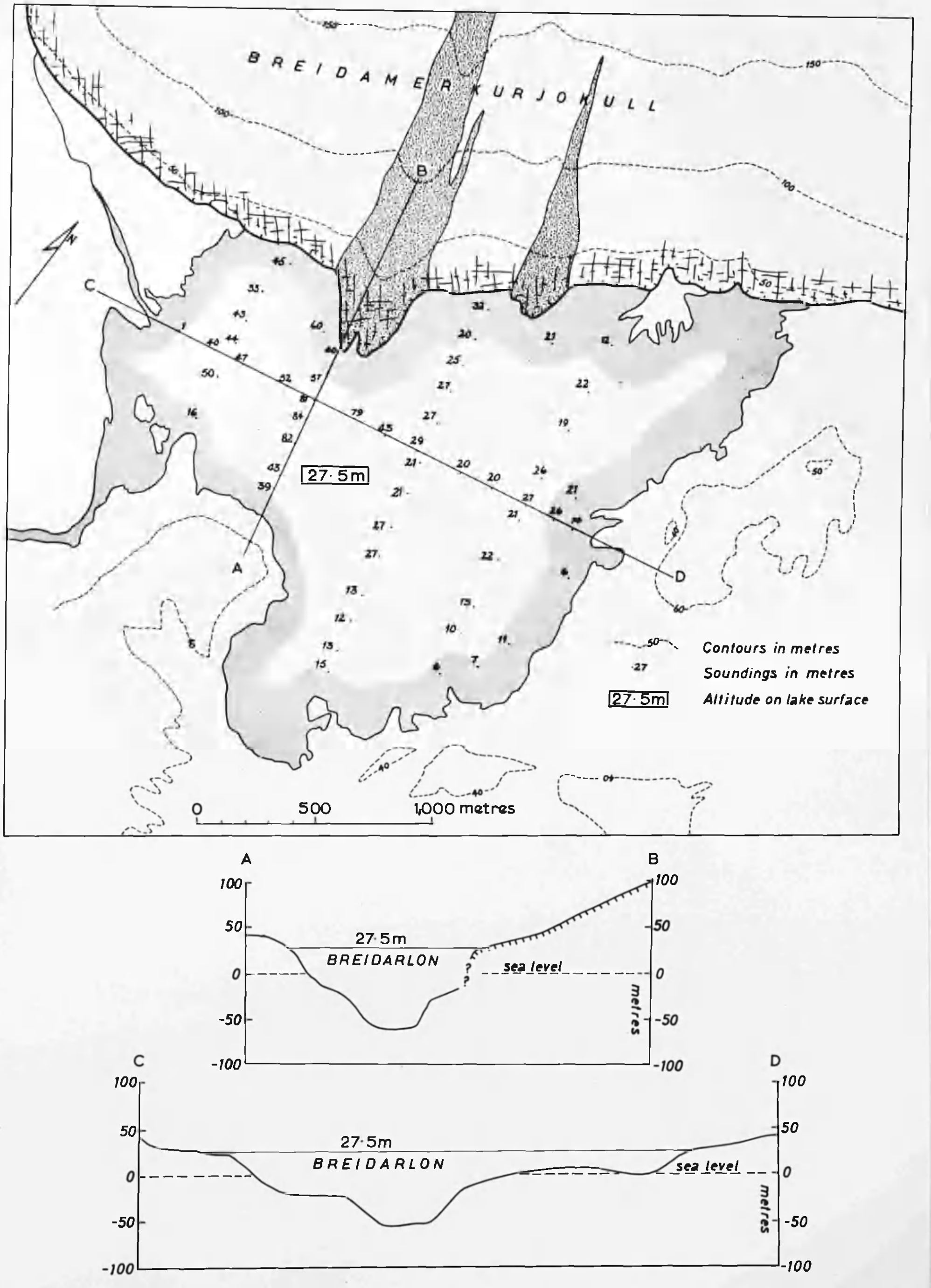


Fig. 5.9 Soundings of Breidarlon combined with photogrammetric data.

discussion on landforms. A summary of the photogrammetric measurements is given in Figure 5.7, and the results of soundings by Price in 1966, coupled with the 1965 photogrammetric measurements by the author, are shown in Figures 5.8 and 5.9.

Geomorphology

Photogrammetry offers the geomorphologist the possibilities of obtaining accurate planimetric positions, shapes, and heights of landforms. This is particularly significant in a glacial area where changes are rapid and where it may be possible to deduce the origins of the landforms from the accurate measurement of the changes. Examples from the Breidamerkur area include eskers and kame and kettle areas.

Eskers

Eskers, which are distinguished by light-toned gravels (averaging approximately 0.05 metre in diameter) deposited in sinuous, steep-sided ridges varying in height from less than 5 to over 20 metres, have been formed in two major series extending in parallel lines from Mavabyggdarond to beyond the 1945 ice margin. The eskers occupy both foreslopes and backslopes, and all are now located on dry land although some are ice-cored.

In order to establish the pattern of development of these eskers and the methods of origin, the author photogrammetrically plotted this area separately using the 1945, 1960, 1961, and 1965 aerial photography. As the method used required considerable care and may be of use to others the procedure is outlined below:

Materials and equipment:

1. Stereo pairs of stable base positive transparencies for each year.
2. Photographic enlargements (paper prints) of the area at plotting scale.
3. A gridded master control sheet at 1:15,000 scale containing all planimetric and height control points established on solid ground in the area of interest.
4. Gridded plotting overlays for each set of photography.
5. The Wild B8 stereoplotter.
6. A magnifying glass.

Procedure:

1. The master control sheet was placed on the plotting table and the 1945 photography inserted in the B8 and scaled and levelled to the known control points.
2. A gridded overlay sheet was then registered to the master control sheet and the planimetric positions of all significant detail were traced, including esker ridges and bases. Ten metre land and 20 metre ice contours were also plotted.
3. The 1945 photographic enlargement was then studied in conjunction with the other enlargements, and a series of points marking height or planimetric changes from 1945 to 1965 were identified on the 1945 enlargment and pricked through. All points pricked through were then identified in the model, heighted,

/and

and their planimetric positions recorded on the overlay plot sheet.

4. The 1945 photography was removed and the 1960 photography inserted. Where possible, scaling and levelling included points used for corresponding operations with the 1945 photography. Again the master control sheet was used for this operation.
5. The 1945 overlay plot sheet was registered with the 1960 sheet by means of the grid and all previously recorded points pricked through. The 1960 plot sheet was then registered with the master control sheet and plotting of detail and contours (for 1960) carried out. Once the plotting was completed, all points previously transferred from the 1945 overlay were identified in the model. Their planimetric position was checked by means of their pricked positions on the 1960 plot sheet and heights were again recorded. In addition to the transferred points, new points were added where later changes were thought to have occurred.
6. This procedure was followed through for each successive set of photography and in all several hundred height and planimetric points were recorded. Errors were avoided by combining visual identification in the model and on the enlargements with the recorded positions on the overlay sheet. Accuracy is ensured only if all work is carried out by the investigator

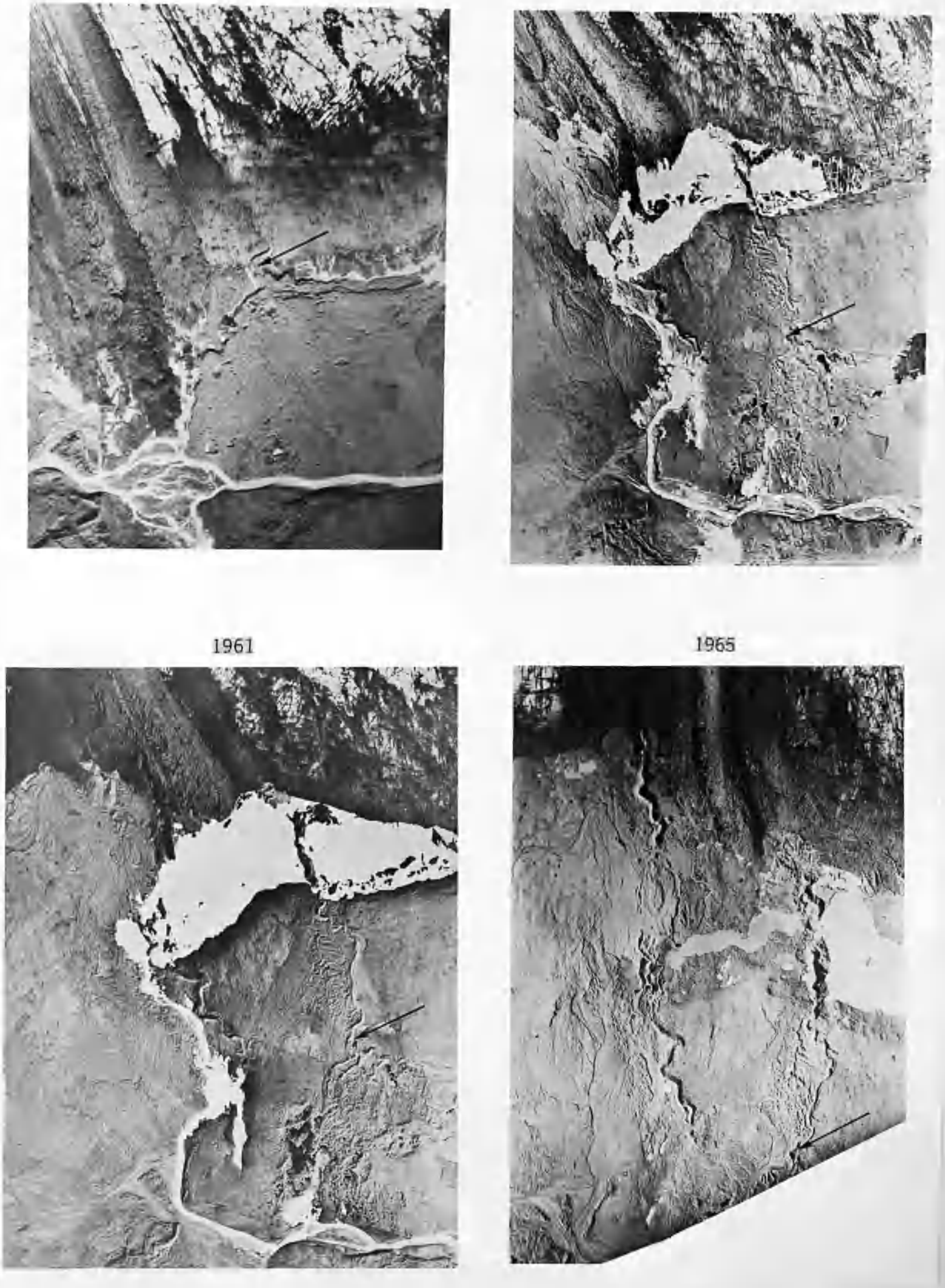
as this eliminates point identification errors and permits the selection of specific rather than random points.

After the above work was completed, all the enlargements were compared and points at which significant changes had occurred were noted. In order to determine significant changes, however, it was necessary to take into account the photogrammetric accuracies, which, in this case, were estimated by tests and ground checks as ± 2 metres in height and ± 0.5 millimetre in planimetric vector. Therefore, only those points at which changes greater than the above standards had occurred have been included in Figures 5.11 to 5.14. Aerial photographic enlargements to approximately the same scale for each year are shown in Figure 5.10.

In the following discussion each plot is considered separately, after which a set of conclusions on the formation of the eskers has been derived from the combined photographic, photogrammetric, and ground evidence.

1945 (Figure 5.11): Immediately adjacent to the medial moraines a large esker was in the process of formation. Its distal (to the ice margin) position appeared to rest on solid ground; however, the proximal section was emerging from within the ice. In addition to the gravels, a small stream issued from the ice, although it immediately disappeared beneath the esker and emerged on the opposite side at the ice margin. At the points where the esker emerged from the ice and where the ice margin disappeared beneath the esker, heights of 43 metres and 41 metres were recorded. A second esker is shown at the front of the medial

/moraine.



1945

1960

1961

1965

Fig. 5.10 Development of eskers 1945 to 1965.

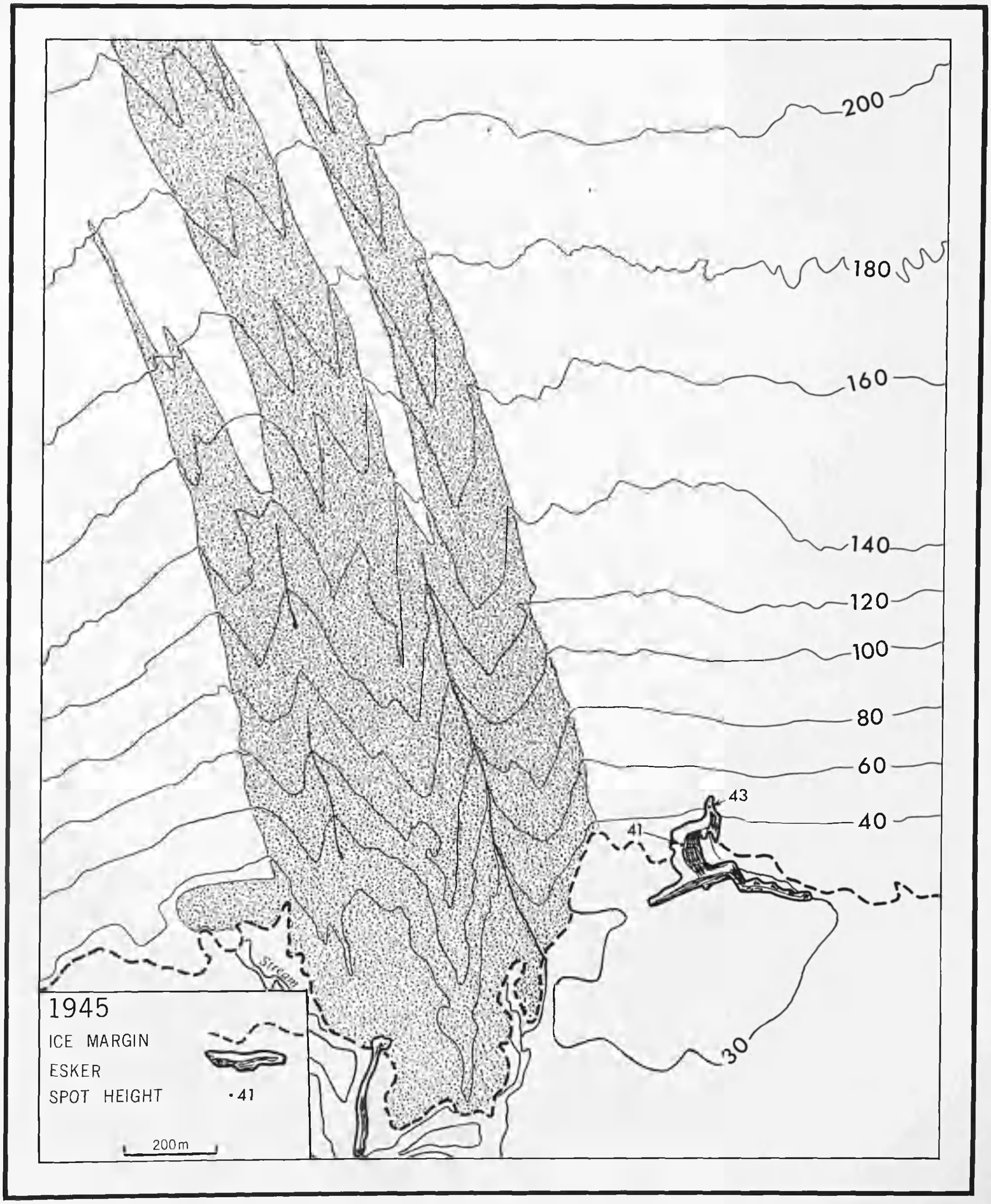


Fig. 5.11 Esker complex in 1945. A large esker is emerging at the ice margin.

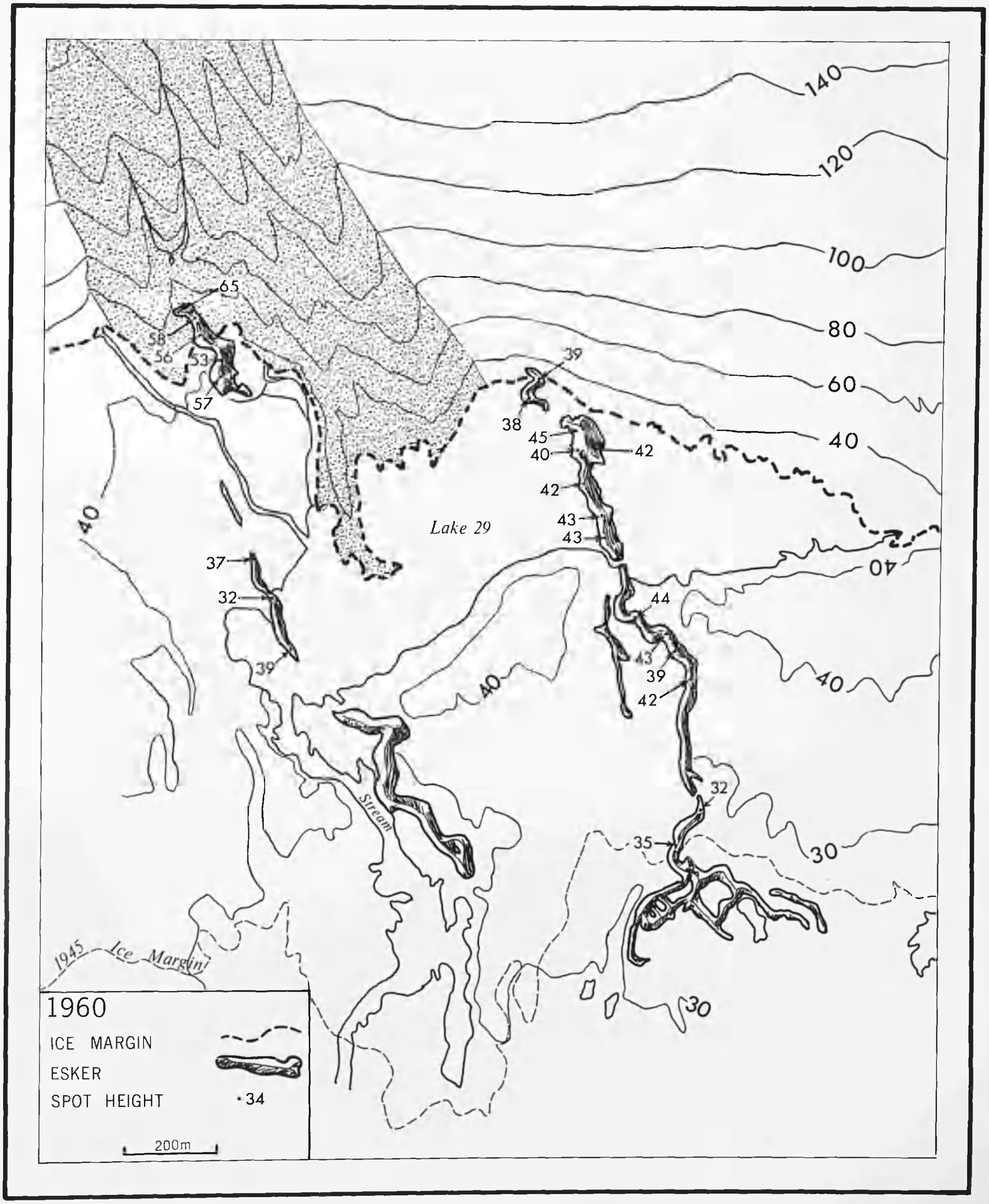


Fig. 5.12 Esker complex in 1960. The ice margin has retreated by approximately one kilometre.

