

THE PHOTOGEOLOGICAL CHARACTERISTICS OF CARBONIFEROUS LIMESTONE

by

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ABSTRACT

This thesis describes an investigation carried out in some areas covered with Carboniferous Limestone in Britain.

Detailed photogeologic studies were made of the appearance of limestones shown as bare rocks as well as in those areas covered by superficial deposits. The surface features of limestones were thoroughly examined on the air photographs and checked with field evidences and geological literature.

Some relations between the photographic appearance and the physical characteristics of the limestones were found, and consequently a better understanding could be obtained in a limestone terrain.

Differing in grey tones was one of the identification clues in differentiating the limestones in different colours or constituent. The photographs could give a clear impression of the limestone terrain by a characteristic subdued topography occupying relatively higher relief with extensive development of fracturing, but some limestone units exhibited different relief indications. Some recognition features were found for various lithologies within the limestones adequately reflected on the photographs. The boundaries with the adjacent rocks could be differentiated being linear. Although some bare rock surfaces exhibited differing fracture patterns, the fracture trace analysis revealed that the Carboniferous Limestone has

a fracture pattern not similar to other rocks nearby and one to another flank of a structure. Apart from the lack of large scale surface drainage in the limestones, drainage patterns and the valley shapes were also indicative of limestone terrain and variations in lithologies within the limestones could be differentiated. The superficial cover, especially the transported soil which carries no identification related to the limestones, usually reduced amount of information that could be obtained from the photographs, but in the areas covered by residual soil the observations of limestones were quite satisfactory in the soil derived from the Carboniferous Limestone.

It is believed that recent techniques in remote sensing will open new horizons in detection and observation of ground conditions of limestones.

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1. INTRODUCTION

The Carboniferous Limestone occupies considerable areas throughout the country. Almost 2 : 3 of all limestone outcrops are of Carboniferous age. The areas chosen for this investigation have shown that a lot of information can be obtained through the study of their air photographs. Also, by using air photographs of the Carboniferous Limestone areas, geologists can gain better understanding of the physical characteristics of Carboniferous Limestone terrains.

The aim of this study is to investigate the surface features of the Carboniferous Limestone depicted on the air photographs and to find out whether there is any relation in the photographic appearance of these features to the physical characteristics of the rocks and to obtain a closer idea of their significance.

It seems that other workers have made studies for a particular project in a limestone region, but no publication is known which deals particularly with a Carboniferous Limestone area.

This thesis reports an attempt to learn more about photogeological characteristics of Carboniferous Limestone in Britain and can only be regarded as a preliminary study.

2. REVIEW OF RELEVANT LITERATURE:

2.1. GEOLOGY OF CARBONIFEROUS LIMESTONE:

The Carboniferous Limestone depicts some of the attractive and picturesque scenery in Britain. The bleak moorlands and immense dales of Yorkshire and Derbyshire "attracted Romans who had lead mines" (SMITH, et al., 1967) in the early years.

The Carboniferous system is traditionally divided into the Lower and Upper Carboniferous in Britain and western Europe. The two systems in North America, the Mississippian and the Pennsylvanian, correspond broadly to these divisions.

At present, "there is no formal British Code of Stratigraphic Nomenclature" (RAYNER, 1967), though the American Code is often taken as a guide in several works. It has been preferred to retain traditional or current British terms, even though a few may not be strictly correct. For instance, the terms 'Yoredale series' and 'Ingletonian series' are, in fact, formations, being rock-stratigraphic (lithostratigraphic) units. However, the term 'Series' is a time-stratigraphic (chronostratigraphic) unit, but it has been widely recognized as a rock, up to date.

The main divisions employed in north-western Europe are given in Table I.

TABLE I

System	Series	Stages	Lithological groups
Carboniferous	Upper Carboniferous	Stephanian Westphalian Namurian	Coal Measures Millstone Grit
	Lower Carboniferous	Visean (Upper Avonian) Dinantian (Avonian*) Tournaisian (Lower Avonian)	Carboniferous Lst.
Devonian			Old Red Sandstone

(*) The term 'Avonian' is an alternative name of Dinantian in Britain.

The lower part of Carboniferous System is made up almost entirely of limestone which is the subject of the present investigation.

It was formerly called the "Mountain Limestone". It forms a region of bold relief well dissected by steep-sided valleys. In some places, it is covered by a thick glacial drift deposits, so that, it appears in a number of separate outcrops.

The Carboniferous Limestone makes up the bulk of the Pennine uplands and the Mendip Hills. Geologically it is best known for the splendid sections exposed in the Avon and Cheddar gorges in the Bristol district. Outcrops also occur in the Gower peninsula, in parts of Pembrokeshire, and along the northern shores of Anglesey and Northern England.

The Carboniferous Limestone trends generally north to south from Northumberland to Derbyshire, following the main structural features of the northern counties. In the South Wales where the folding is in an east to west direction, there are outcrops of Carboniferous Limestone encircling the South Wales Coalfields.

"The base of the Carboniferous is readilly defined where marine Carboniferous sediments conformably succeed Devonian of Old Red Sandstone facies. This is so in the Ardennes and many areas of the Continent, as in the South-West (Bristol-Somerset area), where marine Carboniferous beds follow marine Devonian, transitional marine beds occur and the base of the Carboniferous can only be defined faunally, but in many outcrops the base of the system is not exposed. Elsewhere the Lower Carboniferous rests unconformably upon older rocks.

The history of the Carboniferous is the history of

the spread of marine conditions, of the gradual incursion of the former Old Red Sandstone Continent by chiefly shallow epicontinental seas while to the south strata were deposited in the geosynclinal foredeep.

Most of Britain formed part of the area, to the north of the geosyncline, covered by generally shallow seas. North of line through the Bristol Channel to the Ardennes the Lower Carboniferous rocks are largely of neritic facies. However, downwraping of crust must have been far from uniform within this region, for the gradual transgression of the Carboniferous seas was a complex story" (BENNISON and WRIGHT, 1969). Consequently, the Carboniferous strata show a great variety of succession and facies from one area to another.

In the South-West, the succession of Carboniferous Limestone commences with limy shales, which were laid down as muds, with occasional sandstone and conglomerate beds. These 'Limestone Shales' are widespread in the region, being best developed in the Mendips and thinning northwards. The shales are succeded by limestones which are dominantly bioclastic, some massive and calcitic, but others oolitic or dolomitic representing differences in depositional environment. No true reef limestones occur in this region. The transition from the Limestone Shales

to Main Limestone is relatively rapid. Deeper water conditions give rise to dark limestones while dolomites are common in west Wales.

During the Lower Carboniferous times, there were two main areas of deposition separated by a land ridge (St. George's Land).

Deposition did not take place generally in the Midlands until later in the Carboniferous Period. The transgressive Carboniferous sea did not cover the area north of St. George's Land until late in Lower Carboniferous times. The Carboniferous Limestone on the north side of St. George's Land rests with conspicuous unconformity on older rocks and thins southwards. In Anglesey, particularly at Llangollen basal littoral deposits are present, as the transgressive Carboniferous sea, at first covered the lowland districts of peneplain carved in Old Red Sandstone times. These deposits include impure calcite-mudstone, calcareous sandstones and conglomerates. In the Welsh Borders and north Wales, the limestones which follow the basement beds, are sandy at some horizons. The higher sandy limestones pass northwards into black limestones and reef limestones occur in the north.

The main outcrops of Carboniferous Limestone in the south Pennines occur in the Derbyshire dome, being mainly a massive limestone and sometimes cherty. Reef

limestones make conspicuous hills at the south of the Craven fault and extend as far south as Dovedale. In the north Pennines, the succession commences with deposition of basal conglomeratic and arenaceous beds. Following the basal series, the lowest limestone unit of the succession occurs. This is the 'Great Scar Limestone' which is laterally uniform, and mainly a massive limestone with occasional thin shale bands. Following the Great Scar Limestone, cyclic sedimentation became established giving rise to the Yoredale series which consists of interlocation of limestone, sandstone and shales. The different lithological beds represent changing conditions from clear shallow seas, in which limestones were deposited, silting up with spread terrigenous material. Cyclic conditions of deposition persisted into the Upper Carboniferous.

The accepted classification of Carboniferous Limestone is based on the coral-brachiopod zones[†] which were defined in the Avon Gorge in the Bristol district in the early 1900 s. It is still applied in some areas but with some changes.

([†]) The term 'Zone', as used here, is a biostratigraphical unit.

In this classification, the name of the most distinctive genus is applied to particular zone and is represented by an index letter, or combination of letters. The nomenclature of the individual faunal zones in the succession is rather complicated than the usage of Continental names for these divisions.

The general classification of Carboniferous Limestone is given in Table II.

TABLE II

Stages	Zones	
Upper Avonian (Visean)	Dibunophyllum	or D zone
	Seminula	" S_2 "
	Upper Caninia	" C_2S_1 "
Lower Avonian (Tournaisian)	Lower Caninia	" C_1 "
	Zaphrentis	" Z "
	Cleistopora	" K "

Since these subdivisions are based on entirely faunal assemblage they could not be adopted for photogeologic studies. (see section 5.3)

2.2 PREVIOUS WORK ON THE PHOTOGEOLOGY OF LIMESTONES:

In general, no detailed study has been done on this topic. Some individual works dealing with a particular

aspect of the subject have been published in papers or periodicals. These studies were carried out in limestone terrain, but not in the British Isles.

The interest in limestones starts with RICH (1928), who described the joints on limestones "in the course of an aeroplane trip from Oklahoma to Kansas" and pointed out the direction of research in this field.

The first methodic work and some definitions of fracture trace analysis were described by BLANCHET (1957). This method was applied to a Devonian biohermal reef mass in Alberta, Canada, "to illustrate the effectiveness of fracture analysis for developing emirical data".

TRAINER and ELLISON (1963) studied joints and fracture traces in Virginia and found that the difference in orientation is more conspicuous in carbonate rocks than in shales, and the traces are much more numerous in carbonate rocks.

The following year, LATTMAN and PARIZEK (1964) confirmed their studies on fracture traces by means of some experiments in limestones in Pennsylvania. They studied the relationship between fracture traces and occurrence of ground water in carbonate rocks. Several wells were drilled on or near fracture traces. Higher yields were obtained from wells drilled along fracture

traces and completed in limestones. They also reached the conclusion that "the data are useful as prospecting guide in locating zones of increased weathering, solutioning and permeability".

A detailed study was made to compare the mapped rock fractures and air photo features by BOYER and MCQUEEN (1964) who carried out the investigation in the carbonate rocks which included about half of the Paleozoic area mapped in Texas. They found that the results indicate "a close parallelism of fractures measured on the ground and air photo linear features and suggest that the air photo linear features are largely a reflection of fractures in the rocks emphasized by vegetation and topography".

ERB (1967) carried out a regional geomorphic study on air photographs of a limestone region in a humid tropical environment (Jamaica) and discussed the application of the technique of photo interpretation to geomorphological investigations.

RENNER (1969) discussed the relationship of lineaments to joints and other fractures by comparison of lineament pattern in a limestone terrain in Spain. The results showed that lineaments on the arenaceous limestones "were mainly linear drainage channels and vegetation alignments" whilst on the limestones "there were some straight scarp edges. Minor drainage alignments were

also noticed but many of the lineaments were due to vegetation aligned along fractures".

In addition to those works, a number of interpretations, explanations and illustrations of limestones seen on the air photographs may be found in various text books, manuals and commercial publications of aerial surveys.

2.3 PHOTOGEOLOGICAL WORK ON THE CARBONIFEROUS LIMESTONE:

So far, no specific investigation carried out in this field has appeard except for the doctorate thesis of NORMAN (1968).

Although the thesis "describes an investigation of the geological causes and influences affecting the existance of linear features seen on air photographs of areas where the bedrock is obscured by superficial deposits", some parts of the investigation were made in the area of Carboniferous Limestone.

The following year, NORMAN and WALTHAM (1969) described "the air photograph appearance of karst features with emphasis on those related to underground openings in Northern England". This is the first and only published paper dealing with the Carboniferous Limestone.

In the same year, photographs of areas covered by

boulder clay were attached to the paper of NORMAN (1969). In the explanations of these photographs, the interpretation of some buried linear features of Carboniferous Limestones were described.

The review of literature showed that previous research was not adequate and still there is an obvious gap in research in this field.

The Carboniferous Limestone has been investigated in detail in various other fields of geology for many years. The present work may be regarded as a preliminary study of its type.

3. OUTLINE OF THE INVESTIGATION:

A large part of the British Isles are covered by extensive glacial deposits and this superficial cover tends to mask the geology underneath. To avoid misinterpretation, the most representative areas not covered by the glacial drift were selected. From these suitable localities for photo interpretation, the areas where Carboniferous Limestone is fully developed were chosen. Cliff edges were taken as the ideal places to examine the vertical profile of the bedrock, as well as the cover.

The Carboniferous Limestone exposures along the coasts of Gower, Pembrokeshire and Anglesey were chosen in addition to the outcrops in the Mendip Hills (Bristol district), Pennines (Derbyshire), and Ingleborough (Yorkshire). The areas investigated are shown in Fig. 1.

In selecting the localities of Carboniferous Limestone, emphasis was given to the representation of rocks of different age and lithologies. For instance; in Anglesey the Carboniferous Limestone is in close contact with the Mona complex of pre-Cambrian metamorphics and plutonic intrusions, while in Ingleborough it overlies slates and grits of Silurian age. In the Mendip Hills it is resting on the Old Red Sandstone and is overlain by Keuper marl, but generally the Carboniferous Limestone

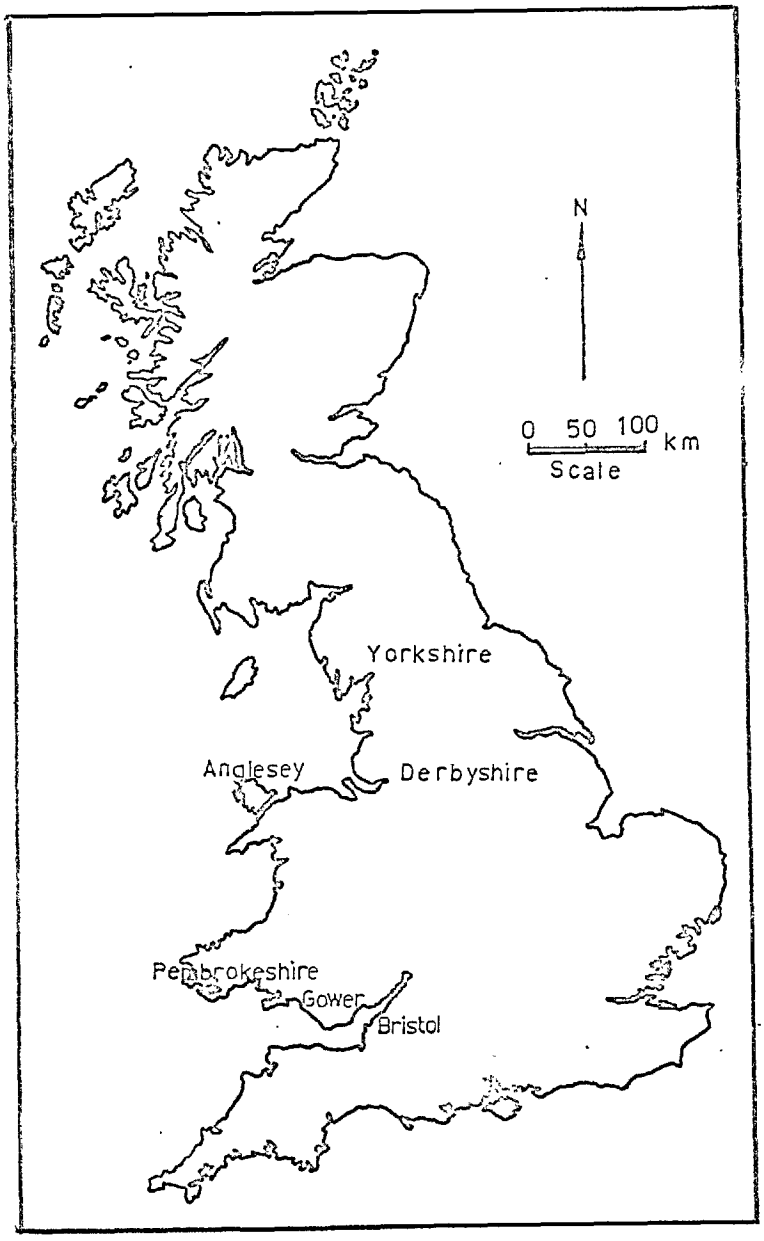


Fig. 1 .- The areas of investigated.

is usually overlain by the Millstone Grit (Upper Carboniferous).

By studying areas with various rock types, a better understanding of photogeologic characteristics of Carboniferous Limestone could be achieved by comparing and correlating the two adjacent rocks. Eventually, various characteristics could be extracted from the areas concerned.

The method of investigation was divided into three stages:-

(i) The photographs were examined under a HILGER and WATTS SB 180 mirror stereoscope and the interpretations on the prints were annotated when using stereovision.

(ii) The annotated information was correlated with the field work, or geological maps, or with both.

(iii) The data collected from the field work, air photographs and geological literature were used for analysis.

4. METHODS AND PROCEDURES

4.1. SOURCES OF THE RESEARCH DATA:

4.1.1. GEOLOGICAL LITERATURE:

The main source of information was the publications of the Geological Survey of Great Britain. These publications were mainly:-

(i) the regional geology series,

(ii) memoirs, and

(iii) maps (1 inch to 1 mile, $2\frac{1}{2}$ inches to 1 mile, and 6 inches to 1 mile).

The publications mentioned above were found useful to supply general background knowledge during the investigation and assisted in obtaining understanding of the geology of the British Isles, as it was necessary to be familiar with the terrain studied.

So far, there is no combined publication dealing mainly with the Carboniferous Limestone. There are, however, a number of studies which have appeared in technical papers in addition to the text books, in which some chapters have dealt with the Carboniferous Limestone.

The following information was used in the investigation; the stratigraphy and the structure of Carbo-

niferous Limestone, its distribution throughout the country, brief description of various lithologies within the limestones, volcanic activity and mineralization (lead mines) in the Carboniferous Limestone.

For the local studies of the Carboniferous Limestone terrain, the Geological Survey regional geology series on the areas concerned were consulted. (These are listed in section 8).

4.1.2 FIELD INVESTIGATIONS:

The field work was concentrated on studying the changes of the relief, lithology, fractures, drainage, superficial deposits, vegetation cover and the contacts between adjacent rocks.

Interpreted photographs were checked in the field wherever the features were accessible and not concealed or distorted by human activity. The checking was more successful on the seashores and lonely moors. The seashores, especially the cliff edges were the most suitable localities where there was an opportunity to examine the vertical profile of the superficial cover and bedrock,

while the lonely moorlands were the best areas to investigate ground features free from undue human interference.

The field observations were re-studied in the laboratory and were cross-checked with the geological maps, so as to revise the interpretation.

4.1.3 AIR PHOTOGRAPHS

The data collected from air photographs were in two groups:-

(i) Information about the photography,

(ii) Information interpreted from photographs.

The types of information about the photography were (1) contract or sortie number, (2) exposure number and (3) the date of the photography. Other information such as: flying height, focal length of camera lens and the time of the day at which photograph was taken, were not recorded on the photographs used in this investigation.

The second group of data collected concerned mainly the qualitative characteristics of the features visible on the air photographs. This involved a through inspection and study of the photographs.

The photographs used in the investigation are listed in Table III.

TABLE III. The air photographs used in the investigation.

Area	Sortie	Scale	Date	No. of photographs	Total for each area
Anglesey	58/RAF/2196	10,000	14. 6.1957	32	32
Bristol	CPE/UK/1869	"	4.12.1946	10	
"	541/RAF/540	"	1. 6.1950	16	
"	58/RAF/1371	"	5. 3.1954	28	
"	543/RAF/2332	"	27. 7.1963	66	
"	543/RAF/2334	25,000	29. 7.1963	12	
"	58/RAF/6155	10,000	5. 2.1964	18	150
Castleton	58/RAF/1094	"	21. 4.1953	48	48
Derbyshire	CPE/UK/2598	"	16. 4.1948	73	
"	540/RAF/34	27,600	18. 5.1948	38	
"	540/RAF/568	10,000	28. 7.1951	96	
"	82/RAF/1243	"	14. 7.1955	63	
"	58/RAF/2315	"	22.11.1957	82	
"	58/RAF/3591	"	3. 6.1960	46	
"	58/RAF/3617	"	21. 6.1960	44	442
Gower	106G/UK/1625	9,600	7. 7.1964	20	
"	58/RAF/4416	10,000	18. 5.1961	23	43
Ingleborough	541/RAF/525	"	14. 5.1950	11	
"	82/RAF/1153	"	18. 4.1955	57	68
Pembrokeshire	106G/UK/1625	"	7. 7.1946	28	
"	58/RAF/9412	63.300	7. 3.1969	7	35
				Total	818

4.2. PHOTOGRAPHIC INFLUENCES AFFECTING THE DATA COLLECTED:

4.2.1. THE INFLUENCE OF THE SCALE OF THE PHOTOGRAPHS:

The scale of air photographs is an important factor to obtain the data required from them. There are several limitations on the choice of the ideal scale for interpretation.

The results of tests on the accuracy of interpreting the outline of rock outcrops showed that "the scale of 1:10,000 is recommended if small outcrops are of interest in the map, however, interpretation on the scale of 1:20,000 or 1:30,000 is sufficient for most geological mapping of bedrock outcrops" (WASTENSON, 1966).

According to another test of the influence of scale on the detectability of soil boundaries and buried rock contacts and faults showed that "the maximum amount of general geological detail is likely to be obtained from a scale in the range 1:10,000 to 1:20,000" (NORMAN, 1968).

It is, in fact, difficult to determine an ideal scale of photography as it depends on the purpose of the study and precision required. Photographs smaller than 1:30,000 have generally been considered inadequate for successful research on this field, while they are sufficient for most routine photo-geological mapping of bedrock outcrops.

Most of the air photographs used in the present work were at a scale of 1:10,000 (Tab. III) which is considered fairly large for most general photography. A few areas were studied using photographs having a medium scale of 1:25,000 - 1:27,600 and only one locality a small scale (1:63,300) set of photographs were used. It would be far from desirable to generalize the findings from this limited range, it is preferable to point out the appearance of ground features on air photographs of various scales instead.

It is clear that, the larger the scale of photographs, the greater the potential gain of geological data. This is more important if the rocks are not well displayed, e.g. in the areas of covered with superficial deposits.

Some rock boundaries and fracture traces were not visible using medium scale photographs, and when small photographs were used the clarity of features was also reduced. For instance, most of the ground features can be interpreated fairly accurately on the photographs at a scale of 1:10,000 in the Pembrokeshire coast, but cannot be differentiated well enough on the photographs at a scale of 1:63,300 (Fig. 2).

In areas where the Carboniferous Limestone has some basaltic lava flows, the changes in lithology may not be appreciated on the photographs at a scale of 1:27,600, but they may be observed clearly and interpreted quite

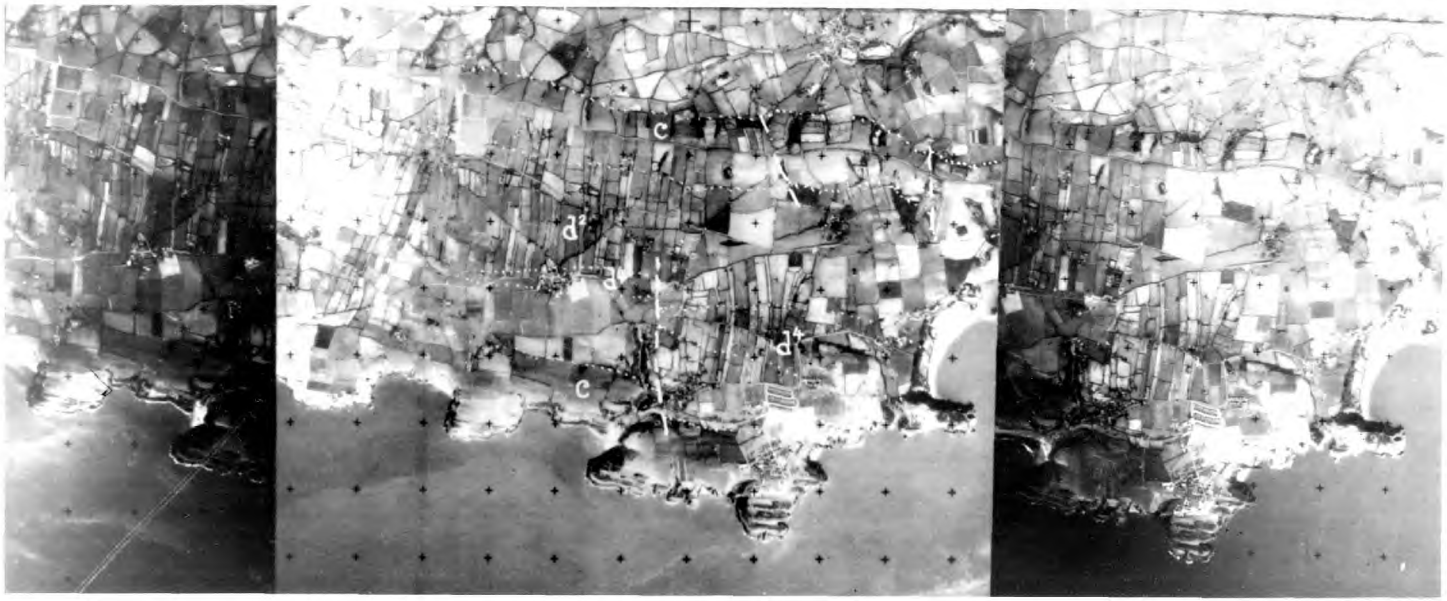


Fig. 2-A . Small scale (1:63,000) photograph shows up major features. The lower and higher ground areas can be easily outlined (white dotted lines) due to the vertical exaggeration which is more than on the small scale photograph. These boundaries correspond with the lithologic contacts. The Old Red Sandstone (c) forms ridges, the Millstone Grit (d^4) occupies higher ground while the Carboniferous Limestone is shown in between. The area is structurally controlled, the major structures lie in nearly E - W . (Manorbier-Lydstep, Pembrokeshire).



