ANALYSIS FROM AIR PHOTOGRAPHS OF FRACTURE TRACES IN NORTHERN IRAQ: A STRUCTURAL GEOLOGICAL STUDY WITH REFERENCE TO OIL EXPLORATION

by

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July, 1976

A thesis submitted for the degree of Doctor of Philosophy in the University of London and for the Diploma of Imperial College.

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ABSTRACT

In this study the term "fracture" is conceived as a break in the physical or mechanical consistency, (or coherence), of a rock mass. Joints, faults and other rock failures are fractures.

A "fracture trace" may be defined as an image of a fracture or an alignment of fractures appearing on an air photograph. Fracture trace analysis is a branch of the technique of photogelogy and often requires the application of statistical methods and data processing equipment.

The subject of this thesis is a structural geological study of an area in Northern Iraq based on fracture trace analysis with special reference to oil exploration in the area. The interpretation of air photographs was the main source of geological data used during the work. A digital computer was employed for processing the fracture trace data.

The thesis consists of eight chapters each of which discusses specific aspects of the work. The first chapters present a comprehensive discussion of the geomechanics of fracturing, the technique of photogeological interpretation and the application of a digital computer in fracture trace analysis. The general tectonics of the Middle East and the history of sedimentation, earth movement, and oil occurrence in Northern Iraq including the study area are extensively surveyed in certain chapters. A comprehensive analysis of fracture traces and structural characteristics

of the area is included in a separate chapter. The analysis covers various topics such as fracture trace rose diagrams and rosemaps, stress-strain trajectories, frequency contours, gravimetric lineaments and drainage.

The thesis also includes a case study of the Ain Zalah oil field. It is a detailed fracture trace analysis of the field based on the various aspects of photo-geological interpretation. At the end of this analysis, a number of conclusions about the structural characteristics of the oil field are set out.

The last chapter discusses the final results of the study and presents the conclusions reached. The latter are concerned mainly with a possible structural relationship between the fracture trace trends and folds in the area, the deep-seated or basement tectonics as expressed in block-faults and other buried structures.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. J. W. Norman for his guidance, encouragement and valuable suggestions throughout this study. Many thanks also to my colleagues in the photo-geological laboratory at the Royal School of Mines, in particular John Huntington and Adrian Lloyd Lawrence. A special thanks to my friend Heulwen Jones for her kind assistance with typing the first draft of the thesis.

The author is indebted to the Ministry of Oil and Minerals of Iraq for providing the scholarship for the study.

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CHAPTER ONE

1.1 INTRODUCTION

The subject of this thesis is a structural geological study of an area in Northern Iraq. The study is based on fracture trace analysis, and includes special reference to oil exploration in the area.

In geology, the term "fracture" is generally conceived as a break in the physical or mechanical consistency, (or coherence), of a rock mass. It can also indicate a plane or zone of failures along which the rock eventually breaks apart. The term is used in this study to describe all kinds of rock failures regardless of their classification. Thus, joints, faults and other rock failures are generally designated as fractures.

The occurrence of fracturing is often ascribed to the tectonic forces or stresses acting on the rock mass. However, many fractures have been observed in rock formations which show no apparent signs of deformation. Many authors believe that the early formation of some fracturing, (or jointing), can begin soon after the deposition of the sediments and before the full consolidation of the rock. This kind of fracturing may be called primary, while that which is caused by tectonic forces is usually called secondary.

Macroscopic rock fractures can vary widely in size. They range from centimeters in length, as with hand-specimen fractures, to several hundred miles, as in the case of regional or crustal geofractures. Descriptive names have been suggested to indicate the relative size of fractures. Examples of these are microfracture, mesofracture, macrofracture, megafracture and lineament. Fractures can occur in all directions, but most regional fractures tend to occur predominantly in specific directions within the region.

The analysis of fractures forms a significant part of structural studies. The number and size of fractures in any analysis usually depends on the type and scale of the structural investigation. In a regional geological study such as reported in this thesis, a large number of long fractures needs to be analysed. Thus, the use of air photographs becomes essential and the term "fracture trace" has to be introduced. A fracture trace may be defined as an image of that part of a fracture or an alignment of fractures appearing on an air photograph.

A fracture trace by definition is a linear photographic feature, but many linear features other than fracture traces may appear on air photographs. There are several photogeological criteria which can be used to differentiate fracture traces. Examples of these are soil tonal differences, stream alignments and vegetational lineaments.

Fracture trace analysis is a branch of the technique of photogeology and often requires the application of statistical methods and data processing equipment. The photointerpretation on the air photographs, (scales

1/20,000 and 1/3,000), was the main source of geological data used during the work. A digital computer, (CDC 6400/6600), was employed for processing fracture trace data.

The absence of a fracture trace analysis of the area as an approach to structural investigation provided the principal motivation for the present study. In addition, the exposure of the geological terrain in the area makes it amenable to photogeological work, and this further encouraged the author to test fracture trace analysis as an economic and rapid method of structural investigation.

The thesis consists of eight chapters each of which discusses specific aspects of the work. A part of chapter one and the whole of chapter two discusses the methodology of the study, the technique of photointerpretation and factors affecting it, and the compilation of the maps and digitization of the fracture traces. Chapter three deals with the theory of the geomechanics of fracturing, the quantitative and qualitative characteristics of fracture traces, and the techniques of fracture trace analysis. Chapter four discusses the application of a computer in processing fracture trace data. Chapter five describes the tectonic framework of the Middle East; the tectonic history, sedimentation and oil occurrence in Northern Iraq. Chapter six presents a comprehensive structural and fracture trace analysis of the study area. Chapter seven deals with the case study of Ain Zalah oil field. It discusses the structural characteristics and a comprehensive fracture trace analysis of the field. Chapter eight is concerned with the final discussion and conclusions.

The total number of fracture traces interpreted on the air photographs and used in this study is 7,709 fracture traces.

Finally, the present work can only be regarded as a preliminary structural study based on fracture trace analysis, and it is hoped that much work of a similar nature will be carried out in the region of Northern Iraq in order to add to the results already acquired and improve the technique of fracture trace analysis.

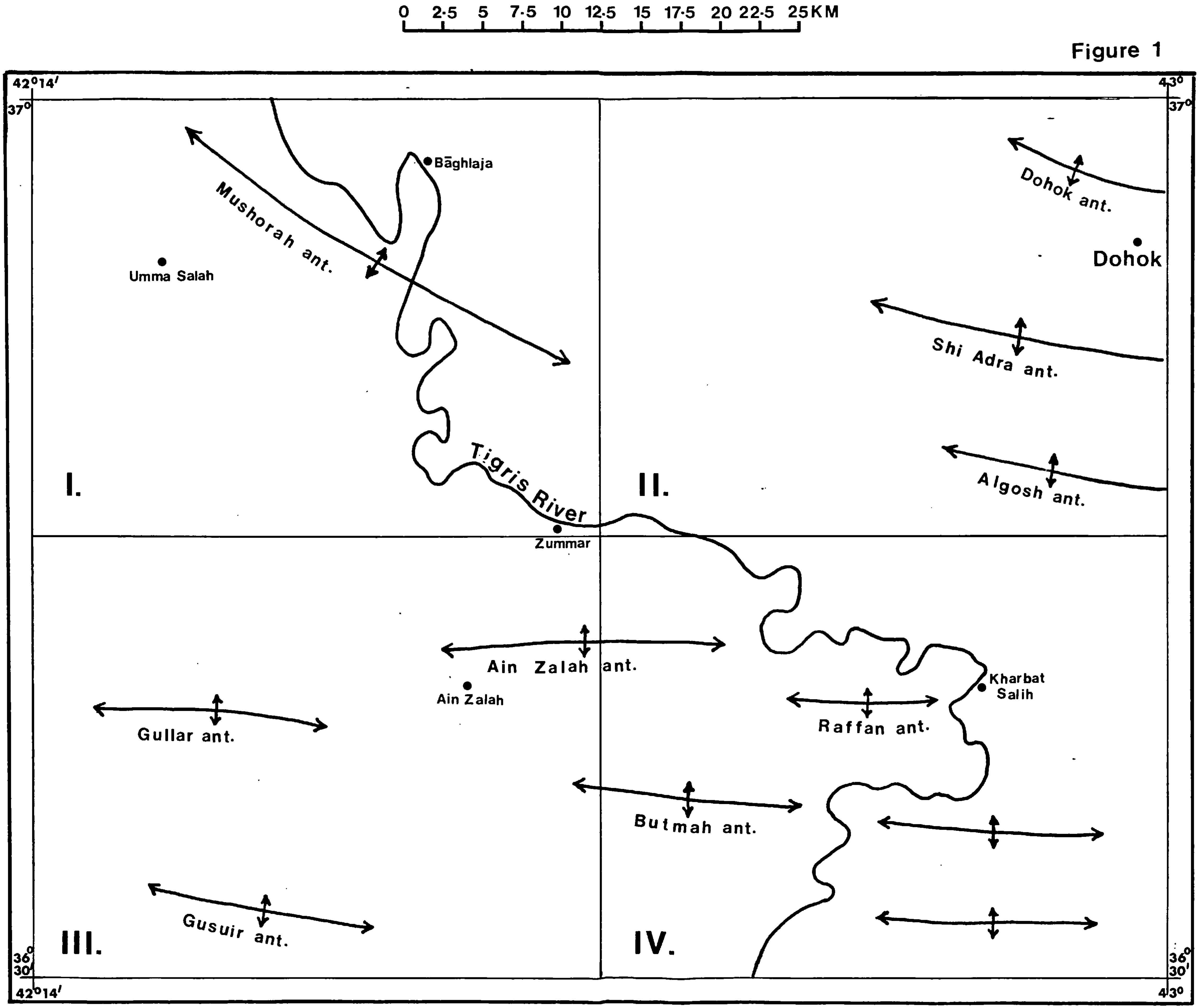
1.2 GEOGRAPHICAL AND GEOLOGICAL SETTING OF THE STUDY AREA

The region of Northern Iraq is characterised by mountainous terrain. The rugged topography of this region gradually gives way to low, hilly land in the centre, and then to flat desert in western and southern Iraq. The Zagros-Taurus mountains form a natural boundary in the east and northeast with Iran and in the north with Turkey. The area of the study is a rectangular portion of Northern Iraq situated in the north western corner, and lies between the northern latitudes 36° 30′ and 37°, and eastern longitudes 42° 14′ and 43°, (Figure 1). The size of the area is roughly 3,640 square kilometers.

The topography of the area is generally moderate and the River Tigris flows through the area, its course being

SIMPLIFIED TECTONIC MAP SHOWING SUB-AREAS OF STUDY

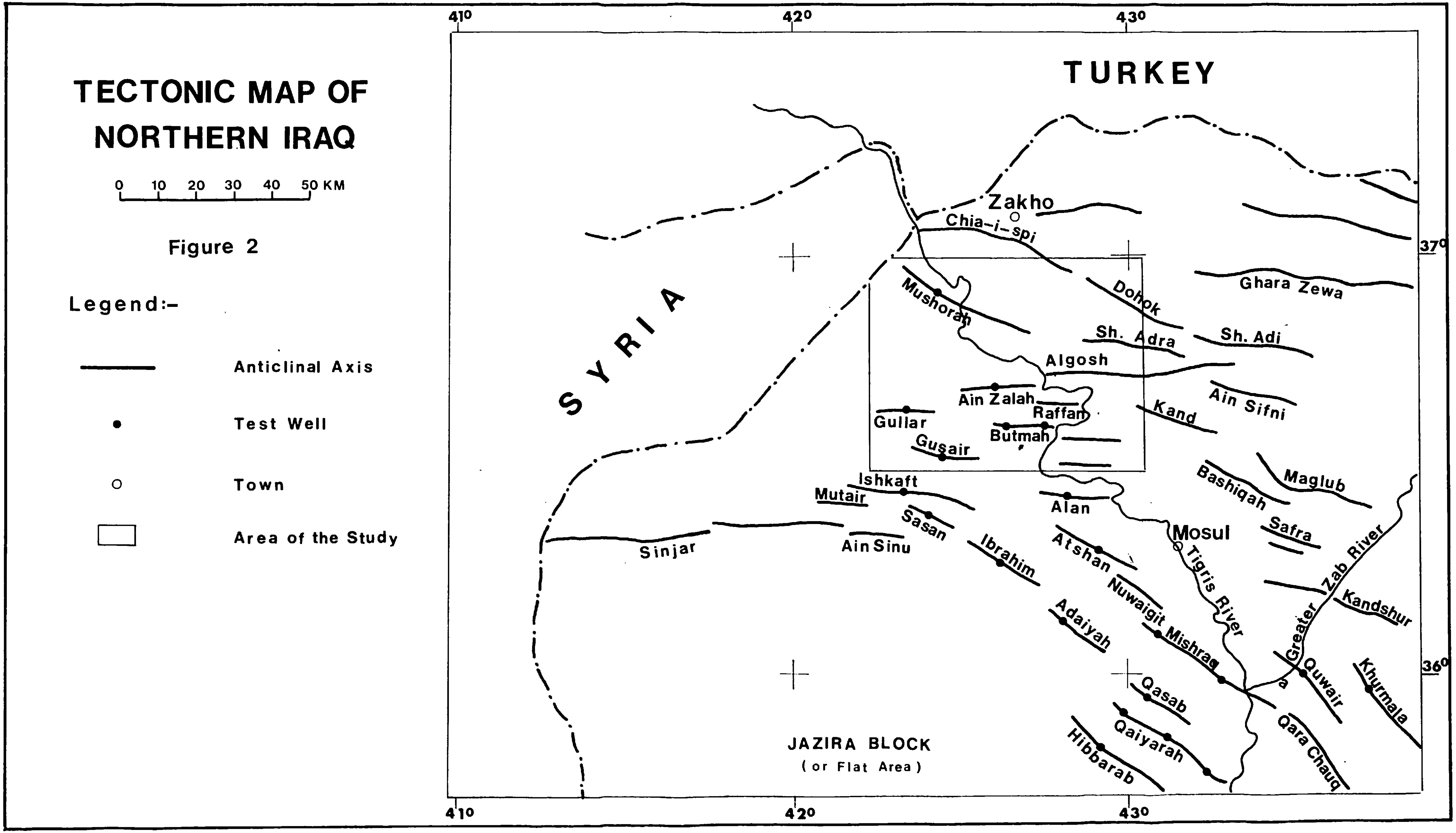
Figure 1



greatly influenced by the geomorphology of the terrain. There are a number of major streams flowing into the Tigris and these form large drainage basins in the area, (Figure 26) The general distribution and pattern of the drainage network clearly shows the impact of the structural configuration on the topography of the area. The network roads in the area is rather limited, and apart from a few asphalt roads there are many tracks connecting the villages. The only town in the area is Dohok and the main villages are Ain Zallah, Zummar, Umma Salah, Baghlaja and Kharbat Salih, (Figure 1).

The climate is mediterranean and characterised by moderate rainfall in winter and a completely dry and warm summer. Cultivation is limited to the valleys and areas near the River Tigris. The soil and natural vegetation have a minimal obscuring effect on the exposure of the geology of the area on air photographs.

Geologically, most of Northern Iraq, including the study area, falls within the foreland zone of the Zagros-Taurus alpine range. This zone is characterised by long and rather sinuous anticlinal folds running parallel to the thrust front i.e the mountain range. The regional strike of the tectonic fabric is north-western in the east, and gradually swings to east - west in the north and north-east. The study area is situated where the change in the regional strike of the zone takes place. The general strike of the fold axes in the area is east - west, with the exception of Mushorah anticline whose axial strike is


TECTONIC MAP OF NORTHERN IRAQ
0 10 20 30 40 50 KM
Figure 2
Legend:-
Anticlinal Axis
Test Well
Town
Area of the Study
TURKEY
SYRIA
Zakho
Chia-i-spi
Ghara Zewa
Dohok
Mushorah
Sh. Adra
Sh. Adi
Algosh
Ain Zalah
Raffan
Butmah
Gullar
Gusair
Ain Sifni
Kand
Maqlub
Bashiqah
Safra
Ishkaft
Mutair
Alan
Mosul
Sasan
Sinjar
Ain Sinu
Ibrahim
Atshan
Nuwaigit
Mishraq
Tigris River
Greater Zab River
Kandshur
Adaiyah
Quwair
Khurmala
Qasab
Qaiyarah
Hibbarab
Qara Chauq
JAZIRA BLOCK
(or Flat Area)
41°
42°
43°
37°
36°

north western (Figure 2). The strikes of some east - west anticlines show a slight swing to the north-west at their western ends; this occurs particularly in Gusair anticline. A comprehensive discussion of the structural characteristics of the area will be given later on in the thesis.

1.3 THE METHODOLOGY OF THE STUDY

Planning is widely recognized as a vital requirement in scientific research. In geological investigation, a systematic and methodical approach is always necessary. The merit of applying such an approach is to direct the course of the investigation to a definite conclusion in which an answer to the problem can be reached. The planning of a geological inquiry is best carried out after sufficient information about the problems involved is obtained.

The plan of this study, i.e the methodical design of the work, was conceived and roughly outlined at the beginning of the research. It was based on the principal characteristics of the study and elaborated as the work progressed. The work was carried out in several stages, each involving a specific set of activities. The stages were interdependent and complementary to one another, and were executed consecutively. The flow-chart (or the plan) of the stages, and a brief description of the activities involved in each one, can be outlined as follows:

THE STAGES OF THE STUDY	DESCRIPTION OF THE ACTIVITY
Literature survey, primary appraisal and photo preparation	General survey of literature; quick reviewing of air photographs and evaluation of their quality; determining photo scale and drawing of flight-line diagram. Preparation of base maps and filing and indexing of photos. Marking photo principal points and transferring them on to base maps. Producing stapled photomosaic.
Photointerpretation (data collection)	1. Interpretation on the photomosaic of major geological structures such as folds and long fracture traces. Delineation of important geomorphological features e.g drainage network. 2. Stereoscopic photo-interpretation of photographs which involved, a) plotting of bedding traces of fold structures and drawing of evident faults, b) plotting fracture traces only, and c) tracing drainage network. 3. Elaboration of the photogeological data by re-examining some photographs and comparing the data obtained from stereoscopic study of pairs of photographs with that obtained from the photomosaic of single photographs.
Compilation of the maps	The scale of the base maps was reduced to the photoscale. Transfer of geological data from photo-overlays on to base maps using principal points and major streams as control. Re-drawing of geological data as separate map sheets with definite scale and geographical co-ordinates.

THE STAGES OF THE STUDY	DESCRIPTION OF THE ACTIVITY
Digitizing of Fracture Traces	Dividing the study area into four sub-areas, each with a fracture trace sheet. Digitizing first the boundary of map and secondly, the fracture traces. This operation resulted in digital representation of the fracture traces on the punch cards.
Data processing and Computing	Modification of existing computer programs and devising other programs. Statistical processing and computing of digital fracture trace data, the plotting of statistical diagrams and re-drawing automatically fracture trace maps to a desired scale.
Analysis and Synthesis	General analysis of geological data and statistical diagrams already obtained. Synthesis and construction of the following figures: the fracture trace trend map, rosemaps, frequency contour map, and stress-strain trajectory maps.
Final Interpretation	Review of previous work and relevant literature. Correlation of all acquired data. Analysis of structural characteristics and fracture trace trends in the area. Analysis of rose diagrams and rosemaps. Stress-strain trajectory analysis. Contour analysis. Drainage analysis.
Conclusions	Discussion of the results i.e findings, and formulation of structural conclusions.

CHAPTER TWO

2.1 SOME THOUGHTS ON PHOTOGEOLOGICAL INTERPRETATION

Photointerpretation, in the general sense, is the act of examining the photographic images of objects for the purpose of identifying the objects and deducing their significance. However, a distinction has been made between the photo-reader whose task it is to detect and identify object images and the photointerpreter, who, in addition to identification, is able to exploit his knowledge to deduce their origin and association. As far as geology is concerned a trained photogeologist is a photointerpreter specialising in geology.

The texture of landscape, in fact, is a product of various geological agents. Tectonic movement and type of rock determine the general shape of landforms. By the reaction of rock to the atmosphere i.e weathering, the soil will form, and by erosion, the surface detail comes into existence. Thus one can infer the mutual and diverse interaction between geology and other sciences. The study of a particular area does not entirely depend on geology; it requires a broad and varied scientific background. However, the photogeologist must understand all active factors that contribute to the geological make-up of a terrain. It is widely suggested that a photogeologist at his best is a structural geologist, geomorphologist and stratigrapher. He should also have considerable knowledge of climatology, pedology and geobotany. As a photogeologist improves his visual and mental acuity and his command of photogrammetry, many obscure and subtle geological data come within his field of observation and understanding and the better his work in photointerpretation.

The geological setting of an area is a manifestation of inter-related natural forces that are dynamic i.e constantly moving and changing. This fact has been true as far back as we can interpret the earth's history, but the rate of change may vary from imperceptible to catastrophic, and the adjustments to these changes may not keep pace with changes themselves. Thus, one may expect to find different geological phenomena in one area, such as various types of rock formations which belong to different geological environments. The knowledge that no area is static, and that the present state of geology forms a record for its past, is a prerequisite for photogeological study. Therefore, the photogeologist is required to comprehend the geological history of the terrain and appreciate the processes which have produced the present geology, before he embarks on photogeological interpretation.

There are some geologists who may suspect the reliability of the information obtained from photointerpretation. This may be due in part to a lack of appreciation of the values as well as the limitations of such information, and also to attempts that have been made to formulate conclusions directly deduced from this information without supplementing it with field observations or other information. One must always remember that photogeological information is interpreted and supplied by a photogeologist, and as such should be attributed to him, rather than be regarded as generally agreed information. However, photogeological interpretation cannot be, and will never be a panacea for all ills in geological investigation, and it is only through a full understanding of its limitations that an assessment can be made of its real value.

Photointerpretation may be regarded as an art of probabilities. Thus, few things are perfectly certain in photointerpretation in the sense that one plus one makes two, but many interpretations are so probable that when all the visible evidence has been considered, they can safely be regarded as correct. The difficult part of photo-interpretation is in evaluating the evidence and judging the degree of probability regarding particular features. Reliable interpretation demands a photointerpreter with an aptitude and much experience.

A substantial proportion of the differences in results obtained by photogeologists can be attributed to variables in photographs. So many objective factors quite outside human control, impose considerable limits in the perception and the interpretation of air photographs. Some geologists who work with photographs are not fully aware of, or at least they do not give due attention to these factors. Some of these factors concern the photography, and others the technique of viewing photographs during interpretation. Therefore, in order to attain good results, the photo-geologist must understand these factors and be aware of their effects.

2.2 FACTORS AFFECTING PHOTOINTERPRETATION

2.2.1 Objective Factors

2.2.1.1 The scale of air photography

The fundamental difference between vertical air photographs and topographic maps is that the photograph is a central or perspective projection of the terrain, while a map is the orthogonal projection of the terrain on a horizontal plane reduced to a given scale. In view of this fact, the scale of a photograph is always taken as approximate, since the relative positions of the images are not identical to those on the ground, and the areas of different elevations above sea-level have different scales.

One basic method of determining the scale of the air photographs is by comparison of the photographs with topographic maps. The ratio of distances between corresponding pairs of points on both the photograph and the map, provided that both points are approximately on the same elevation, is regarded as the scale of the photograph. One of the quickest ways to determine the scale is by using data given on the margin of a photograph. The ratio between the focal length of the camera objective and flight height is the nominal scale of the photograph, and is equal to the ratio of the distances mentioned above.

Two sets of photos of different scales were involved in the study, one the Ain Zalah set, which has a scale of 1/20000 and the other, the Mushorah-Ain Zalah set, has a scale 1/30000. The former set covers the key area i.e.

the Ain Zalah structure only, while the latter set covers the whole area of the study including the Ain Zallah structure.

Colwell (1954) regards the scale as meaningful to the photointerpreter only when it is considered in terms of resolution i.e definition and image sharpness. The resolution of the photograph, has been defined as the smallest image dimension that can be spotted on the photograph and is commonly expressed as lines per millimeter for photographic purposes.

Generally, any attempts which have been made to enhance the resolution of photographs by photographic enlargement have resulted in deterioration of the sharpness of the images. Allum (1970) believes that resolution is not equally important to all photointerpreters. He argues that a clear sharp image is better for all interpretations than blurred ones, in which the minor details of photographs of high resolution blend into one another. Allum's argument can be applied to scale because of the inter-dependence of resolution and scale of a photograph. It is recommended that the type and the objectives of photointerpretation be defined, and then the decision on the scale can be made appropriately. However, the photogeologist must never forget the simple fact that it is impossible to have a large area and a large scale in the same single photoprint.

Regarding the present study, there are noticeable differences both in quality and in quantity between the data obtained from the two sets of photographs. The large scale photographs have provided very detailed data, such as small fractures and surface textures of bedrock which may suggest a lithological difference. Such features were however invisible in the smaller scale photographs.

2.2.1.2 The quality of air photographs

There is insufficient agreement among photogeologists about the quality of photographs. The difference of views mainly centres on what constitutes the cause and the effect as regards image quality. Generally, it is agreed that the quality of photograph cannot be defined and measured in a absolute terms. Photo experts are inclined to define the quality of photographs in terms of distinct image properties that affect the amount of information contained in a photograph. Certain photograph parameters are commonly regarded as having a significant effect on the quality of photograph; these are graininess, tone contrast, image sharpness and grey tone range.

The graininess can be related to the film or photo paper. In both cases it has the same effect on the quality of images. It is known, that fine graininess can produce good sharpness of image and so the photograph can be enlarged or magnified several times without losing its quality. Since the available photographs for this study have been produced with a predetermined graininess, there is nothing more to say about this parameter. Tone contrast is the difference between the image and its background, and it is measured as the ratio of light and dark in the target. The sharpness of the image is the abruptness with which the tone contrast appears to take place on a photograph i.e the distance on the photo over which the change from tone A to tone B appears to take place. The tone range of the photograph may be called the dynamic range of tone; this means the gradation of grey tones that appear on the photoprint, and the wider the range of grey tones the better.

Generally, the quality of photographs that have been used varies from poor to good. Some possessed very high tone contrast and thus some internal details of geological features were rather obscured. Some other photographs were lacking in sufficient tone contrast, which resulted in the geological data being confused with their background and thus reducing the detectibility of the data.

The sharpness of images can be influenced greatly by photographic factors such as processing techniques, chemicals and photopaper. Some photographs used in this study had poor image definition that many geological data could not be detected during the monoscopic and unaided eye examination of the photographs and mosaics. For example, the bedding and fracture traces were blurred and blended with the background.

Since the photogeologist uses "grey tone" as an effective tool to detect and identify the geological data, the range over which the tone varies is very significant. Ideally, the photograph must have all the gradations of grey tone between white and black, but not all photographs have such a tone range. However, the appropriate range of grey tones is always necessary in photogeological study. During the present photointerpretation there have been photographs with poor tone gradation. They appeared flat and featureless. Consequently there was a noticeable decrease in the recognition of data. It can be concluded that the wider the range of tone gradation the more information may be obtained from the photograph.

2.2.1.3 The technique of viewing air photographs

An air photograph is widely regarded as an exact representation of the landscape. When the photogeologist analyses photographs, he is convinced that sound conclusions cannot be formed until a lot of data has been obtained from the photograph. Thus, photogeologists have always tried to diversify and discover new techniques for viewing photographs. They are motivated by the wealth of stored information that could be extracted from the photographs. There are many geological features which cannot easily be recognised on air photographs either due to their nature or to their image characteristics, but with different methods of viewing the photographs the chances of detecting them may well be increased.

There are two principal methods of viewing the air photographs. The first is with the unaided eye as when an individual photograph or photo-mosaic is viewed with the naked eye or with a magnifying lens. This visual activity is in fact comparable to ordinary reading or writing.

When a photogeologist examines a single photograph with the naked eye, he can annotate and measure on the photograph; he may compile a map and finally extend his activity to writing a report. Colwell (1954) called the technique of examining the photos without using a stereoscope, the monoscope method.

The other method is the stereoscopic viewing of the air photographs. The viewer perceives a three dimensional scene as he views a photo-pair under the stereoscope. In black and white photographs, the tonal differences and certain tonal patterns are believed to be related to local and regional geology. So, photogeologists for a long time have been exploiting these photographic characteristics in structural studies and fracture analysis.

During the first stage of the present photointerpretation, the photomosaics and individual photographs were examined with the naked eye. The tonal difference was the main criterion by which the major lineaments and folds were detected and identified. Tonal patterns were a most valuable criterion by which to detect eroded structures and bedding traces in low or flat areas. Lithological boundaries however, have been detected on the same basis. Photographs were viewed systematically at different orientations so that the fracture traces of different azimuths would be more obvious. The mosaics have been viewed at different angles, and nearly parallel to their surfaces with the light behind the observer so as to intensify tonal contrast by reducing the apparent scale of mosaic parallel to the line of sight. Another way of viewing the mosaic is by pinning it up on a wall and viewing it at various distances i.e two to four meters. In this manner, the general scale of the mosaic appears reduced, and as a result tonal contrast of large areas as well as an impression of topographic relief can be perceived. Thus major structures can readily be observed and annotated.

Stereoscopic examination of air photographs is generally regarded as a fundamental aspect of photogeology. For training photogeologists, stereoscopy is indispensable. The unique feature of this technique is the three dimensional model of the scene which is being produced. Another inherent characteristic of stereoscopy with most air photographs is a vertical exageration of the relief. Experience shows so far that the efficiency of the interpreter greatly improves during stereoscopic examination in comparison with monoscopic (i.e unaided eye) examination of photographs. This can be explained by the fact that the three dimensional model offers the photogeologist a sense of reality, even if it is in miniature form.

In the second stage of interpretation all photographs were examined stereoscopically. By virtue of the three dimensional model a great deal of structural detail was clearly observed and plotted. Some data which had already been detected on the mosaic but not conclusively identified were checked and confirmed, yet some others were considered invalid data. The geomorphology of the terrain seen under the stereoscope provided a large number of criteria for recognising geological features. While the land-form components of certain structural complexes were evident under the stereoscope, they were not clear and were often confused on the mosaic. Tonal characteristics of rocks and soil were generally enhanced when photographs were under the stereoscope. This helped to detect and trace out more fractures. The opportunity of using high power stereoscopy was valuable in plotting microfeatures in the study area, particularly in the Ain Zalah structure.

It should be evident from what has been mentioned about the techniques of viewing photographs that there are advantages and disadvantages in each method if it is used exclusively. In comprehensive photogeological study, however, both methods are needed and they are always complementary to one another.

2.2.2 Subjective Factors

All users of photographs whatever their field of interest realise that there are factors affecting interpretation other than objective factors, and yet just as important. They can have a critical effect on photo-interpretation and therefore should be given due consideration. These factors are subjective or human factors. Human factors can be classified into two groups. The first is physical, involving visual ability, particularly in so far as it affects stereoscopic perception. Physical fitness for the work must also be taken into account. The second group involves psychological factors which, however ill-defined, covers personal feelings, disposition and general reaction to photographic stimuli. It is always assumed that photointerpreters have already secured the basic requirements which their work demands as far as physical fitness is concerned.

The majority of photogeologists have agreed that psychological factors are controversial as well as important in photointerpretation. Unfortunately, insufficient attention has so far been given to this, at least by novice photogeologists. It has been assumed that a photogeologist would have obtained sufficient information about his area before starting the photointerpretation. During this study, it was found that a knowledge of the geology of the area however useful, is not enough for the execution of a structural study, particularly one based on fracture trace analysis. The author therefore had to acquire a special knowledge of fracture trace analysis, including the techniques of fracture trace analysis, the theories of geomechanics of faulting and fracturing, and also the wide range of fracture patterns and their structural relationship to folds. This knowledge was indispensable to conducting a satisfactory study and also played a psychological factor in so far as it gave the investigator confidence in his work. Psychologists have disclosed that the knowledge of the nature of the objects before they are perceived or examined, creates a feeling of security and self-confidence in the observer and this is bound to produce a steady and successful performance. The experience acquired during the photointerpretation in this study supports these hyprotheses.

During photointerpretation, it was frequently found that a long period of photoviewing results in eye-strain and eventually leads to mental fatigue. In these conditions the perception of photographs becomes slower and less accurate as the viewer tends to imagine images which do not actually exist in the scene. The same situation could be brought about by lack of variety in the environment such as monotonous working conditions creating boredom. This kind of situation has been avoided during the present interpretation by viewing the photographs discontinuously, at intervals of two hours. It was also found that working with other colleagues in the same room is generally helpful in avoiding boredom. The photointerpretation was often carried out in the evening when the author was alone. So, quiet music in the background proved useful in keeping the working atmosphere animated and cheerful.

Visual activity constitutes an essential part of photointerpretation. Viewing photographs in fact is a process of perception, that is, detecting and identifying something. The eye and the brain are almost simultaneously employed in this process. So the photointerpreter's state of mind is of vital concern. A large amount of experimental work has been carried out by psychologists to investigate the effects of emotional state of the observer such as depression, apathy or anxiety, etc. on perception. Generally, all this work revealed that an observer under any kind of emotional stress is liable to lose his acuity of perception. As far as the photographs are concerned the images may appear blurred and unstable, their straight edges may look rather curved, and otherwise meaningful images turn into meaningless figures. Some other psychologists have studied the relationship between motivation and perception. They have found that clarity and accuracy of images perceived in a complex field appeared to be related to an observer's interest. Interest is a comprehensive and loosely defined term. It may imply in a scientific field such as photogeology a strong motivation in obtaining geological information by means of interpretation of air photographs.

In conclusion, it would be worth mentioning that after years of working with air photographs the author has found that a psychologically stressful situation makes perception rather difficult. The clarity and identity of images becomes doubtful and as the process of photointerpretation goes on, the interpreter begins to rely excessively on his imagination and eventually his perception may be illusory.

2.3 THE PROCEDURE OF PHOTOINTERPRETATION

The process of photointerpretation involves two essential steps:

a) The detection and the identification of the object,

b) The deduction of its significance and relation to other objects.

Detection is merely the act of discovering the existence of an object, while identification is the revealing of its true identity. Detection and identification do not necessarily occur in time according to the sequence suggested above. Logically, an image must be detected before it can be identified, but the experienced interpreter often detects and identifies in the same instant. The photograph provides a suitable stimulus to the observer to enable him to make the identification. So, the process of identification is primarily a photographic problem associated with psychological components. The deduction of the significance of the object however, is more of an intellectual problem. This in no way depends on the photographs, but on the training, experience, background and intelligence of the interpreter.

The interpretation of the photos used in this study has been carried out in three operations. First, the bedding traces and other structural land forms were interpreted and then complied onto one map. Secondly, the photographs were examined for fracture traces only and as a result a fracture trace map has been produced. Lastly, the drainage network of the area was traced out stereoscopically from the photographs.

The practice of splitting up the photointerpretation into various thematic or topical interpretations based on a predetermined class of data, has so far proved of great advantage. As a result of this method, three types of photogeological maps have been produced, each of which represents a specific geological information. The quantity as well as the clarity of the information were remarkable. Each topical map was analysed separately and the results of the analysis of all maps were compared and correlated. So, a conclusion regarding a structural setting of the area has been reached. This method has consumed extra time and material, but it was necessary for the present study and this is generally so for any work of the same nature. Any other way, there would have been a large amount of over-crowded data on one map. This would most likely have confused the author during the analysis of the map.

It is a good practice to examine a photomosaic or the photo-layout of an area, before a stereoscopic examination of individual photographs. In this way, a photogeologist soon acquires and maintains an awareness of the regional geology of an area. By discovering the structural relationship between the main tectonic units, a photogeologist actually draws a structural picture of an area from which the tectonic history can be traced.

In photogeology, the principle of studying regional geology by using photomosaics can be regarded as a synthetic or synoptic method, in so far as the photogeologist is concerned mainly with the major elements of the geological complex of the area. As he encounters a variety of data presented by the mosaic, he may tend to be rather subjective in his recognition and judgement of the data. So it is advisable for the photogeologist to be more cautious during the examination of the photomosaic.

The photointerpretation was started with mosaic annotation. The major structures such as folds and lineaments were annotated with coloured pencils. The indentification of data was based on certain criteria or clues, which can be called photogeological criteria. These are geomorphological features, vegetation alignments, soil tonal differences and drainage network. In most cases, several criteria were used to determine the identity of one geological object.

The stereoscopic examination of photographs is in any case a leading technique in photogeology. Some photogeologists even consider it as the only reliable method that can be used in photointerpretation. However, the regional approach to geology should always entail an initial study of a photomosaic.

There is a tendency on the part of photointerpreters to be rather analytic and objective during a stereoscopic examination. This may be due to the large quantity of data and the complexity of the three dimensional model field.

The stereoscopic interpretation for this study was carried out on transparent overlays cut into sheets of photograph size. Indian ink was used for drawing geological data onto the overlays. To begin with certain data were marked on the overlay of each stereopair. These were the principal point of the photo, the photo number, the principal points of adjacent photographs and some minor control points. As a photointerpretation was made for three classes of geological data, a complete interpretation of the stereotriplet resulted in three overlay sheets for each, they are of the following data : bedding traces, fracture traces and drainage network.

The topography of the area of the study is generally regarded as low to moderate. So, the radial deformation, the inherent characteristic of air photographs, was not a distorting factor. However, the interpretation was mainly carried out on the central part of the photograph so as to minimise the possible effect of radial deformation.

The stereoscope used during the photointerpretation was a Hilger and Watts Ltd. mirror stereoscope giving high and low power magnifications of x 4 and x 2 respectively.

2.4 THE COMPILATION

Before further work could be done on the data resulting from photointerpretation, they had to be compiled at a convenient scale into a photogeological map. There are several methods of compliation. They differ in the degree of accuracy with which the map can be produced. However, topographic characteristics of the area and the nature of the study may determine the method of the compilation. When the topography of a terrain is low to moderate and where the radial deformation of photographs is not pronounced, the compilation of the map can be carried out in simple and straightforward ways.

The present photogeological mapes were compiled on the topographic sheets of the scale 1/20,000, on which the photo principal points had already been located and marked. These points as well as the river Tigris and the main streams in the area were taken as control references for the compilation of the data. The Tigris river was an important control guide since it crosses the area diagonally. There were differences in the scales and the topographic maps were reduced to the scale of the photographs, except for the Ain Zalah photographs of which the scale is approximately the same as that of the topographic maps.

The reduced topographic maps were laid down flat on the top of a large table, joined together, and pinned down on it. Then the individual data overlays were placed carefully on them in such a way that corresponding principal points on both overlays and maps were superimposed on each other. Meanwhile adjustments were made to allow the Tigris river and other main streams to coincide with those already plotted on the overlays. In order to secure the best possible joining of data and their compilation on a topographic map, local compromises were made on the relative positions of these data as they were being adjusted on the maps, provided that this did not affect the general planimetric characteristic of the final map. A photogeological map is generally regarded as a reconnaissance map, and engineering precision is not usually required.

Upon the completion of the assembling of the overlays, a large sheet of tracing paper was placed over the overlays and the interpreted geological data were traced as well as the geographical co-ordinates of the topographic maps.

As a result of the compilation, two sets of photo-geological maps were produced. Each set had its own scale since it had been compiled from two sets of photographs of different scales. The sets of maps are the Mushorah-Ain Zalah maps and Ain Zalah maps, each comprising three maps, a structural map (i.e a map showing folds), a fracture trace map and a drainage network map. For convenient handling, all maps were reduced to an appropriate scale.

2.5 THE DIGITIZATION

Most general purpose computers are digital. They are machines capable of performing operations on data presented in digital or numeral form.

The fact that a computer exists does not mean that it easily analyses or processes a geological map such as a fracture trace map. A computer and maps are like oil and water; they do not mix naturally and it requires a great deal of ingenuity to harness the benefits of the one to the needs of the other. So, in order to use the computer in the processing of fracture trace data, we have to convert the fracture traces from graphic or line form into digital form. This procedure is called digitization. There are two basic methods of digitizing data, one is a point information and the other a line information method. The former method was used during the present operation. Thus, a single point or position was digitized at one time and the digital form of that point was a pair of X, Y Cartesian Co-ordinates.

A British made D-MC graphic digitiser was used. The main components of this equipment are a digitizing table, a crosswire viewer with a readout switch, an electronic unit with control buttons, a visual display unit, and a punch card machine. The crosswire viewer with reference voltage, creates an inductive field when it is positioned on the table. It is moved in each axis by a stepped belt. Separate drives rotate X and Y encoders which transmit distance pulses in the form of electronic binary codes to the electronic unit. When the readout switch is operated, the X, Y co-ordinate values are selected and translated into a chosen output code and put into output equipment. Simultaneously the values are displayed as two five-digit numbers and signs on a visual display unit.

The digitization was begun by placing the fracture trace map on the working surface of the table in such a way that its fore edge was perfectly parallel to the horizontal edge of the table, then it was fixed with adhesive tape to the table. The co-ordinates of the corners of the map's boundary were the first to be digitized. The intersection point of the crosswire was positioned exactly on the lower left corner of the boundary and the digitizer was set to zero position (i.e X = O, Y = O). This point had been taken as the origin of the map and all following co-ordinates were referred to it. Then, the other corners were digitized in clockwise direction, (Figure 3) Afterwards, the digitizing of the fracture traces was carried out.

Fracture traces can be classified geometrically into three categories, rectilinear, simple curvilinear and sinuous, (Figure 3). The large proportion of the present fractures were rectilinear, that is, almost perfectly straight lines. So, the two ends of these fracture traces were digitized and were considered as terminal co-ordinates, (Figure 3). In the case of curvilinear and sinuous fractures, several intermediate points as well as the ends of the fractures were digitized. The intermediate points, were chosen to divide the fracture trace into a number of fairly straight segments so that the original curved or sinuous fractures, could be re-constructed from these co-ordinates. The number of intermediate points or segments is up to the operator's discretion. However, the fracture analysis programmes have been devised to process up to fifteen segments per fracture and any fracture trace can be digitized from either end. In order to distinguish between fracture traces that have been digitized and those which are still to be done, the fracture traces were ticked off as they were digitised.

The digitization yielded a large deck of data cards and the number of cards was almost equivalent to that of the fracture traces.

It is inevitable to find that a few fracture traces have been left undigitized and/or others were mispunched. So, the deck had to be inspected and the faulty cards were removed. To make certain that the data cards exactly corresponded to the fracture trace map, it was redrawn by a computer plotting machine. Thus, the remaining errors could be rectified, and the data cards considered completed and ready for use.

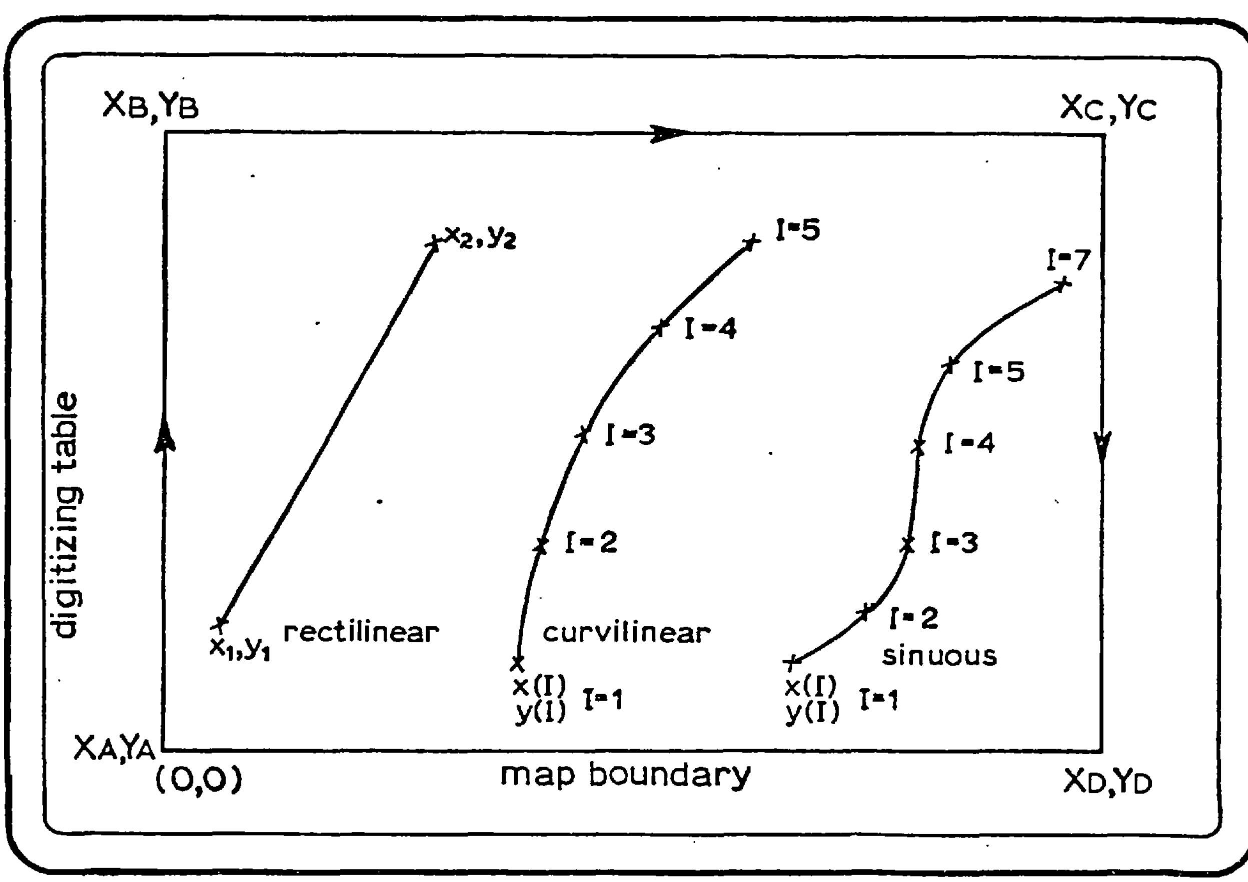


Figure 3

Schematic diagram showing digitizing table with a map displaying samples of fracture traces

CHAPTER THREE

3.1 THE THEORY OF THE GEOMECHANICS OF FRACTURES

3.1.1 Joints as Incipient Fractures

Joints have been conceived as mechanical discontinuities in the cohesive masses of rocks. Joints are commonly seen as a surface phenomenon and have been referred to by different names such as cracks, fractures, breaks and fracture cleavages. The fundamental characteristic of joints is that there is extremely little or no movement along their planes. Despite the fact that joints have been studied widely, their origin remains the most difficult problem to be solved. There is abundant field evidence suggesting that joints may develop at all ages in the history of rocks. In sedimentary rock, joints may develop soon after deposition, while the sediments are not completely consolidated.

N. T. Johannesburg (1966) and others regarded joints as planes of weakness in the rocks characterised by a complete lack of movement. They were originally invisible, but after being subjected to a deformational force or internal chemical action they became visible. Boloussov (1962) gave a useful classification for joints,

(a) open joints; those joints which have been opened and widened after some kind of deformation and thus become visible,

(b) closed joints; those which became perceptible after weathering or any other process which changed the surface of the rocks,

(c) latent joints; those which are not visible but appear as the rock breaks up. G. Gorshkov (1962) referred to Boloussov's latent joints as "fracture cleavage". He described them as numerous weak planes in the rock which are entirely imperceptible but become apparent as soon as a rock sample is struck with a hammer. The sample will then split into pieces. He believed that the split will occur not in random directions but along quite definite plane surfaces in a few regularly orientated directions. Gorshkov thus concluded that joints may initially develop in rocks under generally uniform conditions which prevail over vast areas. Then, under other conditions such as tectonic and/or vertical movements, open joints may develop. Joints may also develop as a result of a drying process as in sedimentary rock, or of a cooling process as in igneous rock.

The relationship between joints and other structures has been widely investigated and it has been established that there is a close relationship between joints and folds as well as faults within the same tectonic province. Studies have also revealed a strong relationship between the orientation of joints as they appear on outcrops in the field and fracture traces on air photographs. E. A. Babock (1974) studied the orientation of different sets of joints in the field and of fracture traces of the same area on air photos. After statistical analysis of both kinds of data he discovered that the fracture traces and the joints have great similarity in their directional characteristics. He therefore concluded that the fracture traces on the photos may well be related to the joints on outcrops. W. K. Overbey and his colleagues (1971) found an interesting resemblance between the orientations (azimuth) of natural or induced fractures of oil reservoirs, bedrock joints and fracture traces on air photographs. They concluded that there is a definite relationship between the fracture system of reservoirs and both joints and fracture traces. So, they recommended the directional analysis of fracture traces interpreted on air photos as a useful tool in the exploring and developing of oil and gas fields.

In view of these facts, one therefore can reasonably assume that the joints in their initial form predispose rock masses to all types of fracturing and faulting and consequently lead to the appearance of the fracture traces on air photos.

3.1.2 The Generation and Propagation of Fractures

3.1.2.1 The fatigue theories

Some earth scientists attribute the fracturing of rock to the fatigue phenomenon. Fatigue fractures are caused by rhythmic stress applied to the rock mass. The stress must reach a critical value when the rocks start to crack. The theoretical interpretation of the stress condition leading to fatigue fracture is based on the behaviour of a plastic body of small size within an elastic body. When a stress of critical value is applied periodically, it produces weak surfaces (cracks) which generally spread until they reach such a length that at the next application of the tensile stress cycle a complete fracture is produced. Fatigue thus offers a mechanism for generating fractures at stress values well below the static breaking strength of brittle rock material.

The following theories are concerned with the generation and propagation of fractures of regional or crustal dimension. They are based on the concept of fatigue as an accumulated strain in the earth's crust which has been produced by an internal and/or external source of stress.

3.1.2.1.1 Earth tides

The tide is the periodic rise and fall of the sea caused by the attraction of the moon and sun, but the effect of the moon is by far the more powerful. In the open ocean the high tide reaches a few meters, but in certain shallow seas it may reach 9 - 16 meters. The reaction of the earth's crust to the force exerted by tides might be compared to the well-known fatigue in metal under continuous vibratory stress. The effect of tidal stress on the earth's crust lies not in the magnitude of the stress produced by one tide but in the repetition of the stress. Tidal stress is applied periodically, twice a day at one point and about 730 times a year. A small but long sustained stress is capable of creating tremendous geological strain.

Blanchet (1957) supported the theory of fracture generation by the periodic action of the tides in the earth's crust. He believes that since the range of lunar tides in the earth is about 9 - 14 inches, they are sufficient to have generated fractures by fatigue. He also believes that tides have caused the upward propagation of fractures. Blanchet pointed out however, that other sources of external forces have undoubtedly assisted in the progress of the propagation.

Hodgson (1961) discussed fracture generation and propagation with special emphasis on the process of fatigue. He offered a working hypothesis of producing systematic joints by tidal forces. The direction of joints is considered to be inherited by the upward reflection of joint patterns in pre-existing jointed rocks. The entire process is thought to occur early in the history of sediments.

3.1.2.1.2 Seismic activity

Crosby (1893) thought the joints in sedimentary rocks are most likely produced by earthquake shock-waves. Crosby related the orientation of systematic joints to the accumulation of stress and strain in the deeper crust. Earthquakes resulting from the release of stored energy would produce the systematic joints in young and weak sedimentary beds.

Mollard (1959) mentioned that the fractures in weak and brittle Pleistocene rocks may develop from severe earthquake shocks. Once these fractures are formed, repeated seismic tremors tend to prevent the cracks from sealing up. In addition, there may be microseisms or minor rhythmic seismic pulses.

Eppley (1958) described a grid of fractures in deeply frozen ground which originated from an earthquake in 1925 in the St. Lawrence Valley, Canada.

Leet (1952) proposed a hypothesis explaining the generation of microseisms by continental compression of the earth's crust causing it to "hum" or vibrate like a highly strained piece of steel. In some places, the earth's surface reacts by shaking like a mosaic of independent blocks. In addition, there are seismic storms which may be explained by wide-spread atmospheric pressure changes moving from one block of the crust to another, temporarily changing the stress conditions on highly strained blocks. Seismic activity may also explain the propagation of existing fractures through successively deposited strata.

3.1.2.1.3 Rotational stress

This hypothesis is based on the assumption that the earth is subjected to two major stresses N - S and E - W. They are caused by the earth spinning around its axis, the precession of the earth's axis and the rotation of the earth around the sun. It is believed that the crustal fractures and lineaments result mainly from these stresses.

The shape of the earth is ellipsoid and its polar diameter is less than the equatorial diameter. This shape is a strain effect resulting from the earth's rotation. It is highly probable that the shape in terms of the ratio of the polar diameter to the equatorial diameter (Dp / De) undergoes a small variation in response to lunar-monthly and annual variation in the radius vector (the distance from the earth to the sun). The ratio has also been affected by the formation and depletion of polar ice-caps during certain epochs.

The departure of the earth's course from a circle around the sun and the variation in the shape of the earth show that the north-south stress system must exist and that it has been active throughout geological time. This stress deforms a circle that fits around a perfectly spherical earth to an ellipse. The area of the ellipse equals that of the circle and its minor axis is orientated north-south.

The earth's crust is apparently subject to even greater stress caused by a tendency in certain annular segments of the crust to migrate eastward farther than the adjacent segments. The two annular segments which appear to have migrated farthest east are those roughly bounded by latitude 30° - 50° North and 30° - 50° South. The equatorial annulus, that part of the earth's crust between latitude 50° North and 50° South, appears to act as a separate entity from the remainder of the crust. Near its boundaries, it tends to migrate to the east, and in the middle (i.e the part between the tropics of Cancer and

Capricorn), it tends to migrate west. This tendency of a differential migration has analogies with the movements of the hydrosphere and the atmosphere.

It has been assumed that the rate of rotation of the earth is gradually decreasing. This slow-down has been ascribed by investigators to "Tidal Friction". The equatorial annulus as a whole has a momentum which is considerably greater than that of the rest of the earth and tends to migrate eastward as the rate of rotation decreases. This is so, because it is the part of the earth farthest removed from the axis and it therefore has greater angular velocity than the rest of the earth. Tidal Friction however, slows the eastward migration as well as the rate of the earth's rotation.

In the decreasing rate of rotation, there is a reasonable explanation of a differential migration within the equatorial annulus. Those parts outside the limit of effective Tidal Friction have therefore moved farther to the east.

The combination of N - S and E - W stresses deforms the hypothetical circle to an ellipse with a minor axis which is roughly oriented North - Northeast. The magnitude of N - S stress is nearly constant for all areas of the earth, but the E - W stress decreases poleward. In high latitudes, therefore, the bearing of the resultant of the E - W and N - S stress should swing closer to the bearing of N - S, causing the fracture system of the crust to rotate anti-clockwise. This theoretical behaviour corresponds with the results obtained in many widespread investigations.

3.1.2.2 The gravitational theories

The gravity force at the earth's crust is regarded by many geologists as an important agent in causing fractures in the rock masses as well as influencing the existing subsurface fractures so that they propagate upward to younger beds. The following hypotheses which have been proposed by known geologists emphasise the role of gravity, in whatever form it might occur, in the generation and propagation of fractures.

3.1.2.2.1 Differential consolidation or compaction

Belcher et. al. (1965) proposed that the consolidation of sedimentary rocks results in shear failure. They wrote that in the consolidation process the sediments come into equilibrium with their load and they remain in such a state until an additional load, static or dynamic, acts on them. Then, the consolidation process will resume until a further or final stage is reached. Compressive forces can start from above as the weight of the surcharge, or from below as force generated by igneous intrusion or salt-dome activity. He maintains that differential consolidation of sufficient magnitude leads to shear failure especially in the early stages of consolidation. As consolidation takes place, the fluids in the voids come under additional pressure and the shear strength of the rock mass becomes extremely low. A failure or adaptation takes place readily under these circumstances, making a selective adjustment to the shape of the surface being buried. Further deposition, creating a surcharge load during the subsidence of the basin, extends the failures in each successive layer of sediment as it is deposited above. The shear failure resulting from differential consolidation will be spaced across limited distances forming failure zones. These zones which appear in the youngest beds may well be reflecting subsurface structure at depth. It was hypothesized and later proved that the spacing between failure zones is related to the magnitude of the slope on the buried surface. Thus, steep slopes will generate more closely spaced failures, and gentle slopes will produce widely spaced failures. The developing of these zones does not only need firm basement rocks but may result from the deposition of sediments on partially consolidated formations.

Sproule (1962) has offered a hypothesis, that clays and muds are known to be compressible to less than 40 per cent of their original volume. In a deep basin the static pressure of overburden can thus result in great differential compaction, as between competent and incompetent layers, with the consequent formation of tension fractures over and around competent masses. Sproule has shown a diagramatic cross-section with tension faults and fractures related to buried competent features.

3.1.2.2.2 Isostatic adjustment

Isostasy is the tendency of the earth's crust to attain an equilibrium. The relatively light masses (sialic) are immersed in relatively heavy substrata masses (sima). Analogy with isostasy is frequently made with wooden blocks of different weight floating in water. But one should not conclude that the earth material is virtually liquid, on the contrary, the seismic waves show that it behaves as a solid to a depth of 3000 km. The erosion of the rocks causes a relief of loads and results in uplifting, while the sedimentation adds more load and results in subsidence. It is believed that isostasy determines the height of mountains and the depth of basins which exist on the earth.

Isostatic adjustment is a slow dynamic process created by vertical movements of the earth's crust so as to attain isostatic balance. Some geologists have tried to present this phenomenon as a factor causing tectonic movements, but this question still remains a matter for speculation. It is generally accepted that the role of isostasy in the shaping of the earth's crust is quite important but certainly not decisive.

Mollard (1957) mentioned that earthquake shocks, or after-shocks occasioned by the restoration of isostatic balance can propagate the fracture pattern in bedrock through unconsolidated material. Another hypothesis refers specifically to glaciated areas and to recent and still active isostatic adjustments following the melting of continental icecaps. Mollard has stated that isostatic recovery following deglaciation probably presents the least controversial of all the mechanisms. Various examples are cited and it seems probable that post-glacial isostatic recovery is at least one factor explaining the origin of some lineaments seen on aerial photographs. Simple elastic rebound following the removal of an icecap may have resulted in slight adjustments of basement along zones of weakness, resulting in jointing, faulting, tilting and perhaps even minor folding of the overlying sedimentary strata.