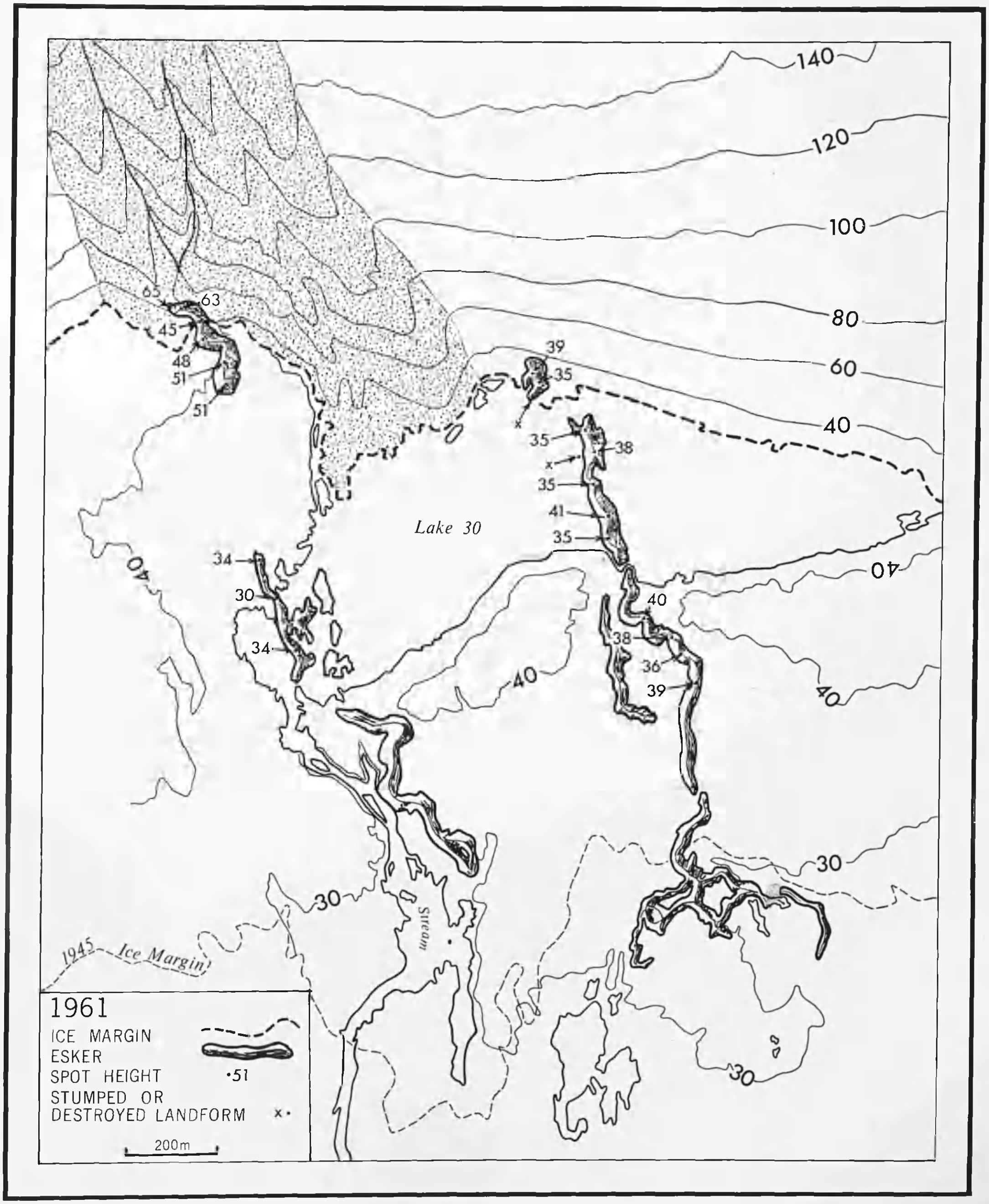


Fig. 5.13 Esker complex in 1961. Major height changes have occurred since 1960.

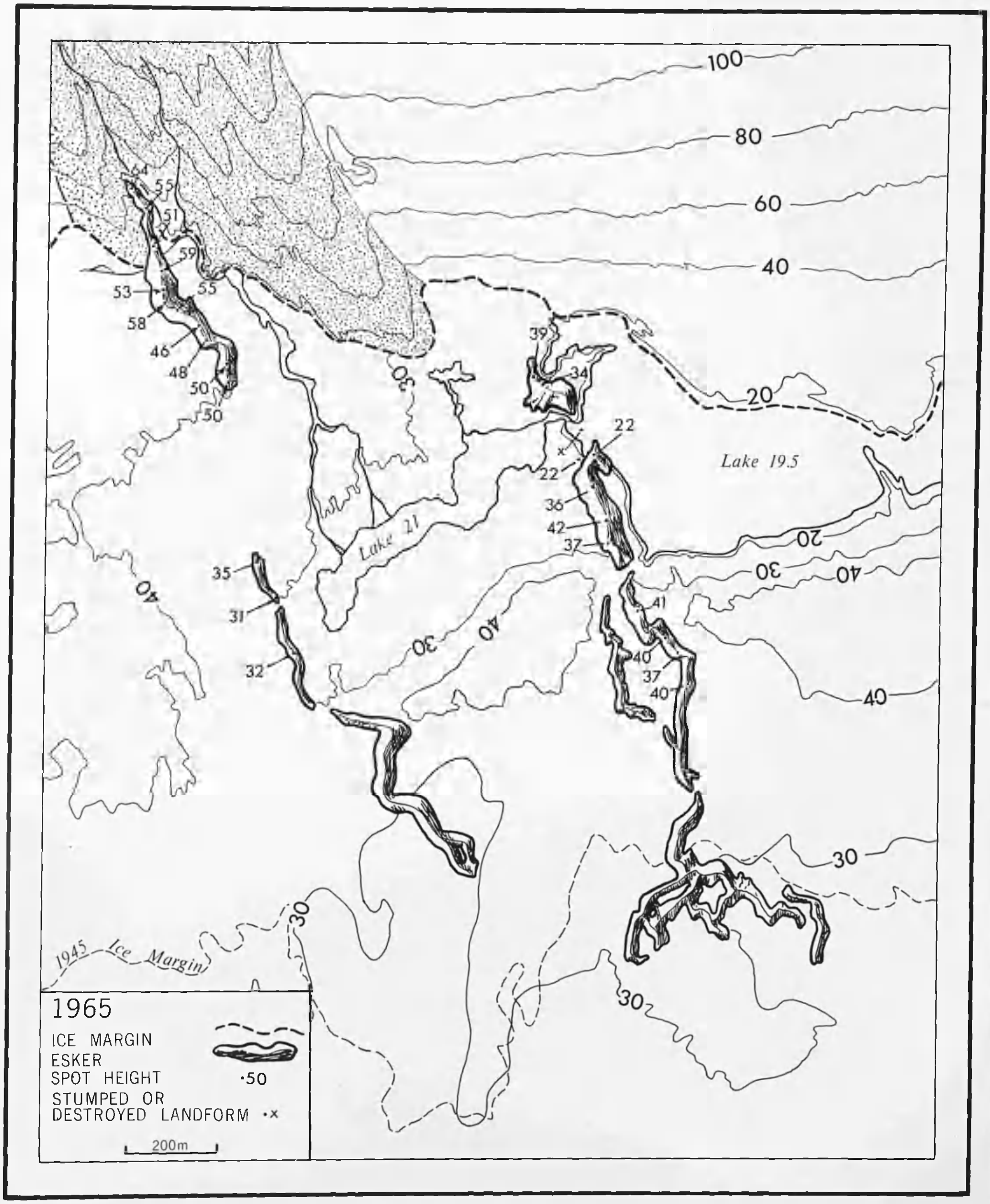


Fig. 5.14 Esker complex in 1965. The lake levels have been lowered and major esker development continues at the medial moraine.

moraine. Its position and heights were not recorded on the 1960 and 1961 photography; however, the large map plotted from the 1965 photography indicates that this esker has not been significantly altered during the 20 year period and was in all likelihood deposited on solid ground. The known presence of ablation moraine on its crest indicates subglacial formation.

1960 (Figure 5.12): By 1960 the ice margin had retreated about a kilometre beyond the 1945 position and the two parallel series of eskers had been formed. In addition, a large lake had developed between the ice margin and the backslope of the ridge. This lake had a height of 29 metres and was drained by a small stream.

The first thing that is noted is the striking changes in the heights and appearance of the esker shown on the 1945 plot. The heights of the ridge crest have been lowered by 11 and 6 metres respectively, indicating the melting out of the ice core. In addition, the ridge is much smaller in appearance and a series of secondary ridges have developed in what was a flat outwash plain in 1945. From this it can be concluded that ice beneath the outwash has melted out leaving a series of ridges and depressions. The ridges were probably former subglacial stream courses that became filled with gravels, whereas the depressions corresponded to the surrounding ice-cored gravel outwash areas.

The original esker has also been extended to the ice margin with the foreslope portion having apparently developed on solid ground and the backslope portions in the ponded lake. The second series of eskers appears to have developed in a similar manner. The large z-shaped esker adjacent to the stream reaches a height of 10 metres (from top to bottom) and has a flat-top in its proximal half. Spot heights in 1960, 1961, and 1965 show no changes in crest or base level, indicating that it was formed on solid ground. As red basaltic ablation moraine covers the proximal portions, it is assumed that the esker was formed at least partially under the front margin of the glacier in the area occupied by the central moraine. The flat-top indicates a former water level (Andersen, 1931) or stream course. From the positions of the ice margins this esker must have been formed in the period 1950 to 1958.

The pattern of formation of the z-shaped esker is confirmed by another esker just beginning to emerge from the medial moraine-covered ice. A smaller esker, between the former two, has developed at the edge of the lake.

<u>1961</u> (Figure 5.13): In the one-year period 1960-61 significant changes in ridge crest heights occurred in the esker emerging from beneath the medial moraine and also those in and near the lake. In both instances height changes of 4 to 8 metres due to melting out of ice or slumping are common, with a maximum lowering of the ridge crest of 13 metres recorded in the esker emerging from beneath the medial moraine. This esker has also been extended by approximately 35 metres over the one-year period. It is interesting to note that the lake level has not changed significantly.

<u>1965</u> (Figure 5.14): Between 1961 and 1965 the ice retreated sufficiently

to permit the lake to drain eastwards, thus lowering its level by approximately 10 metres and causing previously submerged sections of the eskers to become exposed. Although there have been some changes in the lake eskers due to slumping and under melting in the ice-cored areas, the most significant change has occurred at the esker beneath the medial moraine. This esker has increased in length by approximately 285 metres, which is equivalent to a rate of 71 metres per year. However, it should be noted that this increase is not due to terminal retreat alone, but to ablation as well, which has caused the upper portions to become exposed. A lowering of 8 metres in the ridge crest has also occurred for those sections of the esker known to have been located on the ice in 1961. The streams are still prominent above and alongside the esker.

Collateral material and ground observations 1965-66: Price (1964, 1965, 1966) and Welch (1964) have studied eskers in front of the Casement Glacier, Alaska, and also produced photogrammetric measurements. In this instance a large complex of eskers could, on 1948 photography, be seen to extend from dead ice at the glacier terminus into and alongside marginal lakes. The majority of these eskers definitely rested on the ice surface, and the first photogrammetric measurements performed by the author with a parallax wedge indicated the largest esker to be over 35 metres in height (see Price, 1964). By 1962 the lakes had been drained and portions of the esker complex destroyed; however, further ground survey measurements in 1962 correlated with the 1948 photography revealed that portions of the eskers could definitely be linked to the

/1948

1948 complex (Welch, 1964). Recent photogrammetric work by Petrie and Price (1966) and investigations by Price (1966) have provided the basic conclusion that eskers can be let down from the glacier surface to ground level without being destroyed.

Work on Breidamerkurjokull by the Durham University Expedition of 1951 has provided useful information on the melt rates of gravel covered ice, the distribution of surface materials, and the presence of englacial dirt. In the former case, bottom melting was found to exceed surface ablation by a factor which increased with the thickness of the surface covering of gravels. A rough factor of 2 is indicated for sites having a gravel layer of 50 centimetres. The distribution of rock materials in the moraines and on the ice surface was found to be constantly altered by meltwater and supraglacial streams and, on the whole, even the dirtiest ice contained less than eight percent grit.

Limited ground observations by the author in 1965 and 1966 confirmed the presence of ice cores in the proximal portions of the ice margin eskers, although at varying depths. The esker extending from the medial moraine area was, from its point of exit from the glacier to the ice margin, primarily an ice ridge covered by 3 to 4 centimetres of gravels at the crest and exposed at the sides (Figure 5.15). Supra and englacial streams were observed above and along side the esker (Figure 5.16).

At the ice margin a proglacial stream had cut through and beneath the ice core (Figure 5.16) and it appeared likely that the ridge

/in

Fig. 5.15 Upper: esker extending from between the medial moraines of Mavabyggdarond.

Lower: ice core of proximal end of esker.

Fig. 5.16 Upper: supraglacial stream is located alongside the ice-cored esker emerging from the medial moraine.

Lower: a stream flows beneath the ice-cored esker at the margin of the glacier.

in this area might be destroyed by the end of the summer of 1966. Distally, for a hundred metres or so from the ice margin, the esker continued as a sharp-crested gravel ridge apparently underlain by ice at a depth several centimetres to metres, undoubtedly accounting for the preservation of the ridge shape. In the distal one-third there was no external evidence of a remaining ice core, although the presence of larger boulders along the base of the esker indicated previous slumping. In addition, the slow rate of ice movement near the snout (probably less than 10 metres per year) should be noted.

<u>Conclusions from combined data</u>:

1. The formation of large eskers in two parallel series in front of the medial moraine area has been facilitated by the presence of supra-, en- and subglacial meltwater streams carrying and distributing debris furnished by the morainic deposits. Some fine debris may be derived from englacial material but this is in the minority. In addition, the slow ice movement and rapid ablation near the terminus permits the formation and exposure of gravel ridges in and on the ice surface.

2. Eskers can be formed subglacially, englacially, or proglacially with two or even three modes of formation occurring in the same esker system.

3. Eskers formed by direct deposition on solid ground maintain both heights and distinct shapes and will appear so on sequential aerial photography. One exception, however, is when an esker has been formed by the filling in of a subglacial river channel in a separated ice block

covered by gravels. On the first set of photography only a flat outwash surface may be visible, yet on a second set a pitted plain crossed by an esker or eskers may be seen due to the melting out of the ice block.

4. Buried ice and/or ice cores are common and upon melting out will leave a ridge, although much smaller and less pronounced than when the ice was still underneath.

5. Eskers formed subglacially under a medial moraine are likely to have ablation moraine on their surface, although if they emerge englacially the ablation moraine will probably slump away due to melting of the ice bottom or core.

6. Eskers deposited in a lake - but on a solid lake bottom - will be preserved provided they are not subjected to strong currents.

7. Major height changes of several metres due to the melting of buried ice tend to occur within a few years of the formation of the esker. This appears to be due to the fact that the ice is often covered by only a few centimetres of gravel at the top and is exposed at the sides. Once the ice has melted to a point beyond which further slumping is unlikely to occur and the gravel layer is several centimetres to metres thick, further changes are less significant and will be due primarily to bottom melting rather than to surface ablation.

Kame and Kettle Topography

In addition to determining the changes and origins of eskers by photogrammetric methods, it has also been possible to obtain quantitative information on the formation of kame and kettle areas. These areas,

/consisting

consisting of numerous 1 to 3 metre deep depressions in gravel outwash (averaging 0.02 to 0.15 metre in diameter), are to be found near the margin of Fjallsjokull, adjacent to the eastern margin of Breidarlon, and in and around the esker complex in front of Mavabyggdarond. In addition, a small area is located near the western margin of the Jokulsarlon and others are just beginning to form near the base of Rakartindur at the western ice margin. Of these areas, the most striking changes have occurred in the vicinity of Breidarlon and in and around the esker complex.

In regard to the Breidarlon area, it is evident from the 1945 maps that both an esker and an extensive kame and kettle area extended from the ice margin into what was then the eastern region of Breidarlon. Spot heights determined photogrammetrically show the lake level to be 31 metres and the general surface of the esker and kame and kettle areas to be between 33 and 38 metres. The 1965 map, on the other hand, shows a lake level of 17.5 metres and when superimposed on the 1945 map reveals that the present kame and kettle deposits along the shoreline were submerged beneath the lake in 1945, whereas those evident in 1945 have since been destroyed. From photogrammetric measurements performed on the 1961 aerial photography, it is known that the lake level was lowered prior to that time. Furthermore, ground observations in this area in 1965 and 1966 confirmed that a stream was still emerging from the ice front and forming an esker and a small alluvial fan in the same relative position as the kame and kettle area in 1945 (Figure 5.17). In addition,

/ice

Fig. 5.17 In 1966 a stream was still emerging from the ice front and forming a fan. Note the small esker in the middle foreground.