Fig. 2-B . Large scale (1:10,000) photograph of the same area (fig.B) can reveal more information. The Carboniferous Limestone outcrops with steeply dipping beds (along the southern coasts) and the superficial deposits (dark grey) can be distinguished together with some faults (on the north coast). The white patches are clouds. (Lydstep Bay, Pembrokeshire).

accurately at a scale of 1:10,000 on the photographs of Cave Dale, Castleton (Fig. 7). However, there was enough suitable information on those photographs for the study of the drainage network and fracture pattern and to use the findings for later correlations. (see Sec. 5.6).

On the other hand, the scale might be too large to reflect the variations in topography underneath, if the area is considerably covered by soil and has not other reliable surface indicator. This is seen on the air photographs having a scale of 1:10,000 in the Mendips. It is believed that the Old Red Sandstone exposures could be clearly appreciated on smaller scale photographs (see sec. 5.4.1. and Fig. 15).

4.2.2. THE INFLUENCE OF THE QUALITY OF PHOTOGRAPHY:

The quality of a photograph is one of the most important aspects of photogeology. It is a description of the clarity of the photographs. Any classification of quality is far from definite because of its highly subjective nature.

It is very desirable to use excellent quality photographs which are clear, well-printed, and free from tilt

and distortion. Although techniques in photography have been recently developed to eliminate missinterpretation due to tilt and distortion, observed mainly on the edges of the prints, vertical scale exaggeration does exist in most circumstances. Much information and interpretation may be missed when poor quality photographs including those having clouds or haze and no tonal contrasts are used.

Air photographs may be dodged automatically to subdue tonal contrasts and produce uniform tones, but photographs used in this investigation were not dodged by electronic printers, so the dark corners of individual prints (vignetting) remained unlightened.

4.2.3. THE INFLUENCE OF TIME AND SEASON OF THE PHOTOGRAPHY:

One of the factors influencing the photographic appearance of objects is the time of day when the photographs were taken. The time factor is closely related to the sun's illumination of the ground, and can affect the appearance of geological data on air photographs.

The horizontal component of the sun's direction of lighting influences the direction in which shadows are thrown, and consequently some features will have more shadow than other similar features oriented differently.

For example, joints aligned in the direction of sun's rays will contain less shadow than those at right angles to it.

The elevation of sun influences the length of the shadow. Since some parts of the ground features may be concealed behind the shadows, it is not desirable to have long shadows especially in an area with bold relief. When the sun is very low, "the enhancement by shadow effect of topography, especially the microrelief, becomes more apparent" (HACKMAN, 1967). This is useful when working on subdued morphology as seen in Carboniferous Limestone terrain. Some photographs used in the study of the Mendip Hills were locally obscure because of the long shadows of ground features. It should be noted that they were photographed in February when the sun has a relatively low inclination.

Most topography is usually taken shortly before or after mid-day to acquire a short shadow effect.

The individual prints used in this investigation have no record on them of the time at which they were taken; however, most of the photographs were quite suitable for the purpose of the present work.

It is sometimes difficult to specify a particular season for topography because of the geographical location of the area. For example a good photograph can be obtained in South Wales in April, whilst in the Pennine uplands, the surviving snow patches would tend to mask the ground features. However, in Britain the best results can be expected on photographs taken in autumn and spring when the maximum changes in vegetation occur. (NORMAN, 1968).

4.2.4 THE INFLUENCE OF THE PURPOSE OF PHOTOGRAPHY:

For a certain project, it is always desirable to use photographs taken especially for that project. The air photographs used in this investigation were taken previously for other purposes (either military or for specific civilian purposes). Most of the photographs were taken by the Royal Air Force and some of them were war-time coverage. However, some prints of a sortie recently taken, were withheld by ministry officials, because they are not available for public issue in their entirety.

4.3. THE INFLUENCE OF HUMAN ACTIVITY:

Human activity tends to mask the detection of geological features and to interfere unduly with the evidence required. The photographs used in this study included a

number of built-up areas; the areas with a large number of buildings and construction activities were excluded from this investigation.

The work at some parts of the Carboniferous Limestone outcrops involved investigation in the built-up areas of the towns, e.g. Buxton and Matlock of Derbyshire. Several fracture traces, drainage courses and lithologic boundaries could not be detected precisely, but an attempt was made to trace them from the changes in pattern reflected by the buildings and gardens.

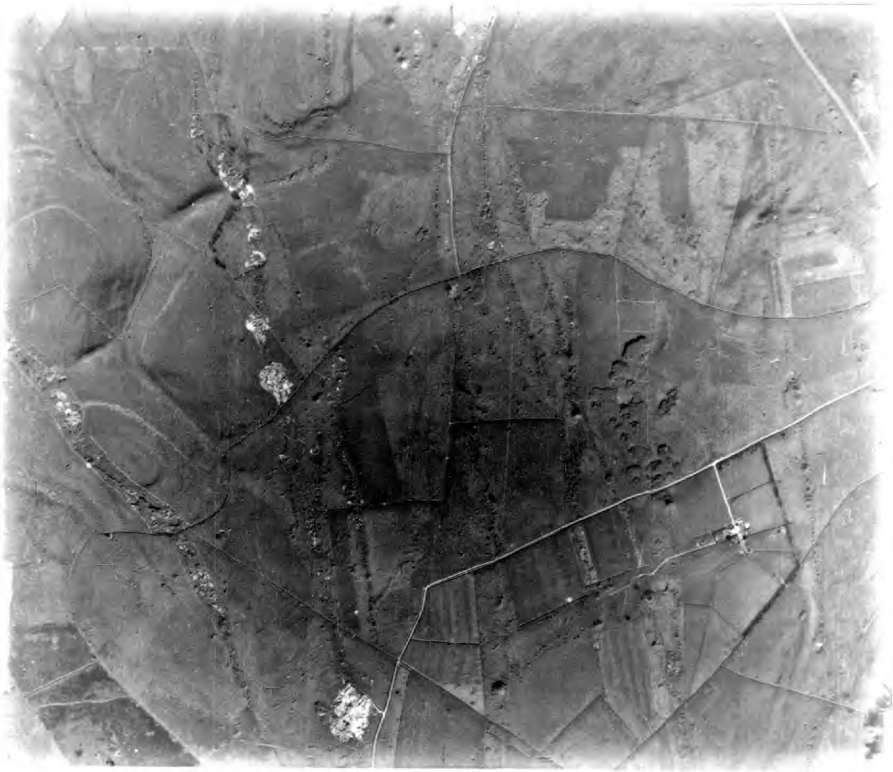
Man's use of land modifies the appearance of natural ground features and sometimes plays a leading role in indicating the rock and soil boundaries, as seen in Fig.3.

Mining is also an influencing factor as well as farming and construction. A great many mine excavations in Yorkshire, Derbyshire and the Mendip Hills locally changed the relief of the Carboniferous Limestone. The sites of former lead workings were easily detected as a number of lines of pitted ground in various directions and lengths. Although most of the spoil heaps are grassed over and the land used as pasture, there are many hundreds of old shafts. This is largely because of one provision of the ancient mining laws forbade the filling-in workings (SMITH, et al., 1967).(Fig.4).

Some of the old mine shafts and openings may be misinterpreted as sinkholes which are common over most of the Carboniferous Limestone terrain.

Fig. 3 . In this stereopair the dotted lines are both faults coinciding with soil boundaries and show the limit of lighter toned, tongue of boulder clay between two areas of thin residual soil on Carboniferous Limestone. The boulder clay boundary has also been selected by the farmer as the limit of regular cultivation whilst the limestone soil is only used for rough grazing. (Norman,1968).

Fig. 4 . The occurrence of very light-toned areas in the photograph is due to lead veins which sometimes affect the growth of vegetation or may be due to the opening in the rock surfaces by intensive mine excavations. (Castleton, Derbyshire).




2018
2020

4.4. OBSERVATIONAL FAILINGS AFFECTING THE DATA COLLECTED:

The Manual of Photographic Interpretation (1960) defines 'photointerpretation' as "the act of examining photographic images for the purpose of identifying objects and judging their significance". Although some investigation have been carried on automation in photointerpretation "the results have not been very promising to the researchers" (DI PENTIMA, 1970). It might be possible to automate the examination of photographs, but the judging of the significance of objects still depends on the viewpoint of the human photointerpreters.

Consequently, personal characteristics are an essential factor in interpretation, and observational failings may occur.

Some misinterpretation did happen while working the fracture traces on the photographs. After some hours of study in a single session, it was found that a number of linear features annotated on photographs were, in fact, imaginative lines. This is due to the state of the interpreter who was tired at the time. Eventually, objectivity of the observer has been lost. Because it is another factor in addition to his ability, past experience, etc., influencing a better interpretation.

Besides the influence of human activity mentioned in preceding section, the observational failings appear to affect the collection of data due to misjudgment.

In the early part of an interpretation study there is often misinterpretation, but this reduces as the study progresses. The investigation reported in this thesis is unlikely to be an exception to this rule.

5. ANALYSIS OF INVESTIGATION

5.1 TONAL CHARACTERISTICS:

5.1.1. GENERAL CONSIDERATION:

Under favourable circumstances, it is possible to ascertain near-surface ground conditions by photographic tone characteristics, alone. However, accuracy is often limited by such factors; as quality of photographs, climatic influence and obscuring vegetation.

Tone is recorded on film as shades of grey from black to white, and is a value of reflection from ground surface. The interpretation depends on an understanding of the various tones of grey colouring on the photographs. It is relative tonal changes that are usually concerned, rather than absolute tones.

The tonal relations of a geological unit hold only locally, and even on successive photographs the same object may appear in variable tones. Therefore, it is not possible to give rules for the identification of ground features by tone alone, but as far as conventional black and white (panchromatic) photographs are concerned in present investigation, the photographic tone may act as a valuable contribution in recognition and interpretation of Carboniferous Limestone on air photographs.

5.1.2 TONAL VARIATIONS IN CARBONIFEROUS LIMESTONE:

The overall photographic tone of Carboniferous Limestone is light grey, similar to any limestone terrain in humid areas. Light tones often indicate well drained materials. This is true for the Carboniferous Limestone in which the surface water infilitrates numerous fissures and lack of drainage gives rise to dry surfaces. Apart from the seasonal variations, the practical interpretation of grey tones on photographs is closely related with the soil-moisture content of the terrain.

The light tone of the Carboniferous Limestone is broken by occurrences of dark circular spots which mark the location of sinkholes. Sinkholes are usually darker than the surrounding tones, because of the presence of soil accumulated in them and its higher moisture content. The overall photographic tone, therefore, becomes mottled in the areas where there are abundant sinkholes.

On the other hand, the darker moisture tones are generally coincident with the lowest areas while the lighter tones tend to occur upon hills and ridges, as the water runs downword and collects in the lower areas.

The shaly limestones reveal darker tones as seen in the Limestone Shales area of Carboniferous Limestone, which occupy lower areas. While the reef limestones

show irregular light and dark grey tones due to their hummocky surfaces in which depressions hold thicker soil and hence more moisture. The cherty limestones show up mottled tones in Derbyshire and the Mendips.

In the photographs of Anglesey, where the Carboniferous Limestone is divided into three types, i.e. white, grey and black, the white - grey limestones appear in light grey tone, whilst the black limestones reveal white photographic tones.

Except for the narrow strips along the coasts of South Wales and in the Ingleborough district, the rest of the study areas are almost covered by superficial deposits which change the light tone to a different range of grey tones, either of uniform and smooth, or mottled tones(see sec. 5.7).

The investigation showed that the characteristic light grey photographic tones of the Carboniferous Limestone exposures are usual in the areas not covered by any sort of superficial cover which tends to mask the ground features as well as the current photographic tone.

5.2 THE RELIEF OF CARBONIFEROUS LIMESTONE AREAS

In a photogeologic study, the overall appearance of a Carboniferous Limestone exposure attracts the photo-

geologist who usually pays attention to the relief at first glance.

The general appearance of the Carboniferous Limestone on air photographs may be said to be representative of the scenery developed on similar limestones in other parts of the world. In the case of Britain, the extensive development of limestone features occurred when the rocks were part of a humid region.

Since the landforms in limestone areas result from regional variations of climate and vegetation, in addition to the physical properties of the limestones themselves, the degree of denudation of Carboniferous Limestone is quite extensive and produces an area of subdued topography rather than a bold relief.

The Carboniferous Limestone forms an upland area with a broad belt of rounded hills in the regions studied. In a number of areas, the rocks are masked by superficial deposits.

The air photographs of Carboniferous Limestones at Ingleborough give a reasonably clear impression of a surface with almost complete absence of soil and the local development of 'grikes'(※) and 'clints'(※).

(※) For further explanation see the section 5.5.

Karstic features may be seen in almost every single Carboniferous Limestone outcrop with or without overburden, and there is no limestone layer, whatever the lithology, on which solution openings or channels have not been formed, except in certain dolomitic limestones. Consequently, spectacular collapse structures are common in most Carboniferous Limestone areas.

The karstic features, in fact, have been excluded from this investigation. They merit through investigation, but cannot be wholly ignored. So the section 5.3 (iv) deals with this, briefly.

The other surface features are the numerous lead mining excavations centred around mineralization. These also cannot be ignored as they can be easily detected on the photographs of Derbyshire and the Mendips as a number of lodes pitted by miners in various directions and lengths.

5.3 LITHOLOGICAL VARIATIONS IN CARBONIFEROUS LIMESTONE:

The Carboniferous Limestone includes beds of varied character ranging form massive limestone and alternations of limestones, sandstones and shales, to dolomites and dolomitic limestones and reef limestones. However, it is generally known as a massive or thickly bedded limestone giving rise to a varied landscape. The shale bands,

calcite-mudstone lenses and minor cherts occur frequently in several horizons, but they are always subordinate in extent to the limestone and tend to be impersistent laterally.

Different limestones exhibit differing expressions on air photographs as they have various characteristics. Some specific criteria for recognition of various limestones or the changes facies within the litho-stratigraphic unit can be detected.

It has been found that the limestones with chert beds show up as a distinct landscape (sec. 5.3.1) compared with the limestones with shale and mudstone beds (sec. 5.6.2). Thin shale bands within the massive limestones act an important part in the development of sinkholes (sec. 5.3.1). On the other hand, dolomitic limestones produce their own characteristics photographic appearance which are subjects of sections 5.3.2 and 5.3.3.

Various litho-stratigraphic units displayed in the Cheddar gorge revealed that the current subdivisions within the Carboniferous Limestone are not always applicable for a photographic study as presented in this investigation. For instance, the Carboniferous Limestone outcrops in the Cheddar Gorge are divided as follows:-

Hotwells Limestone, Clifton Down Group (including Clifton Down Limestone with calcite-mudstone (Chinastone), Cheddar Oolite, Cheddar Limestone) and Burrington Oolite.

The Hotwells Limestone can be seen in the field overlying the uppermost beds of the gorge. It consists of massive limestones with a chert level, associated with thinly bedded limestones above the base.

The Clifton Down Limestone is dark grey, fine-grained, well-bedded limestones. Over most of the district in the Mendips, the following divisions of rocks within the Clifton Down Limestone are differentiated by faunal-stratigraphic studies. (Tab. IV).

"The upper divisions consists dominantly of calcite-mudstone. The rocks are usually well-bedded and of a porcellanous texture (Chinastone- limestone). The middle division consists of fine grained limestones with sheets and masses of Lithostrotion. The presence of chert nodules and bands are characteristic features. The lower division shows rapid alternations of calcite-mudstones, oolite and splintery limestones with scattered Lithostrotion.

The last division is separated into two subdivisions; the Cheddar Oolite and the Cheddar Limestone. The lowest part of the Clifton Down Limestone is underlain by the Burrington Oolite which consists of oolites and crinoidal

limestones". (GREEN and WELCH, 1965).

TABLE IV

The subdivisions of Carboniferous Limestone in the Cheddar Gorge

Faunal-stratigrapic subdivisions		Photogeologic subdivisions
Hotwells Limestones		Hotwells Limestones
Clifton Down Limestones	Calcite-mudstones	Calcite-mudstones
	Lithostrotion beds	Clifton Down Limestones
	Cheddar Oolites	Cheddar Oolites
	Cheddar Limestones	
Burrington Oolites		Burrington Oolites

On the air photographs (Fig. 5), the thin chert beds of the Hotwells Limestone can be identified with their sharp, cragged edges along the southern cliffs of the gorge. They serve as recognition features in differentiating the boundary with the underlying calcite-mudstone member of the Clifton Down Limestone. However, it is rather difficult to trace them between the discontinuous exposures due to the soil cover.

The middle subdivision of Clifton Down Limestone

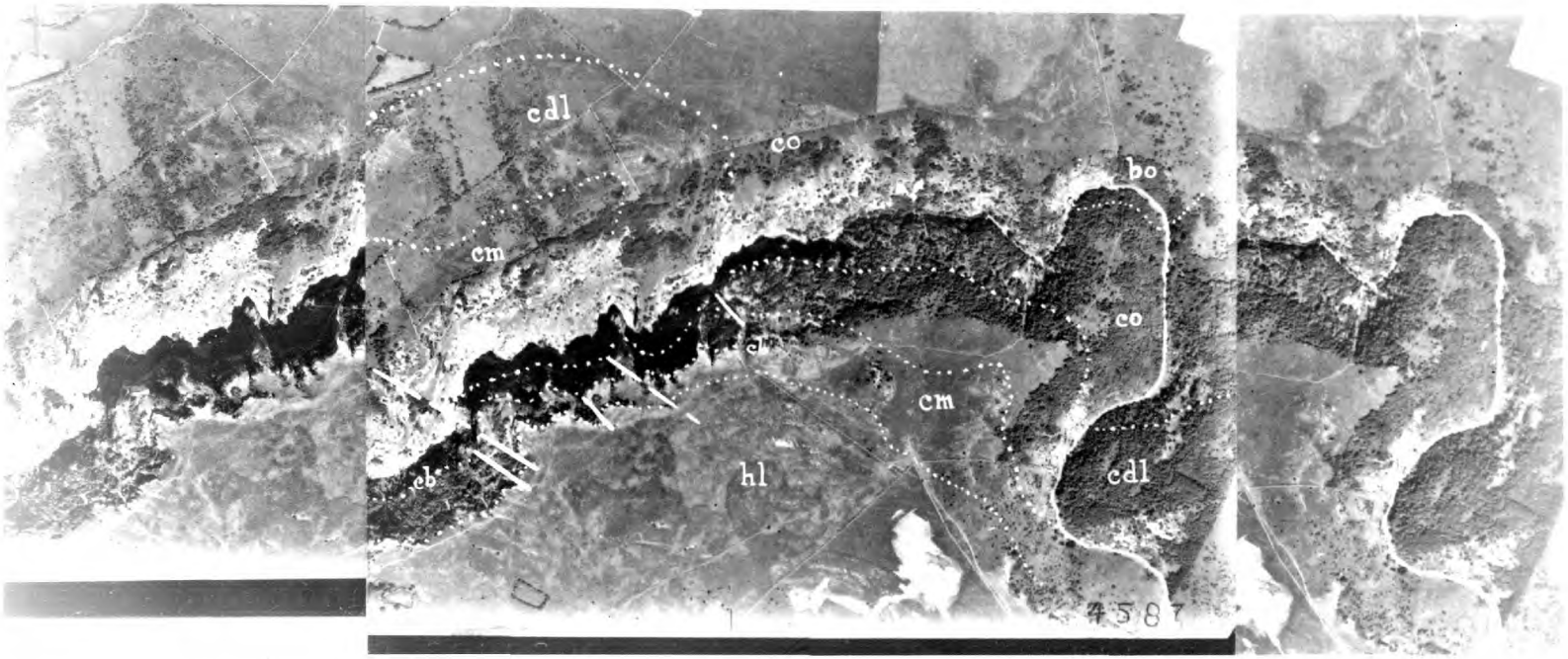


Fig. 5 . Stereotriplet showing various lithologic units of Carboniferous Limestone revealed in a gorge. hl- Hotwells Limestone (cb- chert beds), cm- Calcite-Mudstones, cdl- Clifton Down Limestone, co- Cheddar Colites, bo- Burrington Colites. (Cheddar Gorge, Mendip Hills).
For the detailed explanation see the text.

cannot be differentiated from the overlying 'chinastone', owing to the presence of calcite-mudstones, near the top. The two units reveal almost the same erosional and weathering effects; similar lithology and physical characteristics. The only apparent difference is in the fossil content.

Between the Cheddar Oolite and Cheddar Limestone, there is again no sharp boundary by which these two units can be distinguished on air photographs, but a quite distinct linear feature can be seen between the Clifton Down Limestone and the Cheddar Oolite. This is a vegetation boundary which borders the denser and taller vegetation on the Clifton Down Limestone, with the shorter vegetation and the lighter tone of Cheddar Oolite at the south side of the gorge near the junction with the Black Rock Gate. On the bare walls of the northern side of the valley, this boundary can be differentiated by the well-bedded appearance of Clifton Down Limestone compared with the ill-bedded appearance of Cheddar Oolites.

It appears from the investigation that there is no marked boundary between the divisions as differentiated in faunal classification. It is clear that the beds with abundant Lithostrotion cannot be differentiated from the beds with scattered Lithostrotion on the air photographs.

Therefore, it must be normal photogeological pra-

ctice to base interpretation on litho-stratigraphic boundaries (Tab. IV).

5.3.1 IDENTIFICATIONS OF LITHOLOGIES:

It becomes clear that it takes time and practice to acquire the skill of an interpreter who has to be familiar with most of the identification features of a lithology on the photographs, due to the fact that different limestones exhibited differing photographic expressions.

The study of various lithologies of the Carboniferous Limestone starts with the identification of patterns visible on the air photographs. Areas where bedrock is exposed, are particularly good for providing adequate data for lithologic reconnaissance. The recognition criteria are however local in application and should not be accepted as general rules for all areas.

From this point of view, some criteria for identification of rock units were applied to the different limestone units (see app.), as well as the igneous rocks that occur in some localities. These criteria involve:- (i) Topographic expression, (ii) Superficial cover, (iii) Vegetation cover, (iv) Solution topography (as far as limestones are concerned).

(i) Topographic expression:

The topographic expression is the principle criterion for identification of lithologies. The difference in resistance to the erosion gives rise various surface expressions on the rocks.

A stratigraphical account of the Carboniferous Limestone rocks that have been mapped by the Geological Survey of Great Britain, are classified into several units using the changes in fauna and sedimentary facies. However, the faunal classification is not applicable for a photo-geologic study:(see sec. 2.1.2) the changes in facies could be identified on photographs, if the exposures or character of the topography reflect features of bedrock adequately.