R. H. Barton (1962) has proposed a hypothesis of differential isostatic rebound as a possible mechanism for fault reflection through glacial drift. If a lithological variation exists across a fault, with one side more susceptible to compaction due to ice-loading than the other, then the more compacted side will be depressed less by the ice pressure as some of the pressure is relieved by compaction. Barton assumed that the two sides have a slightly different isostatic equilibrium position and that the differential isostatic rebound tends to reflect the fault trace through the unconsolidated glacial drift cover. Barton pointed out that this hypothesis obviates the necessity of invoking post-glacial tectonic movement along pre-existing faults for every large glacial terrain lineament.

3.2 TECHNICAL TERMS AND DEFINITIONS

In this thesis a number of technical terms are used. These are essentially established terms in the sense that they are being used by other authors with various degrees of modification in definition. In this section these terms are presented in a form relevant to this study in order to clarify their usage in the context of this thesis.

Photogeological Fracture Trace

Hereafter called "fracture trace". A photogeological fracture trace is the image of a natural linear feature, consisting of topographic, drainage, vegetation, soil or rock tonal alignments visible on air photographs or remote sensed (or space) imagery, and possessing the characteristics of the surface trace of a rock fracture. No limitation as to length is implied, and the term applies whether the bedrock surface is exposed or masked. In addition, the term "fracture trace" can be applied when the surface is covered, to describe the feature on the ground, in that this is still a trace or a surface expression of the subsurface fracture (Huntington, 1975).

Fracture Trace Set

An array of parallel or sub-parallel fracture traces visible on air photographs.

Fracture Trace System

Two or more fracture trace sets of different directions, often intersecting one another and visible on air photographs.

Fracture Trace Pattern

Any distinct pattern formed by two or more fracture trace sets and visible on air photographs.

Conjugate Fracture Trace Sets

Any two sets of fracture traces that appear to be caused by the same tectonic force.

Rectilinear Fracture Trace

A fracture trace that appears on an air photograph as a discrete straight line, or nearly so.

Curvilinear Fracture Trace

A fracture trace that appears on an air photograph as a curved line with a distinct curvature in one direction.

Sinuous Fracture Trace

A fracture trace that appears on air photographs as a curved line with more than one curvature in a different direction.

Digitization of Fracture Traces

To digitize a fracture trace is to convert it from a line form to digital representation. This can be done by recording the x, y cartesian co-ordinates of both ends of the trace. In the case of a curved fracture trace, the co-ordinates of a number of points on the trace, including its ends, should be recorded. This operation is usually executed by an electro-mechanical device called a "graphic digitizer".

Fracture Trace Rose Diagram

A fracture trace rose diagram is a radial statistical histogram depicting the angular (or directional) frequency of fracture traces. To draw such a diagram, two fracture trace parameters including the azimuth must be considered.

Fracture Trace Density

The total length of fracture traces or segments of fracture traces per unit area, commonly expressed in meters or kilometers per square kilometer.

Fracture Trace Frequency

The number of individual fracture traces or segments of fracture traces per unit area, commonly expressed as a number per square kilometer.

Fracture Trace Directional Density

The total length of fracture traces or percentage of the total length occurring in a predetermined azimuthal interval (or directional class).

Fracture Trace Directional Frequency

The total number of fracture traces or percentage of the total number of fracture traces occurring in a predetermined azimuthal interval (or directional class).

Fracture Trace Analysis

Fracture trace analysis is a branch of photogeology that applies to the recognition, interpretation and statistical analysis of the surface traces of rock fractures detectable on air photographs or space imagery, (Huntington, 1975).

Fracture Trace Map

A map showing fracture traces obtained by means of the interpretation of air photographs. It may also show major streams, towns or roads serving as reference positions.

Fracture Trace Frequency Contour Map

A map showing contour lines depicting areas containing an equal number of fracture traces. The map provides a visual representation of the spatial distribution of fracture trace frequency occurring in an area.

3.3 QUANTITATIVE AND QUALITATIVE ASPECTS OF FRACTURE TRACES

Fracture traces can be systematically analysed on the basis of their quantitative and qualitative characteristics. The quantitative analysis usually involves the azimuth, length and frequency of fracture traces, and in some cases their geographical position. Certain genetic or mechanical relationships can be established between the fracture traces and the rock in which they occur. The size and frequency of the fracture traces occurring in deformed rock have often been used as criteria in solving structural problems.

The qualitative analysis is based on the characteristics that are related to the geometry and pattern of fracture traces. It has been observed that certain patterns of fracture traces are closely associated with some geological structures. In some cases, a buried structure has been discovered by means of the recognition and analysis of fracture trace patterns on air photographs.

Geologists with a particular interest in fracture trace analysis need to study the various characteristics and patterns of fracture traces.

3.3.1 Quantitative Aspects

The statistical analysis of fracture traces can be carried out by means of their quantitative parameters, which are mainly the azimuth, length and frequency of fracture traces. As regards the size of fractures, there is a wide variety of classification and nomenclature, but the basic concepts are almost the same.

Lattman (1958) considered that the size of a "fracture trace" is less than one mile and that one which equals or exceeds a mile is called a "lineament". Haman (1964) argued that the term "fracture" is more genetic than "lineament" particularly if there is difficulty in separating lineaments of structural and superficial origin such as glacial lineaments. Thus, he used "macrofracture" instead. He also used the term "mesofracture" for Lattman's fracture trace. As to the length classification, Haman used that proposed by Lattman.

Blanchet (1957) classified as "microfractures" those fractures which have a maximum size of 2½ miles, and as "macrofractures" those which have a size of between 2½ to 50 miles.

Permyakov (1949) proposed the term "megajoint" to embrace all forms, shapes and sizes of photogeological linears which may be related to the bedrock tectonic. Some workers have used "megalineament" for a fracture trace more than 20 miles long. The following table sums up all fracture trace nomenclature with the respective authors.

Megajoint (Permyakov)	Fracture trace	(Lattman)	1 mi/1.6 km
	Mesofracture	(Haman	
	Microfracture	(Blanchet)	2½ mi
	Lineament	(Lattman)	1 mi/1.6 km
	Mesofracture	(Haman)	
	Macrofracture	(Blanchet)	2½ - 50 mi
	Megalineament		20 mi/32 km

Lattman and Nickelsen (1958) have interpreted fracture traces on air photos of the scale 1/20000 and have suggested that all sizes between 1/4 and 2/3 of a mile are related to local jointing or small faults. This proposition was confirmed during the present study of the Ain Zalah area.

Kupsch et al. (1958) and Lattman (1958) proposed that the lineaments which range up to several miles long are attributed to probable sub-surface faults. Kaiser (1950) and Blanchet (1957) related lineaments and macrofractures to tectonic activity involving basement rocks.

In view of these facts, it can be concluded that there is a proportional relationship between the size of fracture traces in general and the depth which they may reach. It is also reasonable to assume that lineaments (i. e. regional fractures) or crustal fractures are deep-seated and therefore basement controlled, whereas small or medium sized fracture traces are comparatively restricted to inconsiderable depths and are probably controlled by local structures.

It has been taken as a geological fact that areas which have been subjected to severe tectonic forces are liable to exhibit more fractures than those which have been under minimum tectonic pressure. There is ample evidence that areas of high fracture trace concentration coincide with or run alongside well-known tectonic zones such as Zagros-Taurus range in the Middle East. These areas are characterised by the frequent occurrence of earthquakes which can be explained by their extensive fracturing.

The active geological forces that resulted in the folding and faulting of the rock inevitably produced a huge number of fracture traces.

In the area of the study most of the anticlinal structures are slightly asymmetrical and the southern flanks tend to be steeper than the northern. It was observed that the number of fracture traces on the steeper southern flank is rather greater than of that on the northern while there are considerably fewer fracture traces on the crestal parts of the anticlines where the bedrock is virtually flat.

Gol'braykh et al. (1966) suggested that high concentration areas of fracture traces can coincide with (positive) anticlinal structures. Burnett (1963) observed that swarms of fracture traces mark the position of an anticlinal axis or monoclinal folds. Blanchet (1958) put forward a hypothesis that the areas of low fracture trace density surrounded by areas of high residual density would indicate buried reefal structures or salt domes. Belcher and Schepis (1965) supported this hypothesis during their study of fracture traces.

There is also a distinct relationship between the number of fracture traces and the lithology, as well as the thickness of bedrock strata. The number of fractures is usually greater in thinner beds and in the more brittle rocks.

3.3.2 Qualitative Aspects

The qualitative approach to fracture analysis is based on the geometrical and pattern characteristics of fractures and their relationship to other geological features.

The occurrence and development of fractures are usually influenced by the mechanical and structural characteristics of rock. One may encounter a different geometry and pattern of fractures in different types of rock.

Fracture traces on air photographs appear in linear form. The most common forms are rectilinear, curvilinear and sinuous. Rectilinear fractures are usually frequent in sedimentary rock, while a larger proportion of curvilinear and sinuous fractures are to be observed in hard rock. Ring-like fractures may be encountered particularly in igneous rock. It is widely believed that curvilinear and sinuous fractures developed initially from several very short but straight fractures of different orientations and in the later history of rock these fractures extended further and joined together to form the present geometry.

It is important to be aware of the fact that certain forms and patterns of fracture traces may be closely associated with particular geological structures.

Fracture traces can form any pattern on air photographs. There are however certain patterns which may be observed more frequently such as radial and arcuate (or ring-like) patterns of fracture traces. These are usually associated with domal structures which may be caused by salt or igneous intrusions. Parallel or sub-parallel sets of long fracture traces apparently regularly spaced, can also be seen on air photos. They can transverse an anticlinal fold and be perpendicular to its axis. They are usually tension fractures which have been caused by the elongation and extension of the folded bedrocks. Conjugate sets of fracture traces are quite common in areas which have been subjected to compressive tectonic forces. These fractures can be related to shear failures and usually occur in folded rocks. The structural attitude of the beds can influence the spatial and angular relationships of fractures. In asymmetrical anticlinal structures, the steep flank tends to show fractures which are relatively narrowly spaced and with acute angles of intersection, while on the gentle flank, the fractures are comparatively widely spaced and have angles of intersection which are less acute. It is logical to assume that the effective deforming stress which resulted in the asymmetrical anticline was unequally applied on both flanks. The steep flank was probably subjected to a stronger stress component and therefore exhibits more and narrowly spaced fractures, while the gentle flank might have been subjected to a weaker stress component and thus shows less fractures which are also more widely spaced. Areas with bedrocks which are flat or gently dipping can be seen as the result of very weak or absent deforming forces. These areas usually exhibit suborthogonal sets of fractures which generally look evenly distributed, regularly spaced and may also be of regular size. Examples of fracture trace patterns similar to those mentioned above may be observed on air photographs of the study area.

Blanchet (1957) has used the variation in the angular relationship of fracture traces to outline the presence of buried positive structures such as reef ridges or salt domes.

The directional characteristics of fracture traces are useful in qualitative analysis. A graphical stress model can be established for an area by means of directional frequency rose diagrams. Sets of rosettes (i.e small rose diagrams) distributed over an area can be used in the drawing of stress and strain trajectories. Details of these aspects of analysis will be discussed in a later chapter.

3.4 FRACTURE TRACE ANALYSIS AS A TECHNIQUE

The relationship between fractures and the mechanical and structural behaviour of bedrock is widely acknowledged. In most geological investigations it is most important to know as much as possible about the nature of these relationships.

Conventional methods of measuring rock fractures in the field apart from being time-consuming, often fail to furnish the necessary amount of information for lack of exposure or because of the inaccessibility of the terrain.

Air photograph techniques provide a powerful tool, and in most cases yield information that could not have been obtained otherwise.

Fracture trace analysis is generally understood as the study of linear geological data that can be observed and interpreted on air photographs as breaks or separations in the rock mass. They can be faults, joints and all types of fractures induced by rock failure. Since the number of data that can be obtained from air photographs within a relatively short time is usually large, the study of fracture traces lends itself exceptionally well to statistical analysis. Methods of fracture trace analysis are usually based on their qualitative and quantitative parameters. As in the study, a digital computer can be used to process fracture trace data and also generates statistical plots.

Fracture trace analysis can be used as an exploration technique and generally as a method of geological investigation. Because of the expediency of the technique and the wide-ranging information that can be produced, many workers have applied it in different ways. The best-known methods of fracture trace analysis can be described as follows.

3.4.1 Blanchet's Method

Blanchet (1957) developed a technique for fracture trace analysis. It is based on the premise that the crust of the earth is abundantly and systematically fractured in four principle directions, that is, N - S, E - W, NW - SE and NE - SW. Although the fracturing is partly due to internal stresses, it is the external stresses, which have been active throughout geological time and which continue to act upon the crust today, that are considered to be largely responsible. Three principle external stresses are recognised. They are caused by the following phenomena, first, the earth's tides due to the gravitational effects of the moon and sun on the earth's crust, secondly, the change in the radial acceleration of the earth along its radius vector, and third, the decrease in the rate of the earth's rotation due to tidal friction.

Blanchet proposed that the crust of the earth is systematically fractured in so far as the fractures tend to be symmetrical with respect to the axis of rotation of the spinning earth and consequently with respect to the North and South Poles and the Equator.

In accordance with the above hypothesis, the fracture system would approach complete regularity and symmetry if the crust were laterally homogenous. It is considered that irregularity and departure from symmetry are the direct result of various regional or supra-regional laterally heterogenous conditions within the crust. More particularly, it is found that local departures from the norm are due to local structure or to local stratigraphic anomalies. Local disturbance in otherwise regionally systematic and regular fracture patterns can provide valuable information in fracture trace analysis.

Blanchet applied his technique in six areas of various parts of Alberta, Canada. His objective was to locate shallow to deep structures and/or stratigraphic anomalies. He managed to locate a buried structure in the Wizard Lake area, central Alberta.

The technique started by interpreting air photos for fracture traces. Controlled photomosaics were prepared. The annotated fracture traces were transferred onto transparent overlays and then superimposed on the photomosaics. Measurements of azimuths and lengths of fracture traces were taken and azimuth and length frequency rose diagrams were drawn.

A directional analysis of fracture sets was carried out on the basis of azimuth comparison between the dominant directions of fracture sets and the hypothetical direction-norms of the crustal fracture system which is assumed to exist in the area.

A contour map based on the number of fracture traces per sample unit area was drawn and called a fracture incidence map.

After the directional and contour analysis, a map showing the maximum disturbance zones was drawn. These zones in effect represented areas which cover possible, if not probable, positive structures. Blanchet also suggested that areas of low fracture density surrounded by areas of high density may indicate buried domes or anticlines.

3.4.2 Permyakov's Method

Permyakov suggested a method of structural analysis based on the analysis of fracture sets in bedrock, using empirical formulae. Since the appearance of the original publication, the technique has been applied by various workers with various degrees of success. Some of those who have applied the technique and published the results are Golbraykh et al. (1966) and Huntington (1969).

Permyakov used the term "megajoint" to include all types of fractures whatever their size. He devised and applied his method for megajoint analysis in platform areas where the style and degree of deformation is relatively moderate. His aim was to discover the relationship of megajoints to possible covered fold structures and then to determine the fold strike, style and dimensions of the structure.

He observed that the tectonic joints (bedrock joints) consistently form a diagonal and longitudinal system which can be connected in a certain manner with the parameters of structure.

Permyakov suggested a parallelogram rule to determine the strike of a fold structure. This rule stated the following: "The diagonal of a parallelogram constructed on the principal rays of a megajoint rose diagrams, runs along the axis of the structure." The strike direction is usually the long diagonal. The short diagonal as Permyakov stated, is insignificant, but in fact it may be related to other associated parasitic or superimposed structures if they are present (Golbrahkh et al. 1966).

The dimensions of the structure, such as the length and width as well as the length of both steep and gentle limbs, can be determined by simple trigonometric calculations using the length of principal rays and the angles between them. Further details of mathematical formulae and measurements from rose diagrams can be found in the publications of Huntington (1969) and Golbraykh et al (1966). In general, the longest rays of a rose diagram are selected as diagonals for a parallelogram. If there are several rays of roughly equal length, a series of variations can be tried and the appropriate rays have to be selected.

The minimum number of megajoints (fracture traces) required to have a valid result is 50. It is recommended that the fractures should be distributed over at least four sample areas well within the structure and preferably at right angles to the strike.

3.4.3 Other Methods

Overbey et al. (1971) suggested a method for the prediction of directional trends of fracture systems in oil-bearing rock. It is based on the analysis of fractures obtained in the field as well as those interpreted on air photographs as fracture traces.

It has been acknowledged that there is a relationship between tectonic structures on the surface and subsurface structural features. Overbey et al. mentioned that the tectonic stress field was shown to influence the direction of hydraulically induced fractures in oil reservoirs. So, the orientation of principal compressive stress in oil areas may determine the direction of induced fracture system. Oil reservoirs appear to contain inherent planes of weakness which are sensitive to hydraulic pressures. The frequency and direction of these weak surfaces is controlled by the magnitude and orientation of the existing stress field in the bed formation.

In order to stimulate oil and gas production, various methods have been used to fracture reservoir rocks. Directional flow characteristics from fracture systems in the reservoir influence both the injection and withdrawal of liquids and gases. The extent, distribution and orientation of reservoir fractures, together with the spacing and pattern orientations of wells, are important factors in oil and gas production, particularly from less permeable formations.

Overbey and his colleagues carried out a study on six oil and gas areas in the Appalachian basin. The method by which the investigation was carried out can be summarised as follows.

Joint strike measurements were mapped at selected sites in the field. The number of joint strikes measured at each location ranged from 35 to 227. Azimuth-frequency rose diagrams were drawn five degree azimuth groups of the orientation measurements.

Bottom-hole packer surveys were conducted by setting impression packers equipped with a sensitive rubber covering in the hydraulically fractured zone of the producing formation. The packer tool was retrieved with well-bore fracture imprints.

Oriented cores were cut from a well using a special core barrel and photographic system. The time and depth at which the pictures were taken were used to orient the core for laboratory study. The orientated cores inspected for visible fracture orientations were measured by goniometer.

Air photographs were interpreted for fracture traces and azimuth-frequency rose diagrams of five degrees intervals were drawn for the fracture traces.

In situ strain measurements were carried out, and the magnitude and orientation of stress fields were obtained. These were considered representative of the area under investigation.

The data obtained from all stages of the investigation were plotted, analysed and correlated. The directional analysis of the data played the most important role in the study. Rose diagrams of fracture traces, surface joints, and subsurface reservoir fractures were correlated and compared with the orientation of the in situ stress field.

The results of this study have shown that there exists a definite relationship between bedrock joints and induced well-bore fracture orientations. Also the formation of fractures in oil reservoirs is closely related to the compressive stress field prevailing in the area.

Overbey and his colleagues concluded that the technique of fracture trace analysis on air photos combined with the directional analysis of bedrock joints can be most helpful in planning and developing both oil and gas producing reservoirs.

Pretorius et al. (1974) used the analytical method for mineral exploration based on the analysis of the angular atypicality — the degree of departure in the directional trend of fractures from statistically dominant (typical) orientions of fractures in the field.

During the investigation a great number of fracture traces were interpreted on air photos and mapped. The sum of the lengths of fractures in angular (i.e azimuth) intervals of one degree was calculated and plotted against the azimuth range of 0 to 180 degrees. The result was a sinuous curve showing two peaks (maxima) and three lows (minima). The diagram is shown in Figure 4. From

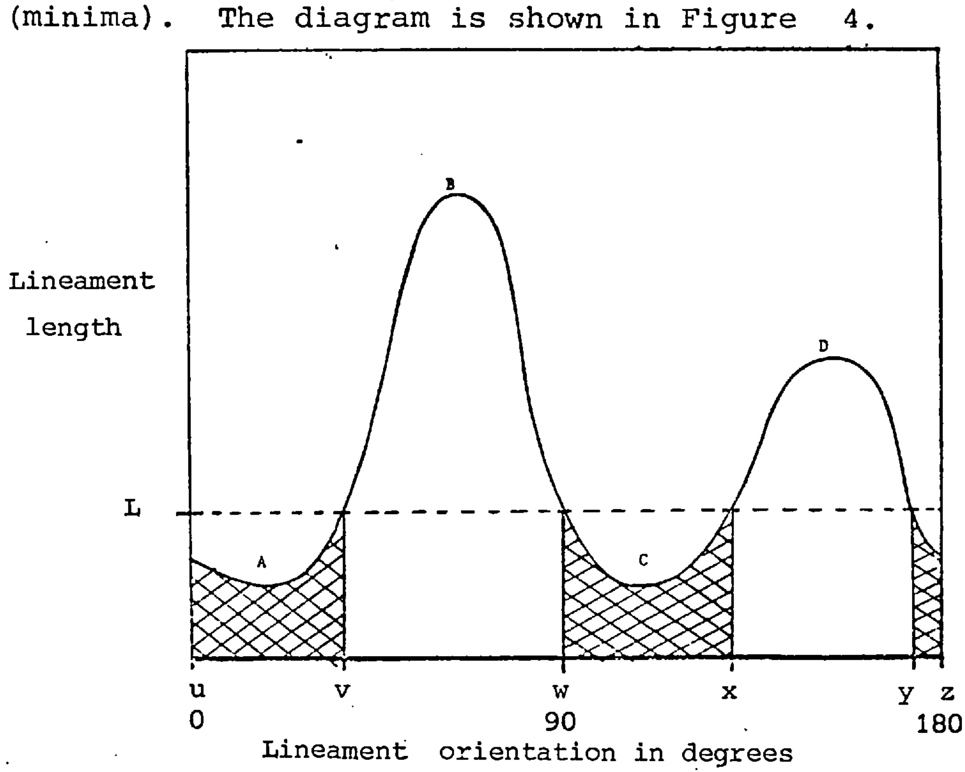


Figure 4 (after J. P. G. Pretorius, et al., 1974) the graph, it could be seen that a high proportion of fractures had orientations near those of the two peaks. These could be regarded as having "typical" orientations. In the same sense, those with orientations near the frequency lows, could be regarded as being "atypical". The proportion of fracture lengths with atypical orientations in a grid square (5 km x 5 km) was calculated. This gave an index of atypicality ranging from 0 to 1. These values were contoured using a standard computer programme.

The contours of angular atypicality were used to delineate target areas in the following ways. Areas with high atypicality indices were noted. Approximately 20 per cent of the total area had indices of 0.5 or more, and 40 per cent of the 180 features were within this part of the area.

The pattern of angular atypicality anomalies was carefully studied in relation to (a) known mineral occurences within the area and (b) photogeological anomalies. An association such as the occurrence of a series of contour peaks around a "quiet" area, within which several known features were clustered, and the occurrence of isolated peaks within areas of very low background were given special significance. In this way, target areas were delineated in which 50 per cent of observed features could be incorporated within 10 per cent of the total area than coincided with clusterings of local occurrences of high atypicality peaks. Further detailed exploration could then be confined to small highly anomalous areas.

In a brief examination of certain of these areas, the locations of ten features were visited. Five of these were proved to be of intrusive or extrusive origin. The location of the areas has not been given as it is regarded as confidential.

Pretorius and his colleagues concluded that an angular atypicality analysis of fracture traces provided an effective screening technique by which unbiased identification of anomalous areas can be achieved. In the case of intrusive or extrusive features, the technique is used most effectively in conjunction with the distribution of known features to determine the patterns and associations by which small target areas can be delineated. Where deep-seated structures have to be detected, angular atypicality analysis can also be applied successfully.

CHAPTER FOUR

4.1 COMPUTER APPLICATION IN FRACTURE TRACE ANALYSIS

In geological studies such as fracture trace analysis there are usually two principal approaches of investigation, they are the qualitative and quantitative approaches. In most cases a combination of both approaches is used, and due to the particular nature of some studies different emphasis on the application of one or the other can always be expected.

The characteristic feature of the qualitative approach is that the investigation is primarily based on descriptive or empirical (observational) analysis. A great deal of emphasis is laid on the quality or type of geological data and the manner in which they occur. Thus, the number of the data and the general quantitative characteristics may be considered less important. In such conditions the number of hypotheses which need to be used during the investigation is rather limited and these hypotheses tend to reflect the empirical nature of the study. It is quite possible that the study will lead to a biased conclusion in so far as it employs a few objective criteria and also, on the other hand, retains a great deal of subjectivity.

A quantitative approach to a geological investigation is often characterized by a large amount of data. These data are usually analysed on the basis of many parameters derived from their quantitative characteristics. In most cases, the data and parameters can easily be represented numerically, and this makes the whole analysis amenable to various statistical techniques and mathematical treatment. Thus, within the framework of numerical analysis, a great number of working hypotheses can be proposed and tested. Finally, a set of objective conclusions can be reached. The acquired conclusions may be considered as the most sound and unbiased criteria which can be used for further investigation.

Fracture trace analysis may be generally regarded as the systematic analysis of the quantitative and qualititative characteristics of fracture traces for the purpose of establishing reliable criteria which can be used as tools or aids in further geological investigation.

In such analysis the number of fracture traces involved always tend to be considerable. The number (or frequency) of fracture traces and their quantitative characteristics as an aggregate or individually, constitute a major source of data to be used in any fracture trace study. Thus, a large number of fracture trace date can be collected and represented in numerical form. Consequently, an appropriate statistical analysis can be applied as a logical step. During such an analysis, the statistical calculations and plotting can be very tedious and time-consuming, especially if they are carried out manually. By using an automatic machine or data processing equipment, the entire process can be performed quickly and with sufficient accuracy.

In this study the statistical data processing began after the digitization of the fracture traces. The statistical analysis of the data and the plotting of the diagrams were performed by a digital computer, CDC 6600/6400. In order to understand the concept of the digital data processing, one must be familar with the fundamental features of the digital computer.

A digital computer is basically an electronic machine capable of performing automatically operation on data represented in digital (or number) form. The method by which the data are represented (or registered) in the computer system is based on binary notation. A series of discrete elements (i.e binary bits or digits) are arranged in coded format to represent numerical data. The binary notation is most widely used because of convenience in constructing logic circuits and storage devices capable of handling data in binary form. For example, a magnetic core store unit consists of several thousand tiny rings of a size ranging from one twelfth down to one fiftieth of an inch in diameter. They are threaded upon a matrix of small wires and arranged into groups so that each group is a unit of data, e.g a word or a character. The wires themselves represent paths along which electronic signals can be transmitted to energize individual cores so that they adopt a particular electromagnetic polarity. Each core represents a binary digit and the polarity of the core at any particular instant determines the value of the digit (i.e 1 or 0).

The term digital computer is almost universally applied to mean a general-purpose computer. Basically, it performs simple arithmetic operations and logical decisions. All operation to be performed must be specified by means of stored intersections called a computer program. The digital computer installations usually consist of input devices, a central processor, backing storage, and output devices.

The advantages of the data processing technique are closely linked with, or attributed to the characteristics of the digital computer. In so far as the fracture trace analysis is concerned, these advantages as well as the characteristics of the computer can be briefly outlined as follows.

1. Speed and accuracy - The concept of statistical analysis almost always implies the involvement of a large number of data. Indeed, this was the case in the present study of fracture traces. In order to obtain meaningful information, the fracture trace data must be systematically classified and statistically treated. In such conditions, two problems are bound to arise; first, the length of time in which the entire process can be completed; secondly, the standard of accuracy of the final results. One can easily imagine how long it would take to carry out wide-range statistical calculations manually on several thousands of fracture trace data and plot the results. The task would certainly be very cumbersome and time-consuming, and there is also the possibility of human error and a tendency to compromise in the precision of the results.

One of the principal features of the digital computer is the extremely high speed of performance and the precision of the data processing. The speed of the most common computers is measured in terms of microseconds, while the precision of calculation can exceed ten numerical digits.

During this study it took the computer remarkably little time to process several thousands of fracture trace data and generate many statistical diagrams and maps.

Thus, the speed and accuracy of the digital data processing can be a vital factor in determining the future of the fracture trace analysis as a viable technique of geological exploration.

2. Data storage and filing system - The amount of primary data prepared for statistical processing is often many times greater than that of secondary data or results obtained as output. Several thousands of data cards were produced as a result of digitization of fracture traces. It is impractical and perhaps unsafe to keep such a large amount of data on card file. In addition, it is not easy to handle large card decks during the input operation, since one is liable to drop or damage some of the cards, thus affecting the final results. The process of reading the data from the card file into the computer by means of a card reader is comparatively slower than from a magnetic medium such as magnetic tape or a magnetic disc.

The great power of a digital computer rests in its ability to store a large volume of data and manipulate them very quickly during the processing. In a modern digital computer, there are two categories of storage systems, the main memory, and the backing store. The commonest form of a main memory is the magnetic core storage described earlier. For economic reasons, this storage medium is allowed only to store the current program and data. Thus, most digital computers have been designed to provide backing storage facilities. These mainly consist of magnetic tapes, a magnetic disc and a magnetic drum. They are sometimes described as mass storage devices due to the large volume of data they can hold.

In the context of the computer system, the concept of the data file is almost analogous to that of the ordinary office file which is meant as a receptacle for documents. The computer file is basically an organised collection of records of data. Each record consists of a number of fields; one field in a record is known as the key. The key of each record is different and will be used to identify it during the data processing. The backing sotres are used to hold permanent files, while the main memory stores only working files which are involved in the current processing. Data files can always be indexed, updated and maintained.

The magnetic tapes are the most suitable and economic storage medium for a large volume of data. They are also flexible and easy to update (i.e delete or add data), and manipulate. During the study, the fracture trace data were transferred from the card file to a magnetic tape file. Thus, the information content of several boxes of data cards were transferred onto two computer compatible magnetic tapes. Subsequently, these tapes were used in conjunction with programs to carry out the process of statistical analysis of fracture traces.

3. <u>Iteration method</u> - An inherent feature of statistical fracture analysis is the frequency distribution of data with respect to a specific characteristic. This entails a constant repetitive process, until the whole amount of data is sorted out or exhausted. Such a process was applied during the process of directional fracture trace distribution and also in the spatial frequency distribution of fracture traces.

A digital computer is the most expedient for the iteration method by virtue of its ability to perform a single cycle of statistical calculation extremely quickly (i.e. in a microsecond). The prerequisites for the iteration process are, first, the setting up of a statistical formula, and secondly, the defining of the conditions within which the iteration is taking place. Then the data in question can be screened repetitively and relevant data are sorted out or distributed continuously until the process is completed. Thus, the digital computer, offers an invaluable service in performing a tedious and repetitive operation at a very high speed.

4. <u>Graphical plotting and drafting facilities</u> - In the statistical analysis of fracture traces, there is always a need to present a graphical summary showing the statistical

behaviour of a specific attribute of the fracture traces. The diagrams used most are histograms and directional rose diagrams. During the study many rose diagrams and rosemaps were used and in addition, several fracture trace maps of different scales were produced. The task of drawing these diagrams and maps is by no means a simple one; it consumes considerable time and also needs patience. Involvement in a long drafting task can deprive the investigator from spending sufficient time on the interpretation of the data.

The computer system offers excellent drafting facilities. Thus, all statistical diagrams as well as fracture trace maps were produced by these facilities. The computer initially generates the plot on magnetic tape in a digital format and then the tape is mounted on a deck attached to a drafting machine which draws the plot as an off-line process. There were three types of drafting equipment operating basically on the same principle. Two use paper as a drafting medium, their trade names being the Calcomp Graphic Plotter and the Kingmatic Drafting Machine. The third was the Microfilm Plotter, which produced the diagram on a reversal black and white film (35 mm or 60 mm). The accuracy of the plotting in the Kingmatic machine, for example, is 0.004 in. and the speed of drafting is 200 in. per minute. All these drafting facilities were used during the study.

4.2 FRACTURE TRACE ANALYSIS PROGRAMS

The use of the computer in data processing is entirely dependent on programs. A computer program, quite simply, is a set of instructions written in symbolic language or codes to direct the computer system during its activity. By definition, a digital computer as a general-purpose processing machine can perform any kind of processing activity. By using a special program, however, one can convert the computer temporarily into a machine whose activity is oriented or restricted to perform a particular task. Thus, the fracture trace analysis programs were designed to instruct the computer to perform the processing of fracture trace data and generate statistical plots and diagrams, which could be produced off-line by computer plotting facilities.

At the beginning of this study there were a number of computer programs dealing with fracture trace analysis available in the photogeological laboratory. Some of the existing programs were modified and others were developed by the author to be used during the study. The programs were written in Fortran IV language, and designed principally to perform the following functions:-

a) Data input

b) Determination of fracture trace geometry

c) Classification

d) Statistical analysis

e) Graphical plotting

Unfortunately, the programs could not be documented to the standard usually accepted, and therefore they cannot be read easily by any person other than the author. This is due partly to their length and partly to the limited period of time given to computer work during the study. It was also the author's intention to give priority to the geological aspects of the study so as to use the computer as data processing tool only. Thus, the listings of the programs were not included in the thesis; they will instead be described further on in the text.

Four principal programs were used in the fracture trace analysis. Each one of these consists of a number of logically independent sections called subroutines, each of which performs a specific function. For convenience, the programs were stored in the computer system as a permanent program file and they were called upon whenever needed. Flow charts of the programs with descriptions of their functions can be outlined as follows:-

1. Program REDRAW - This program is devised to read the digitized fracture traces from the magnetic tape file into the computer, and carry out the classification of the fracture traces and determine their geometrical characteristics. Finally it redraws (i.e reconstructs) the fracture trace map in any desired scale.

Subroutines	Description of functions
MAIN	This routine reads in the required parameters for the program and transfers the control to other subroutines.
RESET	This routine reads in map boundary co-ordinates and resets then to zero origin taken as the left lower corner. It determines the map sheet area and its orientation on the digitizing table. It reads in the traces co-ordinates and resets them to zero origin. It writes the reset traces co-ordinates onto scratch tape (temporary data file).
TRACES	This routine reads in the traces co-ordinates from the scratch tape, and determines the azimuth and length of each fracture trace. It classified the traces into rectilinear, curvilinear and sinuous, calculates the total number and total lengths of the traces and also the average lengths of all traces. It prints out all these data and also writes them on new scratch tape.
REDRAW	This routine converts the traces co-ordinates which were digitized in the metric system into inches. It replots the fracture trace map in the desired scale and also writes the map titles and other symbols.

2. Program ROSES - This program plots three directional rose diagrams using a Calcomp or Kingmatic plotter. These diagrams are drawn inside labelled square display boxes. The sizes of the diagrams and boxes can be predetermined by the user. They are directional frequency, directional density and directional average density rose diagrams.

Subroutines	Description of functions
MAIN ↓	This routine performs the functions referred to in the same subroutine in program REDRAW.
RESET ↓	This routine performs the functions referred to in the same subroutine in program REDRAW.
TRACES ↓	This routine performs the functions referred to in the same subroutine in program REDRAW.
DIRECT ↓	This routine reads in the accumulated fracture trace data from the scratch tape of the previous routine and carries out classification in predetermined directional classes. All statistics concerning directional distribution are calculated in both percentages and absolute values and printed out in listings and written on scratch tape.
COORD ↓	This routine converts percentage angular (directional) frequency data into cartesian co-ordinates for the rose diagram plotting. The co-ordinates are in inches.
ROSES	This routine takes the directional data from subroutine COORD and plots three rose diagrams on the Calcomp or Kingmatic plotter. The diagrams are of directional frequency, directional density and directional average density. The data may also be output on a line printer as histograms.

3. Program ROSEMAP - This program produces three rosemaps, each consisting of several rows of semi-circular rosettes drawn in the centres of square cells. The rosemaps are of directional frequency, directional density and directional average density.

Subroutines	Description of functions
MAIN	This routine reads in the program's parameters and calls other subroutines.
↓ GRID	This routine sets up mathematically a system of square cells to fit the confines of the fracture trace map and distribute the traces over the cells. It determines the azimuth and length of each trace and calculates the total number and total lengths of the traces in each cell. It writes out the data on a temporary data file (scratch tape).
↓ DIRECT	This routine performs the function referred to earlier in subroutine ROSES but processes the traces of each cell at a time.
↓ COORD	This routine performs the function referred to earlier in subroutine ROSES but processes the traces of each cell at a time.
↓ ROSEMAP	This routine takes the data provided by subroutine COORD and generates three plots of different rosemaps in a digital format on a magnetic tape. This tape can be run on a plotter to produce the three types of rosemaps mentioned earlier.

4. Program CONTOR - This program produces a printout of numbers arranged in rows corresponding to the cells of the rosemaps. The numbers are of two types; one represents the total number of the fracture traces occurring in each cell, and the other represents their total lengths. Subsequently, these numbers are placed respectively in the centres of the cells and this enables contour lines to be drawn.

Subroutines	Description of functions
MAIN ↓	This routine performs the function referred to in program ROSEMAP.
GRID ↓	This routine performs a similar function to that in program ROSEMAP.
CONTOR	This routine reads the fracture trace data written on scratch tape by subroutine GRID. It prints out only the numbers which represent the total number of fracture traces and their total lengths in each cell. The layout of the printed numbers corresponds to those of the cells drawn in the rosemap.

CHAPTER FIVE

5.1 THE TECTONIC FEATURES OF THE MIDDLE EAST

Geologically, Northern Iraq is an integral part of the Middle East. Thus, in order to understand the geological and tectonic characteristics of Northern Iraq, one must first become familar with the tectonic framework of the Middle East.

The Tectonic features of the Middle East have been discussed by a number of authors. In general, they agree on the broad tectonic features of the region. However, there are different views as regards the origin and geodynamics of these tectonic features.

The Middle East is generally regarded as having a nucleus of stable basement rock, the Arabo-Nubian Massif, formed mainly of extremely deformed pre-Cambrian igneous and metamorphic rocks. This is exposed in the Hejaz province of Arabia. Around this massif (or shield), there is a succession of arcuate tectonic and stratigraphic zones of Paleozoic, Mesozoic and Tertiary rocks cropping out in a great curved belt bordering the shield. The Lower Paleozoic rocks are in the North-central and North-west of Arabia near the pre-Cambrian basement, where there is as much as 2000 metres. Near the Gulf of Aqaba, however, they are only represented by 45 metres of Cambrian rocks.

Two major tectonic provinces are recognized within the Middle East region: (I) the Stable Shelf, which is a comparatively stable region whose rigidity is attributed to the pre-Cambrian basement, (II) the Mobile Belt, which consists of the Taurus, Zagros and Oman mountains bordering the stable region, (Figure 5).

The Stable Shelf contains (A) the Arabian Shield (or Massif Zone), (B) the Arabian Shelf.

(A) - The Arabian Shield (Massif Zone)

Until Upper Tertiary, the Arabian Shield was a projecting part of the African Shelf, but it is now separated from it by the Red Sea rifting. It crops out over much of western and central Arabia and sporadically along the southern coast of the Arabian Peninsula, (Figure 5). But in the North, due to Mesozoic transgression, only a few marginal exposures are to be seen in Sinai and Jordan.

The structural history of the shield during pre-Cambrian times was complex and is little known. Nevertheless, it can be generalised as several episodes of down warpings, sedimentation and orogenies associated with plutonic injections and levelling before becoming immobile.

(B) - The Arabian Shelf

This forms a belt around all sides of the shield except its south-west; the strata are relatively undisturbed and gently dipping. It differs from the exposed part of the shield only in possessing a thin sedimentary cover. Transgression and regression due to epeirogenic movements of the shield are clearly recorded in the interior of the shelf by unconformities, disconformities, westward and

TECTONIC MAP OF MIDDLE-EAST

200 0 200 400 600 KM

Legend:- Figure 5

STABLE SHELF

ARABIAN SHIELD

ARABIAN SHELF

INTERIOR HOMOCLINE

INTERIOR PLATFORM

BASINS

A. Aafrine, B. Palmyra C. Sirhan-Tureyf, D. El Jafr, E. Zbeir-Northern Persian Gulf, F. Dibdibba, G. Rub al Khali.

SWELLS

A. Mardin, B. Deir Ez Zor, C. Ga'ara, D. Huqf-Haushi

MOBILE BELT

MOUNTAINS

A. Zagros Mountains, B. Oman Mountains

FORELAND

A. Taurus-Zagros Foreland, B. Oman Forelands

STRUCTURAL TRENDS

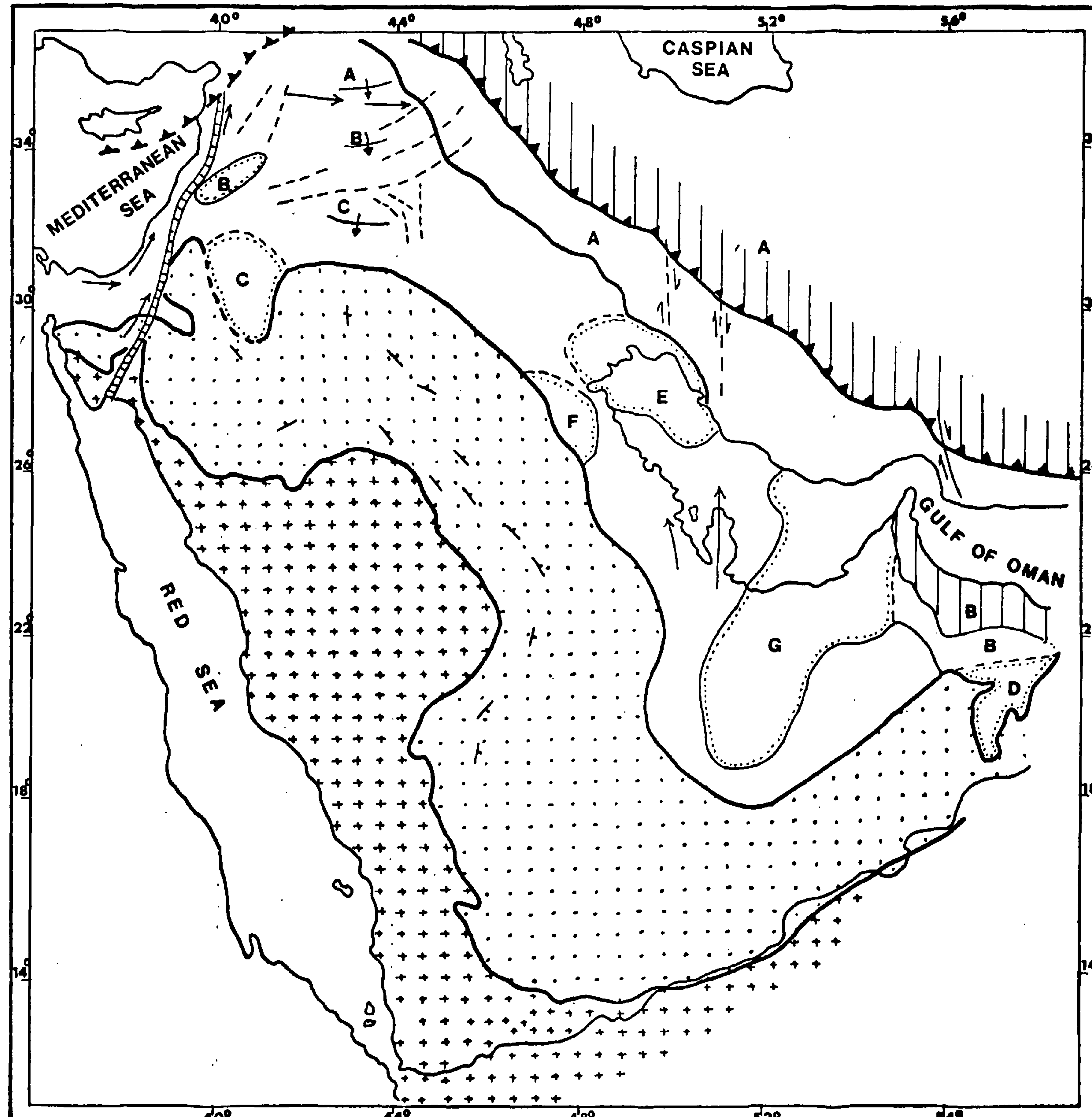
BURIED STRUCTURAL TRENDS

SURFACE EFFECTS OF DEEP STRUCTURE

TAURUS-ZAGROS THRUST

THE LEVANT GRABEN SYSTEM

STRIKE AND DIP DIRECTION OF BEDS



after Al-Warrak, M. 1968.

south-westward thinning of the successive marine cycles. These alternating marine and non-marine continental rocks thin out as the deeper part of the basin is approached. Sediments of the shelf are characteristically of shallow water origin. Limestone, clastic-textured and mechanically sorted, is the main rock type. Sandstone and shale are also present in large quantities. The Arabian shelf is divided into the following sub-provinces:

(a) The Interior Homocline (Figure 5)

The surface geology, structural bore-hole data and seismic surveys over the area bordering the shield, have defined a remarkably constant homocline, with an average width of about 400 km. and a persistent basin-ward dip from about 2 degrees in the Permian and Triassic to one degree in Upper Cretaceous and Eocene beds. Faults occurs within the homocline, and possible fault-controlled anticlines (Henson, 1951) appear in Sinai and Jordan.

(b) The Interior Platform (Figure 5)

This forms a belt of varying width stretching from the end of the homocline to the edge of foreland zones of foldings in the north, north-east and east.

Seismic and drilling data indicate that the beds are rather horizontal in a geological sense, and irregularities are limited to low and gentle structural undulations that lack any definite orientation, (Powers et al, 1966).

The eastern part of the platform directly faces the

Persian Gulf and the dominant structural trend, north - south is represented by several major anticlinal axes. One of these is the En Nala anticline. The folds of Abqaiq and Qatif are other good examples of large North-South trends. These North - South structures extend across the Persian Gulf and have been recognised in the foreland of the Zagros Mountains as zones of normal and transcurrent faulting with associated facies changes in the direction of anticlinal axes (Falcon, 1967).

In west-central and south-west Iraq, gravimetric anomalies and slight structural flexures in the flat-lying Tertiary cover within the Interior Platform indicate important buried structural elements (Figure 5). Some extend for hundreds of miles (Dunnington, 1958). These trends are considered by Dunnington as representing pre-Miocene faults which are oriented predominently N - S, E - W, NW - SE and NE - SW.

Anticlinal features within this area (West Iraq) are small and indefinite, with low dips and possible or no closures, most of them bearing no directional relationship to the trend of folds in the Zagros Mountains foreland, or to the deduced pre-Miocene fault directions.

Geophysical evidence also indicates that salt activity has been tectonically responsible for many observed structures within the Interior Platform. A salt intrusives are prevalent in the southern part of the Persian Gulf, such as the Dammam Dome which was regarded as a salt-intrusion structure (Powers et al. 1966) because of its central faulting, strong negative gravity anomalies, and oval shape. Geophysical surveys and deep drilling have also shown that beneath the flat-lying cover of the Cenozoic sediments of this area, there are patterns of major paleogeographic basins and swells.

The basins, at one time or another, received thick deposits whilst the swells received relatively thin deposits. Their margins follow approximately the dominant structural trends of the area.

Examples of the basins are:- The Palmyra and Aafrine basins in Syria, the Zubair basin in South Iraq, the Sirhan-Turayf basin in NW Saudi Arabia, the Dibdibah basin in West Kuwait, the North Persian Gulf basin, and the Rub al-Khali basin in Saudi Arabia. (Figure 5).

Examples of the swells are:- The Huqf-Hawshi swell in SE Oman, the Ga'ara uplift in SW Iraq, the Aleppo platform in N. Syria and the Mardine swell in NE Syria.

Any conclusions regarding the formation of the basins and swells are rather speculative, but according to Powers et al. the gently undulating parts of the Interior Platform are presumed to be underlined by rigid blocks of basement which have restricted the deformation and thus protected the sedimentary blanket from significant disturbance.

The margins of the old swells and basins approximately follow the dominant structural trends. In view of this, Henson (1951) suggested that the basins and swells were due to slow vertical block movements of the basement, but he admitted that the gravimetric surveys over some known basin margins do not reveal any sign of deep-seated faulting. He therefore suggested that a combination of the latter with broad tectonic warping of the crust had taken place. On the other hand, Baker (1953) considered the swells as isolated positive remnants of the shield igneous basement rocks, while Dunnington (1958) regarded the Ga'ara uplift (W. Iraq) as reflecting basement arching.

Considering the Interior Platform as a whole, Baker and Henson (1952) suggested that the varied strike of the platform structure gives a pattern which is more consistent with a history of taphrogenesis or block faulting than with one of regional compression on a broad front.

The fact, against a purely taphrogenic interpretation, is that major faults mappable on the surface are scarce in the areas outside the rift zones. However, gravity surveys in the region have given a clear indication of numerous major and minor faults, (some with dykes in Syria and Jordan), which do not appear at the surface. Wild-cat drilling has provided stratigraphic evidence, locally, in the form of fault breccia, polygenetic interformational breccia and marked thickness variations, etc. over small distances suggesting block movement (Henson, 1951).

II - The Mobile Belt

This is divided into (A) the mountains (the Thrust Zone) and (B) the Foreland Folding.

(A) - The Mountain (The Thrust Zone)

The Taurus-Zagros mountains form a belt of E - W and NW - SE folded and faulted Paleozoic, Mesozoic and Cenozoic rocks (Figure 5). Complex thrusting and nappe tectonics is a common phenomenon in the younger sediments. This orogenic belt is separated from the foreland by a thrust which is over 1300 km. long in Iran, and extends north-west and west into Iraq and Turkey. The thrust bifurcates at its south-eastern end with one branch going east towards Oman. In this area there has been igneous activity, both intrusive and volcanic as well as metamorphism and extensive emplacement of ophiolite-radiolarite rocks. There is some evidence of tectonic movement subsequent to the main orogenic period that occurred in Late-Tertiary, mainly during the Pliocene.

Orogenic movements began at the end of the Middle Cretaceous period, and were recorded between the Oligocene and Miocene with perhaps one or two compressional episodes (Lees, 1953). With some exceptions, the orogenic belt is differentiated from the platform more by its Late-Tertiary tectonics than by its sediments, and it is possible that platform type tectonics and sedimentation previously dominated the whole region.

The strong Late-Tertiary folding and thrusting of the orogenic zone, with fold-arcs varying in strike, indicate obvious compression. These axial variations are related to differences in resistance offered by the jagged edge of the residual Arabian platform.

(B) - The Foreland Folding

Most of Northern Iraq lies within this zone. The foreland zone can be sub-divided as follows:-

(a) The Oman Mountain Foreland

This is an area of gently deformed and generally westerly dipping beds and Mesozoic rocks almost entirely covered by the flat-lying Tertiary sediments that flank the Oman Mountains. These folds, to a certain degree, resulted from the same orogenic forces which affected the Oman Mountains (Powers et al. 1966).

(b) The Taurus-Zagros Mountain Foreland

To the south-west of the Zagros Mountains, and south of the Taurus Mountains is a belt of gently folded rocks which in North-east Iraq attains an average width of about 160 km. The alignments of the individual folds and the zone itself follow the main mountain ranges, swinging from E - W in the north to NW - SE in the East. The structural features within this foreland area are generally elongated, and mostly symmetrical anticlinal and synclinal folds. There is an overall tendency for anticlines nearer the thrust front to have a greater amplitude. However, there are many departures from this generalization. Thus, in Northern Iraq, the Hamrin-South, Hamrin-North, Makhul and Sadid anticlines are much more tightly folded than some anticlines which occur immediately to the north and north-east, where flat. low domes appear between steep, narrow anticlinal neighbours in the middle of the zone. Other structural anomalies which have been observed, include the following:-

(1) The existence of great elevational differences between adjacent anticlines of otherwise similar dimension.

(2) A train of anticlines plunging successively forming a linear feature.

(3) The appearance of marked asymmetry in some folds.

(4) The successive opposal of the asymmetry in some pairs of adjacent folds.

The closed anticlinal structures in this zone are considered by Baker (1953) to be the result of the mountain ranges being pushed against the Arabian Shield. The great length of these anticlines were considered by Baker, as due largely to simplicity of movement which was not interrupted or complicated by other folding forces, and the decrease in the amplitude intensity towards the shield as due to the absorption of the tectonic forces in a great downward movement. Thus the remaining forces against the stable Arabian Shield produced long gentle flextures.

Henson (1951) put forward the hypothesis, based on the above mentioned structural anomalies and geophysical data, that the Late Tertiary folding in the foreland was intimately controlled by a pre-existing structural complex which pre-disposed the region in an irregular and complex fashion to simple tangential stress. Some important pre-existing tectonic trends have been recognised in the Interior

Platform, and it has been argued (Dunnington, 1958), that the foreland was traversed prior to folding by a tectonic network comparable with that which is now detectable in the platform area.

The boundary between the folded foreland and the platform is abrupt. The southernmost and westernmost anticlines, (e.g. Hamrin-North and Hamrin-South of W. Iraq) are surprisingly large folds, about ten miles long and rising in some cases several thousands of feet out of the adjacent synclines.

Several structural elements can also be seen in the outer area of the foreland. They include the following structures:-

(1) The coastal range mountains of Syria and Lebanon striking NE - SW.

(2) The Afro-Syrian fault system (Levant Graben System) striking N 30° E (Figure 5). These faults run along the Gulf of Aqaba, the Dead Sea, the Jordan River Valley, Bekaa and Orentes Rivers as far as the Taurus range.

(3) The foot-hill folds of Northern Syria striking E - W.

(4) The Palmyra range of Syria striking approximately N 55° E.

The tectonic construction of the Middle East region in general was thought by Lees and Richardson (1940) and Lees (1950, 1951, 1953) to be due to successive waves of compression acting upon the sediments of the Taurus-Zagros-

Oman geosyncline. The compression has been caused by successive Alpine movements, and is oriented from the north (Taurus), north-east (Zagros) and east (Oman) against the edge of the Arabian Shield.

Gass and Gibson (1969) discussed the tectonics of the Middle East in the light of the plate tectonic theory. They suggested that the tangential compression forces which resulted in the Taurus-Zagros range were caused primarily by the movement of the Arabian Plate north, north-eastward against the Eurasia Plate. The evidence supporting this hypothesis is that, (a) in the north and north-east margins of Arabia, the crystalline basement underthrusts the geosynclinal sediments in the Taurus-Zagros thrust zone, (b) in the east and north-west there are sites of extensive transcurrent faulting, such as the Mesirah dextral wrench fault in the east, and the Jordan sinistral wrench fault in the north-west, (c) there is crustal attenuation along the southern and south-western boundaries of the Arabian Shield (Gulf of Aden).

Burek (1970) believed that the orogenic and epeirogenic deformations that produced the tectonic features of the Middle East are due to sea-floor spreading, which originated in the Red Sea rift and Gulf of Aden. The oceanic, igneous material was generated and differentiated from the upper mantle and intruded probably into old zones of crustal weakness. The vector sum of the forces generated by the multiple intrusion was apparently of sufficient magnitude to move continental blocks. Such movement would be greatly facilitated by sliding on viscous layers caused by partial melting or by zones of decreased shear-strength occurring between the crust and the uppermost mantle.

Girdler (1956) has suggested that the Arabian Peninsula has rotated along the Red Sea rift in an anti-clockwise direction, away from Africa. The opening of the Red Sea took place probably after the Miocene Epoch and the rotation has now reached seven degrees east, around an imaginary centre located in the Mediterranean Sea, south of Cyprus.

5.2 SEDIMENTATION, EARTH MOVEMENT AND OIL OCCURRENCE IN NORTHERN IRAQ

The whole of the Middle East has been subjected to successive regimes of sedimentation and earth movement. It would be relevant to consider the main cycles of sedimentation and tectonism which have occurred in the Middle East, and in particular, as they have affected Northern Iraq.

Sedimentary episodes in the Middle East have been long and extensive and have always been controlled by earth movements. In most cases the movement was epeirogenic over considerable periods of time, with or without faulting. In other cases orogenic movements involving mountain building were characterized by the emplacement of igneous bodies by vertical block faulting.

The history of the sedimentation, tectonics and oil

occurrence in so far as it concerns Northern Iraq, can be divided into four major phases as follows:
(A) Paleozoic, (B) Early Mesozoic, (C) Late-Mesozoic - Paleogene and, (D) Neogene.

(A) - Paleozoic

During early Paleozoic times, conditions were generally cratonic, and shallow marine transgression caused mainly clastic sediments with organic limestone. However, the Paleozoic encountered in Northern Iraq, during deep drilling at two localities in the south-west of the Ain-Zalah oil field, consisted of alternations of sub-greywacke, micaceous sandstone, siltstones, quartizite and shale with marine fossils of Ordovician to Permian age. The detail of the stratigraphy of these two widely separate localities is available, though not documented here. Thus, it is possible to assume that similar sedimentation underlies most of Northern Iraq.

The complete similarity of sedimentation between the two known occurrences, some 300 km. apart, may suggest that Northern Iraq was extensively covered by sea. The nature of Paleozoic sediments indicates that the sea was very shallow, and sedimentary facies were affected by slight microtectonism. The next Paleozoic sediments, which are also found in the area, are of the Upper Devonian to Lower Carboniferous age.

A comparison of the lithology of the two sections suggests that some differential subsidence or most probably gradual tilting took place during this period. This tilting was in the southern part of Mosul Province and whether it was accompanied by faulting is not known. The sea in this period remained essentially shallow, deepening towards the north-east and the north.

After Lower Carboniferous, a major disturbance appears to have taken place. During this interval faulting on a substantial scale must have occurred, and a portion of Northern Iraq broke from the main shield mass in the south-west. The break occurred probably along a set of intersecting fault lines, one in an east - west direction, south of the Singar structure (Figure 2), the others at 45^{o} to it, in a NW - SE alignment. The area to the north and north-east of these faults subsided, and subsequently received and retained Permian sedimentation, while a positive block south and west emerged and was partially denuded.