Fig. 5.18 Ice (black) is clearly visible beneath the gravels in the outwash area near Breidarlon and the ice margin.

ice is known to exist beneath one to two metres of gravels in both the fan and the gravel outwash near the ice margin (Figure 5.18).

In the second case, the major portions of the kame and kettle areas in front of Mavabyggdarond have developed since 1945. At that time, the exposed area was generally flat and only a few kettles were evident (as shown on 1945 map). On the 1960 photography, however, the same area is pock-marked with water-filled kettles and by 1965 most of the kettles were dry. An exception is the development of the large pit which is presently occupied by a clear water lake with a surface level of approximately 21 metres (Figure 5.19). This indicates that the area was underlain by ice up to 5 metres thick, and this is confirmed by the kame and kettle areas nearest the ice front which are presently developing. In these areas, ice is known to be buried beneath 2 to 3 metres of gravel (Figure 5.20).

From the above photogrammetric evidence, coupled with the ground observations, it can be concluded that it is not uncommon for the front margin of a glacier to extend beneath a lake or to occupy a depression and to subsequently become covered by gravels and detached. Kame and kettle areas then develop by undermelting and, provided this occurs on solid land, the patterns will be preserved (also see Thwaites, 1926; Rich, 1943). However, if the underlying ice forms a temporary bottom of a deep lake, the gravels will eventually be let down into the lake and the pattern destroyed. As has been indicated by the spot heights, vertical changes of greater than 5 metres are not uncommon.

Fig. 5.19 Clear water lake in 1966. Ice melting out from beneath the gravels has formed this lake since 1945.

Fig. 5.20 Ice is present beneath 2 to 3 metres of gravels in a kame and kettle area near Mavabyggdarond. Note the kettle pond in the foreground.

Ecology

As the Breidamerkur area is devoid of vegetation that can be distinguished on the panchromatic photographs, and as soil areas correspond to the vegetated areas, photogrammetry has not been particularly useful for ecological purposes.

Conclusion

Photogrammetry is valuable for the study of a glacial area when the following are required:

1. Accurate maps.
2. Information on the changes in glacier area, heights, and volumes, and the relationship of ablation to accumulation.
3. Spot heights and/or planimetric positions of lakes and landforms.

Photogrammetry is particularly useful in areas undergoing rapid change, such as the Breidamerkur area. However, both sequential aerial photography and ground control are important.

In regard to photographic scales, flying heights and types of photography, it can be stated that all the panchromatic photography, including the 1:46,000 AMS material, was adequate for the plotting of glaciological or geomorphological features at 1:15,000 scale, but that vegetation could not be mapped. Furthermore, spot heights accurate to ± 2 metres, planimetric positions to within ± 0.5 millimetre, and contour intervals of 10 metres were produced without great difficulty and provided adequate representation of all features. For these reasons, it is felt that modern photography flown with a wide-angle survey camera (f = 6 inches) from altitudes of 20,000 feet (6,100 metres) to 30,000 feet (9,100 metres), resulting in scales of 1:40,000 to 1:60,000, will provide sufficient information and photogrammetric accuracies for mapping large glaciers and rapidly changing areas. In this regard, it should also be mentioned that as changes in landforms or glaciers must be fairly large to be significant, and that as changes usually take place over periods of one or more years, there is little point in planning photograhy on a monthly or even yearly basis, or in flying from altitudes lower than that required to obtain spot heights to approximately ± 1 metre. Therefore, it can be said that aerial photogrammetry is unlikely to provide accurate or reliable data on:

1. Rates of ablation over periods of a few weeks or months.
2. Rates of ice movement over periods of a few weeks, or, for that matter, over periods of a year or more unless distinctive objects are present on the ice surface and on two or more sets of photography.

This information is best derived from ground measurements.

THE USE OF PHOTO-INTERPRETATION

In this section those features of the Breidamerkur area which could be analysed primarily on the basis of photo-interpretation will be discussed. In addition, various types of aerial photography and methods of photo-interpretation for the study of these features will be evaluated. Numerous illustrations are employed to indicate the significance of scale, tone, shape, pattern, texture and position.

Equipment and Methods

Both paper prints and positive transparencies of all available photography were employed. These included the panchromatic photography of 1945, 1960, 1961, 1964, and 1965 at scales of 1:27,000 to 1:46,000 and the 1965 1:16,000 scale panchromatic, infra-red, colour, and false colour photography. Major supporting information includes the 1903 map (Danish, 1:100,000 scale), 1945 map (AMS 1:50,000 scale) and the 1945 and 1965 1:15,000 scale maps in the rear pocket. In addition, smaller scale work maps were produced from the latter by photographic reduction. Ground information and photography obtained during the summer of 1965 and 1966, and discussions and correspondence with Mr. Flosi Bjornsson of Kvisker, are used where relevant.

In order to extract the maximum amount of information from the photography, the previously described monocular and stereo viewing equipment was used. In addition, coloured filters were employed on the light table when viewing objects on the colour transparencies having definite colour tones such as red ablation moraine or green vegetation. However, as this provided little if any additional information over the unfiltered colour photography, it is not considered to be a particularly useful technique.

Glaciology

The appearance of Breidamerkurjokull on the aerial photography is readily observed on the mosaics (Figures 5.21 and 5.22). As can be

Fig. 5.21 Mosaic of the Breidamerkur area, 1945.

Fig. 5.22 Mosaic of the Breidamerkur area, 1965.

seen, dirt bands are prominent and there is a zone of black ice along the front margin, indicating near stagnation. Surface streams are common and crevasses are particularly evident near the ice-dammed lake and Jokulsarlon. By using photo-interpretation methods it has been possible to determine the terminal retreat and to estimate rates of ice movement. These are discussed below.

Terminal retreat and ice movement

From the various sets of maps, and photography used in conjunction with the maps, it has been possible to delineate the ice margins for 1903, 1945, 1960-61, and 1965. In addition, from information supplied by Mr. Bjornsson, and the positions of end moraines which form three distinct belts parallel to and approximately two kilometres in front of the 1965 ice margin, the 1880 and 1937 ice margins have also been plotted. These were shown on the previously mentioned 1:100,000 scale maps (Figures 5.4 and 5.5).

Based on these maps the following pattern of glacier retreat for Breidamerkurjokull west of the Jokulsa has been determined.

Period	West Margin of Breidarlon	Midway between Mavabyggdarond and Esjufjallarond	At the Jokulsarlon
1880-1894	Maximum advance	Maximum advance	Maximum advance
1894-1903	-150 m (17 m)*	-300 m (33 m)	-100 m (2 m)
1903-1937	-350 m (10 m)	-150 m (7 m)	
1937-1945	-700 m (87 m)	-900 m (112 m)	-275 m (34 m)
1945-1961	-900 m (56 m)	-780 m (49 m)	-1875m (117 m)
1961-1965	-225 m (56 m)	-350 m (87 m)	-300 m (75 m)
Total	-2325 m (35 m)	-2580 m (36 m)	-2550 m (36 m)

*per year

From the total it is evident that the entire margin has retreated by approximately the same amount; however, the periodic retreat has varied greatly. The reason for the overall retreat appears to be the distinct warming trend since 1880, becoming particularly strong in the 1930's and 1940's (as shown in Figure 5.2)[1]. On the other hand, the large periodic variations between the Jokulsarlon section and the other two areas appear to have been due to two factors which can be derived from the aerial photography in combination with collateral information. In the first case, the aerial photography of all years reveals that the prominent dirt bands on Breidamerkurjokull are very highly distorted for several kilometres behind the Jokulsarlon, and that longitudinal crevassing is much more extensive than in any other area near the ice margin (Figures 5.23 and 5.24). This indicates that ice movement is rapid relative to adjacent areas of the glacier. Although this is normally the case in the centre of a glacier where there is little or no lateral friction, bottom friction is also reduced due to the large subglacial valley of Breidamork and the 110 metre deep Jokulsarlon. It is likely, therefore, that rapid ice movement tends to offset the effects of ablation.

The second factor is the location of Esjufjallarond. This large medial moraine extends back from the Jokulsarlon and, on the 1903

/map

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[1] Increased precipitation could also cause an increase in the rate of terminal retreat; however, the precipitation appears to have remained relatively constant from 1880 to 1965.

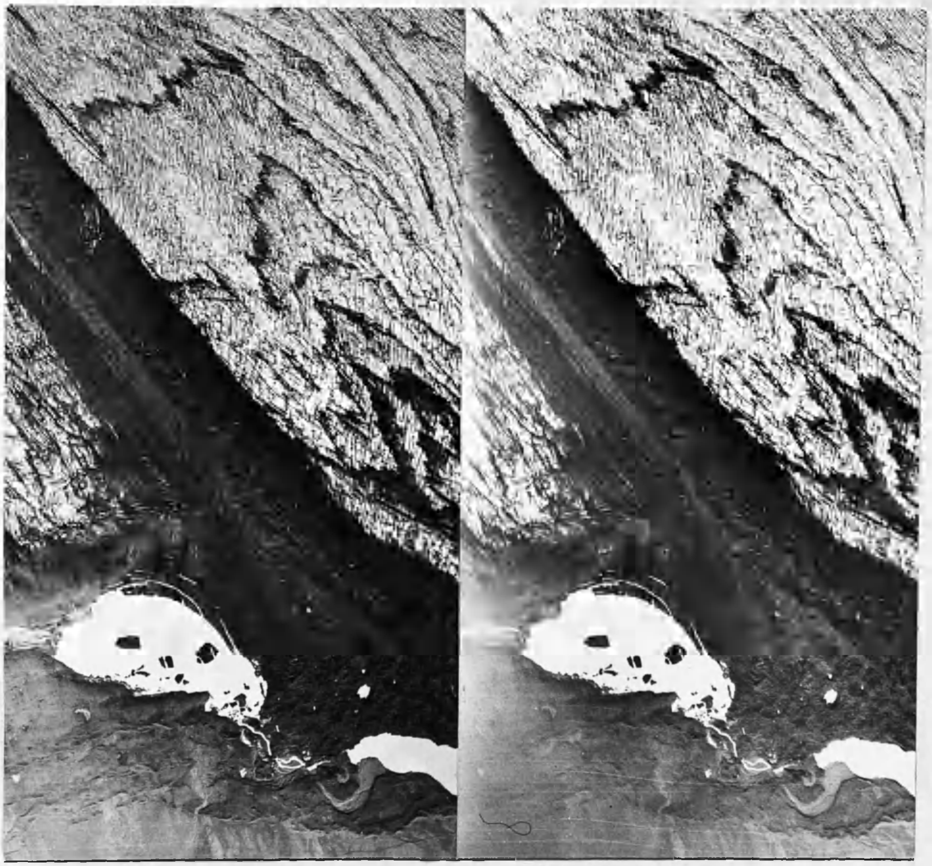


Fig. 5.23 Stereopair of the Jokulsarlon region in 1945 at a scale of 1:46,000. Note the highly distorted dirt bands, the bulbous morainic region, and the relatively heavy crevassing.

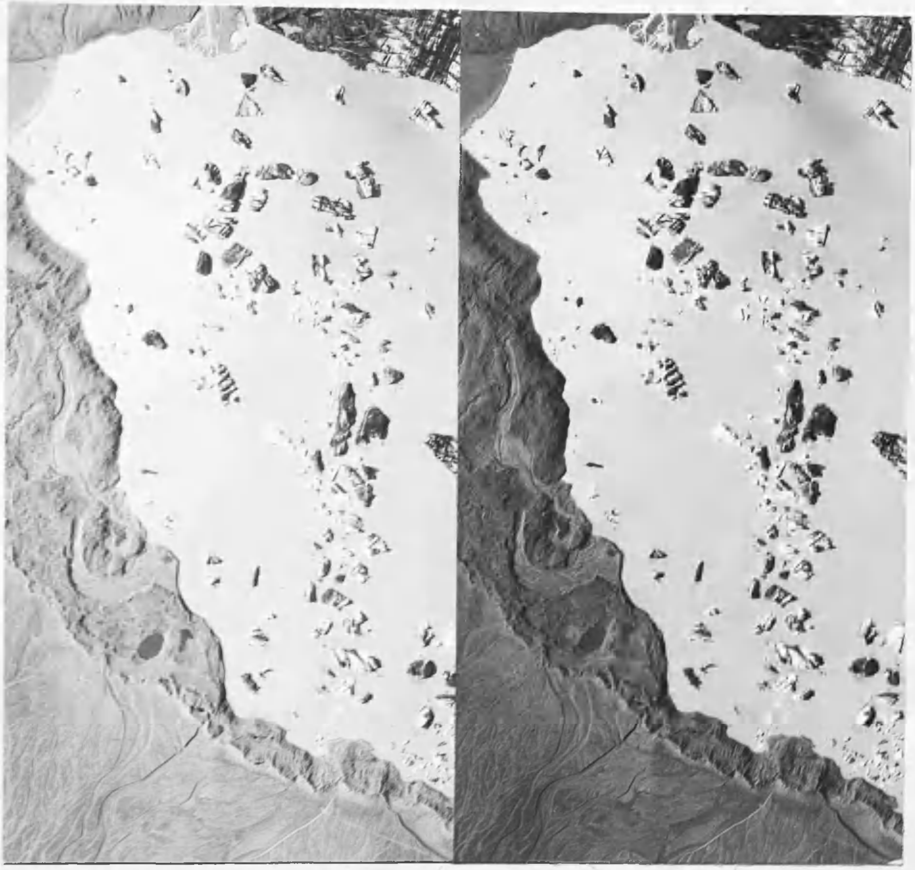


Fig. 5.24 Stereopair of the Jokulsarlon region in 1965 at 1:27,000 scale. The terminus of the medial moraine and ice margin form a cliff, and icebergs are common. Note that although detail is clearer to the unaided eye, the spatial relationships are less evident at this larger scale.

map and 1945 aerial photography, is much more bulbous at the ice margin than at the present time. As the materials from which the moraine is formed reduce the rate of ablation by about 30 percent (Lister, 1953), it can be assumed that terminal retreat was also retarded.

It is likely, therefore, that the above factors of rapid re-supply of ice and retarded ablation worked together to prevent retreat of the ice margin in this area until the late 1930's. However, once the ice margin had become completely free of and lost support of the land surface in the early 1950's (Durham University Map, 1951), calving into Jokulsarlon resulted in rapid recession. This is confirmed by heavy transverse crevassing, an ice cliff, and the presence of large icebergs in the Jokulsarlon on all photography since 1945.

Another indication of ice movement is ogive banding (Vallot, 1925; Washburn, 1935; Fisher, 1949; Ives and King, 1954; King and Ives, 1956; Lliboutry, 1957; King and Lewis, 1961), consisting of regularly spaced light and dark bands. The combined width of a dark and light band is approximately equivalent to a year's movement and as ogives are visible along the western margin of Breidamerkurjokull (Figure 5.25), it has been possible to estimate the annual rate of ice movement relative to the distance from the ice margin. For example:

Distance back from the western ice margin	1945	1961	1965
2 kilometres	50 m	55 m	38 m
3 kilometres	69 m	67 m	75 m
4 kilometres	93 m	-	-

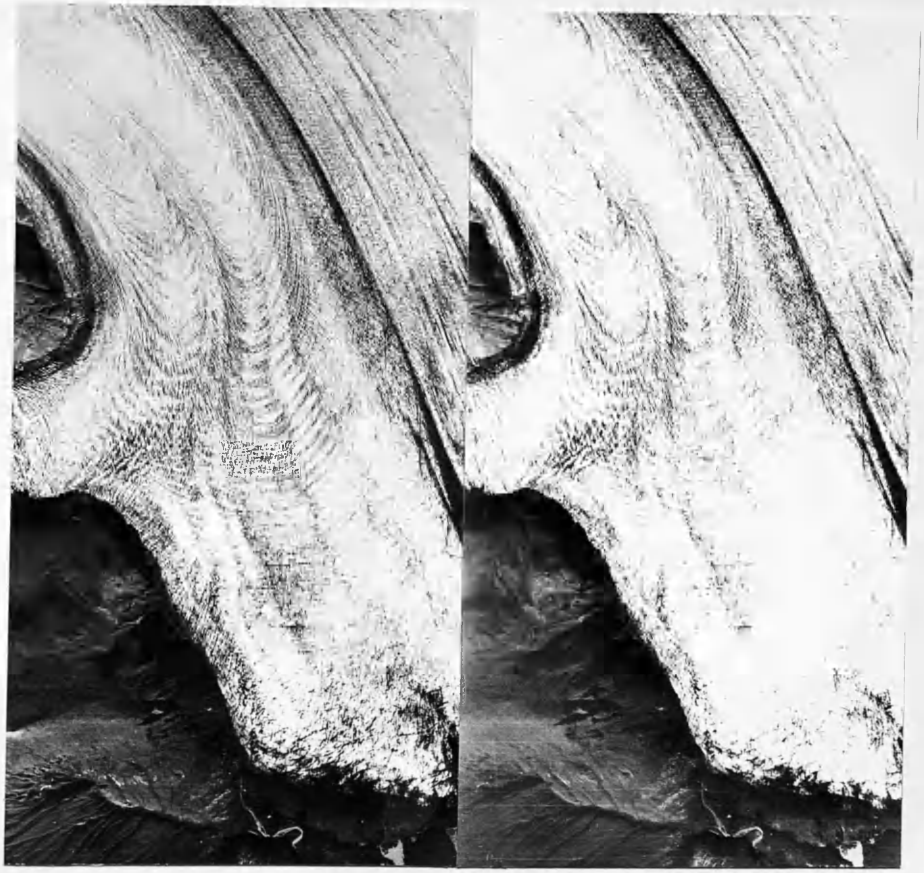


Fig. 5.25 Stereopair of the ogives near the ice-dammed lake in 1945 at 1:46,000 scale. Note the distinct pattern of black and white bands.

As can be seen, the annual movement appears to remain approximately the same relative to the distance from the ice margin, although the margin retreated about 1200 metres between 1945 and 1965.