After an overall study of the photographs in the areas covered with Carboniferous Limestones, it seemed that some certain lithologic subdivisions could not be expressed precisely in some places. For instance, in the Mendip Hills, there is a fuller development of Carboniferous Limestone that may be subdivided into three units (i.e. Lower Limestone-Shales, Black Rock Limestones and Clifton Down Group) as recognized on photographs, but uppermost unit of the succession (Hotwells Limestone) could not be distinguished. In fact, they are well

defined from the underlying group (Clifton Down), due to one or more thin beds of calcite-mudstone. On the other hand, the latter mentioned group shows much facies variation and may be subdivided into several units which could not be recognized as separate lithologies on the photographs of this area, but this could be achieved in the Cheddar gorge (see sec. 5.3). Most of the Cheddar gorge has been cut through the middle and upper beds of the Clifton Down Limestone, therefore, there is an opportunity to examine the vertical profile of the rocks as well as the horizontal on the air photographs.

Relatively small variations of permeability* have apparently disproportunate effects on the development of landscape. Thus the Carboniferous Limestone, a hard, well bedded, and strongly jointed rock, is highly permeable and forms high plateau, escarpments and ridges. However, towards the base of the succession shaly beds (The Lower Limestone Shales) are common, permeability is reduced and increased surface erosion results. Consequently, the Lower Limestone Shales are characterized by lower relief while the succeeding unit(the Black Rock Limestone) occupies relatively higher relief. This can be well seen on photo-

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(*) The term 'Permeability' refers to the capacity of a rock for allowing water to pass through it.

graphs of the Mendips between The Old Red Sandstone upland and the limestone ridge (Fig. 6).

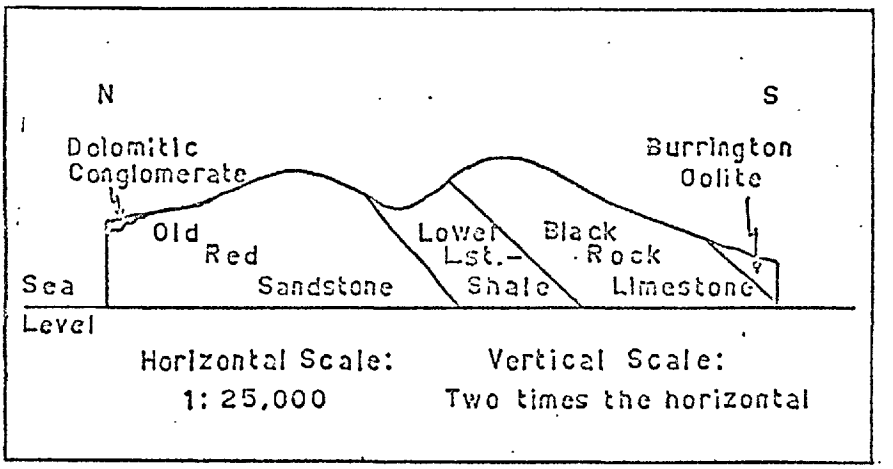


Fig. 6 . Section through the southern part of the Mendip Hills, from Shipham in the north to Cheddar Wood in the south. The Lower Limestone-Shale forms a low relief. It is comparatively thin, being wedged between the resistant Old Red Sandstone and Black Rock (Carboniferous) Limestone.

The overall exposure of Lower Limestone Shales forms a very narrow belt at the foot of the scarp of Black Rock Limestone and surrounds the structures in the area together with thick soil cover.

In the Gower Peninsula and South Pembrokeshire, the Limestone Shale units were distinguished on the basis of weathering and erosional characteristics in addition to the development of sinkholes (see sec. 5.4.1). The Limestone Shales occupies lowland areas while the Main Limestone exhibit relatively higher ground, since

Limestone Shales is less resistant than the Main Limestone.

In the same way, the occurrence of chert beds in the Carboniferous Limestone in Derbyshire gives rise a distinct topographic expression on air photographs. The Monsale Dale beds carrying cherts make conspicuous hills and are recognized by their mottled tone while the adjacent massive limestones (Bee Low Limestone) with uniform lithology exhibit relatively flat and smooth topography (Fig. 7). This can be appreciated in spite of the soil cover of the area.

(ii) Superficial cover:

It is the author's experience that at the beginning of an interpretation (e.g. of a subdued area of Carboniferous Limestone containing extensive superficial cover) familiarity in detecting the ground features could be achieved after several through examinations of the photographs, even if it took a long time.

The masking effect of superficial cover sometimes plays an important part in the appearance of surface features of various lithologies. This is more essential in the detection of different lithologies within the

Carboniferous Limestone. Extensive cover of soil made the interpretation difficult on many photographs. In the areas covered by the limestones with a thin cover of soil (in Ingleborough and the Cheddar gorge) the recognition of units was quite clear, but in areas where there are dolomites, dolomitic limestones and dolerites as well as a considerable cover of soil (the Matlock district of Derbyshire) the interpretation was rather difficult as the superficial cover gives the rocks almost the same appearance.

(iii) Vegetation cover:

Vegetation cover is another criterion for the identification of various lithologies. The presence of vegetation is closely related to the moisture content of the soil in which they are grown. The limestone terrains have scanty water and consequently have little vegetation. Since the soil types derived from the limestones vary as the variations in lithology from one locality to another, the vegetation cover may provide an indication of the nature of the bedrock.

Various attempts were made to find a relationship between the vegetation cover over the Carboniferous Limestone areas and the lithologies, but no reliable recogni-

tion feature was found to detect the lithologies by means of the plant community alone.

The boundary between the two units of Carboniferous Limestone on the south side of Cheddar gorge (Mendip Hills) can be appreciated by a curvilinear expression in the vegetation cover. The lithologic contact has been reflected on the height of the plant community exhibited on both sides of the line which borders the high plants growing over the Clifton Down Limestone and short plants growing over the Cheddar Oolite (Fig. 5).

In the areas investigated, there has not been found any specific type of vegetation growing extensively on Carboniferous Limestone exposures, except for some grazing and woodland areas which cannot be considered as indicators of rock types. On the other hand, the vegetation cover might be much more important or even the only clue in reflecting the various lithologies of underlying bedrocks in humid tropical climates.

(iv) Solution topography:

In the present investigation, solution topography is particularly important as far as limestones are concerned. The solubility of limestones gives rise to the variations of landscapes with a considerable development

of sinkholes as a result of the percolation of water. There is no limestone layer on which solution openings or channels have not been formed, except for certain dolomitic limestone horizons. (see sec. 5.2).

In many cases, the characteristics of solution morphology are subject to a much clearer analysis than in the field.

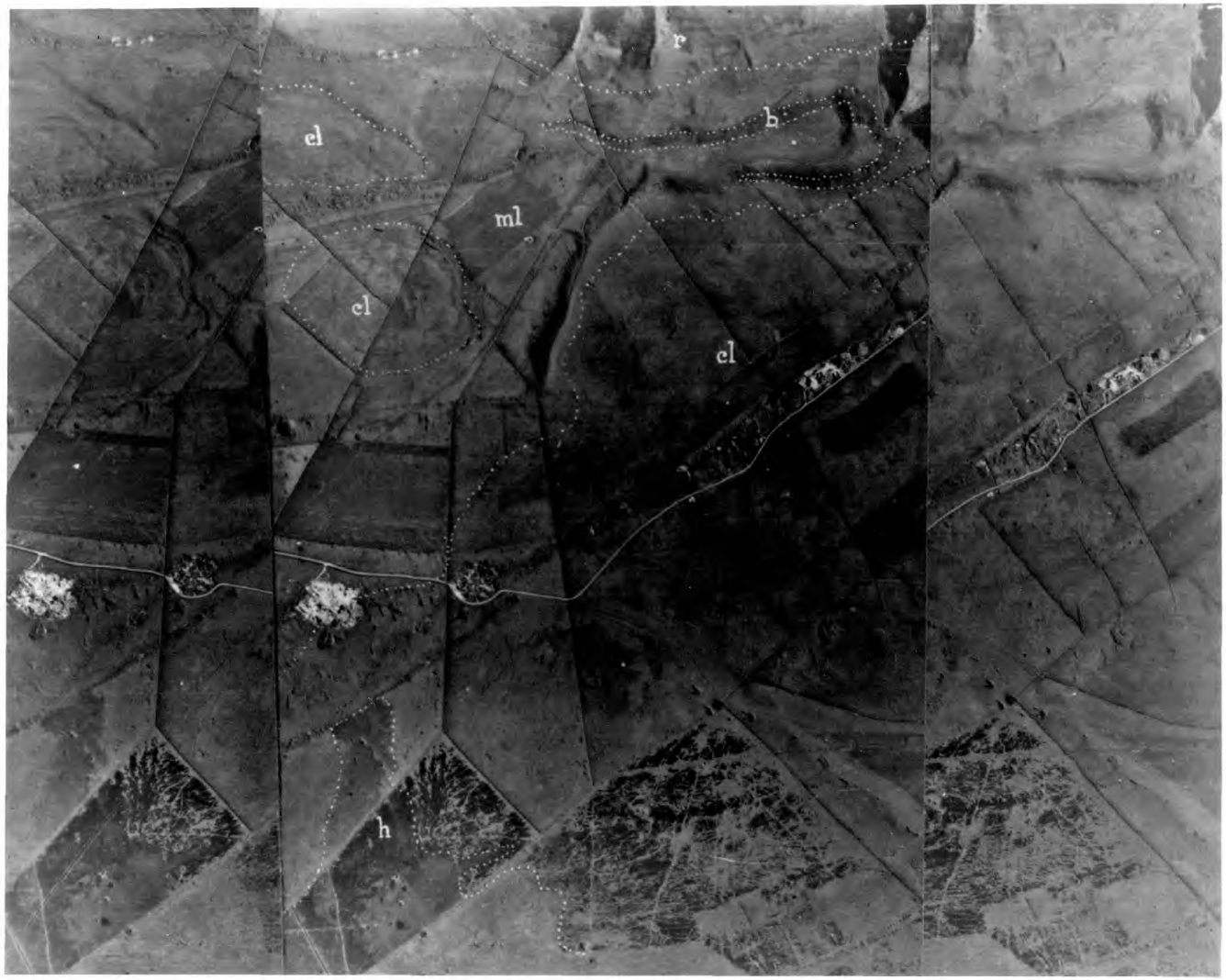
Since the different types of limestones produce a differing solution features, the study of solution depressions helps to identify the lithology to some extent.

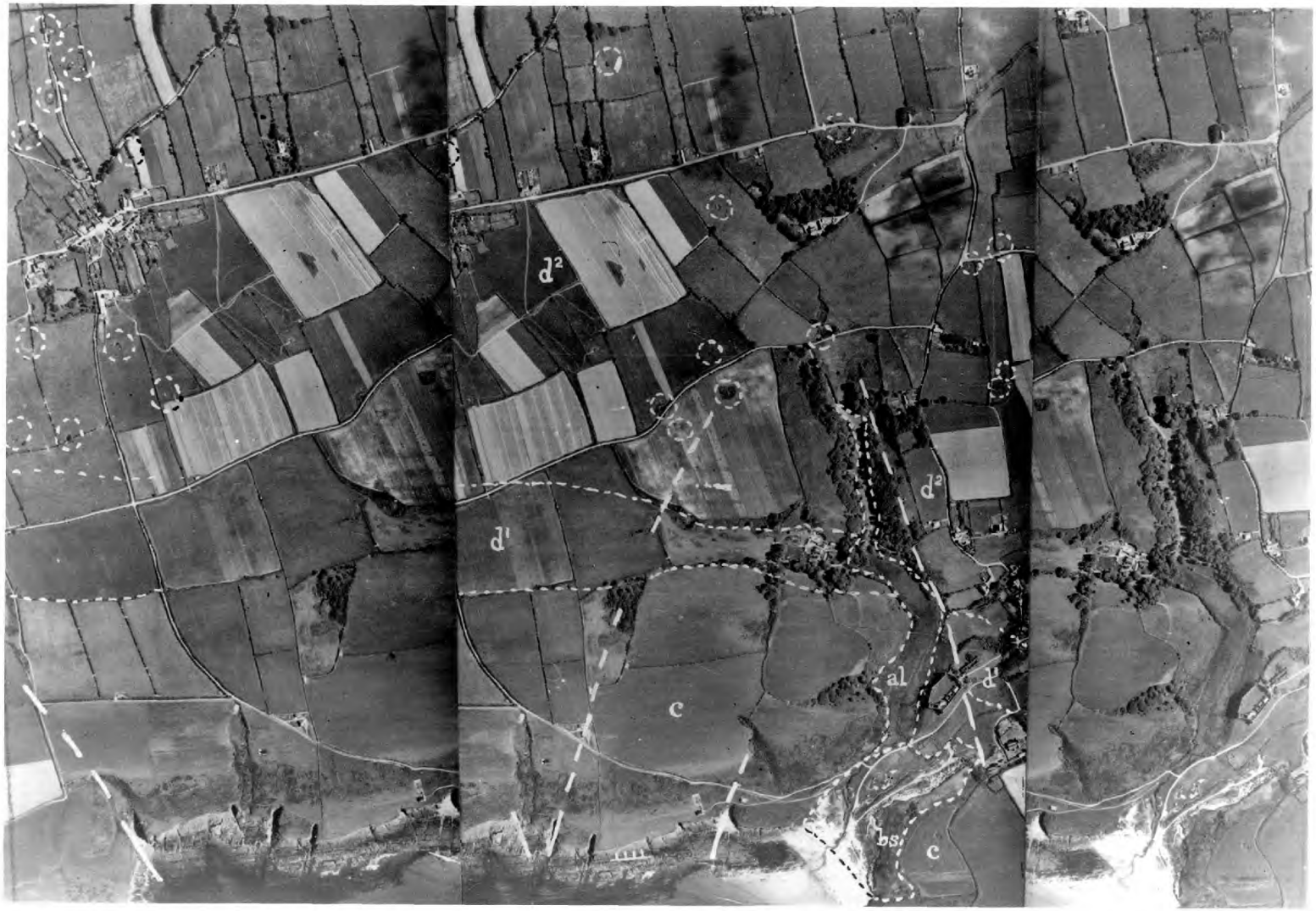
In the Gower peninsula and in Pembrokeshire, the Main Limestone and the Limestone Shales units can be differentiated by means of the sinkholes. They are still detected under a soil cover as dark spots over the Main Limestone which is dominantly a massive limestone, while the Limestone-Shales surfaces have no such features and exhibit rather smooth grey tone (Fig. 8).

In some circumstances, the shape of individual sinkholes may reflect the general attitude of strata. In the limestone areas where circular depressions are dominant, the beds are more likely horizontal or nearly horizontal, while the elongated depressions reveal the inclined beds, due to percolating water enlarging the openings along the direction of the dip. This is not

Fig. 7 . Stereotriplet showing different lithologies within the Carboniferous Limestone; massive limestones (ml) producing flat and smooth topography; cherty limestones (cl) occupying relatively higher ground, forming conspicuous hills, showing mottled tone; reef limestones (r) revealed by irregular surface features, and basaltic lava (b) dark tone and jagged edges on both sides of the valley. Several lead mine excavations with spoil heaps and a cover of head (h) can also be seen. (Castleton, Derbyshire).

Fig. 8 . In this stereotriplet upper half of the area is entirely of Carboniferous Limestone, although there are no distinct surface features. A close examination shows that a number of sinkhole developments (encircled by white dashed lines) can be detected on the surface in the Carboniferous Limestone (d^2) area. A thick soil cover masks the geology underneath, but the Limestone -Shales (d^1) can still be appreciated by its smooth surface and relatively lower ground than that of Carboniferous Limestone and the Old Red Sandstone (c) which is dominantly mudstone in this area. On the south east of the photograph, the blown sand (bs) can be distinguished from alluvium (al) and beach sand by its mottled tone. (Manorbier Bay, Pembrokeshire).


cl
ml
cl
r
b
cl
h


d²
d²
d¹
al
d¹
c
bs
c

always so in the Ingleborough district where the Carboniferous Limestone lie almost horizontal. Intensive development of fractures tend to elongate the depressions along the directions of fractures (Fig. 9).

The Great Scar Limestone in the Ingleborough district consists mainly of massive, blue-grey, fine-grained calcarenites. There are also thin shale beds within the succession, but they are usually subordinate to limestones. Limestone pavements, scars and sinkholes are abundant and distinctive. "The karst morphology of the district has mainly formed in the Great Scar Limestone. Thin shale beds, together with joints and faults played a leading part in development of karstic features". (WALTHAM, 1970). At first stage, the initial streams collected and flowed on the impervious shales until they could drop through them down a joint. Concentrated stream-flow then rapidly eroded the shale and the enlargement took place in the limestone. At the next stage, the collapse of roofs gave rise to depressions and eventually the numerous sinkholes and underground openings were formed around the boundary between the limestone and the overlying shales.



Fig. 9 . Stereopair showing the elongated depressions due to intensive development of fracturing.
Ingleborough district, Yorkshire.

5.3.2 DOLOMITES AND DOLOMITIC LIMESTONES:

Dolomites and dolomitic limestones may have originated, like certain limestones, as chemical deposits (primary dolomite) or they may result from the alteration of limestone (secondary dolomite) the change taking place either during or immediately after the accumulation of the deposit or long after its consolidation. In the Carboniferous Limestone, "dolomites are probably all or almost all of subsequent origin in being the product of the diagnetic alteration of other kinds of limestones" (GEORGE, 1958).

Intense dolomitization affects almost every stratigraphic unit in the Carboniferous Limestone. Large areas have been dolomitized in Derbyshire, particularly in the Matlock district whilst the dolomites are mainly confined to the Black Rock Limestone of the Mendips (SMITH, et al, 1967).

Since dolomites are markedly different in physical properties from limestones, weathering affects them in different ways and produces a distinctive scenery. The smooth landscape of the Carboniferous Limestone country is replaced by jagged crags with dark grey tone. Dolomitic limestones show no sinkholes whatsoever. These features can be easily observed on bare rock surfaces, but in the covered areas these indicators may not be

seen. For instance, the surface features of covered dolerites were almost the same or very similar to the features produced by covered dolomites on the photographs of the Matlock district.

5.3.3 REEF KNOLLS:

An interesting feature in the Carboniferous Limestones of the Pennines is the occurrence of reef knolls which occur at many horizons as thick lenses of highly fossiliferous limestones which often give rise to prominent hills or mounds.

The term 'knoll' is a topographical expression rather than photogeological. It is employed in the present investigation, as it has been widely used since 1892 (TIDDEMAN). In fact, the reef knolls "were not quite like fringing reefs or barrier reefs, nor were they even comparable to modern coral reefs", but the term "has been indiscriminately used to describe features which do not confirm to the strict definition" (BOND, 1950).

They contain a distinctive, exceptionally well preserved fauna of their own (brachiopods, together with gastropods and lamellibranchs), are mostly composed of porcellanous limestone in light colour and show characteristic outward dips away from the central core. The reefs reach all sizes from in significant mounds to hills

few tens of metres in height.

Reef limestones were studied in two principle areas: the Castleton district and the Dovedale area of Derbyshire. In the Castleton district, they occur along the northern edge of the Carboniferous Limestone outcrops, e.g. Treak Cliff and Eyam, whilst in Dovedale they are displayed on both sides of the River Dove and in the vicinity under a residual soil cover. In both areas the surface expression of reef masses were almost the same and could be distinguished without difficulty, but a shape of a knoll could not be detected in every exposure, e.g. the Dovedale reef limestones for the most part do not exhibit the knoll topography.

Reef limestones form little mounds and prominent features and show up as a hummocky topography on the air photographs. They contain more solution cavities than the usual massive limestones. The apparent change of facies from massive limestones to reef limestones can be easily distinguished on the photographs (Fig. 10 and 11). The knoll-like topography is the main criterion to recognize the features of reef mass in addition to the slightly rougher surface mixed with light and dark photographic tones. The photographic expressions of reef limestones might be confused with the dolomitic limestones as they

Fig. 10 . The photograph shows the Alsop Moor (Carboniferous) Limestone (d^2) dipping to the north-northeast (white arrows), whilethe reef limestone (r) shows no bedding planes but reveals irregular mounds (knolls). The Gateham shales of Millstone Grit (d^3) is characteristic with a darker tone, more smooth surface and abundant of drainage channels or gullies on the left of the photograph. The long dashed lines imply faults, short dashed lines show the lithologic boundaries. On the right of the photograph, the common U shape of valley has been converted into a deep U with narrow bottoms due to the presence of the breccia beds within the Alsop Moor Limestones. (Dovedale, Derbyshire).

Fig. 11 . The reef limestone (r) is quite distinct from the massive Alsop Moor (Carboniferous) Limestone (d). (Dovedale, Derbyshire).


d3
d2
r
r


r
d

revealed a jagged relief, but a more careful study of the photographs reveals that the dolomitic limestones have a more jagged topography with dark photographic tone, and have no karstic features as seen on the reef rocks.

5.4. BOUNDARY CHARACTERISTICS:

In the stratigraphic column, the Carboniferous Limestone rests on a set of sandstone and shale beds (Old Red Sandstone) and is overlain by another sandstone with shale intercalations (Millstone Grit). However, this is not always the same in every exposures of Carboniferous Limestone.

In many areas studied, the Carboniferous Limestone is conformably succeeded by Devonian of Old Red Sandstone* facies as seen in the south-west. Elsewhere i.e. in the north of England, and in North Wales (Anglesey) the Old Red Sandstone is absent, and an angular unconformity is

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(*) "The marine Devonian beds of south-west England and the continental strata, known as the 'Old Red Sandstone' naturally differ in rock types and fauna. The term Old Red Sandstone has frequently been used in a stratigraphic sense. It is essentially a descriptive term while much of the succession is not red nor is it entirely sandstone.

found on an evenly eroded surface of older rocks, e.g. Ordovician, Silurian and Pre-Cambrian rocks.

The Millstone Grit(*) rests unconformably on some Carboniferous Limestone outcrops studied in the South-west and in Derbyshire. But in the northern Pennines (particularly at Ingleborough), it succeeds the Yoredale facies formed by intercalations of limestones shales and sandstones (cyclic sedimentation). The Carboniferous Limestone emerges beneath a covering of Triassic strata (Keuper Marls) to form the Mendips.

Apart from the lithological changes detected on air photographs, the boundary characteristics between older and younger sedimentary beds vary.

(*) The term 'Millstone Grit' refers to rocks of Namurian, but a particular (deltaic) facies, forming coarse sandstones (grits) interbedded with marine shales. This is broadly analogous to the restriction of the term Old Red Sandstone to certain rocks of Devonian." (BENNISON and WRIGHT, 1969).

5.4.1. BOUNDARY CHARACTERISTICS ADJACENT TO THE OLDER ROCKS:

The strongly developed unconformity between the older rocks exhibiting Caledonoid folding and the Carboniferous Limestones is one of the best-known in the British Isles.

At Ingleborough, the Carboniferous Limestone overlies the Pre-Cambrian slates and grits, locally known as the Ingletonian Series. Flat lying limestone rests on steeply dipping beds which are seen in a quarry at Chapel-le-Dale near Ingleton. The line unconformity is distinguished by means of numerous springs issuing at the base of the Carboniferous Limestone ~~Ingletonian series~~ which are often enlarged due to solution. (Fig. 12).

