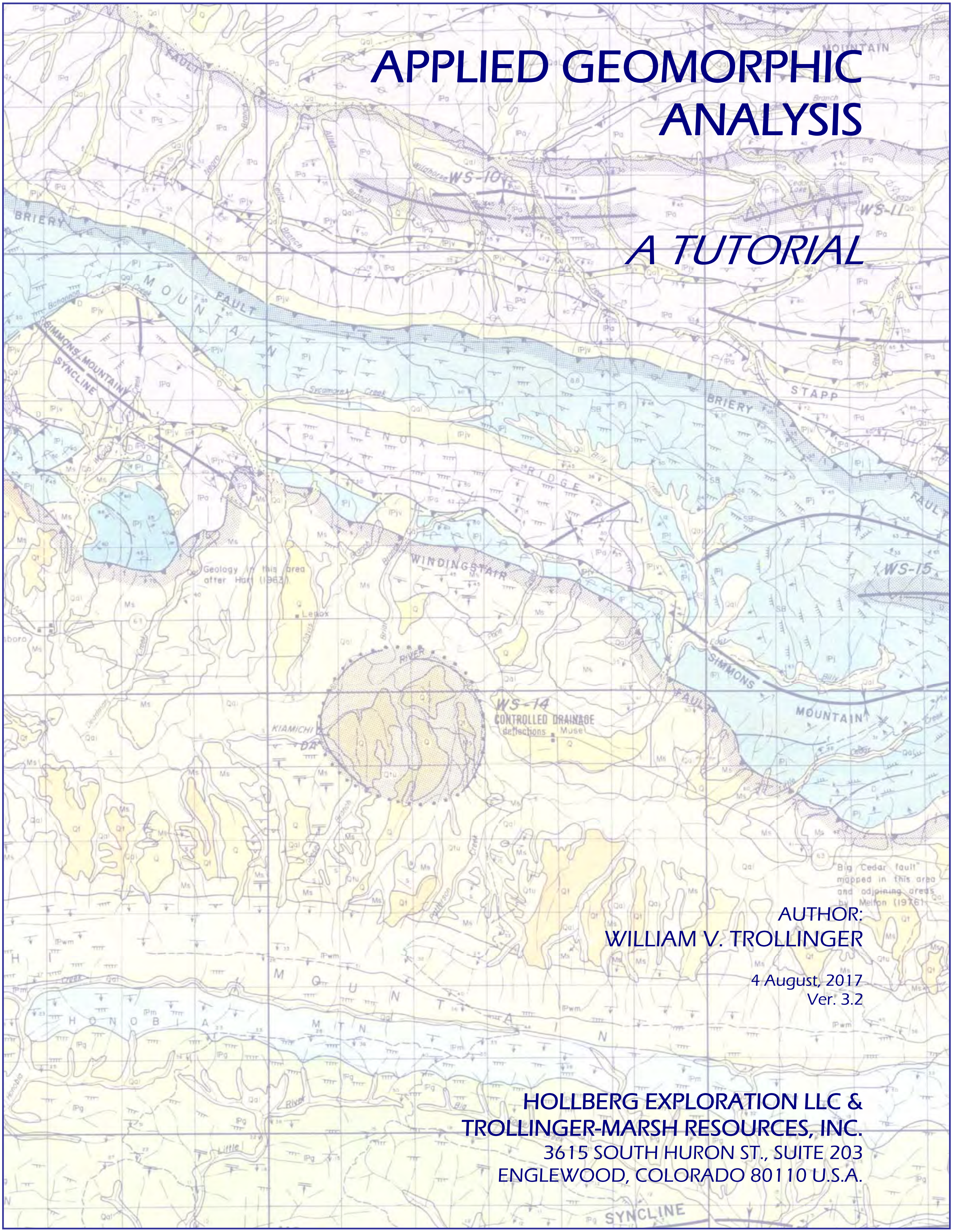


# APPLIED GEOMORPHIC ANALYSIS

## *A TUTORIAL*


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# INTRODUCTION

HOLLBERG EXPLOATION LLC & TROLLINGER-MARSH RESOURCES, INC. (HOLLBERG/HOLLBERG/TMR) is a consulting firm for natural resources exploration specializing in comprehensive photogeologic-geomorphic mapping and advanced remote sensing analysis. HOLLBERG/TMR was established to provide developing countries and international oil and gas companies with broad scale natural resources investigations – using computer enhanced satellite imagery and special purpose aerial photography – not only in areas of abundant outcrops and obvious structure but also in low dip, mantled and heavily vegetated areas where the surface has been long ignored in the search for energy and other natural resources.