The slowing of ice movement near the front of the glacier is also revealed by the black band of near stagnant ice extending as much as 500 metres back from the ice margin. The blackness is caused by the merging of ogives and dirt bands, the upward curling of shear planes, and the rapid ablation. Rapid ablation also is responsible for the steep slope of the ice margin.

Geomorphology

The sequential aerial photography is particularly useful for obtaining geomorphological data on landforms with distinctive shapes, patterns, or textures. Furthermore, as many landforms indicate certain types of deposits, such as till or gravels, it is possible to delineate these as well.

The appearance of the various landforms and deposits of the Breidamerkur area on the aerial photography are discussed below under glacial erosion, glacial deposition, fluvioglacial erosion, and fluvioglacial deposition. Where available, ground observations or collateral information is used to support the information obtained from the aerial photography.

Glacial Erosion

The only major features caused by glacial erosion which are visible on the aerial photography are the aretes and cols of the mountains and ridges on the western margin of the glacier. However, the erosive forces of the glacier have also exposed the basaltic lava beds and these are easily distinguished by colour tone on the colour aerial photography (Figure 10 in the enclosed publication).

Glacial Deposition

Deposits and features due to glacial deposition which are visible on the aerial photography can be divided into two groups: 1) till, end moraines, and fluted moraine; and 2) medial moraines and ablation moraine.

Till, end moraines, and fluted moraine:

From ground observations, it is known that till, consisting of sub-angular and sub-round gravels averaging 0.03 to 0.05 metre in diameter and imbedded in a sandy-clay matrix, occupies the top one to two metres of the stratigraphic column in both end moraine and fluted moraine areas. Therefore, it can be said that the distribution of till corresponds to the moraine and fluted moraine areas shown on the maps. This is a good example of surface morphology indicating the type of deposit or soil (also see Curtis, 1962). Furthermore, as till is only found in areas relatively unscathed by meltwater, and as many meltwater channels have exposed sections with till on top (Figure 5.26), it can be assumed that till was more extensive at one time.

The formation of the till appears to be due to the saturation of sands and gravels from summer meltwater and the pressure from overriding ice. These two factors tend to produce a very plastic surface

/material

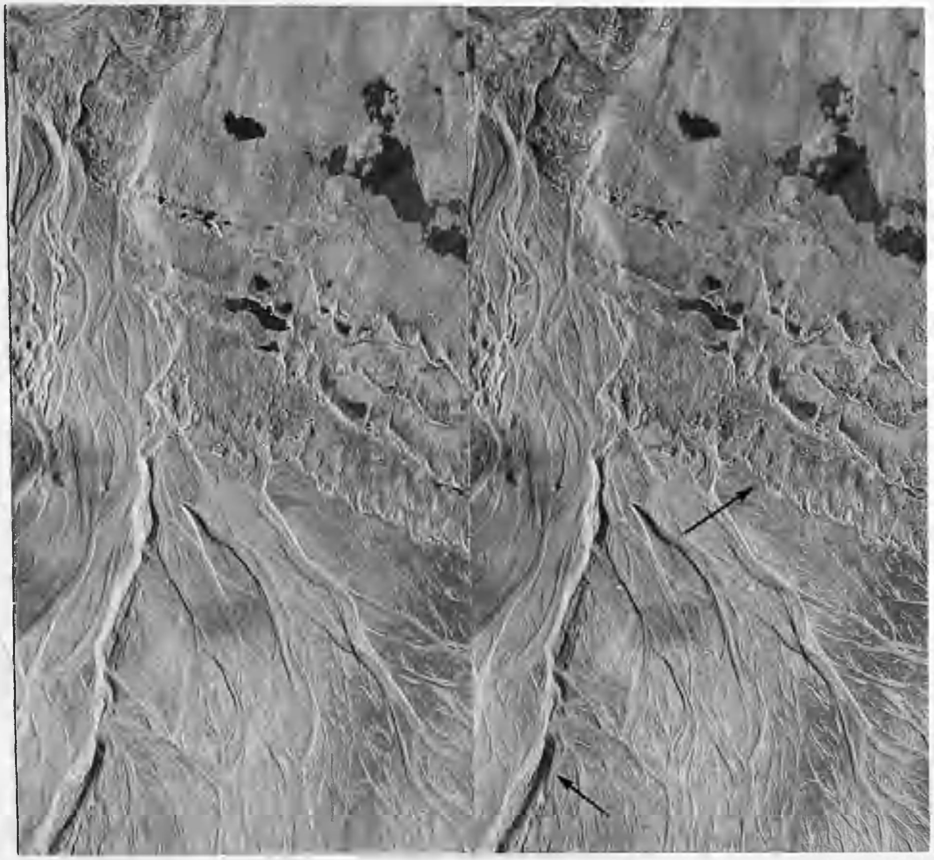
Fig. 5.26 Till occupies the top 1 to 2 metres of the stratigraphic column in moraine areas.

material, which in 1965 and 1966 occupied the areas on either side of Breidarlon within 100 metres of the ice margin. In fact, it was only possible to reach the ice margin by stepping on large boulders and even these often sank into the saturated ground. As the Breidamerkur area has undergone several glacial advances and retreats, with the consequential dredging and outpouring of gravels, it is logical that the till would consist largely of sub-round and sub-angular gravels and differ little from the underlying gravels. The same situation currently exists in the region of the Casement Glacier, Alaska, and probably in many other areas as well.

End moraines are distinguished on the Breidamerkur aerial photography by their long, narrow ridge shape and their orientation parallel to the ice margins (Figures 5.27 and 5.28). As can be seen from both the 1945 and 1965 maps, distinct belts of end moraines are located two kilometres in front of Breidamerkurjokull. A similar moraine, although orientated perpendicular to the above, is located about one kilometre in front of Fjallsjokull. These moraines vary from 2 to 15 metres in height and are covered by boulders ranging in size from a few centimetres to more than two metres in diameter.

As all of the above moraines were formed prior to the 1945 photography, the dates of origins were discussed with Mr. F. Bjornsson, whose family has lived in this area for several decades. He has stated that the outer moraine marks the limit of maximum advance of the glacier in historical time - about 1880 - and was formed at that time. The

/second



5.27 Stereopair of the end moraines of both Breidamerkurjokull and Fjallsjokull at a scale of 1:16,000. Note the long, narrow, sometimes arcuate ridge shape and the numerous boulders. The Fjallsjokull moraine (lower left) and the outer Breidamerkurjokull moraine indicate the position of the ice margin in 1880.

Fig. 5.28 Ground photo of the end moraines in Fig. 5.27.

second and third belts were formed as the ice retreated and their approximate dates of formation are 1907 and 1937 respectively. These dates are largely confirmed by the 1903 map and Thorarinsson (1943). As such they were the basis for the 1880 and 1937 ice margins indicated on the 1:100,000 scale maps in Figures 5.4 and 5.5. The near junction of the outer Breidamerkurjokull moraine with the Fjallsjokull moraine, of course, indicates the joining of the glaciers in this area in the late 1800's, a state which lasted until the 1940's.

Examples of end moraines which have been formed since the 1945 photography and are readily discernible because of their distinct pattern, are a series of small arcuate ridges of 1 to 2 metres in height, 2 to 3 metres in width, and from less than 100 to several hundred metres in length. These are located on two mounds in front of Fjallsjokull and in most instances are separated by distances of 5 to 30 metres (Figures 5.29, 5.30, and 5.31).

The formation of these ridges appears to have occurred at a rate of one per year. For example, 19 moraine ridges are located on the northernmost mound which, from the aerial photographic evidence, became free of ice in 1962 or 1963. On the 1945 aerial photography only three moraines are exposed, indicating that 16 moraine ridges were formed between 1946 and 1962 or 1963. Similarly, on the southern mound 8 or 9 ridges had been formed by 1945, with approximately 14 additional ridges being added between 1946 and 1961 or 1962.

In regard to their mode of origin, it would appear from the

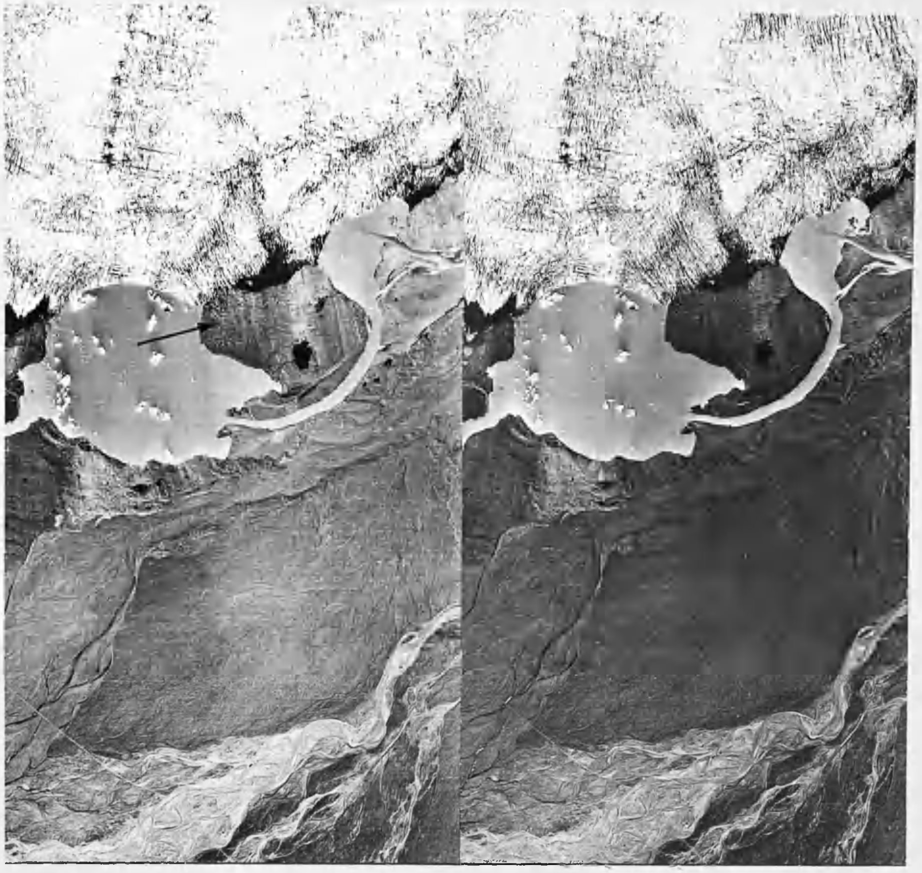


Fig. 5.29 Stereopair of the southernmost mound of moraines in 1961 at a scale of 1:37,000. Note that the ice margin of Fjallsjokull still occupies part of the mound.

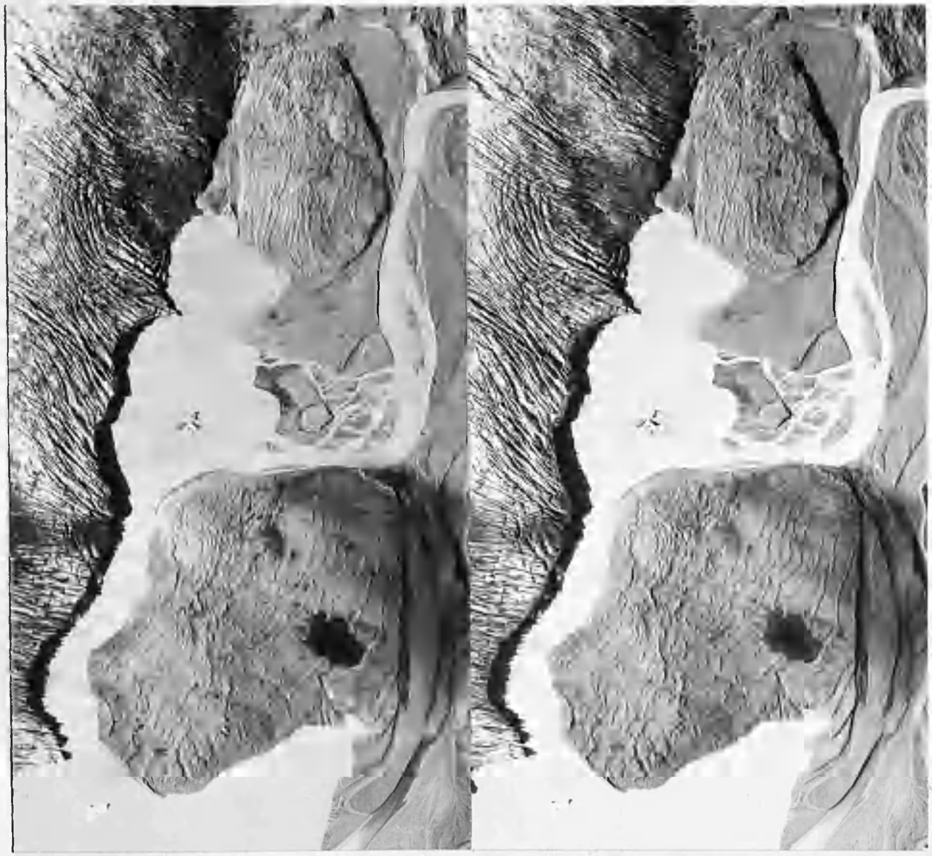


Fig. 5.30 Stereopair of both mounds in 1965 at a scale of 1:16,000. The mounds were free of ice by this date.

Fig. 5.31 Ground photo of the small end moraines. The pattern of these moraines is much more evident on the aerial photographs.

photogrammetric and photographic evidence, in conjunction with the ground observations of similar moraines being formed along the front of Fjallsjokull in 1965 and 1966, that plastic ground moraine is squeezed from beneath the ice margin into an arcuate shaped ridge during the summer months. Fluctuations in lake level over the course of the meltwater season, combined with the continuing retreat of the glacier, may account for more than one crest in the moraine ridge. In the winter the ground moraine is firm but ablation continues, resulting in continued retreat of the ice front without the formation of ridges. In particularly severe winters ablation at the front may be retarded and a small amount of forward movement may occur in the early spring, resulting in modification of the moraine by 'pushing' or perhaps even the formation of a secondary ridge (Dyson, 1952).

Similar ridges are also found parallel to the front margin of Breidamerkurjokull (e.g. to the west of Breidarlon). Although these are probably formed in a similar manner, it has not been possible to document this from the aerial photography.

Fluted moraine is another type of moraine which is common in the Breidamerkur area and is readily distinguished on the aerial photography by lineations perpendicular to the ice margins (hence the name fluted moraine). These flutings or lineations range in size from 1 to 12 metres in width and are usually less than a metre in height. On the ground, the lineations are often invisible and this may cause some to favour the term 'ground moraine', implying a broad distribution of morainic materials (including ablation moraine) rather than a distinct landform type.

Distinct flutings are, however, recognisable near the western margin of Breidamerkurjokull (Figures 5.32 and 5.33).

Groovings or flutings in till have been noted by several investigators, including Tarr and Martin (1906), Dyson (1952), Gravenor and Kupsch (1959), and Schytt (1963) and all of these references mention two factors: 1) the presence of saturated till or ground moraine; and 2) that the till could easily be squeezed into longitudinal cracks on the undersurface of the glacier. Furthermore, the latter three indicate that these cracks may be crevasses or cavities formed behind boulders fixed solidly in the sub-stratum. At Breidamerkurjokull, the location of the fluted areas adjacent to the large and very deep marginal lakes, and the fact that the lake levels have varied over the years during which the fluted areas were formed and may also fluctuate seasonally, suggests that these fluctuations may cause vertical movements of the glacier front, hence resulting in sufficient pressure to squeeze saturated till into cracks on the undersurface of the glacier.

Medial moraines and ablation moraine:

Medial moraines are easily distinguished on the aerial photography by their long narrow shape, their position on the ice surface parallel to the direction of ice movement and, in this case, by their dark tone (see mosaics and Figure 8 in the enclosed publication). As previously mentioned, there are three major medial moraine groups; Esjufjallarond, Mavabyggdarond, and an unnamed western moraine. All of these moraines consist of an ice ridge with a surface covering of gravels

Fig. 5.32 Aerial photographic enlargement of fluted moraine near the western margin of Breidamerkurjokull. Note the distinct lineations perpendicular to the glacier.

Fig. 5.33 Ground photograph of the fluted moraine area shown on the aerial photographic enlargement.

and angular basaltic rocks ranging from a few centimetres to greater than a metre in diameter (Figure 5.34). The heights of these moraines vary from a flat streak of dirt above the 400 metre contour to a steep-sided (although often flat-topped) ridge at the terminus. Near the ice margin the moraines rise 10 to 30 metres above the general glacier surface.

All three moraine groups have been traced to nunataks several kilometres back from the ice margin, and Young (1953, p.32) mentions that near their points of origin the moraines are also ridged, reaching heights of 60 metres. Furthermore, he states that rock colours indicate the sources of the moraines. As the colour photography brings out these colour differences (Figure 8 of enclosed publication), it would probably be possible to trace the moraines to their sources by photo-interpretation if sufficient coverage were available.

An examination of the crevasses near the sources of the moraines by members of the Durham University Expedition of 1951 indicated that they were not solid formations extending to the bottom of the glacier, such as those described by Washburn (1935). The question then arises as to why the moraines disappear into a streak of dirt over most of the distance from the source to the ice terminus. Although ground observations of these moraines have been limited, it may be that the surface materials accumulated near the source become dispersed by ice movement once they leave the zone of friction caused by the nunataks. This material then maintains a relatively constant course and begins to reappear as a ridge in the lower portions of the glacier where movement

Fig. 5.34 Medial moraines. Note the relatively thin layer of ablation moraine and flat-top (upper).

slows and ablation is strong (Tarr and Martin, 1914; Sharp, 1949). In addition, it is known that shear planes begin to curl upward near the snout and these may bring some of the finer materials to the surface. From an examination of the ice cliff at the terminus of Esjafjullarond (Figure 5.35), there is little doubt that large boulders are incorporated in the upper ice layers and are exposed by ablation.