The detection of the contact between the Carboniferous Limestone and the Pre-Cambrian rocks in Anglesey was quite distinct as both rocks reveal different photographic expressions. In Anglesey, the Pre-Cambrian Mona Complex is extensively developed and is directly overlain by Ordovician shales; but in a number of places the Ordovician is absent and the Carboniferous Limestone is in close contact with the Mona Complex. The complex has been divided into several groups of rock-types (gneisses, bedded series, plutonic intrusions etc.) which were involved

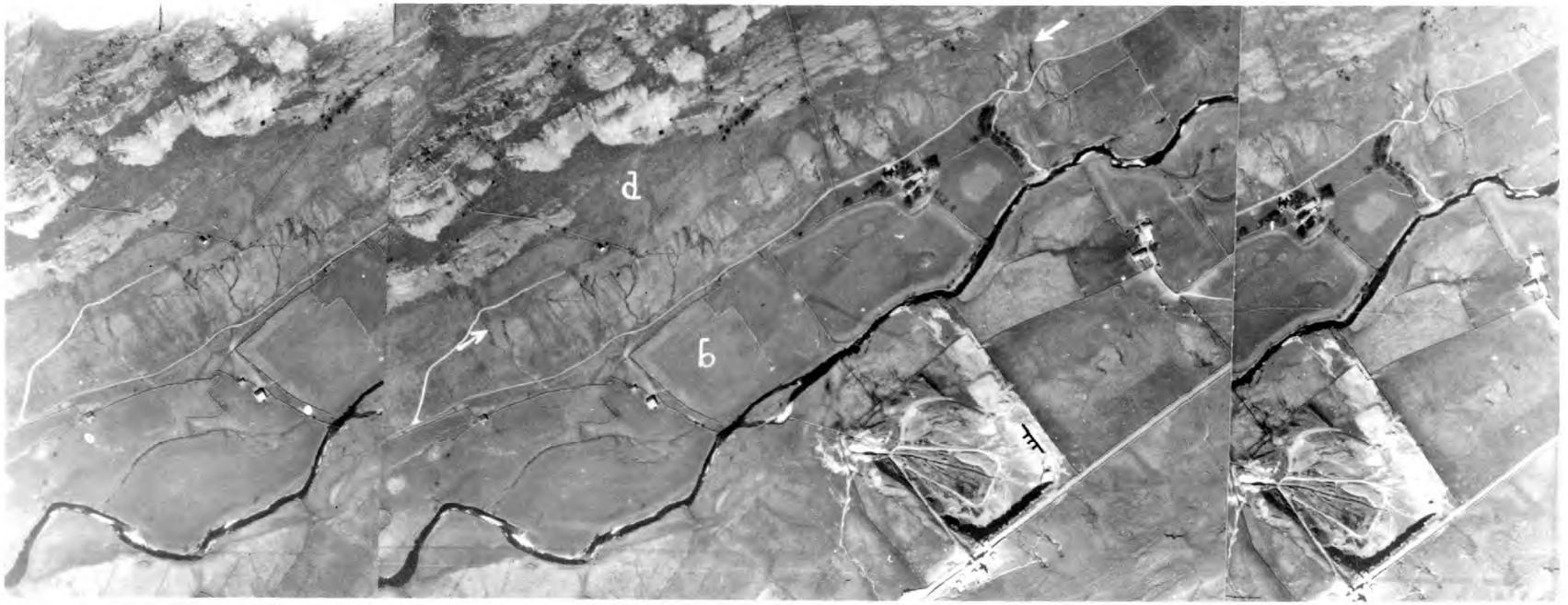


Fig. 12 . Stereotriplet showing a part of line of small springs, between the two white arrows which border the flat lying Carboniferous L$_i$mestone (d) and the Ingletonian series (b) slates and grits. Although alluvium deposits mask the underlying rocks in the valley, the steeply dipping beds are seen in the quarry nearby. (Ingleton, Yorkshire).

in an extraordinary sequence of complicated folds. In general, the various types of schists of the Complex revealed rough and rugged minor ridges with intervening low areas and formed parallel alignments due to cleavage or foliation. They also tend to have mottled photographic tones compared with the light tone of Carboniferous Limestone (Fig. 13 and 14).

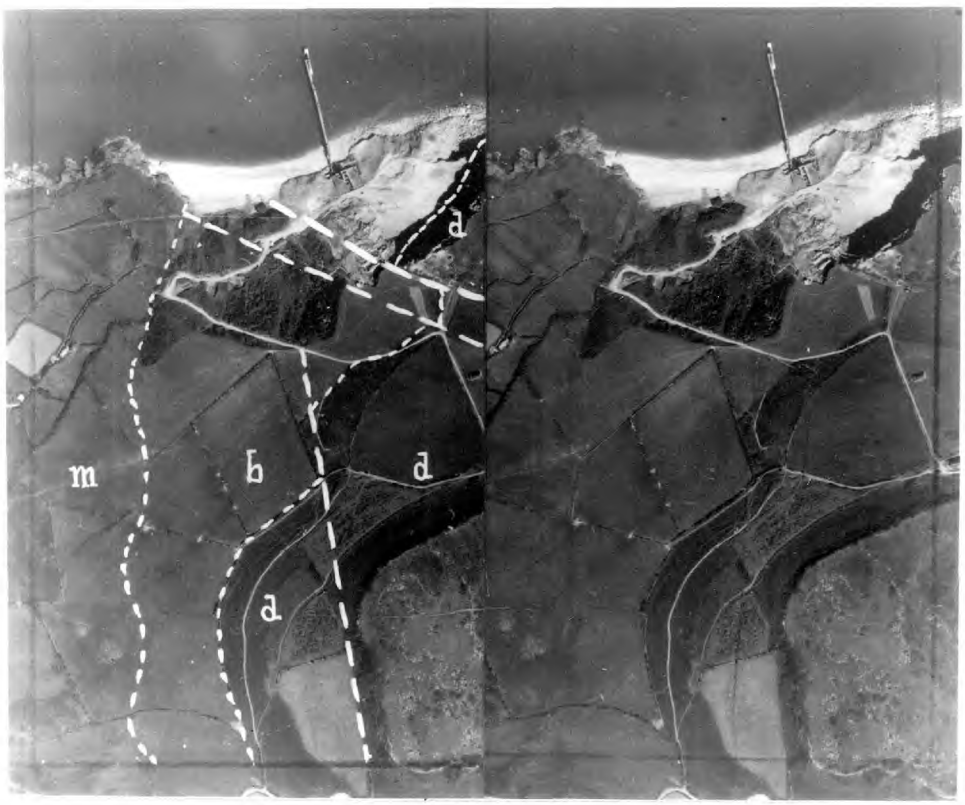
Since the uppermost part of the Silurian and the Old Red Sandstone are absent at the Penmon area of Anglesey, the Carboniferous Limestone rests with marked unconformity on the Ordovician shales. The grey shale beds with minor mudstones are cleaved and highly folded. On the photographs, the Ordovician shales reveal darker tones than the nearby limestone and in the areas where the rocks are covered with residual soil, 20-25 cm in thickness, the only clue for idenfification is the relief. The limestone occupies high ground, while the shales form lower ground. This is due to differential erosion by the atmospheric agents. On the other hand, the shales have smaller angle of slope than the limestones and present a smooth and well-rounded terrain. The boundary between the two rock-types is distinct and linear (Fig. 14).

In the Mendip Hills, the Old Red Sandstone is exposed in the cores of periclines and surrounded by the Lower

Fig. 13 . The photographic expression of the Carboniferous Limestone (d) is quite distinct from the metamorphic Mona Complex (m) under a residual soil cover. The rough and rugged minor ridges and intervening low areas are characteristic for the Mona complex and these give rise a mottled tone. The Carboniferous Limestone occupies relatively lower ground, smooth and lighter tone while the alluvium (al) reveals dark and irregular tone on a flat surface. (Red Warf Bay, Anglesey).

Fig. 14 . Stereopair showing the Ordovician shales (b) in a lower ground and darker tone while the Carboniferous Limestone (d) occupies higher ground. The boundary between the two rocks is distinct and linear. On the left of the photograph, an outcrop of Mona Complex (m) is seen. The area is covered, but considerable bare rock surfaces can be seen over the three rock-types. Gwna Green-schists of the Mona complex are seen on the cliffs. The shales crop out in the west of the quarry with a very dark tone. The bare rock surfaces of the Carboniferous Limestone are at the lower right corner of the photograph with a light grey tone. (Llanfihangel, Anglesey).


d
m
m
m
al
d
d
d


d
m
b
d
d

Limestone Shale of the Carboniferous Limestone succession. The dominant rock-type is a dull reddish sandstone interbedded with sandy purplish shales. On air photographs, it cannot be distinguished due to a considerable cover of soil and the scale which is too large to reflect the bedrock underneath. It appears at high levels as the Carboniferous Limestone, and forms a smooth surface without marked features. The only distinction is the presence of the narrow belt of the Lower Limestone Shale in between the Carboniferous Limestone and the Old Red Sandstone, with the usual appearance of more eroded surfaces in the adjacent rocks. Although the banded effect produced by the bedding in the sandstone can not be clearly distinguished due to a thick cover of soil. The overall examination of photographs reveals that the boundary tends to form a line which borders the upland area of sandstone and the lowland area of limestone due to folding (Fig. 15).

Another characteristic appearance of the boundary of the Old Red Sandstone is seen at the southern coast of Pembrokeshire where the outcrops are well displayed in the cliffs. In this part of the country, the Old Red Sandstone is composed of sandstones and marls with conglomerates at the top of the succession. In the inland areas, a thick cover of soil masks the geology underneath, however, a number of sinkhole developments can be detected



Fig. 15 . Stereopair showing the boundary between the Keuper Marl and the Carboniferous Limestone. The uplands (d) setting is Carboniferous Limestone distinguished by its rough surface, lead mine excavations (v) and grazing and woodland. In the lowland (f) the Keuper Marl produce a smoother topography and arable land. (The north of the Mendip Hills).

on the surface in the Carboniferous Limestone area. Some of these depressions are temporarily filled with water and form nearly circular ponds. A linear boundary cannot be differentiated on the photographs at a scale of 1:10,000 (Fig. 8), but on the small-scale (1:63,300) photographs of Pembrokeshire, due to the smallness of photographic scale the topographic expression reveals a distinct boundary between the lowland and the upland areas representing the Carboniferous Limestone and the Old Red Sandstone. (Fig. 2). However, it is impossible to be certain in distinguishing the lithology and structure on the small-scale photographs when they are used alone.

5.4.2 BOUNDARY CHARACTERISTICS ADJACENT TO THE YOUNGER ROCKS:

Except for the Bristol District, in which the Carboniferous Limestone is overlain by the Keuper marl, the areas studied show the Millstone grit resting on the Carboniferous Limestone. The Millstone Grit comprises a group of grits and sandstones with intervening shales and mudstones occurring between the Carboniferous Limestone and the Coal Measures (Upper Carboniferous). They give rise to a very different type of landscape due to their arenaceous nature. The alternation of

sandstone with shale produces a succession of marked escarpments in the areas where the rocks are inclined. But when the rocks are almost horizontal, they form flat-topped moorlands intersected by steep-sided valleys. On the photographs, the Millstone Grit appearing in a relatively dark tone occupies the lowland areas with a denser drainage network than that in the underlying limestone.

The association of specific drainage characteristics with the shale (Edale Shale) member of the Millstone Grit and the Carboniferous Limestone in Derbyshire have been discussed in section 5.6.

The study of the photographs of Gower and Derbyshire shows that there are a number of surface expressions which can be used to distinguish the boundary between the two rock units. In Gower, the extensive but ill-exposed area of Millstone Grit shales forms a convenient boundary, sharply marked from the Carboniferous Limestone. Due to differential erosion, the soft shales form an area of low lying ground while marshes and woods occupy the drift cover with a dense intermittent drainage network. Although the beds are dipping at a medium to steep angle, the area of Carboniferous Limestone shows a distinct smooth surface expression and some sinkholes can be still distinguished under the thick cover of drift. (Fig. 16).

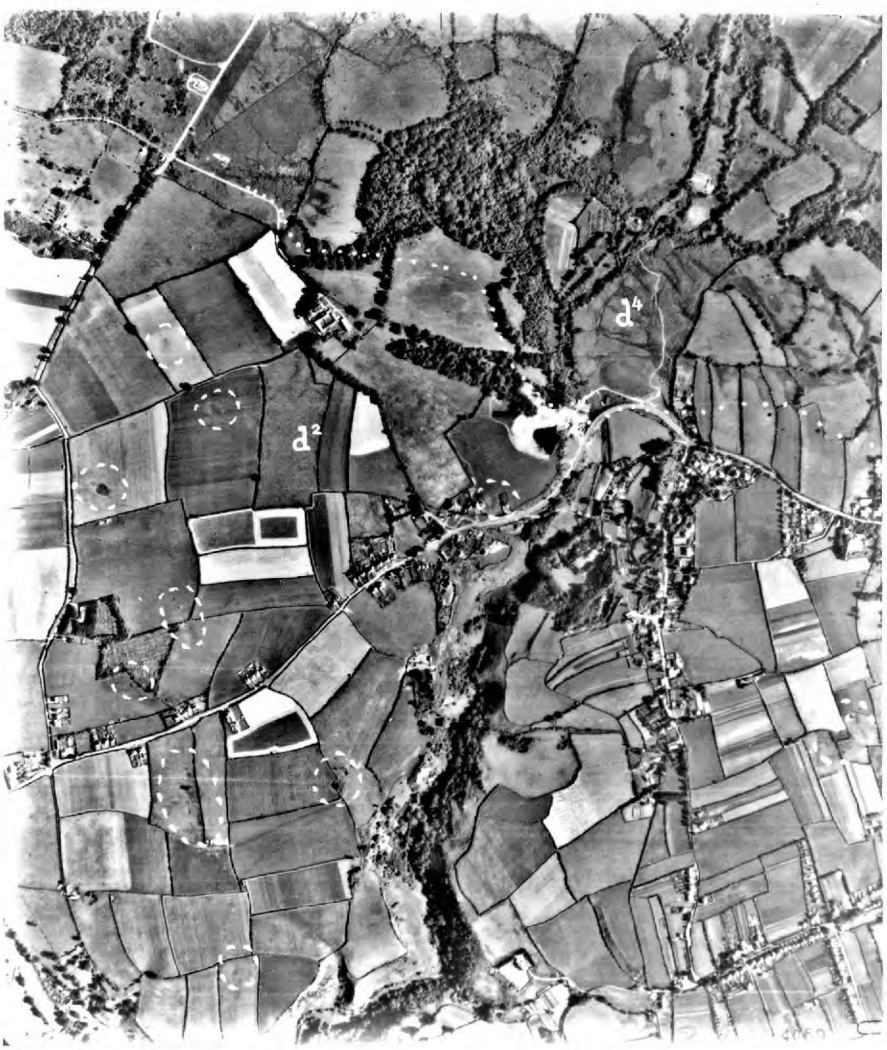


Fig. 16 . The boundary between the Carboniferous Limestone (d^2) and the shale member of the Millstone Grit (d^4) can be clearly detected on the upper half of the photograph shown in dots. (Gower).

In the Mendip Hills, the Carboniferous Limestone is overlain by the Keuper marls of Triassic age. The Keuper deposits rest unconformably on an uneven surface of eroded Paleozoic rocks and are mainly composed of marls. They are subdivided into several units i.e. Dolomitic Conglomerate, Keuper Marl and Green Marl. The usual transitional zone between the Carboniferous Limestone and the Keuper deposits is not seen on the photographs. The abrupt change - a linear boundary - is due to the steep contact of the formation. Although there is a thin soil cover on the limestone, limestone areas show light tone, rough and high relief whilst the Keuper deposits occupy a flat and rather smooth surface having a somewhat darker tone at the foot of the Carboniferous Limestones. (Fig. 15).

5.4.3 DOLERITES:

Being usually dark in colour, they have long been recognized and described locally as 'Toadstone'. Some are lava flows, others are beds of volcanic ash or tuff while others are minor intrusions along joints and bedding planes.

The last-named group are known as sills, usually consisting of dolerite. They occur mainly in Castleton,

the Millers Dale and the Matlock district and are confined to the main body of the Carboniferous Limestone.

Since the term dolerite is "applied in Britain to fresh basaltic rocks" in the Dictionary of Geological Terms (1962) and since there is not much difference in photographic expressions, throughout this investigation the basaltic lavas have not been mentioned as a separate group.

At one of the several localities in the Castleton district, the lava flows occur along the upper part of Cave Dale occupying a few square kilometres only; they are a dark blue-grey, with at least one layer of coarse tuff. Although it was difficult to distinguish at first sight on a small-scale photographs of the area mentioned, they could be appreciated fairly easy on large-scale photographs, after several attempts have been made to determine the recognition features. (Fig. 7).

As a result of extensive volcanic activity, there are two main lava flows occurring at separate horizons in the country around Matlock. It was rather difficult to distinguish one individual flow from the other, because the surface expressions of both lava flows were almost the same. On the other hand, the extensive dolomite and dolomitic limestone exposures also tended to be misinter-

preted in some parts of the district due to their similar surface expressions to the relatively dark toned and erosion-resistant surfaces of the dolerites. The tendency to spheroidal weathering of the dolerites which is characteristic for doleritic rocks, could not be appreciated on the air photographs because of the thick cover of soil. If they are exposed adequately and reflected well enough on the air photographs, the edges of rocks can be outlined to some extent and the form of sill can be appreciated, as seen in Matlock, Derbyshire. Otherwise, it is impossible to distinguish the dolerites from the dolomite. (see sec. 5.3.2).

The boundary between the Carboniferous Limestone and dolerites cannot be easily differentiated in many areas because of the lack of evidence required for identification. In Anglesey, for instance, some dolerite dykes have caused a little thermal alteration to the Carboniferous Limestone on either sides of the contact. They were not detected on photographs because of the very small outcrops relative to the photo scale (e.g. in Traeth Bychan bay on the northern coast).

5.5. FRACTURE TRACE CHARACTERISTICS:

5.5.1. GENERAL CONSIDERATIONS:

Fracture trace analysis consists of a study of natural linear features i.e., topographic, vegetation, drainage and soil tonal alignments, visible on photographs which may be related to bedrock fractures. There is frequently an association between the characteristics and relationships of the fracture traces and the local geological structure.

Due to limestones fissured nature, fracture trace analysis merits study in detail. The findings and conclusions reached in this field are helpful for further investigations in various photogeological studies.

It seems from the review of relevant literature that most of the investigations on limestone terrains have concentrated mainly on the studies of fracture characteristics as mentioned in section 2.2. However, no specific study of fracture traces on air photographs in Britain has appeared so far. NORMAN's detailed work dealt with linear features in the areas where the bedrock is covered by superficial deposits. It is understood that some parts of the areas investigated were in Carboniferous Limestone regions.

In the present investigation which has dealt with only the Carboniferous Limestone, the study of fracture traces has been focused mainly on two types of characteristics: qualitative information (manifestations of fracture) and quantitative statistics (orientations, frequencies and densities of fractures) rather than on their causes.

5.5.2. DEFINITIONS AND CLASSIFICATION:

A fracture trace is "a natural photogeological linear feature consisting of topographic, vegetation and soil alignments" (LATTMAN, 1958). Although this basic definition is common to most workers, there is a wide variability of nomenclature. It should be remembered that these terms are only strictly applicable to the interpretation of air photographs.

The term 'trace' also needs to be explained as it is widely used throughout the present work. By fracture is meant a break in the rocks. This must be observed on bare rock surfaces. The actual fractures, in fact, may not be seen in covered terrain (i.e. areas of cultivation, or where natural vegetation or any other features masks the rock surfaces). On the photographs of these areas, the linear features seen are only the surface expressions or traces of the hidden fractures. From this point of

view, the term 'fracture trace' is used here to refer to the photo-manifestation of joints and faults.

Another term 'megajoints' has been introduced by GOLBRAYKH et al., (1966). The definition of megajoint is in fact very similar to that of fracture trace. It refers to "the totality of the linear elements in relief, vegetation, soil, drainage and rocks that are readily distinguishable on aerial photographs".

The term 'fracture trace' is still prefered in this investigation as it embraces all types of photogeological linear features. 'Lineament' is not used because of the large scale and world wide significance attached to this term by some workers. (LATTMAN, 1958).

Before describing the classifications, it is necessary that some terms should be explained. For instance: the density of fracture is the total length of all fractures and parts of fractures per unit area. The frequency of fractures is the total number of fractures per unit area.

BLANCHET (1957) divided fractures into two principle classes: micro-fractures (up to about $\frac{1}{2}$ mile in length) and macro-fractures (2 to 50 miles, or more, in length). In this classification the macro-fractures are considered to be generated "at the level of the basement", whilst the micro-fractures are considered to have originated

much further up in the geological column.

LATTMAN (1958) introduced the terms 'fracture trace' and 'lineament' with specific lengths. Fracture trace is applied to the linear feature of less than 1 mile in length while lineament is applied to features of many miles in length (tens or hundred of miles long). Fracture traces include natural linear features, i.e. local bedrock joints and small faults etc., while lineaments may represent zones of large-scale shatter or faults of deep-seated basement origin.

HAMAN(1961) has classified fractures as micro-lineament if they are less than 2 miles long and as macro-lineament if they are longer than 2 miles. This classification is not the same as BLANCHET's. The difference is in the use of the term 'lineament' instead of 'fracture trace' and in the specific lengths between the different fracture types.

HAMAN has revised the previous work and selected the term 'meso-fracture' to replace with the term 'micro-lineament' in his later published paper (HAMAN, 1964). Meso fractures originate within the sedimentary column, whilst macro fractures generally originate in the basement rock and extend for many miles over the earth's surface.

5.5.3. APPEARANCE OF FRACTURES:

Fracture traces are present in nearly all landscapes. However, their recognition on air photographs depends on the ability and experience of the interpreter and such other factor as thickness of superficial cover, types of vegetation cover, lithology and attitude of strata.

The fractures are expressed as linear features of various lengths. Their appearance on air photographs is a guide in locating zones of structural disturbance in rocks. The structural discontinuities, i.e. fractures, are more easily eroded than surrounding rock. They produce linear depressioned at the surface.

As the standing water within these depressions is more chemically active, the effects of solution have produced pronounced and varied changes to the limestone terrain. The solution tends to be more active along the depressions and tends to widen and deepen the fractures. Consequently the fracture traces can be expressed as linear features occupying relatively lower ground of considerable width. On photographs of Ingleborough where the fractures are well displayed, this effect is clearly observed especially in the manifestation of major fractures oriented northwest-southeast (Fig. 17).

The vegetation alignments are not manifested as sharp area boundaries of abrupt change from woodland to grassland or one sort of plant to another. They may be recognized as linear gap in the tree pattern or slight linear tonal change in the grey tone of vegetation cover.

Fractures rarely show as actual breaks. Vegetation is remarkable sensitive to soil and moisture conditions, therefore, deep soil and greater water content over a fracture as compared to the surrounding soil cover, gives rise to luxuriant vegetation or narrow linear changes in vegetation which are visible on air photographs.

The location of fractures on limestone surfaces are often appreciated by an alignment of vegetation. The rapid weathering of these rocks along fractures results in the development of soils in which plants thrive. Consequently, the plants are aligned along the fractures as dark tones compared with the light tones of limestones.

Fractures can be easily detected in the areas where the bedrock is close to the surface, e.g. the Gower and Pembrokeshire coast, Mendip Hills (Cheddar gorge), but more fractures remain undetected in the areas where bedrock is covered by thick unconsolidated material, e.g. Mendip Hills (Black Down pericline), Derbyshire (Fig. 18). They can be observed more easily and are much more common in the Ingleborough district due to well exposed rock

Fig. 17 . Fracture traces on a Carboniferous Limestone surface can be seen between the white arrows as linear features occupying relatively lower ground, as the differential solutioning is more active along these furrows. (Ingleborough district, Yorkshire).

Fig. 18 . Two fracture traces are seen between the white arrows on the residual soil over the Carboniferous Limestone. (Castleton, Derbyshire).





surfaces.

Observed variations in the density of fracture traces appear to be attributed mainly to variations in the thickness of the soil cover. The density or frequency of the fracture traces increases where there is a thinning of the soil. This is clearly seen in an air photo fracture trace map (Fig. 19) of Gower coast where there is a narrow strip of bare rock surfaces of Carboniferous Limestone along the coast. But towards to the inland where there is considerable cover of soil, the density decreases.

5.5.4. FRACTURE PATTERN ON CARBONIFEROUS LIMESTONE:

The orientation of fracture traces is significant as it is related mainly to structure and lithology. Histograms and rose diagrams are the best means of demonstrating the overall directional pattern of fractures. The different fracture orientations can be correlated and compared by using rose diagrams and consequently a lot of information can be extracted from them.