It is suggested that this positive block be given a geographical name because of its important role in shaping the subsequent tectonic and structural setting of Northern Iraq (Mosul Province). The name proposed is the "Jazira Block" (Figure 2). It corresponds roughly to the present-day unfolded area of Northern Iraq and extends westward into Syria.

(B) - Early Mesozoic

During this phase almost the whole Arabian Shelf submerged slowly, possibly with faulting, and with ophiolite extrusion around the Taurus-Zagros Zone. Some thousands of feet of sediments, mainly of chemical limestone, ranging in age from Triassic to early Cretaceous, were laid down very uniformly, with evaporite horizons in certain areas corresponding to epeirogenic breaks, and with some basal and marginal clastic sediments.

The Triassic is better known in the area from a number of well sections. In Atshan anticline (Figure 2) the entire Triassic succession, about 4000 ft. of sediments, was encountered. The sediments at the bottom of the Triassic are thin alternations of silty shale, arenaceous limestone and calcareous sandstone, followed in the middle by thick beds of limestone and dolomite, and then 700 ft. of anhydrite. The uppermost Triassic sediments are mainly limestones interbedded with anhydrite and dolomite. These sediments were laid down conformably over the Permian.

On the whole, the Triassic sediments, as found in various localities of Northern Iraq, are lithologically uniform over the area, except for one member, "the Beduh formation", which varies from red-brown shale in the north-east to grey and green shale in the west. This may suggest that some volcanicity occurred in the north-eastern area. In contrast to the continuous sedimentation in Atshan, the Jazira block has no Lower and Middle Triassic.

The Triassic sediments in Northern Iraq appear to have been laid in a shallow basin similar to that of the

Permian.

Towards the beginning of the Jurassic, the whole area subsided and the sea encroached on the entire Jazira block, which up to that time had remained above the zone of sedimentation.

Conditions of deposition remained unchanged during the early Jurassic. Neritic limestone, anhydrite and shale continued to be laid down in most parts of Northern Iraq. However, the evaporite zones of this period such as the Adaiyah and Alan anhydrite, suggest a recurrence of restrictive conditions which controlled the supply of sea water to the Liassic basin.

These shallow conditions gave way eventually to deeper sedimentation during the Middle Jurassic. The basin sagged differentially and a trough was formed on the northern and eastern fringes of the Jazira block. In this trough, thick basinal sediments of shales, limestones and breccias were deposited. The thickness of deposits varies with their respective basinal positions. In the deepest part, near the Ain Zalah anticline, more than 1500 ft. was encountered, while in the north-eastern part, the basinal sediments averaged only 250 ft.

The subsidence of the Middle Jurassic was followed by tilting during the upper Jurassic. The areas of Ain Zalah and Butmah, the areas north-west of these, and the Jazira block were all raised above sea-level, while the areas of Atshan, Qalian and east of the Tigris subsided. Consequently, sediments of the Upper Jurassic (dolomite, oolitic limestone and basinal shale), were deposited.

Towards the end of the Jurassic, an important phase of epeirogenic uplift occurred with some faulting, and the sediments were removed from up-tilted areas and generally became more variable in the whole region. During this period the Northern Iraq parageosyncline took a definite NW - SE trend, and the thickest basinal sediments were laid in that direction.

As far as the Middle East as a whole is concerned, the first horst structure began to rise in the Levant. The Arabo-Nubian massif came under more active erosion, and terrigenous clastic material fanned out radially from the nucleus into the surrounding basin.

No commercial oil has been found in the Triassic, but the Jurassic developed bituminous shale and dolomite facies over much of Southern Arabia and the Zagros ranges of Northern Iraq. In one oil field, at least, (the Ain Zalah oil field), Jurassic oil migrating upwards through fractures seems to have contributed to accumulation in the higher Upper and Middle Cretaceous formations.

(C) - Late Mesozoic - Paleogene

In Early and Middle Cretaceous times, the Middle East underwent strong tectonic movements, approximately on the same strike as the Upper Jurassic tectonic zones. These movements continued intermittently thereafter, determining the succession of sedimentary cycles. Synorogenic vertical movements of less intensity produced four dominant fracture trends (N - S, NW - SE, NE - SW, E - W), over the Arabian Shelf. Thus, a pattern of major basins with superimposed block-folds have been intermittently developed. The details of this pattern changed progressively in some sectors due to differential intensity of the movement in particular trends, but sedimentation was remarkably constant and repetitive throughout Cretaceous and Eocene times (Henson, 1951).

In Northern Iraq, the tectonic movements were most probably accompanied by faulting and further fragmentation on the fringe of the Upper Jurassic parageosyncline, east of the rigid Jazira block. A master fault which delineated two sedimentary regimes cam be imagined lying along the course of the Tigris river. South-west of this fault, where the area stood above sea-level and was subjected to extensive denudation, and East of the Tigris, (i.e. east of the fault), the sedimentation continued uninterrupted with basinal calcareous mudstone being deposited in a linear zone immediately east of the Tigris, and basinal radiolarian shales and limestone further to the north-east.

In Northern Iraq, the axis of the geosyncline remained essentially in the same position up to the Aptian. This is not altogether unexpected since the tectonic movements were a continuation of those already started in the Upper Jurassic.

Evidence of the folding movement is deduced from the drilling records in the Ain Zalah oil field where it was found that the Albian Qamchuqa formation varied in thickness by as much as 200 ft. between crustal and flank wells. This variation is attributed to the structural deformation of the field prior to erosion. This indicates that the date of the orogenic movements in the area is post Albian to pre- Turonian. This observation is not at variance with observation in other parts of the Middle East (Nasr, 1960).

The Upper Cretaceous was a period of extensive transgression in both Iraq and Anatolia. In Northern Iraq the sea encroached over the subsiding, previously segmented province, and deposited sediments of vastly variable thicknesses and facies. The variations occur over short distances and frequently in adjoining localities. Ain Zalah, for example, has 2500 ft. of Shiranish formation (U. Campanian - Maestrichtian), Butmah has 1800 ft., and Sasan has 5000 ft. Undoubtedly this variation was due to the difference in the rate of sinking of the various segments. The same is also true of the variation in facies.

The Upper Cretaceous subsidence must have been of considerable magnitude. In the north-east, the flysch sediments were derived from an uplifted cordillera, (the Iranides), which began to rise betweem the Middle and Upper Cretaceous in Southern Turkey and north-western Iran. The effects of this movement were probably felt throughout Northern Iraq, and caused the formation of a fore-deep in front of the chain, and readjustment and further fragmentation of the geosynclines. Even the Jazira block, which had stood above sea level at least since the Middle Jurassic, was finally depressed and covered by the late Upper Cretaceous reef limestones.

In the Upper Cretaceous to Early Tertiary, rocks are predominantly calcareous, and chemical sediments were deposited in the basin with organic, mainly reef limestone over palaeoridges and highs. There is no need to mention that such sedimentological conditions are very favourable to oil occurrence. Henson (1951) has described such deposits as the most productive oil source rocks. This fact has already been established in Northern Iraq, as in the great Kirkuk oil reef-reservoir and in the Jawan structure. The age of formations in these structures ranges from Middle Eocene to Oligocene. Henson also believes that the primary accumulations of oil occurred first in reef-stratigraphic traps, located on the ridges and highs of the faulted blocks, and subsequently redistributed and concentrated in the later anticlinal traps through fracturing in limestone. Unfolded reef-stratigraphic traps may well be awaiting discovery.

The uplift at the end of the Mesozoic produced an extensive unconformity in Northern Iraq. The denudation was heaviest in the south-west, while in the north-west and north the trough continued to receive sediments, mainly of the flysch type, over the period from the Upper Cretaceous to early Palaeocene.

During the Middle and Upper Eocene, Northern Iraq, (including the Jazira area), was finally and totally submerged to form part of a broad basin which extended from Turkey, across Iraq, to Iran. In the Northern Iraq sector of this basin, a succession of NW - SE sedimentary belts were deposited. They are mainly limestone, marls and globigerinal marls facies.

After the Pyreneic Orogeny, at the close of the Eocene, a regression accompanied by the partial withdrawal of the sea occurred. The basin narrowed and its axis shifted to the south-west. In the deeper part, (Sinjar area), basinal and deep shoal globigerinal marls and marly limestones were deposited, while along its north-eastern margin a series of reef-complexes developed. The alignment of these complexes is NW - SE.

The Oligocene is missing in some parts of Northern Iraq, such as the Butmah, Alan and Atshan areas (Figure 2). From the re-worked Oligocene fossils found in the overlying formations, it is assumed that these areas were also covered by Oligocene sediments, which were later removed prior to the deposition of the Miocene.

(D) - Neogene

At the end of the Palaeogene, widespread epeirogenic uplift occurred. Folding and thrusting are recorded in the Taurus ranges. Much of the region emerged and continued thereafter above sea level, however, some extensive residual basins remained. In certain areas the preceeding depositional regime of reef and globigerinal facies continued into the Middle Miocene, though the exposures and faulting ridges have virtually excluded the prospects of commercial oil accumulation in this setting.

On the other hand, in the Iraq-Iran basin a different set of conditions followed the Aquitanian regression. A partially barred basin remained, and evaporite deposition occurred, which has only been interrupted by a new Miocene transgression of marine limestone.

Subsidence, accompanied by transgression during the early Miocene, started a new period of sedimentation, "the Miocene cycle". During the whole of this cycle, the part of the basin in Northern Iraq remained essentially shallow, and its sediment alternated between lagoonal and evaporite. At the south-eastern end of the basin near the Iranian border, the basinal conditions remained unchanged, and the thick oil-productive Asmari limestone was deposited.

The depression of the basin and encroachment of the sea brought about a new cycle of lagoonal sediments, (the Jeribe Limestone). This in turn was terminated by either a rise in the lagoonal base, or by sedimentary fill-up. The result in another case, produced an environment suitable for the deposition of evaporites, (the Lower Fars).

The Lower Fars consists of gypsum, anhydrites, thin limestone, marls and clays with salt deposits in some places. The Lower Fars exceeds 2000 ft. in thickness, indicating that the shallow middle basin continued to sag as deposition proceeded.

The salt of the Lower Fars forms the plastic cover over the productive anticlines of south-western Iran and north-eastern Iraq.

At the close of the Middle Miocene, the first phase of the Zagros orogeny elevated a chain of mountains to the north-east of the area. From these mountains, an immense quantity of detritus, (the Upper Fars), was laid down in the basin. Apparently the orogenic movement also caused a down folding in the basin, and shifted its axis from the ares of the Tigris to a parallel position some 50 km. to the north-east. However, the axis alignment remained unchanged, as NW - SE.

The Upper Fars pediments covered most of Northern Iraq from the Zagros chain to the edge of the Jazira block, where they tapered off into deposits of marls and silts with plastic characteristics.

The rejuvenation of the Zagros orogeny during the Lower Pliocene and later at the end of the Pliocene and early Pleistocene, brought into the basin a new and increasing supply of mollasse-type sediments (the Bakhtiari Formation). These consisted mostly of sand and grit grading upwards into a coarse conglomerate. They attained their maximum thickness in the synclinal areas, as by this time the structural differentation of the region was in existence. Very little of the Bakhtiari conglomerates extend south-westwards beyond the Tigris valley.

In this cycle of sedimentation, the commercial oil has been found in thick Asmari limestone in south-western

Iran, whereas in Northern Iraq, (Qaiyarah oil field), the Miocene limestone often contains reefs and biostomes of an open-shoal type, and these may have accumulated some indigenous oil beneath a conformable Lower Fars cover.

5.3 THE HISTORY OF OIL DEVELOPMENT IN NORTHERN IRAQ

The extraction of oil and bitumen from the seepages and bitumen deposits occurring in Northern Iraq, is not new. From the evidence available, the working of those deposits goes back several scores of centuries, when there must have been a thriving industry related to the then local requirements. Evidence is still available in the great temples and ziggurates that large quantities of bitumen were utilized in these edifices as binding material for the bricks used in their construction. Most of this bitumen has probably come from the great bitumen "lakes" of the Hit-Abu Jir area, or from the Qayiarah deposits. Crude oil, known during the Babylonian period as "stone-oil" has been used by the inhabitants of Iraq for feul and lighting from time immemorial. Primitive refining came much later. The Greeks and Romans who penetrated into Mesopotamia knew of these deposits, and the early Arab historians and geographers often described them in detail.

However, in more recent times, the interest in Northern Iraq as a source of crude oil for export became apparent towards the end of the nineteenth century, following the discovery of great quantities of crude oil in the

Caucasus. This interest was shown by German and British concerns. Negotiators for these interests managed to obtain sometimes overlapping promises regarding the right to explore the petroleum possibilities of what was then the Wilayat (Province) of Mosul from the Sultan of the Ottoman Empire, and later from the National Government of Iraq.

The first attempt to develop the petroleum potential of Northern Iraq was made during the first world war by the Germans, who drilled three shallow wells at the Qaiyarah anticline, (Figure 2), near the active oil seepages. A small distillation unit was erected and its products, which were extremely sulphurous, were hauled by tank cars. The British Occupation Forces and later the British Oil Developments Co. Ltd. (B. O. D. Ltd.) continued this practice for a number of years.

The earliest geological work in Northern Iraq was carried out by Halse in 1918. He was followed by Noble and Evans in 1919. These authors were mainly concerned with the seepages. They both recommended the testing of the area. Among the early investigators were Prof. Bockh (1925 - 26), Viennot (1926), Shaw (1925 - 26), Andrau, Briand and Browne (1927), Biraud (1928) and Fowle (1929).

During the period 1928 to 1939, some ninety wells were drilled all over Northern Iraq. They were located on surface anticlines, and were either dry or contained heavy sulphurous oil of the Qaiyarah type. In a few exceptional cases indications of lighter oil were encountered, but on testing, were found to be non-commercial.

In 1939, a well on the Ain Zalah anticline discovered light commercial oil in the Cretaceous. This was the first success in a long and expensive programme which has continued unabated for nearly twenty years. As a result of this discovery, the drilling effort was concentrated at Ain Zalah.

By 1959, a total of twenty-two wells had been drilled, including a deep test which proved a second oil horizon in the Middle Cretaceous.

In 1951 drilling was started on the Butmah anticline where an oil horizon, equivalent to the Ain Zalah first zone, was discovered. The deepening of one of the wells drilled on this structure (well no. 2) found the second Ain Zalah non-productive oil horizon, and also discovered a Triassic pay zone. Thirteen wells were drilled on this structure.

Since 1947 other structures, both geological and geophysical have also been tested. Apart from heavy oil in Gusair, Butmah East, Gullar, Mushurah and Falluja, and non-commercial lighter oil in two other structures, no additional production potential has been found. However, further development wells are planned in the Ain Zalah and Butmah field. Seismic work and exploration drilling are still continuing in the whole area.

CHAPTER SIX

6.1 SURFACE GEOLOGY OF THE STUDY AREA

The area of the study forms a rectangular portion of the western part of Northern Iraq which is bordered by Syria. Thus, any discussion concerning the regional geological features of the area should be extended to the adjacent parts of Northern Iraq.

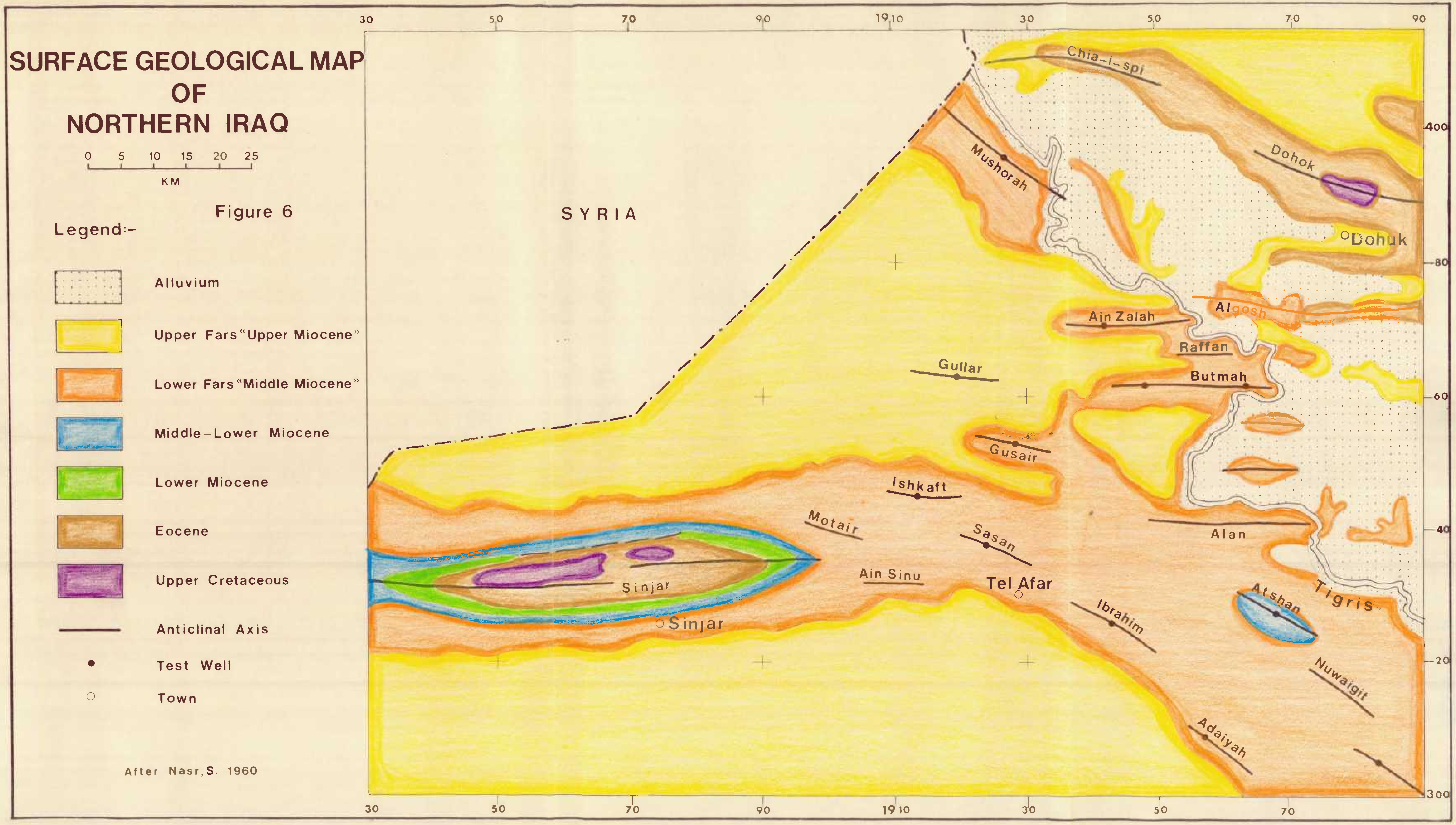
Tectonically, most parts of Northern Iraq lie within the foreland (folding zone) of the Taurus-Zagros mountains. The general trend of folding in this zone follows the strike of the mountains (or the thrust zone). The anticlinal structures in Northern Iraq assume a NW - SE strike at the southern limit of the foreland and swing to east - west in the northern and western parts of the zone. However, there is some deviation from this rule where an anticline (e.g Mushorah), or the extreme end of an anticlinal axis takes an oblique direction (e.g Maglub) to the strike of adjacent folds (Figure 2).

The oldest rocks exposed in the western part of Northern Iraq are to the south and north-east of the study area, in the Sinjar and Dohuk areas. The Shiranish formation of the Upper Cretaceous crops out in the core of the Sinjar and Dohuk anticlines. It consists of globigerinal limestones interbedded with basinal marls. This formation is overlain in both areas by an Eocene rock series. The

Sinjar formation of the Lower Eocene is exposed in the central part of the Sinjar structure, and in a wider area to the north-east of the study area (Figure 6.). This formation is made up of recrystallised, white and grey limestones. It is characterised by the abundance of algal reef facies. The Jaddala formation of the Middle - Upper Eocene lies unconformably on top of this formation. It is composed of marly limestone and marls. Grey and black chert nodules also occur sporadically throughout the beds.

Lower and Middle - lower Miocene rocks are exposed in the Sinjar and Atshan anticlines. In the Sinjar, the Serikagni and Jeribe formations of the Lower Miocene outcrops and circumscribe the anti-clinal structure, while the Jeribe Formation is exposed on the whole of Atshan anticline (Figure 6). The Serikagni Formation consists of thick beds of globigerinal and chalky limestones. The lithology of the Jeribe formation is recrystallised, dolomitized massive limestone. It is overlain in some places by a thick gravel bed or a basal conglomerate, suggesting the presence of unconformity.

In the study area, Lower Miocene sediments have been encountered in the Ain-Zalah and Butmah oil fields. These sediments were represented by the formations of Jeribe Limestone, Dhiban Anhydrite and Euphrates Limestone. The total thickness of the formations in Ain-Zalah (well no. 16) is 650 ft. According to stratigraphic and lithogical analysis, Nasr (1960) believes that the formations indicate a lagoonal and reef environment which may have been predominant over most of Northern Iraq in the Lower Miocene.


SURFACE GEOLOGICAL MAP
OF
NORTHERN IRAQ
0 5 10 15 20 25
KM
Figure 6
Legend:-
Alluvium
Upper Fars "Upper Miocene"
Lower Fars "Middle Miocene"
Middle-Lower Miocene
Lower Miocene
Eocene
Upper Cretaceous
Anticlinal Axis
Test Well
Town
After Nasr, S. 1960
SYRIA
Chia-i-spi
Mushorah
Dohok
Dohuk
Alqosh
Ain Zalah
Raffan
Gullar
Butmah
Gusair
Ishkaft
Motair
Sasan
Alan
Sinjar
Ain Sinu
Tel Afar
Sinjar
Ibrahim
Atshan
Tigris
Nuwaigit
Adaiyah
30
50
70
90
19 10
30
50
70
90
400
80
60
40
20
300

The Lower Fars formation of the Middle Miocene is exposed extensively in Northern Iraq, including the study area, with the exception of the Gullar anticline (Figure 6). The formation consists mainly of alternating beds of limestones, anhydrites and grey marls, with gypsum and brown shales as minor constituents. Generally, the limestones and marls tend to be thinly bedded, while the beds of anhydrite vary from thin to very thick and massive. In the Ain-Zalah and Butmah oil-fields, the total thickness of the formation is approximately 1800 ft. The top and bottom of the Lower Fars are arbitrarily taken to be at the first and last beds of anhydrite.

It is generally agreed that the environment that gave rise to the evaporite series of the Lower Fars is typical of partially enclosed basins which are intermittently connected with the open sea, allowing the periodic encroachment of sea water.

The youngest bedrock which is exposed in the study area is the Upper Fars of the Upper Miocene. This formation consists rhythmically of reddish-brown to grey sandstone, red to grey siltstone and red, sandy marls. These beds are generally exposed on all the flanks of the anticlines, and in the synclines in between.

In the Gullar anticline, 800 ft. of Upper Fars sediments have been penetrated by a structural bore hole. The lithology in this locality is a sequence of marls with sandy patches, but no individual sandstone beds. This may suggest that Upper Fars sediments were derived from the north-eastern part of the region, and were deposited in closed basins (Nasr, 1960).

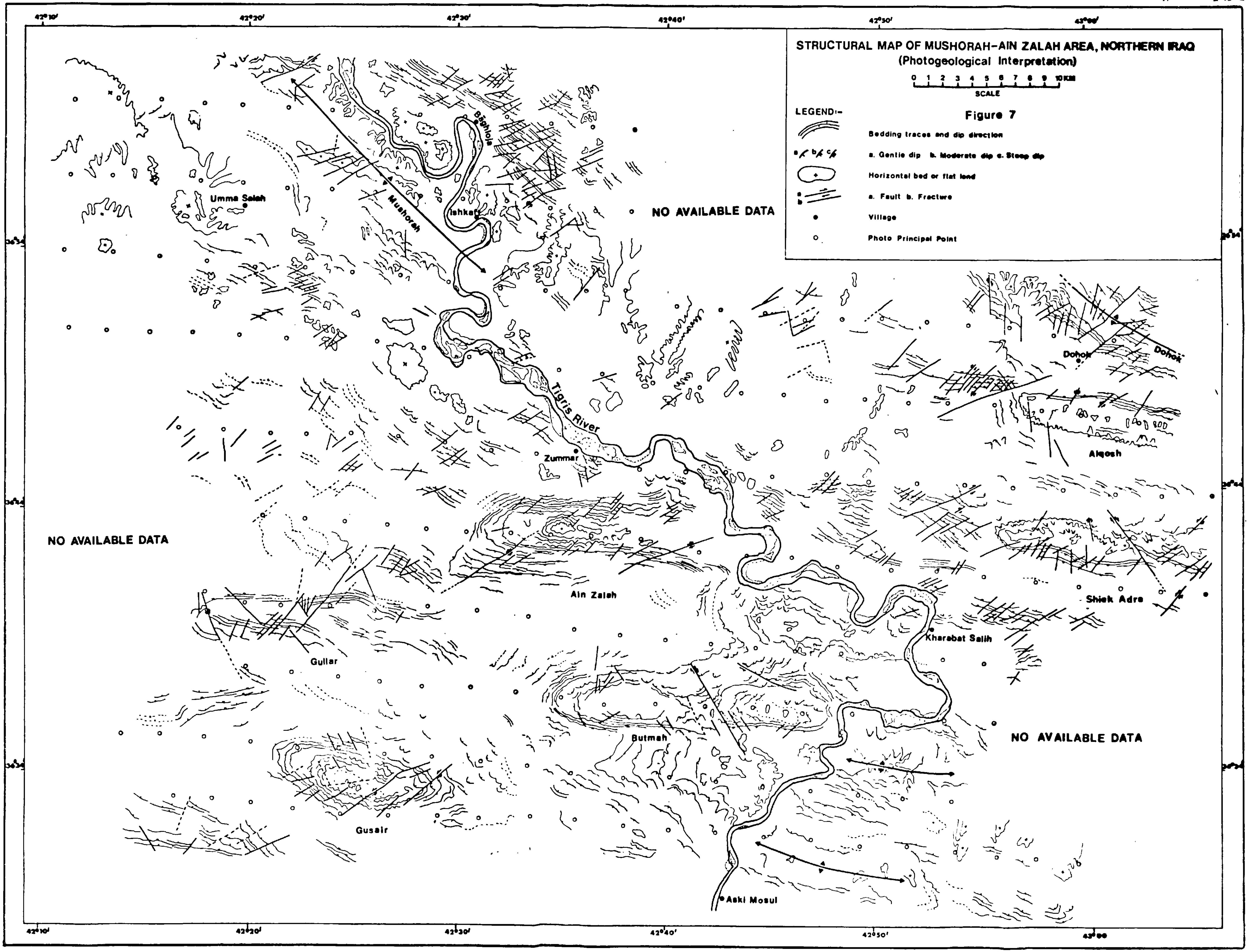
There is no recognisable Middle Fars in the study area, although sediments of this formation are known in other parts of Iraq. It is possible that the marine limestone, which is a characteristic sediment of Middle Fars formations, changes laterally in this area into continental sediment of the Upper Fars, in such a way that it cannot be distinguished from the latter formation (Nasr, 1960).

The upper limit of the Upper Fars has been considered as the first pebble bed of the Bakhtiari formation (Pliocene), and the lower limit is the lower occurrence of gypsum.

6.2 STRUCTURAL CHARACTERISTICS OF THE STUDY AREA

The "Mushorah-Ain Zalah area" is the name given to the study area, because the Mushorah anticline is the largest structure in the area and situated in the north, and the Ain Zalah is a producing oil field in the central part of the study area.

The structural map of the area (Figure 7) is the result of interpretation of the structural data in the study area carried out on the air photographs. The map primarily shows traces of the bedding outcrops, most of which tend to outline the anticlinal folds in the area. The map also shows some fractures and faults which are associated with fold structures and are obvious on the air photographs. Lines ending with arrow-heads representing



STRUCTURAL MAP OF MUSHORAH-AIN ZALAH AREA, NORTHERN IRAQ
(Photogeological Interpretation)
0 1 2 3 4 5 6 7 8 9 10KM
SCALE
LEGEND:-
Figure 7
Bedding traces and dip direction
a. Gentle dip b. Moderate dip c. Steep dip
Horizontal bed or flat land
a. Fault b. Fracture
Village
Photo Principal Point
42°10'
42°20'
42°30'
42°40'
42°50'
NO AVAILABLE DATA
Umma Salah
Mushorah
Ishkaf
Tigris River
Zummar
Dohok
Alqosh
Ain Zalah
Gullar
Shiek Adre
Kharabat Salih
Butmah
Gusair
Askl Mosul

plunging fold axes were drawn in some parts of the map to indicate the presence of the anticlines which are not well-defined by the bedding traces. The bed-dips were grouped into gentle, moderate and steep dips and each group was differentiated by special signs. The bed outcrops with an almost horizontal attitude were also given a special sign. It was relevant to mark the photo principal points on the map, since the air photos were the basic and indepensible material of the study, and consequently the construction of the map. For the sake of clarity the photograph numbers were not written on the map with the principal points. They are shown instead on a separate Figure, No. 8.

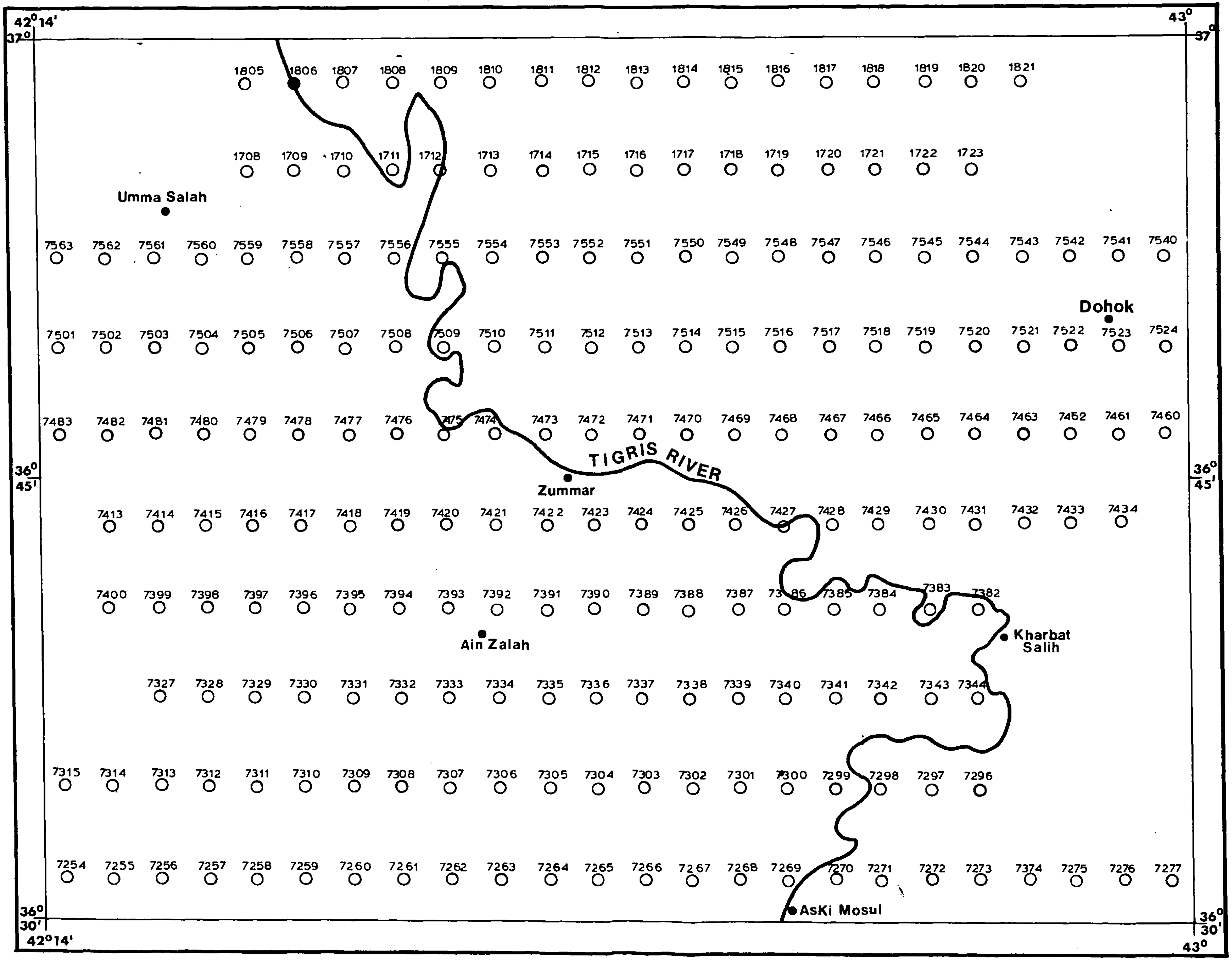
The River Tigris meanders between the anticlines as it crosses the study area diagonally. In the centre and south of the map the river makes curved turns or arcuate bends where it passes around the structural limits of the folds. In the north, the Tigris flows along the axial region of Mushorah anticline. Abrupt changes in the course of the river can also be seen in some parts of the map and these may be attributed to the possible occurrence of faults or fractures.

The folds in the area, are generally elongated and doubly plunging. They tend to assume an echelon pattern, which is a common feature in northern Iraq. The pre-dominant strike of the folds is east-west, with the exception of Mushorah anticline which assumes a NW - SE strike. The western extremes of some E - W folds show a slight tendency to the NW, particularly in the case of Gusair fold.

Map showing schematic layout of principal points of air photographs
(Mushorah–Ain Zalah Area, Northern Iraq)

0 2·5 5·0 7·5 10·0 12·5 15·0 17·5 20·0 KM

FIGURE 8



Among the anticlines which occur west of the Tigris, the Ain Zalah anticline occupies the centre of the map. It is an elongated, slightly asymmetrical fold striking E - W. The western plunge of the anticline is steeper than the eastern one. This structure was taken as a case study, and detailed discussion regarding its structural characteristics is included in Chapter Seven.

Adjacent to Ain Zalah in the south-east, there is a small dome-like structure called the Raffan anticline. The present photogeological data show that this anticline is symmetrical and linked to the adjacent folds of Ain Zalan and Butmah by saddle-like depressions rather than proper synclines.

The Butmah anticline is situated in the south-west of Raffan. It consists of two slightly asymmetrical domes which are separated by a narrow saddle. Sub-surface data suggest that this saddle may be caused by a strike-slip fault (Nasr, 1960). Much photogeological evidence supporting this assumption was obtained during the study. The eastern dome is a producing oil field, but it has less potential than Ain Zalah.

A long and probably asymmetrical syncline lies between the Ain Zalah and Butmah anticlines. Few bed outcrops can be seen within the structural confines of this syncline.

Farther to the south-west of Butmah, there is the elliptically shaped anticline of Gusair. This structure is comparatively small and rather symmetrical. It is extensively fractured with two apparent left-lateral tear faults dissecting the eastern part. The axial strike of the anticline tends to swing from E - W to WNW at the western end.

The northern flank of Ishkaft anticline with several fractures can be seen to the south-west of Gusair anticline. The Gullar anticline strikes E - W to the north of Gusair. It is an unusually narrow and long fold with extensive shear fractures. The northern flank of the anticline is slightly steeper than the southern, and the western plunge appears to be steeper than the eastern. The synclines adjacent to both the Gusair and Gullar anticlines seem to be relatively narrow and asymmetrical. They are also very fractured as will be seen on the fracture trace map.

Several structures can be seen east of the Tigris. There are two small anticlines in the south-east of the map. These anticlines are rather low and partially exposed folds, forming between them a small syncline. All of these three structures seem to be symmetrical and plunging at both ends. The river forms remarkable arcuate bends around the western ends of these folds delineating their plunges.

In the east of the map, there are asymmetrical and tightly folded anticlines. They are parts of long and rather sinuous anticlines which extend beyond the limits of the study area. The southernmost of these anticlines is the Algosh anticline. It is very fractured and apparently crossed by a right-lateral shear fault. Its southern flank tends to be steeper than the northern. There are two narrow synclines striking E - W on the both sides of the anticline. They are possibly asymmetrical.

To the north of Algosh anticline, there is Sheik Adra anticline. It has similar structural characteristics to the Algosh anticline, however, it tends to be more closed and fractured as will be seen on the fracture trace map. Farther to the north, there is an intermediate part of the Dohok anticline. It strikes NW, which is different from the E - W strike of the other two anticlines. A narrow and probably asymmetrical syncline lies between Sh. Adra and Dohok anticlines. The high density of fracture traces and tightness of folding of these anticlines, suggest that they were subjected to relatively strong compressive stress.

In the north of the map, there is the Mushorah anticline. It is a very broad and gently dipping fold. A common characteristic in the area is that the crestal zones of the folds are sub-horizontal, but in the case of Mushorah anticline the axial region is unusually wide and flat. The axial strike of the anticline is NW which is a noticeable departure fron the E - W strike of most folds in the area. The structural characteristics of Mushorah anticline may suggest an interesting geological problem and therefore need further investigation.

It is logical to assume that synclines must flank the Mushorah anticline on both sides. However, on the western side the terrain shows no definite trace of fold structures, and only very low and scattered bed outcrops could be seen on the air photographs. If we assume that there is a synclinal structure to the west of Mushorah, we could infer that there is a complementary anticlinal structure beside it on the farther west, since the extent of the terrain within the map limits is too large for one syncline of size comparable to Mushorah anticline. Therefore, the question of a buried structure in the west of the map area seems possible and will be discussed later on within the context of fracture trace analysis.

6.3 FRACTURE TRACE ANALYSIS OF THE STUDY AREA

The fracture trace analysis, which is used as a structural technique in this study, is based on the common assumption that the propagation and development of fractures and other types of structures in an area or geological province, can be reasonably related to specific cycle or cycles of tectonic movement. Thus, it should be possible to establish definite relationships between fractures and other structures. These relationships can then serve as a useful tool in solving geological problems, especially those concerned with structural geology.

A difficulty involved in fracture trace interpretation is that almost any linear feature visible on air photographs can appear to be a fracture trace. Therefore, the possibility of mapping misleading linear features as fracture traces is always present. Because of this uncertainty, caution is very necessary during fracture trace interpretation. In addition, a number of photogeological criteria which usually suggest the occurrence of fractures in the bedrock, should be exploited. During the present photointerpretation, it was possible, wherever there were bare and well-exposed rocks, to observe directly on the air photograph fracture traces as breaks or joints in the bedrock, particularly when the photographs were examined under a stereoscope. But such cases were not very frequent since most rocks were covered to various extents by soil or vegetation. Several criteria relevant to the characteristics of fracture trace appearance on air photographs had to be used. These were drainage alignments, tonal differences probably due to soil moisture, vegetation alignments, straight stream segments, and linear positive or negative topographic features. In many cases two or more of such criteria were used to identify one long fracture trace.

After the completion of the photointerpretation, during which the fracture traces were drawn on transparent overlays, base maps of the study area were prepared. The overlays were laid down systematically on the joined base maps, and fracture traces were compiled onto their corresponding positions on the base map by using photo-principal points and major streams as guides or controls. As a result, a large map of fracture traces, representing the whole study area, was drawn with geographical coordinates. For the sake of convenience this map was divided into four sheets each of which represents a sub-area. The relative positions of the sub-areas are clearly shown on Figure 1. Subsequently, the fracture traces of each sub-area map were digitized using a D-MAC electronic graphic digitizer, and the conputer cards of the digitized fracture traces were prepared for data processing by a CDC 6400/6600 digital computer.

6.3.1 Analysis of Fracture Trace Maps

The term "fracture trace" as mentioned before in this thesis, is basically a linear impression (or image) of a mechanical discontinuity in bedrock, observed (or interpreted) on air photographs. Thus, a fracture trace can be a joint or fault. There is a long-held idea that joints and faults have a common origin in deformative stress which acts on the rock mass. Joints may develop into faults through a gradual transition. Joints, which initially have no obvious rock movement along their faces, may in time acquire a little movement. Later on they may develop into small faults and then into large faults (De Sitter, 1964). However, Price (1959, 1966) proposed a hypothesis for the origin of joints, which implies that they differ from faults. He considered that joints, particularly shear joints, result from the release of residual strain energy, which has been stored since earlier periods of compression. He mentioned that this energy would be released when the originally compressed rocks were able to expand laterally under less load. Price suggested that this occurs within a few thousand feet of the surface. Hancock (1968) discussed the contrasting characteristics of joints and faults as being reasonable evidence supporting Price's theory.

The majority of the fracture traces interpreted during this study showed no obvious bed displacement along their sides, therefore, they were regarded as joints or mega-joints. The fracture traces with noticeable differential rock movement along their sides were taken as faults. There were, however, very few of these. It is possible that there were more faults among the fracture traces, probably of small size, which could not be detected because of the limitations imposed by the available air photographs.

The fracture trace maps of the sub-areas are regarded as basic maps, in so far as they display all fracture traces which were interpreted on air photographs during the study. There are also two other maps showing significant fracture traces, and their principal trends in the area as whole. The construction of these two maps was made on the basis of the sub-area maps. Thus a separate discussion will be conducted for each category of fracture trace maps.

6.3.1.1 Fracture trace maps of the study sub-areas

One of the advantages of the computer plotting equipment was the ability to reconstruct the original fracture trace maps when these maps were digitized and input into the computer with a data processing programme. In this manner, the fracture trace maps of the sub-areas were produced. Afterwards, they were reduced to the present scale by the author. The geographical coordinates are not marked on these maps but are shown on other fracture trace maps of the area. Each sub-area map was attached to the transparent overlay on which the outlines of the anticlines were drawn.

Many authors acknowledge that some kind of relationship exists between the geometrical characteristics of fracture traces and associated fold structures. Such a hypothesis, which has usually been supported by empirical observation, leads ultimately to the fact of the dynamic affinity between the fracturing and folding of the rock mass. Thus, geometric criteria based on such relationships can be established and then used to correlate folds or detect concealed fold structures. Some relevant fold-fracture relationships which can be seen on the sub-area fracture trace maps are suggested below.

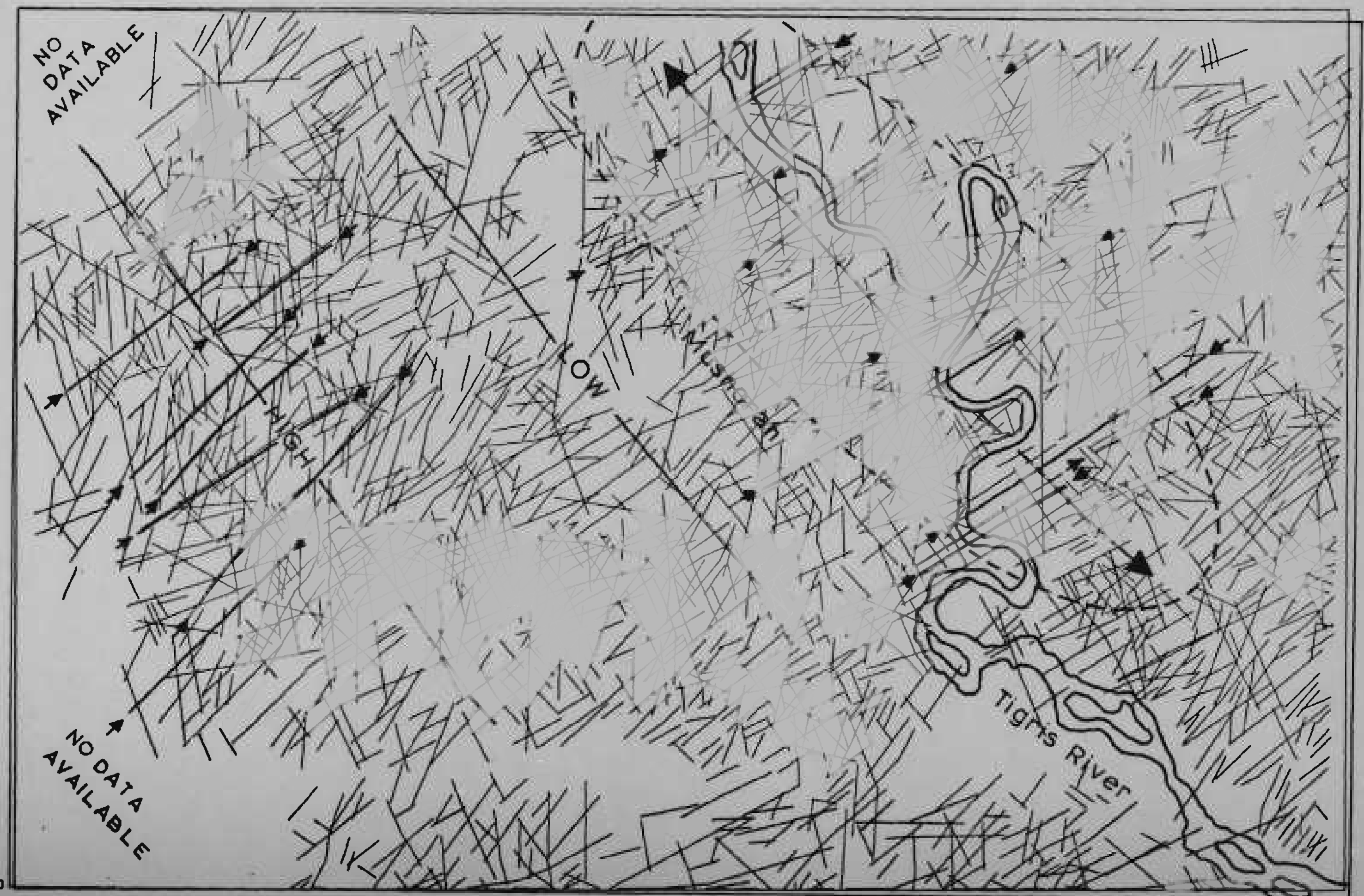
(1) The relative density of fracture traces with regard to the structural parts of the fold, or to the whole fold structure.

(2) The pattern and directional properties of fracture traces in relation to the structural parts or to the entire fold structure.

I. <u>Fracture trace map of sub-area I</u> (Figure 9)

The Mushorah anticline is the only exposed fold structure in this sub-area. As mentioned earlier, the anticline is broad and gently dipping. It is intensively eroded so that the bedding outcrops were rather scattered and obscured, when they were examined on the air photographs.

FRACTURE TRACE MAP OF MUSHORAH-AIN ZALAH AREA
(SUB-AREA I)



Overlay Figure 9

Figure 9

0 1 2 3 4 5KM

FRACTURE TRACE MAP OF MUSHORAH-AIN ZALAH AREA
(SUB-AREA I)

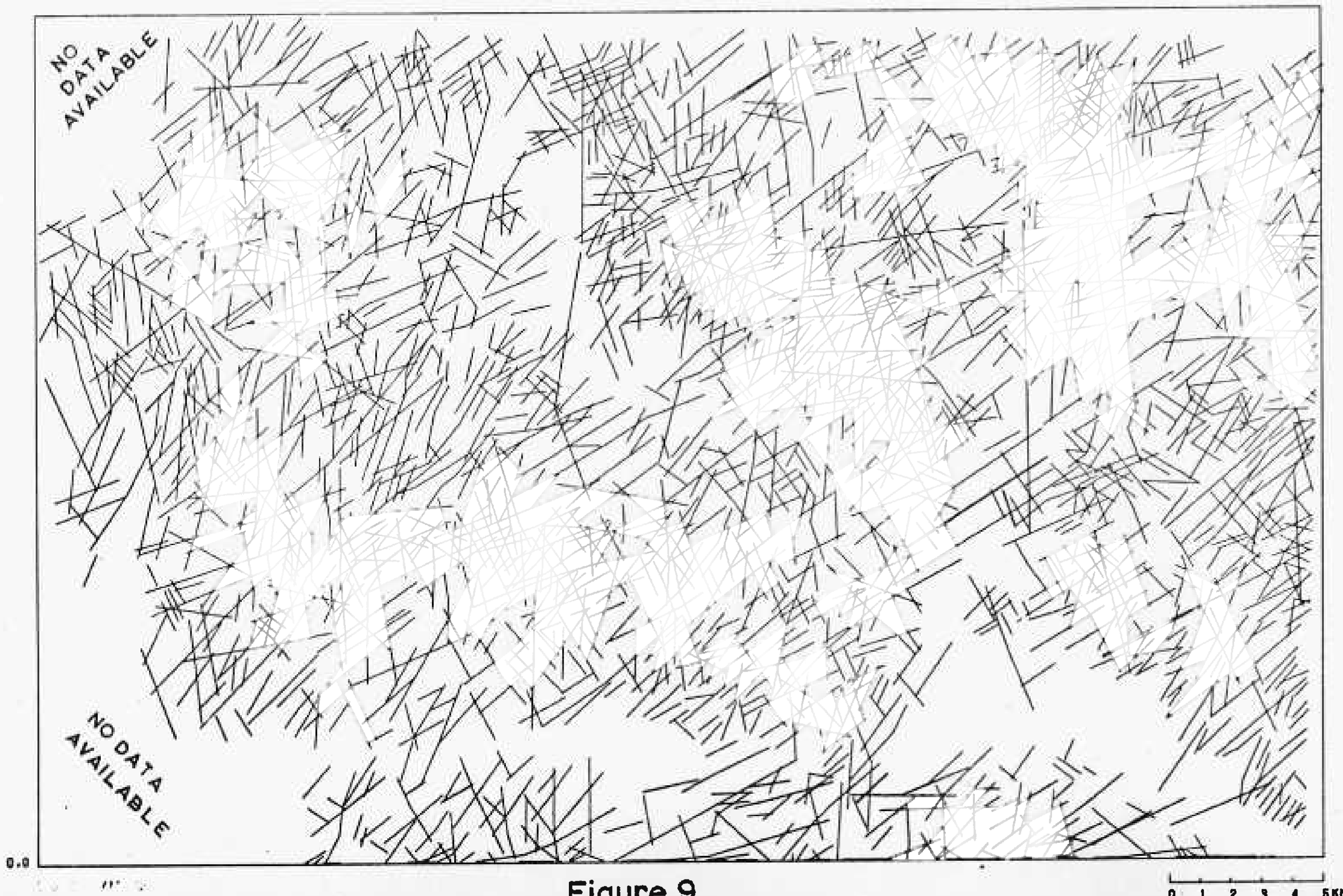


Figure 9

However, an approximate structural outline of the anticline was drawn in broken lines on the attached overlay of Figure 9. The river Tigris meanders within the structural boundary of the anticline in its course across the eastern part of the sub-area. Part of the river flows parallel to the axis of the anticline, in the far north, while in the south it seems to be controlled by the fractures particularly those of a N - S trend. Over the anticline the general density of fracture traces appears to be higher than that of the adjacent areas, particularly to the south-west. In addition, the density within the anticlinal limits seems to be higher in the flanks, especially the south-west flank, than in the axial region.

Regarding the directional characteristics of the fracture traces and their relationship to the anticlinal fold, there are several fracture traces of medium length, which noticeably transverse the anticline in a NE - SW direction, i.e perpendicular to the anticlinal axis. Some of these fracture traces indicated on the Overlay and can be described as cross-fracture traces. It has been suggested that this type of fracture can be closely associated with the development of the plunging fold, and they are caused by the stretch or the tensional stress occurring parallel to the axis of the anticline (De Sitter, 1964, and Hills, 1964). De Sitter attributed the tensional stress to the fact that the low points of the anticline at the plunging ends remain fixed, whereas other points along the axial line move upwards forming an arch. He referred to the cross-faults of Elk Basin oil field and Kettelman Hills dome (in the United States) as classical examples for such phenomenon.

To the south-west of the Mushorah anticline, there are two distinct areas of different fracture trace densities. The area next to the anticline has a relatively low density, while that farther to south-west has a rather high fracture trace density. They are indicated on the overlay by the words "high" and "low", and by lines passing roughly through their central parts. The general orientation of the low and high density areas seems to assume a NW - SE direction, that is, parallel to the Mushorah strike. A close examination of the high fracture trace density area, reveals two features. First, the frequency of fracture traces on the borders of the area (i.e on both sides of the middle line), seems to be slightly higher than in the central zone (i.e along the middle line). Secondly, there are a number of fracture traces in the area which tend to have similar characteristics to those of the cross fracture traces of Mushorah anticline, and these are indicated on the Overlay.

The tectonic history of Northern Iraq, including the study area, is characterized by long periods of epeirogenic movements and a number of tectonic movements involving mountain building and block faulting. In the Early and Middle cretaceous, in particular, strong tectonic movements associated with block-faulting took place approximately along the same strike of the pre-existing tectonic zones of Upper Jurassic. Block-faulting and vertical re-adjustments produced a pattern of localised sedimentary troughs or basins which became sites for the intermittent development of block-folds (Henson, 1959).

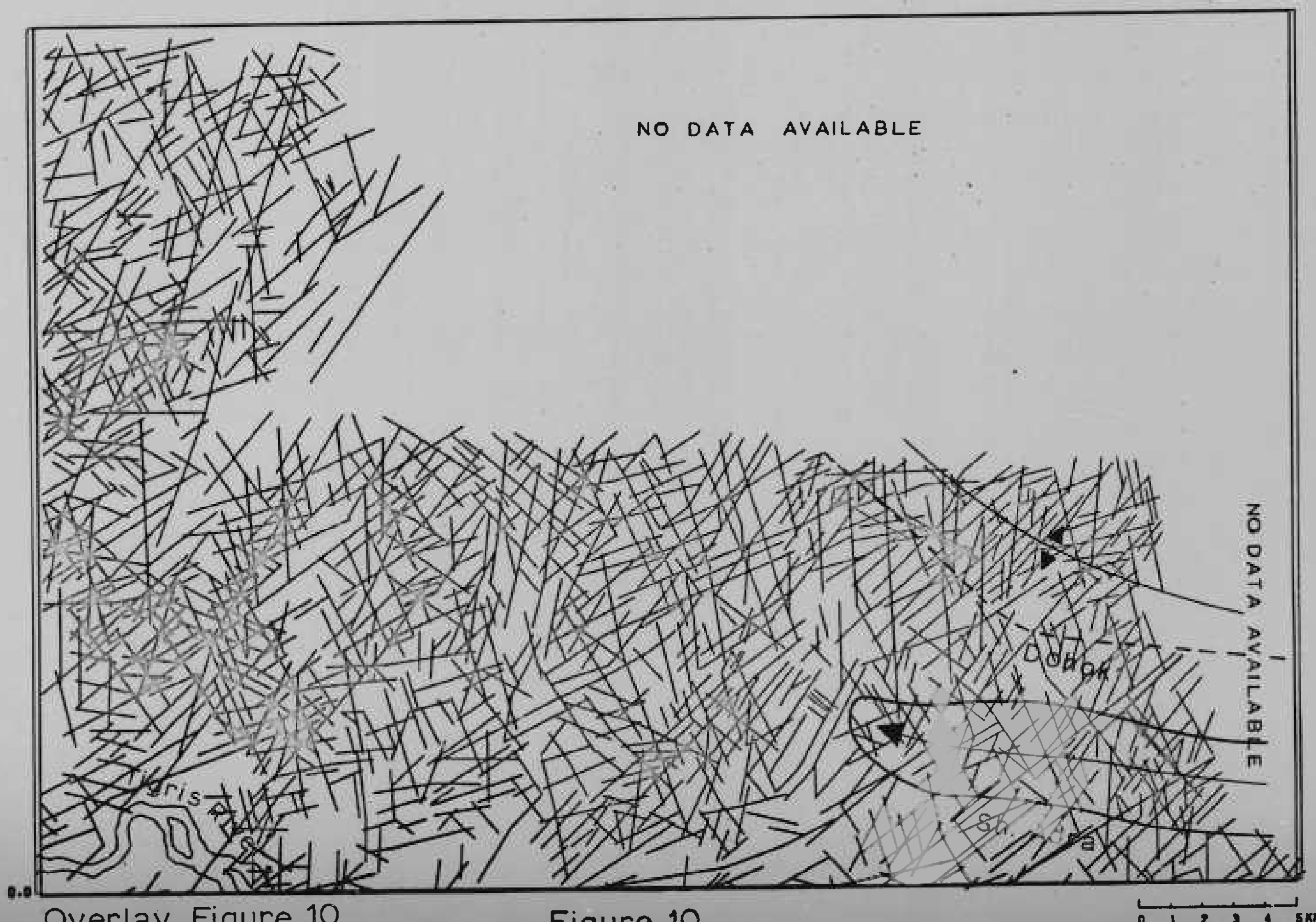
Against this tectonic background, it seems rather unusual that the whole area to the south-west of the Mushorah anticline is lacking in any surface fold structure. On the basis of structural and geometrical considerations, one can reasonably deduce that some kind of synclinal structure must exist on the south-west side of Mushorah anticline. Most of the synclines in the study area exhibit less frequency of fracture traces in comparison with the anticline. This is understandable since the synclines are not usually severely affected by erosion. On the contrary, some of them are the sites of recent deposits which tend to cover the indiginous bedding outcrops. Thus the low fracture trace density area which occurs to the south-west next to the anticline might suggest, however roughly, the location of a possible syncline. It was mentioned in Chapter Five that sufficient stratigraphic information has been obtained from the drilling operations which covered most of Northern Iraq and in particular, the study area. These data revealed that the area was dissected by block-faulting, and eventually a number of restricted sedimentary basins were developed. It is possible, therefore, to imagine that the suggested syncline is of comparable size to neighbouring anticlinal structurs.

Blanchet (1957) and other authors put forward a number of theories which were outlined in detail in Chapter Three concerning the relationship of fracture trace characteristics and possible concealed structures. One of these theories, in effect, proposed that zones or areas of high fracture trace density may suggest or mark a positive buried structure such as a palaeo-high or an unexposed dome. A buried positive fold structure can also be developed as a result of sedimentary deposit compaction over a palaeoridge caused by a block-fault. The high fracture trace density area which extends parallel to the low density area in the west of the map, exhibits some fracture trace characteristics, (mentioned above), similar to those of the Mushorah anticline. Since we have already assumed that the low density area represents the site of a synclinal structure, then by implication, the high fracture trace density area may represent a concealed antiform (anticlinal) structure. However facile this conclusion may appear to be, the author nevertheless finds himself inclined to entertain it.