Ablation moraine, consisting of large, angular grey or reddish-brown boulders ranging in size from 0.2 metre to greater than one metre in diameter, has been observed on the ground along the west margins of Breidarlon and Jokulsarlon (Figure 5.36), and to some extent in the area between Mavabyggdarond and the hut shown on the 1965 map. In addition, it is also evident in the area between the stream, Breida, and the base of Rakartindur. As the ablation moraine is found primarily in line with the medial moraines and is often of similar colour and shape, attempts were made to distinguish it on the aerial photography. This is possible to some extent on all aerial photography due to the coarse nature of the materials (hence a coarse texture). Effective tonal distinction, however, was limited to the colour photography. With the aid of this photography, the ablation moraine areas were outlined on a 1:100,000 scale work map that had been produced by photographic reduction. This in turn was superimposed on the 1903 Danish map. As the area occupied by the medial moraines in 1903 and the outlines produced from the 1965 photography corresponded, it can be stated that the ablation moraine is derived from the medial moraines. The only exception to this

Fig. 5.35 Ice cliff marking the terminus of Esjufjallarond.

Fig. 5.36 Ablation moraine along the west shore of Breidarlon. Note the western medial moraine in the background.

is the area near the base of Rakartindur. This area was occupied by stagnant ice joining Fjallsjokull and Breidamerkurjokull in 1945 (see 1945 map).

Fluvioglacial Erosion

The major features produced by fluvioglacial erosion are meltwater channels. These are distinguished on aerial photography by their broad, U-shaped bottoms and steep sides, by terraces, and/or by the light tones of gravels strewn along their bottoms. Also, gravels usually present a much finer texture than the surrounding features and this is readily detected on all scales of aerial photography.

Over the last 100 years a complex series of meltwater channels has developed in the Breidamerkur area. The development of these channels has been noted by the local inhabitants and, in later years, recorded on the aerial photography. From these two sources and the 1903, 1945, and 1965 maps, it has been possible to determine both the sequence of development and to some extent the modes of origins of these channels. However, before considering their development, it is appropriate to describe them.

Generally, it is possible to classify the channels in three categories based on size, shape, and the length of the period during which they were occupied.

Category 1: this group of channels includes those which have functioned as major drainage channels for periods of 10 years or longer and have had outlets to the sea or to the Jokulsarlon. They have well defined,

/broad

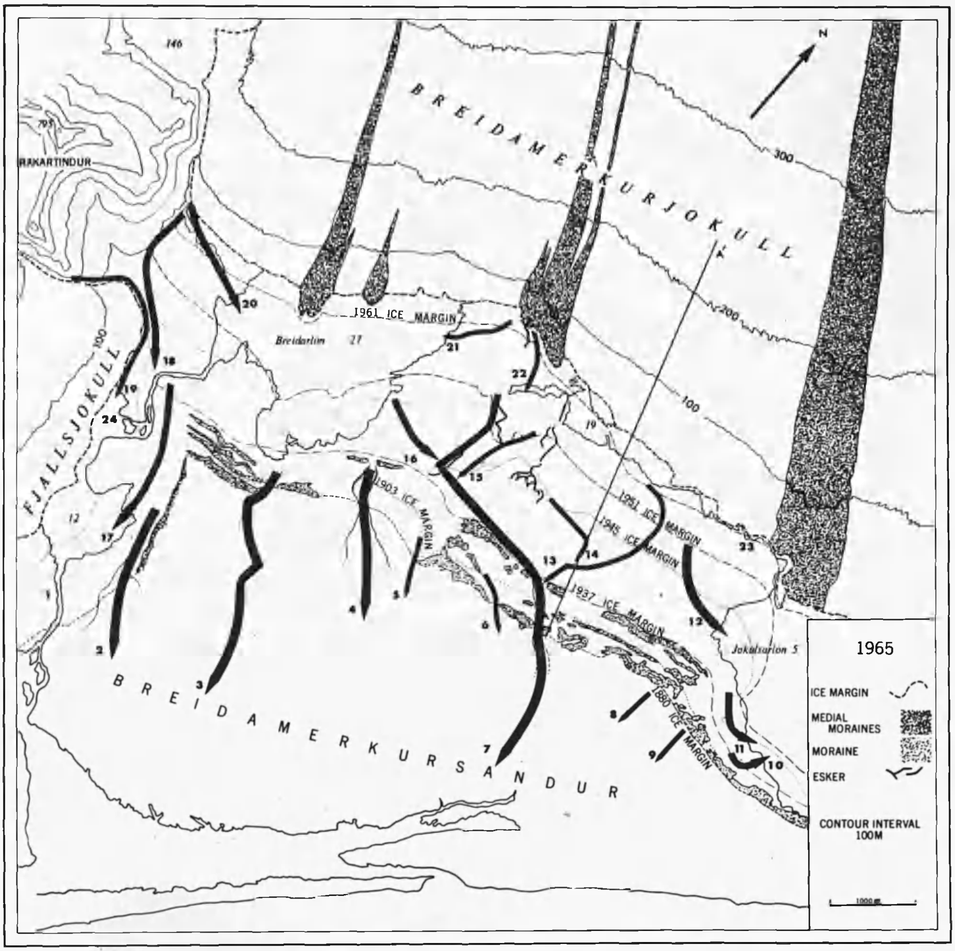


Fig. 5.37 Meltwater channels (arrows) in the Breidamerkur area west of the Jokulsa. The three categories of channels indicated by different arrow widths are discussed in the text.

broad U-shaped bottoms, are usually greater than 100 metres in width, and reach depths of 5 metres or more in their upper portions, although diminishing to a complex of braided channels near their outlets. This group includes 1 (the present Fjallsa), 2, 3, 4, the lower portion of 7, and 12, and are indicated by the broad arrows in Figure 5.37.

Category 2: includes major drainage channels with well defined courses, often as wide and deep as Category 1 although without direct outlets to the sea. These channels have functioned for periods of 5 years or longer and include the upper portion of 7, and all of 10, 11, 16, 17, 18, 20, 23, and 24 (Breida). They are indicated by the intermediate sized arrows in Figure 5.37.

Category 3: includes channels which have poorly defined bottoms or sides, have functioned for less than 10 years and/or are purely transitory, as indicated by terraces. Channels 5, 6, 8, 9, 13, 14, 15, 19, 21, and 22 are members of this group and are indicated by the narrow arrows in Figure 5.37.

1880 to 1935 (Although this discussion is based primarily on collateral information, channels 1, 2, 3, 4, and 7 are clearly visible on the mosaics in Figures 5.21 and 5.22):

Most of the channels in Category 1 and all the channels in front of the outer belt of moraines developed during this period - when the ice was retreating from its position of maximum advance. According to local knowledge and the 1903 map, major drainage in the late 1800's and early 1900's was limited to the general areas of channels 2, 3, 5 and, 6. In the west, channel 2 appears to have been formed about the time

Figure 5.38 Looking south along Fjallsa (channel 1) from the bridge shown on the 1965 map. Note the 10 metre deep gorge.

Fjallsjokull began to retreat from its position against the outer end moraine in the late 1800's, with drainage taking place between the retreating ice edge and the end moraine. It is also likely that early drainage from the western margin of Breidamerkurjokull followed this route. By 1903 the ice margin had begun to retreat up the front slope of the ridge along the east margin of Fjallsarlon and by the late 1930's had reached the reverse slope. At this time, water ponded between the ridge and the ice margin began to escape by way of channel 1 (Fjallsa). In this latter instance, major channel cutting to a depth exceeding 10 metres took place during the late 1930's and early 1940's (Figure 5.38). With the establishment of channel 1, channel 2 was abandoned.

At the same time as channel 2 was active in the west, channels 3, 5, and 6 were being formed in the central portions of the area. Channels 5 and 6 correspond to drainage on the 1903 map and are reported by F. Bjornsson (personal communication) to have functioned for a few years during the late 1800's and early 1900's. Although they are not particularly deep, they appear to have destroyed portions of the 1880 moraine. From the positions of the ice margins and the channel slopes, it is likely that major drainage in this area had shifted to channels 4 and 7 by the 1920's.

Drainage patterns in the vicinity of channel 3 (old Breida) are also shown on the 1903 map and appear to have formed the terraces east of the main portion of the channel (see 1965 map). By the 1930's, however, the main channel had been established and was the major outlet for meltwater from Breidamerkurjokull until October 1954 (Todtman, 1960) when,

Fig. 5.39 Channel 4. Upper: looking west from the head of channel 4 where it has been cut through the moraine and ridge crest. Note Fjallsjokull in background. Lower: the bottom and east bank of channel 4. Depth is from 6 to 10 metres.

from the photogrammetric evidence, it appears that the level of Breidarlon dropped and channel 3 was abandoned.

Channels 4, 8 and 9 were established in the 1920's and were not abandoned until the ice had retreated to the 1937 position. Channel 4, with a depth of 10 metres, is one of the deepest channels in the western area and has apparently been responsible for the destruction of portions of the end moraines. Evidence of this is the narrow gorge cut through a portion of the end moraine formed in the late 1930's, and boulders of 1 to 2 metres in diameter scattered along the bottom of the upper portions of the channel (Figure 5.39). Once the ice margin had retreated beyond the backslope of the ridge marking the head of channel 4, drainage was west into channel 3 and, by 1942, east into channel 16.

1935 to 1960:

By the late 1930's the ice margin had retreated sufficiently to permit meltwater to escape by new routes. Because of the complexity of the drainage at this time, the area will be considered in three separate sections; eastern, middle, and western.

Eastern: Channels formed during this period included 10, 11, and 12. All these channels are steep sided, reach depths of at least 5 metres, and extend to the Jokulsarlon. Channels 10 and 11 are located on the backslope of the ridge adjacent to the Jokulsarlon, whereas channel 12 occupies part of the eastern foreslope of the ridge which parallels the ice margin between Breidarlon and Jokulsarlon (Figures 5.23 and 5.40).

Channel 10 (Figure 5.41) was formed during the 1930's and

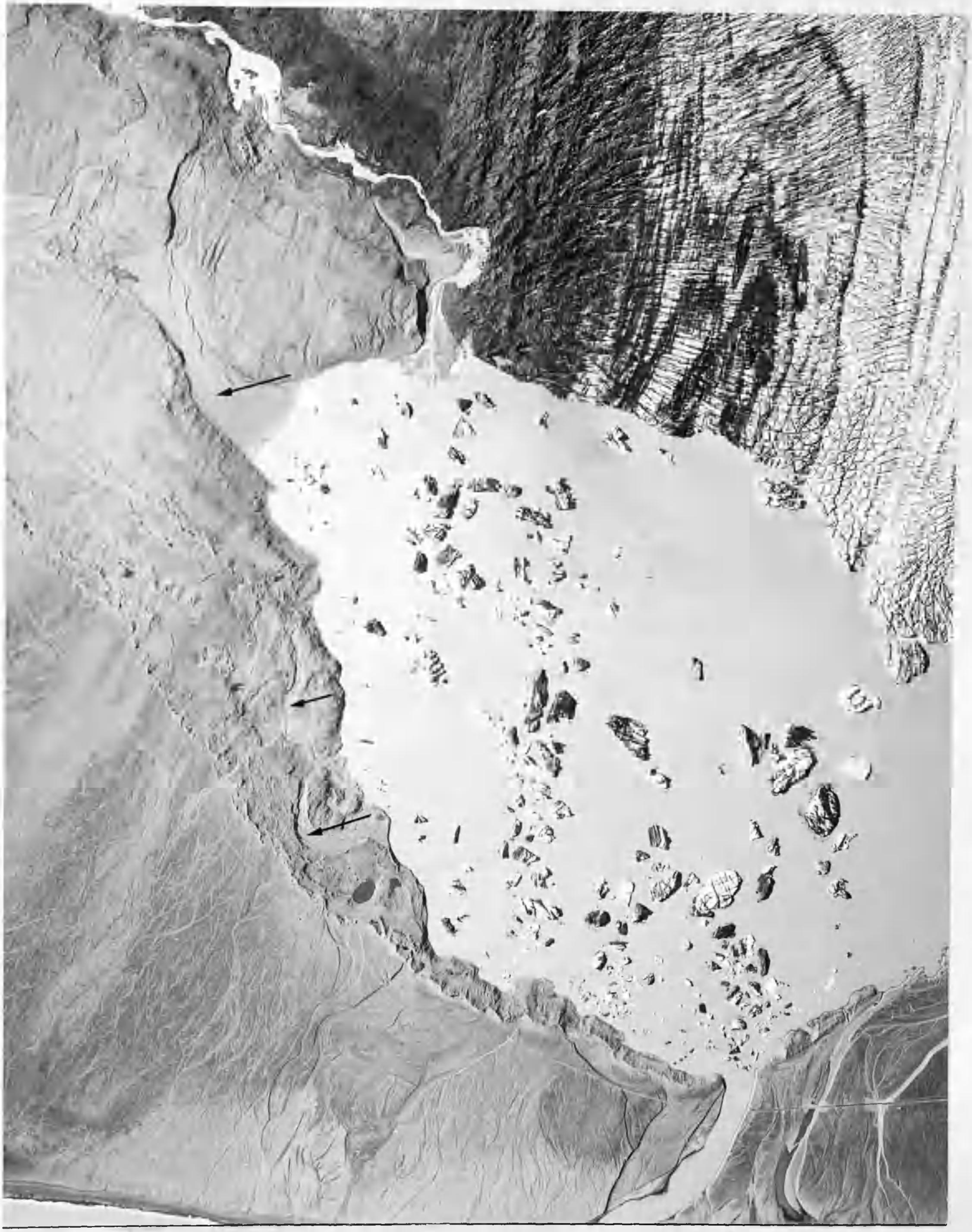


Fig. 5.40 Channels 10, 11, and 12 (bottom to top) as they appeared in 1965 at 1:27,000 scale.

Fig. 5.41 Upper: ablation moraine in the bottom of channel 10. Lower: the level of Jokulsarlon is about one metre below the general surface of the fan at the mouth of channel 10.

apparently developed beneath the stagnant, medial moraine-covered ice which occupied this area at that time. This is indicated by the large angular blocks of ablation moraine to be found in the channel (Mannerfelt, 1945). As the alluvial fan at the mouth of the channel is situated about a metre above the present level of the Jokulsarlon, it must be assumed that drainage via this channel continued until the early 1940's when the Jokulsarlon reached its present level.

The origin of channel 11 appears to be similar to that of 10. In this case, however, the channel was being formed at the time of the 1945 aerial photography and connected a small lake occupying the mouth of channel 12 (22 metres) with the Jokulsarlon (5 metres). As the channel was both surrounded and covered by dead ice, it must have been formed subglacially (see 1945 map and Figure 5.23). Again, this is confirmed by the presence of angular blocks on the floor of the channel (Figure 5.42). This channel probably continued to function until the early 1950's as the Durham University map of 1951 indicates that the medial moraine-covered ice was still present against the shore and the smaller lake had not yet merged with the Jokulsarlon.

Channel 12 begins on the ridge crest about 500 metres in front of the present ice margin and, although its upper portions were still beneath the ice margins, appears to have been largely formed by 1945. By 1951, however, the entire channel was almost completely exposed and, according to the Durham map, responsible for most of the eastern drainage, By 1960, the ice margin had retreated beyond the crest of the ridge and

Fig. 5.42 Head of channel 11.

major drainage was eastward along the ice margin.

Middle: Channels which developed in the area in front of Mavabyggdarond during this period included the upper portion of channel 7, and channels 13, 14, 15, and 16.

Channel 7, a well-defined, 5-metre deep channel throughout most of its course, extends from near the western edge of the small lake in front of Mavabyggdarond (21 metres on the 1965 map) to the lagoon on Breidamerkursandur. Although 7 began to form in the early 1900's, it was not until between 1940 and 1945, when Breidarlon was extended northwards, that drainage paralleled the ice front to form channel 16. Channel 16 in turn connected with channel 7, and a major drainage course was established. This was also termed Breida.

During the 1940's the eastern and western Breidas (channels 16/7 and 3) were the major streams draining Breidarlon. However, in the late 1940's channel 16 was abandoned (possibly because of a drop in the lake level), although frontal drainage from the Mavabyggdarond area continued to escape via the upper portion of channel 7, and also by channel 15 which had been formed by that time. Channel 15, which is generally shallow except for a depth of about 7 metres where it passes between the backslope of a small ridge and the z-shaped esker shown on the 1965 map, was a minor drainage course until the ice margin retreated beyond the ridge crest in the middle 1950's, resulting in the formation of an ice-margin lake. This lake was at least 10 metres higher than the levels indicated on the 1965 map and drainage was westwards into the upper

/portion

portion of channel 7. When the lake level dropped in 1962, channel 7 was abandoned.

Channels 13 and 14, which were established by broad frontal drainage at approximately the same time as 15, lack well-defined channels. From the positions of the ice margins and the aerial photographic evidence, it appears that 14 was abandoned in the mid- or late 1950's, and 13 in 1962.

Western: West of Breidarlon and adjacent to Fjallsa, channels 17, 18, 19, and 24 were altered several times in the 1940's and 1950's (Figure 5.43). Channel 17 is between 5 and 10 metres deep in its middle section and is comprised of several terraced channels, formed at successively lower levels along the retreating front margin of Fjallsjokull in the late 1930's and early 1940's. By 1945 a continuous drainage system from the base of Rakartindur to Fjallsarlon had been established in which channels 18 and 19, emerging from under the margins of Breidamerkurjokull and Fjallsjokull, joined at the base of Rakartindur to form a common channel (18). In addition, meltwater from what is now the western edge of Breidarlon drained west through the upper portion of channel 24 (Breida) to join with 18 at the point where 24 makes a right angle bend. This combined meltwater drainage system then continued south into Fjallsarlon by way of channel 17. The channel 18/17 combination remained as the main drainage course for the northern margin of Fjallsjokull, the western margin of Breidamerkurjokull, and Breidarlon until the early 1960's.