The studies of fracture traces on the Carboniferous Limestone outcrops were made in the Mendips, the Gower coast, Derbyshire and Ingleborough. In each area selected, the fracture traces reflect their own characteristics. For instance: the Mendips, being a huge anticlinal stru.-

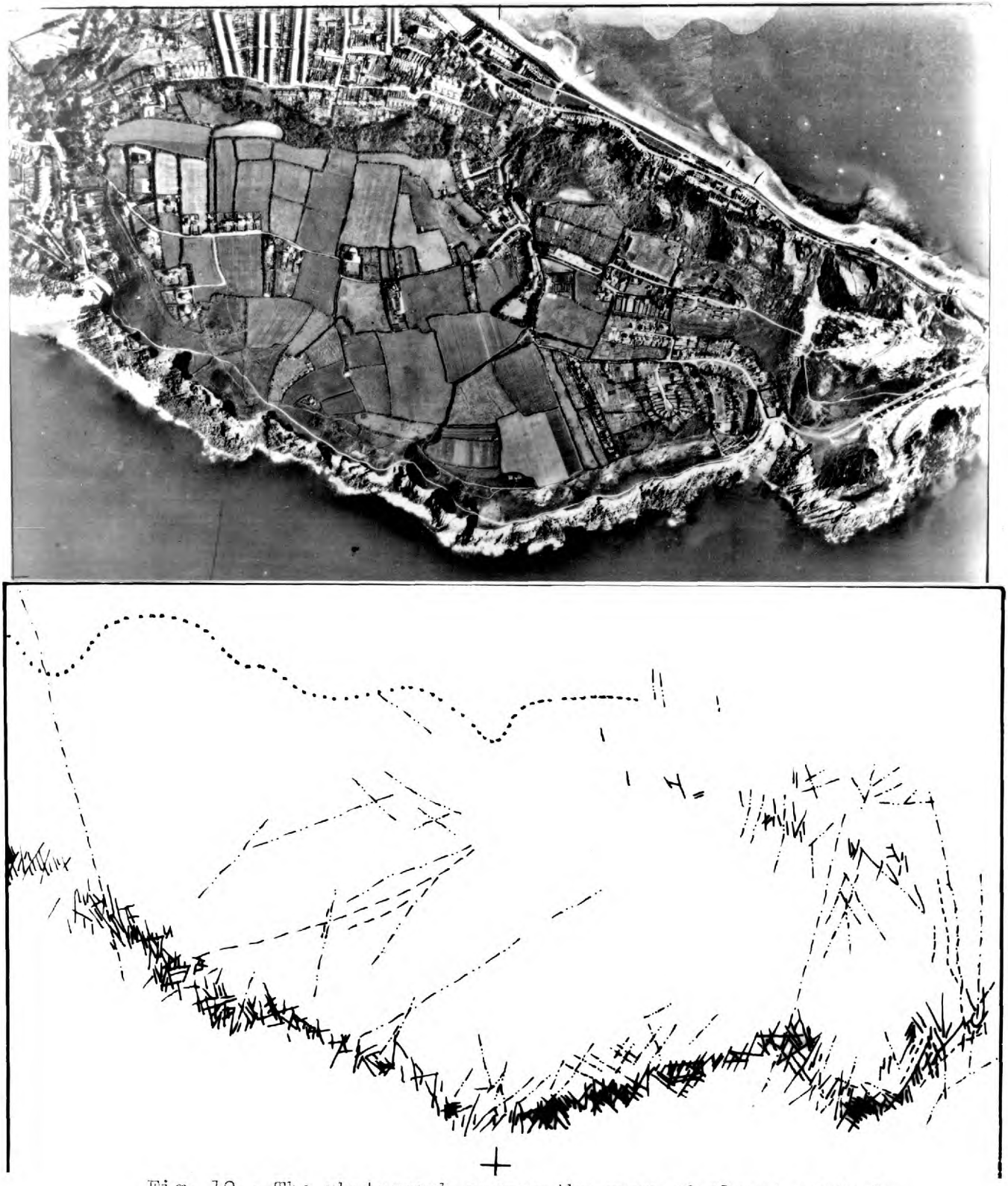


Fig. 19 . The photograph covers the area of almost entirely Carboniferous Limestone, but extensive soil cover tends to mask the surface features except for a narrow strip of bare rock surfaces along the coast where a number of fractures can be detected, as seen in the map of the same area. The dotted line marks the boundary between the Carboniferous Limestone and the Millstone Grit. (Mumbles Head, Gower).

cture, dissected by the Cheddar gorge in south flank, is covered by superficial deposits. The Gower coast has bare rock surfaces of Carboniferous Limestone, with steeply dipping beds giving rise to fracture patterns different to many other outcrops. Derbyshire is the area where the Carboniferous Limestone occupies the highest ground with extensive old lead mines. Ingleborough is an area of bare rock and horizontal beds displaying well known fracture patterns.

The lines of lead rakes(*) in the limestone area are not shown on the fracture trace map. However, they occur as material filling fissures associated with faults and major joints.

Over the Carboniferous Limestone outcrops of northern part of the Derbyshire dome, comparison of the drainage and air photo-fracture trace maps shows many instances where drainage courses of all sizes coincide with individual fracture traces (Fig. 20 and 30).

Since the study area is considerably covered with superficial deposits and the photographs are at a scale of 1:27,600 which is considered as medium scale for this purpose, small fractures have been ignored.

(*) The name 'rake' was given by the lead miners of Derbyshire to long veins.

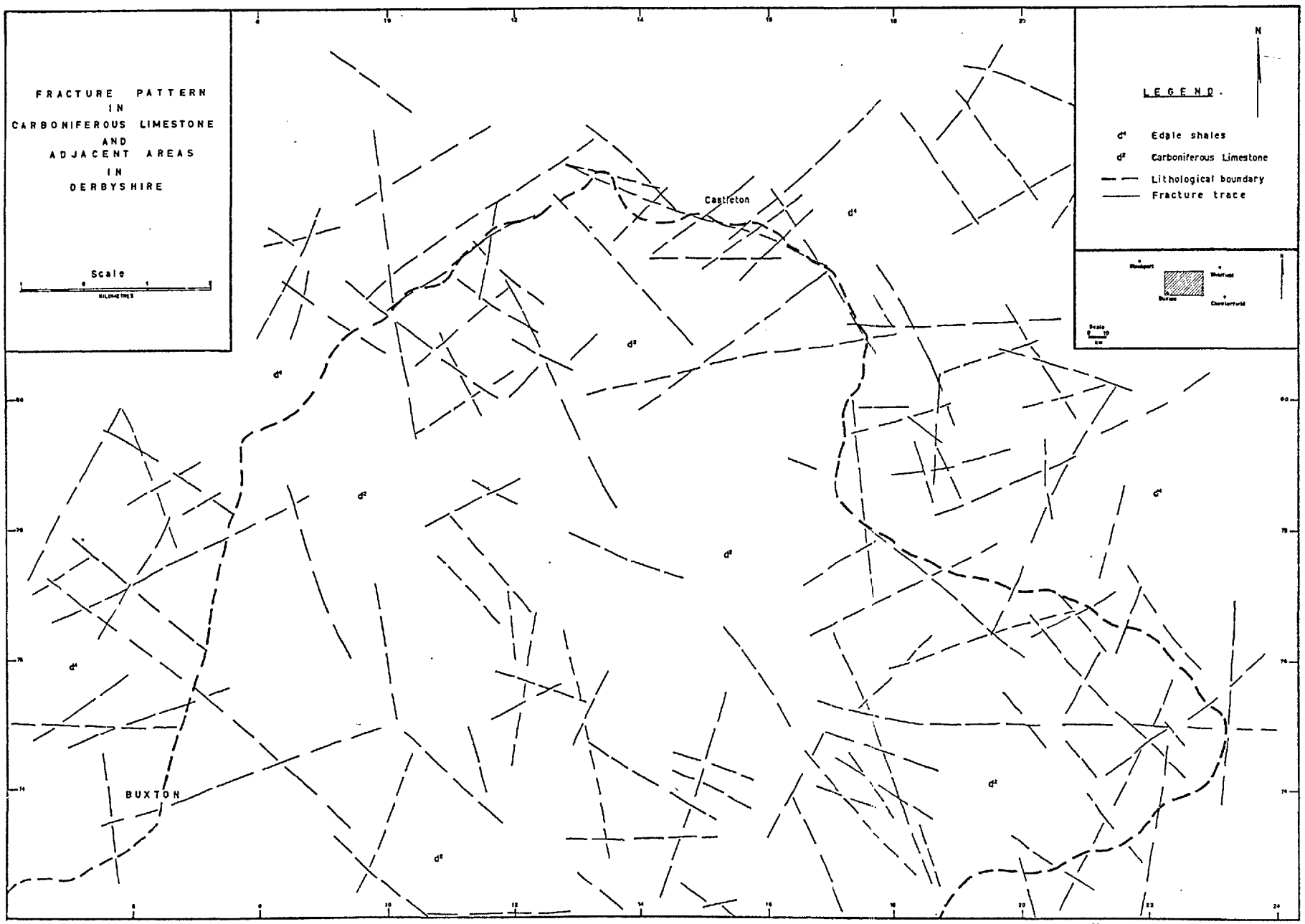


Fig. 20 .- Air photo fracture trace map.

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It is difficult to estimate just how much control bedrock fractures have over the development of drainage. In the Carboniferous Limestone area, many of the streams flow generally northwest-southeast, whilst some tributaries are in the direction of northwest-southwest. These directions are almost the same as the directions of the dominant fracture traces. In the adjacent shale area, fracture directions are different and so the drainage pattern is different to that of limestone.

It can be said that fracturing in the Carboniferous Limestone area commonly controls the drainage.

The Carboniferous Limestone in the Ingleborough district has been studied intensively by geologists for many years, and varied conclusions concerning the fractures (especially joints), their orientations, modes of origin and relation to earth movements have been published.

The study of fracture traces has received considerable attention in this area as their recognition is fairly easy on air photographs. The Carboniferous Limestone is characterized by well-developed faulting and jointing. Over a considerable proportion of its outcrop, it gives rise to bare rock surfaces, occuring as horizontal beds or dipping up to 5 degrees. The relief is made up of alternating cliffs (scars[*]) and pavements. The pavements

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([*]) These rocks are also known as the Great Scar Limestone.

correspond quite often with bedding planes and consist essentially of bare level, furrowed blocks of limestone called 'clints'. Each clint has its own dip which may or may not be the same as the local bedding or the regional dip of the limestone. The clints are intersected by deep fissures or widened joints called 'grikes' which separate the clints. It is apparent that these two typical features are formed by chemical weathering of limestones. An overall pattern of clints and grikes is shown in the frontispiece and Fig. 21.

The generally rectangular plan of the clints is accounted for by the occurrence of two sets of master joints. The typical clint block is about 1 - 2 metres wide, whilst the grike is about 15 - 60 cm wide at surface, narrowing towards the base.

The joints in the Carboniferous Limestone of the area form a number of systems and are mostly vertical. The distance between the adjacent joints is usually 0.5 - 3 metres. The area is also cut by a considerable number of relatively minor faults which exhibit evidence of mainly horizontal displacement.

A close examination of the photographs of Ingleborough district reveals (Fig. 22). that every individual bed or horizon of Carboniferous Limestone has its own typical

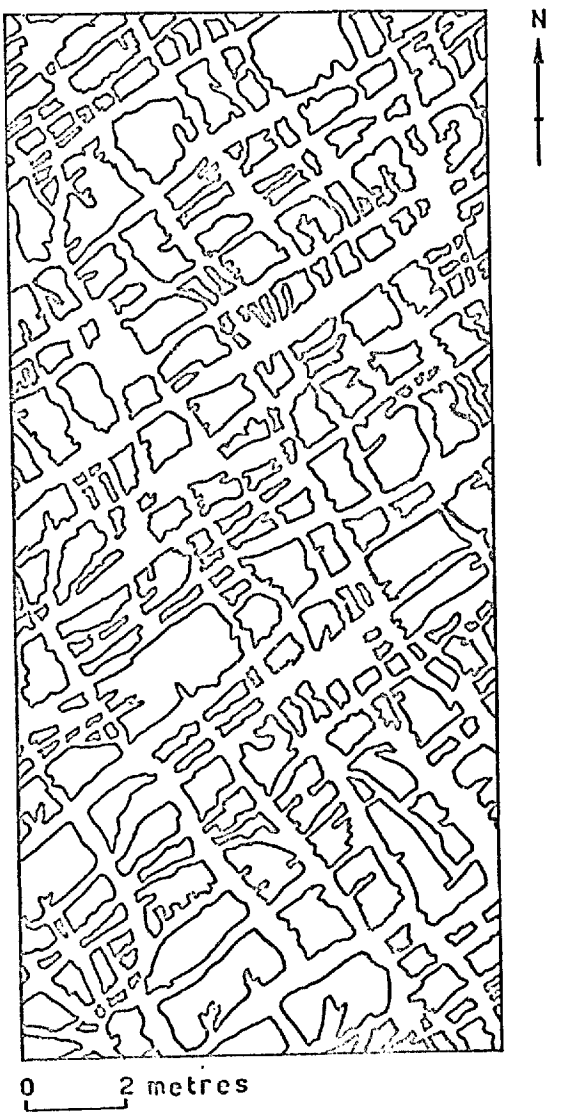


Fig. 21 .- Plan of a typical Carboniferous Limestone pavement in Ingleborough district, Yorkshire. (Wager, 1931).



Fig. 22 . Various limestone pavements (a,b,c,...) exhibit different fracture density pattern.

fracture density pattern different from that in the bed above or below. It can be said that there are as many fracture patterns as there are pavements in this area. The following factors may be responsible for the variations in the pattern of fractures; (i) the thickness of individual beds, (ii) the grain size and texture of the limestones, (iii) the stress involved during folding and faulting.

A more detailed study was carried out on the fracture traces displayed in the Ingleborough district in order to analysis the fracture pattern on the Great Scar Limestone and the adjacent areas; the overlying Yoredale series and underlying Ingletonian series. The emphasis was placed upon the macro fractures rather than the numerous small joints. The macro fractures imply the fractures which have been interpreted on the photographs without stereoscopic examination. It must be remembered that the fracture traces annotated on air photographs represent both joints and faults. (Fig. 23). A total of 722 fracture traces was observed. The lengths of individual fractures were measured in metres. The directions of the fractures were plotted in 10-degree sectors. From these measurements histograms and rose diagrams were constructed.

As the frequency diagrams show (Fig. 24-A), the

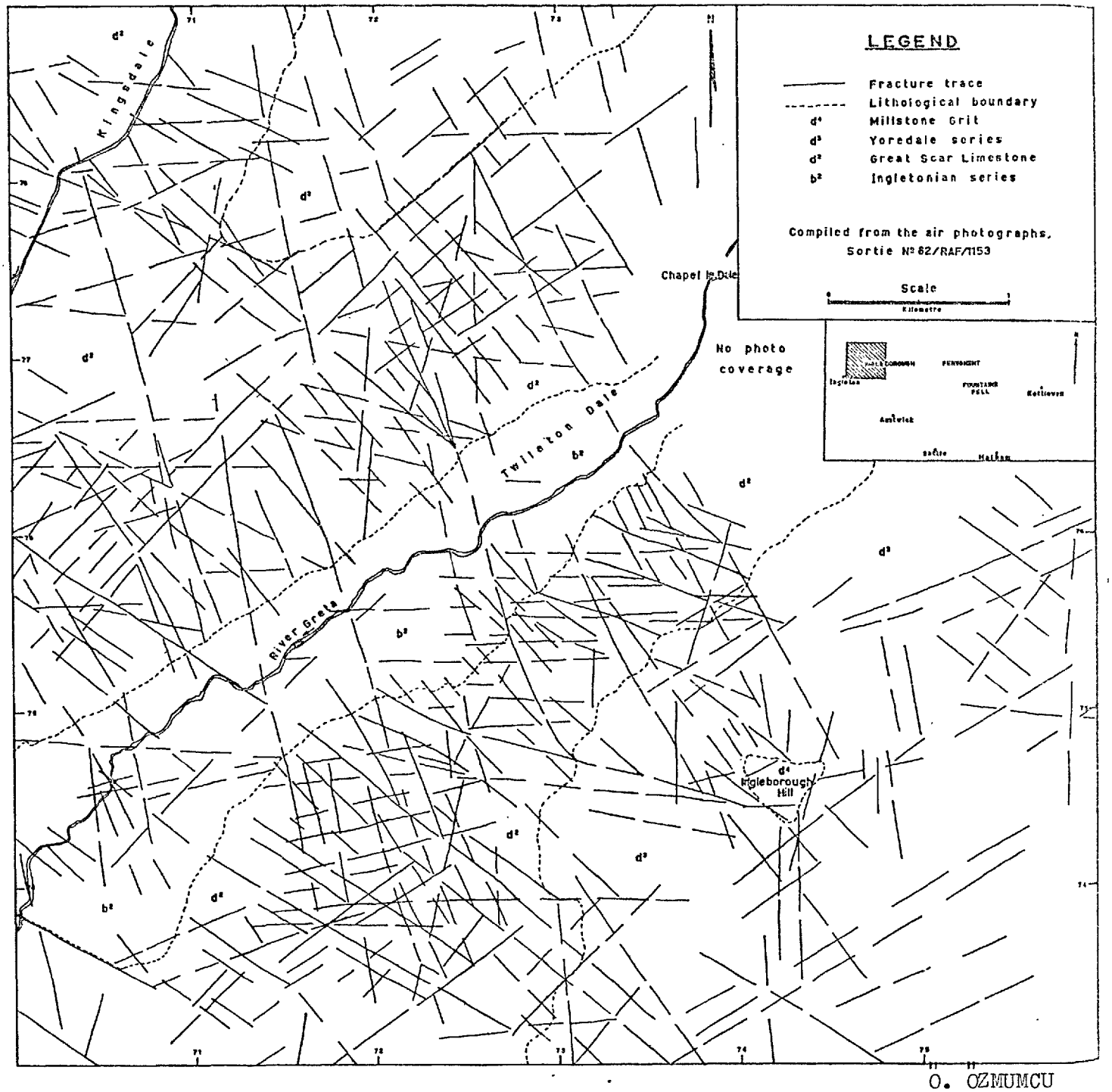


Fig. 23 .- Fracture trace map of a part of the Ingleborough district.

E - W and N 10 - 20 W trending fractures form distinct directions on the Ingletonian series. The N 40 - 50 W and N 40 - 60 E trending fractures form the common directions on the Yoredale series. The Great Scar Limestone forms another dominant direction of E - W in addition to the common directions of Yoredale series and has at least a few fractures in every direction. In the Ingletonian series there are few fractures in the NE quadrangle, whilst in the direction of N 20 - 30 E, no fracture occurs.

The total length of fractures (directional densities) follow a very similar distribution to the directional frequency as in Fig. 24-B. In the Ingletonian series, the length of fractures in the direction of N 50 W is occured also in the Great Scar Limestone area as it coincides with the major faults throughout the valley. In the Yoredale series, the directions of N 60 E and N 50 W are the two dominant directions in which the total lengths of fractures have been concentrated. In the Great Scar Limestone, the range between N 20 W and N 60 W is the direction in which the individual classes have total length of fractures in excess of one kilometre. In the direction N 50 E, the length of fractures is the maximum of its quadrangle. This direction is also perpendicular

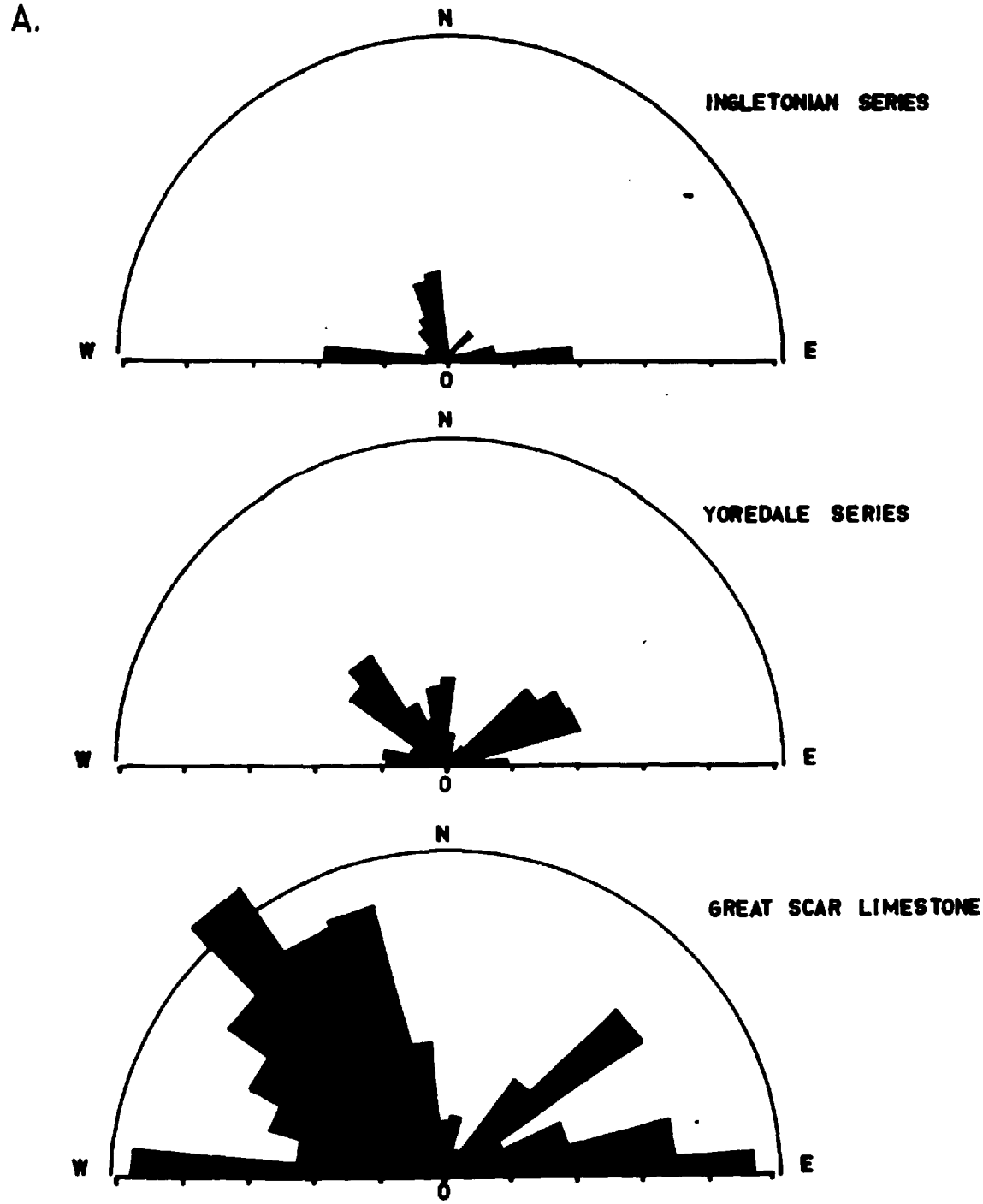


Fig. 24-A . Rose diagram of fracture trace directional frequency distributions.

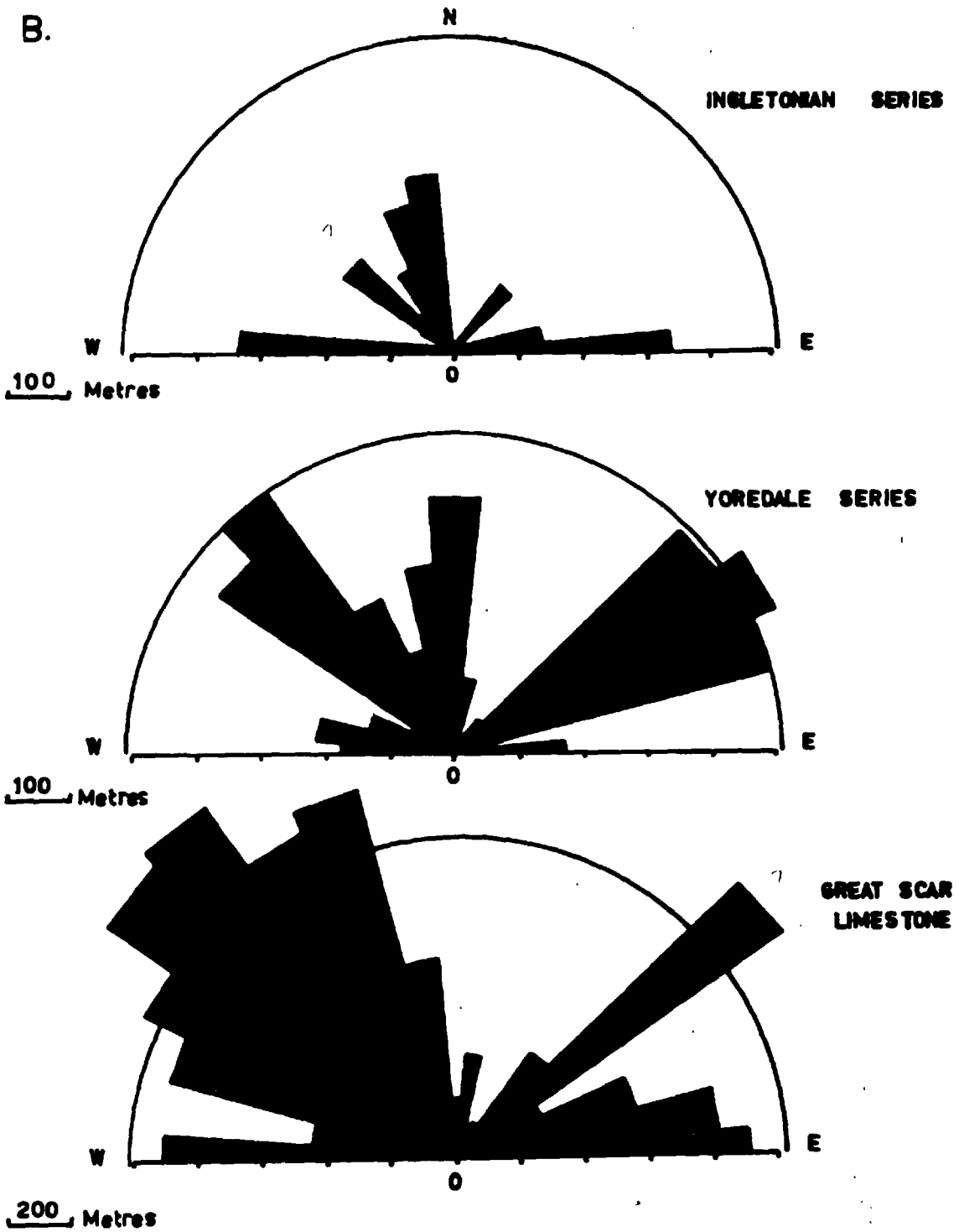


Fig. 24-B . Rose diagram of fracture trace directional density.