THE HOLLBERG/TMR ORGANIZATION was founded on its principals' long experience and reputation for extracting the maximum amount of useful geologic and geomorphic detail from aerial photographs and satellite imagery. HOLLBERG/TMR and its predecessor company, Trollinger Geological Associates, Inc. (TGA), have conducted mapping projects covering more than six million square kilometers of the earth's surface. Pioneers in developing effective methods in applied geomorphic techniques and satellite image analysis, the HOLLBERG/TMR team continues to lead the way in conducting timely and efficient natural resource evaluations and successful energy resources exploration in every part of the globe.

IN RECENT YEARS, HOLLBERG/TMR has consulted for a number of developing countries in North Africa, Asia, and the Middle East as they looked to develop their natural resources. In one instance, HOLLBERG/TMR's work resulted in a major gas discovery; in another instance, HOLLBERG/TMR's studies resulted in a complete revision of the country's five-year economic and development plan.

Standard photogeologic structural and stratigraphic methods are inadequate to effectively map many areas of the world, areas of:

- Limited rock outcrops,
- Very gently-dipping strata,
- Poorly indurated surface formations,
- Dense vegetation, alluvial deposits,
- Areas of extensive sand dune cover, and
- Glaciated regions.

In these regions it is necessary to supplement "standard" photogeologic mapping techniques with **detailed geomorphic analysis** to thoroughly analyze the surface for clues to subsurface geologic conditions.

This paper has been prepared to describe the techniques our company, HOLLBERG EXPLORATION LLC & Trollinger-Marsh Resources, Inc. (HOLLBERG/TMR) has developed and utilized for more than 35 years of photogeologic-geomorphic mapping.

# APPLIED GEOMORPHIC ANALYSIS

In this paper, "standard" photogeologic methods refer to stratigraphic and structural analyses by detailed stereoscopic examination of aerial or satellite images, including photography, multi-spectral scanner, thematic mapper or radar imagery. These studies always begin with an analysis of all available publications and geologic maps of the region. Stratigraphic units for photogeologic mapping are selected on the basis of three criteria: (1) consistency with published literature; (2) photo-appearance and ease of mapping as lithologic units; and, (3) value for structural and geomorphic interpretation. The attitudes of the strata are visually determined and dip symbols used to denote the direction and amount of dip of the sedimentary formations. Faults, lineaments, anticlinal and synclinal axes and other structural features are observed and indicated on the maps.

However, in many areas of limited rock outcrops, as described earlier, standard methods fall short of revealing all the clues the surface has to give regarding subsurface geologic conditions. In these areas, geomorphic analysis is required.

## GEOMORPHIC ANALYSIS

Geomorphic analysis or "applied" geomorphology, is simply the application of geomorphic principles to geologic problems.

Geomorphic analysis is <u>not</u> a search for anomalies, but rather a methodical study of norms. The purpose of this paper is to summarize a rationale – a practical approach to geomorphic analysis for petroleum and mineral exploration.