II. Fracture trace map of sub-area II (Figure 10)

The abundance of the fracture traces and the diversity of their lengths and azimuths indicate that this area has been subjected to relatively strong tectonic forces. The rugged topography of the terrain and the steep dips of the bedrocks in the area can also be attributed to the same tectonic conditions. Other factors such as the exposure of the bedrocks and the absence of thick soil coverage or river deposits may have increased the number of fracture

FRACTURE TRACE MAP OF MUSHORAH-AIN ZALAH AREA
(SUB-AREA II)



Overlay Figure 10

Figure 10

FRACTURE TRACE MAP OF MUSHORAH-AIN ZALAH AREA
(SUB-AREA II)

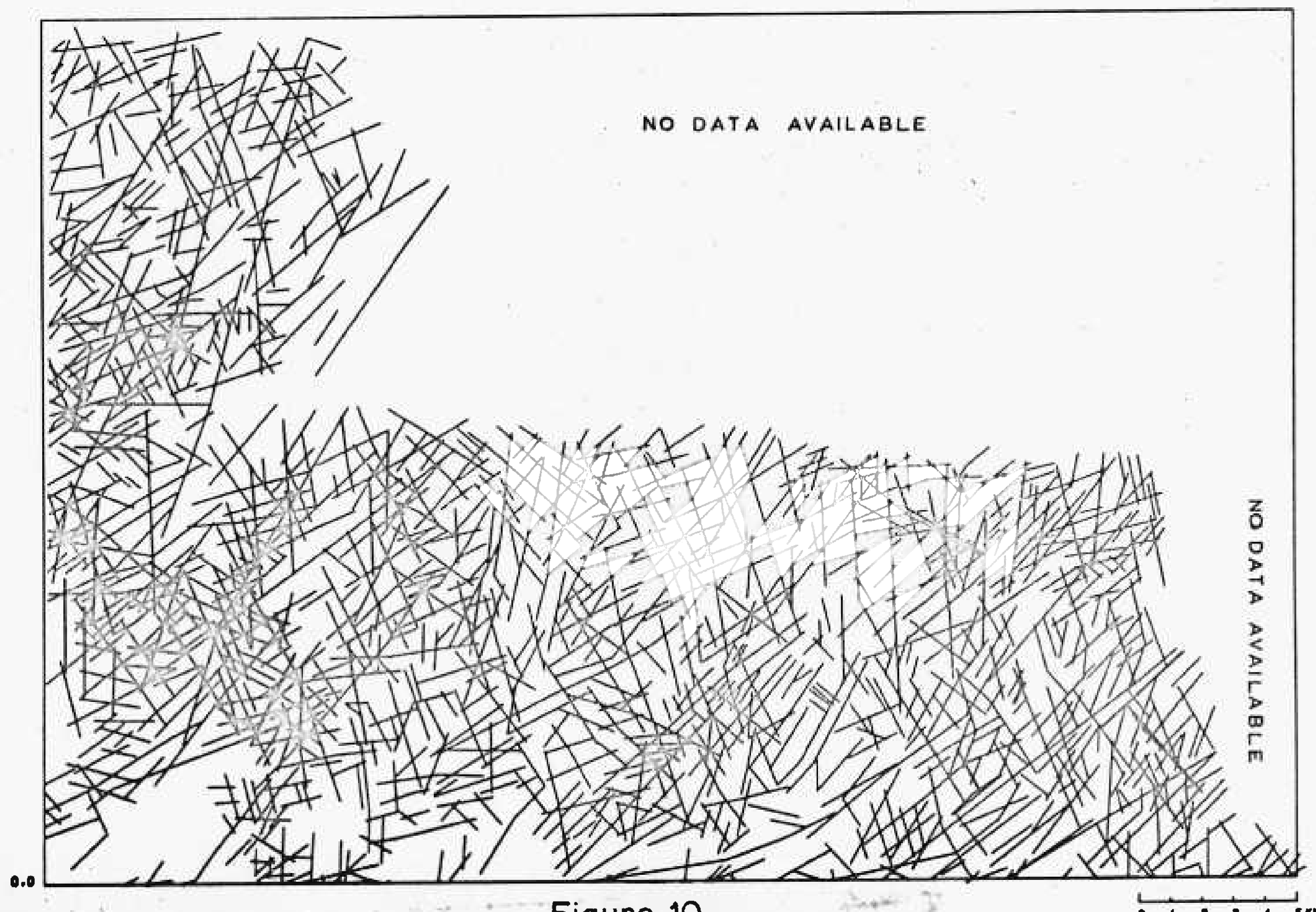


Figure 10

traces as well as extended some of them.

The fracture traces of this sub-area can be grouped into several directional sets, each of which comprises fracture traces of various lengths. They may vary from very small to long. The medium and long fracture traces are tectonically the most significant. They were redrawn on a separate map and will be discussed later on.

Two anticlinal structures can be seen in the east of the sub-area; these are Sheikh Adra and Dohok anticlines. They, represent parts of long and rather curved anticlines which extend beyond the limits of the study area. Sheikh Adra anticline was outlined on the attached overlay of the map Figure 10, by a solid line, because it exhibits persistant ridges of bedding outcrops on its outer boundary. Dohok anticline on the other hand does not display such a feature and it is therefore indicated by broken lines.

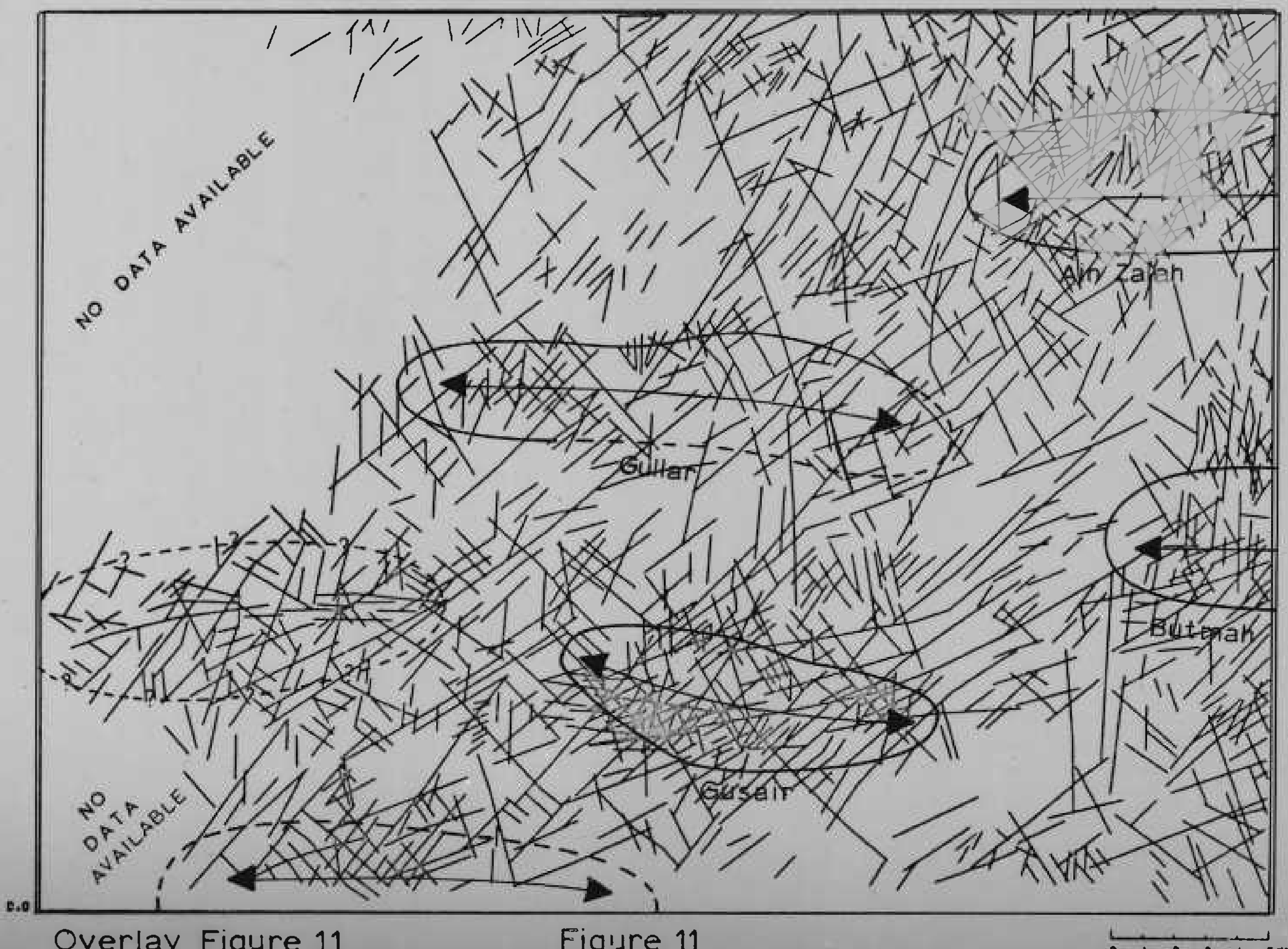
The general distribution of fracture traces of the sub-area map, at first glance, appears to be uniform, but on close examination one can see different local fracture trace concentrations. Within the boundaries of the anticlines, the small fracture traces tend to increase, thus the density of fracture traces seem to be slightly higher than that of the adjacent areas. Among several sets of fracture traces, which can be seen on the anticlines, there are two or three sets of medium or long fracture traces. They are probably rather significant in their structural relationship to the anticlines. These sets in Sheikh Adra anticline strike NE and NW, and in most cases intersect each other at an angle of less than 90 degrees. In the Dohok anticline, the sets strike NE and NNW or N-S, and intersect one another at an angle of less than 90 degrees. The fracture traces of the NE set tend to be more frequent and predominantly longer than the other sets in both anticlines. If we consider the east - west strike of the Sheikh Adra anticline, then we could assume that the compressive force which gave rise to this structure should have been active in the north - south direction. A similar assumption can reasonably be applied to the Dohok anticline, perhaps with a small change in the orientation of the compressive force to NNE. Thus, the above mentioned sets seem to be oblique fracture trace sets and mechanically may be considered as shear fracture trace sets.

III. <u>Fracture trace map of sub-area III</u> (Figure 11)

From the general distribution of fracture traces in the map, one may observe a kind of association between the positive structures such as the anticlines, and areas of fracture trace concentration. On the other hand, most of the synclines or troughs exhibit zones of low fracture trace density. This feature seems predictable, in view of the fact that the bedrocks usually outcrop in the anticlinal structure, whereas the synclines often host recent deposits and soil cover which tend to obscure the appearance of fracture traces. Also beds in the trough of a syncline tend to be under compression and open fractures less frequent.

Most of the anticlines in this sub-area are well exposed,

FRACTURE TRACE MAP OF MUSHORAH-AIN ZALAH AREA
(SUB-AREA III)



Overlay Figure 11

Figure 11

FRACTURE TRACE MAP OF MUSHORAH-AIN ZALAH AREA
(SUB-AREA III)

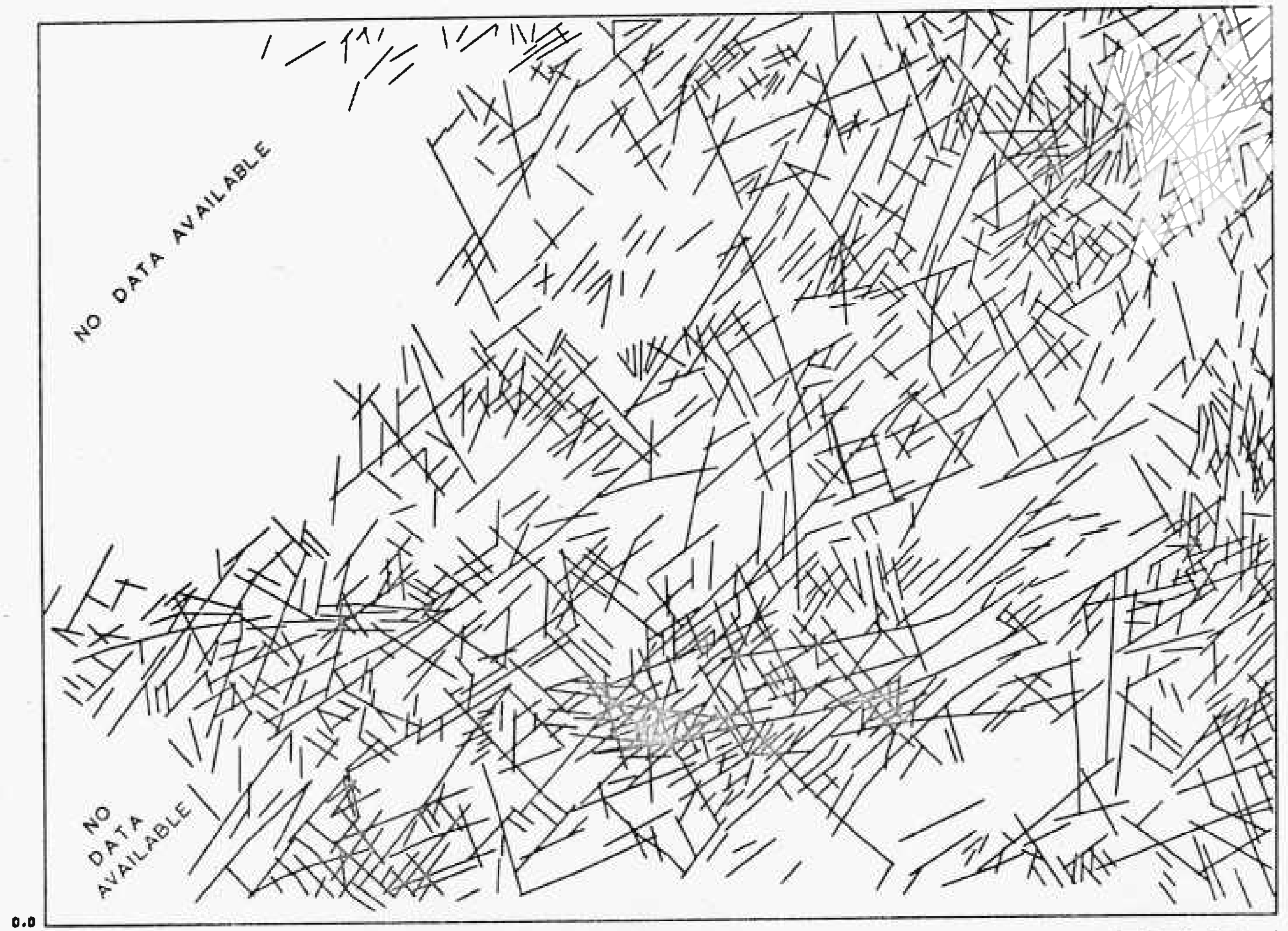


Figure 11

and they tend to be bordered by long ridges of bedrock outcrops. The general pattern of anticlines in the sub-area tends to be en-echelon. This is a familiar feature in Northern Iraq. The regional strike of the structures is east - west, except in Gusair anticline in the south of the map which shows a slight tendency to the north-west, particularly in its western end. The approximate surface boundaries of the anticlines are shown on the attached overlay of the map Figure 11. In the east of the map there are parts of Ain Zalah and Butmah anticlines. In the case of Ain Zalah anticline, the number of fracture traces on the flanks appear to be greater than in the central area. Most of the fracture traces on the flanks strike NW and NE. Thus, they are oblique to the axis of the anticline and may be regarded as shear fracture traces. In the central and northern parts of the anti - cline there is a set of fracture traces striking N - S or almost so. A few fracture traces striking E - W can also be seen in the north-West. These fracture traces can be provisionally classified, in view of their geometrical relationship to the anticlinal axis, as tension sets. It is possible, that not all the above-mentioned fracture trace sets are mechanically related to the same or a single compressive stress. In the Butmah anticline the central part shows a considerable number of fracture traces. There is a distinct set of N - S azimuth and another less obvious set striking almost E - W. In the south flank, the pre-dominant azimuth of the fracture traces is north-east.

In the middle of the map, Gullar anticline has a relatively long and rather irregular shape. In the central part of the anticline, the northern flank seems to be twisted inward to the axial region, making the western half of anticline appear narrower than the eastern half. In the twisted part, there is a distinct number of small fracture traces which fan out towards the north. The number of fracture traces in the western half appears to be greater than that in the eastern, and most of them tend to strike NW or NE i.e making oblique or shear sets. A few small fracture traces striking N - S can also be seen in the centre and near the easter end of the anticline. A combination of all the above mentioned features may suggest that the anticline, during its development, has been subjected to different stress fields which have mainly been active in the N - S direction. To the south of the Gullar anticline, there is the small and dome-like anticline of Gusair. It is extensively fractured as it appears on the map. In the eastern part, two tear faults were interpreted photogeologically and are shown on the structural map Figure 7. There are three predominant sets of fracture traces, in so far as they are frequent and comprise some long fracture traces. Two of these sets strike NE and NW and they tend to transverse the whole structure. The NE set contain some long fracture traces. The third set tends to strike parallel to the anticlinal axis i.e almost E - W. There is also a minor set of small fracture traces striking N - S and sparsely distributed. The southern flank of the anticline exhibits more fracture traces than the northern. Further to the north-west of the anticline, there is an area of noticeable fracture trace concentration (marked with question marks). Some fracture traces in this area display similar characteristics to those of Gusair anticline. Such fracture traces as these are E - W and NE sets which are rather similar to their counterparts in Guisair anticline. In addition, there is the possible significance of the occurrence of such an area of concentration within a comparable distance of the anticline and towards the north-west, which is the directional tendency of the strike of the fold.

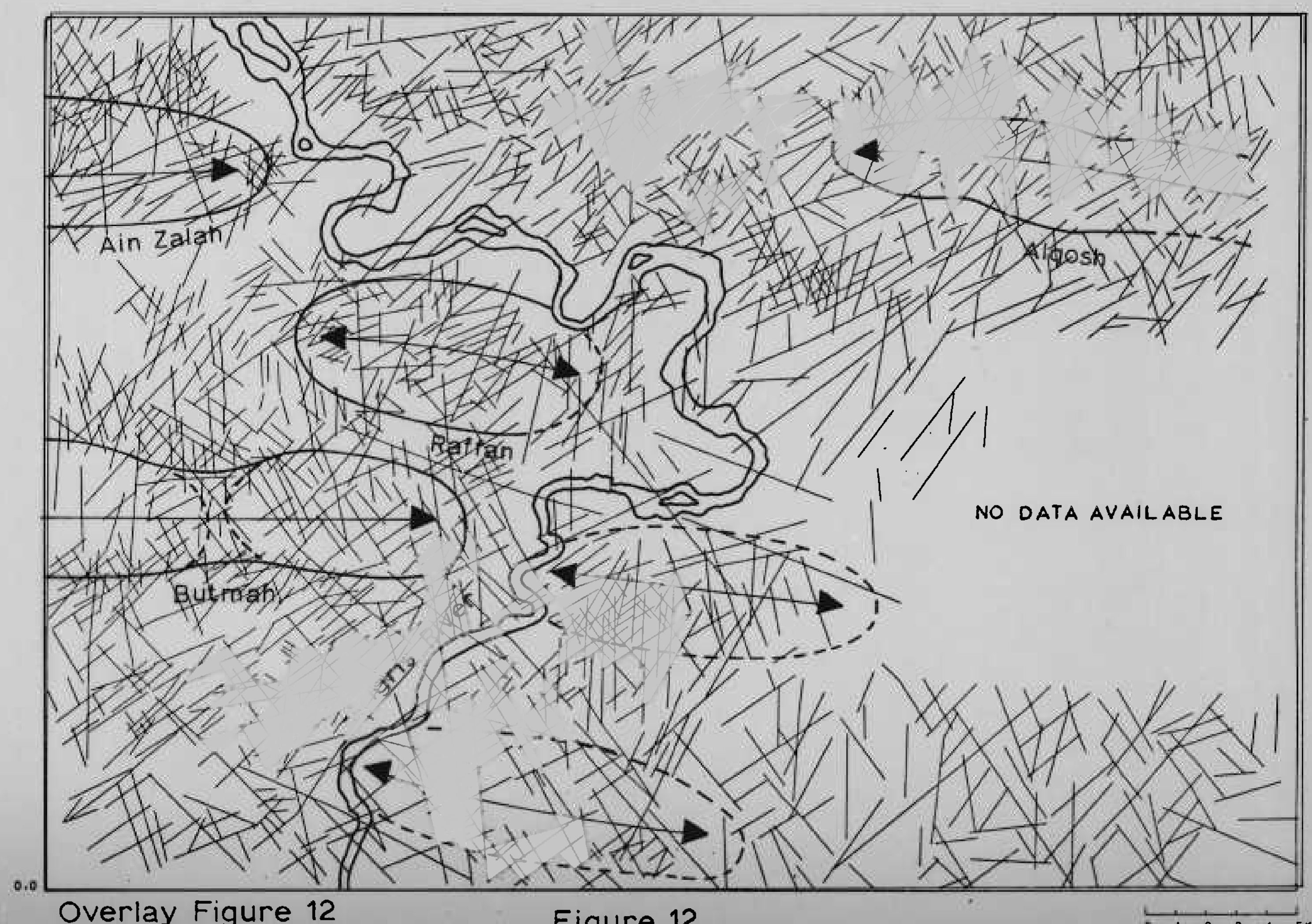
In view of this, it seems not unreasonable to suggest that this area of the fracture trace concentration may represent a buried domal extention of the Gusair anticline or may suggest a separate concealed positive structure which has been caused by a fault-block.

To the south-west of Gusair anticline, there is the north flank of Ishkaft anticline which is associated with oblique (i.e shear) sets of fracture traces. This anticline extends to the south outside the study area.

IV. Fracture trace map of sub-area IV (Figure 12)

The outlines of the anticlines which occur in this sub-area and the river Tigris are shown on the overlay of the map Figure 12, and one can see the controlling effect of the anticlines on the course of the river. The regional strike of the structures is east-west. Most of

FRACTURE TRACE MAP OF MUSHORAH-AIN ZALAH AREA
(SUB-AREA IV)



Overlay Figure 12

Figure 12

FRACTURE TRACE MAP OF MUSHORAH-AIN ZALAH AREA
(SUB-AREA IV)

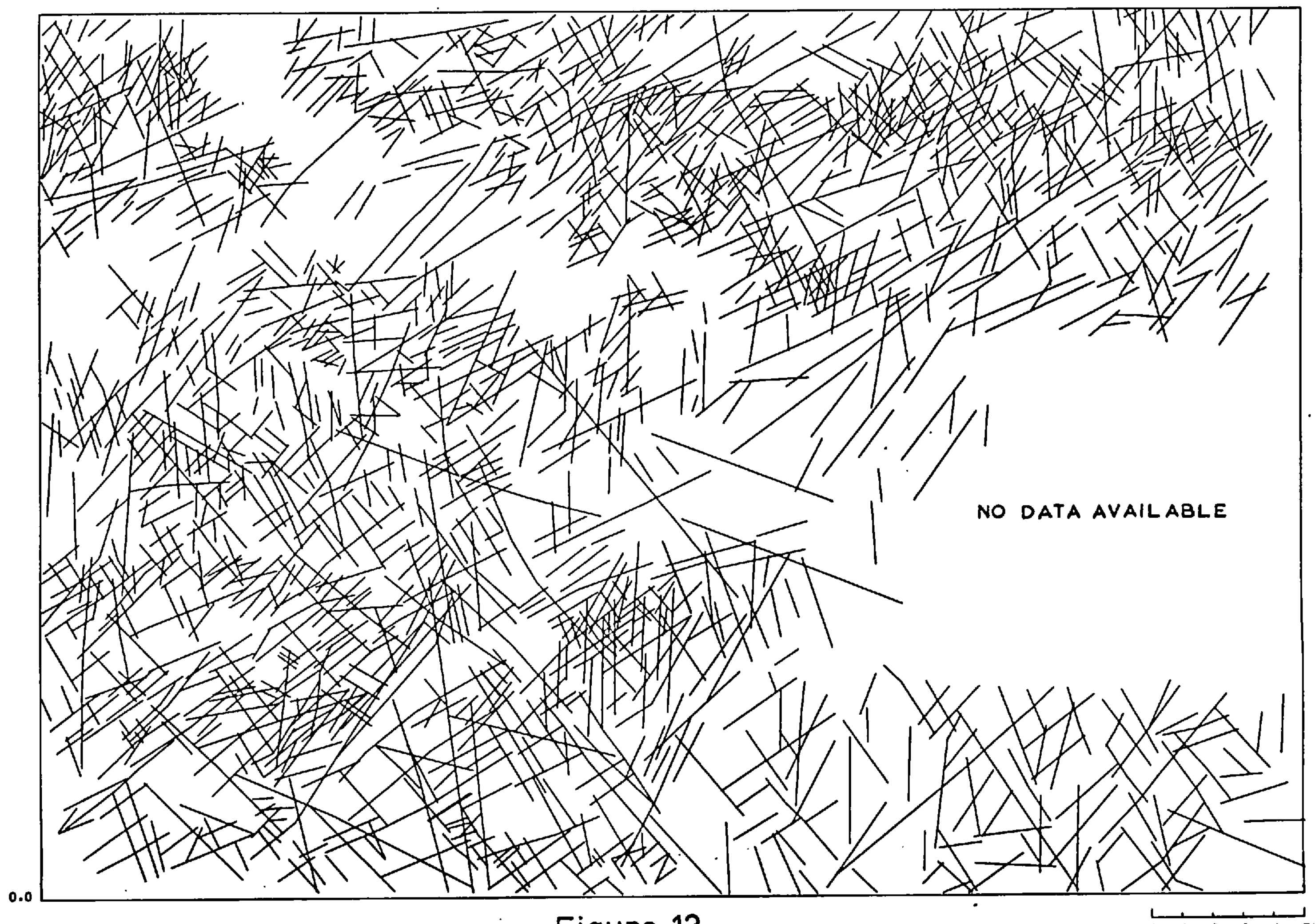


Figure 12

the anticlines are slightly asymmetrical and vary in shape and size. The western part of Algosh anticline is in the north-east of the map. It is a relatively narrow, asymmetrical and long anticline which extends beyond the study area. The steeper northern flank of the anticline exhibits more fracture traces. Most of the fracture traces are oblique to the anticlinal axis and some of them are long and transverse the entire structure. There is also a minor set of fracture traces striking N - S. The characteristics of the fracture traces indicate that this anticline has been subjected to the relatively strong compressive stress. To the south of the map on the eastern side of the river there are two small anticlines. The river Tigris curves around their eastern plunging ends. The northern anticline, displays a high frequency of fracture traces on its southern flank which is slightly steeper than the northern flank. There are two oblique sets striking NE and NW. A remarkable N - S set can be seen crossing the southern flank.

The southern anticline is of comparable size, but exhibits less fracture traces. Their characteristics are similar to those of the previous anticline, except that the N - S set is limited to a few long fracture traces crossing the entire anticline in the west.

In the north-west of the map, there is the eastern half of Ain Zalah anticline (the western half lies in sub-area III). There are three distinct sets striking ENE, NNW and N - S. Some of the fracture traces are relatively long and cross the anticline. One of the ENE fracture traces was interpreted as a fault and shown on the structural map Figure 7. A larger number of fracture traces can be seen on the northern flank most of which are related to oblique sets. West of the Tigris, in middle of the map, there is Raffan anticline. It is a small and dome-like fold structure. In this anticline the fracture traces may be grouped into three major sets which strike N - S, E - W (or ENE) and NNE, and some of them are rather long. There are also two sets of the azimuths NE and NW of which the NE fracture traces tend to be longer. The major part of Butmah anticline is to the south-west of Raffan. The western portion of this anticline was shown on the map of sub-area III. This structure consists of two small domes (western and eastern domes) separated by a narrow saddle. On the eastern dome two remarkable oblique sets can be seen. They tend to be distributed evenly over the dome. In the Western dome there are a few long fracture traces crossing the dome in the N - S direction. On the flanks of the dome and near the saddle, there is a relatively high frequency of oblique fracture traces. There is a long fracture trace striking NW and extending along the saddle. This fracture trace is shown on the structural map Figure 7, as a fault. One of the characteristics of fracture traces in this sub-area is the prominence of the N - S set which tends to be pervasive in the sub-area. The same characteristics are present to a lesser degree in the ENE fracture trace set.

6.3.1.2 Maps of the significant fracture traces in the study area

The question of the generation and propagation of fractures forms a fundamental geomechanical concept in fracture trace analysis. Conditions of stress in the rock-mass are a prerequisite for fracture occurrence. A rock-mass is said to be in a state of stress whenever it is subjected to a system of forces. Geological stress can be caused by two kinds of forces, external (exodynamic) such as forces caused by lunar tides and earth rotation, and internal (endodynamic) such as gravity and tectonic forces. Stress fields may be local, regional or crustal (super-regional) depending on the scale and intensity of the forces, and often large scale stress induces small or local stress fields. Crustal fractures (geofractures) are a world-wide phenomenon and are usually attributed to crustal stress caused by external forces. A number of theories concerned with these forces and their role in the process of the generation and propagation of fractures, have been mentioned in Chapter Three. Most local and regional fractures are caused primarily by forces acting within Earth's confines. It is a fact that the above mentioned forces are dynamically interrelated, and thus a geological event such as the fracturing of rock can be seen as a resultant of these forces. The large thrust zone of the Taurus-Zagros belt in Northern Iraq clearly indicates that tectonic forces played an important role in the folding and fracturing of the rock in the area.

The propagation of deep-seated fracture zones or tectonic trends may assume different surface features. As to the fracture traces, there are several examples of fracture patterns which may suggest underlying buried structures. Some examples of these were seen on the fracture trace map and they are as follows:

(a) a zone of parallel or sub-parallel fracture traces striking consistently in one direction,

(b) an alignment of small fracture trace trends in one direction over a long distance,

(c) a distinct zone with a high frequency of fracture traces which are not necessarily uniform in length or azimuth.

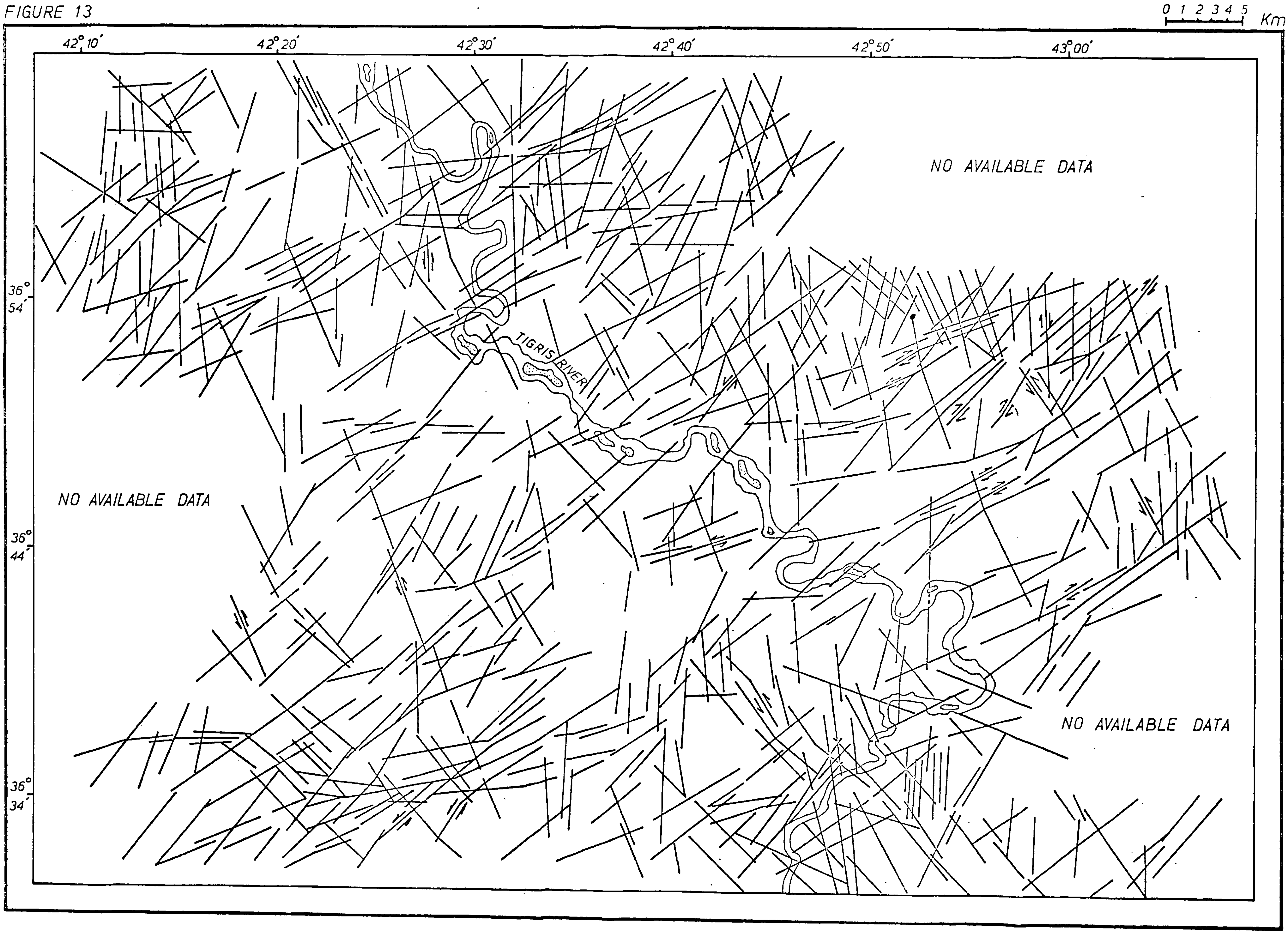
The present discussion will involve two maps: the first shows fracture traces which were redrawn from sub-area maps and are regarded as significant; the second, displays the main fracture trace trends in the study area.

1. <u>The significant fracture traces in the study area</u> (Figure 13)

As stated earlier, this map exhibits significant fracture traces and it is compiled from the fracture trace maps of the sub-areas. The structural significance of fractures was assessed on the basis of their lengths, orientations and relative positions. The length of a fracture traces is often compared to its depth, that is, the longer fracture indicates a deep zone of failure, and it

MAP SHOWING THE SIGNIFICANT FRACTURE TRACES IN THE STUDY AREA

FIGURE 13



is therefore structurally significant. The fracture traces of prominent orientations and those whose relative positions bear a structural relationship to the anticlines were included in this map. A number of faults can also be seen among the fracture traces in the map.

On inspection of the map, one may see that fracture traces with N - S azimuths, or nearly so, are unevenly distributed over the map. In the east and north-east of the map, there is a considerable number of N - S fracture traces. A comparable number of similar fracture traces can also be seen in the southern part near the Tigris. There is a subtle zone of N - S fracture traces running from the southern to northern boundaries along the middle of the map. In the north-west, there is a noticeable frequency of N - S fracture traces, and towards the central north the frequency decreases and the spacing of the fracture traces tends to be regular.

In the south-west, N - S fracture traces are almost absent, while a noticeable incidence of E - W fracture traces can be seen. Some E - W fracture traces tend to form zones which appear to swing to the NE as they approach the centre of the map. Similar fracture traces of various lengths appear also in the north and middle of the map.

The oblique fracture traces are the predominant class in the map. Most of the faults which appear in the map have an oblique orientation. The NE and ENE are the predominant directions along which a great number of fracture traces strike. The fracture traces of these azimuths tend to be frequent in the eastern parts of the map, where some faults of a similar orientation can also be seen. A few NNE fracture traces occur in the north, on both sides of the Tigris. Fracture traces with azimuths of NW and NNW appear in most parts of the map; few of them are represented as faults. In the west there is a noticeable alignment of NNW fracture traces including a fault. In the north, there is a remarkable zone of small NNW fracture traces running parallel to the Tigris. In the south and south-east of the map many NW fracture traces can be seen.

2. - The main fracture trace trends in the study area (Figure 14)

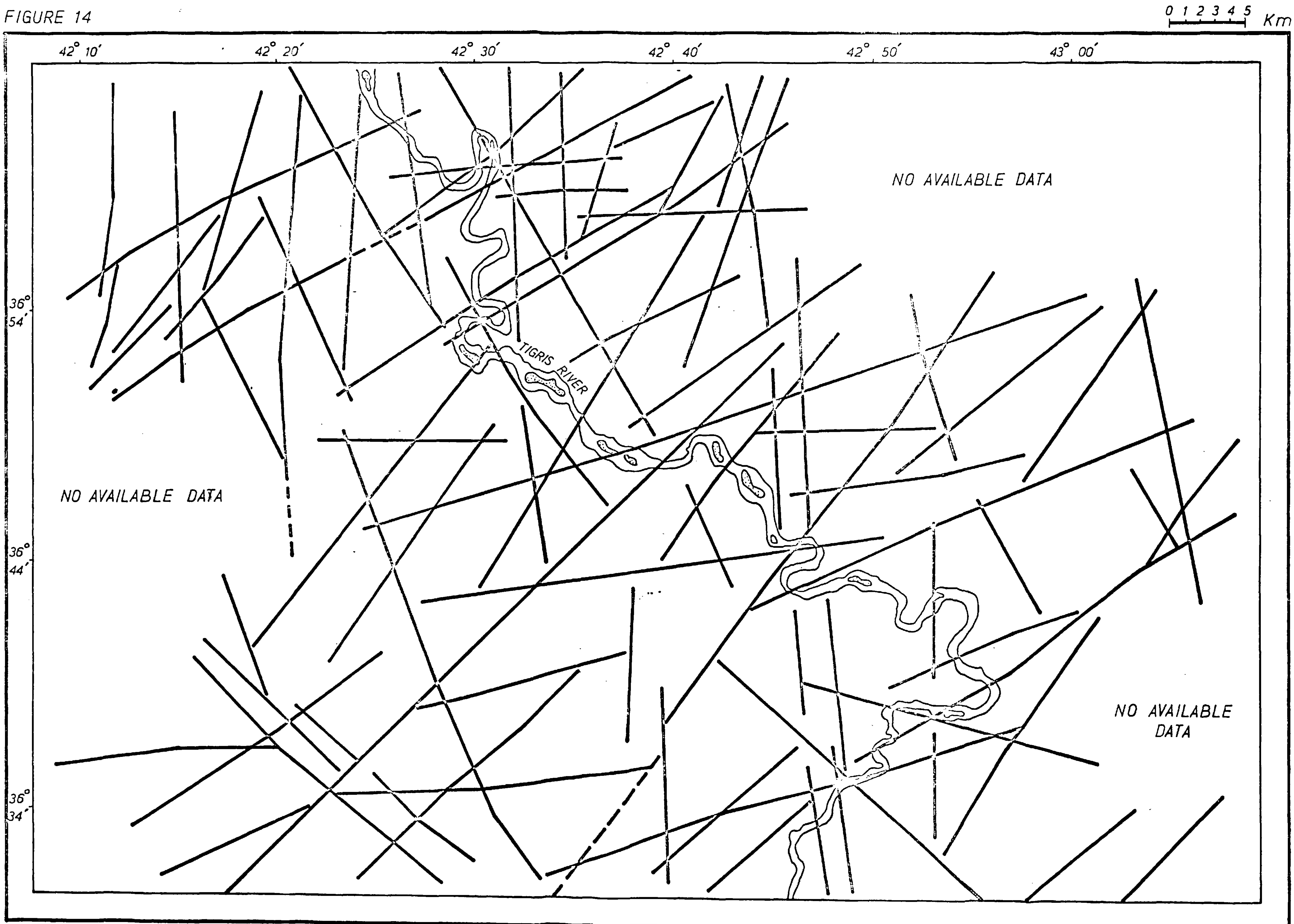
The term "fracture trace trend" in the present context basically represents a linear zone or alignment of fracture traces which tend to strike in one direction. Thus, these trends were regarded as linear locations (or loci) of the rock weaknesses in the study area. Figure 14 was drawn primarily on the basis of the previous map Figure 13, and supplemented by the fracture trace maps of the sub-areas.

One of the main purposes of this study is to acquire a comprehensive picture of the subsurface tectonics of the area through the analysis of the fracture traces. This aim may not be reached simply by the study of individual fracture traces, since the majority of the interpreted fracture traces range from small to medium in length. Therefore the trends of fracture trace zones or alignments as well as some very long fracture traces may be more relevant to the subsurface structure of the study area.

The most noticeable characteristic of the map is that

MAP SHOWING MAIN FRACTURE TRACE TRENDS IN THE STUDY AREA

FIGURE 14



the oblique trends are longer and more pervasive in comparison with N - S and E - W trends. Among the oblique trends, the NE and ENE are the longest and most extensive. One of the longest is the NE trend which extends from the south-west to the centre of the map crossing the Tigris. The other is ENE and runs along the middle of the map. There are many other NW and ENE trends which tend to be more apparent in the northern and eastern parts of the map. As to other oblique trends, there are two remarkable NW trends in the north which flank part of the Tigris and run parallel to its course. In the west of the map there is a long NNW trend and to its east, in the south-west, there is a zone of small trends striking NW. There are few NNW trends in the east, but the general frequency of the NW and NNW trends appears to be higher in the northern and western parts of the map. The number of E - W trends is rather noticeable in the west and in the centre; they show a tendency to the NNW direction as they approach the east. In the north a few similar trends can also be seen. The trends of N - S orientation, or nearly so, appear in most parts of the map and are characterized by being rather short. A prominent belt of small N - S trends runs along the central-west and transverses the map from the southern to the northern boundaries. An appreciable number of N - S trends appear in the north-west and tend to be regularly spaced. In the south-West, there are almost no N - S trends and in the south they are very few.

6.3.2 Analysis of Fracture Trace Directional Distribution

The concept of the "distribution" is a basic and widely used technique in statistics. It is a method of representing the frequency of measurements carried out on a group of items with respect to a specific characteristic. The use of such a method, was indispensable during the directional analysis of the fracture traces. The word "frequency" acquires a definite statistical meaning when it is used in conjunction with directional distribution. In the present case it can be defined as a number of fracture traces or the measurements of specific parameter (e.g length) in a predetermined directional class or azimuth interval.

If we imagine a map of two hundred fracture traces, it is more informative to state that 25 per cent of the fracture traces strike NW, for example, than to say that fifty fracture traces in the map strike NW. Thus, in order to make the data of the distribution more interpretable, the frequency values were converted to percentages and then used in the plotting of a rose diagram.

The rose diagrams were used to show graphically the directional distribution of fracture traces. A rose diagram can be described as a radial form of histogram. Its principal advantage is to present a summary of the directional frequency of fracture traces, or their parameters in predetermined azimuth intervals. From a rose diagram one may be able to construct a graphical model for the stress system which probably caused the fracturing.

In this study, three types of rose diagrams were prepared for the fracture traces of each sub-area and all the diagrams were produced by computer. These are as follows:

1. The directional frequency rose diagram, or simply the frequency rose diagram.
2. The directional length distribution rose diagram or the directional density rose diagram.
3. The directional average length rose diagram, or the directional average density rose diagram.

The azimuth or angular interval of these rose diagrams were a series of 10^{o} angles measured from the nothern axis of the rose diagram. The length of the individual rose ray is directly proportional to the percantage of the directional frequency or distribution. The terms "rose maximum" and "rose minimum" indicate the relatively high and low percentages of the directional frequency as revealed graphically by rose rays. Where there is more than one rose maximum, the order of their importance corresponds to the order of the lengths of the rays they represent. Accordingly, the terms "primary", "secondary" and "tertiary" were adopted and will be used to describe the size and relative importance of rose maxima.

The rose diagrams were compiled into three maps, each of which is composed of four similar types of rose diagrams representing the sub-areas. The discussion of the maps will be conducted separately on the following bases.

(a) First, the study of individual rose diagrams in terms of the significant rays which reveal the directional characteristics of prominent fracture traces in each sub-area.

(b) Second, the comparison of the principal characteristics of the rose diagrams of the sub-areas, so as to establish common aspects, similarity or differences, between the rose diagrams. This may lead to the establishing of general directional characteristics for fracture traces of the whole study area.

(c) Third, the comparison of the results obtained from the directional analysis of all diagrams, so as to deduce a general conclusion based on the three categories of the directional distribution of fracture traces.

1. Frequency rose diagrams (Figure 15)

The map Figure 15 shows four rose diagrams placed in the centres of the rectangular outlines of the sub-areas. The number of fracture traces in each sub-area involved in the directional distribution is shown under each rose diagram. As stated earlier, these rose diagrams depict the directional frequency or distribution of the fracture traces which is expressed in the percentage numerals.

Map showing the Frequency Rose Diagrams of the Study Area

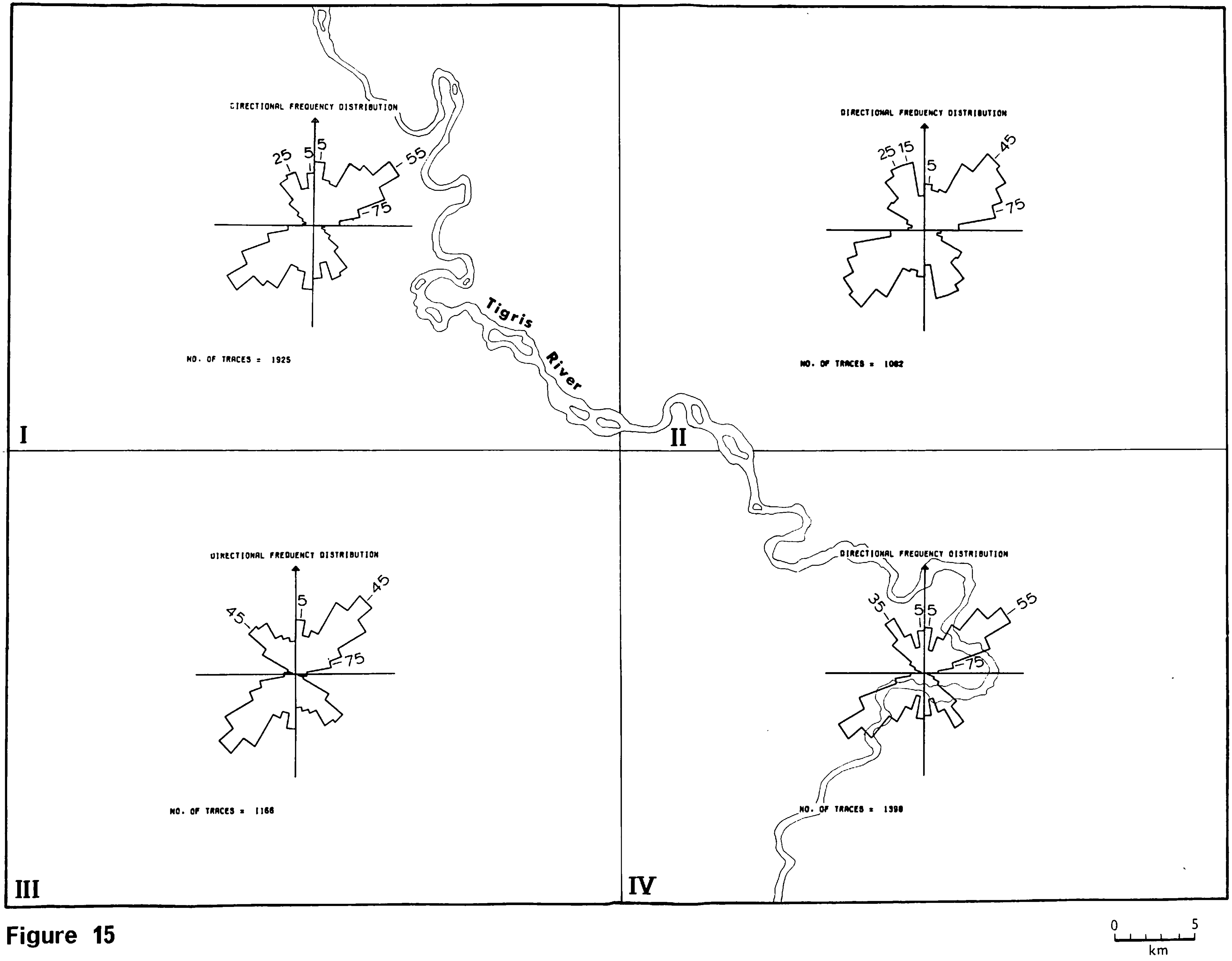


Figure 15

In the rose diagram of sub-area I, there are two oblique maxima of different size. The long maximum (primary) strikes N 55° E, while the short (secondary) strikes N 25° W. There are two other maxima along a N - S direction. The primary strikes N5 E and the secondary strikes N 5° W. Judging from the above mentioned maxima, the majority of the fractures in the sub-area are obliquely orientated to the north. The most frequent sets strike around the azimuth N 55° E. Among non-oblique fracture traces, those which strike N 5° E or nearly so appear to be more frequent than the others. The significant rose minima are along an E - W direction indicating that a few fracture traces strike in that direction. The ray with N 75° E orientation shows some fracture traces strike in a direction sub-parrallel to E - W.

The rose diagram of sub-area II, basically displays four maxima, three of them oblique. The primary has an azimuth of N 45° W. The shortest maximum strikes N 5° E. The significant minimum is in an E - W direction, but the N 75° E ray indicates that some fracture traces strike near an E - W orientation. From the characteristics of the rose maxima it is obvious that oblique fracture traces are the most predominant sets in this sub-area.

The rose diagram of the sub-area III, shows three significant maxima. They are N 45° E (primary), N 45° W (secondary), and N 5° E (tertiary). There is a minimum in an E - W direction and a significant ray can be seen in a N 75° E direction. The principal directional characteristics in this sub-area are similar to those of sub-areas I and II. However, there is some change in the azimuths of the oblique maxima.

There are four principal maxima in the rose diagram of sub-area IV. Two are oblique with azimuths N 55° E (primary) and N 35° W (secondary), and the other two are almost the same size and strike N 5° E and N 5° W. The rose minimum which appears along an E - W direction is the most significant. There is a small ray of azimuth N 75° E. The general characteristics of this rose diagram are similar to those of sub-area I with some change in the azimuth of the secondary oblique maximum.

The common characteristics of the frequency rose diagrams are as follows.

1) The orientations of the major rose maxima are in a general NW - SE and NE - SW while the minor maxima appear along a N - S direction. The rose minima always occur along an E-W direction.

2) The oblique primary rose maxima strike consistently in a NE direction while the oblique secondary maxima generally strike NW.

3) The azimuth of the oblique primary maxima is N 55°E in the sub-areas I and IV. The azimuths of oblique secondary maxima are N25°W, N25°W, N45°W and N35°W in the sub-areas I, II, III, and IV respectively.

2. Density rose diagrams (Figure 16)

This map shows four density rose diagrams depicting the directional length distribution of fracture traces in the sub-areas. This distribution involves the percentages of total lengths of fracture traces in the directional classes.

In sub-area I the rose diagram shows four maxima of different lengths, two oblique with azimuths N 55° E (primary) and N 25° W (secondary), and the other two with azimuths of N 5° W and N 5° E. The significant minimum appears in an E - W direction and the ray which has an azimuth of N 75° E indicates that a number of fracture traces with similar azimuths are present in the sub-area. From the characteristics of rose maxima, one can imagine that a high percentage of the fracture trace lengths in this sub-area fall along oblique directions, particularly the N 55° E azimuth.

The rose diagram of sub-area II shows three maxima. The oblique rose maxima appear in the azimuths N 45° E (primary) and N 25° W (secondary). There is also a small maximum with azimuth N 5°E. In the direction E - W there is a minimum, and a significant minimum ray can also be seen with azimuth N 75° E. From the configuration of the rose maxima it appears that most lengths of the fracture traces in the sub-area fall in an oblique direction, particularly around N 45° E.

The rose diagram of sub-area III displays very similar characteristics to those of the rose diagram of sub-area II.

Map showing the Density Rose Diagrams of the Study Area

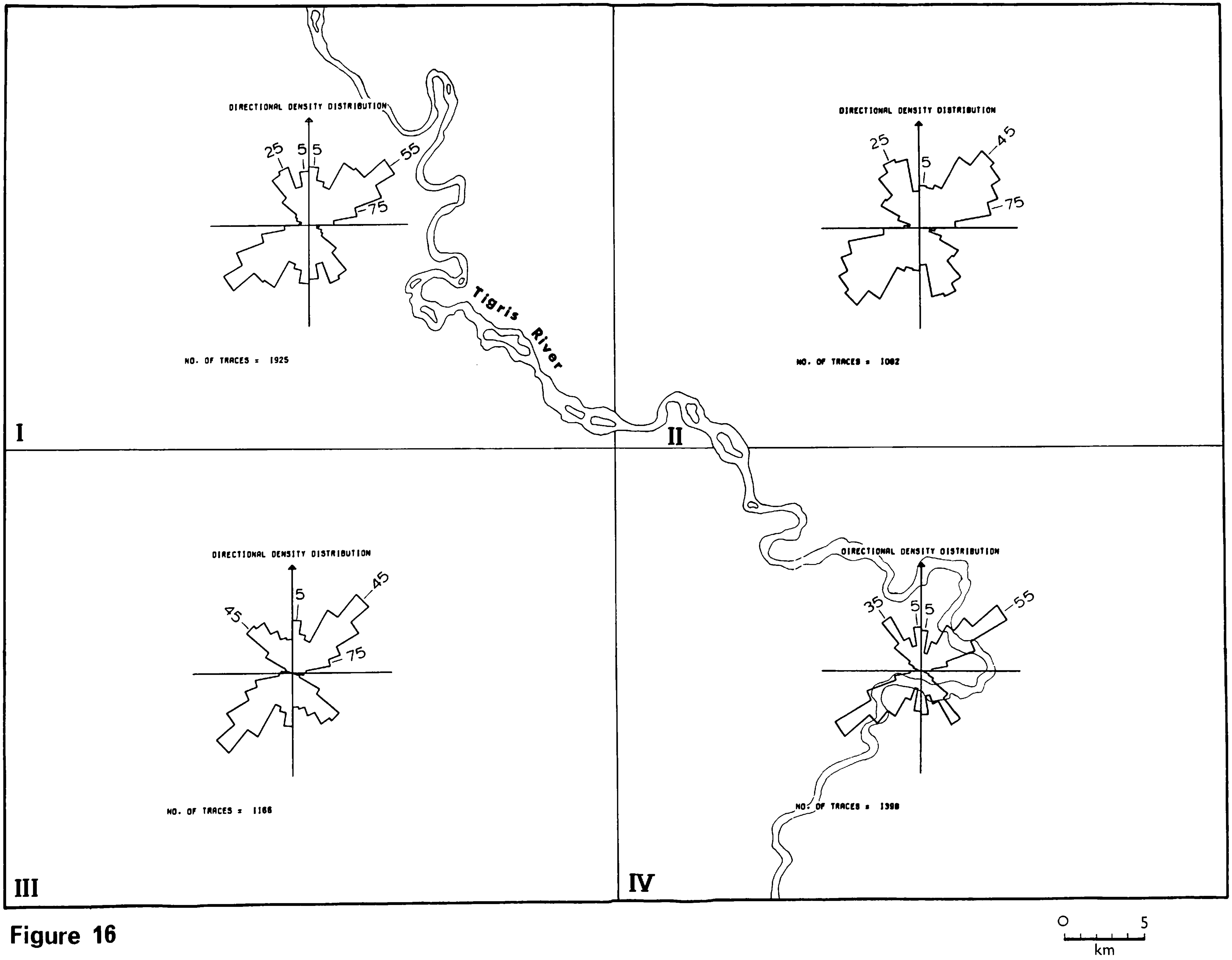


Figure 16

The only difference is that the oblique secondary maximum of this rose diagram has an azimuth of N 45° W.

In the sub-area IV the general characteristics of the rose diagram are similar to those of sub-area I diagram. In both rose diagrams the azimuths of the maxima and minima are very similar, with the exception of the oblique secondary maximum striking N 35° W in the rose diagram of sub-area IV.

The density rose diagram exhibits general characteristics remarkably similar to those of frequency rose diagrams (Figure 15). However, there are very minor differences in the lenghts and azimuths of some rays in both types of rose diagrams. Therefore, the general conclusions which have been drawn for directional frequency distribution may well be applicable to the directional length distribution.

3. Average density rose diagrams (Figure 17)

This map shows four rose diagrams which depict the directional average density of the fracture traces in the sub-areas. They were drawn on the basis of the average length values obtained by dividing the total lengths of fracture traces in each ten degrees directional class by its corresponding frequency number. The average values were then converted into percentages.