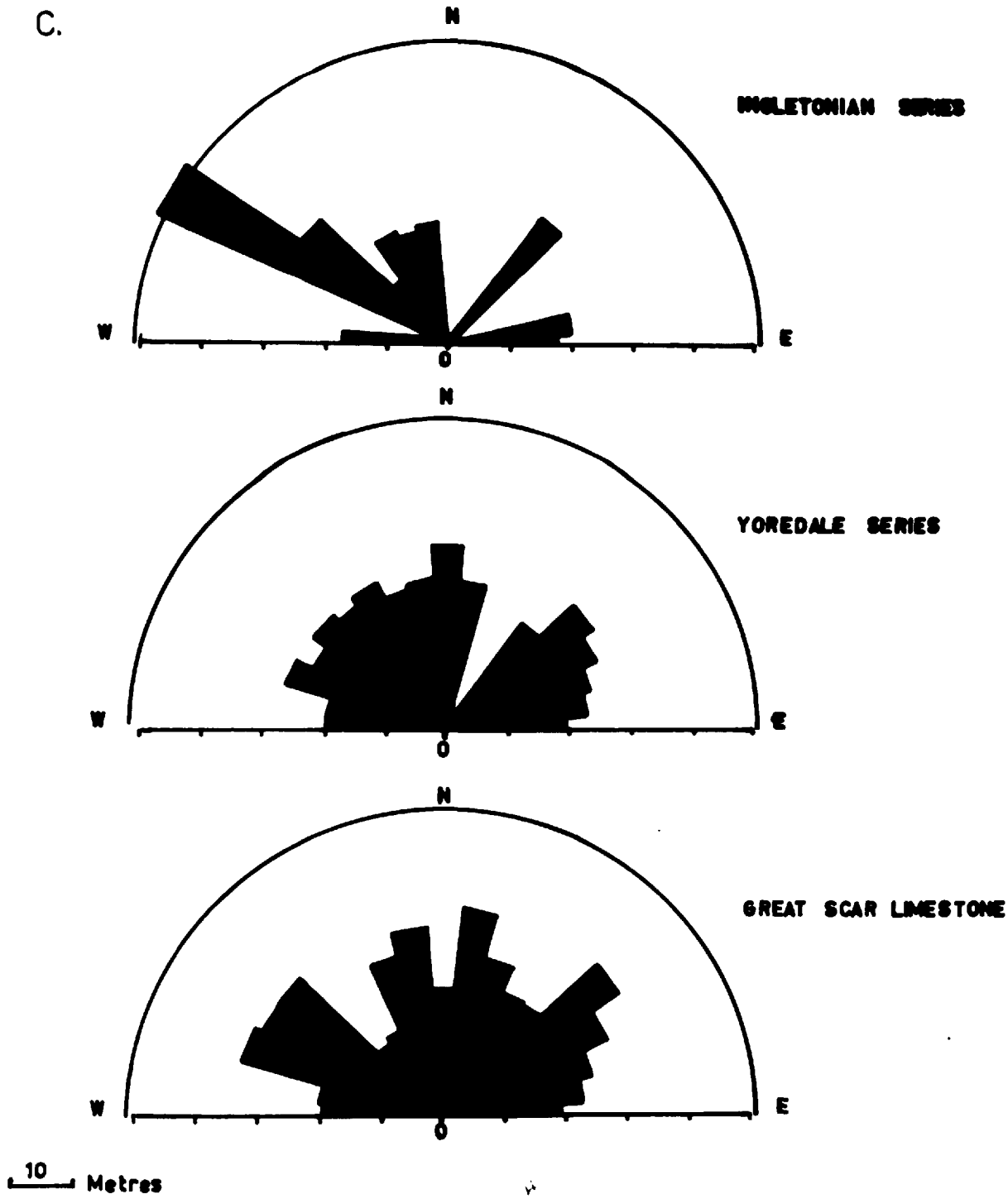


Fig. 24-C . Rose diagram of fracture trace directional average length.

to N 40 W which is the maxima in the NW quadrangle.

The average density of fractures (Fig. 24-C) is very constant for all directions in the Yoredale series. However, the N - S direction may have slightly greater significance. The E - W direction is average in the Great Scar Limestone. In fact, it carries almost the same value (less than 20 metres) in all three rock types. It may have been due to the bias of the interpreter who was over careful to avoid the misinterpretation of long alignments which may be caused parallel to the roll of film during the processing of photographs. In the Ingletonian series, there is an unusual peak on the diagram in the direction of N 60 W. It is believed that this is a major fault line parallel to Craven faults direction which cuts all three units and extends still further beyond the study area.

The interpretation of length frequency histogram (Fig. 25) shows that in the area studied up to 1200 metres length of fractures can be traced on the photographs of Great Scar Limestone, while this is limited about 600 metres long in other two rock series. The overall shape of the histogram of Great Scar Limestone corresponds with that might be expected on theoretical grounds. It seems possible to differentiate these three lithologies by their respective length frequency distributions. The average

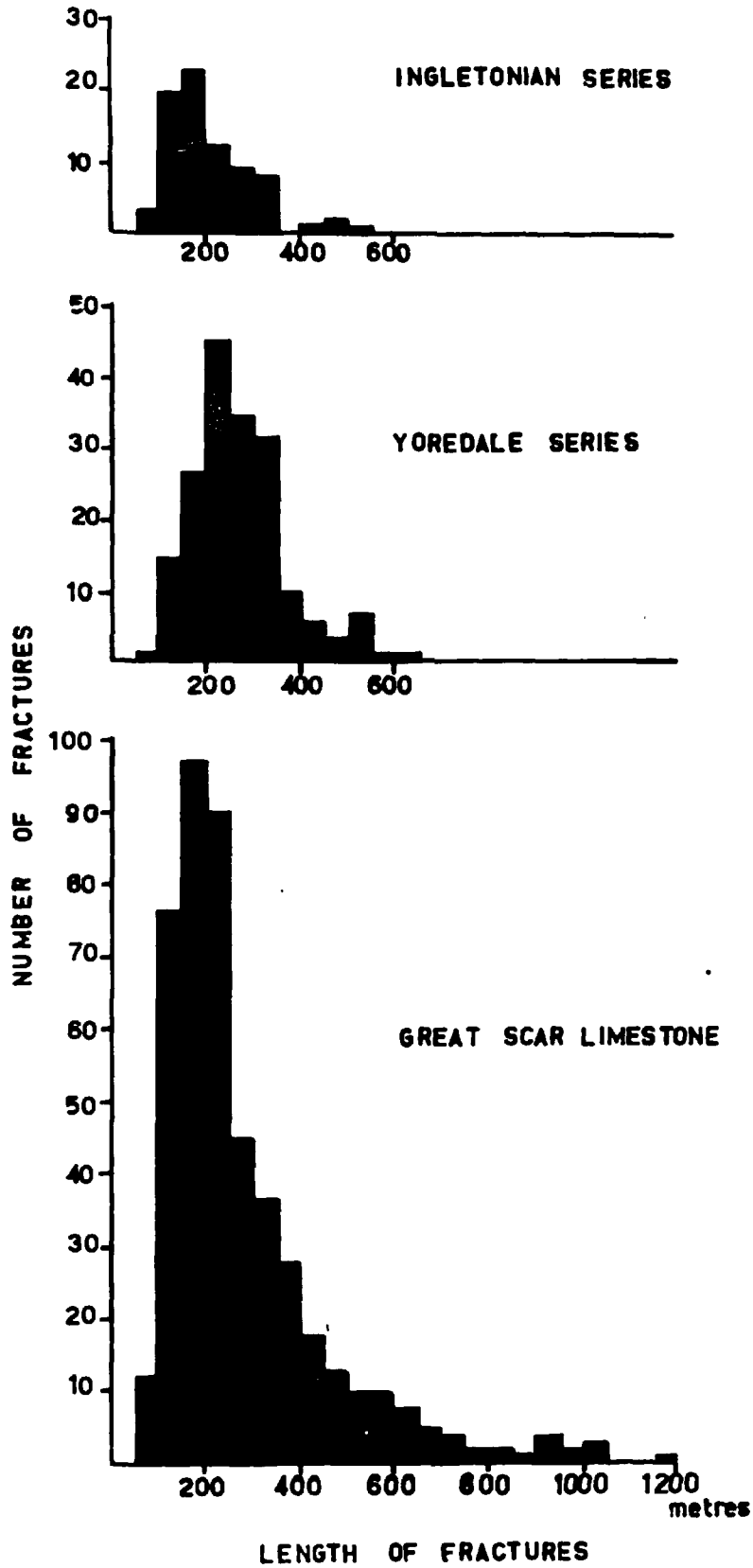


Fig. 25 . Histogram of fracture trace length frequency distributions.

length of fractures is slightly greater in the limestone than in other two rocks. The primary cause is that the Great Scar Limestone is made up essentially of thick bedded limestones with thin shale bands. The competency of limestone appears to give much more pronounced fractures and longer lengths than the slates and grits of Ingletonian, and alterations of limestone, shale and sandstones of Yoredale. The secondary cause is that the masking effects of alluvium and drift in the valley over the Ingletonian and peat over the Yoredale series. The length values of the Ingletonian may also be related to outcrop size, because some of the Ingletonian fractures are in fact, parts of fractures extending from the Carboniferous Limestones on both sides of the valley.

A similar study was carried out in the Mendips where the Carboniferous Limestone crops out on both flanks of the Black Down pericline. The study areas were near Burrington in the north and Cheddar gorge in the south (Figs. 26 and 27). The fracture trace maps of the areas were made and several histograms and rose diagrams were constructed.

The aim of the study was to analyse the various orientations of fractures on both flanks, their manifestations, lengths, density and frequency distributions.

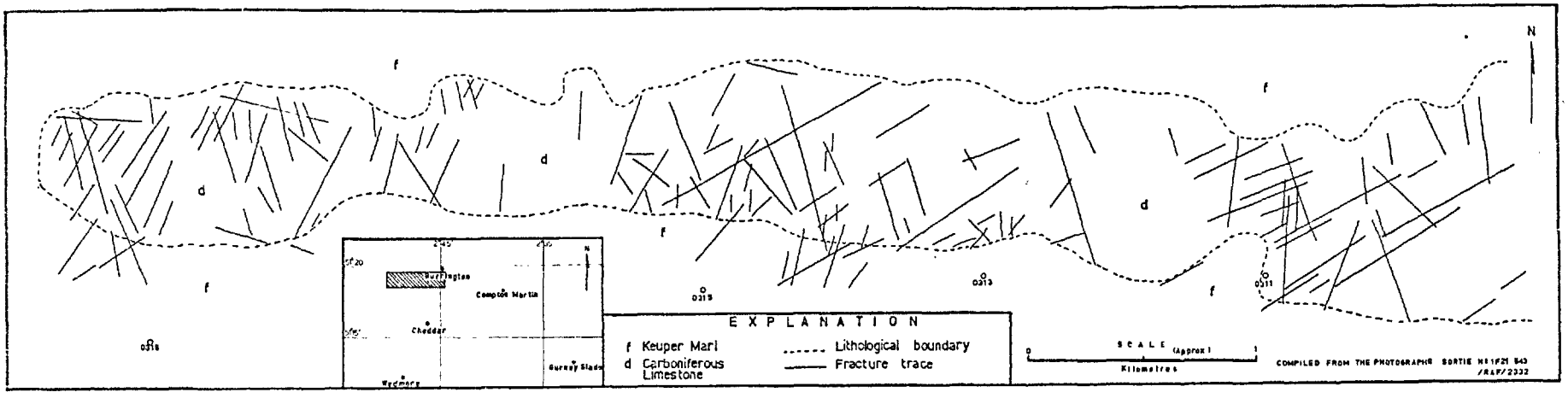


Fig. 26 . Fracture trace map of a part (north flank) of the Black Down pericline.(Burrington).

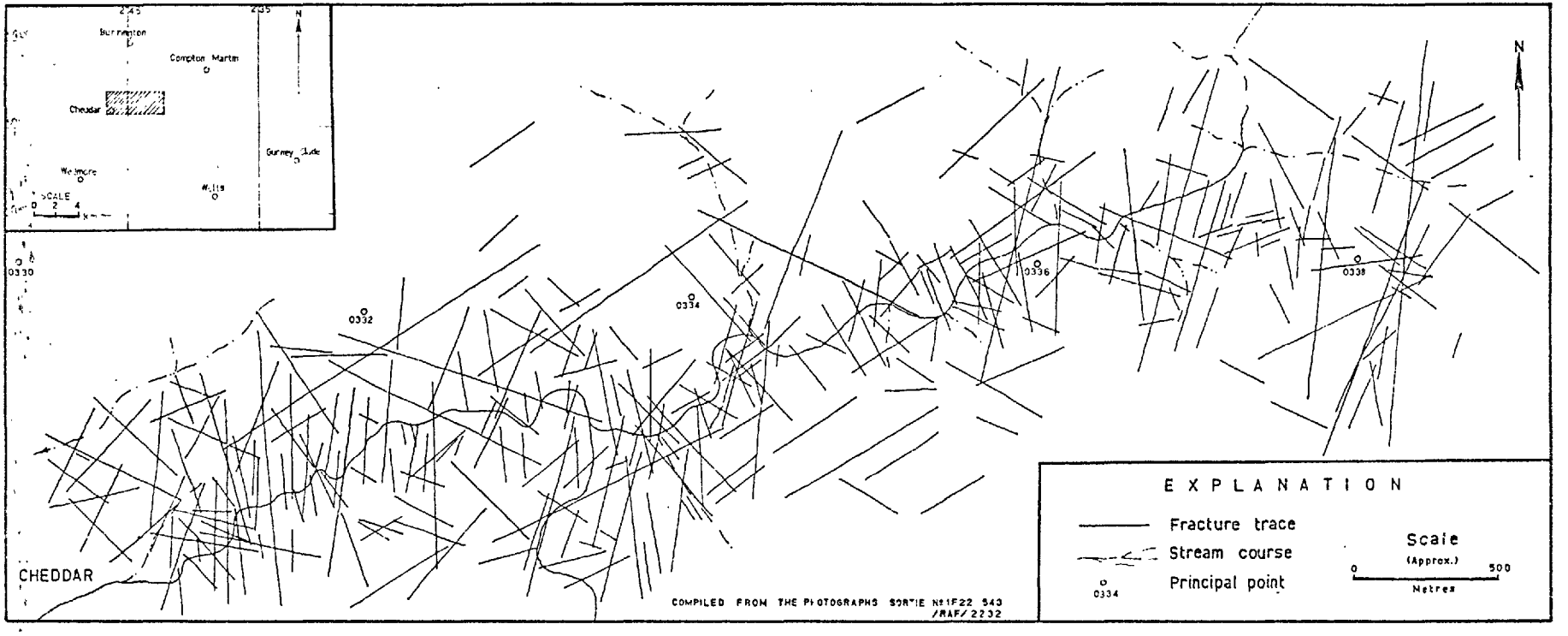


Fig. 27 . Fracture trace map of a part (south flank) of the Black Down pericline.(Cheddar Gorge).

The overall examination of the maps showed that the small number of fractures in the north may be due to the soil mantle which masks the fractures to some extent. It affects not only on the frequency and density of fractures, but also the individual length. For instance: the maximum length of fracture is 140 metres in the south while it is 100 metres in the north (Fig. 28). The most visible fractures are those of a length between 10 and 20 metres on each flanks.

Fig. 29-a shows the frequency distribution for the two areas. The three prominent directions are seen on each flank, but they are not in the same directions except for the one (N 60 - 70° E).

Fig. 29-b shows that the prominent directions of densities coincide with the prominent directions of frequencies.

Fig. 29-c shows a general increase of average length is maximum in northerly direction on both flanks. The diagram of south flank shows the general increase of average length usually at the fracture maxima, while the maximum in northerly direction is not characteristic in this direction on the north flank. Most of the fractures have a length between 20 metres and 30 metres.

The difference in frequency and length of fractures

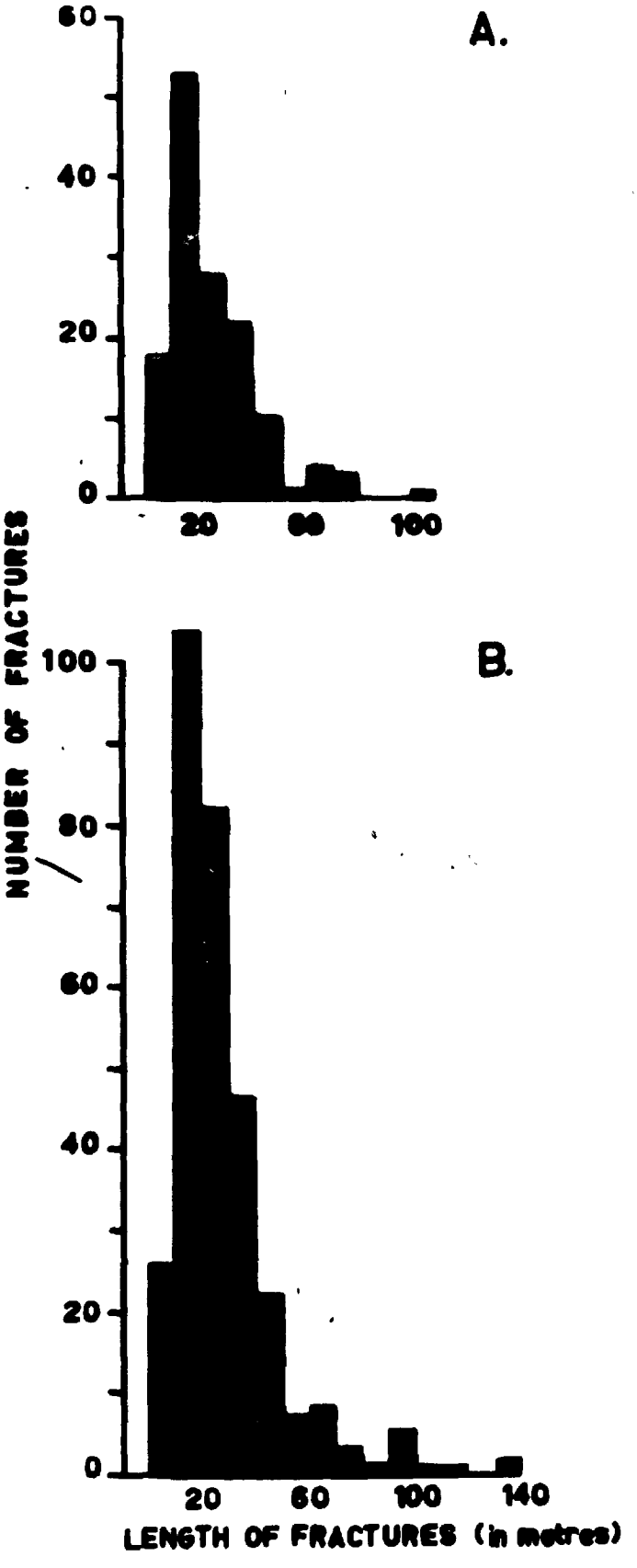


Fig. 28 . Histogram of fracture trace length frequency distributions.
A- North flank, B- South flank.

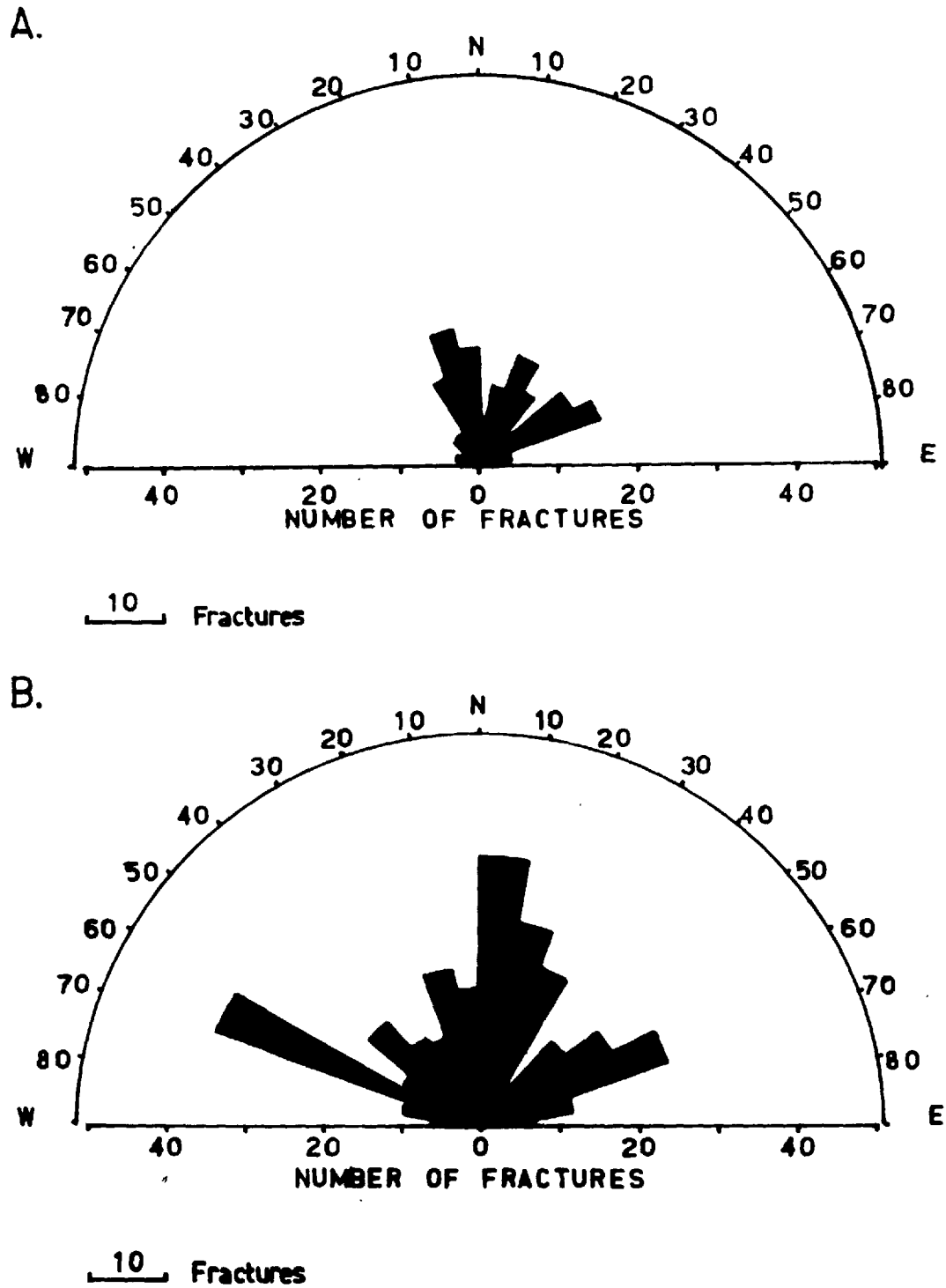
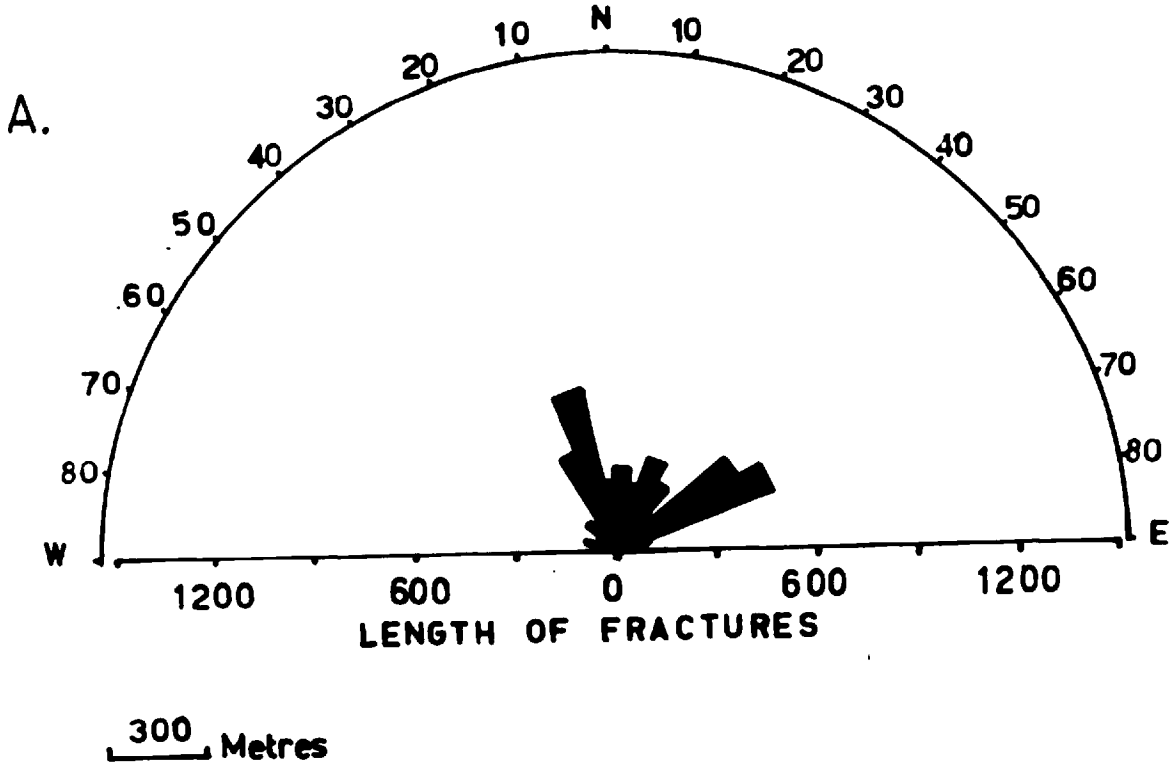


Fig. 29-a . Rose diagram of fracture trace directional distributions.