1960 to 1965:

By the early 1960's an entirely new drainage system had begun

/to

Fig. 5.43 Upper: channel 17. Note the water in the left centre of picture which marks the old stream course. Breidamerkurjokull is in the background. Lower: meltwater from Breidarlon flowing west and south towards Fjallsarlon through channel 24 (Breida).

to form, including channels 20, 21, 22, 23, and the lower portion of 24. In the west, Fjallsjokull had retreated sufficiently so that a small lake (which had a height of 19 metres in 1961 and is presently the upper portion of Fjallsarlon) had begun to form between the mounds on which the small end moraines occur. Drainage along the lower portions of channel 24 (Breida) was also established, although in 1961 some meltwater was still continuing directly into channel 17. In 1962 or 1963, channel 18 was abandoned in favour of two separate courses, channels 19 and 20 (Figure 5.44). At approximately the same time, the terminus of Fjallsjokull became completely separated from the northern mound of end moraines and 19 drained directly into the small lake. This lake, in turn, drained into Fjallsarlon proper by way of 17. In late 1964 or 1965, the aerial photography reveals that the terminus of Fjallsjokull became separated from the southern mound of end moraines, resulting in the joining of the upper and lower portions of Fjallsarlon and the abandonment of 17 in favour of the direct drainage route. Although it is likely that the lakes were partially joined by a subglacial tunnel prior to 1961 (Bjornsson, 1959), the photogrammetric evidence indicates they did not attain the same level until 1964.

Similar changes were also taking place along the western margin of Breidamerkurjokull. On the 1961 aerial photography (Figure 5.45) channel 18 was still the major outlet for drainage emerging from beneath the western margin of the glacier and most of the area near the ice margin now occupied by channel 20 was covered by ice, yet on the 1964 and 1965

/photography

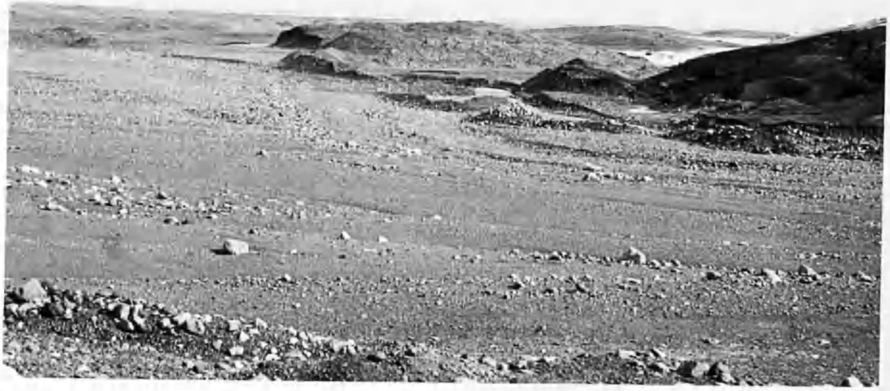


Fig. 5.44 Upper: abandoned channel 18 (L) and occupied channel 19 adjacent to the margin of Fjallsjokull (R). Note the northern mound of end moraines in the background. Lower: looking towards Breidarlon along channel 20. Breidamerkurjokull is visible along the left foreground. Note the black ice under the far bank.

Fig. 5.45 Stereopair of the western margin of Breidamerkurjokull in 1961 at a scale of 1:37,000. There is no evidence of a major drainage channel (20) along the ice margin at this time.

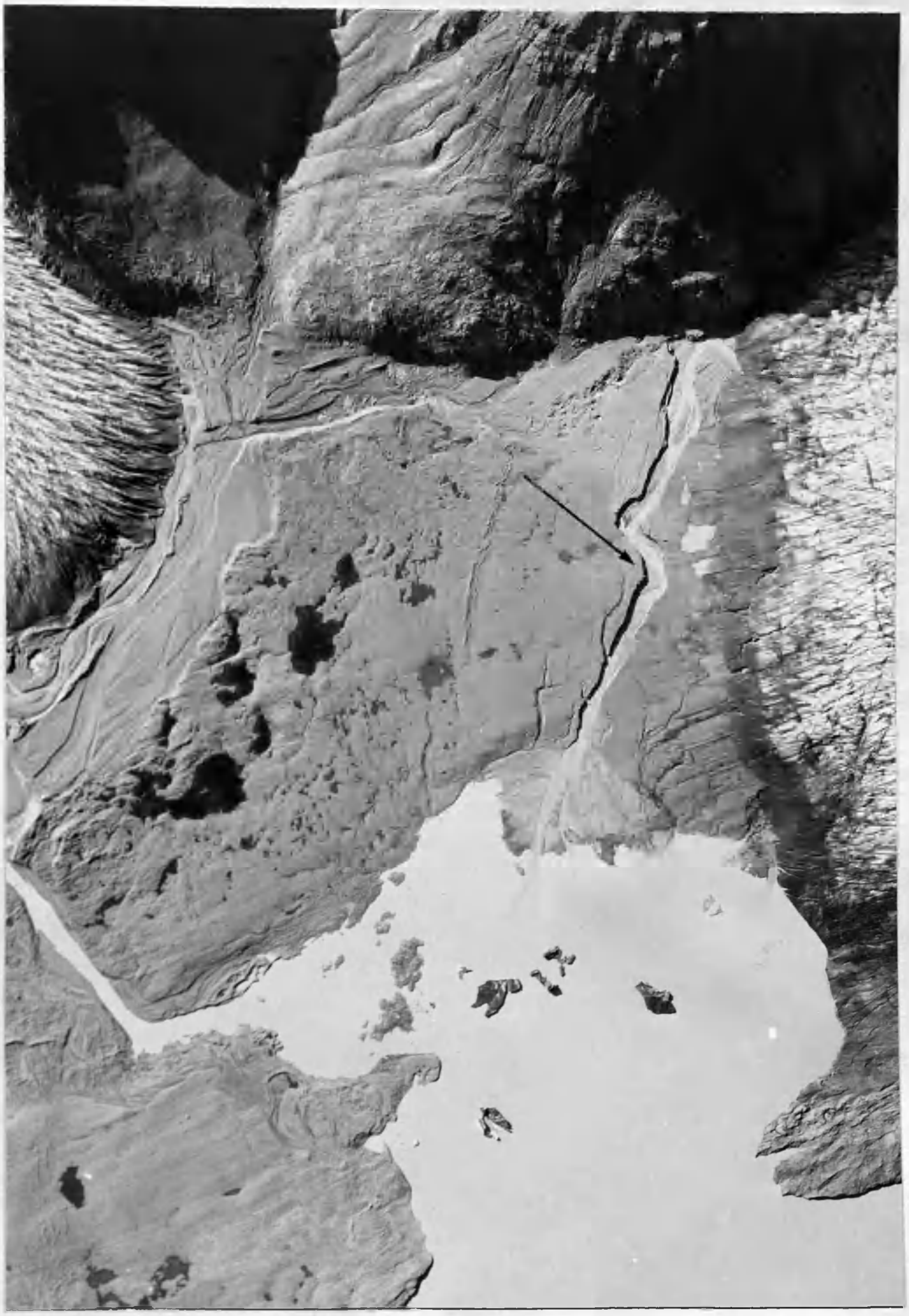


Fig. 5.46 A single photograph of the western margin of Breidamerkurjokull in 1965 at a scale of 1:16,000. This photograph is orientated in the same manner as the stereopair in Fig. 5.45. As can be seen, channel 20 has already been formed.

photography meltwater had already established the 5 to 8 metre deep channel 20 which extends from the ice margin to Breidarlon (Figure 5.46). This indicates that channel formation was largely proglacial along what was a very small stream course in 1961 (Hoppe, 1950). Meltwater emerging from a tunnel beneath the western margin has continued through this channel since the abandonment of 18, although severe undercutting is presently taking place in the gravels near the ice margin (Figure 5.44). The present gradient of channel 20 is approximately 1:12.

The region in front of Mavabyggdarond has undergone many changes since 1960 (refer to Figure 5.10). For instance, the aerial photography of 1960 and 1961 reveals a large lake extending between the ice margin and the backslope of the ridge which parallels the ice front. From photogrammetric measurements the lake was at a level of 30 metres at this time and drainage was into channel 7. By 1962, the margin of the glacier had retreated sufficiently between Mavabyggdarond and Esjufjallarond to permit meltwater to escape east into Jokulsarlon. This resulted in both and eastward extension of the former lake, and a rapid lowering of its surface level.[1] Consequently channel 7 was abandoned in favour of the new channel - 23.

The evolution of channel 23 is particularly interesting from the geomorphological viewpoint. Due to the narrow valley and steep slope from which the ice front was retreating, the ice margin was not abrupt but instead curled up the backslope of the ridge, resulting/

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[1] The old shoreline is clearly visible on the 1965 aerial photography.

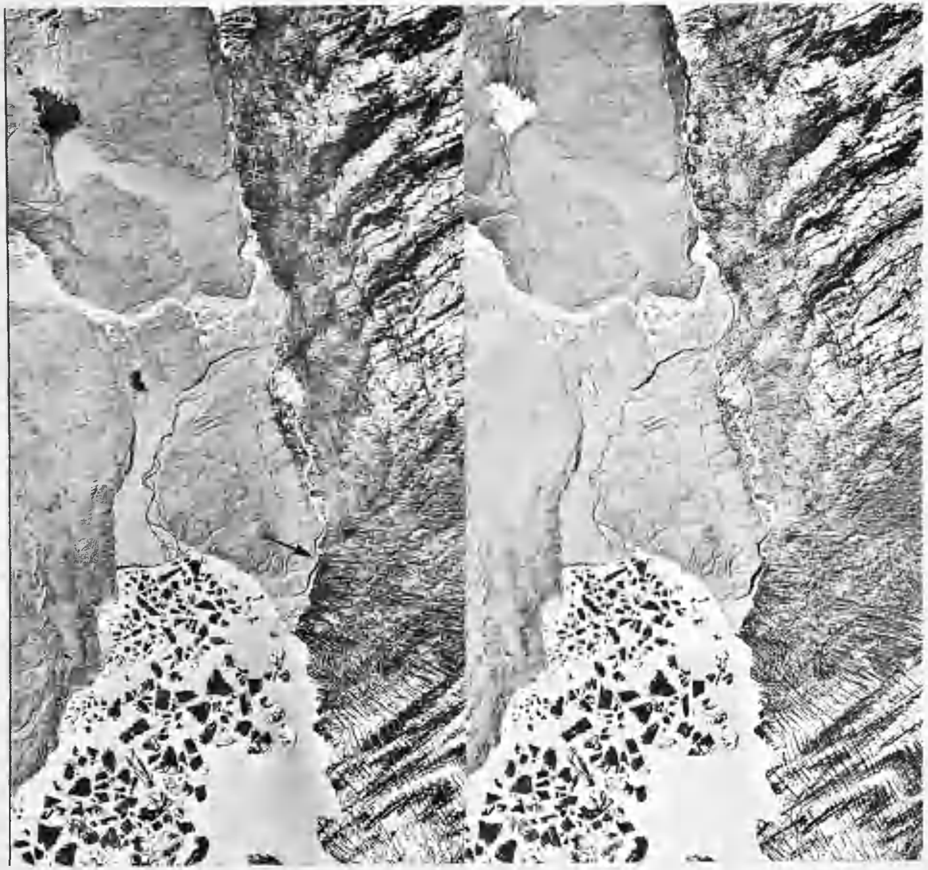

Fig. 5.47 Stereopair of channel 23 in 1960 at a scale of 1:36,000. The upper portion of channel 23 is established on stagnant ice, whereas the lower portion has already been cut through the gravels.

Fig. 5.48 A 1:27,000 scale photograph of channel 23 in 1965. Note the new course adjacent to the ice margin.

resulting in an ice-filled valley bottom. Consequently, the upper portions of channel 23 were established on ice rather than land. However, on the 1960 aerial photography, the lower portion of the channel can be seen to have already been cut to a depth of 20 metres in the gravels, yet ice connected to the glacier still covers the highest ground in this area (Figure 5.47). From this it is evident that the lower portions of the channel have been formed subglacially and that there was probably sub- or englacial drainage, as well as supraglacial drainage, parallel to the ice margin at this time. It is of further interest to note that in the early part of the summer of 1965, the lake which parallels the ice front was much more extensive than is indicated by the map. Approximately one week prior to the aerial photography - a period of heavy rain - the course of the channel shifted from that established in 1960-61 to closer to the ice margin (Figure 5.48). As a result, the eastern portion of the lake was drained and masses of black stagnant ice covered by as much as a metre of silt and bottom sediment were exposed, thereby establishing beyond doubt that the lake and channel had been established on ice. Figures 5.49 and 5.50 indicate these ice remnants and the deepest part of the channel immediately adjacent to Jokulsarlon.

In addition to channel 23, which acts as the major drainage channel eastwards along the front of the glacier, channels 21 and 22 indicate significant aspects of present and possibly future drainage patterns of the entire area of study. For instance, the area immediately in front of Mavabyggdarond acts as a drainage divide, with all drainage

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to the east into Jokulsarlon and that to the west into Breidarlon. If this divide is removed by further retreat of the ice margin or by downcutting of the stream presently flowing in channel 22, all drainage would be eastwards into Jokulsarlon. As a similar sequence of events appears to be taking place in the area east of Jokulsarlon, it is not inconceivable that the entire future drainage of Breidamerkurjokull will be into Jokulsarlon. Such a drainage system would undoubtedly render access to the ice surface extremely difficult and quite possibly endanger the suspension bridge now being constructed across the Jokulsa.

Fluvioglacial Deposition

Deposits or features produced by fluvioglacial deposition which can be identified on the aerial photography include outwash plains (sandur), alluvial fans, kames and kettles, and eskers. The former two are distinguished by their gentle slopes, numerous braided channels, even texture, and position in relation to streams. Kames and kettles have a pock-marked appearance, whereas eskers are recognised by their distinct ridge shape and sinuosity. As all of the features are made up of gravels, light tones are common (see Lueder, 1959), although the presence of grass or moist soils may alter this in the case of older features.

Breidamerkursandur and alluvial fans:

From the aerial photography, Breidamerkursandur appears to begin at the outer end moraine and extend to the ocean (Figures 5.21, 5.22, and 5.51). It is identified by the fine texture produced by gravels ranging in size from greater than 0.1 metre near the moraines to

Fig. 5.51 Ground photograph of Breidamerkursandur looking towards the ocean from the 1880 end moraine.

Fig. 5.52 Ground photograph of the beach deposits east of the lagoon.

less than 0.03 metre near the ocean, by numerous channels which reach depths of 3 metres in their headward ends but disappear near the coast, and by the general lack of relief. From the contour maps it is evident that the slope of the sandur decreases away from the outer moraine and is generally less than one degree. Furthermore, on the 1965 map, it can be seen that numerous small streams begin to appear at about the 10 metre contour, indicating the ground water level at the time of the aerial photography. These streams, unlike the silted meltwater streams, are clear (dark tones on all photography).

Near the coast a lagoon has been formed between the sandur and a spit. Changes since 1945 (observed by superimposing the 1945 and 1965 maps) indicate that the western portion of the lagoon has appreciably broadened and that the spit and coastline have been altered. The formation of the lagoon appears to be partially due to the issuing of silt-laden meltwater streams into the ocean, where finer materials are transported by lateral ocean currents and the coarser materials by waves (Hjulstrom, 1954, 1955).

To the east of the lagoon there is a long, narrow strip of light-toned beach deposits consisting of black sand and large boulders. These deposits appear similar to the spit and it is likely that they have been built up over the years by wave, wind, and storm action. Figures 5.52 and 5.53 illustrate these deposits.

Alluvial fans, which are identified primarily by their 'fan' shape and by their position at the mouths of meltwater channels or streams,

/are

Fig. 5.53 1:27,000 scale aerial photograph of beach deposits east of the lagoon. Note the light tones.

Fig. 5.54 Ground photograph of the fan at the mouth of channel 12. Note the icebergs in Jokulsarlon.

are found at the mouths of channels 10, 12, 17, 20, 23, and 24 (Figure 5.54). In addition, smaller fans extend from the mouths of englacial streams between Mavabyggdarond and Esjufjallarond, and in the eastern portion of Breidarlon. As is characteristic of alluvial fans, gravels decrease in size towards the mouth and they have been formed by streams heavily laden with gravels and silts emptying into ponded water (Russell, 1893). This process is presently occurring at the mouths of channels 20 and 24, and is easily detected on the aerial photography. As previously mentioned, the colour aerial photography is particularly useful, as colour tones of blue, green, or brown indicate whether the water is clear, lightly silted, or heavily silted (Figure 8 of enclosed publication). The above streams are all heavily silted.

The time and mode of formation of the fans at the mouths of channels 12 and 23 is evident from the sequential aerial photography. For example, on the 1945 photography, ice partially covers the fan at the mouth of channel 12 and the water level is nearly 17 metres higher than at present (Figure 5.23), yet the exposed portion of the channel appears to be completely formed, indicating that the fan, although largely submerged and still undergoing formation at that time, began to develop subglacially. Of course, the final form of the fan has been produced by proglacial drainage. Similarly, the fan at the mouth of channel 23, although covered by ice in 1945, is well developed on the 1960 photography (Figure 5.47). The fact that ice still covered part of the channel at that time indicates subglacial formation.

Of the smaller fans, the one extending from the englacial stream into Breidarlon (Figure 5.17) has already been discussed in regard to kame and kettle topography. Those between Mavabyggdarond and Esjufjallarond have developed in a similar fashion between 1960 and 1965.

Kames and kettles, and eskers:

Both of these features have been discussed in the photogrammetry section; however, certain additional comments in regard to their interpretation from aerial photography are in order. For example, the pock-marked pattern of kame and kettle topography (Figure 5.55) and the distinctive ridge shape of eskers can easily be missed if there is insufficient shadow to emphasise the microrelief. Therefore, stereo-viewing is particularly valuable in studying these forms (Figure 5.56). In addition, other important points include whether or not kettles contain water, or dark patches are visible on the sides of either kettles or eskers.

Examples of these two points, which may indicate the presence or absence of buried ice, occur in the kame and kettle area in channel 17 and in the esker complex in front of Mavabyggdarond. In the first case, water occupied the bottoms of all the larger kettles on the 1945 photography and ice blocks could be detected in the stream occupying channel 17. Therefore, it is fairly safe to assume that ice was present beneath the gravels. By 1961, however, most of the larger kettles were dry and it was apparent that many new kettles had developed as a result of the melting of the buried ice. The 1965 photography shows most

Fig. 5.55 Kame and kettle area in front of Mavabyggdarond. Note the pock-marked appearance and also the ridge shaped eskers near the left hand medial moraine.