In order to achieve an appropriate analysis of average density rose diagrams, a frequent reference to the particular rays in the frequency and density rose diagrams is

Map showing the Average Density Rose Diagrams of the Study Area

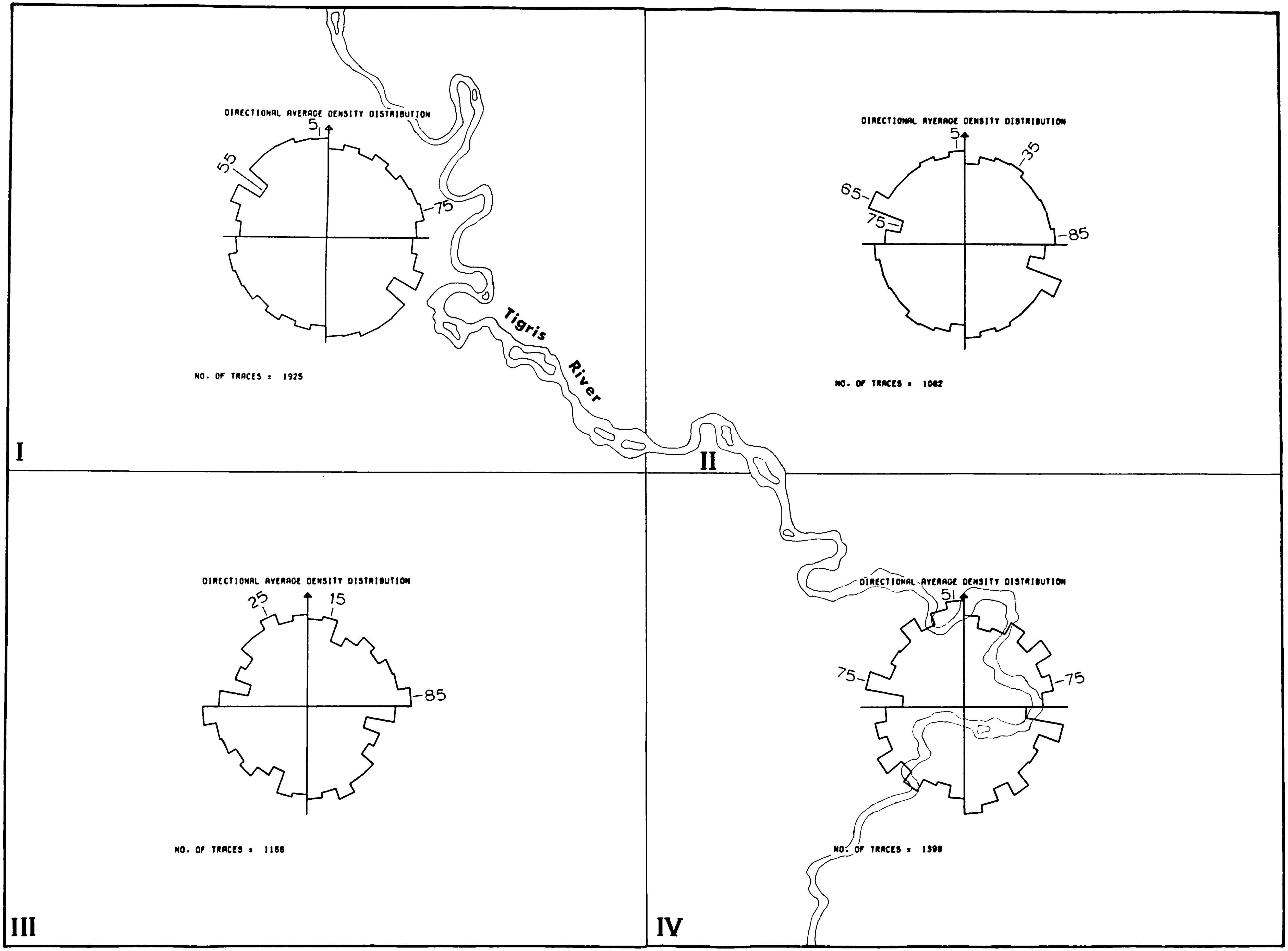
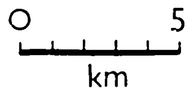


Figure 17



required. The following points outline a general guide line for the ways by which the present rose diagrams can be analysed:-

A - If a particular rose ray has identical lenghths in both the density and frequency rose diagrams, it will appear in the average density rose diagram in the following forms:

(a) As a maximum; which indicates that the majority of the fracture traces of that directional class are medium to long.

(b) As a minimum; which indicates that the majority of the fracture traces of that directional class are relatively short.

(c) As equal in size to the adjacent rays (or nearly so); which indicates that the majority of the fracture traces of that directional class are relatively uniform in length.

B - If a particular ray occurs in the frequency rose diagram as a maximum, and appears in the density rose diagram as a minimum; it will always be represented in the average density rose diagram as a minimum. This will indicate that the fracture traces of that particular directional class are relatively frequent and the majority of them are short.

C - If a particular ray appears in frequency rose diagrams as a minimum, while it occurs in the density rose diagram as a maximum; it will always be represented in the average density rose diagram as a maximum. This will indicate that the fracture traces of that particular directional class are relatively less frequent and some, if not the majority, characteristically long.

The above guide lines can be used more effectively in conjunction with the fracture trace map, particularly when the characteristics of fracture traces need to be checked.

The discussion of the present average density rose diagrams will be concerned only with those rose rays which show significant changes in the characteristics of the fracture traces in the sub-areas.

In the rose diagram of the sub-area I, the ray of azimuth N 5° W indicates that the majority of fracture traces in this directional class tend to be medium in length and their number is rather limited. The minimum of azimuth N 55° W shows that the fracture traces of this directional class are very small. The ray of N 75° E indicates that the majority of fracture traces are medium in size but less frequent in comparison with some fracture traces of neighbour directional classes.

In the rose diagram of sub-area II, the rays with azimuths N 65° W, N 5° W, N 35° E and N 85° E represent fracture traces which tend to be medium in size, but numerically they are rather limited. The ray of azimuth N 75° E represents very small fracture traces in the sub-area.

The rose diagram of sub-area III shows important rays of azimuths N 25° W, N 15° E and N 85° E. These rays represent fracture traces ranging from long to medium, but they are limited in number.

In the rose diagram of sub-area IV, the most significant rays are in azimuths N 75° W and N 5° W. These rays represent groups of fracture traces which tend to be rather long, but due to their limited number they were not well represented in the other types of rose diagram. Other rays in the rose diagram tend to reflect similar characteristics to their counterparts in the frequency and density rose diagrams.

The conclusions drawn from the above fracture trace directional analysis, can be outlined as follows:

(1) The majority of the fracture traces in the sub-areas are obliquely oriented, and the most prominent orientations of the oblique fracture traces are represented by the average azimuths N 45° E and N 55° E of the rose rays.

(2) The fracture traces of the sub-areas which are regarded (in this study) as not being oblique, are predominantly represented by the rose rays with average azimuths N 5° E, N 5° W and N 75° W.

Figure 18 shows rose diagrams representing the whole study area. The number of fracture traces involved in these rose diagrams is the combined total of the fracture traces in the sub-areas.

The frequency and density rose diagrams of the map exhibit very similar characteristics in terms of the lengths and azimuths of the rays. The principal maxima in both rose diagrams have the same azimuth and they are as

Fracture Trace Rose Diagrams of the Whole Study Area

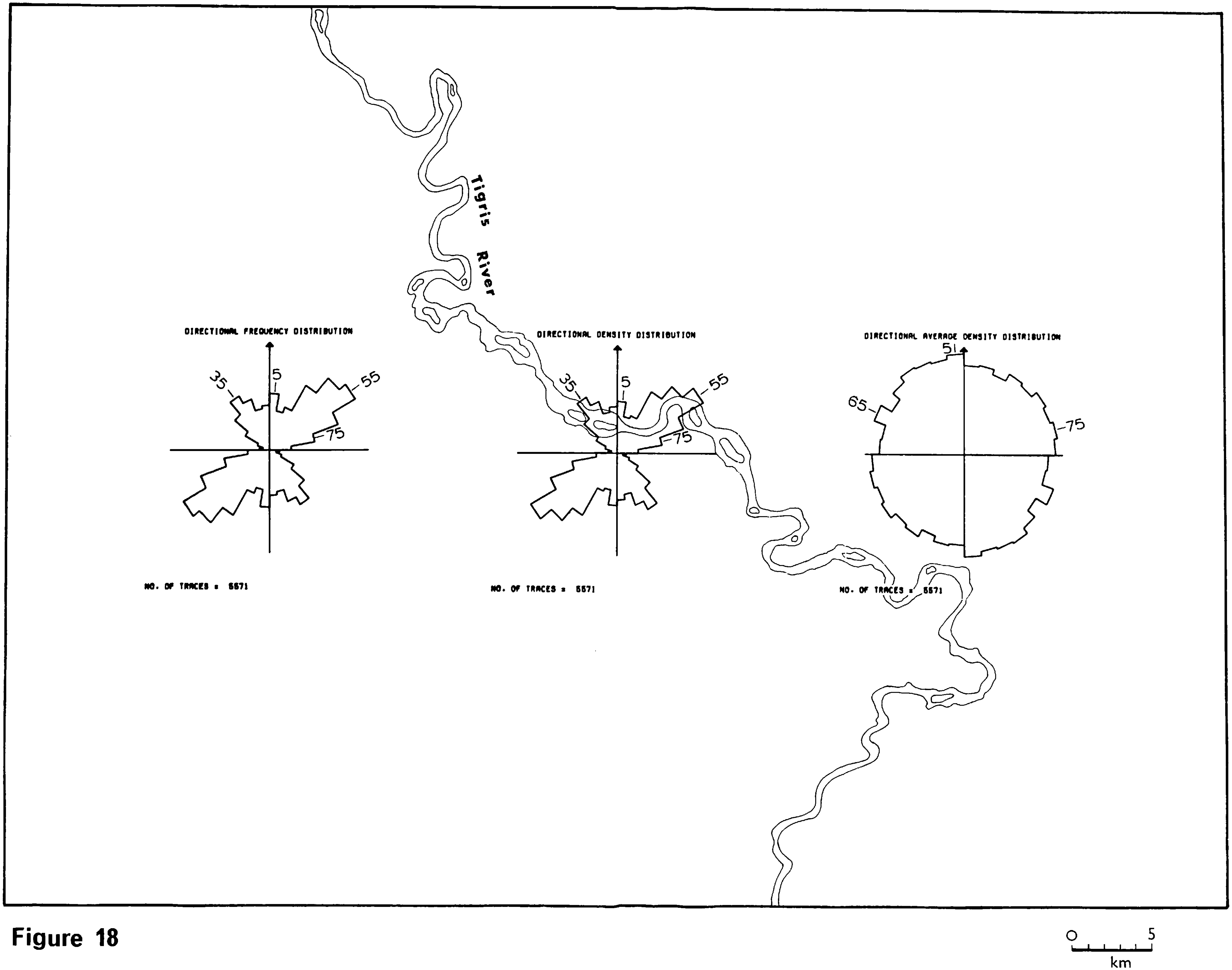


Figure 18

follows; N 55° E (primary), N 35° W (secondary), and N 5° E (tertiary). The significant rose minimum occurs along the E - W in both rose diagrams. An important but short ray with azimuth N 75° E is also present in both.

In the average density rose diagram there are three rays which can be regarded rather significant; and they have azimuths of N 65° W, N 5° W and N 75° E.

The directional characteristics of the above rose diagrams have already been encountered during the analysis of the sub-area rose diagrams. This may ascertain the fundamental features of the directional distribution of the fracture traces in the study area.

6.3.3 Analysis of Fracture Trace Rosemaps

The term "rosemap" used in this study describes a four-sided plane figure which displays rows of equispaced rosettes i.e small rose diagrams.

The rosemaps were constructed From the data of the fracture trace maps. First, the fracture trace map was divided into small square boxes (or cells) of equal size. Secondly, the fracture traces on the map which occurred in each of the square boxes were treated statistically as being related to a discrete small fracture trace map. Thus, a rosette was drawn in the centre of each cell. The percentage data, upon which the rosettes were drawn, were calculated with respect to the sum of the fracture traces in each cell and not to the total fracture traces of the map. The statistics, planning and drawing of the rosemaps were carried out by a digital computer system.

For this study the chief use of the rosemap is to show graphically the prominent directional characteristics of fracture traces. The maxima of the rossettes usually indicate that a great number of fracture traces, or their lengths, fall within specific directional classes. Therefore, an alignment of maxima of several rosettes in a rosemap can mark a general direction along which fracture traces predominently strike. Thus, the analysis of the rosemap will be basically concerned with the detecting of the alignments of significant rays.

Three types of rosemaps were prepared, these are:

A) a frequency rosemap,

B) a density rosemap, and

C) an average density rosemap.

A - <u>The frequency rosemap</u> (Figure 19)

The frequency rosemap shows rosettes which depict the directional frequency of fracture traces.

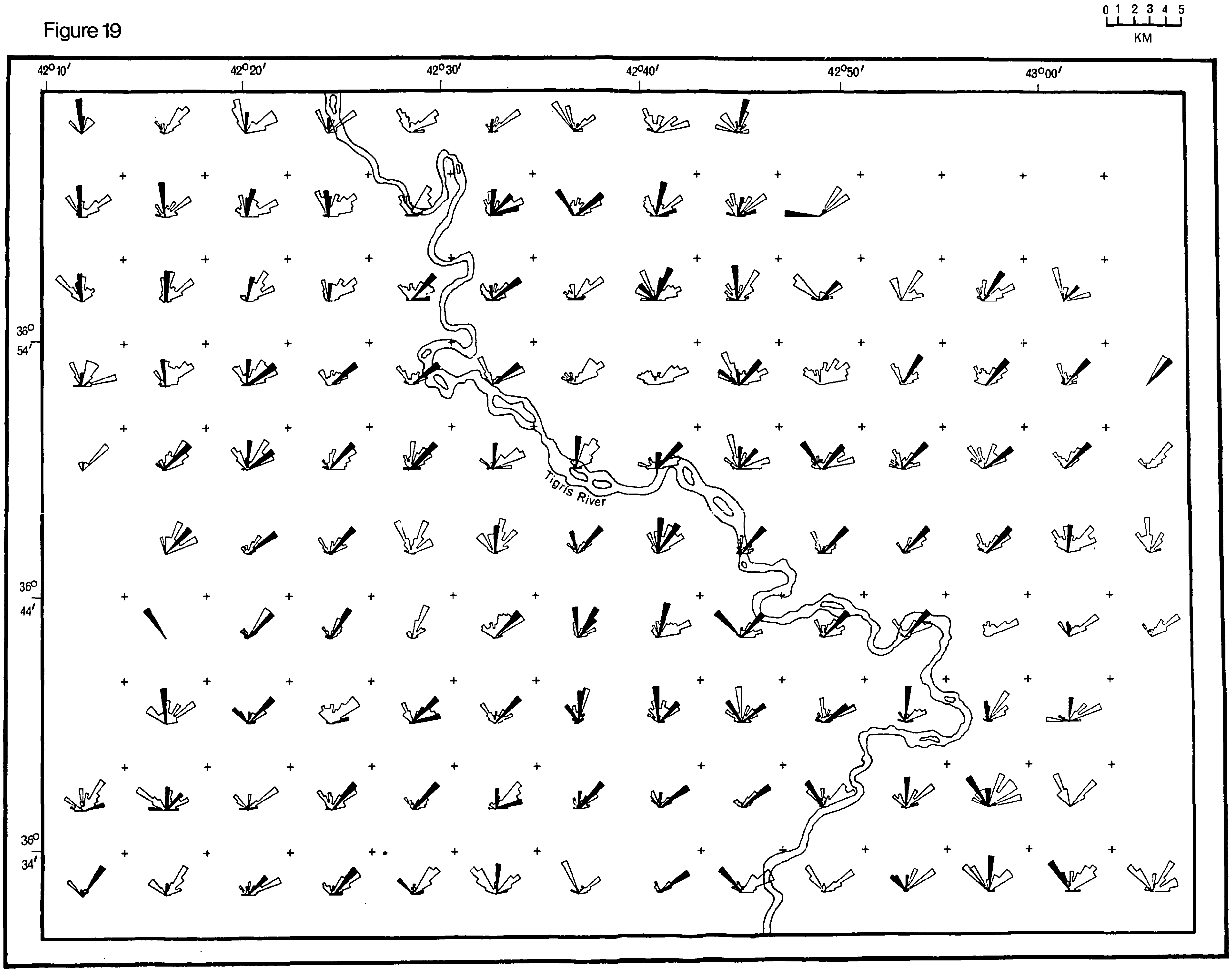
The oblique alignments constitute a characteristic feature of the frequency rosemap. The NE ray alignments are the most prominent in terms of their lengths and number. Some of them transverse the entire rosemap along the central part. Most of these alignments are composed of long rosette rays (or primary maxima).

The NW ray alignments tend to be short and relatively few. They occur mainly in the south of the rosemap.

The N - S ray alignments tend to be short or discontinuous. They are fairly frequent in the north and

FRACTURE TRACE FREQUENCY ROSEMAP OF THE STUDY AREA

Figure 19



south of the rosemap. These alignments are mostly composed from medium rosette rays.

The E - W ray alignments are comparatively few and consist generally of short rays. They occur mainly in the north and south-west of the rosemap.

B - <u>The density rosemap</u> (Figure 20)

The density rosemap shows rosettes which depict the directional distribution of fracture trace lengths. The general characteristics of the density rosemap appear to be similar to those of the frequency rosemap.

The NE ray alignments are the most prominent, but in this rosemap tend to be relatively shorter than those of frequency rosemap. They are mostly composed of primary maxima. They appear almost all over the rosemap.

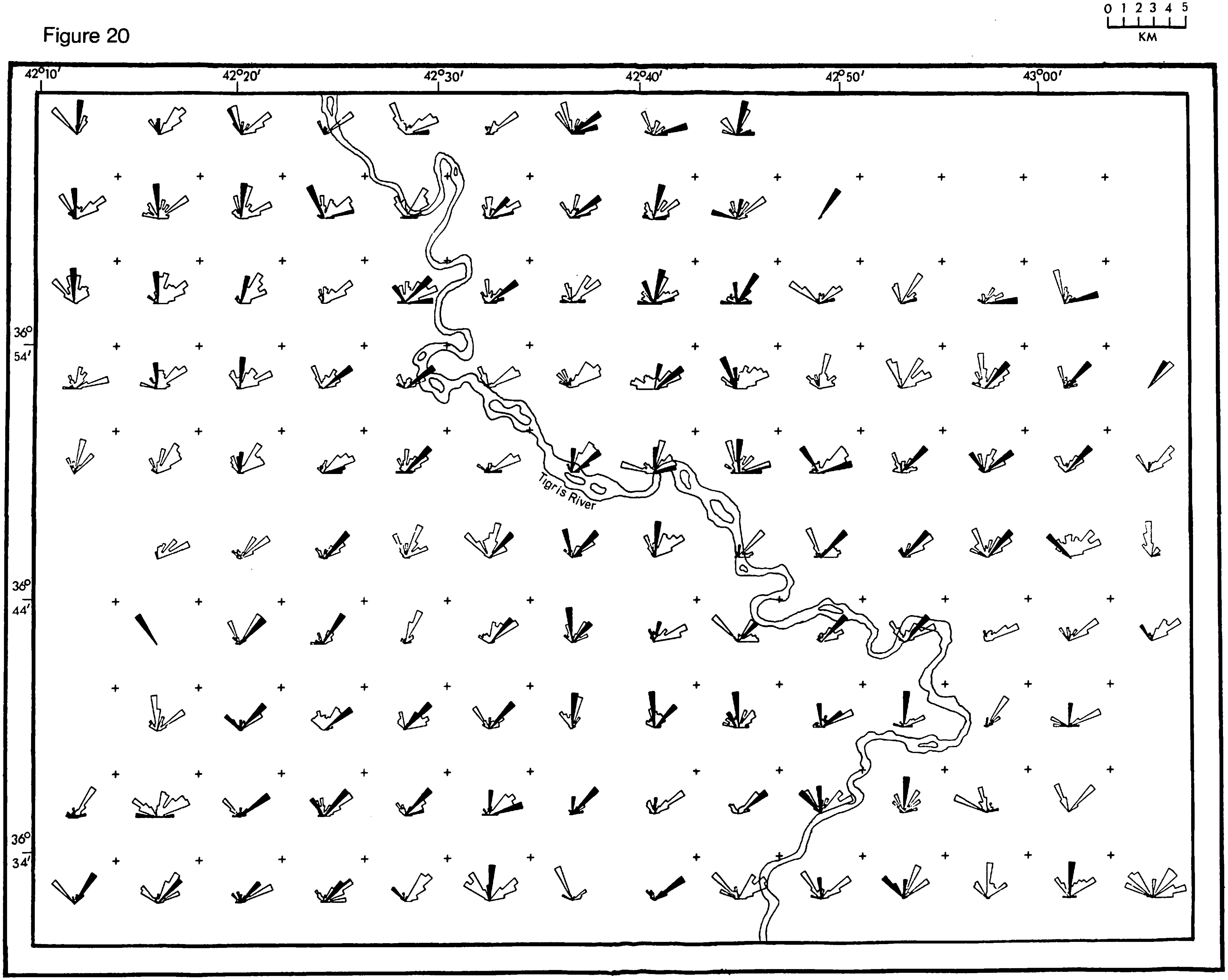
The NW ray alignments are very few and short in length. They generally consist of short rays and appear in the north, east and south of the rosemap.

The N - S ray alignments are rather limited in number, but some of them tend to be long. They are generally composed of medium to long rays, and occur mainly in the north-west, centre and south of the rosemap.

The E - W alignments are composed of very short rays. Their number is very limited and they occur in the north where some of them are fairly long. They can also be seen in the centre and south-west of the rosemap.

FRACTURE TRACE DENSITY ROSEMAP OF THE STUDY AREA

Figure 20



C - The average density rosemap (Figure 21)

The average density rosemap displays rosettes which show the directional distribution of the average fracture trace lengths. The primary advantage of this rosemap is to exhibit and extend the lengths of some ray alignments which represent obscured fracture trace sets. Some of the alignments in this rosemap have not appeared in the frequency or density rosemap or have appeared in short lengths and restricted positions.

The E - W ray alignments are the most frequent and long alignments in the rosemap. They generally consist of medium-sized rays. They occur all over the rosemap and appear longer in the north than in the south.

The N - S ray alignments are generally short and fairly frequent. They are composed of medium and long rosette rays. They appear in almost every part of the rosemap.

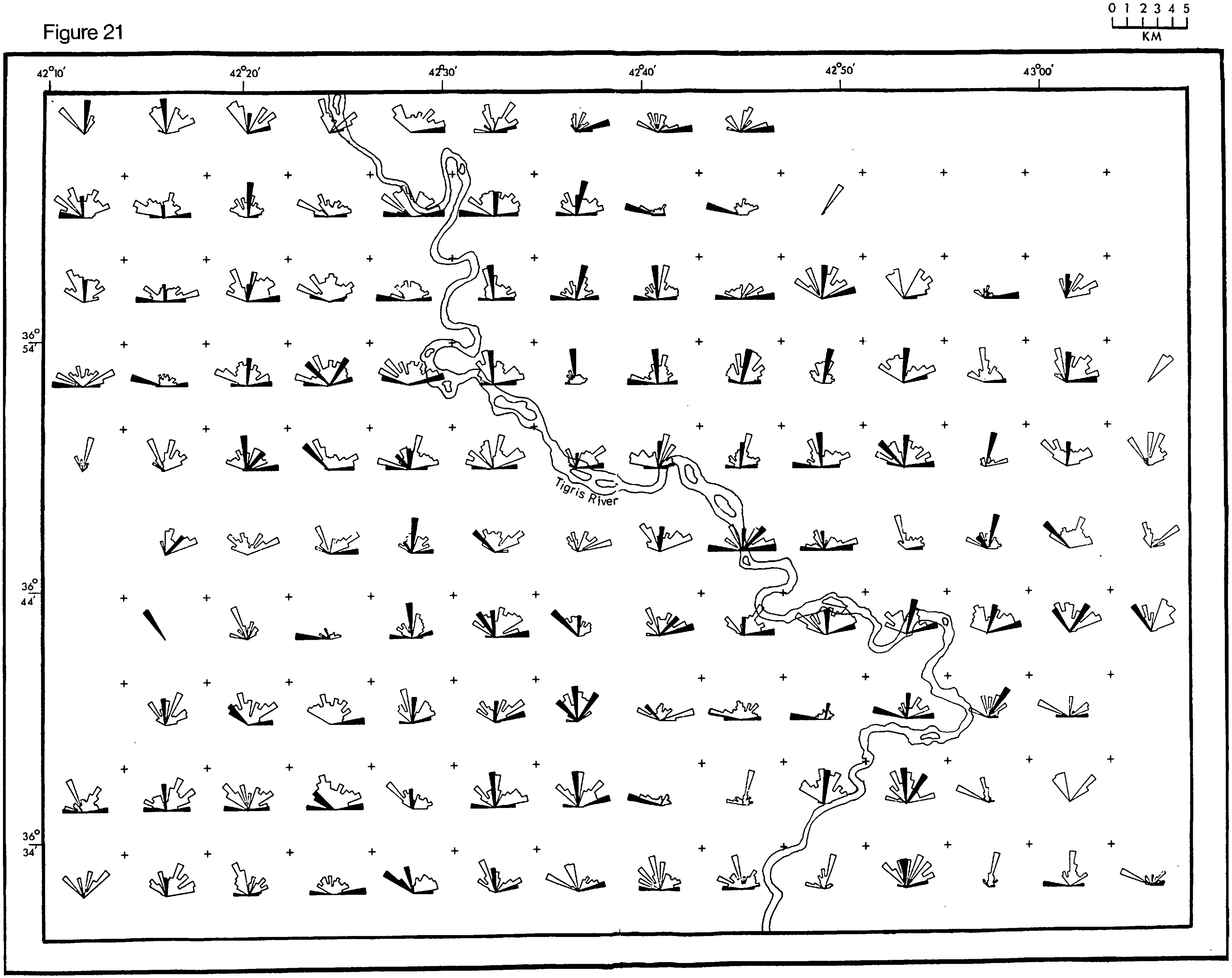
The NW ray alignments are very few in the rosemap and are composed of medium-sized rays. They are short and appear in the central-west and south-west, east.

6.3.4 Analysis of Fracture Trace Spatial Frequency Contour Map

In this study a contour map was conceived as a graphic representation of numerical data, which basically illustrate how a specific parameter varies over a planar area. Mathematically, a contour line is a graph of a function

FRACTURE TRACE AVERAGE DENSITY ROSEMAP OF THE STUDY AREA

Figure 21



Z = f (x, y), where Z represents the value of the mapped parameter (in this case a frequency count) and x, y are Cartesian co-ordinates by which the position of the mapped variable (Z) can be defined. Thus, the frequency contour map (Figure 22) attempts to depict the spatial (or geographical) variation of fracture trace frequency (number) over the study area.

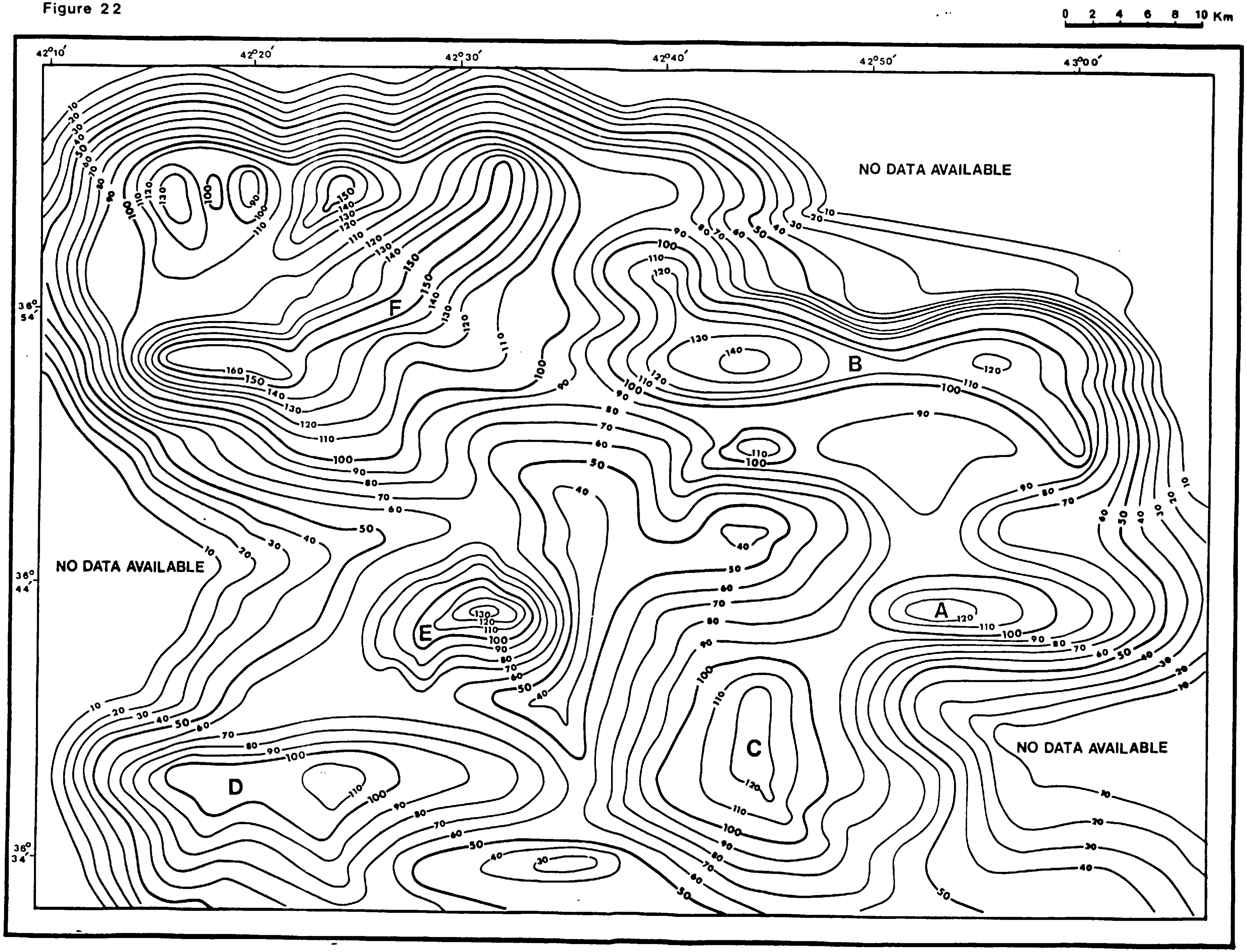
The procedure by which the contour map was produced was made up of two operations. First, a grid of orthogonal lines which fit the boundary of the fracture trace map was mathematically generated by a computer. This divided the map into rows of small, square cells. Then the fracture traces frequency count for each cell was obtained. Secondly, a graphic layout of the cells was drawn to scale on a sheet of paper and the frequency numbers were placed in the centres of the cells as regularly distributed data points. Then the contours were drawn by the interpolation and to adjust the contour patterns appropriately, a continuous visual reference to the fracture trace map was required.

The overall characteristic of the contour texture or configuration of the map (Figure 22) tends to follow an east - west direction. This may be explained by the similar direction of the regional structural fabric of the study area.

In the east of the map, there is a frequency high (A) which is flanked by a steep contour gradiant in the south. This distinct contour feature appears to correspond to the

FRACTURE TRACE SPATIAL FREQUENCY CONTOUR MAP OF THE STUDY AREA

Figure 22



Alqush anticline (sub-area IV), and the area north of it where fracture density is noticeably high. The E - W orientation of the frequency high is also similar to that of the anticline.

To the north there is an elongated frequency high (B) trending to the E - W. It is flanked by a steep frequency gradient to the north and composed of two small and rather similar frequency highs. This composite of frequency highs can be ascribed to the area of high fracture trace density in sub-area II, where Sheikh Adra and Dohok anticlines occur. In the far north-east, the orientation of the contours swings to the NW; this may be attributed to the orientation of the Dohok anticline.

In the south of the map, there is the frequency high (C) with a general N - S orientation. Its relative position corresponds with that of the two small anticlines in the south of sub-area IV. The relatively regular spacing exhibited by the contours of this part of the map including the "high (C)" may indicate a rather uniform fracture trace distribution. The frequency lows to the north and south-west may be related to the areas which the river Tigris passes through and where the number of mapped fracture traces is very limited.

In the south-west of the map the frequency high (D) has an irregular shape, but with an E - W orientation. According to its relative position this high can be attributed to the Gusair structure and the area around it, (sub-area III). The number of fracture traces in this area is rather large.

The frequency high (E) is relatively small and irregular, though a slight tendency to an E - W orientation can be seen. Its location can be roughly compared with that of the Gullar structure.

In the north-west of the map, there are a number of frequency highs with different shapes and orientations. The frequency high (F) has a remarkably long shape, with its northern part striking NE while the southern part swings to the E - W. To the west there are only two small frequency highs of any significance and they have no definite orientation. All the above-mentioned frequency highs have a comparable location with that of Mushorah anticline and the neighbouring area to the west (sub-area I), which displays a high density of fracture traces.

In conclusion, it appears that most of the positions of the frequency highs correspond roughly to the occurrence of the anticlinal structures in the study area. On the other hand, some positions of the frequency lows may be compared to those synclines or valleys which exhibit a limited number of fracture traces. Some frequency highs or steep contour gradients may be related to the flanks of the anticline (particularly the steep flank) rather than to the crestal regions of the anticlines which tend to be flat (horizontal) in most cases. The east-west orientation of most of the contour lines indicates that there is some harmony between the regional fracture trace frequency and the east-west structural trends in the study area.

6.4 STRESS AND STRAIN TRAJECTORIES IN THE STUDY AREA

In geological literature many authors use the terms "force" and "stress" synonymously in a dynamical sense, though there are fundamental differences between the two concepts.

A "force" is always defined in terms of magnitude and direction, therefore it is a vector quantity. By vector analysis one can obtain a resultant of a number of forces or resolve a force into its components acting in different directions. In such an analysis, the force is conceived as acting on a "particle" or an infinitely small portion of a body and is independant of its effects within the particle itself, which is virtually a point.

A "stress" is defined as a force acting on a unit area in any chosen direction and is expressed mathematically as a "tensor", (Hills, 1964). A "stress tensor" is a scalar quantity which can only be measured in magnitude and not in direction, as in the case of temperature. Thus, the analysis of stress connot be carried out by the use of vector analysis as with forces. A body is said to be in a state of stress when it is subjected to external forces, which tend to change its shape or size (i.e cause a strain). The body simultaneously resists the strain by internal forces resulting from action and reaction between adjacent parts within the body.

If a solid body e.g rock mass, is stationary under a system of forces, it is possible to choose at any point, three mutually perpendicular planes intersecting at that point and so oriented that resultant stresses on the planes are entirely normal compression or tension. The lines along which the planes intersect are known as the "principal axes of stress" and the stresses acting along them are the principal ones at the point in question. In general, the principal stresses are unequal, so that there is a maximum principal stress(δ_1), an intermediate principal stress (δ_2) and a minimum principal stress (δ_3) at specific points. The algebraic stress-difference "$\delta_1 - \delta_3$" is usually regarded as the agent of deformation (Hills, 1964). The surfaces in any direction other than that of the three orthogonal planes above mentioned, will be subjected to shearing stress as well as to normal stress. The shear stress is a maximum in the surface oriented at 45° between the axes of the maximum and minimum stresses.

It is common geological practice to infer the stress conditions of the rock from the tectonic features (folds and fractures) which are caused by deformative stress. The tectonic structures can be illustrated and their displacement variables measured on the planes which are perpendicular to the axes of the structures. Therefore, the analysis of stress is usually carried out on a two-dimensional (or plane) system.

The stress trajectories are sets of curves which generally depict the state of stress in the rock. They are usually drawn on planes basically normal to the axes of the structure. In this study an attempt was made to deduce a general picture of the stress conditions which prevail in the rock of the study area. The stress-strain trajectories (Figure 23) were drawn primarily on the basis of the directional length distribution of fracture traces, and there were no field stress measurements or other mathematical data involved. Therefore, this approach to stress analysis may be reagrded as qualitative (or descriptive), and tends to illustrate the regional trends of stress in the area.

The preparation of the trajectories was started by a rosemap which displayed rows of rosettes of directional length distribution, similar to the density rosemap discussed earlier, but with a greater number of rosettes. This map was produced by the off-line computer graphic plotter. The rosettes which occur within the sites of the mapped anticlines in the study area were delineated. In the context of fracture-fold geometrical relationships, it is not unreasonable to suggest that prominent rosette maxima obliquely oriented to the fold axis, represent, statistically, shear fracture traces. The majority of these rosettes showed two significant maxima which are oblique to the north. Two short orthogonal lines were drawn at the centre of each rosette studied, and one of the lines always bisected the angle between the oblique maxima. A similar operation was carried out on the other rosettes which occurred in adjacent positions or between the anticline-related rosette groups. At this juncture special care was taken in selecting the appropriate rays or maxima. In addition, an attempt was made to relate the orientation

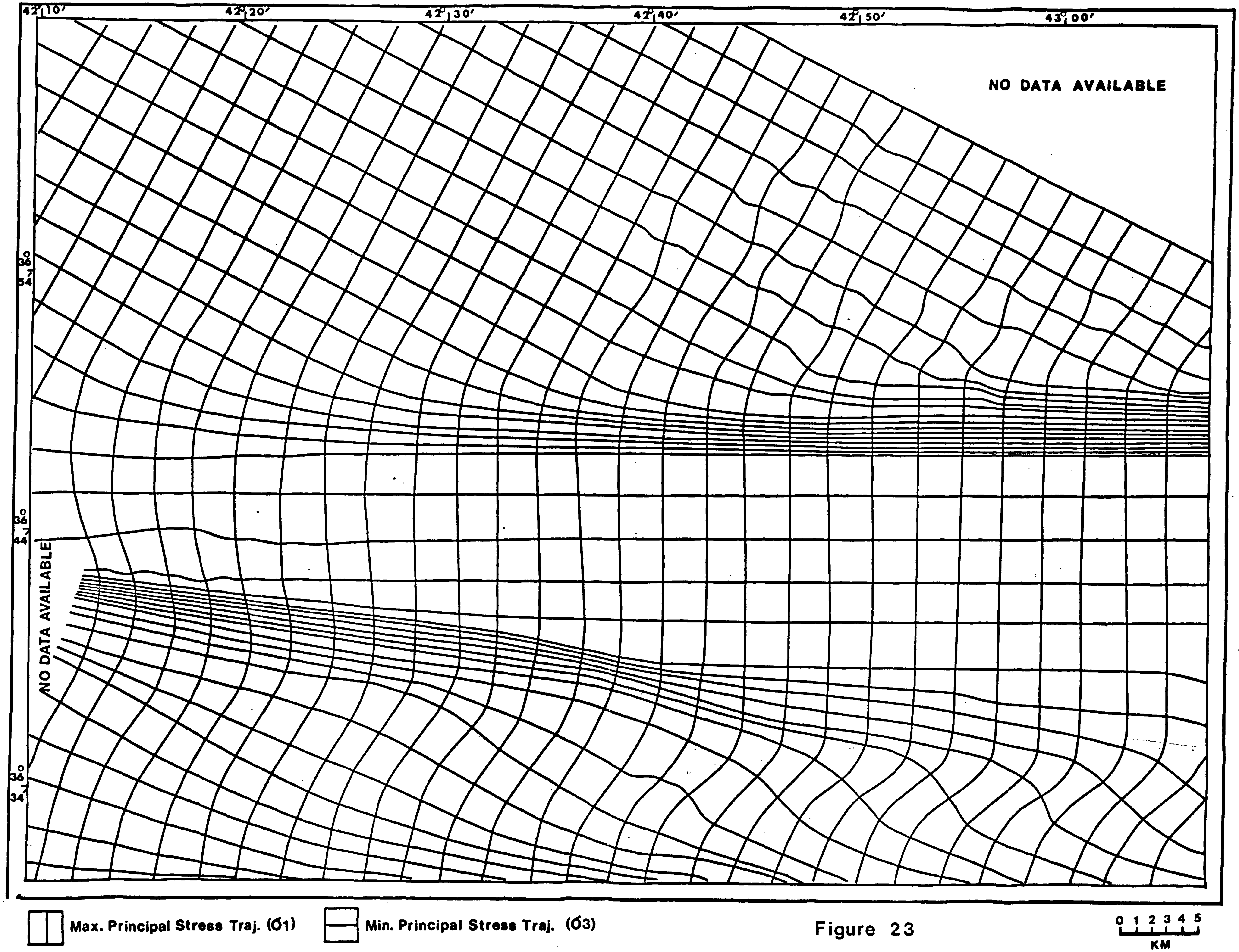

42°10′
42°20′
42°30′
42°40′
42°50′
43°00′
36°54′
36°44′
36°34′
NO DATA AVAILABLE
NO DATA AVAILABLE
Max. Principal Stress Traj. (σ1)
Min. Principal Stress Traj. (σ3)
0 1 2 3 4 5
KM

Figure 23

of these maxima to the axial strike of relevant fold. structures which occur nearby. The above-mentioned orthogonal lines were regarded as short sgements or bases for the potential stress-strain trajectories. They occurred uniformaly (equispaced) over the surface of the map.

Mechanically, the line which bisected the oblique (shear) ray maxima was considered to indicate the direction of the maximum principal stress (δ_1) at the centre of the rosette, and the other orthogonal line indicates the direction of the minimum principal stress (δ_3). The direction of the mean principal stress (δ_2) is supposed to be normal to the plane which contains the other stress axes, that is, the surface of the map.

The maximum shearing-stress trajectories (Figure 24) were prepared upon the completion of the principal stress trajectories. They were drawn simply by joining bisecting lines through the right-angles of intersection of the stress trajectories.

On examining the maximum stress-strain trajectory map (Figure 23), one can easily see three distinct patterns of trajectories. In the north, the orientations of the trajectories are generally oblique to the north-south.

This stress-strain pattern conforms to a large extent to the structural grain of the northern part of the study area. The Mushorah anticline in the central north, and Dohok anticline in the north-east strike mainly in a NW direction. The extensions of some other folds into the northern part of the area, also tend to follow the same direction. Thus, one can reasonably infer that the

MAXIMUM SHEARING STRESS TRAJECTORIES OF MUSHORAH-AIN ZALAH AREA

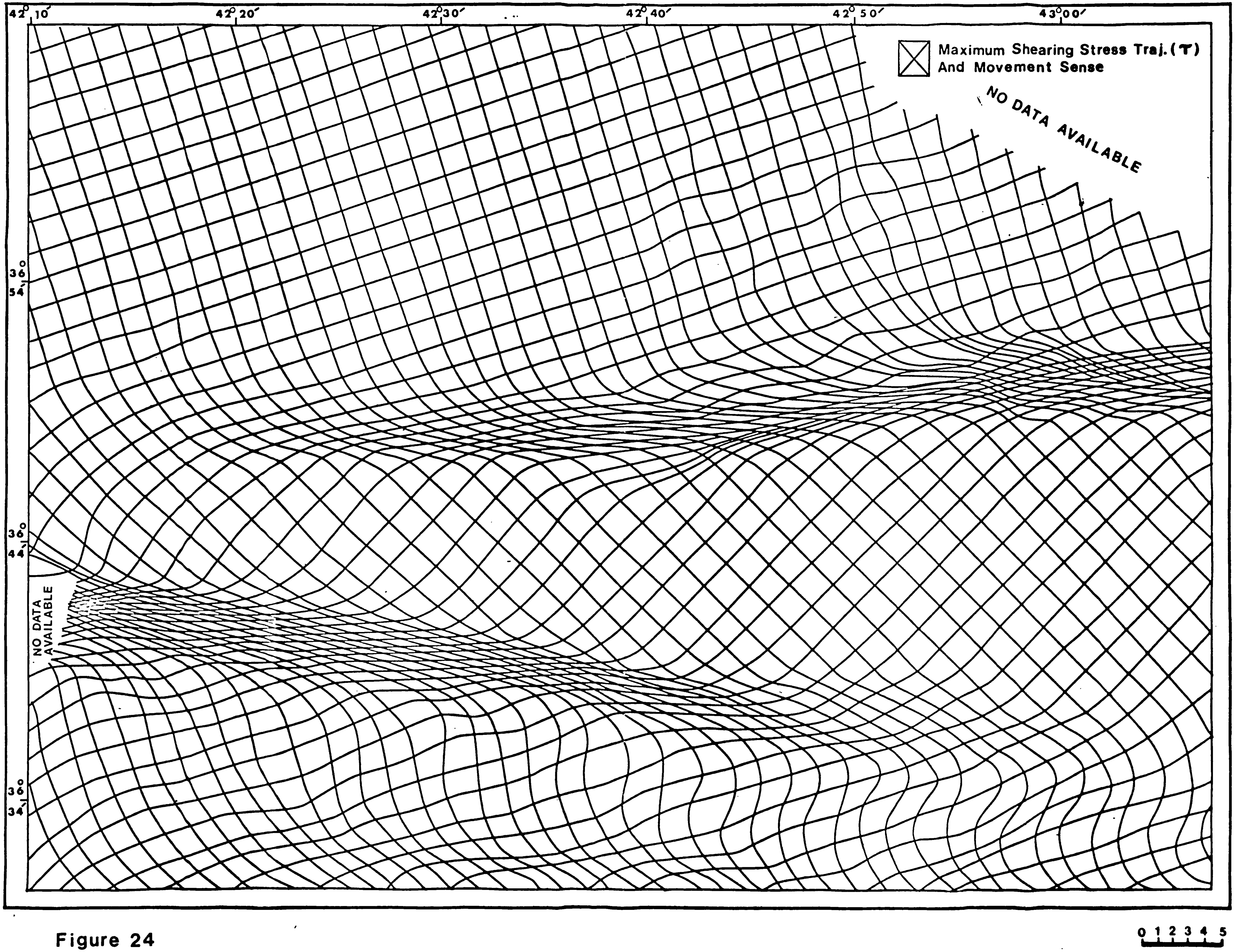


Figure 24

direction of the effective stress in this part of the study area is north-east, and the maximum rock deformation occurs in a north-west direction.

In the central part of the map the trajectories swing to N - S and E - W, and the minimum stress trajectories tend to converge and become very closely spaced on both sides of this zone. The east-west orientation of the fold axes is by far the most common structural characteristic of the anticlines in this part of the area. Thus the similar orientation of both the fold axes and minimum (or strain) trajectories indicates that the deformative forces were being active in a north-south direction, and this is represented by the maximum stress trajectories. The apparent convergence of minimum stress trajectories in the east and west of the map may be explained by the strong tendency of the folds in that part of the area to change their strike from E - W to a NW direction. In addition, the anticlines in these particular areas (i.e. Sheikh Adra in the east and Gullar in the west) are characterized by being tightly folded and rather long; and their western ends show a slight tendency to strike NW. This structural configuration might be induced by basement structural controls.

In the south of the map, the trajectories change their orientation slightly to NW and NE, thus forming a distinct pattern. Most of the fold structures in this part of the area show a tendency to strike NW, particularly in the case of the Gusair anticline. Thus, it appears that the stress pattern is in harmony with the structural configuration in this part of the study area.

Figure 24,, displays the maximum shearing stress trajectories in the study area. They suggest in effect, the potential failure surfaces along which the shearing-stress reaches its maximum. These surfaces occur in conjugate planes making angles of 45° on both sides of the maximum stress axis. The mechanical conditions for such an occurrence are almost ideal, and can never be encountered in the field.

One can see two distinct belts of closely spaced trajectories, which divide the map into three zones of rather different patterns. In the north, the orientations of the trajectory sets are NNW and ENE. These azimuths can be seen as the directions along which the maximum shearing stress can take place, thus causing shear fractures. Allowing 5° to 15° azimuth deviation from the orientations of the trajectories, which are being regarded as theoretical norms, the majority of the fracture trace trends in the north of Figure 14, appear to have very comparable azimuths to those of the trajectories. Specifically, the frequency of the fracture trace trends with a N - S azimuth or nearly so, is very noticeable in the northern part (Figure 14), and there are also a number of rather long trends striking ENE.

Towards the centre of the map the trajectories change their orientations to a near E - W direction, particularly, along the dense trajectory belts. These azimuthal characteristics seem compatible with those of long fracture trace trends which transverse the central part of Figure 14.

The NW and NE trajectories are also similar in orientation with some long fracture trends in the middle of the same Figure.

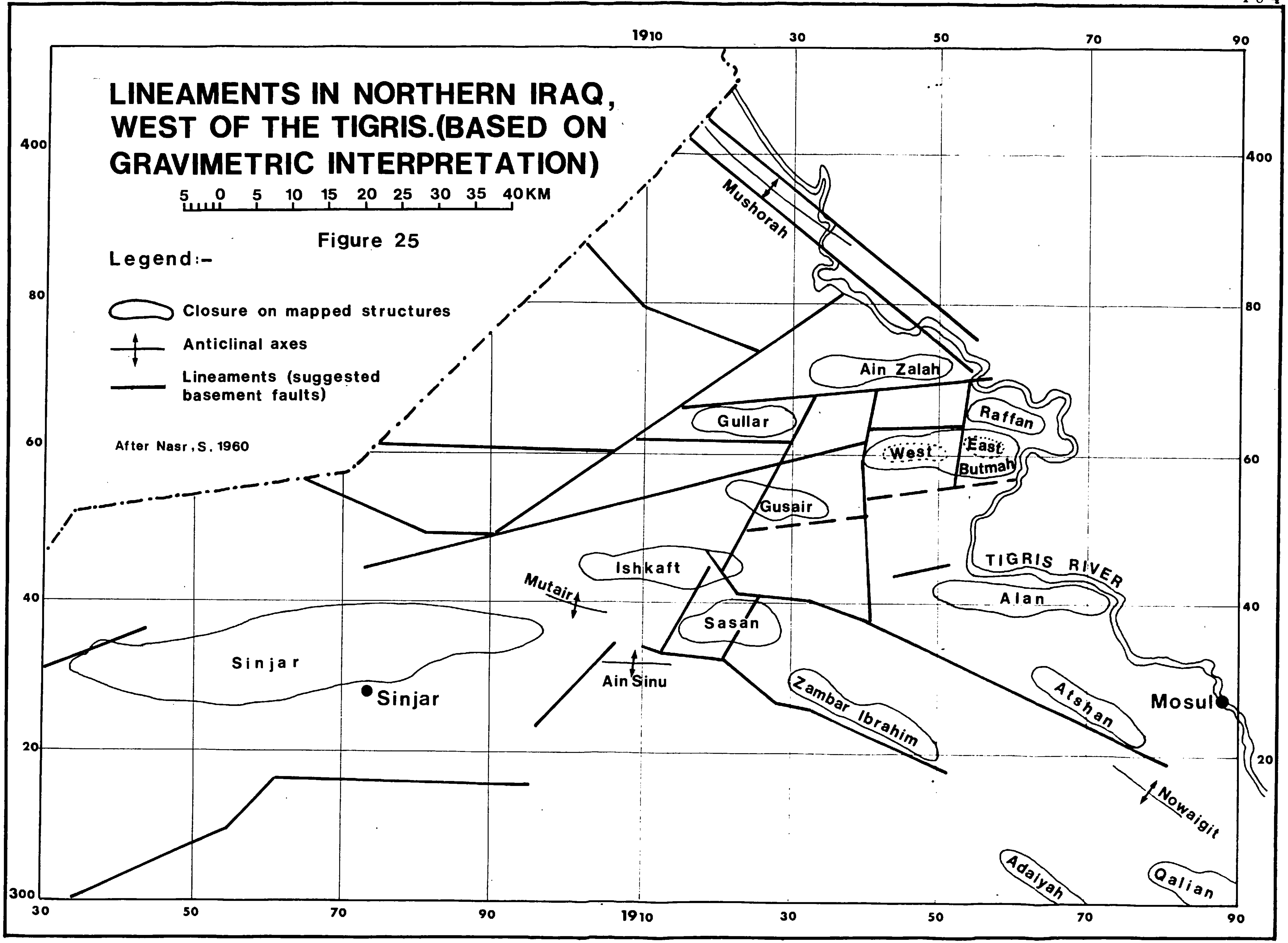
In the south, the trajectories have rather irregular orientations, though they are mainly ENE and NNW. The fracture trace trends in the south (Figure 14) generally have similar azimuths, and those which are ENE or NE are relatively frequent. There are also a number of N - S and E - W fracture traces trends which are in azimuthal agreement with the shearing stress trajectories occurring in the corresponding positions.

6.5 GRAVIMETRIC LINEAMENTS IN THE STUDY AREA

The measurement of gravitational field at the earth's surface, and the utilizing of the data thus obtained to detect subsurface structures, is a widely-used geophysical technique. The difference in density of rock is the physical basis of the gravitational method. Thus, a subsurface structure which is denser than the average material of the earth's crust in its neighbourhood, exerts a greater force on the unit mass (measured by gravimeter) than would have been exerted if the structure has been absent. A comprehensive picture of differences of rock density can be obtained from residual (or absolute) gravitational anomalies, which, to a certain extent, reflect major subsurface structures. The magnitude of the gravitational anomaly is dependent not only upon the density of the rock, but also on its geometric configuration, the depth and location of the structure with reference to the position at which the gravitational effect of the structure is measured (Jakosky, 1950).

By the analysis of the variation of residual gravity values, one can outline subsurface structural conditions. For example, a profile of the gravity values across a granite ridge in less dense sedimentary rocks would show a gravity maximum over the crest of the ridge, whereas the profile would show a gravity minimum over concealed salt dome. In a similar manner, a subsurface block-fault which tends to bring dense rock closer to the earth's surface, on the up-thrown side, would show a gravity anomaly (depicted in contours or profile) which follows the shape of the dense basement rock quite closely, (Jakosky, 1950).

Figure 25, shows subsurface tectonic lineaments, based on gravimetric interpretation, occurring in Northern Iraq, west of the Tigris, (Nasr, 1960). The prime use of these lineaments in this study is to provide a kind of subsurface information compatible in character with those data which were obtained from air photographs, specifically, the fracture trace trends in Figure 14. There is an appreciable similarity both in the positions and azimuths of some gravity lineaments and fracture trace trends. The long lineaments which strike SW - NE, in the west of the map, (Figure 25), and end at the River Tigris (west side), may be compared with the fracture trace trend (Figure 14), of similar azimuth and relative geographic position, though it is shorter. The lineament which flanks


LINEAMENTS IN NORTHERN IRAQ, WEST OF THE TIGRIS.(BASED ON GRAVIMETRIC INTERPRETATION)
5 0 5 10 15 20 25 30 35 40KM
Figure 25
Legend:-
Closure on mapped structures
Anticlinal axes
Lineaments (suggested basement faults)
After Nasr, S. 1960
Mushorah
Ain Zalah
Raffan
Gullar
West
East
Butmah
Gusair
Ishkaft
TIGRIS RIVER
Alan
Mutair
Sasan
Sinjar
Sinjar
Ain Sinu
Zambar Ibrahim
Atshan
Mosul
Nowaigit
Adaiyah
Qalian
1910
30
50
70
90
400
80
60
40
20
300

Ain Zalah anticline in the south and strikes almost E - W, is comparable with the fracture trace trend which exhibits similar characteristics and appears in the centre of Figure 14. The two lineaments of azimuth N - S, occurring in the central part of the map, (the short one crosses Butmah anticline at the centre), are similar in their characteristics to the narrow zone of short fracture trace trends which crosses Figure 14 (at central part) in a N - S direction, and to the other short fracture trace trends appearing nearby to the west. There are short lineaments which border the southern flanks of the Butmah, Gusair and Gullar anticlines, and striking almost E - W. Together with these, there is a very long lineament striking ENE, and extending further to the west. These above-mentioned lineaments can be compared with the fracture trace trends appearing on Figure 14, which have similar orientations and corresponding positions.

There are two remarkable parallel lineaments flanking the Mushorah anticline in the north of the map and striking SE - NW. The lineaments are quite similar to the pair of fracture trace trends which run NW parallel to the Tigris on both sides, (Figure 14), thus bordering Mushorah anticline.

General conclusions about the comparable characteristics in both lineaments and fracture trace trends can be outlined as below:

(a) In the central part of Figure 14, the fracture trace trends tend to strike E - W which also coincides with the general orientation of the structural grain in that part of the study area. The lineaments in the corresponding area show a similar tendency to strike E - W.

(b) The occurrence of a very long lineament in the western part of the map, striking NE, may indicate that the subsurface structures in the vicinity area have a similar azimuthal tendency. Thus, the number of long fracture trace trends of similar orientation which occur around the corresponding position in Figure 14 , might reveal some degree of structural affinity, with the above-mentioned lineament.

6.6 ANALYSIS OF THE DRAINAGE NETWORK IN THE STUDY AREA

Drainage as a surface feature, dependent to a large extent on the lithology and structure of bedrock. Mathematically, it may be expressed in a function of two variables (i.e lithology and structure) as $D = f(L, S)$, where D, L and S stand for drainage, lithology and structure. Thus, drainage analysis has been frequently used as a tool in regional structural study. The drainage network is perhaps the most conspicuous land feature which can be seen on air photographs regardless of the type of geological terrain.