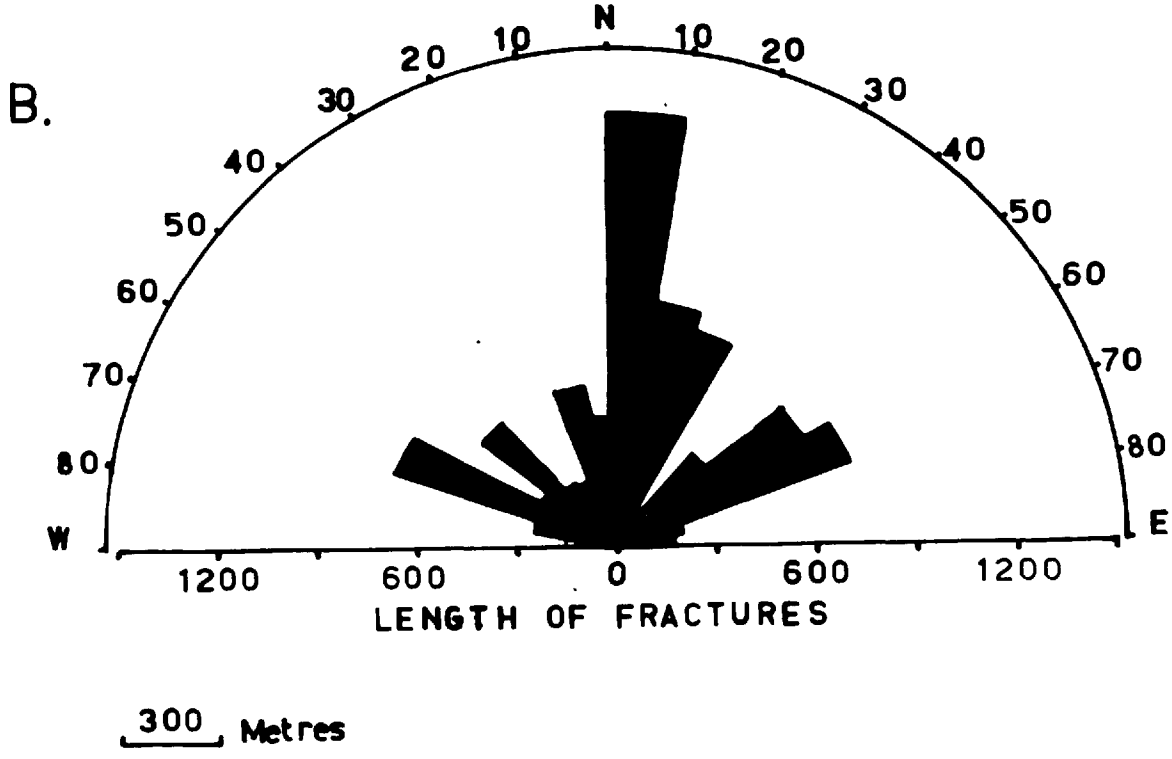
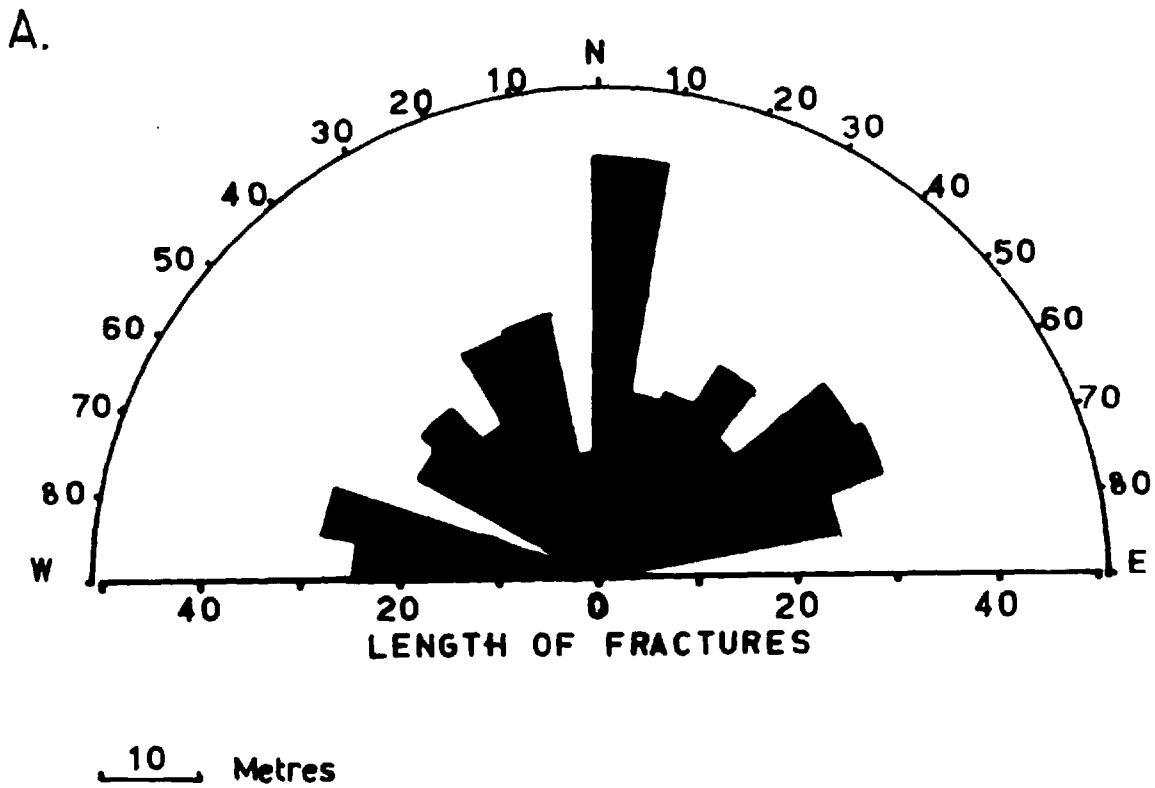


Fig. 29-b . Rose diagram of fracture trace directional density.



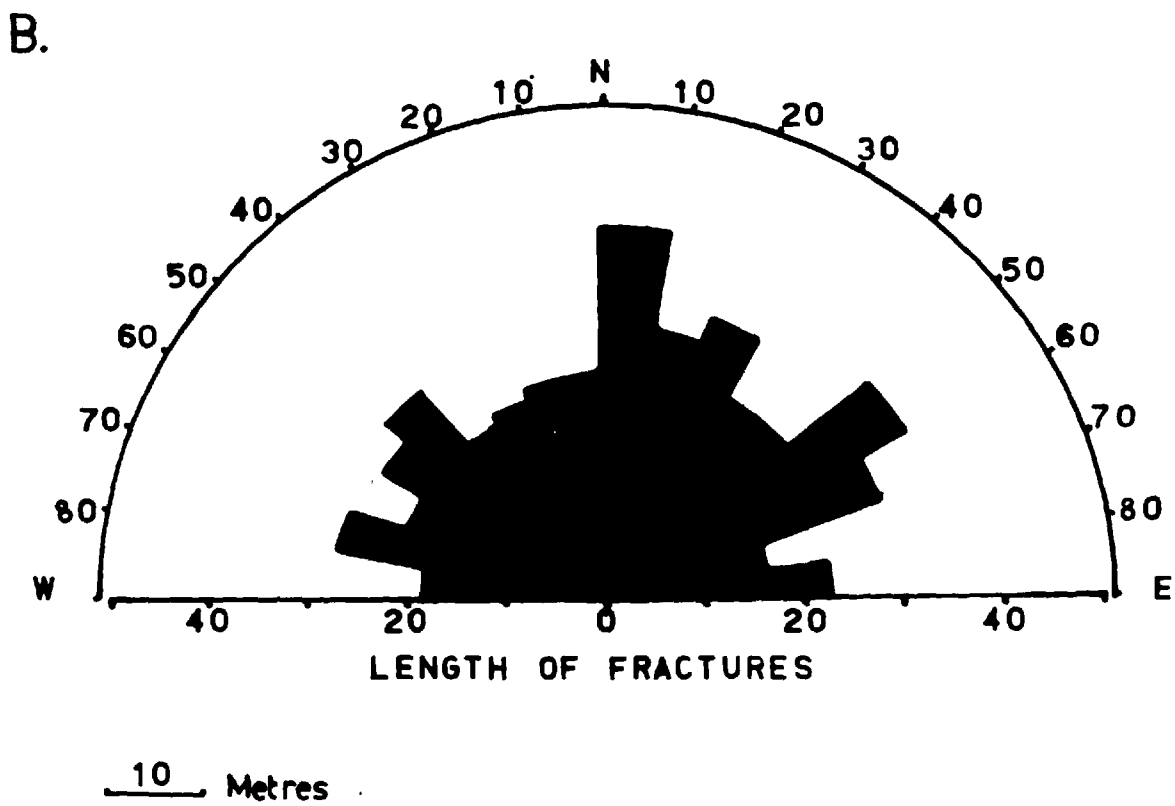


Fig. 29-c . Rose diagram of fracture trace directional average length.

between northern and southern flanks could have been due to: - (i) the difference in the area of exposures on both flanks, (The area of the southern flank where the study was made, is larger than the area on the northern flank. If the exposures on the southern flank are taken as 100%, then the percentage of exposures on the northern flank is approximately 50%), (ii) the thickness of the soil cover, (The photographs reveal that the northern flank is much more covered by a soil mantle than the southern flank.), (iii) the attitude of bedding, (The beds on the southern flank dip at 60° - 70° while on the southern flank they dip at 20° - 30°.), (iv) the difference in magnitude of stress in the flanks.

5.6. DRAINAGE CHARACTERISTICS:

5.6.1 GENERAL CONSIDERATION:

It should be emphasized that throughout this investigation, the term 'drainage' refers to both wet and dry courses. It is often only the expression of surface swales or low areas.

Drainage analysis is an important part of air photographic investigation. A study of the drainage system can produce information in several ways. It is controlled by the slope of the surface and the types and attitudes of the underlying rocks.

There are also noticable differences in drainage patterns in regions where the rocks are bare or are covered with superficial deposits. "Drainage patterns are formed of straight and curved lines. Where there is no structural control stream channels are curved". (PARVIS, 1950). Therefore, they reflect to some extent the lithology and structure of a region. However, it is not be assumed that the drainage pattern element can be relied upon alone in the identification of lithologies by the use of air photographs, but it might be used in conjunction with the other elements.

The drainage network is the most outstanding characteristic for the identification of limestone areas. In limestone regions, sinkholes and underground solution channels are developed and absorb the runoff because of the solubility of the rock and its fissured character. Consequently, there is a general absence of large scale surface drainage. This criterion can be applied to areas of Carboniferous Limestone, except where the limestone is covered by impermeable soils.

5.6.2. DRAINAGE PATTERN ON CARBONIFEROUS LIMESTONES:

An analysis of drainage characteristics in the northern part of the Derbyshire dome revealed that the

change of the drainage pattern coincides with the change of lithology. (Fig. 30).

Where the Carboniferous Limestone is surrounded by Edale Shale, a member of Millstone Grit. The drainage patterns in each unit are quite distinct. The drainage pattern in the shale area is rather centripetal. The first order tributaries join the second order tributaries at acute angles and a group tributaries converge to a common point. The density and frequency of drainage is great when compared with the limestone area, as the density refers to the relation of stream length and the frequency refers to the number of streams. On the other hand, the drainage pattern in the limestone is subdendritic or angular.

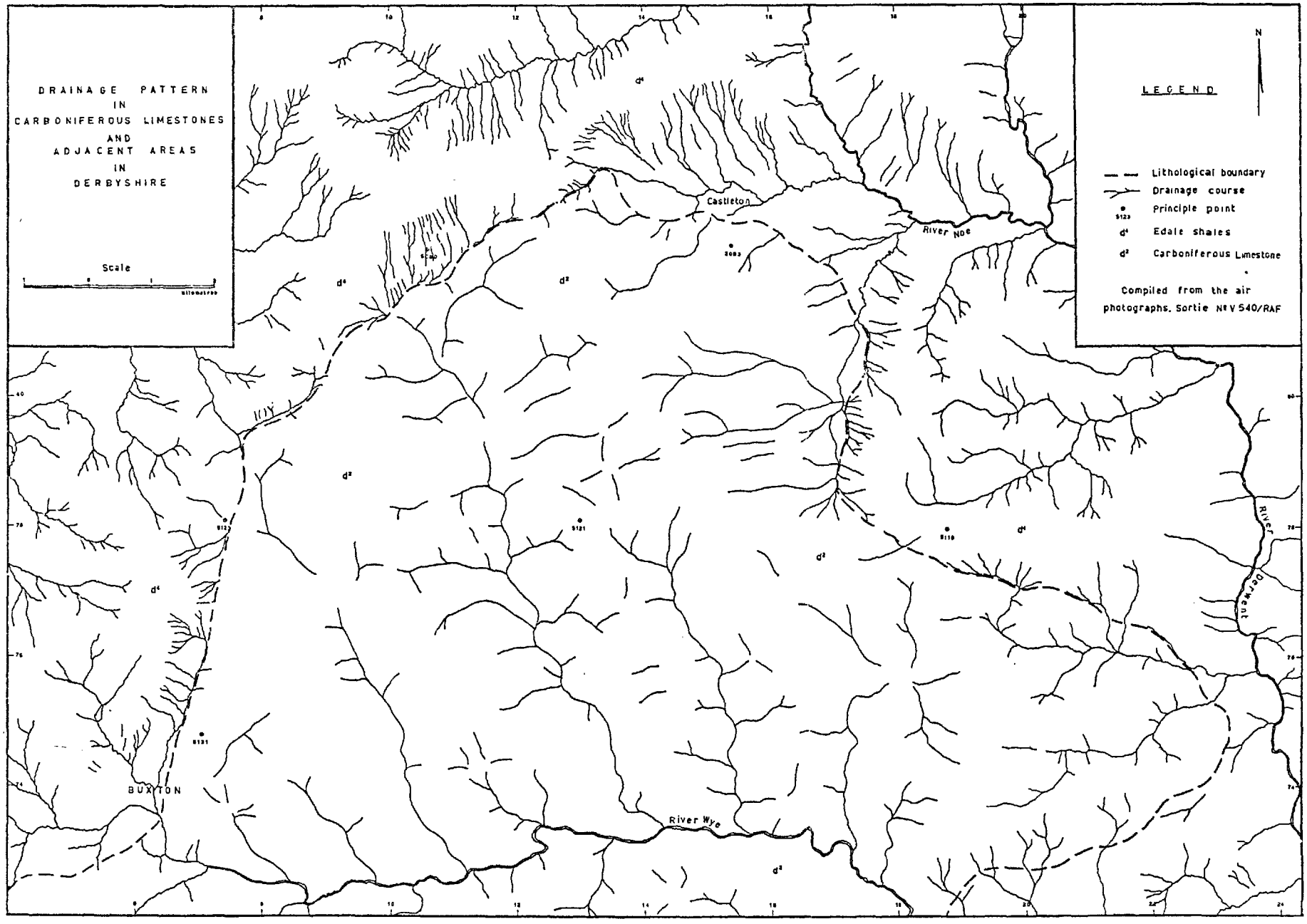
The frequency of drainage in the limestone indicates that immediate runoff is less than for the adjacent shale area. However, it reveals a considerable amount of surface drainage.

The texture of drainage is also affected by the intensity and spacing of fractures. If the drainage map is compared with the fracture trace map of the same area, (Fig. 20), it is found that there is a close relation between the both patterns within the Carboniferous Limestone areas.

A different type of investigation was made to show

Fig. 30 . Air photo drainage map.

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the influence of structure on the drainage pattern. A study was carried out in measuring the angles at which tributaries join in two areas chosen as a representative respectively of Carboniferous Limestone and Edale Shale.

The study revealed that the majority (23%) of tributaries that join main stream at right angles in the limestone area whilst 13% are in shales. The study of fracture traces in the region showed that there is a close relationship between the angles of tributaries and the directions of fracture traces. (Fig. 31). It is believed that the drainage pattern is to some extent controlled by the geological structure of the area. The second most frequent group of angles (in the class 65° - 70°) is 22% in limestone, whilst it is 19% in shales. The number of angles of the class 30° - 60° is almost the same (nearly 40%) in both rocks. No tributary joints with an angle of less than 30° in limestone, in fact, only 3% of the whole tributaries are in this group. On the other hand, in shale 20% of the whole number of tributaries are in class 10° - 30°. (Tab. V.)

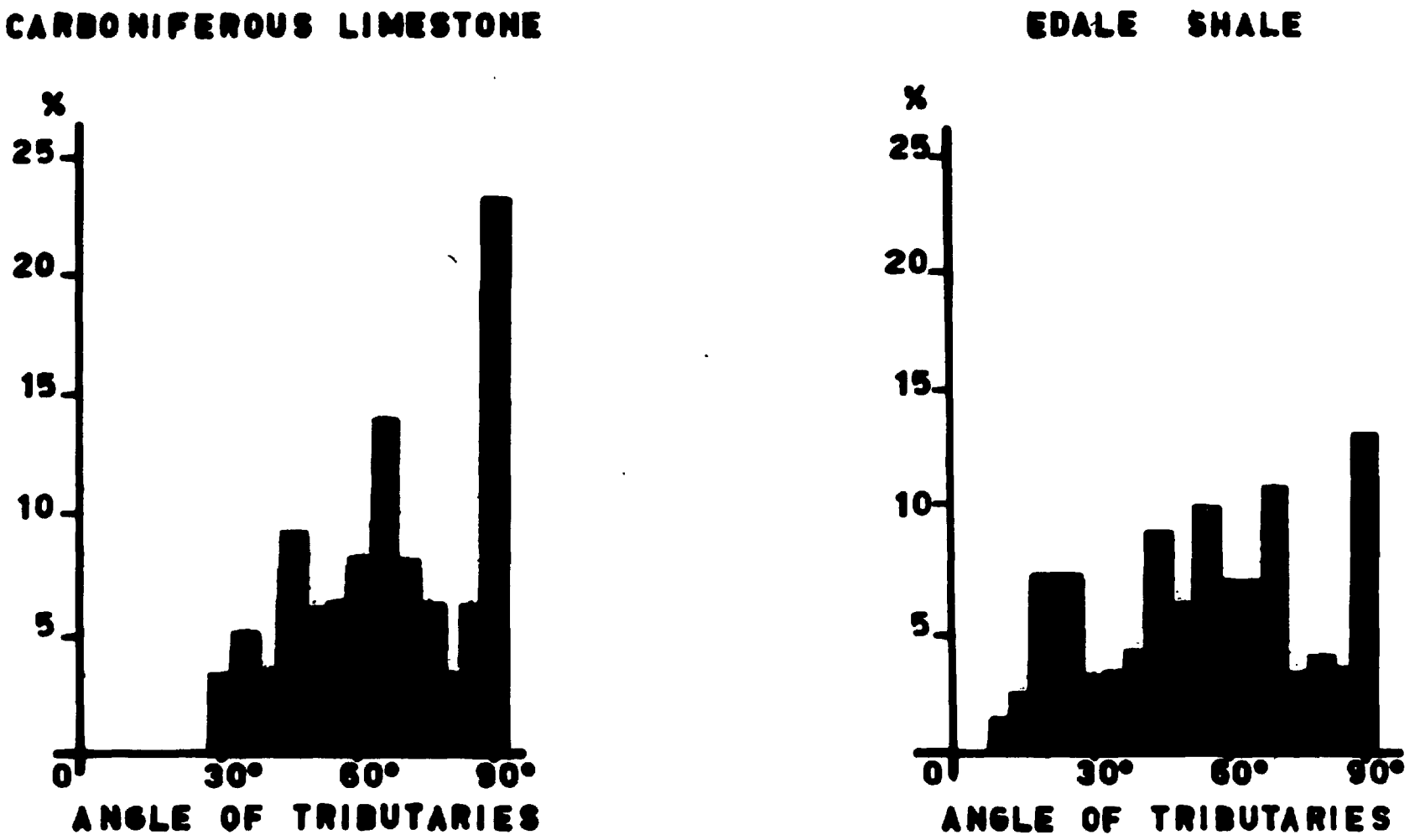


Fig. 31 . Histogram of stream tributary angles (angles of junctions) frequency distributions.

TABLE V.

Rocks	Class (Angles of tributaries) 0°-30°	30°-60°	60°-90°	No. of cases
Carboniferous Limestones	3%	37%	60%	35
Edale Shales	20%	39%	41%	70

The above mentioned tests have been carried out mainly on the drainage pattern. The individual valleys also have some characteristics in cross section and profile. In the limestone terrains, the valleys have been cut rather deeply with steep valley-walls and flat bottoms, having usually an U shape.

These characteristics are almost the same for most of the Carboniferous Limestone outcrops with some difference locally. Apart from climatic conditions and the structural setting of the rocks, the lithology may be detected by means of the study of the valley forms.

The valleys have been observed in a careful inspection of the photographs of Carboniferous Limestone in the area between Dove Dale and Wirksworth, Derbyshire. The common U shape has been converted into a deep U's with narrow bottoms. The smooth edges of the valleys have also been modified into sharp edges and corners. (Fig. 10).

It is thought that this must be due to the presence of the individual breccia beds which are usually no more than 0.5 metre thick ("a foot or two in thickness" PARKINSON, 1949) and have tended to modify the valley form to some extent in the massive limestones.

A similar study was carried out on the photographs of the Peak Forest district, Derbyshire where the lower beds of Carboniferous Limestone, locally known as 'Woo Dale beds', crop out and are surrounded by other limestone beds, locally known as 'Bee-Low Limestones' in the middle zone of the succession.

The Bee-Low limestones produced valleys having a cross sectional shape of a symmetric U with nearly vertical sides, whilst the Woo Dale beds formed valleys having an assymetric U cross section with inclined sides. It is believed that this is due to different lithologies and textures. The Bee-Low limestones consist of massive limestone, for the most part of uniform lithology, fine grained with a characteristic vertical jointing. The Woo Dale beds are thin bedded limestones with calcite-mudstones in thick lenses and bands.

Consequently, the change in valley cross section may reflect local changes in facies, and it was possible to differentiate the two formations by means of the diffe-

rence in the shapes of valleys.

However, it must be remembered that this sort of study can only be applied in the areas covered with a residual soil.

5.7 SUPERFICIAL COVER:

'Superficial cover' is meant to be the deposits of unconsolidated detritial material lying on the bedrock, generally unstratified.

The superficial cover sometimes plays a leading part in photogeologic investigations. In the areas where the large proportion of the geological features are covered extensively by superficial deposits, as in most parts of the British Isles, the identification of the ground characteristics on air photographs may be considered as an important field of study for researchers. So far, the only specific investigation was carried out on linear features in areas obscured by superficial cover. (NORMAN, 1968).