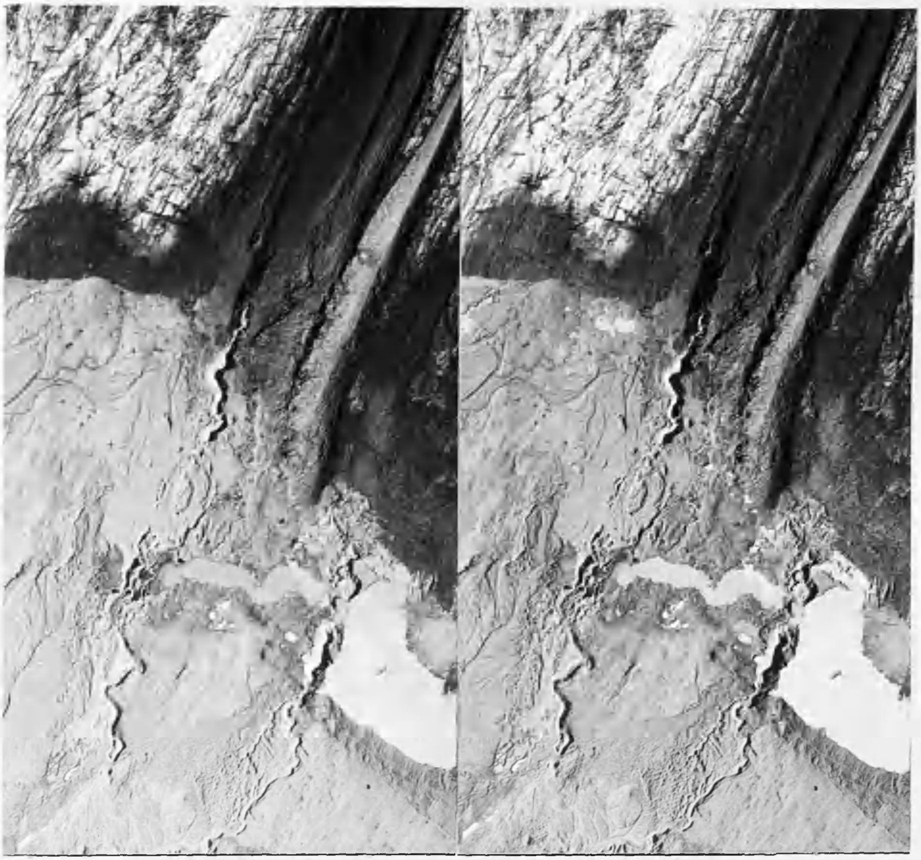

Fig. 5.56 1:27,000 scale stereopair of eskers and kames in front of Mavabyggdarond (1965).

Fig. 5.57 Photographic enlargement of buried ice on the side of an esker. Note the contrast between the dark-toned ice and the lighter gravels.

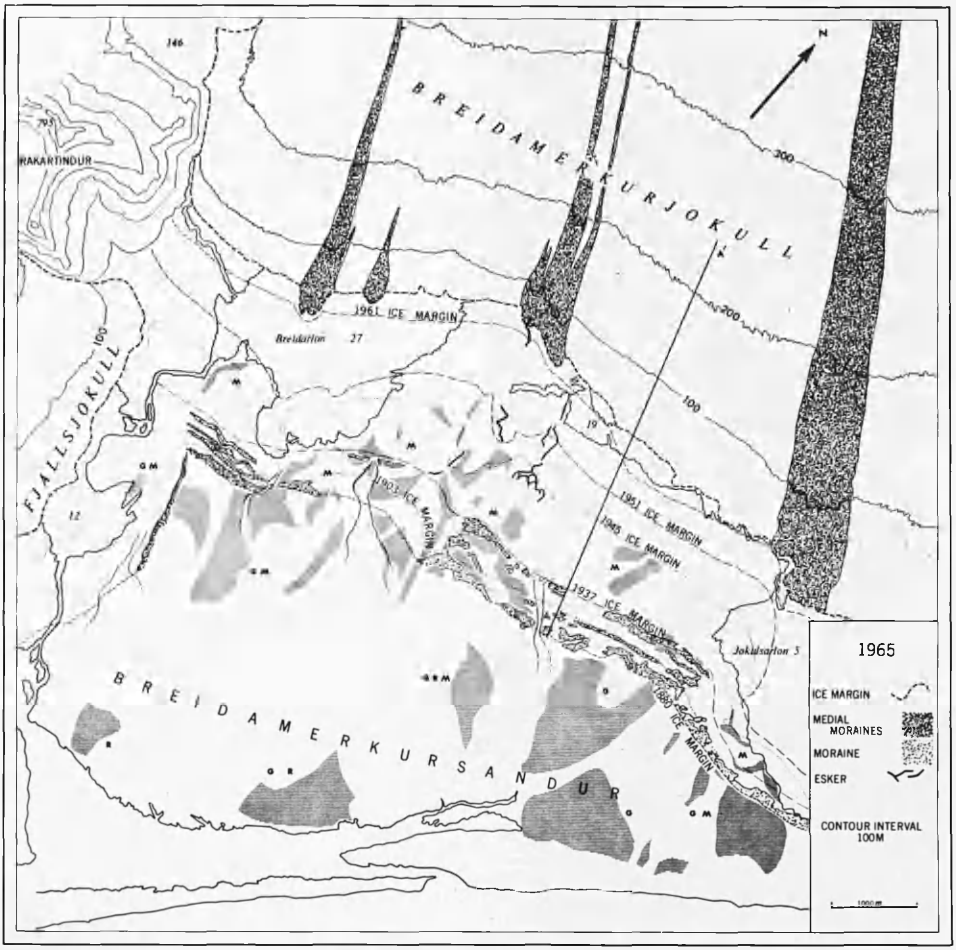

Fig. 5.58 Distribution of grass (G), moss (M), and rushes (R) in western Breidamerkur area is indicated by the line pattern.

kettles are dry even though the aerial photography was taken shortly after a period of extensive rain. From the photography, therefore, it can be said that most of the ice melted out between 1945 and 1961, and that little, if any, remained by 1965. Although the presence of buried ice in the esker complex has been considered previously, its appearance on the aerial photography has not been clearly illustrated. Figure 5.57 is a photographic enlargement showing how buried ice is revealed by a dark patch on the sides of the otherwise light-toned feature. Again, when tone is considered, colour photography is particularly useful (Figure 8 of the enclosed publication).

Ecology

In the glaciology and geomorphology sections, emphasis was placed upon shape, pattern, and texture rather than tone. Furthermore, only the sequential panchromatic photography was really considered, although colour was mentioned as being particularly useful for certain aspects. In ecological studies of a glacial area, however, both vegetational rates of succession (Welch, 1965; Lindroth, 1965) and soil development (Goldthwait et al, 1966) are of interest, and, as has been pointed out, the infra-red portion of the spectrum should be considered. In this regard, tone is important, unless vegetation or soil groups are distinguished by distinct shapes or morphological patterns. The importance of tone is particularly relevant to the Breidamerkur area where vegetation is primarily limited to grasses (*Festuca sp.* and *Agrostis* sp.), mosses (*Rhacomitrium sp.*), or rushes (*Juncus balticus*);

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and soils are only reasonably developed in those areas covered by vegetation. Therefore, the false colour photography is considered far superior to either the infra-red or colour, as it is possible to both delineate the major concentrations of vegetation, and to distinguish between mosses and grasses, or mosses and rushes, by colour tone (see Figure 9 of the enclosed publication). Furthermore, this is rapidly accomplished because of the contrasts between the magenta tones of vegetation and the blue-green tones of gravels. It is not possible to distinguish species on either the infra-red or colour photography without ground information, although the major concentrations can be discerned.

Using the false colour photography, the major concentrations and species of vegetation were plotted on a reduced scale map in the matter of a few hours (Figure 5.58). Furthermore, it is thought that because of the unmistakable colour contrasts, it would have been possible to have obtained the same information from false colour photography at a scale of 1:30,000 or smaller, thus reducing the number of photographs. This, in turn, would result in less time spent in producing the map.

The map itself is of interest as it clearly indicates that grass is only common in those areas which have been free of ice for 80 years or longer, and that there is little vegetation in areas deglaciated for less than 20 years. As mosses predominate in areas free of glacial ice from 20 to 80 years, it can be assumed that they are among the primary colonisers. Soils are best developed in the two large grass areas. Figure 5.59 illustrates the value of photography sensitive to

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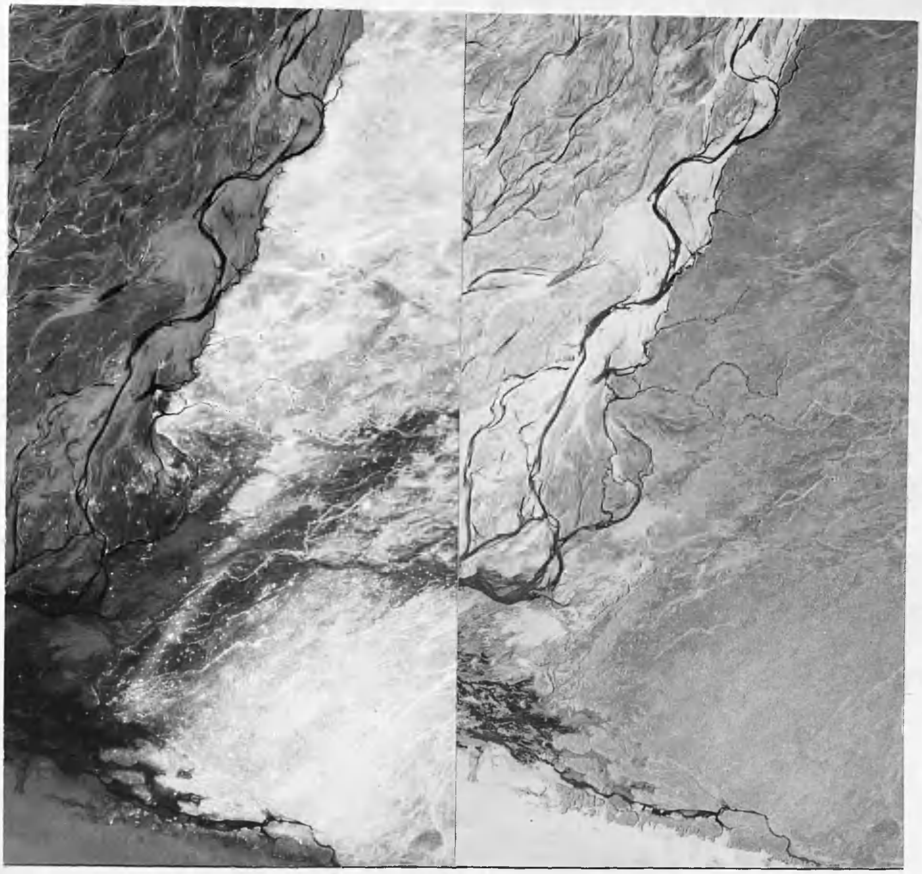

Fig. 5.59 1:16,000 scale comparative example of panchromatic (R) and infra-red (L) photography of the same grass covered area. Note the contrast between water, vegetation, and gravels on the infra-red.

the infra-red portion of the spectrum.

Conclusion

Based on the application of photo-interpretation to the study of the Breidamerkur area, the following conclusions have been reached.

First of all, most major glaciological and geomorphological features are identified and analysed on the basis of shape, pattern, texture, and relative position rather than tone. As a result, scale is only important insofar as it is sufficient to permit the recording of the features. As previously shown, this depends not only on the scale but also on the characteristics of the lens, film, exposure, etc. In fact, smaller scales result in larger area coverage and permit the spatial relationships between features to be more easily determined. Tone, however, is very important for the separation of different objects of similar shape, texture, or pattern, such as types of rock and/or vegetation and may also permit the delineation of soil types through a study of vegetation patterns and/or relative moisture content. These latter aspects are of particular importance to the ecologist. In addition, good tonal separation speeds the interpretation through ease of detection and analysis. From this study, therefore, it would appear that two types of photography, colour and false colour, at scales of 1:30,000 or smaller will permit the detection and delineation of all major features.

Secondly, sequential aerial photography is extremely useful for determining glacial retreat and landform development and every effort should be made to obtain all available coverage. Even if some of the coverage appears poor, significant information can often be derived when it is compared with better photography and/or correlated with ground information.

Thirdly, ground knowledge and information is important for conducting an area study from aerial photography. If the interpreter is unaware of what eskers, kames and kettles, or moraines look like, and does not realise the significance of certain patterns and shapes, a valid study cannot be conducted. Furthermore, aerial photography alone does not provide information on pebble size, small vegetative species, exact rock type, or soil moisture content, and a certain amount of field study will probably be required to obtain this information. However, the real value of aerial photography lies in the fact that for a person with previous experience in other glacial areas, it is possible to reduce the fieldwork to limited ground checks.

SUMMARY OF DEGLACIATION AND CHANGES IN THE BREIDAMERKUR AREA, 1880 TO 1965

In the late 1800's Breidamerkurjokull reached its maximum extension in historical times, forming a well-defined end moraine. Between 1894 and the early 1930's the ice margin retreated at a rate of generally less than 20 metres per year. As a result of this slow retreat, and possibly even minor advances, additional belts of end moraines were formed in the period 1905 to 1910 and also in the 1930's. Since the early 1930's, a definite warming trend has resulted in a rate of retreat exceeding 50 metres per year and, as a result, morainic deposits are limited to small ridges at yearly intervals or to a scattering of ground moraine. Where there has been sufficient vertical pressure by the ice on the saturated ground moraine, definite flutings parallel to the direction of ice movement have been formed.

The retreat and downwastage of the glacier has also produced a tremendous volume of meltwater which has, in turn, resulted in a series of meltwater channels being successively formed and abandoned. The larger channels, which are often more than 200 metres wide and 10 metres deep at their headward ends, were all formed during the advance and/or the initial retreat of the glacier between the late 1800's and early 1900's, and have carried meltwater directly to the ocean.

By the late 1930's the ice margin had retreated beyond the morainic belts and marginal lakes had begun to develop. At this time the present streams of Fjallsa and Breida were established and most major drainage was into the sea. However, by the early 1960's the level of Breidarlon had been significantly lowered and the entire drainage pattern had altered, with Fjallsa in the west and Jokulsa in the east remaining as the only outlets to the sea. Marginal drainage of Breidamerkurjokull was directly into Breidarlon for those areas to the west of Mavabyggdarond, and into Jokulsarlon for those areas to the east. In addition, a new marginal lake had formed between Mavabyggdarond and Esjufjallarond.

In 1965 and 1966 the above drainage pattern still existed. However, it was clearly evident that should the drainage divide in front of Mavabyggdarond be eliminated, either by fluvioglacial erosion or

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continued retreat of the ice margin, drainage from the entire western margin would be into Jokulsarlon.

As the terminus retreated, the heavily silt and gravel laden meltwater streams produced numerous alluvial fans at the mouths of streams and along the ice margin. Where the ice retreated into a depression or down the backslope of a ridge, areas of stagnant ice were buried by the gravel outwash and became detached from the glacier. Subsequent melting out of this buried ice has caused large areas of kame and kettle topography to be produced. The largest and most pronounced of these areas are adjacent to the east side of Breidarlon and in front of Mavabyggdarond. In 1966 ice was still present beneath the gravel deposits along the ice margin.

During the period 1940 to present, two parallel series of eskers developed in front of and under Mavabyggdarond. Photogrammetric measurements revealed that many of these eskers had been produced englacially, but that the largest and most pronounced had been deposited on solid ground. Ground observations and collateral information indicate that the materials forming the eskers are derived from the medial moraine and transported by supra-, en- and subglacial streams. Slow ice movement and rapid melting at the glacier snout prevent them from being destroyed during formation.

The vegetation of the Breidamerkur area is limited to sparse grass, moss, and reeds. A map of the vegetation types and distribution indicates that 20 years or longer are required for the mosses to become

/well

well established and that grass is only prominent in those areas which have been free of meltwater and glacier ice for at least 50 years.

CONCLUSION TO CHAPTER V

From the application of aerial photography to the study of the Breidamerkur area, it is evident that if aerial photographic, photogrammetric and photo-interpretation procedures are combined, a comprehensive study of a glacial area can be conducted in the office. This is particularly true if fieldwork is carried out to ensure a satisfactory ground control system and to investigate and obtain information about the glacier, landforms, and/or vegetation not readily derived from the aerial photography. The following chapter, then, concludes the thesis by outlining the requirements for obtaining and analysing aerial photography of a glacial area, and also discusses the uses and limitations of aerial photography.

CHAPTER VI

THE APPLICATION OF AERIAL PHOTOGRAPHY TO THE STUDY OF A GLACIAL AREA - SUMMARY AND CONCLUSION

The overall purpose of this thesis has been to determine: 1) a photographic system for obtaining improved aerial photography of a glacial area; and 2) the feasibility of using aerial photography to conduct a detailed study of a glacial area. For this end, it was necessary to consider all factors which would affect photographic quality and relate these to ground objects in the Breidamerkur area. By doing so, previously unpublished environmental and photographic data have been obtained. In addition, use has been made of photogrammetric and photo-interpretation techniques, and although these techniques are not new, it is hoped their application to the study of the Breidamerkur area has indicated the potential of aerial photography for conducting a study of a glacial area.

Based on the experience with the Breidamerkur photography, a systematic approach to obtaining and analysing aerial photography of a glacial area is summarised below. This is followed by a brief discussion of the uses and limitations of aerial photography in the fields of glaciology, geomorphology, and ecology.

A SYSTEMATIC APPROACH TO OBTAINING AND ANALYSING AERIAL PHOTOGRAPHY OF A GLACIAL AREA

If an overall study of a glacial area is to be conducted, the following must be considered:

1. Environmental characteristics.

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2. Photographic considerations.
3. Ground survey, photogrammetric, and cartographic requirements.
4. Photo-interpretation methods.

The important points in each of these categories are discussed below.

Environmental Characteristics

Environmental characteristics include such factors as illumination, the luminance and spectral reflectance of natural objects, and the effects of the atmosphere. These factors are important in determining exposures film-filter combinations, and flying heights, and are usually linked to the photographic process through tone reproduction diagrams. Therefore, data was established for the Breidamerkur area and as this region is believed to be representative of other glacial areas of similar latitudes, the derived data should be applicable to parts of Alaska, the Soviet Union, northern Canada, and southern Chile. The relevant information is discussed below:

Illuminance

For the Breidamerkur area, an illuminance of 5700 foot-candles was found to be representative of solar altitudes of 35 to 45 degrees during the months of June, July, and August.