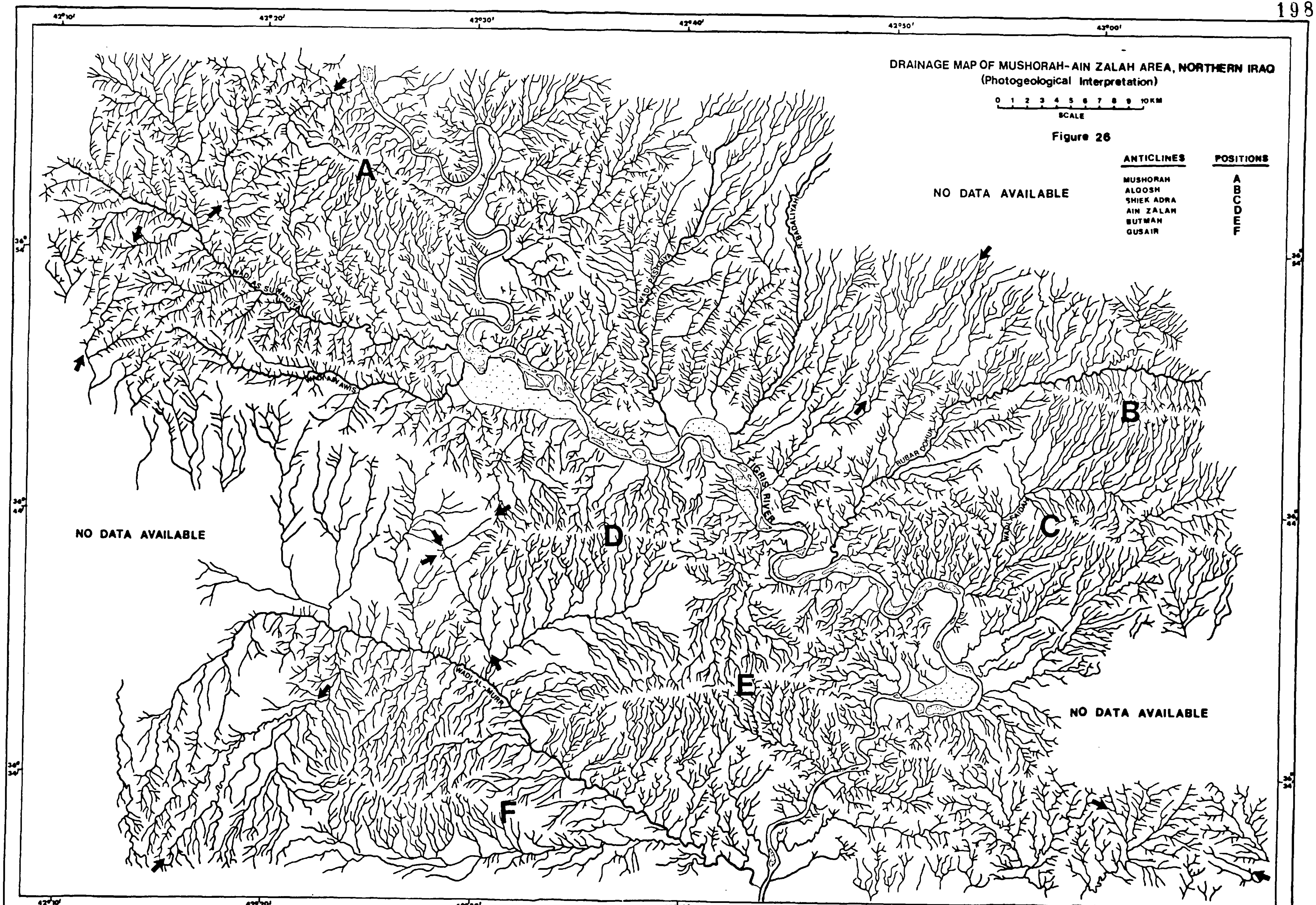
As mentioned in the preceeding chapters, the drainage criteria were mainly used to help in detecting and interpreting the fracture traces on the air photographs, and also, to a lesser degree, to deduce some of the structural characteristics of the folds in the study area.

The drawing of the drainage map (Figure 26) was accomplished by tracing out the drainage system from the air photos onto strips of transparent overlay, each nine inches wide. This operation was carried out under a mirror stereoscope. Subsequently, the drainage strips were compiled onto the surface of maps of a scale approximately the same as that of the air photographs (i.e 1/30000).

Slight adjustments had to be made to match the positions of some of the streams with their counterparts on the base map, thus, minimizing and correcting the effect of photographic radial displacement. Then the assembled drainage networks were redrawn on one sheet, together with the geographic co-ordinates of the base map. The present drainage map is a reduced copy of the original.

It is an observed fact, that the structural configuration of the bedrock in the study area has an appreciable influence on the topography of the terrain. This is, to a large extent, manifestedin the drainage distribution. The drainage analysis can successfully be carried out through the application of two basic concepts; these are the drainage pattern and drainage anomaly.

The drainage pattern may be defined as a spatial arrangement of streams which have adjusted to certain structural or topographical controls. In this area, the lithological effects on the drainage appear to have been



DRAINAGE MAP OF MUSHORAH-AIN ZALAH AREA, NORTHERN IRAQ
(Photogeological Interpretation)
0 1 2 3 4 5 6 7 8 9 10KM
SCALE
Figure 26
ANTICLINES
POSITIONS
MUSHORAH A
ALOOSH B
SHIEK ADRA C
AIN ZALAH D
BUTMAH E
GUSAIR F
NO DATA AVAILABLE
NO DATA AVAILABLE
NO DATA AVAILABLE
A
B
C
D
E
F
TIGRIS RIVER
RUBAR DOHUK
WADI AL-MURR
42°10'
42°20'
42°30'
42°40'
42°50'
43°00'

rather minor compared with the structural effects.

The drainage patterns which are associated with anticlines should easily be identified. It is often possible to delineate the boundary of the anticline as well as form an idea about its structural characteristics by analysis of the drainage pattern which is associated with it. On the drainage map, there are several drainage patterns indicating known anticlines. These patterns are basically similar in so far as they consist of two principal zones of parallel or sub-parallel streams (or consequent tributaries) flowing in opposite directions and leaving between them a linear, very narrow and undrained zone.

Examples of these drainage patterns were encountered in the drainage map in the position A, B, C, D, E and F. All these positions represent the sites of anticlines. On close examination of these drainage patterns, one can deduce the axial region, flanks and plunging ends of the anticlines. The drainage patterns in the positions (D) and (E) indicate Ain Zalah and Butmah anticlines. They clearly show the shape and size of both anticlines, as well as their structural divisions. In the position (F), the drainage pattern suggests a typical dome-like structure which is Gusair anticline. In positions (B) and (C) the drainage patterns are related to the Alqush and Sheikh Adra anticlines, by which one can infer their structural characteristics. In addition, the asymmetry of these structures, particularly Sh. Adra anticline, can be deduced from the difference in length of the streams which flow on both flanks. The streams flowing northwards are apparently shorter than those flowing southwards; this indicates that the northern flank is rather steeper than the southern. The drainage pattern in position (A) indicates the Mushorah anticline. It has a different strike which is shown by the orientation of the central undrained zone of the drainage pattern. The streams in this pattern are less parallel compared with the others, which may be ascribed to the gentle dipping of the flanks of the anticline.

Some large streams in the drainage map flow mainly in valleys which occur between the anticlines. These streams may indicate the locations of some synclines in the area. Examples of these are Wadi Al-Murr stream in the west and Rubar Dohuk and Wadi Aidah streams in the east.

The notion of the drainage anomaly is often applied in the detection and interpretation of fracture traces on air photographs, particularly when the area concerned has poorly exposed bedrocks. The drainage anomaly, for this study, is meant to describe one or more streams or their segments, which appear incongruent with the local or regional drainage pattern. It is logical to relate such anomalous drainage characteristics to a geological cause. As far as the identification of fracture traces is concerned, the indicative drainage anomalies which were encountered during this study can be listed as below:

(a) A noticeable alignment of streams or their segments occuring over a long distance against a background of a rather different drainage characteristics.

(b) An abrupt change in the direction or linear characteristics of the stream.

(c) An unusually rectilinear stream occurring in surroundings with a different drainage pattern.

(d) Small but very straight tributaries intersecting each other at obtuse or right-angles. Such an occurrence is familar in drainage patterns associated with the site of an anticline.

Some examples of fracture-controlled drainage anomalies are indicated by small arrows on the drainage map.

CHAPTER SEVEN

7.1 A CASE STUDY OF THE AIN ZALAH OIL FIELD

In the study area there are two oil fields, the Ain Zalah and Butmah fields, but due to its potential oil productivity, Ain Zalah is regarded as the principal oil field in the western part of Northern Iraq (Musol Province). This field is located in the central part of the study area, about 65 km north-west of the city of Musol in North Iraq.

Ain Zalah was chosen as the key structure during the present study, and therefore a detailed photogeological study, including fracture trace analysis, was carried out for this area. Field work was carried out to check or substantiate photogeological data on the ground, and also additional structural and lithological data were also gathered.

The main reasons for which Ain Zalah was chosen as the key structure are as follows:-

(a) Since the reservoir of the field is known to be a fractured reservoir (i.e. the oil is contained in highly fractured limestone rocks). So, fracture trace analysis may be tested as an appropriate technique for detecting (or predicting) the directional characteristics of the reservoir fracture system. This may help the future development of the field and also further the exploration in the area.

(b) The geological characteristics of the Ain Zalah structure have been frequently observed in other structures in the study area and generally in the foreland zone of Northern Iraq.

(c) In comparison with other structures within the study area, the Ain Zalah oil field is well documented, and literature concerning its geology, particularly its subsurface geology, is available.

7.1.1 Stratigraphy and Oil Occurrence in Ain Zalah Field

Ain Zalah is an elongated anticlinal fold striking east - west with dimensions 20 km long and 5 km wide. It rises about 600 feet from the surrounding plain to a height of 1786 feet above sea level. The topography of the exposed part of the structure is in complete sympathy with the folding characteristics, as the geomorphological ridges of the flanks correspond perfectly with the structural outline of the fold. In the central region of the anticline (i.e. along the crestal zone), the beds of the Lower Fars formation are almost horizontal and therefore form flatlands (plateaux or mesas) of various size. The anticline plunges at both ends. The River Tigris meanders around the eastern plunge. The geomorphology and structural characteristics of the bedrocks forming the structure have a great influence on the spatial distribution of the drainage in the terrain.

Erosion has removed the outer soft rocks (i.e sand and marls) of the Upper Fars (U. Miocene), leaving the more resistant beds (limestone and anhydrite/gypsum) of the Lower Fars (M. Miocene). However, Upper Fars beds can only be encountered in the outer and lower flanks of the anticline as well as in the adjacent flat areas. Thus, the Lower Fars beds are the oldest exposed beds and can be mapped over considerable distances all around the anticline.

A subsurface study of the oil field, based on stratigraphic data obtained from well-logging, core analysis and seismic survey was published by Hart and Hay in 1974. The study included a useful summary of the rock formations which have been penetrated during the drilling of the structure. It was appropriate, in the present study, to have some knowledge of the stratigraphic succession that occurs in the Ain Zalah field. Thus, Table Number 1 shows the names of the formations, lithology, thickness and age. It is slightly modified after Hart and Hay.

The uppermost oil occurrence is in the upper part of the Shiranish Formation of Upper Cretaceous age. This reservoir has been named the "First Pay". The Shiranish Formation is essentially a globigerinal limestone with little natural porosity and negligible permeability. The oil is contained in post-depositional fractures on the crestal part of the structure, and is limited to the uppermost part of the formation. The second accumulation is in the Qamchuqa Formation of Middle Cretaceous. Hart and Hay (1974) recognized Qamchuqa as a group of three formations, the Mauddud, Gir Bir and Wajnah Formations which appear in ascending order in Table No. 1. These formations

Table No. 1 -

STRATIGRAPHIC SEQUENCE IN AIN ZALAH FIELD

FORMATION	LITHOLOGY	THICKNESS (Ft)	AGE
Upper Fars	Sandstones, siltstones and marl, outcropping only on low flanks of anticline.		Late Miocene
Lower Fars	Rhythmic, sequence of gypsum/anhydrite, limestone with silt-stone and marl shale	400 - 110	Middle Miocene
Jeribe	Recrystallized lime-stone, with fossil detrital and pellety	220	
Dhiban	Anhydrite or gypsum, thin bedded limestone	80	Early Miocene
Euphrates	Recrystallized lime-stone, nodular anhyd-rite	350	
	---UNCONFORMITY---		
Bajawan	Reef limestone	130	
Baba	Fine-coarse-grained dolomite	140	
Shurau	Dense reefal limestone	40	Oligocene
Sheik Alas	Fine-coarse-grained dolomite	135	
	---UNCONFORMITY---		
Avanah/ Jaddala	Dense limestone, loc-ally cherty and anhy-dritic	1800	Late-Middle Eocene
	---HIATUS---		
Aaliji	Shale, locally calcare-ous with limestone tongues	1700	Early Eocene - Palaeocene
	---UNCONFORMITY---		
Shiranish	Dense marly limestone	1800 - 2500	Maestrichtian-Late Campanian
Mushorah	Dense limestone with bedded chert member	200	Early Campanian
Wajnah	Calcareous limestone with dolomite and conglomerate at base	275	Early Campanian
	---UNCONFORMITY---		
Gir Bir	Dense limestone with bioclastic texture	up to 150	Cenomanian
	---UNCONFORMITY---		
Mauddud	Porous dolomite and limestone	475	Albian
Nahr Umr	Fissile shale	100	
	---UNCONFORMITY---		
Sargelu			Middle Jurassic

consist in Ain Zalah field of dolomitic limestone, dolomites and crystallised limestone. The Qamchuqa Formations together with the lowermost of the Upper Cretaceous sediments, (chert and limestone sequence), form the reservoir of the "Second Pay". The oil in this reservoir occurs both in porous and fractured rocks. The two pays are separated by about 2400 feet, except for a restricted connection through fractures which can be readily identified by reservoir and other field observations (Hart and Hay, 1974). Thus the field is rather unusual in that the oil in the first pay originated from, and is at present replenished by, oil from the second pay (Dunnington, 1958).

7.1.2 Structural Characteristics of Ain Zalah Field

The asymmetry of the anticlinal structure is a common feature in Northern Iraq. This is so in the case of Ain Zalah anticline where the southern flank is relatively steeper than the northern flank. The central part of the anticline is rather broad and horizontal. The dip of the southern flank ranges from 20° to 30°, whereas the northern flank ranges from 15° to 20°. The anticline plunges at both ends, the western plunge being slightly steeper than the eastern plunge. The dip of the flanks decreases towards the plunges. The axial strike is east - west, with a slight tendency to south - west at the western end.

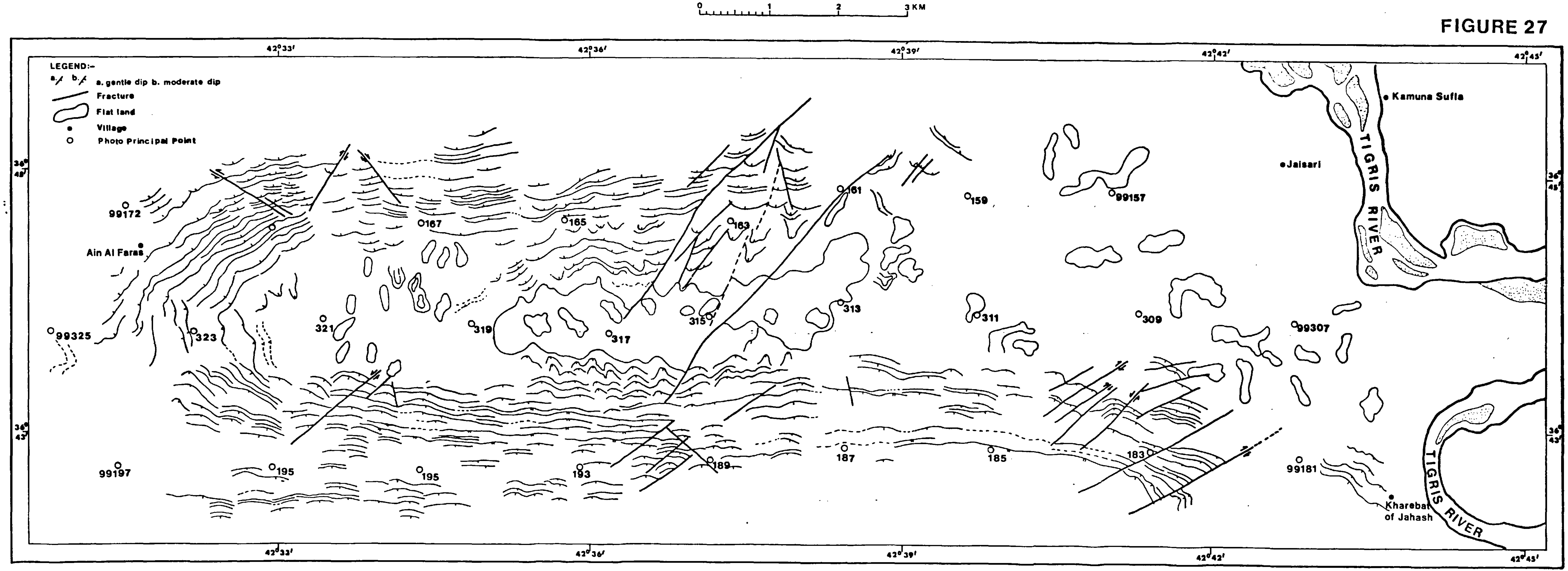
A photogeological structural map was produced for the Ain Zalah anticline. It is a result of photointerpretation carried out on photographs of a scale 1/20000. The data were then compiled onto a base map. The map, (Figure 27) shows mainly the bedding traces of the exposed rocks (mostly Lower Fars beds), which clearly outline the shape of the structure. It is obvious from the map that the southern flank is steeper than the northern flank, and horizontal beds (i.e. flatlands), are prevalent in the central region of the anticline. Two very long fractures striking SW - NE, cross the northern flank into the crestal part of the anticline with smaller fractures occurring between them. At the eastern end of the anticline, there is a group of fractures which cause an obvious displacement of beds in the southern flank.

It is thought that Ain Zalah and similar structures in Northern Iraq rose during the Miocene-Pliocene Orogeny. Evidence of earlier movements and uplifts is also known in the area. It is probable that vertical movement took place at the end of the Oligocene. Some 500 feet of Oligocene limestone occurs in Ain Zalah, whereas none is present in the adjacent structure of Butmah (Nasr, 1960). This would suggest a differential emergence with consequent erosion in the Butmah area, and probably contemporaneous but less intensive uplifting in Ain Zalah.

The data obtained from drilling and seismic survey suggest that the subsurface flexure of Ain Zalah is in harmony with surface folding down to Middle Cretaceous (Nasr, 1960). Knowledge of the structure below the Middle Cretaceous is based entirely on one well, (No. 16), sited on the crest of the anticline. Core and dipmeter records from this well suggested that at depth the well lies on the

STRUCTURAL MAP OF AIN-ZALAH OIL FIELD
(PHOTOGEOLOGICAL INTERPRETATION)

FIGURE 27



southward dipping flank of the subsurface part of the anticline. The seismic profile of the same well (No. 16) suggests that the crestal region of the deep part of the structure lies to the south of the surface anticlinal crest. This is contrary to the evidence obtained from dipmeter records, which indicates that the subsurface axis is displaced to the north. However, in both cases, the data suggest that any axis older than Middle Cretaceous must be disharmonius with the axis of the surface structure.

A major unconformity occurs between the Lower Cretaceous and Middle Jurassic. The Upper Jurassic is completely missing in Ain Zalah and Butmah. This indicates that the areas emerged above sea level and underwent extensive erosion. It is thought that the emergence was due to block movement rather than fold deformation. The block might be terminated by a fault to the north-east of the two structures, where Upper Jurassic and Lower Cretaceous sedimentation continued in a basin to the north and east of this fault.

The present structure of Ain Zalah is interpreted as being the result of two phases of fault-block movement during the Late Cretaceous, upon which the late Tertiary folding was superimposed, (Hart and Hay, 1974).

7.1.3 Fracture Trace Analysis of Ain Zalah Field

Three different approaches to the fracture trace analysis of Ain Zalah were adopted. These approaches differ basically in the way in which the air photographs were viewed and interpreted for fracture traces. First, a stapled photomosiac of the whole Ain Zalah structure was interpreted with the unaided eye. Secondly, interpretation was carried out on individual air photographs, which were examined as stereopairs under low power stereoscopy. Thirdly, the same sets of photographs were interpreted again with the stereoscope, this time using high power magnification. The interpreted fracture traces were mapped on transparent overlays of clear acetate material. The overlays of each method of interpretation were assembled separately on a base map of the scale 1/20,000, which is approximately the same scale as that of air photographs. Control points and features were used to locate and adjust the fracture traces into their corresponding positions on the base map. As a result of the compilation, three fracture trace maps were produced. Each one represented a method of interpretation. They obviously differ from each other in the number and sizes of fracture traces. The object of these approaches was to learn about the advantages and disadvantages of each method of interpretation, and the degree of similarity or discrepancy between their final results. It was also hoped to throw light on the effects of photo-viewing techniques on the interpretation of fracture traces.

In Ain Zalah area, erosion and weathering have had a pronounced influence on the bed rock, so much so that the Lower Fars rocks have been extensively affected. Most drainage networks and the pattern of the bed outcrops clearly indicate the fracture system in the area. The differential resistance to erosion exhibited by different types of rocks such as limestone, anhydrite and marls, has resulted in linear topographic features that served as a useful criteria in fracture interpretation. Additional care had to be taken to detect fractures which strike parallel or sub-parallel to the bedding.

It was important, when this inquiry was under way, to outline a number of questions concerning the structural characteristics of Ain Zalah field in so far as they were related to fracture trace analysis, and to direct the study towards reaching satisfactory answers the these questions. They are as follows:

1. The density and patterns of fracture traces and their relationship to structural divisions (i.e. domains) of the Ain Zalah anticlinal fold.
2. The structural relationship between fracture traces and possible subsurface structures.
3. The question of the directional characteristics of the reservoir fracture system inferred from fracture trace azimuth analysis.
4. The influence of the lithology and thickness of the beds on the frequency of fracture traces.
5. The anomalous pattern of fracture traces due to possible local structure.
6. To establish a stress model for the structure based on the analysis of fracture trace rose diagrams.

7.1.3.1. Field Work

Field work was carried out for the purpose of confirming and checking on the ground, fracture trace data which had been interpreted on air photographs. The fracture traces checked in the field, were regarded as samples representing, roughly, sets of fracture traces occurring in various parts of the structure. It was also intended to observe and document the joint system on the outcrops, and the structural as well as lithological characteristics of the bedrock in different parts of the anticline. A plan of traverses and observation points was tentatively outlined before the field work was started. During the field work, several traverses normal to the bedding strike and crossing the entire structure, were inspected. Separate observation stops on the plunges and a traverse along the axial region of the anticline were also surveyed. At each observation station, the appearance of fracture traces on air photographs were compared with their ground features in the field. Other features which may be associated with fracture traces on the ground, yet may not be seen on air photographs, such as bedding dislocation and water springs etc., were also checked. The joint systems and the types of rocks, along with dip and strike measurements were documented at each observation station.

The field observations have shown that the geomorphology of the terrain has been greatly influenced by the secondary structural characteristics of the bedrocks such as fracturing. Thus, most valleys and drainage networks prevalent within the structural confines of the anticline, tend to assume systematic patterns corresponding to those of the fracture traces and the joint systems of the bedrock. It was also noticeable, that most of the outcrops, especially those on the flanks of the anticline, exhibited "V" shaped rock-cuts, and in some places a continuous zig-zag line. No doubt, this feature can be related to a well-developed fracture system, which has strikes oblique to the E - W anticlinal axis.

Successive beds of limestone, anhydrite and marl are exposed on the surface of the anticline. These rocks are related to the Lower Fars Formation. The limestone is the most competent and fractured rock in this sequence, and its thickness varies from several centimeters to about 10 meters. A single limestone bed can easily be traced over a long distance particularly on the flanks of the anticline. Thus, the beds of limestone may offer good geological markers. The anhydrite rock tends to be thick and massive in some places. This rock is remarkably susceptible to erosion. Marl occurs sporadically and is very thinly bedded.

Two major joint systems were observed in the field. The first system was well-developed and frequently encountered. The joint sets of this system always strike obliquely to the regional bedding strike, that is, obliquely to the axis of the fold. The strike of these joint sets varies greatly, however, they can be represented as N 30° E to N 70° E and N 35° W to N 70° W. The dips of the joints measured in the field ranged from 45° to 80°, and their lengths from one meter to several meters. Generally, these joints tend to be straight and closed and are particularly prevalent on the flanks of the anticline. This system, thought to be a shear joint system, probably resulted from the compressive stress which has acted normal to the axis of the anticline. The second joint system is characterized by two principal sets. One set strikes E - W parallel to the bedding strike and fold axis, and the other set strikes almost N - S, perpendicular to the fold axis. The planes of these joints were vertical to the bedding surface. They were observed all over the structure, but more frequently on the axial region and near the plunging ends of the anticline. The joints tend to be comparatively short in size and less developed in comparison with the first system, i.e. the shear system. They are probably tension joints, resulting from secondary stress conditions.

In various parts of the anticline, small gravity faults were encountered. They were few, however, and restricted to the locality. In most cases, the rock movements along those fault planes were very small. Ground photographs displaying examples from the field work data are shown in the Appendix.

7.1.3.2 Analysis of Fracture Trace Maps

The concept of the classification of joints with reference to their characteristics such as shape and size, as well as their relationship with other structure can be applied appropriately to the fracture traces of this study.

A fracture trace set was defined as a number of parallel or sub-parallel fractures. Two or more fracture trace sets intersecting one another is a fracture trace system. A big fracture trace that extends over a relatively long distance, and may cut across another structure such as a fold, may be described as a master fracture trace. A fracture trace of medium size, and of evident structural significance, may be called a major fracture trace. A relatively small fracture trace which has no obvious structural importance and is restricted to a small bedrock unit may be called a minor fracture trace.

The association between fracture traces and fold structure is a common geological phenomenon. It is believed that specific stress conditions have contributed to the development and association of these structures. Thus, a dynamic classification for fracture traces, based on their geometrical relationship to the fold axis, and therefore indirectly related to deformative stress can be suggested. If a, b and c are the tectonic axes of a fold, of which a - axis is the direction of fold movement, b - axis is parallel to the fold axis, and c - axis is perpendicular to a and b, the fracture set which is parallel to the fold axis may be called the ab - set or longitudinal fracture traces. They are tension fractures probably caused by a release in compressive stress which acted perpendicularly to the fold axis. The fracture trace set perpendicular to the fold axis is the ac - set or cross fracture traces. They are also tension fractures, which are probably caused by an extension or a slight arching parallel to the fold axis. All other fracture traces that can not be related to the above mentioned sets have to be obliquely oriented to the fold axis. They are usually called oblique fracture traces. In mechanical terms, these two sets of oblique fractures intersecting one another, can be compared to a conjugate set of wrench faults, which have resulted directly from primary compressive stress. Thus, these oblique fracture traces are in fact, commonly shear fractures. It has been suggested that the majority of tension fractures may have developed as a result of secondary stress conditions which prevailed after the principle compressive force had taken effect. (De Sitter, 1964).

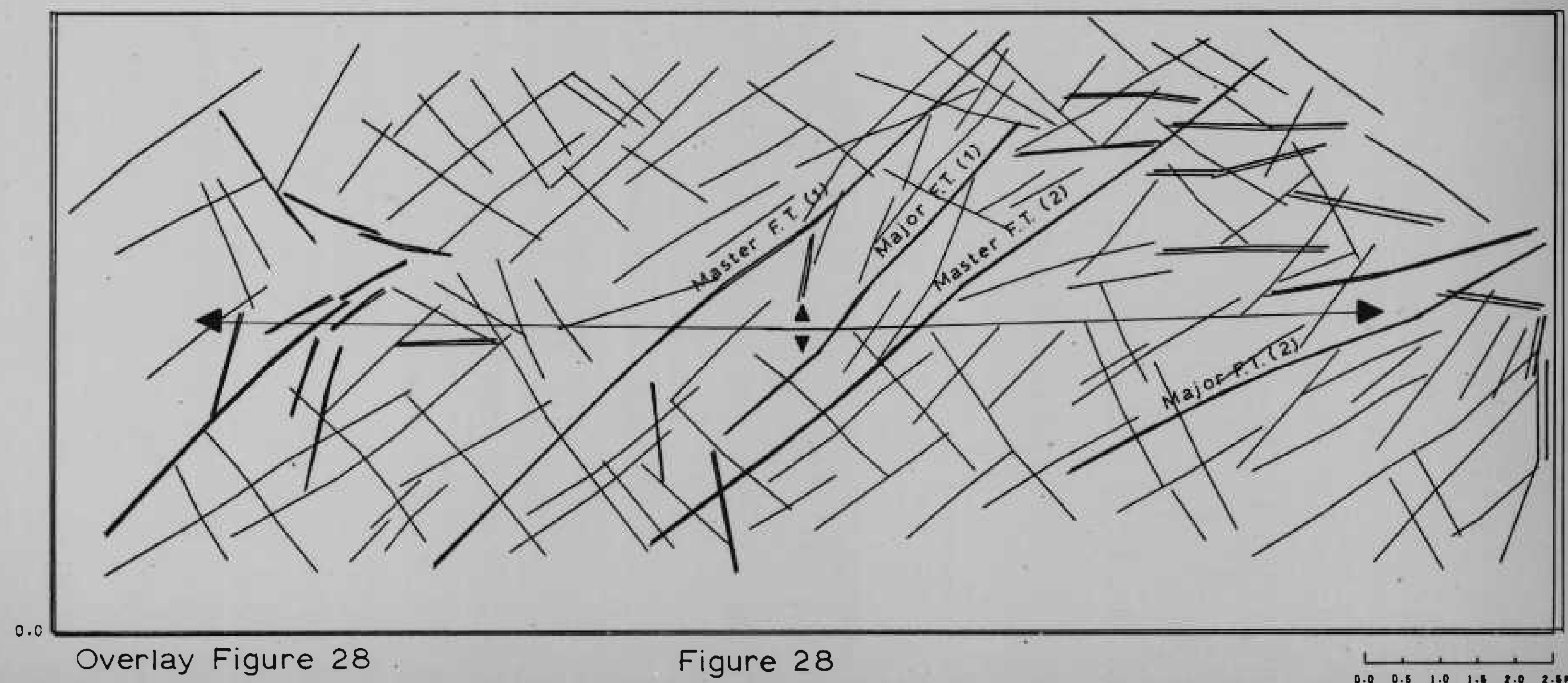
As stated earlier, three fracture trace maps were prepared, (Figures 28, 29, 30). The maps were initially made by compiling the interpreted fracture traces onto base maps. They were then digitized and redrawn by computer. For convenience of handling, they were reduced photographically to the present scale.

To attain a satisfactory result for this study and to assess the value of each method of interpretation, the fracture trace maps will be discussed below separately.

A - Photomosaic fracture trace map (Figure 28)

This map shows fracture traces which were interpreted on the photomosaic with the unaided eye. The general characteristics of the fracture traces on this map and their relationship to the structural division of the anticline can be outlined by the following points.

FRACTURE TRACE MAP OF AIN-ZALAH OIL FIELD
(PHOTOMOZAIC INTERPRETATION)



Overlay Figure 28

Figure 28

FRACTURE TRACE MAP OF AIN-ZALAH OIL FIELD
(PHOTOMOZAIC INTERPRETATION)

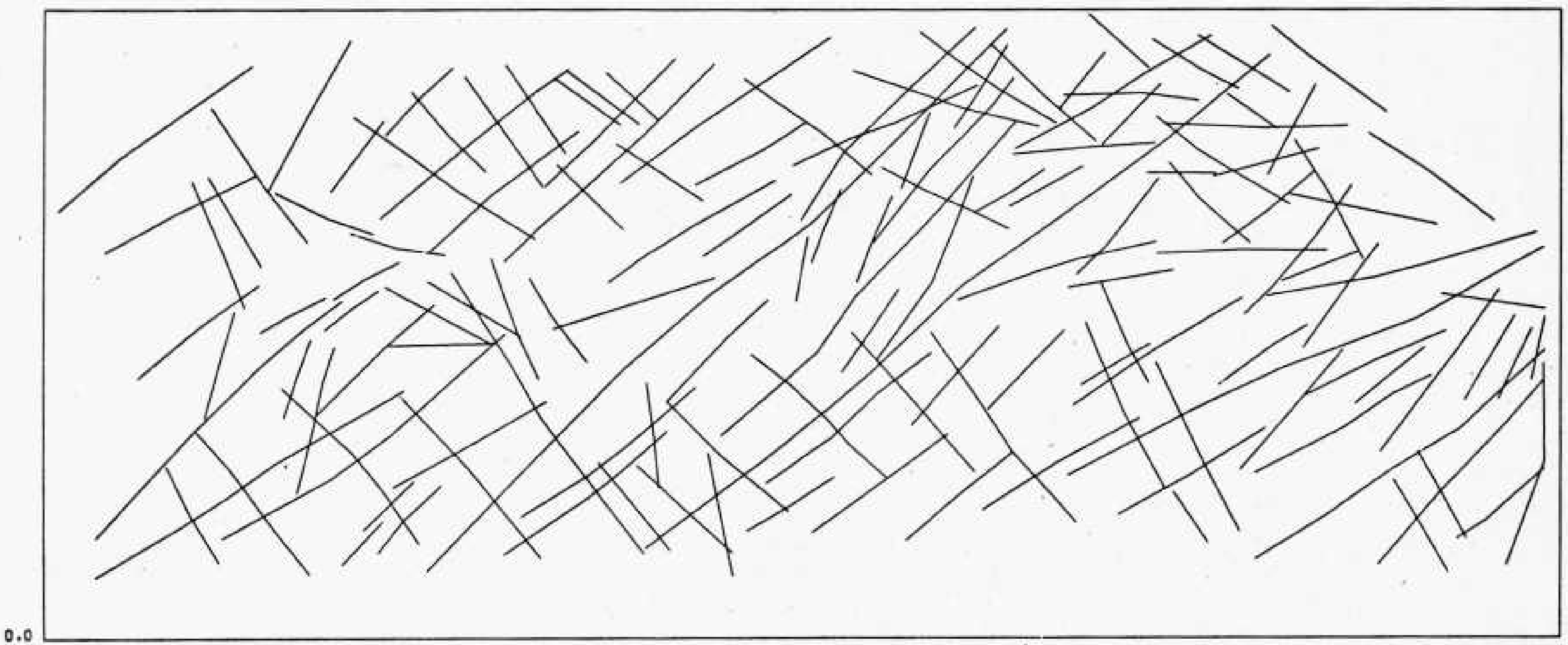


Figure 28

1. The south flank of the anticline shows a relatively high density of shear (i.e. oblique) fracture traces in comparison with the northern flank. The fractures of this flank, in general, tend to be longer and frequent, particularly those of a NE orientation. There are very few tension fracture traces i.e. fractures parallel or perpendicular to the fold axis, on the south flank. Only two small fracture traces striking almost N - S can be seen in the centre of this flank. The northern flank shows more tension fracture traces. They strike almost E - W, (Overlay Figure 28).

The axial region of the anticline shows an obvious low density of fracture traces in comparison with the flanks of the anticline. A few fracture traces striking almost parallel to the fold axis are to be seen in the region. The tension fracture traces generally appear to be shorter than most shear fracture traces in this map.

2. In the west, the fracture traces assume a particular pattern tending to bifurcate at a point on the axial line, and the orientation of the fracture traces appear to swing to the NW and SW, as they approach the western limit of the anticline (Overlay Figure 28). There are a few fracture traces striking almost N - S. They are probably tension fracture traces. The traces on the eastern end show no particular pattern, but they have a tendency to strike sub-parallel to the fold axis.

3. There are two master fracture traces striking SW - NE, (i.e. obliquely to the fold axis) and crossing the anticline diagonally. Two major fracture traces also appear, one in the eastern part of the anticline with an ENE orientation, and the second occurs between the master fracture traces, and strikes NE. (Overlay Figure 28).

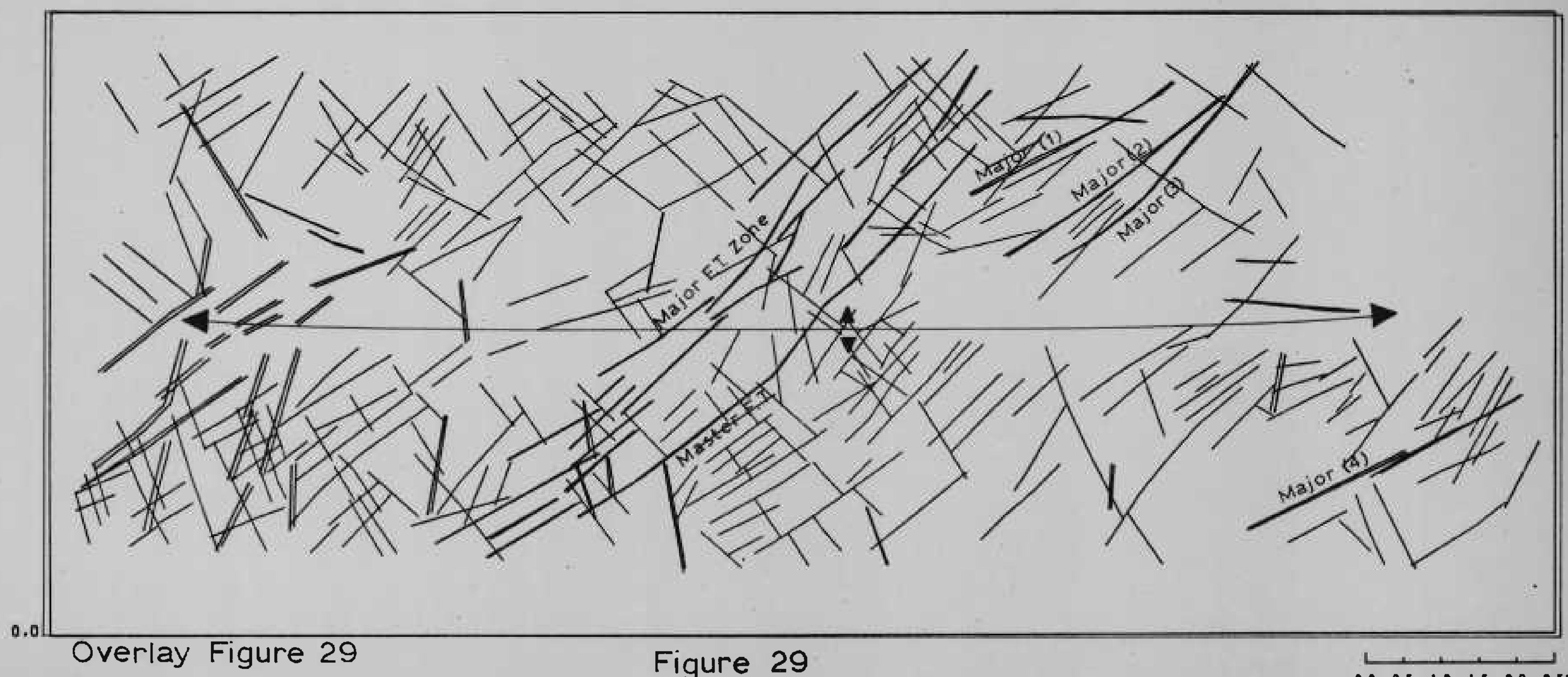
B - <u>Low power stereoscopic fracture trace map</u> (Figure 29)

The fracture traces of this map are the result of the low power (x 2) stereoscopic examination of photographs. The characteristics of the map can be described as follows:-

1. The density of the fracture traces on the southern flank, particularly towards the western part of the flank, is noticeably higher in comparison with the northern flank. Those shear fracture traces striking NE are prevalent and more developed than the fractures of other orientations. A few short tension fracture traces, striking almost N - S are scattered along the southern flank, while on the northern flank there is one tension fracture striking E - W, (Overlay Figure 29)

2. The map shows a few fracture traces along the axial region, particularly in the eastern part of the region, where the fracture traces are almost non-existent. Those which occur along this zone are generally short, and strike almost parallel to the fold axis, (i.e. they are tension fracture traces).

FRACTURE TRACE MAP OF AIN-ZALAH OIL FIELD
(L.P. STEREOSCOPIC INTERPRETATION)



Overlay Figure 29

Figure 29

FRACTURE TRACE MAP OF AIN-ZALAH OIL FIELD

(L.P. STEREOSCOPIC INTERPRETATION)

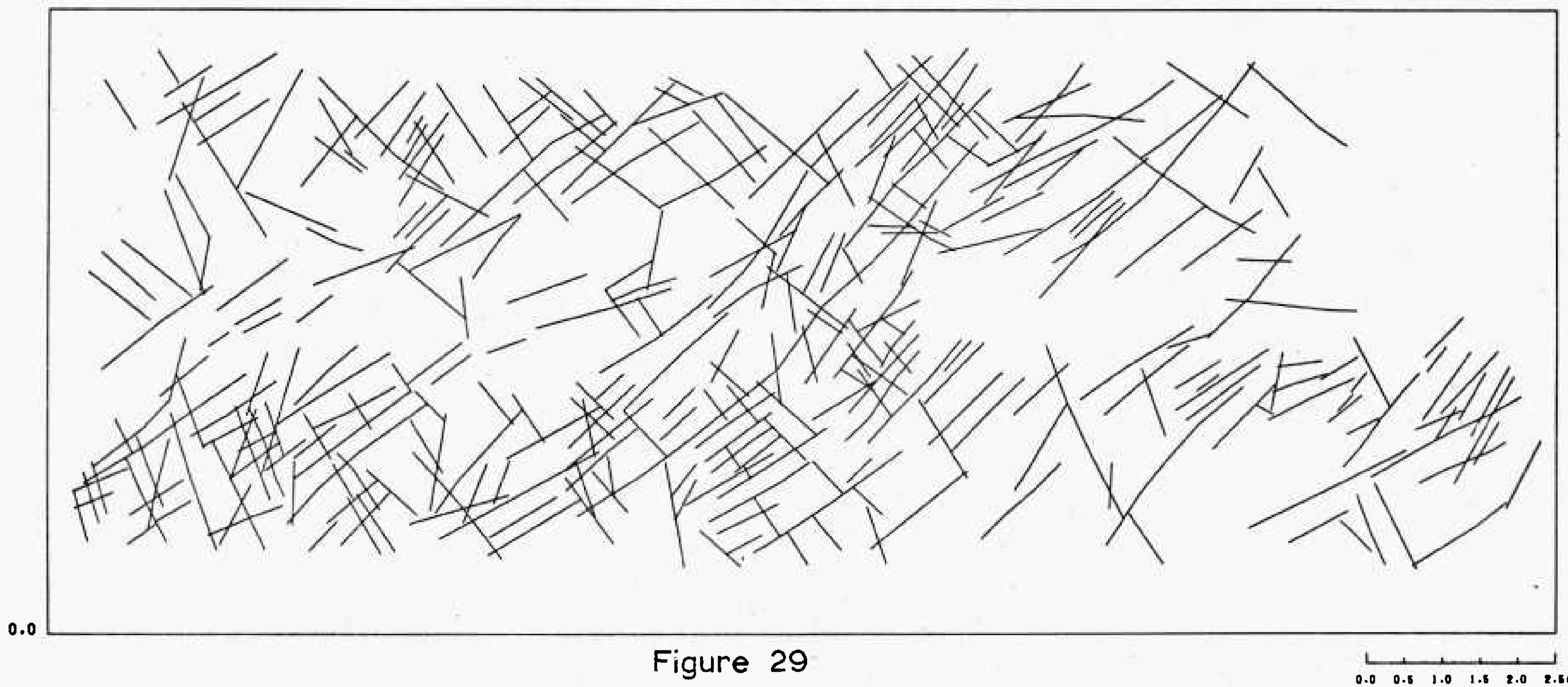


Figure 29

3. In the central part of the map, there is a master fracture trace which strikes NE and crosses the anticline obliquely. There is also a zone of shorter fracture traces which runs parallel to the master fracture and crosses the anticline. Three major fracture traces occur in the northern flank striking NE. One is on the southern flank with an azimuth ENE, (Overlay, Figure 29). The master amd major fracture traces are comparable with those which are shown on the photomosaic fracture map, (Figure 28).

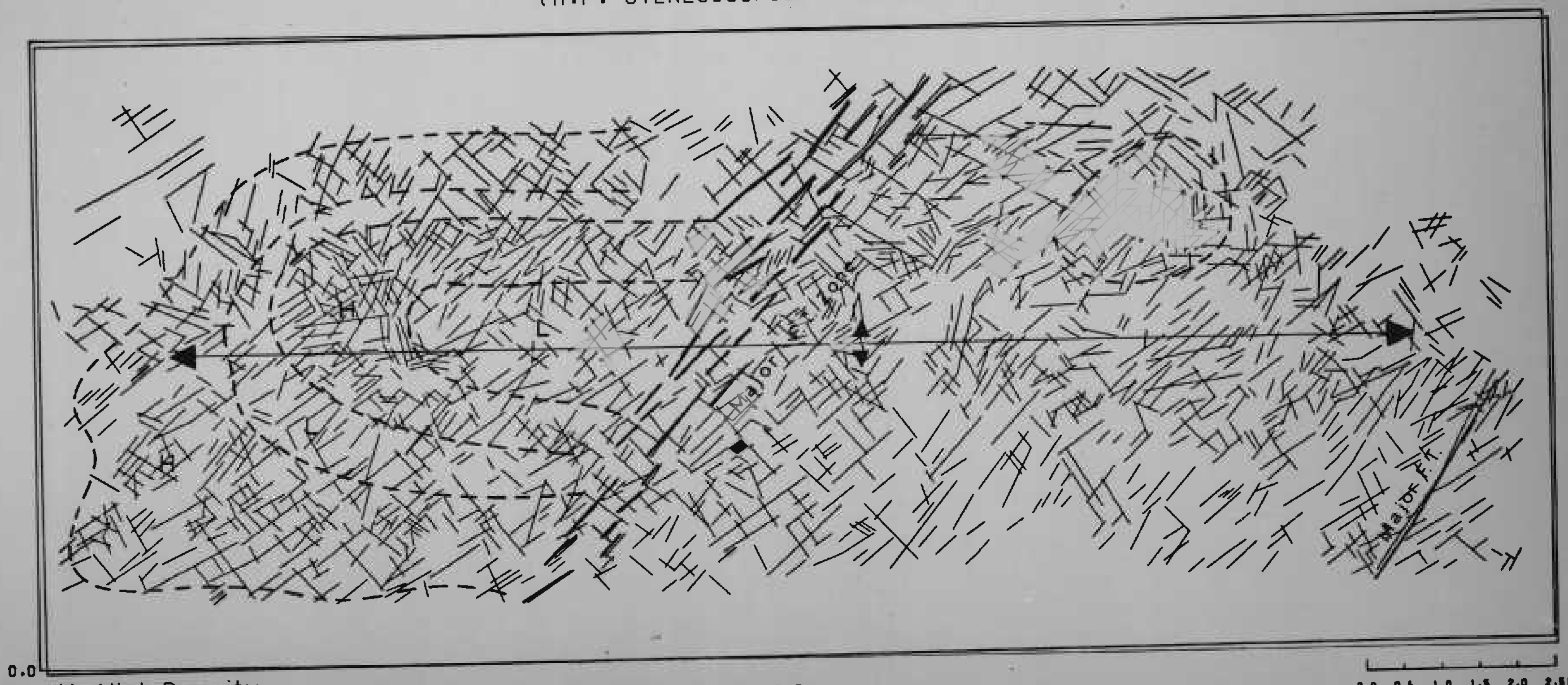
4. At the Western end of the anticline, the fracture traces show a tendency to diverge from an almost E - W orientation in the axial region to the NW and SW as they approach towards the Western confines of the anticline, (Overlay, Figure 29). This feature was observed in the photomosaic fracture map (Figure 28).

5. The overall feature of the fracture trace distribution of the map shows that a distinct high density of fracture traces occurs in the western half of the map, i.e. in the western half of the anticline. This feature will receive special attention during the structural conclusions further on.

C - <u>High power stereoscopic fracture trace map</u> (Figure 30)

This map is a result of the stereoscopic interpretation of air photographs throughout which high-power

FRACTURE TRACE MAP OF AIN-ZALAH OIL FIELD
(H.P. STEREOSCOPIC. INTERPRETATION)



H - High Density
L - Low Density

Overlay Figure 30

Figure 30

FRACTURE TRACE MAP OF AIN-ZALAH OIL FIELD
(H.P. STEREOSCOPIC.INTERPRETATION)

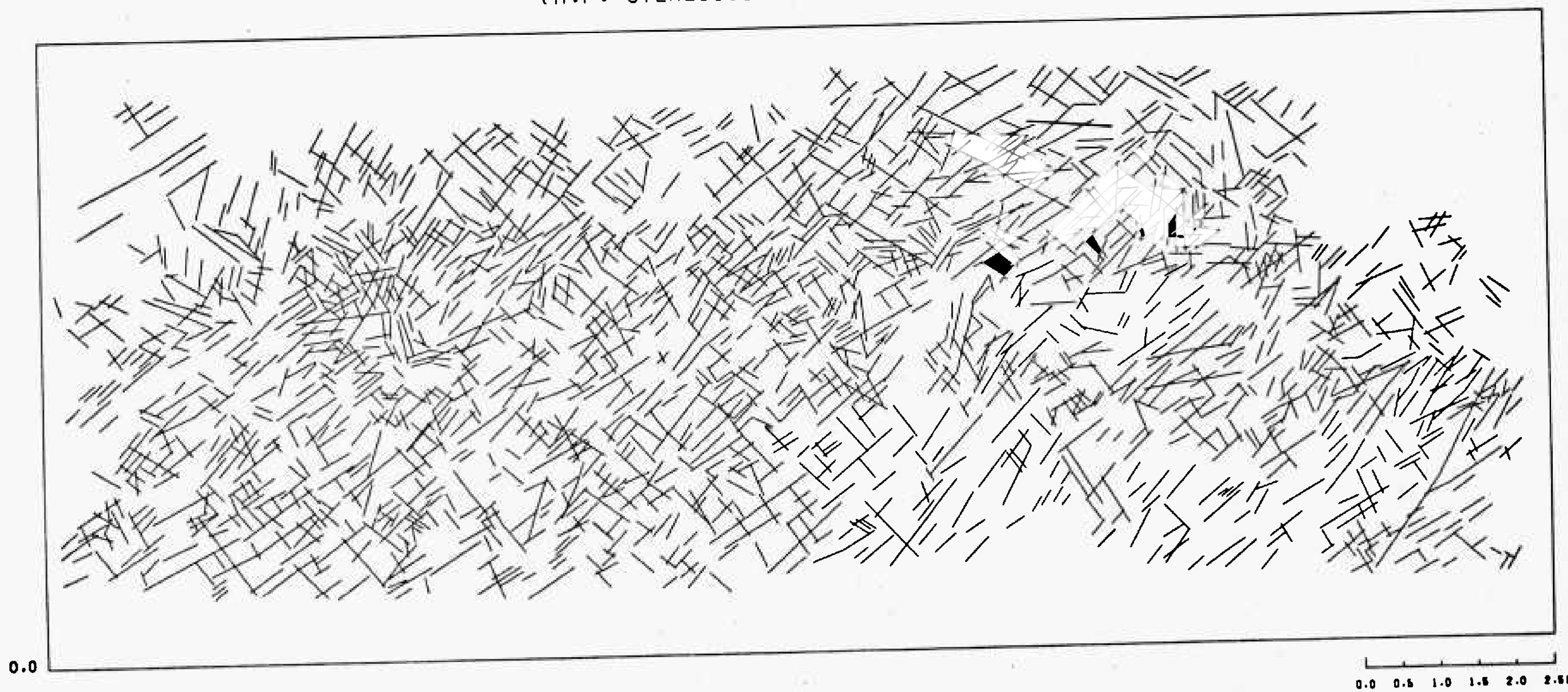


Figure 30

(x 4) magnification was used. The general characteristics of this map can be described as follows:-

1. The relative size of fracture traces exhibited by this map, is the most striking feature by which the map differs from the other two fracture trace maps. Except for a few exceptions, the majority of the fracture traces can be regarded as minor. One relatively large fracture trace appears in the eastern end of the anticline.

Small minor fracture traces are usually regarded as being caused by relatively shallow breaks in bedrocks, and most of them may be restricted to a single stratum. Thus, it is reasonable to believe that the lithological characteristics and the thickness of the beds may have an appreciable influence on the distribution and frequency of the minor fracture traces.

2. In the western part of the map, two distinct belts of relatively high fracture trace density can be observed, (Overlay, Figure 30). Such feature traces may indicate a difference in the physical properties of the bedrocks, and may be related to the type of rock in the case of this study. The outcrops of beds in the Ain Zalah anticline consist mainly of alternating beds of limestone and anhydrite. Limestone is, on the whole, the most competent and fractured rock of the anticline.

3. In the north eastern part of the map, there is a noticeable circular zone of fracture trace con-

centration. In this zone there is a well-defined tension system of two fracture sets striking N - S and E - W. There are also two sets of shear fractures with azimuths NE and NW, (Overlay, Figure 30).

4. There is a linear zone of sub-parallel shear fracture traces running SW - NE, and crossing the anticline obliquely. This zone is comparable with similar feature traces encountered in the previous fracture trace maps.

5. The frequency of tension fracture traces in this map is comparatively higher than in the fracture trace maps previously mentioned. The tension fracture traces parallel to the anticlinal axis, i.e. the ab - set, appear to be relatively longer and more frequent than those normal to the anticlinal axis, i.e. the ac - set. This is particularly evident in the eastern part of the map.

6. On close examination of the map, it appears, that the occurrence of fracture traces in the western half is relatively greater than that in the eastern half of the map. A similar feature has already been noted in the low power stereoscopic fracture trace map. The map also shows, that the frequency of fracture traces along the axial region of the anticline is comparatively low. It can be noticed, that the western part of the south flank exhibits more fracture traces than the corresponding part of the northern flank.

7.1.3.3 Analysis of fracture trace directional distribution

For each fracture trace map previously mentioned, there are three types of rose diagrams as follows:-

1. The directional frequency rose diagram, or simply the frequency rose diagram.
2. The directional length distribution rose diagram, or the directional density rose diagram.
3. The directional average length rose diagram, or the directional average density rose diagram.

The directional analysis of fracture traces concerning each fracture trace map for the whole of the Ain Zalah structure now follows.

A - Directional analysis of photomosaic fracture traces (Figure 31)

There are 143 fracture traces involved in this analysis. Their directional distribution is expressed in the following rose diagrams.

1. Frequency rose diagram (Figure 31a)

This rose diagram depicts a directional distribution of the number frequency of fracture traces per azimuth interval of 10 degrees. There are two distinct rose-maxima with orientations N 45°W and N 55° E. The right hand maximum is relatively longer (primary) than the left hand maximum (secondary). Since the axis of Ain Zalah anticline strikes east-west, the maxima represent two sets of shear

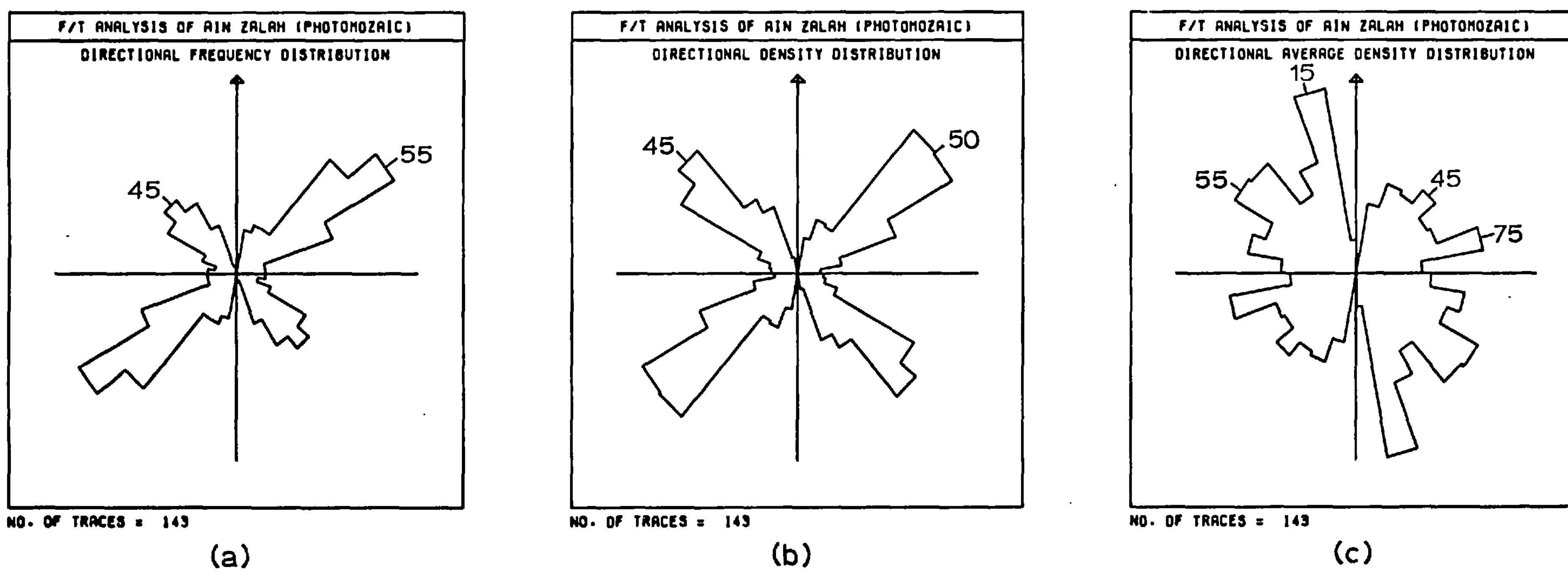

F/T ANALYSIS OF AIN ZALAH (PHOTOMOZAIC)
DIRECTIONAL FREQUENCY DISTRIBUTION
45
55
NO. OF TRACES = 143
(a)
F/T ANALYSIS OF AIN ZALAH (PHOTOMOZAIC)
DIRECTIONAL DENSITY DISTRIBUTION
45
50
NO. OF TRACES = 143
(b)
F/T ANALYSIS OF AIN ZALAH (PHOTOMOZAIC)
DIRECTIONAL AVERAGE DENSITY DISTRIBUTION
15
55
45
75
NO. OF TRACES = 143
(c)

Figure 31

fracture traces obliquely oriented to the fold axis. The minima of the rose diagram can clearly be seen along the axes of the diagram, i.e. in the N - S and E - W directions. The east-west rose-minimum indicates that a small percentage of fracture traces strike parallel to the fold axis, while the north-south minimum in this diagram shows almost no fracture traces with a N - S azimuth. These minima represent the frequency of tension fracture traces in the photomosaic fracture trace map.

2. Density rose diagram (Figure 31b)

This rose diagram shows the directional distribution of the length frequency of fracture traces. There are two diagonal rose-maxima, the right-hand maximum is primary, with an orientation of N 50° E and the left-hand maximum is secondary, with an azimuth of N 45° W. Both maxima are oblique to the fold axis and related to the shear fracture traces. The manifestation of the rose-minima is almost similar to that of the frequency rose diagram. They show the scarcity of the tension fracture traces in the map.