It is believed that recent techniques in remote sensing will open new horizons in detection and observation of ground conditions of concealed bedrocks. There is ample scope for further research in this branch of photogeology.

The current conventional photography has limited facilities to work with; deep penetration through the

mantle is not so satisfactory and the interpretation still depends mostly on the photogeologis's stereoscopic vision.

The present investigation involved working in the covered areas as well as bare rock. Almost everywhere the Carboniferous Limestone is covered by superficial deposits varying from one or two centimeters to some tens of centimeters in thickness. In most parts of the Ingleborough district, the Carboniferous Limestone outcrops are found as bare rocks at almost every level, and a narrow strip along the seashore of the Gower peninsula is also uncovered by the wave action. Consequently, a lot of geologic information can be obtained without much difficulty. The rest of Carboniferous Limestone regions is covered by soils, either derived from the limestone over which they lie, or else they have been transported.

5.7.1 TRANSPORTED SOIL:

The detection of the surface indications of various physical changes in rocks under a superficial cover is usually difficult, and the interpretation is sometimes far from certain. This is true for the areas where the rocks are obscured by extensive transported soil.

The most common transported soil in the areas studied is the boulder clay. Being of glacial origin, boulder clay is an unstratified or little stratified, unsorted deposit of silty and clayey materials in which are embedded particles in the size range from sands to boulders, rather than a true clay.

A mantle of drift, as it is collectively called, not only covers the actual topography but also tends to change the surface features. Deposits originally carried by ice scraped off the ground. The linear features on the drift deposits or the scratches on the limestone pavements may show the direction of ice movement. This is clearly shown in Fig. 32.

On the air photographs, glacial drift appears in mottled tones as it is composed of various materials of different origins. Because "mottling of tones indicates non-uniform soil conditions within short distances" (LIANG, et al., 1951). Sometimes erratics of rocks of different ages may be found over the Carboniferous Limestone exposures. However, "the medium grey tone and the gently undulating ground are typical of clayey glacial soils". (NORMAN, 1969).

There is, in fact, no specific criterion for recognition of the underlying rocks in the transported soil cover areas. In the areas where there is a thin cover

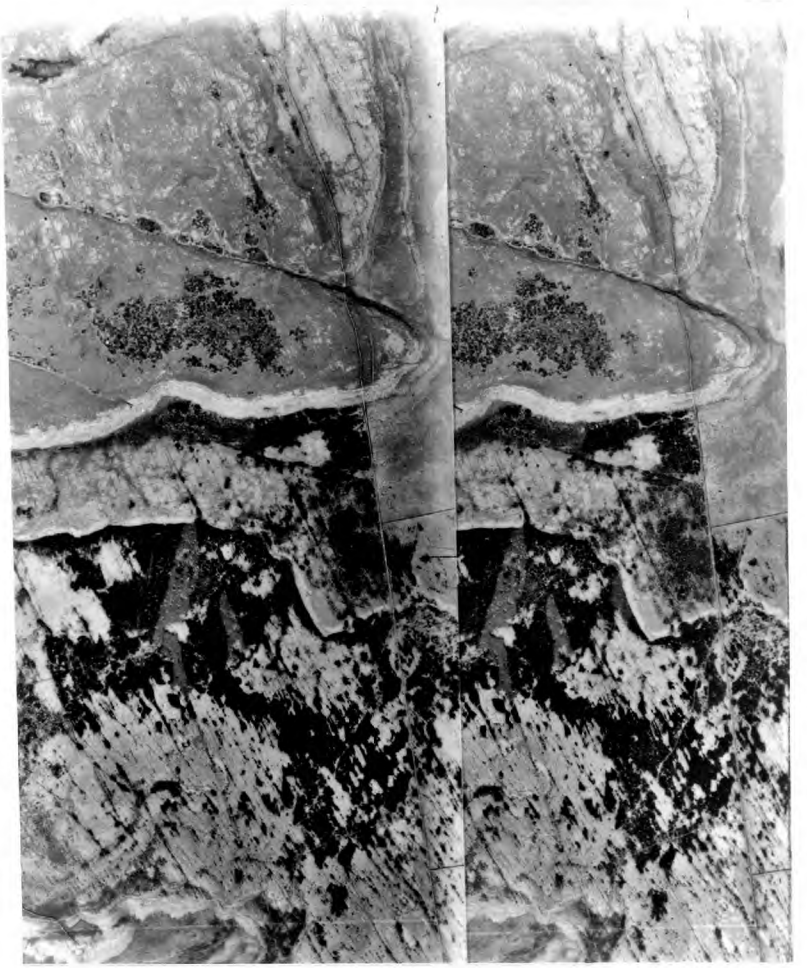


Fig. 32 . Glacial features (including grooves found in unconsolidated deposits) are indicative only of glacial action and their shapes have special terrain significance. Striae and grooves indicate the general direction of glaciation. In some areas, the glaciation can obscure fracture lines parallel or near parallel to glacial flow. But in this stereopair the dominant direction of fractures is in 330° on the upper half of the photograph, while the 340° indicates the direction of glaciation on the lower half of the photograph. (Ingleborough district, Yorkshire).

of boulder clay, the rock contacts and faults may be reasonably detected (see sec. 5.3 and 5.5.), but not to same extent as in the areas covered with residual soil.

One of the main difficulties in the aerial view of the ground features of the Carboniferous Limestone areas is the blown sand which occupies quite a large area. It is spread over several hundreds of metres of the inland areas on the Pembrokeshire and Gower coasts, and on the northern coast of Anglesey.

The blown sand forms unconsolidated dunes, yellow-brown in colour, with scanty vegetation usually scrub growing on them. The areas where the plants thrive over the sands tend to have higher moisture content and reveal a darker tone. Consequently, the overall appearance tends to be mottled tone ranging from white to dark grey.

Therefore, the interpretation in the Carboniferous Limestone areas covered with extensive blown sand may not be certain, as the sand mantle carries no lithologic identification related to the limestones. At the localities covered by a thin blown sand, some of the recognition features of the Carboniferous Limestone may be seen with difficulty (Fig. 33).

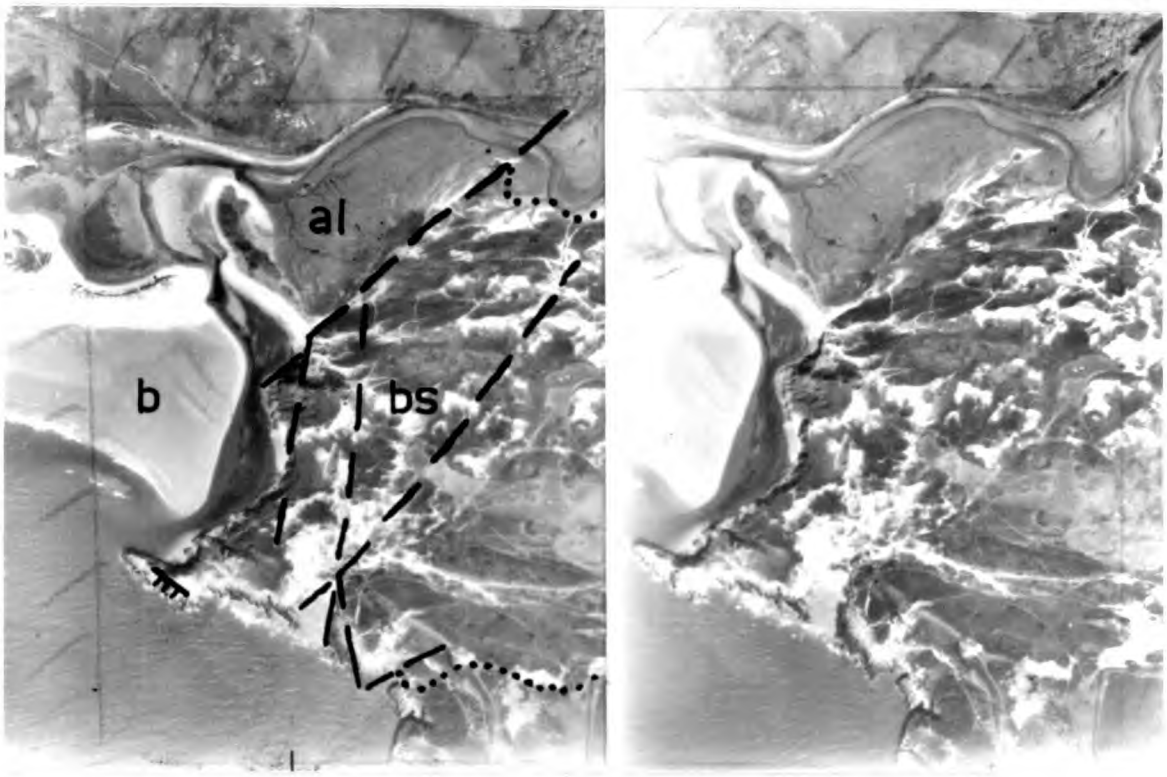


Fig. 33 . The blown sands (bs), enclosed by dotted and dashed lines (possibly faults) are revealed in mottled tone ranging from white to dark grey and are distinguished from alluvium (al); rather dark grey, smooth surface and beach sand (b); shown up in light grey tone. On the south west coast, the Carboniferous Limestone outcrops can be seen with their bare rock surfaces and steeply dipping (50^{o}-60^{o}) beds. Although the dip of beds seems more steep, this is due to vertical exaggeration of the photograph. (Three Cliffs Bay, Gower).

5.7.2 RESIDUAL SOIL:

The term 'Residual soil' is used for the soil which formed in place by the disintegration and decomposition of bedrock. On the photographs of the areas where the Carboniferous Limestone is masked by residual soil cover, the interpretation of the rocks underneath may be reasonably accurate compared with that of transported soil, but not as much as the bare rock surface.

Residual soil reflects to some extent the bedrock underneath. It does not depict the lithology, but change in lithology can be interpreted. This is true for residual soil only, in fact, the superficial cover tends to obscure the topographic features related to lithology and complicate the analysis of erosional topography.

For interpreting the residual soil covered areas, it is necessary to have acquaintance with the photographic expression of the soil derived from the Carboniferous Limestone, as it plays an important part in differentiation of various lithologies. This, of course, depends mostly on the thickness of the cover; the thicker the cover, the more obscure the bedrock surface.

In the areas studied, the soils developed on Carboniferous Limestone are usually quite deep because of the humid climate. In some localities the thickness reached

up to two metres (e.g. in the Derbyshire plateau), being dominantly clay and loam carrying luxurious growths of vegetation which obscures the photographic tone of soil. Generally the tone of the residual soil is medium to dark grey.

In the present investigation, most attention was paid to the recognition of the residual soil derived from the Carboniferous Limestone.

6. EVALUATION OF THE RESULTS OF THE INVESTIGATION:

The following results have materialized from the investigation:-

6.1 PHOTOGRAPHIC TONE

The study of photographic tones in the Carboniferous Limestone areas showed that:-

(i) The light grey tone is common for the exposed limestone rock similar to any limestone terrain in humid areas.

(ii) In those parts of the study areas covered with considerable soil, the photographic tones are rather dark grey.

(iii) The presence of shales and cherts also changes the overall tone from light to dark and mottled. The reef limestones show irregular light and dark grey tones, while the black limestones reveal rather white to near white photographic tone.

(iv) The light tone is also broken by the occurrences of dark spots or patches which mark the sinkholes.

6.2 RELIEF:

It seems that the air photographs can give a quite clear impression of the relief characteristics of the

limestone. Such as:

(i) The degree of denudation of limestone is quite extensive and produces an area of subdued topography rather than bold relief.

(ii) Karstic features can be seen in almost every limestone district with or without overburden. Collapse structures are common and can be seen in most areas.

(iii) In the areas of bare rock surfaces, the nature of the Carboniferous Limestone is typified by the appearance of the extensive development of fracturing.

(iv) In a number of areas, the Carboniferous Limestone is masked by superficial cover and the rock surfaces cannot be seen. However, it forms an upland area with a broad belt of rounded hills, cut steeply sided valleys.

(v) The numerous lead-zinc mining excavations are also typical for many Carboniferous Limestone landscapes, and show as a number of lodes pitted by miners.

6.3 LITHOLOGY:

The studies of lithologic variations in the Carboniferous Limestone on the air photographs showed that:-

(i) The current subdivisions of the Carboniferous Limestone are not always suitable for a photographic

interpretation study, since this classification is based on mainly faunal zones and since there is no marked boundary between the divisions as differentiated in faunal classification.

(ii) Instead, recognition features have been found for various types of Carboniferous Limestone as listed in the appendix. However, these features are local in application and should not be accepted as a general guide for all areas.

(iii) The masking effect of superficial cover on the Carboniferous Limestone outcrops made the interpretation difficult on many photographs, but in areas covered with only a thin soil, the recognition of units was quite easy.

(iv) Attempts to find a relationship between the vegetation over the Carboniferous Limestone areas and the lithology were made, but no reliable recognition features were found to detect the lithologies by means of the plant community alone on the panchromatic photography available.

6.4 BOUNDARY CHARACTERISTICS:

The Carboniferous Limestone landscapes could be easily distinguished from other terrains and the boundary

could be detected quite accurately. As far as boundary characteristics are concern, the study of photographs revealed that:-

(i) The boundaries with the sedimentary rocks, e.g. Ordovician shales, Old Red Sandstone, Millstone Grit and Keuper Marl, showed no transitional zone, but were linear instead, although the photogeology textbook of the Cornell group (LIANG, et al., 1951) described the presence of "a transitional zone when adjacent to other sedimentary rocks". It is believed that the lack of well exposed surfaces of Carboniferous Limestone is responsible for this statement.

(ii) The boundaries with the metamorphics, e.g. Mona complex and Ingletonian series, were almost the same, i.e. linear.

However the adjacent rocks could be differentiated by their own pronounced photographic characteristics controlled mostly by differential erosion and lithological constituents.

(iii) Although the dolerites have caused thermal alteration to the Carboniferous Limestone at the contacts, it has not been detected on the photographs studied because of the small outcrops and the thick soil cover.

6.5 FRACTURE TRACE

Fracture trace analysis on Carboniferous Limestone areas showed that:-

(i) According to the comparison of the drainage and air photo fracture trace maps, the fracturing in the Carboniferous Limestone area (northern part of the Derbyshire dome) commonly controls the drainage.

(ii) The fracture patterns in every individual bed or horizon of Carboniferous Limestone exhibit different patterns from that in the bed above or below, and easily seen on bare rock surfaces of the area (the Ingleborough district).

(iii) In the Ingleborough district the average length of fractures is slightly greater in the Carboniferous Limestone (Great Scar Limestone) than in the adjacent Yoredale series (limestone, sandstone and shale intercolations) and the Ingletonian slates and grits, because the Great Scar Limestone is made up essentially of thick bedded limestones with thin shale bands and the competency of limestone appears to give much more pronounced fractures and longer lengths than the other two rocks. The secondary cause is the masking effects of alluvium and drift over the two rocks.

(iv) In addition to the above mentioned causes, the differences in orientation, frequency and length of

fractures in the Carboniferous Limestone displayed on the flanks of the Black Down pericline (Mendip Hills) are due to the size of the outcrop, the dip of the beds and the difference in magnitude of stress in the flanks.

6.6 DRAINAGE

The drainage pattern is the most consistently reliable indicator of limestones because of the general absence of large scale surface drainage, except where they are covered by impermeable soil.

The study of the drainage patterns on the photographs of the Carboniferous Limestone and adjacent shales revealed that the change of the drainage pattern coincides with the change of lithology.

Valley shapes were also indicative to some extent in reflecting the lithologies within the Carboniferous Limestone. The change in facies from massive limestone to limestones with breccia beds or calcite-mudstone lenses and bands, was locally reflected in the valley cross sections.

6.7 SUPERFICIAL COVER

The superficial cover over the Carboniferous Limestone exposures has usually reduced the information that can be obtained from the photographs.

This was quite serious in some areas covered with an extensive transported soil, e.g. glacial drift, blown sand. No reliable indicator could be found as the mantle carried no lithologic identification related to the Carboniferous Limestone.

This is not the same for the residual soil as it reflects to some extent the lithology underneath, e.g., medium to dark grey tone is usual for the Carboniferous Limestone areas.

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8. APPENDIX

The following recognition features have been obtained from the investigation:-

Type of limestone	Characteristic appearance	Typical example
Massive limestone	Rough surface, higher ground, grazing and woodland, sinkhole development	Black Rock Limestone of the Mendip Hills, Main Limestone of Gower peninsula and Pembrokeshire
Massive limestone fine grained	Valleys having a symmetric U shape, with nearly vertical sides	Woo Dale beds of the Peak Forest district, Derbyshire
Massive limestone with breccia beds	Besides the usual appearance of massive limestone, deep U shape valleys with narrow bottoms, and sharp edges and corners	Alsop Moor Limestone of Dovedale and Wirksworth, Derbyshire
Massive limestone with abundant lead-zinc mineralization	Pitted ground, in various directions usually along the major fractures with a pile of spoil white in colour	The Derbyshire dome and Black Down pericline, Mendip Hills
Medium to thick bedded, black limestone with thick shale beds	White photographic tone	Upper Dark Grey Limestone of Trwyn Dinmor (the Penmon area) Anglesey

Type of limestone	Characteristic appearance	Typical example
Thin bedded limestone with calcite-mudstone lenses and bands	Valleys having an asymmetric U cross section with inclined sides	Bee-Low Limestone of Peak Forest district, Derbyshire
Flat lying, fine grained limestone (bare rocks)	White or near white, abundant fractures, numerous circular sinkholes	Great Scar Limestone in the Raven and Twisleton Scars, Ingleton, Yorkshire
Flat lying limestone covered by thin soil and peat	Light grey tone broken by black patches of peat	Great Scar Limestone of Houghton Scars, Ribblesdale, Yorkshire
Moderately dipping limestone with some superficial cover	Light to dark grey changing with the thickness of superficial cover, elongated sinkholes, smooth surfaces due to soil cover	Most parts of the Derbyshire dome and the Mendip Hills
Grey limestone, medium to thick bedded with thin shale bands	Light grey photographic tone	Middle White Grey Limestone of Parc Trwyndu (the Penmon area) Anglesey
Limestone-Shales	Darker tone, smooth surfaces, lower ground	Lower and Upper Limestone-Shales formations of Pembrokeshire, Gower and the Mendips

Type of limestone	Characteristic appearance	Typical example
Oolitic limestone	Lighter tone, poorly-bedded	Burrington and Cheddar Oolites of the Mendips
Cherty limestone	Mottled tone, higher ground, sharp and cragged edges	The chert bands of Hotwell Limestone in the Cheddar gorge, Mendips and the cherty beds of Monsale Dale beds, Derbyshire
Reef limestone	Irregular light and dark grey tone, largely unbedded, hummocky topography, sometimes knoll shape	Castleton and Dovedale, Derbyshire
Dolomitic limestone and dolomites (covered)	No adequate recognition feature were detected	Matlock-Wirksworth area, Derbyshire and the Mendip Hills

9. REFERENCES:

AMERICAN GEOLOGICAL INSTITUTE. 1962. Dictionary of geological terms. Doubleday and Company, Inc., New-York.

AMERICAN SOCIETY OF PHOTOGRAMMETRY. 1960. Manual of photographic interpretation. Washington, D.C.

BENNISON, G.N. and WRIGHT, A.E. 1969. The geological history of the British Isles. Edward Arnold Ltd., London.

BLANCHET, P. H. 1957. Development of fracture analysis as exploration method. Bull. Ame. Ass. Petrol. Geol., V. 41, no. 8, pp. 1748-1759.

BOND, G. 1950. The Lower Carboniferous Reef Limestones of Northern England. Jour. Geol. U.S.A., v. 58, no. 4, pp. 313-329.

BOYER, R.E. and MCQUEEN, J.E. 1964. Comparison of mapped rock fractures and air photo linear features. Photogramm. Engg., v. 30, no.4, pp. 630-635.

DI PENTIMA, A.F. 1970. Automation in photo interpretation. Photogrammetria, v. 26, no. 5/6, pp.167-182.

EDWARDS, W. and TROTTER, F.M. 1954. British regional geology, the Pennines and adjacent areas, H.M.S.O., London.

ERB, D.K. 1967. Aerial photo interpretation in the study

of humid tropical geomorphology in Jamaica. 33th Annual meeting of Ame. Soc. of Photogramm., Washington. (Abs. Photogramm. Engg., v.33, no. 6, p.674. and v. 34, no. 11, pp. 1148-1160).

GEORGE, T.N. 1958. Lower Carboniferous paleogeography of the British Isles. Proc. Yorks. Geol. Soc., v.31, no. 10, pp. 227-318.

GEORGE, T.N. 1961. British regional geology, North Wales. H.M.S.O., London.

GEORGE, T.N. 1970. British regional geology, South Wales. H.M.S.O., London.

GOLBRAYKH, I.G. et al. 1966. Tectonic analysis of mega-jointing. Int. Geol. Rev., v.8, pp. 1009-1016.

GREEN, G.W. and WELCH, F.B.A. 1965. Geology of the country around Wells and Cheddar. Mem. Geol. Surv. G.B., London.

HACKMAN, R.J. 1967. Time, shadows, terrain and photo interpretation. U.S. Geol. Surv. Prof. paper 575-B, pp. B155-B160.

HAMAN, P.J. 1961. Lineament analysis on aerial photographs. West Can. Res. Publ., ser. 2, no. 1, Calgary.

HAMAN, P.J. 1964. Geomechanics applied to fracture analysis. West Can. Res. Publ., Calgary.

KELLAWAY, G.A. and WELCH, F.B.A. 1948. British regional geology, Bristol and Gloucester district. H.M.S.O. London.

LATTMAN, L.H. 1958. Technique of mapping geological fracture traces and lineaments on aerial photographs. Photogramm. Engg., v. 24, no.4, pp.568-576.

LATTMAN, L.H. and PARIZEK, R.R. 1964. Relationship between fracture traces and the occurence of ground water in carbonate rocks. Jour. Hydrology, v.2, no.2, pp. 73-91.

LIANG, T.A. et al. 1951. A photo analysis key for the determination of ground conditions. Tech. Rept. 3, U.S. Office of Naval Research, Cornell University, New-York.

NORMAN, J.W. 1968. The geological significance of natural linear features occuring in areas of superficial deposits, as revealed by air photographs. Ph.D. Thesis, University of London.

NORMAN, J.W. 1968. The air photograph requirements of geologists. Photogramm. Record, v.6, no.32, pp. 133-149.

NORMAN, J.W. 1969. Photo interpretation of boulder clay as an aid to engineering geological studies. Q. Jour. Engg. Geol., v.2, no.2, pp. 149-157.

NORMAN, J.W. and WALTHAM, A.C. 1969. The use of air photographs in the study of karst features. Trans. Cave Res. Group G.B., v.11, no.4, pp.245-253.

PARKINSON, D. 1949, The stratigraphy of the Dovedale area, Derbyshire and Staffordshire. Q.Jour.Geol.Soc., v.55, no.2, pp. 265-294.

PARVIS, M. 1950. Drainage pattern significance in airphoto identification of soils and bedrocks. Photogramm. Engg., v.16, no.3, pp.387-409.

RAYNER, D.H. 1967. The stratigraphy of the British Isles. Cambridge University Press.

RENNER, J.G.A. 1968. The structural significance of lineaments in the Eastern Montesch area, Province of Lerida, Spain. ITC Publ. ser. B, no.45. Delft.

RICH, J.L. 1928. Jointing in limestones as seen from the air. Bull. Ame. Ass. Petrol. Geol., v.12, no.8, pp.861-862.

SMITH, E.G. et al. 1967. Geology of the country around Chesterfield, Matlock and Mansfield. Mem. Geol. Surv. G.B., London.

TIDDEMAN, R.H. 1892. The theory of knoll-reefs. Craven Herald (29 January).

TRAINER, F.M. and ELLISON, R.L. 1963. Fracture traces in the South-Central Shenandoah Valley, Virginia. Geol. Soc. Ame. Special paper 76, (Abs. for 1963), p..260.

WAGER, L.R. 1931. Jointing in the Great Scar Limestone of Craven and its relation to tectonic of the

area. Q. Jour. Geol. Soc., v.87, no.347, pp.392-424.

WALTHAM, A.C. 1970. Cave development in the limestone of the Ingleborough district. Geog. Jour., v. 136, no.4, pp.574-585.

WASTENSON, L. 1966. Mapping of bedrock outcrops by aerial photo-interpreation. (Swedish text). Sveriges Geologiska Undersokning. ser. C, no. 606.