Luminance and Spectral Reflectance

Based on light meter data, the mean luminance of the Breidamerkur area was 490 foot-lamberts; however, clear water with a luminance of 240 foot-lamberts and white ice at 4900 foot-lamberts are the two extremes.

Gravels, which are common in freshly deglaciated areas, averaged about 700 foot-lamberts.

The spectral reflectances of the natural objects could be grouped in three major categories: 1) vegetation; 2) gravels, soils, silted water, and basaltic rock; and 3) ice and clear water. The latter two categories were generally neutral in the visible spectrum with gravels, etc. increasing slightly from about 8 percent in the blue to 15 percent in the red, whereas ice and clear water decreased from maximums of 72 and 16 percent in the blue to 58 and 4 percent in the red. In the infra-red, gravels and basaltic rock maintained a reflectance of 10 to 15 percent; however, fluted moraine, medial moraine, silted water, and mud all decreased to about 8 percent because of their water content or the presence of ice or water. Similarly, clear ice decreased to a reflectance of about 45 percent in the infra-red and clear water, of course, absorbed all the near infra-red radiation.

Vegetation increased from approximately 1 to 2 percent reflectance in the blue and blue-green to 10 to 15 percent in the green. This was followed by a slight decrease in the red and then a sharp increase to between 25 and 45 percent reflectance in the near infra-red.

Several interesting points emerged from the luminance and spectral reflectance measurements, the most important being that the luminances of a given subject can vary more than ± 150 foot-lamberts and that spectral reflectance differences in the visible spectrum between vegetation, gravels, and clear water are slight. Furthermore, as

/spectral

spectral reflectance differences and luminance differences are the same for practical purposes, and as these differences are negligible or often overlap in the useful red-green portion of the spectrum, little is to be gained by the use of several film-filter combinations. However, significant differences do exist in the infra-red portion of the spectrum and it should be considered (in conjunction with the visible spectrum) for aerial photography of a glacial area. By doing so, it should be possible to distinguish major groups of features - clear water, ice, vegetation, and gravels - on the basis of tone.

Atmosphere

In the study of the Breidamerkur area, atmospheric luminance plus camera flare was found to range from approximately 300 foot-lamberts at 10,000 feet to 600 foot-lamberts at 20,000 feet. Above 20,000 feet the increase in atmospheric luminance is thought to be slight, perhaps reaching a maximum of 700 foot-lamberts in the vicinity of 30,000 feet. Attenuation by the atmosphere is most severe in the blue wavelengths, thus rendering this portion of the spectrum impractical for aerial photographic work.

The effects of the atmosphere and camera flare on the ground luminance ratio of 20:1 for ice and clear water are to compress it to less than 10:1 at altitudes above 10,000 feet and to approximately 5:1 at 20,000 feet and above. However, compression is most serious in the luminance range in which most glacial objects fall - 300 to 800 foot-lamberts. This represents a log luminance difference of 0.4 units on the ground, but only 0.22 units at 10,000 feet and 0.17 units at 20,000 feet. From this it can be seen that the compressive effects of the atmosphere have considerably reduced the contrasts between ground objects before they are imaged on the film, and that the most significant reduction has already occurred by the time an altitude of 10,000 feet has been reached.

The implications of the above are that it is very important to record small tonal differences as well as the overall luminance range. However, as has already been shown, there is very little difference in ground luminances or reflectances, further emphasising the fact that meaningful tonal separations are difficult to obtain and if they are recorded on a negative, they must be maintained in the positive.

Photographic Considerations

Photographic considerations include the selection of a camera, lens, film and filter, and the specification of exposure, processing conditions, flying height, and scale. In addition, flight lines, overlaps, and time of flight must be considered.

Camera and Lens

The choice of a camera and lens should be based on whether the study is to include photogrammetric work or to be limited to photo-interpretation, the type of film to be employed, and the desired flying height or scale. Based on the experience with the Breidamerkur photography and the study of the Breidamerkur area, it is believed that a "distortion-free" survey camera such as the Wild RC8, Zeiss RMK A15/23, or Fairchild KC series, employing a 6-inch lens cone corrected for

/chromatic

chromatic aberrations from 400 to 800 millimicrons and equipped with an intra-lens rotary shutter, should be considered. Such a camera will produce high definition panchromatic, colour, or infra-red photography to altitudes of 30,000 feet, while providing the accuracies required for photogrammetric work and the area coverage desired for both photogrammetric and photo-interpretation studies.

Film and Filter

From the analysis of the Breidamerkur photography, it is believed that two types of photography flown at the same scale can provide sufficient definition and tonal contrasts to detect and study all groups of natural objects in a glacial area. In this regard, a polyester base, reversal colour film such as Kodak MS SO-151 is recommended as the first choice, and either a false colour, infra-red, or fine grain panchromatic film as the second choice. Colour photography will prove particularly valuable if fieldwork is minimal or non-existent and if water, vegetation, ice, and landforms must all be delineated and studied in detail. In addition, reversal transparencies are obtained directly and can be used either in the plotting machine or for interpretation work. In this way, the considerable expense of producing positives from negatives is avoided and maximum definition is maintained.

If financial considerations allow, false colour film (Kodak Type 8443) is recommended to supplement the colour. False colour photography permits vegetated and moist areas to be delineated and, to some extent, different species of vegetation or soil to be identified. Used together, the colour and false colour photography should provide both maximum information content and ease of interpretability.

If false colour photography is considered unnecessary, then either an infra-red film such as Kodak Type 5424, or a fine-grained, polyester base panchromatic film such as Kodak SO-136 should be considered. In regard to the infra-red film, it should be possible to record all groups of features at density intervals of greater than 0.1 units, place the important glacial area features of gravels and vegetation in the zone of maximum definition, and satisfactorily record the entire luminance range by exposing and processing for moderate gammas. Disadvantages of the infra-red film, however, are a granularity factor approximately two times greater than that of either the colour or false colour films, and a reduced low-contrast resolution capability. As these are likely to result in a detection threshold approximately twice that of the finer grain films, lower flying heights or larger scales must be considered.

The panchromatic film, Kodak SO-136, possesses several desirable features for high altitude aerial photography. These include: 1) an extended red sensitivity, which permits lower filter factors and makes use of the superior atmospheric transmission characteristics of red light; 2) a high gamma, which causes the compressed luminance range of low reflectance objects in the visible spectrum to be extended for better tonal contrasts; 3) a dyed backing, which reduces internal reflections between the film base and the gelatin layer, thus improving definition; and 4) a low granularity combined with a good low-contrast resolution, which should result in detectability thresholds twice those of ordinary air survey films. The problem of using a panchromatic film, however, is that gravels and sparse grass or moss vegetation are unlikely to be distinguished on the basis of tone.

The recommended filters and their filter factors for each type of film are shown below:

1. Colour
   - a) haze - 420 millimicron (peach tint) at altitudes above 8,000 feet (2,440 metres).
   - b) anti-vignetting - preferably 2.2x at all altitudes. A 1.4x filter can be used; however, maximum apertures should be employed to reduce reflections from the diaphragm.
2. False colour
   - a) haze - 500 millimicron filter (1.5x) is mandatory to exclude blue light which would destroy the "camouflage detection" properties of the film.
   - b) anti-vignetting - is not absolutely necessary; however, a 1.4x filter would greatly reduce tonal distortions in the corners of the transparencies.
3. Infra-red
   - a) haze - 500 millimicron filter (1.5x) to exclude blue light.
4. Panchromatic
   - a) haze - 600 millimicron filter (3x) will provide maximum

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definition and contrast with minimum atmospheric compression.

Exposure and Processing Conditions

From the experiences with the Breidamerkur photography, it is believed that for ground speeds of 200 to 250 m.p.h. and altitudes above 8,000 feet, 1/400 second or higher shutter speeds are sufficient to preclude translational image motion from degrading detectability. If lower altitudes, increased aircraft speeds, or longer focal length cameras are contemplated, then the exposure must be proportionately increased. If a choice of apertures is possible, f 8 will provide maximum definition with panchromatic or infra-red photography, and f 6.3 or f 5.6 will reduce reflections from the diaphragms which may cause a purple spot in the centre of colour or false colour photographs.

The determination of exposure is possible through the use of exposure meters, manufacturers' exposure index computers, and by means of a formula into which known parameters are substituted. The first two methods are probably best for reversal films sensitive to the visible spectrum, including colour and reversal panchromatic films. The formula method is preferred for negative systems and where films are senstitive to both the visible and infra-red portions of the spectrum. Also, the use of the formula permits the entire photographic process to be linked by means of a tone reproduction diagram.

To ensure successful photography, regardless of the method used to determine the exposure and processing conditions, several test exposures should be made either at the beginning or end of the roll of film. These

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can then be cut from the film and processed first in order to establish the required development time. In this way small errors in exposure can also be overcome.

Flying Height and Scale

Flying height and scale should be determined on the basis of: 1) size of smallest object which must be detected; 2) tonal compression by the atmosphere; and 3) number of models (or area-coverage), photogrammetric accuracies, and photo-to-map enlargement ratios. Based on the analysis of the Breidamerkur photography, it is believed that the detection of low-contrast objects one to two feet in diameter is sufficient for the study of a glacial area and that tonal compression above 10,000 feet is minor compared with that occurring below this altitude. In regard to models or area coverage, it is desirable to have as few models as possible while still retaining the possibilities of spot heighting accuracies of one to two metres and the production of maps at scales of 1:10,000 to 1:20,000. From the photo-interpretation viewpoint, large area coverage on a single photograph (hence small scales and large formats) permits the handling of fewer photographs and, more significantly, provides a unique means of seeing and correlating the spatial relationships desired for glaciological, geomorphological, or ecological studies.

Based on the above considerations and the experience obtained with the Breidamerkur photography, it is thought that, provided the previously mentioned camera-film-filter conditions are met, photographic scales of 1:40,000 to 1:50,000 are suitable for the comprehensive study of a glacial area. These, of course, necessitate flying heights of 20,000 to 25,000 feet.

Flight Lines, Overlaps, and Time of Flight

It is recommended that flight lines be orientated to provide the best control distribution and the minimum number of models. Care should be taken, however, to avoid flight lines which will result in models with relief differences of greater than 15 to 20 percent of the flying height. Forward overlaps of 80 percent and sidelaps of 30 percent are recommended.

The time of year for the flight will be dictated by user requirements and weather; however, for glaciological or geomorphological purposes, the end of the ablation season is preferred. For ecological studies an earlier date may be necessary. The time of day is often difficult to specify; however, mid-morning or mid-afternoon, when shadows tend to emphasise microrelief, are preferred.

Ground Survey, Photogrammetric, and Cartographic Requirements

The purpose of a ground survey is to provide sufficient planimetric and height control points for scaling and levelling the photogrammetric models, whereas that of the photogrammetric and cartographic operations is to produce accurate and specialised maps.

Ground Survey

If possible, three well distributed height points should be established for each model. Enough planimetric control is required to

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permit aerial triangulation procedures to be employed.

The method chosen for establishing points is a matter of preference; however, intersection of glacier points from solid ground is essential as ice movement and ablation preclude accurate resections from the glacier surface. Land points can be established at any time during the project; however, it is essential to survey active glacier points on the day of the photography, or within plus or minus one day if the glacier is stagnant and ablation is low. Yellow flags for land points and red for ice points were found to be the most suitable colours.

The required accuracy of the survey system will be largely dependent on the model area, photogrammetric machine capabilities, and whether or not aerial triangulation is to be performed. For example, unless final planimetric coordinate values are desired from the photogrammetric work, little is to be gained by conducting ground surveys at accuracies greater than that necessary for graphical plotting (0.2 millimetre at plotting scale). Heights, however, should be established to accuracies compatible with the maximum heighting capabilities of the photogrammetric equipment to be used. For operational purposes this can be taken as 0.02 to 0.03 percent of the flying height.

In regard to pre-marked control, it is recommended that white be used on non-ice areas and black on white glacier surfaces. However, if colour film is to be utilised, orange-red should be considered for clean ice areas and yellow for black ice or medial moraines. A square is usually the most convenient shape for markers, and it is recommended

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that side length be at least 50 microns at image scale for land markers and 100 microns for ice markers. A scale of 1:40,000 requires markers 2 metres square for land areas and 4 metres for ice.

Photogrammetric and Cartographic Considerations

Two points are particularly important in mapping a glacial area for specialised studies. The first is that the planimetric outlines of features, accompanied by spot heights, are usually more important than a close contour interval. The second is that although close contour intervals are unnecessary, a high contouring accuracy is required if volume or height changes are to be analysed. In this regard, the relative errors between contours on two separate maps of the same area must be small in relation to both the contour interval and the changes which have occurred in the glacier during the period between maps.

A useful photogrammetric technique, where more than two sets of photography must be plotted, is to plot the best controlled set first and then use these plots to control the second set. This ensures that both maps are produced on the same system and results in accuracies compatible with graphical plotting - provided moderate model-to-plot enlargement ratios are used. As the final map is usually produced at a reduced scale by photographic reduction, a significant gain in relative accuracy is possible.

The design of the final maps is largely a matter for the specialist user to decide upon; however, for black-and-white compilation copies, plastic overlay patterns (e.g. Zip-a-Tone) are particularly useful for delineating and emphasising planimetric detail. A common grid should be placed on all maps so that they can be accurately superimposed for comparison studies.

Photographic Analysis Techniques

In the visual analysis of aerial photography, it is desirable to obtain the maximum definition and tonal contrasts. This can be accomplished by using positive film transparencies on a light table which has been masked to prevent stray light from reducing visual contrasts. Monocular magnifiers of 8x to 10x are useful for interpreting the majority of image detail; however, stereo-viewing is particularly beneficial with colour and false colour photography, and when shadows are insufficient to bring out microrelief patterns.

If quantitative measurements of tone are contemplated, sensitometric processing is essential and densitometers will be necessary. However, the information that can be derived from quantitative measurements of tone is limited to the separation of major groups of objects on a statistical basis. This separation is usually accomplished at a glance by an interpreter familiar with the subjects found in a glacial area.

USES AND LIMITATIONS OF AERIAL PHOTOGRAPHY IN THE STUDY OF A GLACIAL AREA

Based on the study of the various sets and types of Breidamerkur photography, it has been possible to assess the uses and limitations of aerial photography for the study of a glacial area. These are discussed below under the separate disciplines of glaciology, geomorphology, and ecology.

Glaciology

The usefulness of aerial photography to the glaciologist lies primarily with the photogrammetric production of accurate contour maps at periodic intervals. From these maps it is then possible to determine area, height, and volume changes in the glacier. However, if such measurements are to be of value, the maps must cover the entire ablation area, or preferably the complete glacier. For this reason, smaller scale photography may be more suitable due to the increased area coverage and reduction in models. Of course, photogrammetric contouring accuracies will also be reduced somewhat; however, this is unlikely to cause significant errors for large glaciers which have undergone considerable changes during the mapping interval.

Other uses of aerial photography in glaciology include the production of profiles and the heighting of marginal lakes by photogrammetric methods, and the delimitation of glacier boundaries by either photogrammetric or photo-interpretation techniques. Surface features such as crevasses, streams, and dirt bands can easily (and perhaps only) be studied on aerial photographs.

Aerial photography alone, however, will not permit a complete glaciological study to be conducted. For example, short term surface velocity and ablation measurements are best carried out by ground methods, and, of course, the internal structure of glaciers or the depths and temperatures of marginal lakes cannot be established from aerial photographic evidence.

Geomorphology

In glacial geomorphology both photogrammetric and photo-interpretation techniques are of value. Photogrammetry, for example, permits the accurate location, outlining, and heighting of landforms. As such, it provides a quantitative basis for deducing changes. Photo-interpretation, on the other hand, allows the pattern of landform development and deglaciation to be traced with ease and rapidity. Of course, sequential aerial photography and collateral information are important in both cases.

The limitations of aerial photographic techniques in geomorphology are such that the size and shape of small gravels or the internal constituents of morainic deposits cannot be determined directly. Because of these limitations, some fieldwork may be necessary.

Ecology

To the ecologist working in a glacial area, colour and/or false colour aerial photography should permit the accurate separation of vegetated and non-vegetated areas and perhaps the major species to be identified and delineated. As soil development can often be inferred from vegetation patterns, it may also be possible to produce a soils map. By relating both vegetation and soil development to glacier retreat, the rates and sequence of plant succession and soil development can be estimated.

The limitations imposed by aerial photographic techniques in ecological studies are obtaining adequate tonal separation and definition. For example, only major covering species of vegetation are likely to be identified directly unless exceedingly large scales are used in conjunction with false colour and/or colour film. Soil groups, although limited, have to be mapped on the basis of surface morphology as expressed by landforms, vegetation, and relative moisture content. However, a short period of fieldwork, undertaken in conjunction with aerial photographs, would overcome many identification or classification difficulties.

CONCLUSION

This study has demonstrated how, through the use of a systematic approach, it is possible to develop methods and techniques for obtaining and analysing aerial photography of a glacial area. To the author's knowledge an approach of this type has not previously been made, although with increasing emphasis on obtaining rapid and accurate data about the earth's resources, similar studies of various types of terrain can be expected in the near future. In fact, one such programme, the Earth Resources Survey Programme, is currently being undertaken by the National Aeronautics and Space Administration, using satellite photography in different zones of the spectrum (Badgley, Colvocoresses, and Centers, 1967).

The major problem in conducting comprehensive area studies from aerial photography, however, appears to be the lack of adequately trained personnel. One solution to this problem, perhaps, is to combine groups of specialists in a joint undertaking, which for a glacial area

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would involve glaciologists, geomorphologists, and ecologists with some knowledge of photogrammetric and photo-interpretation techniques. In addition, competent personnel familiar with aerial photographic, ground survey, and cartographic procedures should be available. If such a group can obtain suitable aerial photography, in combination with a period of two to three weeks of fieldwork, it should be possible to conduct a comprehensive study of a glacial area in the office.

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