3. Average density rose diagram (Figure 31c)

This type of rose diagram depicts the directional distribution of the average lengths of fracture traces. Four rose-maxima can easily be seen in the diagram. Two of them are significant in so far as they display new orientations along which the previous rose diagrams show no maxima. The azimuths of these rose-maxima are N 15° W and N 75° E. They represent fracture traces which are numerically few and relatively short, so that they were obscured by other fracture traces and not clearly represented in both the frequency and density rose diagrams. The other two maxima are relatively short. Their azimuths are N 55° W and N 45°E. They represent fracture traces some of which are long, but which are on the whole less frequent than the other fracture traces, so that they were not represented as maxima in previous rose diagrams.

B - Directional analysis of low-power stereoscopic fracture traces (Figure 32)

The total number of fracture traces involved in this analysis is 321. They are shown on the low-power stereoscopic fracture map.

1. Frequency rose diagram (Figure 32a)

In this diagram there are two rose-maxima which have different lengths. The longer maximum (i.e the primary) has an azimuth of N 55° E and the shorter maximum (i.e the secondary) has an orientation of N 35° W. According to their orientation the maxima appear to be related to shear fracture traces.

The minima of the rose diagram are in the directions of N - S and E - W. They indicate that fracture traces with these orientations (the tension direction) are very few.

2. Density rose diagram (Figure 32b)

In this diagram there are two maxima of different lengths. The azimuth of the long one is N 55° E, and the azimuth of the short one is N 40° W. They represent the

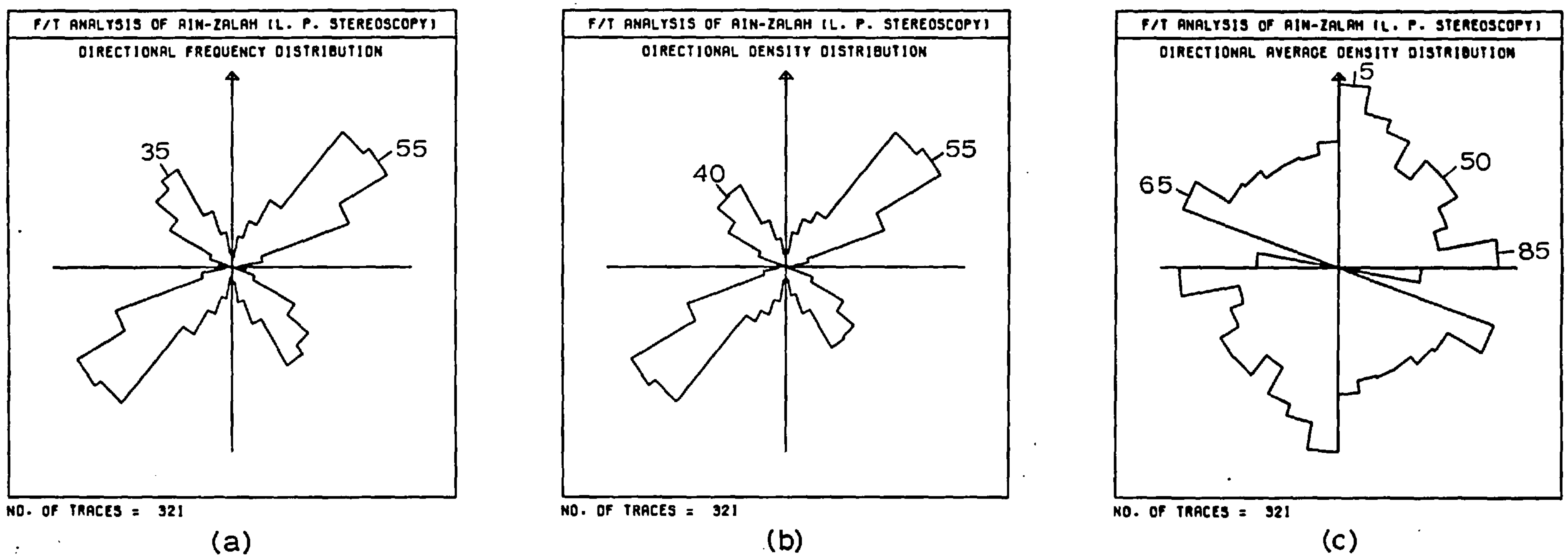

F/T ANALYSIS OF AIN-ZALAH (L. P. STEREOSCOPY)
DIRECTIONAL FREQUENCY DISTRIBUTION
35
55
NO. OF TRACES = 321
(a)
F/T ANALYSIS OF AIN-ZALAH (L. P. STEREOSCOPY)
DIRECTIONAL DENSITY DISTRIBUTION
40
55
NO. OF TRACES = 321
(b)
F/T ANALYSIS OF AIN-ZALAH (L. P. STEREOSCOPY)
DIRECTIONAL AVERAGE DENSITY DISTRIBUTION
5
50
65
85
NO. OF TRACES = 321
(c)

Figure 32

length frequency of the fracture traces with shear directions. The rose-minima are almost identical with those of the frequency rose diagram (Figure 32a). They are related to fracture traces in the tension directions.

3. Average density rose diagram (Figure 32c)

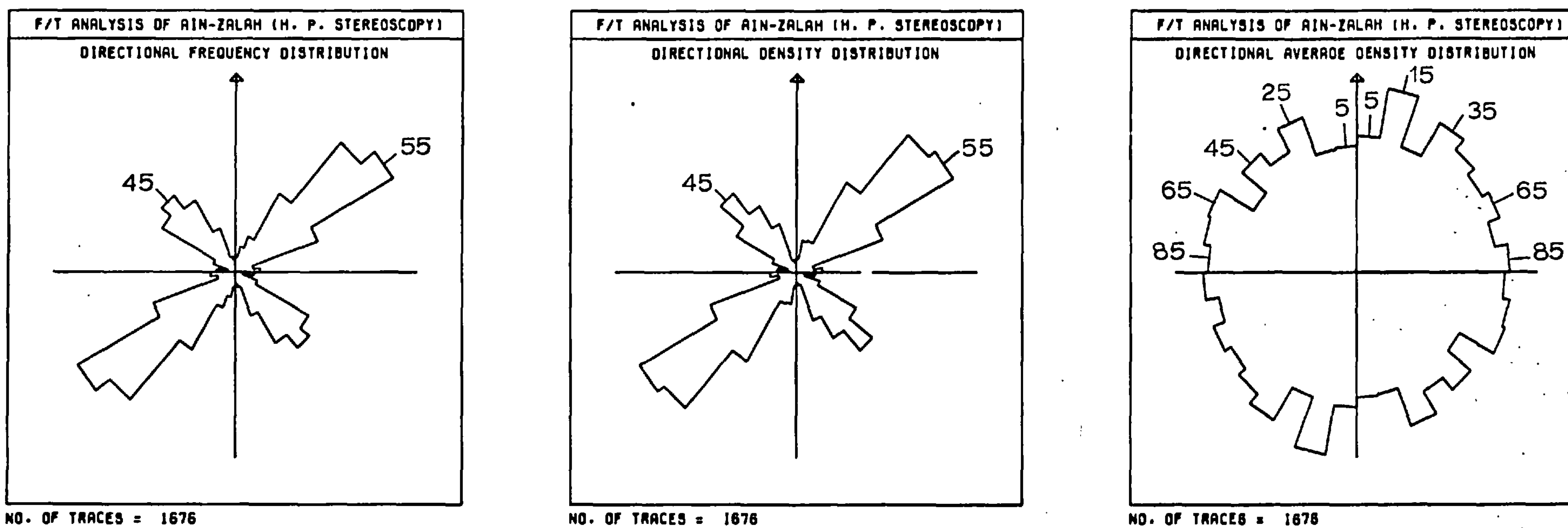
Four rose-maxima can be seen in this diagram. The azimuth of two of them are N 5° E and N 85° E. They are probably related to tension fracture traces which are numerically very few in the map and also short in comparison with shear fracture traces. The azimuth of the other maxima are N 65° W and N 50° E. These maxima represent shear direction fracture traces which tend to be relatively long and less frequent than other shear fracture traces in the map.

C - Directional analysis of high-power stereoscopic fracture traces (Figure 33)

The fracture traces of this analysis are shown on the high-power stereoscopic fracture map and their total number is 1676.

1. Frequency rose diagram (Figure 33a)

This diagram is made up of two maxima of the azimuths N 45° W, (secondary), and N 55° E (primary). These depict the orientation of the predominant frequency of shear fracture traces in the map. The tension fracture traces are represented by the minima which appear in the N - S and E - W directions. They show clearly that tension fractures



(a) (b) (c)

Figure 33

are very few in this map.

2. <u>Density rose diagram</u> (Figure 33b)

The maxima and minima of this diagram have similar characteristics to those of the frequency rose diagram (Figure 33a). The azimuths of the maxima are N 45° W (secondary) and N 55° E (primary). The rose-minima have the orientation N - S and E - W.

3. <u>Average density rose diagram</u> (Figure 33c)

This rose diagram shows several maxima and minima, which may be grouped on the basis of their relationship to the tension and shear fracture traces. First, the azimuths of the maxima and minima which may be related to tension fractures are N 85° W, N 5° W, N 5° E, N 15° E and N 85° E. Secondly, the azimuths of the maxima which may be related to shear fractures are N 65° W, N 45° W, N 25° W, N 35° E and N 65° E. However, the occurrence of some minor fractures can be attributed to local or secondary stress conditions rather than the principal compressive stress to which the development of the whole fold structure can be related. By comparing the azimuths of these maxima with their equivalents in frequency and density diagrams, we find that they were represented in those diagrams by small to very small rays. These maxima represent fracture traces which are relatively few in number but are comparatively long.

7.1.3.4 Analysis of fracture trace rosemaps

There are three types of rose maps for each fracture trace map. These are (a) a frequency rosemap, (b) a density rosemap and (c) an average density rosemap. All the rosemaps were produced by a computer. Each type will be discussed separately as follows:-

A - Fracture trace frequency rosemaps (Figures 34a, 34b, 34c)

There are three frequency rosemaps, one for each fracture trace map. These rosemaps depict the directional distribution of the number frequency of fracture traces. On a careful examination of these maps one may discover the following characteristics:-

1. As a general characteristic, most rosette maxima are obliquely oriented to the E - W anticlinal axis. Since these maxima represent shear sets, it is reasonable to conclude that the shear fracture sets are the most prevalent in fracture trace maps. Among the oblique maxima, the NE maxima tend to be the longest (i.e. primary) as well as more frequent than the others.

2. Rosettes with rays of azimuths E - W and/or N - S, or near these azimuths, can be observed in the frequency rosemaps. In the eastern and north-eastern parts of the map (Figure 34a) E - W rays can be seen, while in the western part a number of rosettes with rays of azimuths near N - S can be seen. Few similar types of rays can be seen in other parts of

FRACTURE TRACE FREQUENCY ROSE MAP
AIN-ZALAH OIL FIELD
(PHOTOMOZAIC INTERPRETATION)

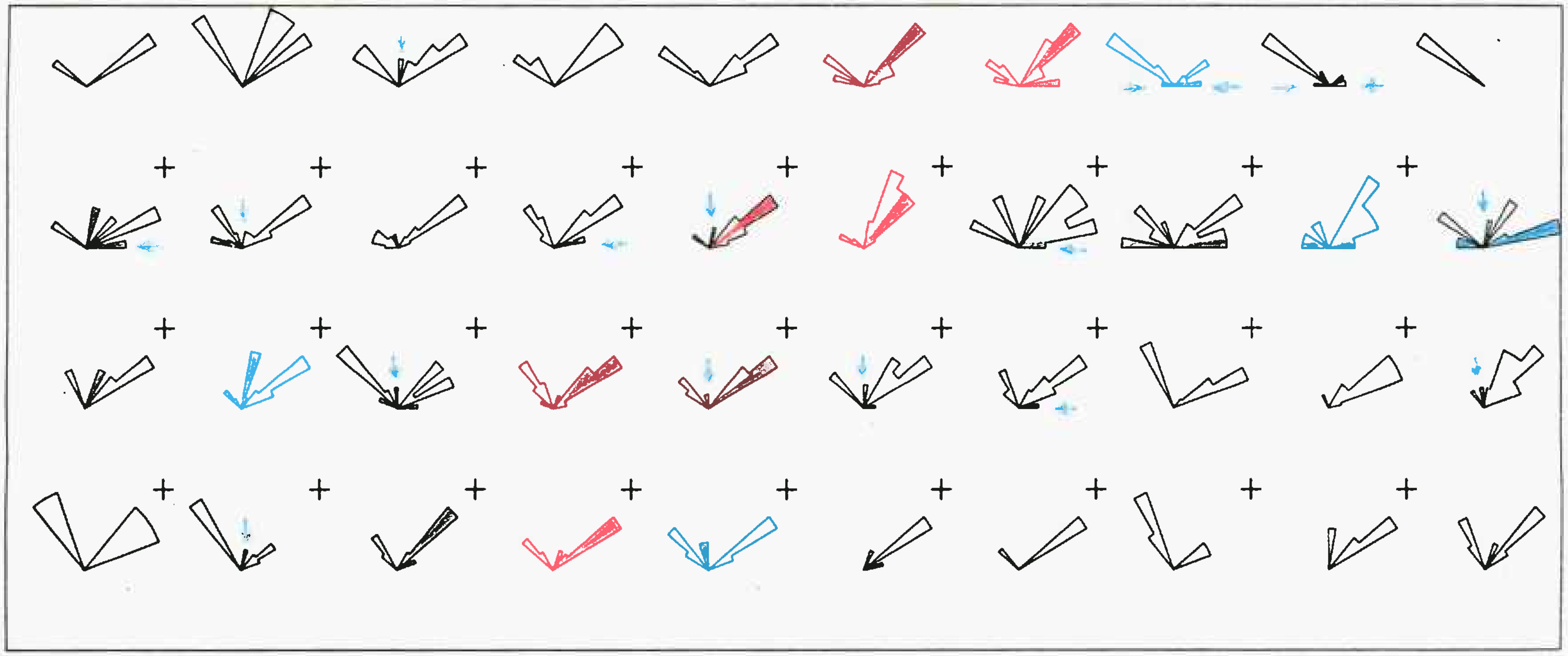


Figure 34a

FRACTURE TRACE FREQUENCY ROSE MAP
AIN-ZALAH OIL FIELD
(L. P. STEREOSCOPIC INTERPRETATION)

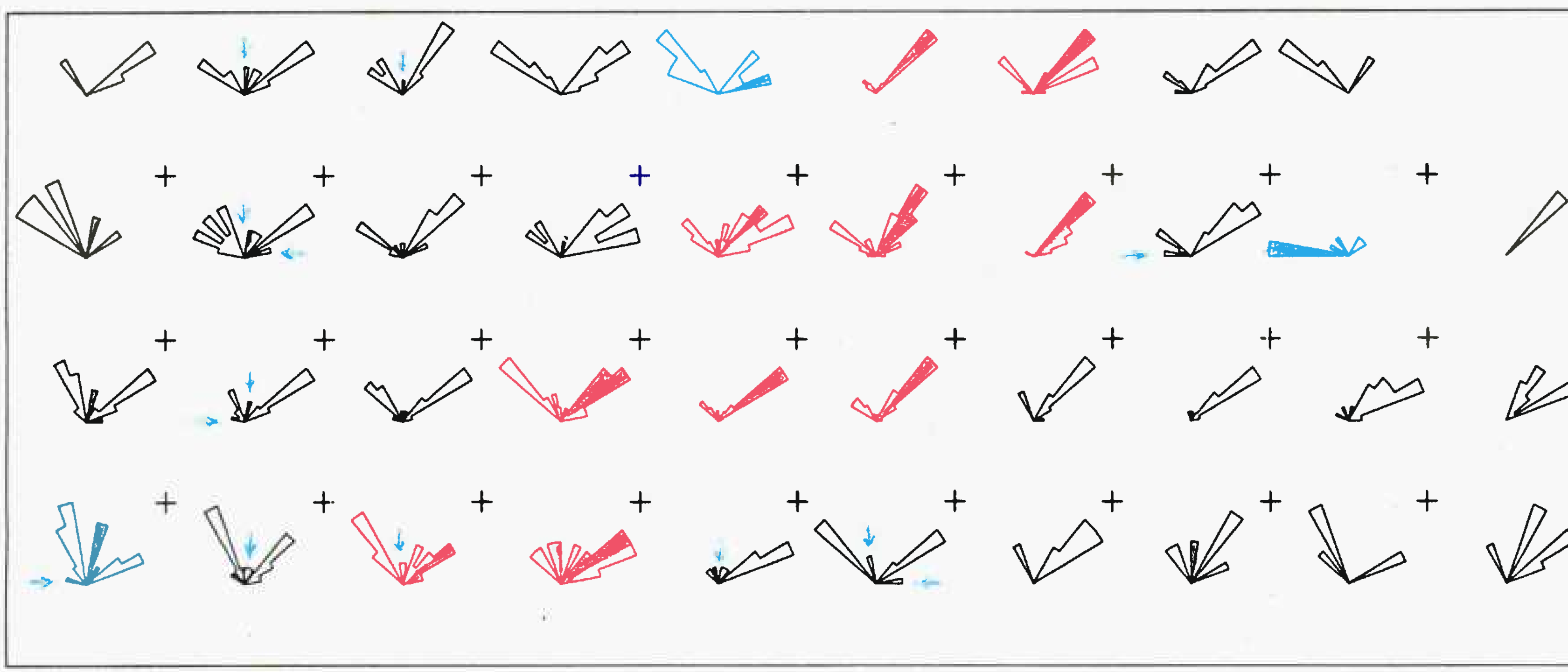


Figure 34b

FRACTURE TRACE FREQUENCY ROSE MAP
AIN-ZALAH OIL FIELD
(H. P. STEREOSCOPIC INTERPRETATION)

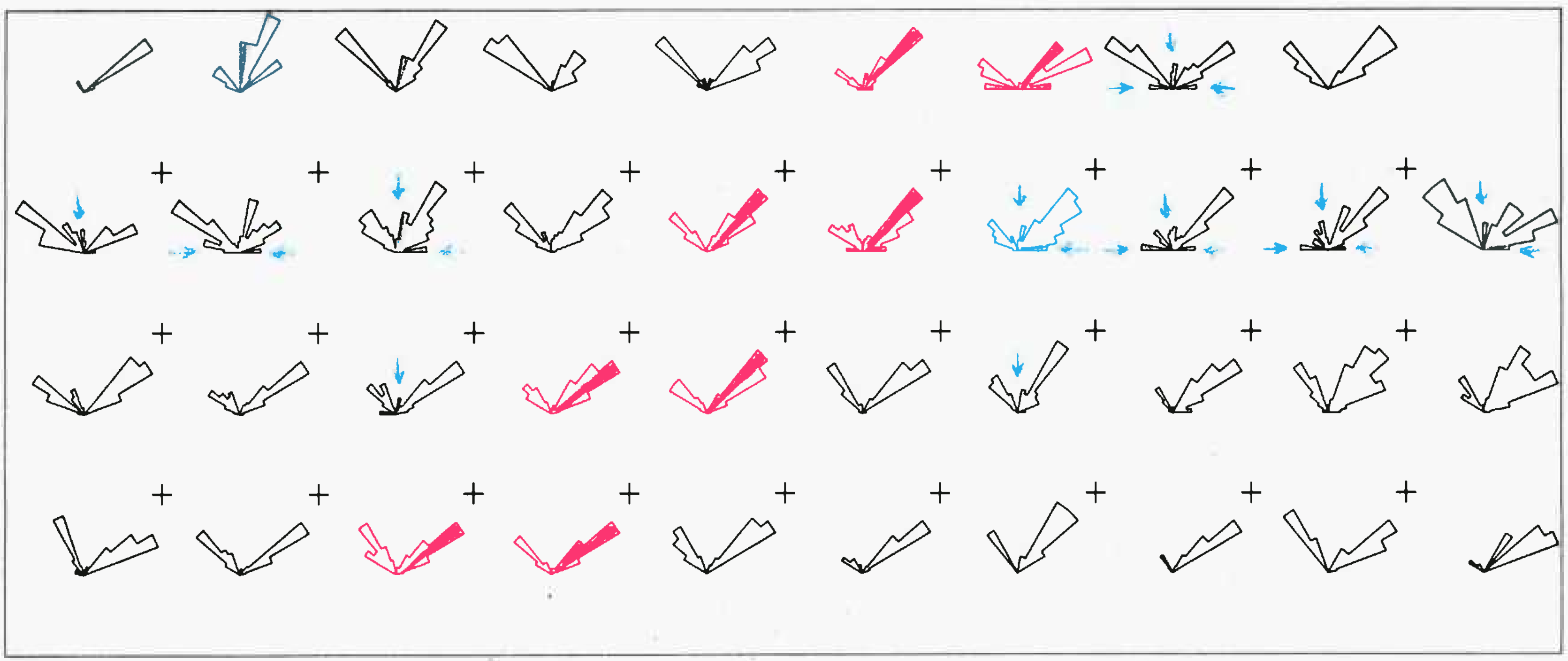


Figure 34c

the same map. All these rays are coloured in blue or indicated by small blue arrows.

The same classes of ray, (i.e E - W and N - S) can easily be seen in the frequency rosemaps (Figures 34b, 36c) with similar distribution characteristics. It was mentioned earlier that these rays can be related to tension fracture trace sets.

3. There are two oblique lines of rosettes in the rosemap (Figure 34a), crossing the central part of the map from SW to NE and characterized by two principle maxima; those on the right are relatively long and are consistently aligned in a NE direction. They are coloured in red. The rosemaps, (Figures 34b, 34c), exhibit almost the same feature. These maxima, indicate a zone of high frequency of fracture traces which crosses the Ain Zalah anticline in a NE direction, and was discovered during the study of the Ain Zalah fracture trace maps.

B - Fracture trace density rosemaps

These rosemaps (Figures 35a, 35b, 35c) display rosettes of the directional distribution of fracture trace lengths. There is a rosemap for each type of fracture trace map. Study of these rosemaps reveals the following points:-

1. The general characteristics of these rosemaps are comparable with those of the frequency rosemaps. The majority of the rosettes of these maps are either composed of two clusters of rays oblique to the axis of the anticline or the oblique rays represent the leading component

FRACTURE TRACE DENSITY ROSE MAP
AIN-ZALAH OIL FIELD
(PHOTOMOZAIC INTERPRETATION)

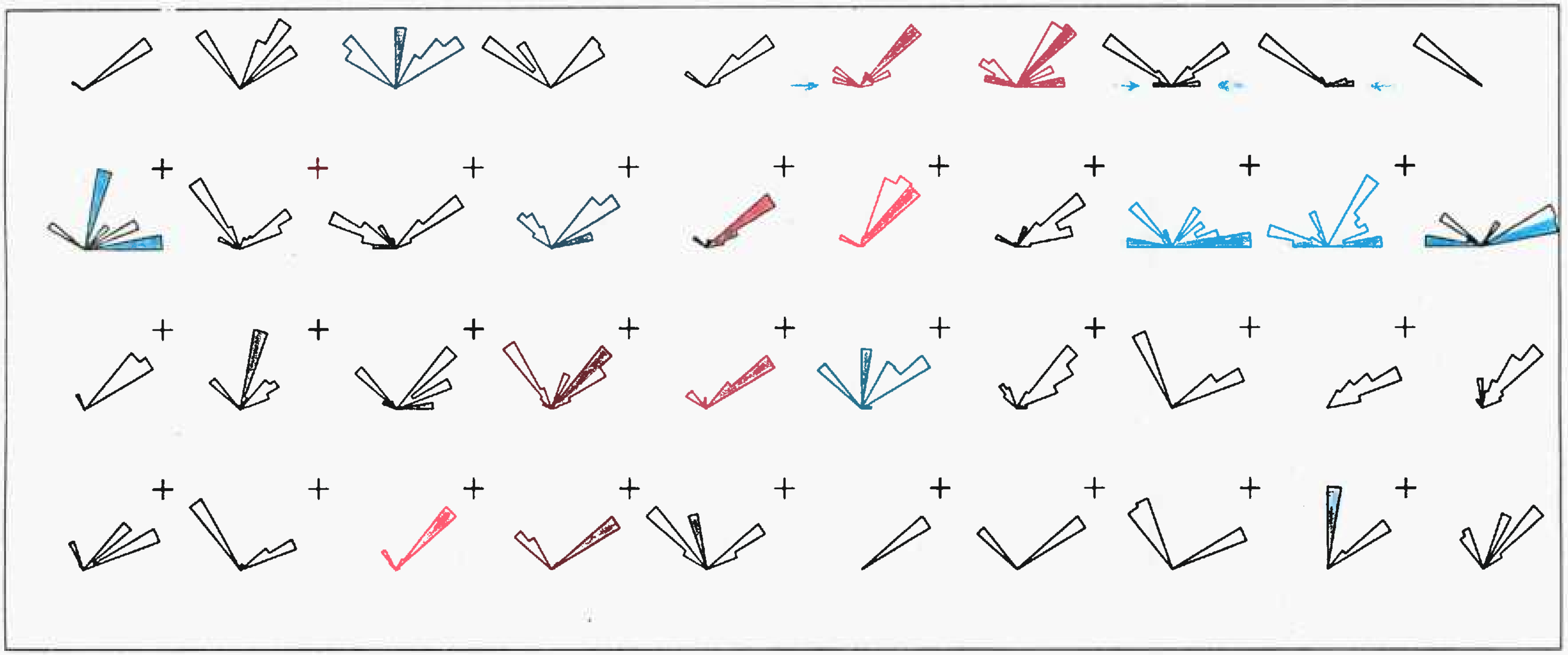


Figure 35 a

FRACTURE TRACE DENSITY ROSE MAP
AIN-ZALAH OIL FIELD
(L. P. STEREOSCOPIC INTERPRETATION)

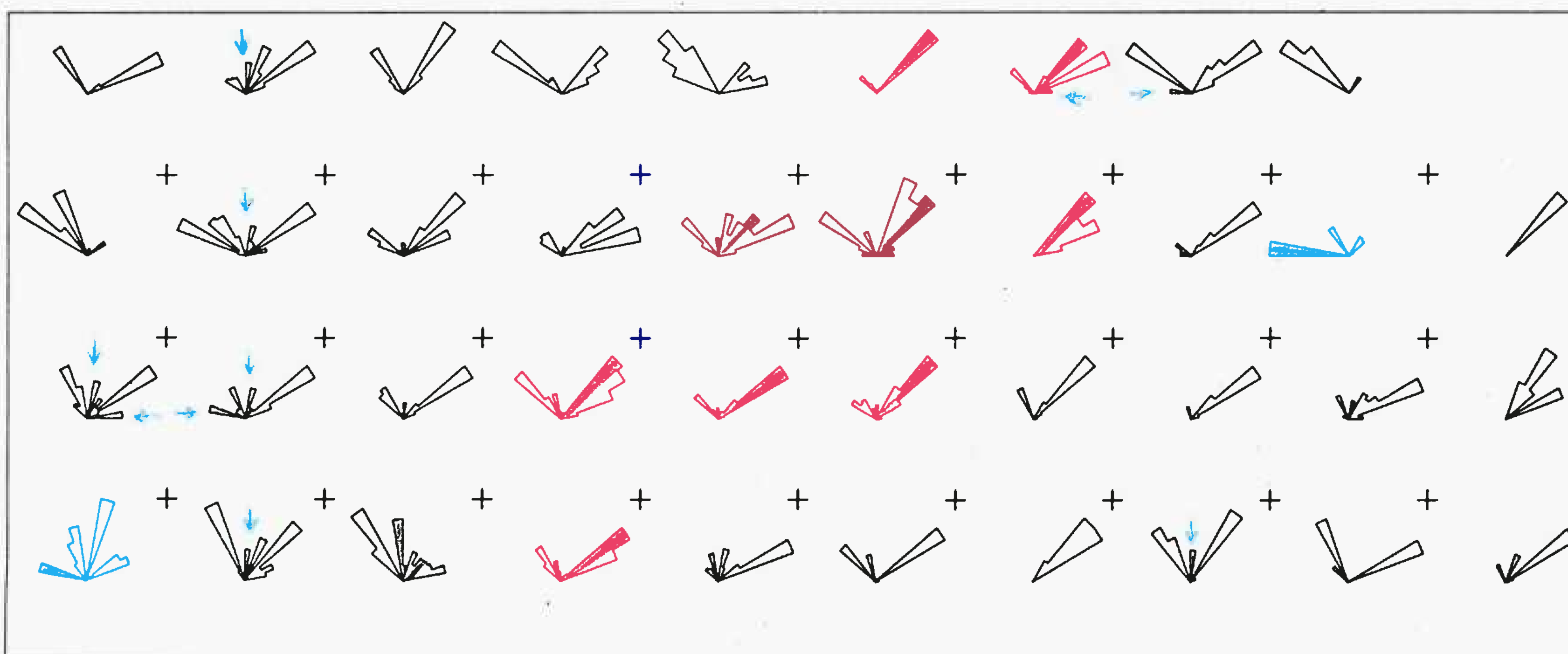


Figure 35b

FRACTURE TRACE DENSITY ROSE MAP
AIN-ZALAH OIL FIELD
(H. P. STEREOSCOPIC INTERPRETATION)

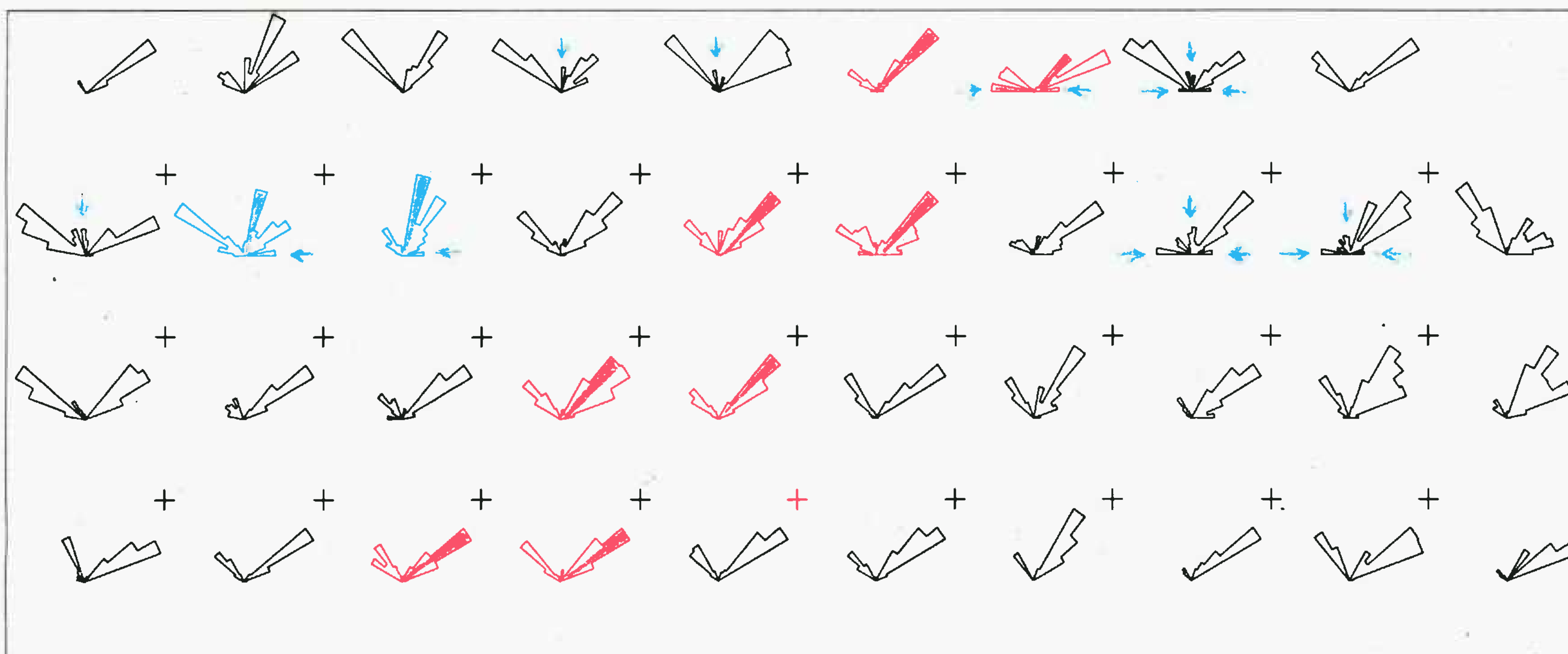


Figure 35c

of the rosette. This indicates that a great percentage of the fracture trace lengths fall in the directions oblique to the E - W orientation of the anticlinal axis.

It is also noticeable in the rosemaps that NE maxima are both frequent and longer in comparison with other oblique maxima. This shows that the fracture traces of a NE azimuth represent the dominant sets. It seems that the NE shear sets are the most developed fracture traces in the Ain Zalah structure.

2. Tension fracture traces are usually represented on the rosemaps by E - W and N - S rays, and are coloured in blue. In the eastern and north-eastern parts of the rose-map (Figure 35a), there are rays parallel or sub-parallel to the E - W direction, while in the west of the map, rather long N - S rays can be seen. However, there are few N - S and E - W rays eslewhere.

Similar features to those of the tension sets rays can be seen in the rosemaps Figures 35b and 35c . However, they are less clear here, particularly in the rosemap Figure 35b.

3. There are parallel lines of NE maxima, (coloured in red), crossing the rosemap obliquely (Figure 35a). The same feature is repeated in the rosemaps (Figures 35b, 35c) and it is comparable with that which has already been observed in the frequency rosemaps. These lines of NE maxima, indicate that a considerable percentage of fracture trace lengths fall in the direction of, and along the position of these lines of maxima in the fracture trace maps.

C - Fracture trace average density rosemaps

These rosemaps (Figures 36a, 36b, 36c), display rosettes which depict the directional distribution of average density, (i.e. the average length), of the fracture traces. For this study, the primary advantage of these rosemaps, is to show, in terms of maxima, those fracture trace sets which have been obscured on the fracture trace maps by the predominant fracture sets, due to their limited number and/or short lengths. In this case, the predominant sets are the shear i.e. oblique sets, while the obscured fracture traces are generally represented by the tension sets. These sets are usually depicted by the rays parallel or sub-parallel to the E - W and N - S directions. By examining the rosemaps we find the following characteristics:-

1. In the rosemap Figure 36a, the blue coloured rays are either parallel or sub-parallel to E - W and N - S directions. Several E - W rays can be seen in the eastern part of the map. They make two parallel lines extending from the eastern boundary to the central part of the rosemap. N - S rays tend to appear in the central and western part of the map. In the central part, three N - S rays are aligned in one trend extending from the southern boundary to the middle of the map. There are also two N - S rays in the south-West of the rosemap.

2. The rosemap Figure 36b shows remarkable N - S ray alignments in the east. There are two N - S alignments extending from the northern to the southern boundaries of the

FRACTURE TRACE AVERAGE DENSITY ROSE MAP
AIN-ZALAH OIL FIELD
(PHOTOMOZAIC INTERPRETATION)

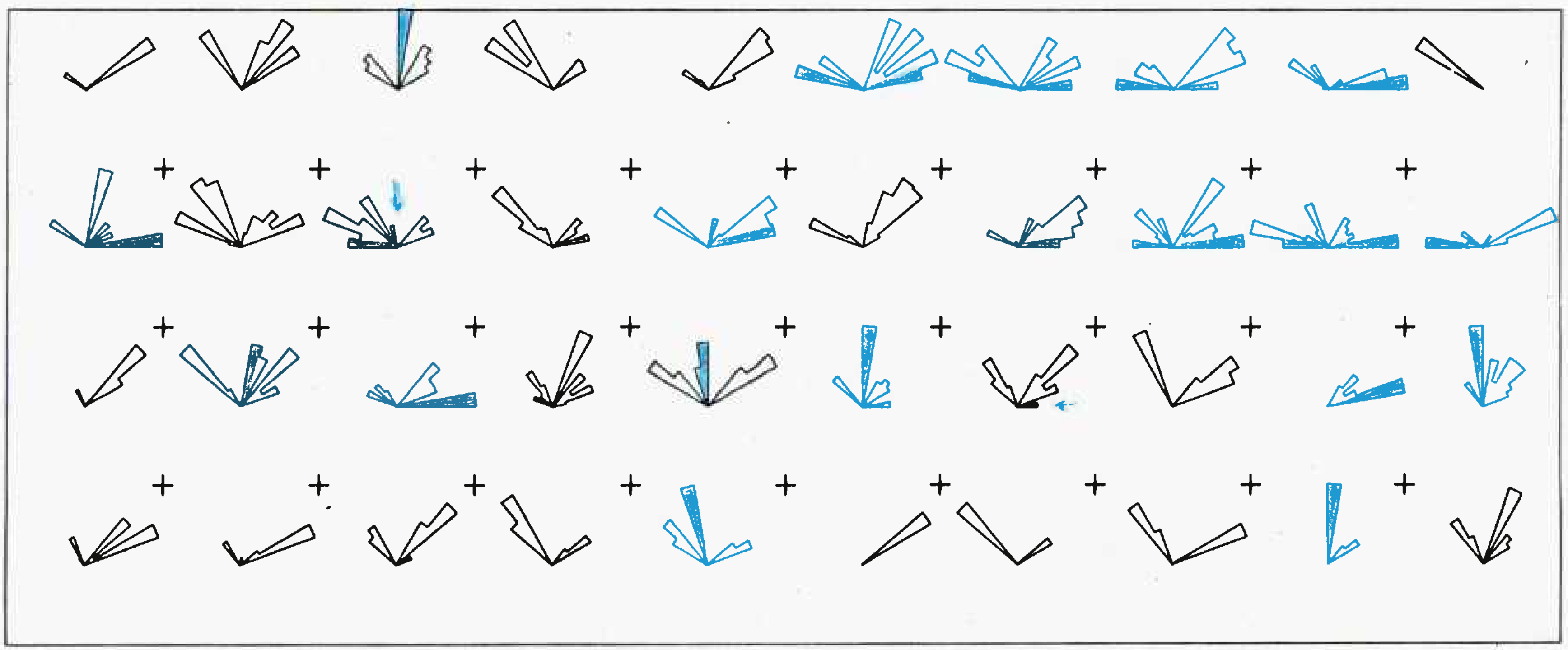


Figure 36a

FRACTURE TRACE AVERAGE DENSITY ROSE MAP
AIN-ZALAH OIL FIELD
(L. P. STEREOSCOPIC INTERPRETATION)

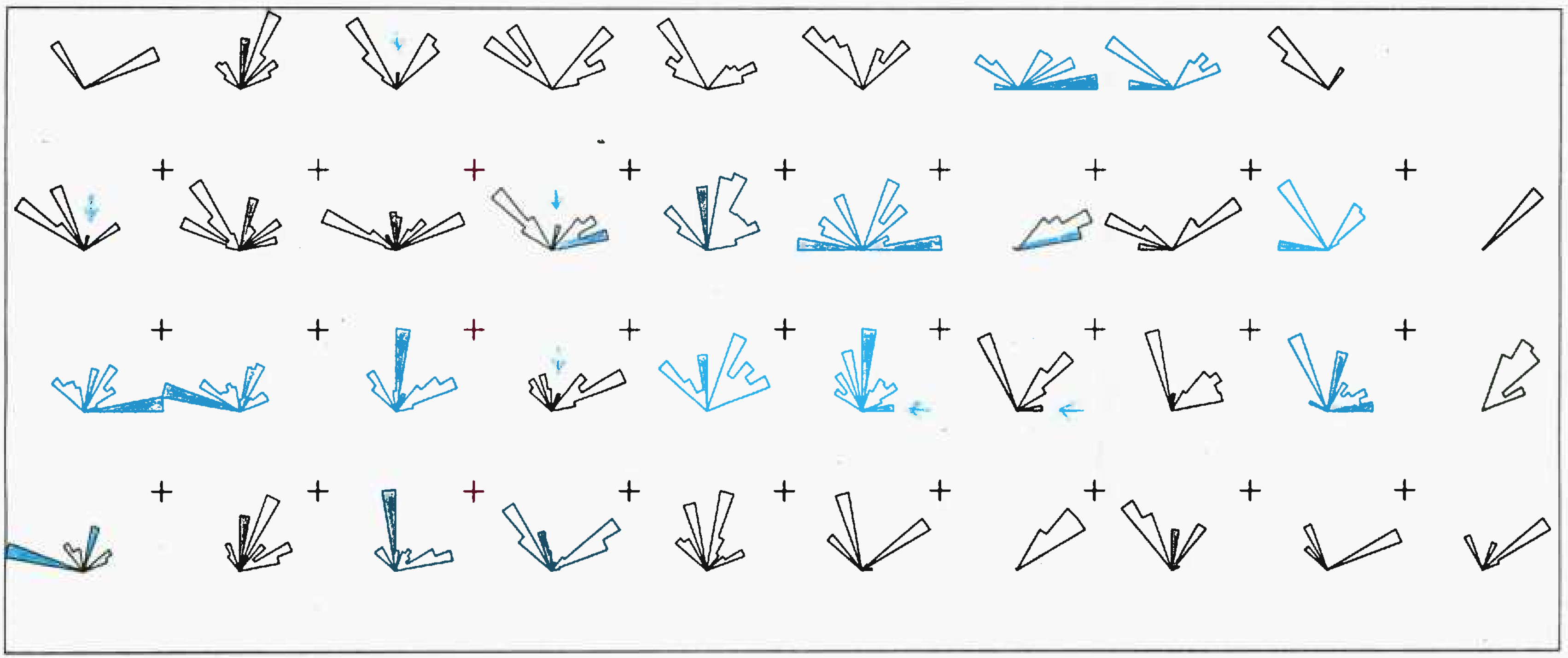


Figure 36b

FRACTURE TRACE AVERAGE DENSITY ROSE MAP
AIN-ZALAH OIL FIELD
(H. P. STEREOSCOPIC INTERPRETATION)

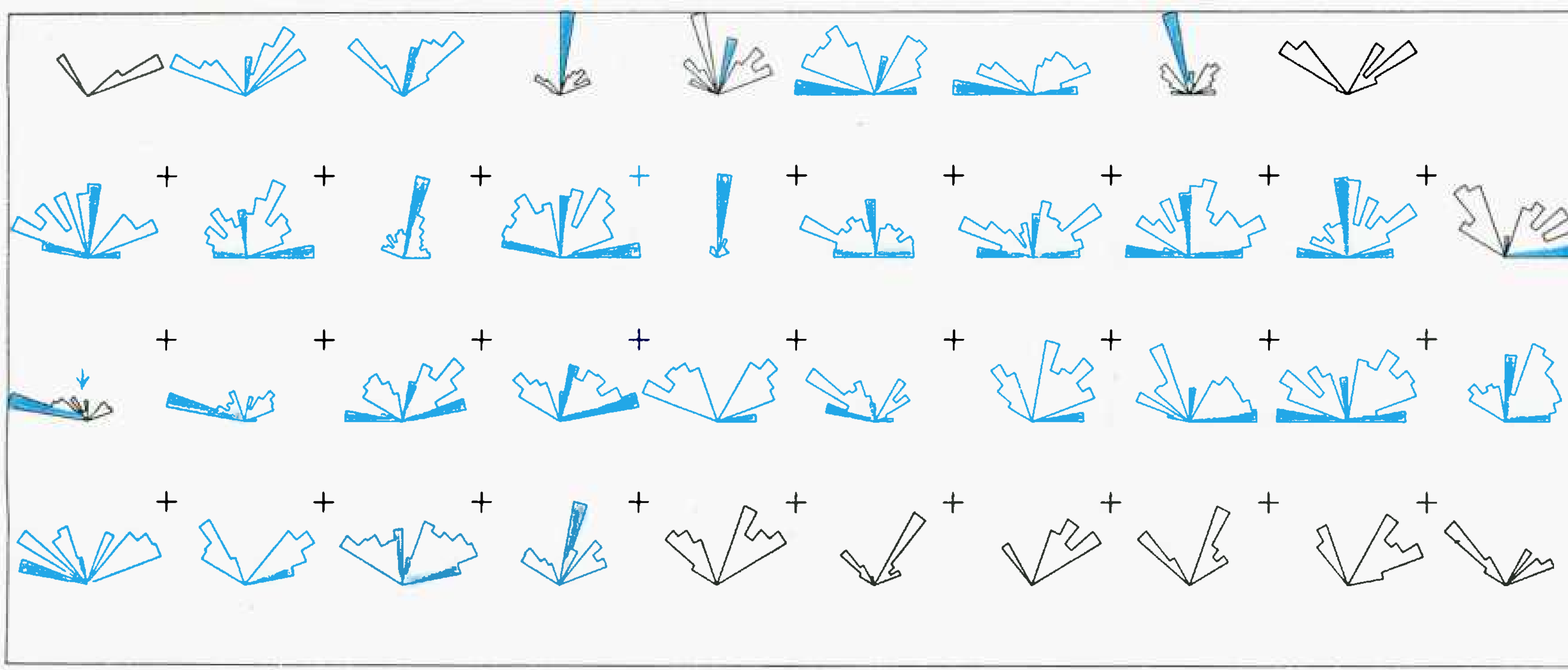


Figure 36c

map. There are also other minor N - S ray alignments in the extreme east and in the middle of the map. E - W rays tend to be more frequent in the east of the map in comparison with the west.

3. The rosemap Figure 36c displays good examples of ray alignments. In the west there are two N - S ray alignments corssing the map from the southern to northern boundaries. Two E - W ray alignments can also be seen extending along the central part of the map from the western to the eastern boundaries. Apart from these, there are other minor alignments which are mostly composed of three rays. These are exemplified by the N - S ray alignment in the east and west of the map.

From all the above mentioned observations, it appears that N - S rays expressed both in alignments or individually are generally frequent in the western parts of the rosemaps. However, the rosemap (Figure 36c) showed an unusually high frequency of E - W rays all along the central region of the rosemap.

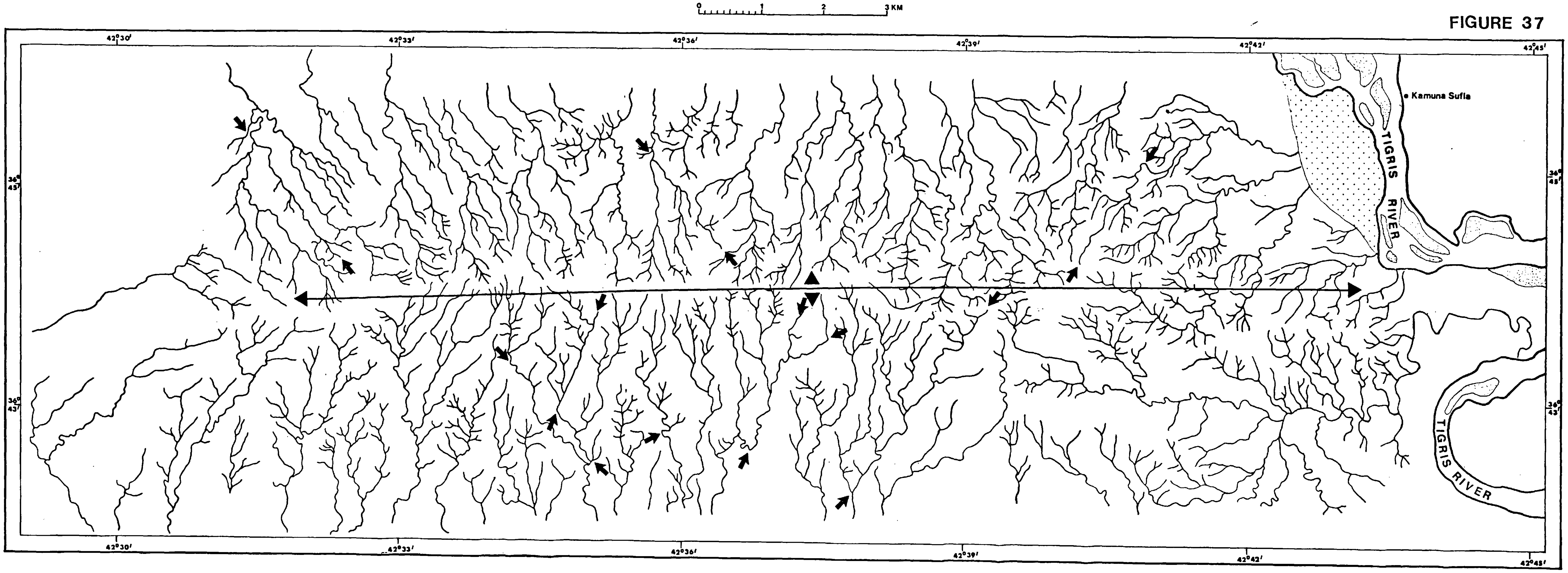
7.1.4 Drainage Analysis of Ain Zalah Structure

The analysis of the drainage on air photographs is an important tool in structure interpretation. Thus, during this study, the drainage characteristics were frequently used as the principal criteria in detecting and interpreting the fracture traces on single air photographs and photo-mosaics.

The drainage map of the Ain Zalah area (Figure 37)

DRAINAGE MAP OF AIN-ZALAH AREA
(PHOTOGEOLOGICAL INTERPRETATION)

FIGURE 37



was produced by tracing out the drainage network stereoscopically from the air photos onto the transparent strip-overlays. These overlays were then compiled, with a little adjustment, onto the base map. Subsequently the whole drainage network was redrawn on the map.

From the appearance of the general drainage distribution on the map, one can easily visualize the anticlinal characteristics of the Ain Zalah structure. In the north of the map, the tributaries and main streams generally flow toward the north, while those in the south, flow towards the south. These zones of drainage have between them a narrow, almost undrained zone striking east-west. Thus, one can easily relate these distinct zones to the north and south flank, and the crestal region of the anticline. The flat topography of the axial zone can also be inferred from the absence of the drainage in it. In the east and the west of the map, the drainage flows away in different directions and tends to form a kind of radial pattern, particularly in the west. These features clearly indicate the plunges of the anticline.

The drainage on the southern flank tends to assume parallel or sub-parallel patterns, and the majority of the tributaries tend to make an acute angle when entering the consequent streams. The preferred orientation of the long tributaries is SW - NE, while the short have an orientation SE - NW. Towards the east of the flank, the drainage pattern tends to be sub-dendritic, i.e. the tributaries flow more unrestrictedly. In the south-east of the map, there is a subsequent stream flowing in an easterly direction parallel to the bedding strike. Further to the east, the stream changes its direction to the north and then east to enter the River Tigris. This stream is a good example of the influence of bedding on the drainage. Most of the drainage on the northern flank generally shows less parallelism, particularly towards the east where the drainage assumes a sub-dendritic pattern. This is probably due to the slope of the terrain which reflects the general dip of the bedding. It is already known that the general dip of the northern flank is less than that of the southern flank. The pattern of the drainage on the western end of the anticline is sub-dendritic and the tributaries flow in a restricted direction into the main streams, while the drainage in the eastern end shows a dendritic pattern, that is, the tributaries with more branches meander freely before entering the streams. The difference between the drainage patterns of the western and eastern plunging ends of the anticline indicate that the western is slightly steeper than the eastern one.

The effect of the bedrock fractures on the drainageways is obvious from their restricted orientations. Most of the tributaries on the flanks and ends follow the surface weakness of fractures and joints on the bedrocks. Some examples of tributaries, such as straight segments or tributary alignments which suggest fractures, can be seen on the drainage map (Figure 37), indicated by arrows.

7.1.5 Discussion and Conclusions Regarding the Ain Zalah Case Study

An appreciable amount of geological information was obtained during the study of Ain Zalah field. Many observations on the various approaches to the fracture trace interpretation were also recorded. In order to reach conclusions about certain points of interest, it is necessary to discuss these results systematically. The discussion will be conducted in two parts, the first concerning the techniques of photointerpretation, and the second, the geological aspects of the study.

7.1.5.1 On the characteristics and merits of the approaches to fracture trace interpretation

As a result of different methods of photointerpretation, three fracture trace maps of Ain Zalah anticline (Figures 28, 29, 30) were produced. These methods basically differ in the ways of viewing the air photographs. This can be seen in terms of two factors; first, the size of the area (domain) immediately available for interpretation; secondly, the three dimensional model inherent in the stereoscopy. The size of domain of interpretation decreases, from the photomosaic, through lower power, to higher power stereoscopic interpretation. The three dimensional vision is absent in photomosaic interpretation, but exists in the stereoscopic interpretations.

The relative length and number of the fracture traces of the maps mentioned above are characteristically different. The photomosaic map (Figure 28) exhibits fracture traces which are relatively longer but fewer in number. The high-power stereoscopy map (Figure 30) shows small fracture traces. They occur in large numbers. The fracture traces in the low-power stereoscopy map (Figure 29) are generally medium both in length and number. However, there are a few fracture traces in these maps which are exceptionally long, or short if compared with their background.

The notion which proposes a relationship between the length of a fracture and its depth (i.e. downward extension) is being widely acknowledged. A long fracture trace such as a master fracture trace in Figure 28 is often considered as the surface reflection of a deep-seated structure. Thus, a long fracture trace interpreted on a small scale photomosaic, may be regarded as a regional geological feature. Short fracture traces tend to be restricted to a smaller rock unit, thus being rather shallow in depth. Very short or minor fracture traces such as those appearing in Figure 30, have a special significance in detecting the type of rocks, as related to their physical characteristics. It was attempted in the high-power stereoscopy map (Figure 30) to delineate the most fractured rock unit, presumably the limestone, from other rocks.

There are certain similarities and differences between the characteristics of the fracture trace maps. By describing these features one can indirectly outline the merits and shortcomings of each approach to fracture trace interpretation. One feature which occurs in all three maps is the relatively narrow zone of fracture traces crossing the anticline obliquely. However, the appearance of this zone is rather different in each map in as far as the size and number of its fracture traces is concerned. In Figures 28 and 29 the radiating pattern of fracture traces indicating the plunging end of the anticline can be seen. This feature is absent in Figure 30. The general density of the fracture traces in the western half of Figures 29 and 30 appears relatively higher than in the eastern. This particular feature is not present in Figure 28.

When a certain fracture trace feature occurs only in one map and not in the others, it may be regarded as a diagnostic characteristic of that map. Such features are (a) the occurrence of a high frequency of long fracture traces in the photomosaic map, (b) linear zones of a relatively high density of fracture traces in the high-power stereoscopy map, and (c) the prevalence of medium-length fracture traces in the low-power stereoscopy map.

In the light of the above discussion, one can outline the principal advantages and disadvantages of each type of the interpretation method. The high-power stereoscopic method of interpretation can be useful in a detailed fracture trace study. Such an interpretation may be expected in photogeology concerned with rock mechanics or engineering geology. It may also be needed in lithological interpretation based on the fracture characteristics of rock. The apparent disadvantage of this method is that it is time-consuming and there is a likelihood of eye strain or fatigue caused by constant viewing with high magnification.

The advantage of low-power stereoscopic interpretation is that the field of viewing during the interpretation in this method is much larger. Thus the interpreter can observe larger features or fracture traces and can also follow long fracture traces over the adjacent photograph without interruption. The time consumption is relatively small compared with the previous method. Possible eye strain or fatigue is also less likely. However, the disadvantage of this approach is the decrease in photographic resolution due to low magnification. The result of this is that, finally, less data are obtained.

The special advantage of the photomosaic method of interpretation is the presentation of a whole geological complex with its inter-related phenomena as one scene. This enables a photogeologist to detect and interpret larger or regional geological features. It is significant in fracture trace study to investigate large scale structures or fracture traces, since their tectonic influence on other features cannot be ignored. An advantage of this method is that no equipment (i.e. stereoscope) is involved, except that sometimes a magnifying lens may be needed. Other material (i.e overlays) can also be considerably reduced. The time consumed in this interpretation is much less than that in other methods. Eye strain and fatigue can be minimal or nil. The major shortcoming of this method is the absence of stereoscopic vision (3D model). This makes the photomosaic interpretation difficult for an inadequately trained photogeologist. It may also increase the hazards of subjective judgement during photointerpretation. The quantity of fracture trace data gathered by this approach is comparatively less, and this is mainly due to a reduction in photographic resolution associated with the viewing as well as the production of a photomosaic.

Finally, given a reasonably good quality air photographs, the best approach to fracture trace interpretation in normal working circumstances, (in the author's opinion), is the combination of a photomosaic and low-power stereoscopic interpretation. The examination of the photomosaic should preferably be carried out first, and followed by the stereoscopic interpretation of individual photos. However, the nature or conditions of the work might dictate the order or even the type of appraoch. In this case it should be left to the discretion of the photogeologist.

7.1.5.2 On the relationship between the fracture traces and the structural characteristics of Ain Zalah field

Several questions have been put forward in the beginning of this chapter concerning the fracture traces and their relationship to the other structural aspects of Ain Zalah anticline. During this study, an attempt was made to answer these questions and suggest appropriate explanations for the structural problems implied by them. The questions will be presented and discussed below.

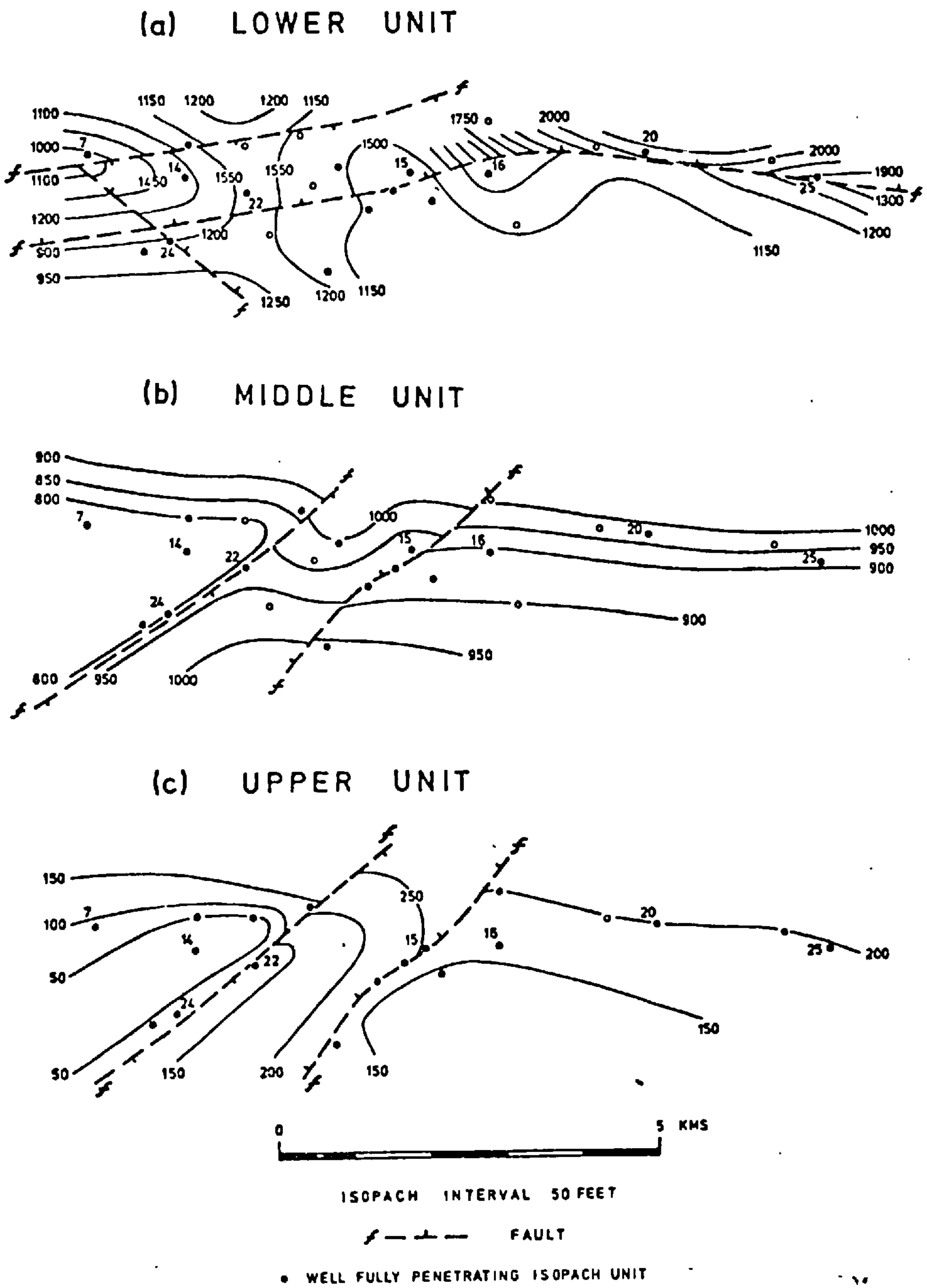
A - <u>The relationship between the density and pattern of the fracture traces and the structural divisions of Ain Zalah anticline</u>

It was observed, (Figures 28, 29), that the general density of fracture traces occurring in the southern flank of the anticline is relatively higher than that in the northern. It could also be seen that the oblique (shear) fracture traces in the southern flank are more frequent than in the northern flank. These observations may be explained by the fact that the dip of the southern flank is comparatively steeper than that of the northern flank. It is not unreasonable to suggest that the effective stress which occurred in the southern flank was relatively greater, thus resulting in more fracturing and deformation.

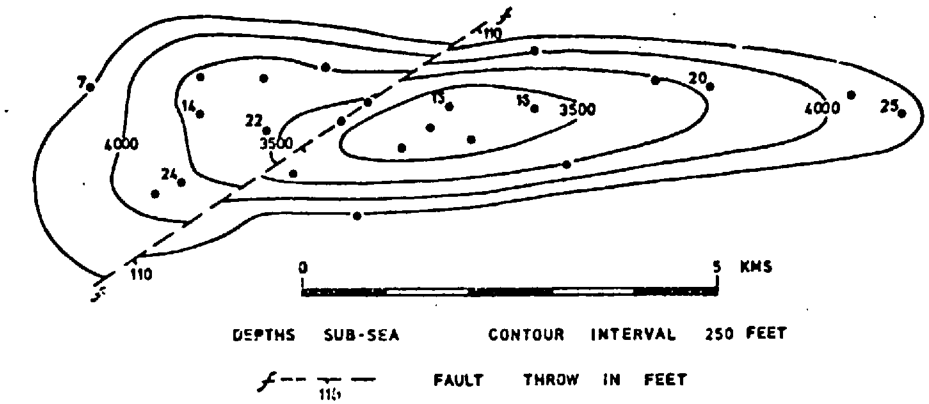
As the fracture traces approach the western end of the anticline they tend to swing from an almost E - W orientation to NW and SW, and splay out into a radiating pattern (Figures 28, 29). In the eastern end this pattern could not be detected, and this occurrence in the western end may be attributed to the plunging of the anticline being relatively steeper. Many authors reported such a fracture pattern as often being associated with a doubly plunged anticline, and it has been ascribed to the differential stress conditions which prevail in the plunging end of the anticline during the deformation.

B - Subsurface structures as suggested by the fracture traces of Ain Zalah anticline

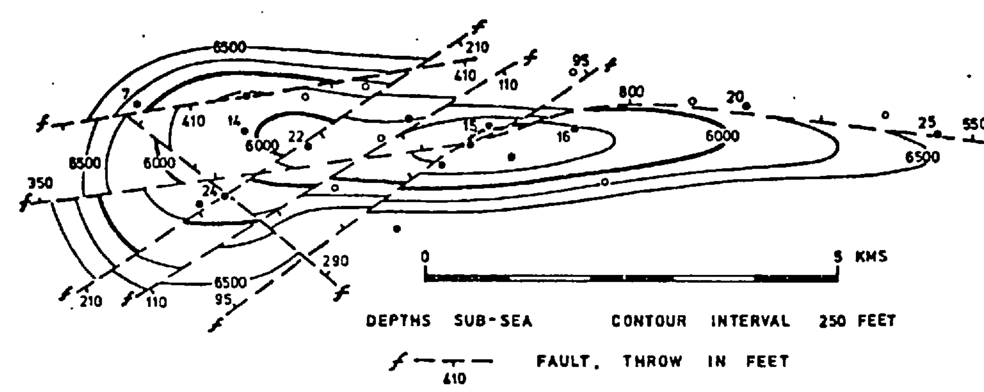
The occurrence of the oblique master fracture traces and the similar zones of fracture traces transversing Ain Zalah anticline in a NE direction, (Figures 28, 29, 30) represent significant features. The remarkable characteristics of these fracture traces suggests that certain subsurface tectonic factors have caused or contributed to their occurrence. This assumption seems quite in agreement with a subsurface study carried out by Hart and Hay (1974) and depicted in a number of Isopach and structural contour maps (Figure 38). The Isopach maps of the upper and middle parts (units) of the Shiranish formation which make up the First Pay (5000 ft. below the surface) show two parallel normal (or reverse) faults of a NE orientation, with their down-throws towards each other. The structure-contour map on top of the Shiranish formation (i.e. above the First Pay) shows the western fault. But, both faults appear again on the subsurface contour map on top of the Mushorah formation (Second Pay). The recurrence of these faults in several stratigraphic horizons of different depths, and their great similarity in orientation, size and relative position to the fracture traces mentioned above, indicate a probable structural relationship between the faults and the fracture traces. Other faults with different orientations can also be seen in the structure-contour map on top of Mushorah formation, in particular, the fault which occurs in the north-east of the structure with an E - W



Isopach maps of three subdivisions of Shiranish used in final structural analysis.



Simplified structure-contour map on top of Shiranish Formation (first pay).



Structure-contour map on top of Mushorah Formation (second pay).

Figure 38 (after Hart and Hay, 1974)

orientation and northward down-throw. This fault might have contributed to the appearance of a number of E - W fracture traces in a similar position in Figure 28.

In the Figures 28 and 30 the western half of Ain Zalah anticline exhibits a relatively greater number of fracture traces compared with the eastern half. There are many factors affecting the appearance of fracture traces in general, but in this area, two factors probably have a considerable influence on the fracture traces. One is the soil or recent sediment coverage as related to the exposure of outcrops. The other is the degree of deformation and structural attitude of the bedrocks. The soil cover in Ain Zalah anticline is generally thin and often has not impaired the manisfestation of the fracture traces on the air photos, with the exception of a small area around the River Tigris in the eastern end. Thus, the tectonic condition of the bedrock might be the cause of the greater fracture trace frequency. In this case there may be two relevant contributory factors. The first is the relative steepness of the bedrock in the western part of the anticline, and second, the possibility that the western part has been slightly elevated due to the vertical movement associated with the subsurface faulting mentioned above. This seems not impossible in the light of the subsurface fault with a westward upthrow, occurring in the structure-contour map on top of the Shiranish formation (Figure 38).

C - Predominant directions of the fracture system in the Ain Zalah reservoir as inferred from the directional characteristics of the fracture traces

There are two reservoirs in the Ain Zalah field; the first is situated in Upper Cretaceous limestones and is named "First Pay"; the other includes part of the Lower Senonian and the Middle Cretaceous, and is called the "Second Pay". Both Pays are separated by a barren sequence, some 2,400 feet thick in the crestal part of the structure. However, the two reservoirs are connected by vertical fractures in the western sector of the anticline.

To present a comprehensive picture of the reservoirs, it is necessary to quote, briefly, the physical and lithological characteristics of the reservoir rocks.

The "First Pay" occurs in the fractured globigerinal marly limestones of the Shiranish formation (Upper Cretaceous). The reservoir rock is overlain by Aaliji Shale (Lower Eocene - Palaeocene) which acts as a cap rock to the oil accumulation. There is an unconformity between the two formations. The fracturing of the reservoir is limited to the upper 200 - 300 feet and is definitely post-depositional. The fractures often contain secondary calcite veins which indicate recurrent fracturing (Nasr, 1960). The depth of the reservoir from the crustal region on the surface is about 5,000 feet.

The oil accumulation occurs in the fractures and the productivity of the individual well, depends entirely on the well entering a fractured region when drilled. A general idea about the well as a producer can be formed by the amount of drilling fluid lost on entering the reservoir. It has been found that wells which have low or negligible fluid losses, even after subsequent acidation, prove to be poor producers (Nasr). The porosity of the rock matrix is very low and permeability is effectively zero. The drive energy of the first reservoir is maintained by the migration of the Second Pay oil through vertical fractures between the Pays. These fractures occur in the western end of the field in the vicinity of well No. 14.

The oil of the Second Pay occurs in a variety of rocks, extending from the lower part of the Shiranish formation (Upper Campanian), through the Mushorah formation (Lower Campanian) and the entire Qamchuqa sequence (Middle Cretaceous). The lithology of these rocks ranges from calcite veined limestones, flint and chert, dolomitic limestone, and dolomites. They are fractured and porous only in certain horizons. Multiple fracturing is common. The source of reservoir energy in the "Second Pay" is a very strong water drive, which is indirectly the source of the drive of the "First Pay".

It is widely recognized that fracturing in a reservoir can enhance oil productivity, in particular in a reservoir with dissolved gas drive energy. Without natural fractures (or hydraulically induced fractures) one can imagine that many low-permeability reservoirs might never be commercial. The characteristics of the directional flow from the fractures influence both the injection and withdrawal of liquid and gas to and from the reservoir. Thus, distribution and orientation of the fracture system together with the spacing and directional configuration of the wells are important factors in production, particularly, from less permeable formations.

In order to obtain conclusive knowledge of the fracture system of the reservoir, a number of engineering and logging methods must be used in combination.

The acquisition of comprehensive experience of the geomechanics of rock fracturing on a local and regional scale, including the systematic formation and propagation of the fractures prompted some authors to study the relationship between the fractures appearing on the surface or on photographs, and those occurring in the reservoir rocks.
Allen Alpay (1973) studied the relationship between the directions of fracture traces mapped on and around eight oil fields and the orientation of fractures occurring in their reservoirs. The depths of these reservoirs ranges from 4,500 to 7,000 feet from the surface, and they are distributed over an area of 9,600 square miles in Midland, Texas. He compared the directions of fracture traces with the reservoir fluid movement pattern revealed by injection and production behaviour, analysis of pressure transient data, impression packer work, tracer surveys and bore-hole televiewer logs. He found in all the fields studied, that there is a remarkable correspondence between the predominant fracture trace orientations and preferential fluid movement trends in the reservoir. He, therefore, concluded that the directional analysis of fracture traces may provide significant

information on the orientation of natural fracture planes in a reservoir, and the analysis can be carried out relatively cheaply, quickly and effectively on air photographs.

Komer et al. (1971) and Overbey et al. (1971) applied similar techniques on a number of oil and gas fields in the U. S. A., and obtained satisfactory results. Thus, they arrived at almost the same conlcusions as the previous author.

Regarding Ain Zalah field, it has been established that the fractures in the reservoirs are post-depositional (Nasr, 1960). Thus, their occurrence can perhaps be associated with the tectonic history of the Ain Zalah anticline. There is little doubt that the tectonic stresses which caused or contributed to the occurrence of the fracture traces on and around the anticline, had a strong influence on the development and orientations of the fracture system in both reservoirs.

In view of the observations regarding the correlation between the fracture traces and the subsurface faulting of Ain Zalah, and the established connection between the fracture traces and reservoir fractures which has been revealed by the above-mentioned authors, the predominant orientations of fractures occurring in the Ain Zalah reservoirs may be predicted.

The directional distribution of the fracture traces as depicted by the rose diagram (Figures 31, 32, 33) revealed four distinct directions of rose maxima. They are

N 45° W, N 55° E (shear directions) and N 75° E, N 15° E (tension directions). The predominant and perhaps most significant among these directions are N 55° E and N 75° E. These azimuths, in fact, represent (statistically) intermediate values of two directional classes of rose diagram. By comparison, the suggested predominant orientations of fracture systems in the reservoirs of Ain Zalah would be among the azimuthal ranges N 45° - 55° E and N 75° - 85° E.

D - Fracture trace anomaly due to superficial or near surface local structure

As mentioned before, the Lower Fars formation occurs in most parts of the exposed structure of Ain Zalah. It consists mainly of the interbedding of limestones, anhydrite and thin marl rocks. The anhydrite often occurs as thick and massive rock underlying the limestone beds. This is considered a characteristic feature of the Lower Fars which can be encountered in many parts of Northern Iraq. In the Ain Zalah anticline, the anhydrite can often be found with gypsum, particularly in weathered areas.

The anhydrite, through hydration caused by groundwater or long periods of rain and weathering, changes into gypsum, and this process increases the volume and plasticity of the rock (Hill, 1964). This process can take place on the surface as well as below the surface. In some parts of Ain Zalah anticline, the anhydrite expands by hydration causing more fracturing in the overlying limestone beds. Occassionally, a gravity collapse structure such as the slabs of a limestone bed sliding over anhydrite, can also be seen.

In the north-east of the Figure 30, there is a zone of high fracture trace density. It is roughly circular and exhibits a great number of oblique and orthogonal fracture traces. The occurrence of such a zone is rather unusual if compared with the general distribution of fracture traces in the anticline. Taking into consideration the gentleness of the dip of bedrocks in this part of the anticline, the proximity of the Tigris and the intensity of the weathering and unloading of rock occurring in the area, then one can imagine that the anhydrite has been considerably affected by water, particularly underground water. This influence has produced an expansion (or swelling) in the massive anhydrite rock. The overlying competent limestone has been pushed upward thus forming a local uparching or dome-like structure. The limestone is therefore subjected to an additional vertical stress field, more fracturing has occurred, and this is depicted in the above-mentioned zone.

E - Graphical stress model for the Ain Zalah structure, based on the directional analysis of the fracture traces

In structural geology, the notion of a graphical stress model is often used to illustrate the kinematic or mechanical aspects of a specific structural phenomenon seen as a discrete geological event. In this context, the stress model (Figure 39) basically represent a schematic figure showing the principal compressive stresses and types of fracture traces in relation to the axial trend of the anticline. The directions of the principal compressive stresses were inferred from the orientation of the anticlinal strike. The types of fracture traces (i.e shear and tension fracture traces) and their azimuthal ranges in the model were defined on the basis of rose diagram analysis and within the framework of the geometrical relationship between fold axis and fracture traces.

The azimuthal tension regions (T) are N 15° - O E, N 15° - O W, N 75° - 90° E and N 75° - 90° W. The azimuthal shear regions (S) are, N 15° - 75° E and N 15° - 75° W. These are represented in the stress model of Ain Zalah anticline (Figure 39).

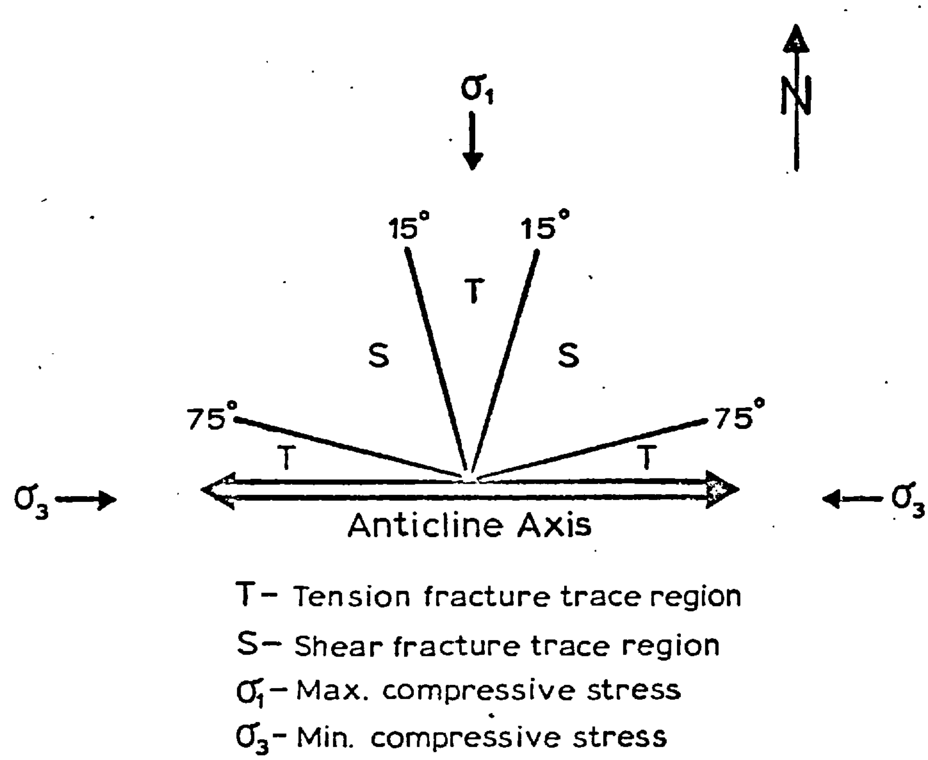


Figure 39

CHAPTER EIGHT

8.1 DISCUSSION AND CONCLUSIONS REGARDING THE STRUCTURAL FRAMEWORK OF THE STUDY AREA

This study produced a large amount of structural data and observations concerning the tectonic setting of the area. If this information is to be fully utilized, it must be appropriately discussed and correlated. Finally, conclusions about specific structural questions can be reached. It is intended in this chapter first to discuss the structural information obtained during the study, and secondly draw conclusions.

8.1.1 Discussion of Structural Data Obtained During the Study

Northern Iraq, including the area of study, is a part of the tectonic framework of the Middle East region. In Chapter Five a discussion of the general tectonics of the Middle East was presented. It is relevant here, to recapitulate briefly some aspects of these tectonics.

Specifically, Northern Iraq lies within the "Interior Platform" of the Middle East, which is called by Henson (1951) the "Unstable Shelf" (Figure 5). This region has been divided by many authors into three subsidiary zones; (a) the Nappe Zone, (b) the Folded Zone, (c) the Unfolded Zone. Recent gravity and seismic work in the so-called unfolded area has shown a succession of subsurface folds and other buried structures in spite of its general flat appearance at the surface. The name given to this a area in Northern Iraq is the "Flat Area" or the "Jazira Block" (Figure 2).

The Nappe Zone is confined to the north-eastern corner of Northern Iraq, where complex thrusting and nappe tectonics prevail. In this zone, igneous activity (intrusive and volcanic), metamorphism and extensive emplacement of ophiolite-radiolarite occurs. The area has been inadequately investigated and the nature of its tectonism, previously ascribed entirely to tangential forces directed from the north-east, has been questioned (Nasr, 1960).

The Folded Zone covers most of Northern Iraq (including the study area), except the Jazira area and the north-eastern corner. This zone is about 160 kms in width and consists of anticlines which gradually change their axial directions from NW - SE to E - W. The folds seem to have a number of similar characteristics and have been described as being simple autochthonous folding. However, geophysical work in some parts of the zone has indicated a different tectonic pattern underlying the folds.

The Flat Area shows little apparent surface folding and the country on the whole is flat. As mentioned earlier, both gravity and seismic surveys in this area show that a number of buried fold structures exist. Some of these structures are large anticlines with a very broad and low amplitude bordered by shallow synclines. The tectonic pattern of this area is certainly different from the

"Folded Zone" and can be convincingly ascribed to block faulting and the draping of a sedimentary cover over the blocks (Nasr, 1960).

The area in which the study was carried out is a part of the Folded Zone in north-western Iraq (Figure 2). The tectonic history of this area as a whole (i.e Folded Zone) has been a subject of controversy for many years. The argument is between those who believe that the folding of the Taurus-Zagros mountain belt is a product of extreme compression resulting from continental collision, and those who postulate a "regime of repetitive vertical movements building up to such a degree of instability as to stimulate the obviously compressional Late-Tertiary orogeny" (Nasr quotes Henson's unpublished paper).

Those of the former school see the area as classical folded geosyncline with nappes nearest the thrust front, progressively giving way to autochthonous folding, and then unfolded conditions. They quote that some areas within the zone contain large anticlines show little faulting. Other examples are also quoted, for instance from the oil fields where in a number of cases different oil horizons are often separated by thin sediments. It is argued, therefore, that these oils would have mixed if faulting of any kind was present in the structures.

Henson (1951), Daniel (1954) and others, on the other hand, have an alternative theory which proposes that the Late-Tertiary folding was moulded upon already-existing irregularities of block-faulting. Henson also believes that long straight anticlines which occur in the folded area can not be adequately explained by tangential or by block-faulting. He maintains that they may have been formed by wrench-faulting in the basement rocks. The process, as he sees it, is one in which first, the basement is broken up by wrench-faulting and then the fault-block is pushed upward by further compressional movements, in other words, a form of vertical thrusting. Jabal Abd-el-Aziz in Western Syria, is an example where such block-faulting formed the surface anticline and then burst through it. Sinjar and Butmah (East) anticlines in Northern Iraq are seen as probably being in an earlier stage of this process (Nasr).

The hypotheses put forward by both schools are being entertained by many geologists who are interested in the regional geology of the Middle East. In our case, a number of structural observations have been recorded during the study. In order to adopt or refute any of these hypotheses, one should consider the compatibility of the gathered data with the hypotheses. The structural observations are summed up in the following points:

A - The major fracture trace trends which are shown in Figure 14 indicate the existence of several zones of rock failure (or weakness) in the area. These linear zones (or trends) of fracture traces occur predominently in the directions NE, ENE, and E - W. Some trends occurring in other directions mainly NW and N - S, can also be seen but are less remarkable.

The gravimetric lineaments which appeared in Figure 25 and were seen as being related to basement tectonics, or to deep-seated block faulting, show great similarity in their charater-istics with fracture trace trends. The obvious coincidence in the configuration of both features suggests demonstrably their structural affinity. On the other hand, the area in question has probably been subjected, during its geological history, to conditions of block-faulting, and this has had a great impact on its present structural framework.

In Ain Zalah oil field, a number of subsurface faults have been discovered during drilling opera-tions. These faults are mostly reverse faults. They were not detected by gravimetric surveys carried out in the area, which indicate that they were not probably caused by basement block-faulting. Thus, they can reasonably be related to the horizontal compressive stress which has affected Ain Zalah anticline.

B - The stress-strain trajectory maps (Figures 23, 24) exhibit distinct patterns of different azimuthal and spatial characteristics. This indicates that the stress conditions which produced the structural features have not been uniform throughout the area. The regional compressive stress which affected the folded zone in north-western Iraq was directed mainly N - S. The reaction to this stress seems to have been different in various parts of the area, thus resulting in anticlines of diverse orientations and non-uniform characteristics. One can therefore infer that the various zones of stress-strain trajectories indicate deep-seated features whcih have responded with irregular tectonic behaviour.

C - The configurations of the anticlines and their structural characteristics casts some light on the tectonic history of the area. The anticlines strike predominently E - W in the central part of the area. In the north, the Dohok and Mushorah anticlines strike NW - SE, while in the south, the western end of Gusair anticline swings to the NW. Other anticlines exhibit a similar tendency the further west they occur. This remarkable change in the orientations of the anticlines occurring within a comparatively short distance may be ascribed to deep-seated tectonic controls. In addition, most of the anticlines are slightly asymmetrical and characterized by a broad and horizontal crestal zone.

It is worth noting that in the gravimetric lineaments map, (Figure 25), the outlines of some anticlines in the west Tigris are confined within the compartments formed by the lineaments, and the larger the compartment, the larger the anticline it contains and vice-versa. The longtudinal axes of most anticlines are aligned with the long segments of the lineaments, and the steeper flanks of the asymmetrical anticlines are close and parallel to the lineaments. Thus, these can be seen as evidence supporting the assumption that the basement rock has a remarkable effect on the structural setting of the area.

D - It was mentioned in Chapter Five that drilling operations in several locaties in the study area revealed the occurrence of appreciable variations in the thickness of rock formations belonging to the same age and sedimentary environment. The Table No. 2, shows these thickness variations and stratigraphic breaks. It can be assumed that the thickness variations in basically similar sediments are due either to subsidence allowing additional sedimentation or removal by erosion. In the Table, the best example of severe thickness variation is the case Allan and Atshan, two neighbouring anticlines (Figure 6). The Upper Cretaceous sediment in the former anticline is 950 feet thick, while in the latter it is 560 feet thick. The Butmah anticline provides an example of a stratigraphic break. The Middle Cretaceous sediment in the east dome of the anticline is missing, but occurs in the west dome to a thickness of 450 feet. Similarly, Oligocene sediments occur in Ain Zalah anticline to a thickness of 525 feet, while they are completely missing in Butmah anticline, a short distance to the south. These abrupt changes in thickness and/or sedimentary breaks which occur over short distances can be

THICKNESSES OF SEDIMENTS IN FEET OCCURRING IN MAJOR ANTICLINAL STRUCTURES

	Ain Zalah	Butmah		Gullar	Sasan	Allan	Atshan	Jazira Area
		West	East					
Oligocene	525	0	0	1300	150	0	0	270
Eocene-Palaeocene	3700	3200	3750	1900	300	1900	1310	400
Upper Cretaceous	2600	2000	1370	3020	6000	950	560	250
Middle Cretaceous	730	450	0	720	1530	450	230	0
Lower Cretaceous	100	100	0	100	200	340	160	0
Upper Jurassic	0	0	*	0	0	0	340	0
Middle Jurassic	1310	1120		70	*	730	820	0
Lower Jurassic	*	1770		*		3670	2380	530
Triassic		*				*	4010	1535
Permian							*	0

Table No. 2, (after Nasr, 1960)

* Sediments not completely penetrated.

indicative of a disturbed tectonic history characterized by vertical movements associated with block-faulting.

8.1.2 Structural Conclusions

The problem of the tectonic mechanism of the study area should be approached from two standpoints, first, within the framework of the tectonic development of the Middle East as a whole, and secondly, through the structural information obtained from the area. All authors agree that the Middle East region has had a long history of epeirogenic and orogenic movements. The present tectonic features of the region have been ascribed to two major orogenies which occurred in the Middle-Late Cretaceous and Late-Tertiary. Continuous basement faulting and vertical block movements have been occurring since the Paleozoic.

In the light of the general tectonic history of the region, and also the structural observations recorded during the study, (mentioned above), one cannot escape the proposition that both compressional forces and block-faulting were responsible for the shaping of the structural architecture of the area. In any attempt to explain the tectonic mechanism of the area, it would be very difficult to exclude either of these two factors. The former supporters of the two opposing theories on the tectonism of the Folded Zone now seem to agree on this point. It can also be safely assumed that the differential vertical block movements were recurrent.

In view of the above, the sediments which overlaid the unequally disturbed blocks, prior to any particular orogenic movement, must have formed a sheet of heterogeneous sediments. This sheet must have been heterogeneous in the sense that neither its lithology nor the thickness of its sedimentary units could have been uniform across the whole area. Furthermore, the differential movements of the blocks result in the displacement of the strata on either side of the fault plane, thus breaking the homogeneity of an otherwise continuous unit. Physical variation in the sediments alters to the elasto-plastic properties of the rock formations in relation to stress transmission and deformation. Thus, stress transmission and stress behaviour across the sedimentary sheet becomes irregular along any given horizontal plane. Conversely, homogeneity in the degree and style of deformation is limited to the sediments within each section of the sheet. The nature of stress field distribution in the study area is depicted in the stress trajectory map (Figure 23). The irregular patterns of the trajectories almost correspond with the axial strikes of the anticlines in the area.

The author, therefore, sees the area as one which was initially covered with a heterogeneous sheet of sediments composed of an aggregate of sedimentary sections (or segments) overlaying a block-faulted basement with very irregular topography. Thus, the sedimentary sheet was lacking in both physical and lithological continuity, and the homogeneity for transmitting stresses. The regional compressive stress which was directed mainly N - S, has affected the sedimentary sheet which filled and covered several small basins each of which has a different thickness of sediments, physical properties, and plane of decollement. The regional stress also affected the overlain fragmented basement and induced nudging and jostling of the blocks, which produced unequally distributed and vertically directed secondary local stress fields. The sediment of each basin was independently folded primarily by the horizontal compressive stress, and secondarily by vertically induced stress. The thicker sediments above the detachment plane probably produced more pronounced folds, and larger basins produced larger folds.

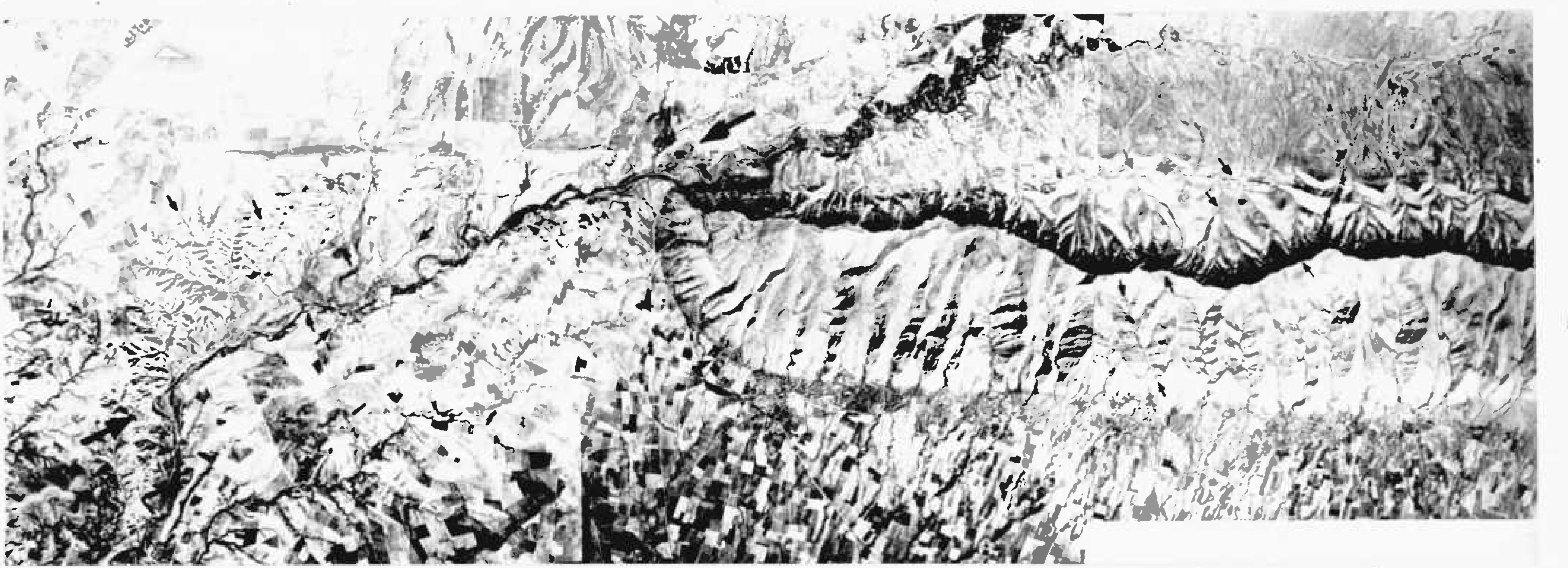
The lack of homogeneity of stress transmission and the deformation of the sediments, has led to complex directional resolutions of the stress fields in different parts of the area. This may well account for considerable differences in the axial orientations and alignments of the anticlines occurring within short distances, and also for certain structural aspects such as the asymmetry and axial plunging of some anticlines.

It has been observed that compressive horizontal stresses have been active since as early as the Middle Cretaceous, while the block-faulting dates from at least the Middle Palaeozoic and continued intermittently up to the Late Tertiary.

A P P E N D I X

Plate 1

A mosaic of three air photographs showing the western part of Algosh anticline. The structure is a relatively long and closed anticlinal fold with many fracture traces occurring on both flanks and striking NE and NW i.e. obliquely to the east - west axial strike. These are thought to be shear fracture traces and some of them are indicated by small arrows on the photograph. West of the anticline a rectilinear stream can be seen indicated by arrows. It represents a long fracture trace or possibly a shear fault striking NE. Small fracture traces striking almost perpendicular to the direction of the stream occur on its northern side, and indicated by small arrows. They are probably caused by secondary stress field resulted from the adjacent long fracture trace or shear failure.



0 1 Km
SCALE

Plate 1

Plate 2

A mosaic of air photographs showing two domes of Butmah anticline i.e. Butmah West (B. W.) and Butmah East (B. E.). There is an alignment of rectilinear streams transversing the saddle between the domes in a NW direction, and indicated by white arrows. This can be interpreted as a manisfestation of a long fracture trace or a surface reflection of a possible deep-seated fault occurring between (or causing) the Butmah domes. Other fracture traces indicated by black arrows can also be seen in the saddle region. Drainage anomalies and soil tonal alignments are the main criteria for interpreting these fracture traces.

The photograph shows that the dips of the bedrocks occurring in the southern flanks of both domes are relatively steeper than those in the northern flanks. The southern flanks are dissected by many oblique (shear) fracture traces some of them marked by arrows.

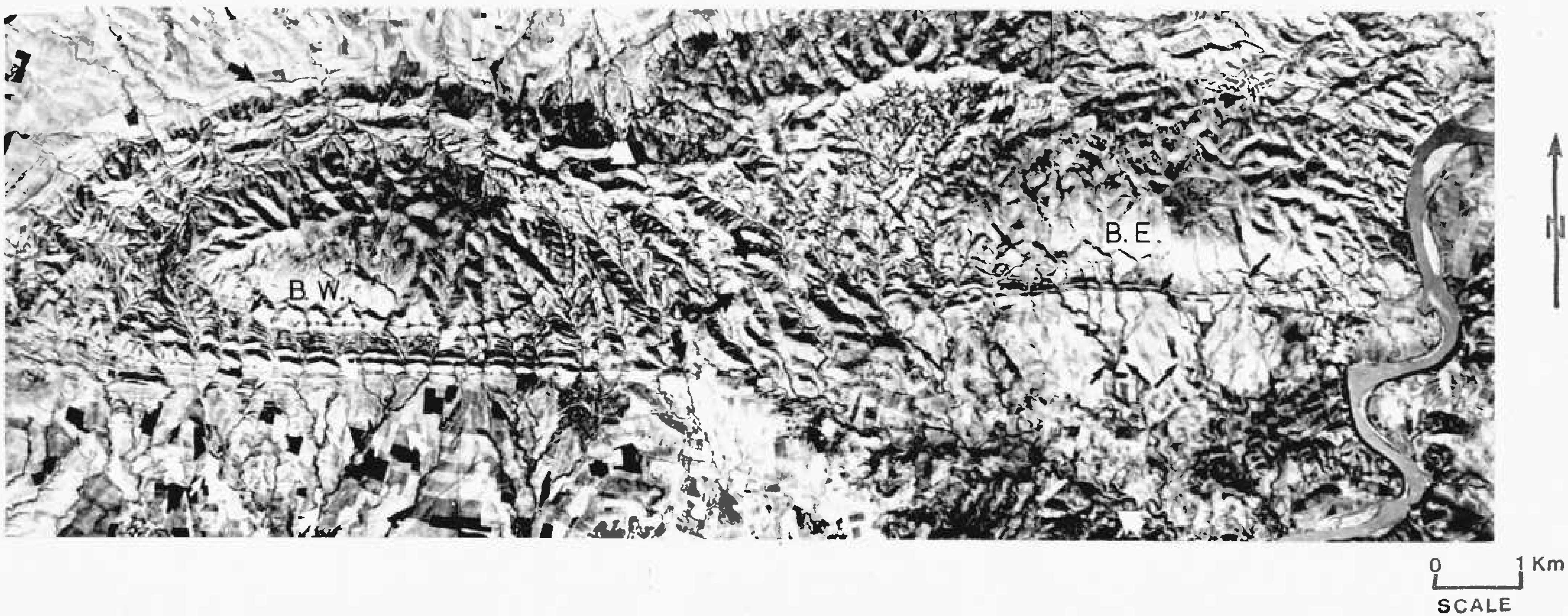


Plate 2

Plate 3

A mosaic of air photographs showing Gusair anticline. There are two long fracture traces striking NE and transversing the eastern part of the anticline. Because of the apparent bedding displacement which occurs alongside them in the northern flank, these fractures can be regarded as tear (or shear) faults. Another long shear fracture trace transversing the anticline in a NW direction is also indicated by arrows. Two sets of short shear fracture traces striking NE and NW can be detected on the southern flank and some of them are indicated by small arrows.

0 1Km

SCALE

Plate 3

Plate 4

This stereo-triplet covers a locality in the central part of the study area. The rock in this area consists mainly of interbedding of marl/shale, limestone and anhydrite. The terrain is extensively drained and fractured. Geomorphological linear features and drainage anomalous characteristics are the most useful criteria for fracture trace interpretation in this type of terrain. Examples of fracture traces interpreted by such criteria are indicated by arrows in the stereo-triplet.

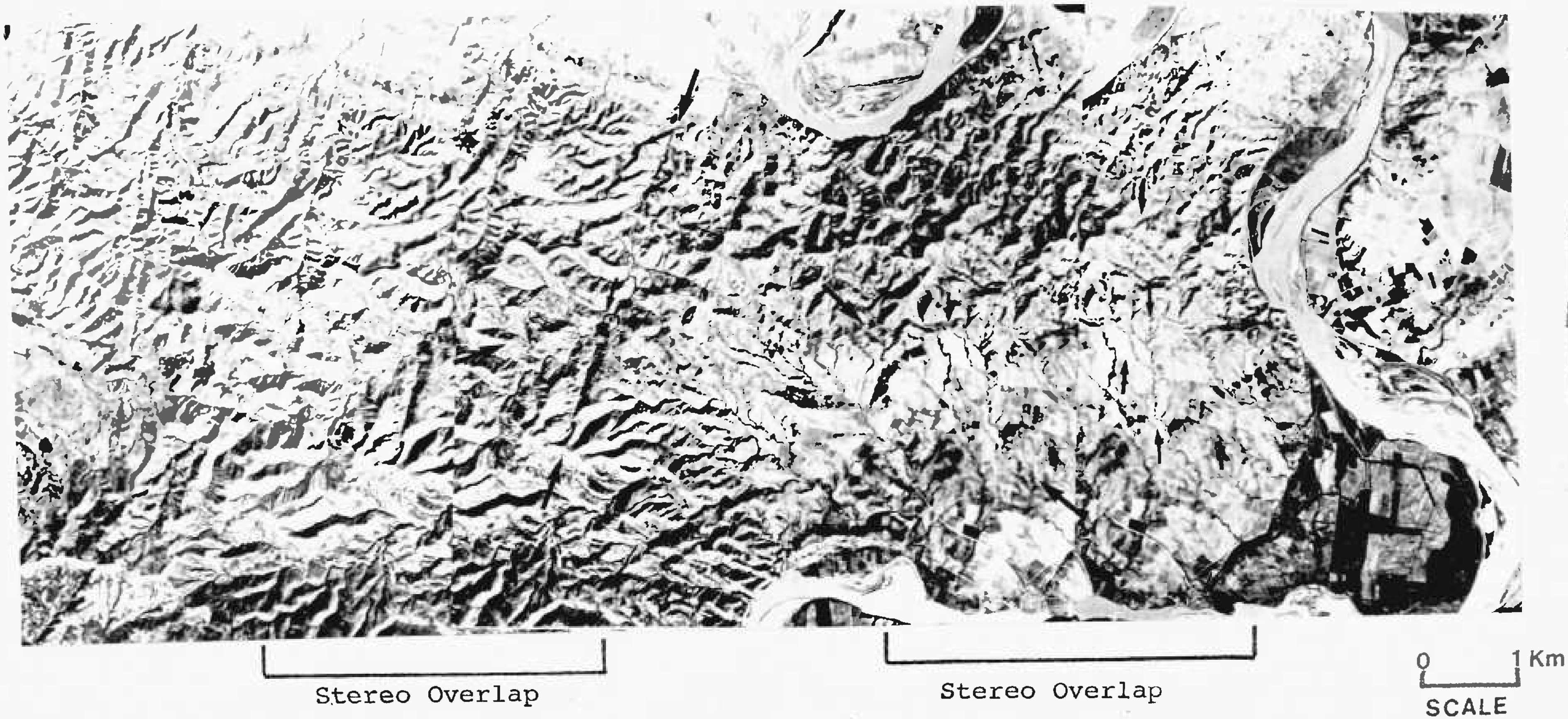
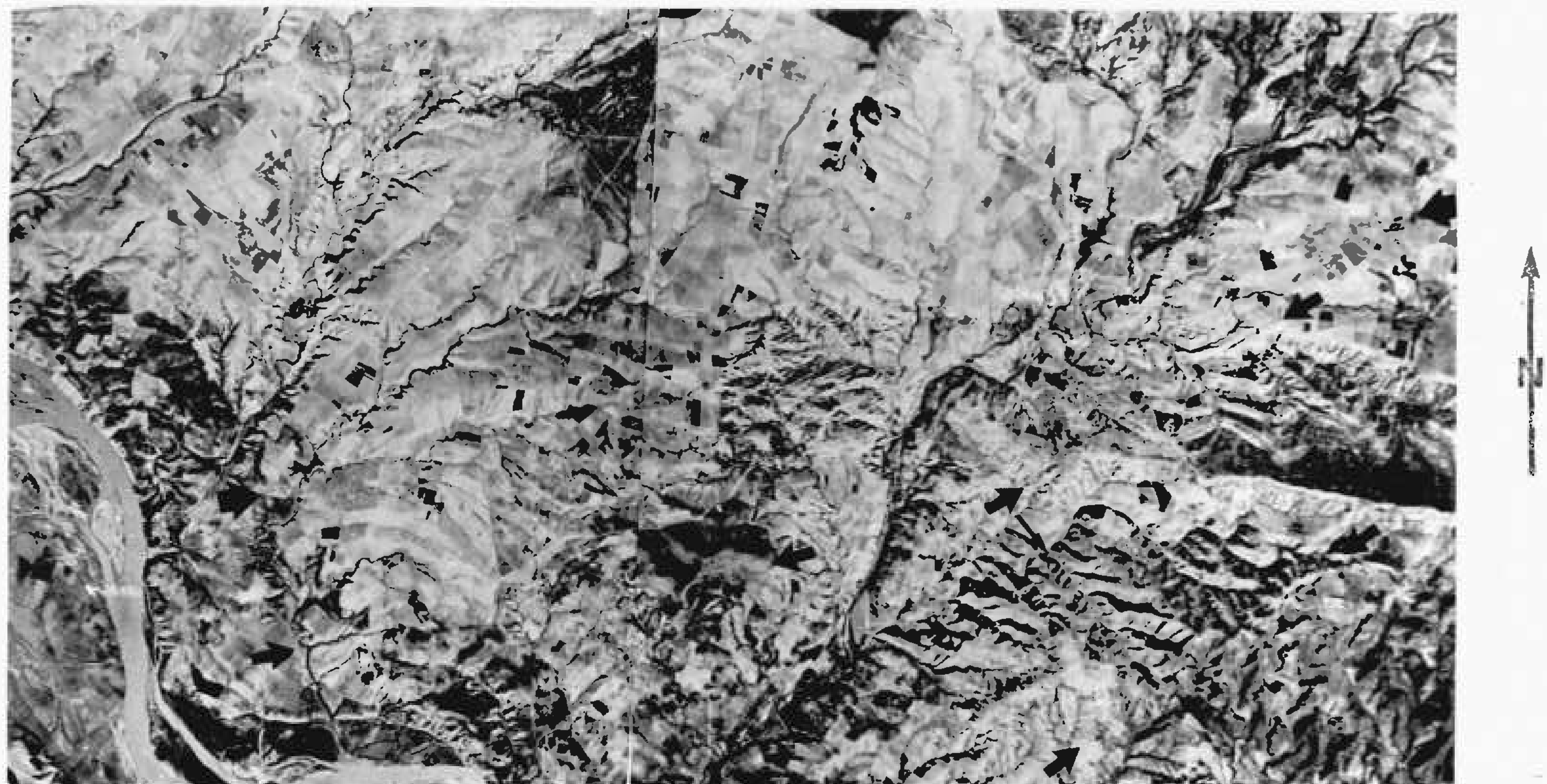


Plate 4

Plate 5

These air photographs exhibit a long fracture trace striking ENE and indicated by large arrows. Its presence is manisfested by a remarkable combination of drainage and soil tonal alignments. This fracture trace may well be a reflection of sub-surface failure.

Some short fracture traces detectable by similar criteria can be seen to the south of the long fracture trace.



0 1Km
SCALE

Plate 5

Plate 6

A stereo-pair of air photographs showing a fault occurring in the southern flank of the eastern part of Ain Zalah anticline. The rock displacement along the fault-line suggests right lateral movement (as indicated by arrows). To the south-east of the fault a few fracture traces striking parallel to the fault can also be seen. The directional (or geometrical) relationship between the axis of Ain Zalah anticline striking E - W and the above-mentioned fault and fracture traces striking NE suggest that they are shear failures. There is a short fracture trace striking almost N - S which crosses the fault. It is probably a tension fracture trace. Other examples of shear fracture traces also occur in the western part of the stereo-pair.

Plate 6

0 1Km
SCALE

Plate 7

A stereo-pair of air photographs covering a locality in the central east of the study area showing a prevalent system of shear fracture traces striking NE and NW. They are obliquely oriented to the general strike of the bedding traces (i.e. E - W) in the area. The rectilinear characteristics of some streams and their abrupt changes in course indicate the influence of fracture traces on the geomorphology of the terrain.

Plate 8

A stereo-pair illustrating examples of fracture traces which are detected and interpreted mainly by means of drainage system criteria.

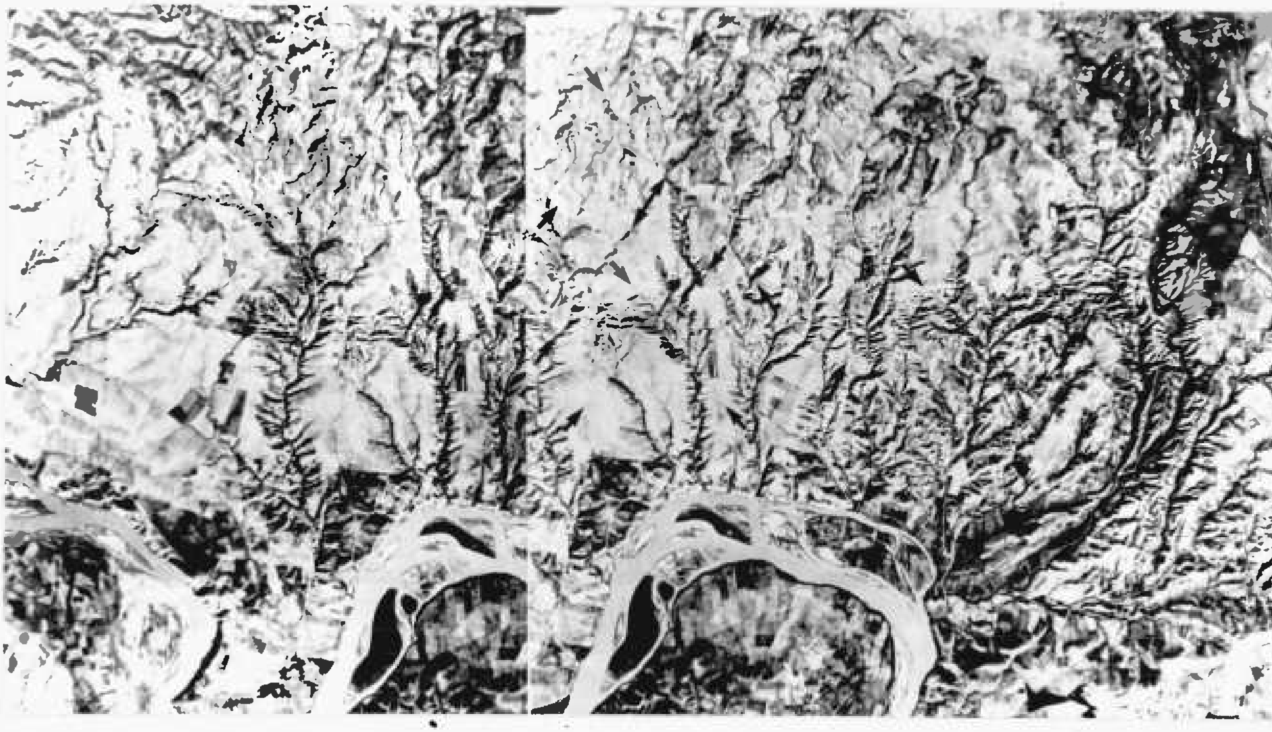


Plate 7

0 1 Km
SCALE

N

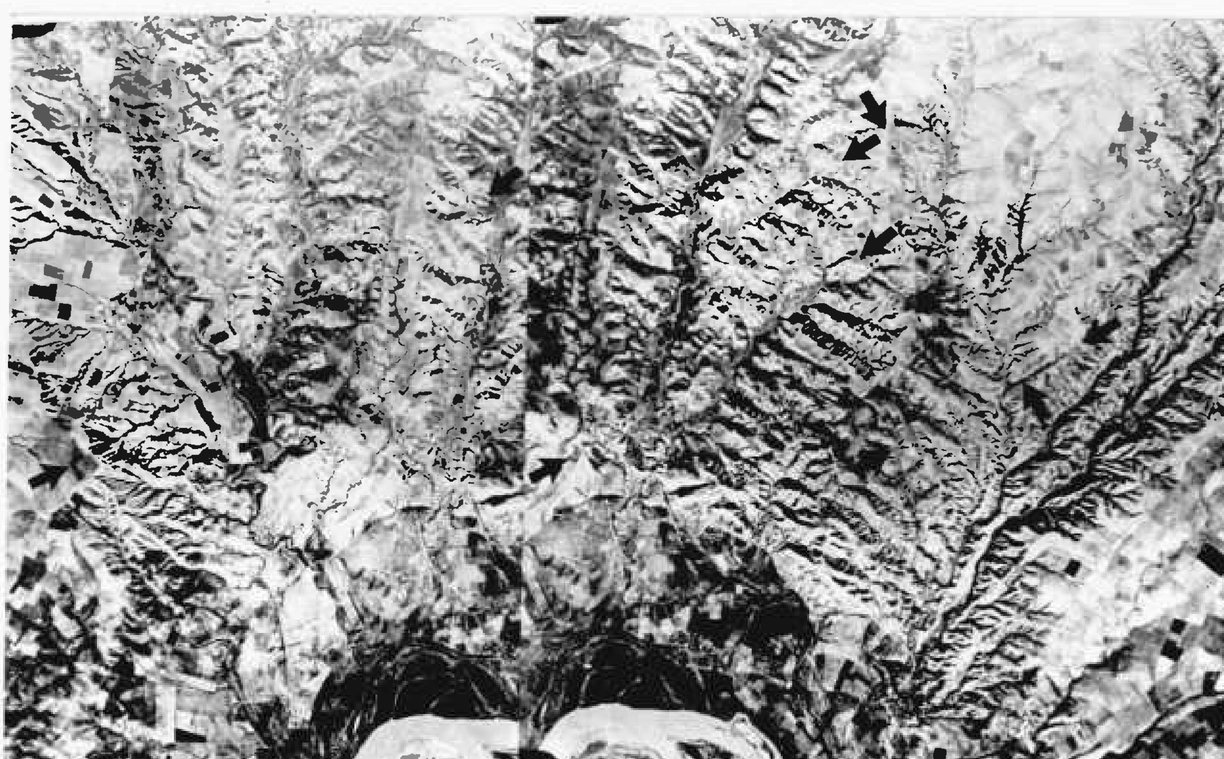


Plate 8

0 1 Km
SCALE

Plate 9

A stereo-pair showing anomalous characteristics of drainage which indicate fracture traces.

Plate 10

An air photograph showing a very straight stream occurring in the northern part of the study area. This stream represents a long fracture trace or linear zone of rock failure controlling the course of the stream. There are four parallel fracture traces striking ENE, and two of them cross the stream. The above-mentioned fracture traces are detectable by soil tonal difference and drainage alignment criteria.

0 1 Km
SCALE

Plate 9

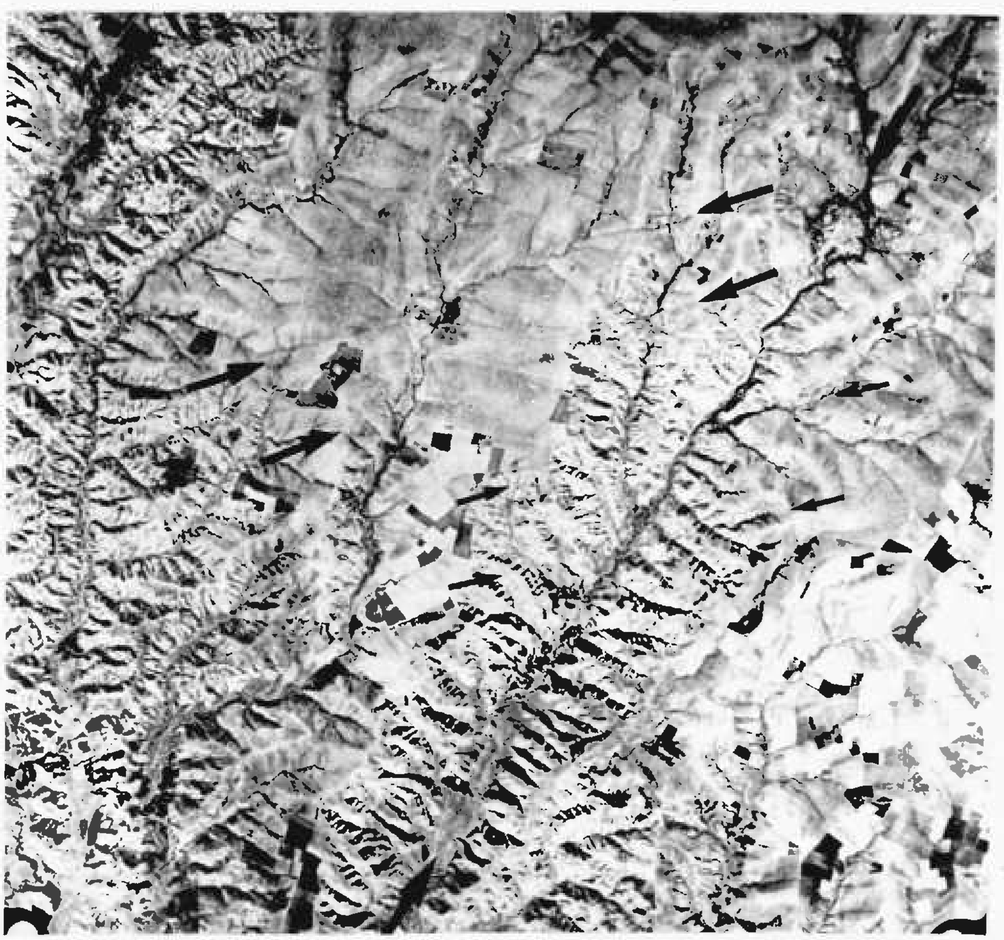


Plate 10

0 1 Km
SCALE

Plate 11

A ground photograph of a locality in the central (or crestal) region of Ain Zalah anticline. It shows a thin limestone bed lying horizontally over massive anhydrite rock. Both rocks are related to the Lower Fars formation. The occurrence of such a geological feature is quite common in the axial areas of most of the anticlines in the study area.

Plate 12

A mosaic of ground photographs showing a locality on the northern flank of Ain Zalah anticline. The limestone beds of the Lower Fars have undergone a slight arching (or local doming) caused by upward expansion of the underlying anhydrite rock. This phenomenon is common in Northern Iraq and is ascribed to a hydration process which occurs in massive anhydrite rocks of the Lower Fars subjected to water and weathering. Gypsum usually forms as a result of this process.

Plate 11

Plate 12

Plate 13

A ground photograph taken at the southern flank of Ain Zalah anticline (near western plunging end) showing two sets of open joints intersecting each other at almost 90 degrees.

Plate 14

A ground photograph showing a system of tension joints consisting of two sets intersecting each other almost orthogonally. The locality of this photograph is the same as in Plate 13.

Plate 13

Plate 14

Plate 15

A ground photograph showing an example of rather closed and slightly weathered shear joints intersecting each other at acute angles, and occurring in the central part of the southern flank of Ain Zalah anticline. A similar jointing pattern in the limestone can be encountered frequently on both flanks of the anticline.

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