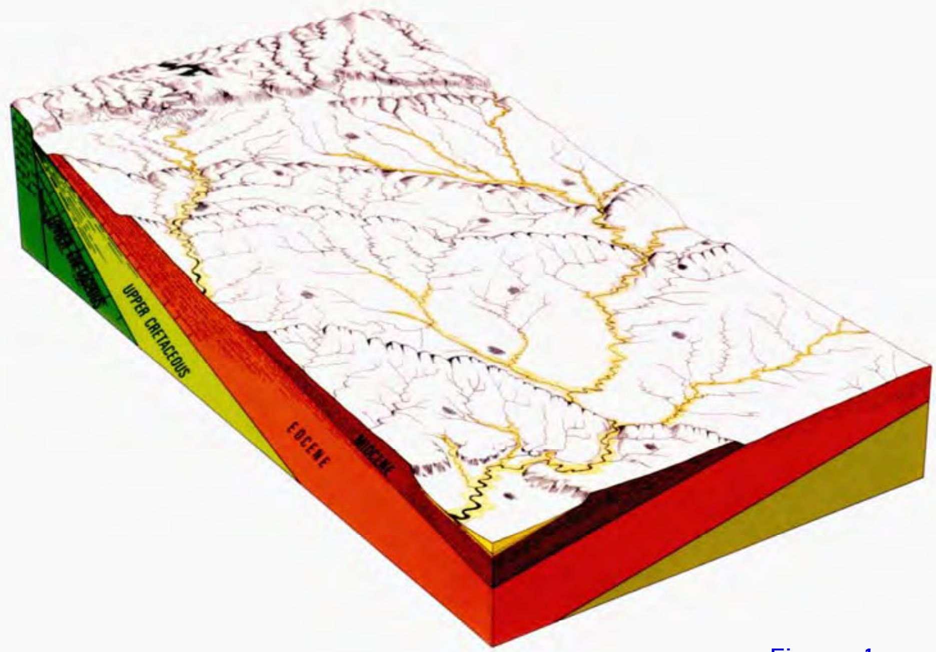



Figure 1

The rationale is simply this. Geomorphic analysis is concerned first with determining the degree of influence which structure and lithology of surface or near-surface formations have had on the morphologic development of an area. By establishing regional relationships between geologic and geomorphic features, local "interruptions" to regional "norms" take on increased significance as indicators of buried structural and (or) stratigraphic anomalies. This generalized block diagram of the Austin, Texas, 1:250,000 Quad (Figure 1) illustrates the close relations between morphology and geology in a typical coastal plain region. The area is in the mature stage of the geomorphic cycle and the terrain and drainage system have developed in sensitive response to the lithologic and structural peculiarities of the underlying bedrock.

Generally, there are four basic facets, which are quite interrelated, of detailed geomorphic analysis. These are:

- Drainage Analysis
- Landform Analysis
- Fracture Patterns Analysis
- Photo tonal (or color) Analysis

Due to special conditions in some areas, the study might also involve:

- Desert or Sand Dune Analysis
- Glacial Analysis
- Bathymetric (Sub-sea Topographic) Analysis

The following summary explanation of geomorphic analysis is considered to be general for the technique.

## DRAINAGE ANALYSIS

Drainage analysis is the study of regional drainage systems and individual stream courses with respect to genesis, texture, uniformity, orientation and form. This study involves the analysis of both wet and dry drainage channels, easily seen on the aerial photographs or satellite imagery. Drainage "patterns" reflect the influence of the lithologic and structural character of the underlying rocks, as well as the climate, age and erosional position of the area.

## GENETIC TYPES

It is generally necessary to study the behavior of an entire drainage system in order to appreciate the significance of local irregularities of the individual streams. The first step is to determine the genetic types of streams represented in the area under examination. The following types are significant: Consequent streams flow in the direction of the initial slope of the land surface, often concordant with the direction of dip of the strata. Resequent streams are recent consequent streams developed at a lower level, and are frequently tributary to subsequent streams. Subsequent streams develop valleys along belts of underlying weak rock and are often called "strike streams" because they generally follow the strike of the formations. Obsequent streams flow in a direction opposite to the dip of the strata, generally opposite to that of the original consequent streams of the area. They flow down the steep sides of cuestas in homoclinal beds and are usually shorter than the nearby consequent and resequent streams. Insequent streams are those that are not controlled by any detectable cause. These are often young and not yet "adjusted" to the lithology or material in which they are flowing. Superimposed streams extend across geologic structure older than itself, having been let down from a younger terrain which has been removed by erosion. An Antecedent stream extends across geologic structure younger than itself, having kept pace with uplift by rapid downcutting of the uplifted area.

## DRAINAGE TEXTURES:

The most significant effect of lithologic control on drainage development is that of drainage texture. Texture (or drainage density) refers to the relative spacing of all drainage lines in terms of fine, medium and coarse, and is readily observed on the aerial photographs. Permeability of the surface rock is the most important factor influencing drainage texture, although other factors are involved. Where the surface rocks are relatively impervious and easily eroded, internal drainage is retarded and a fine-textured drainage network of closely spaced channels develops. In areas of pervious rock affording greater internal drainage, surface erosion is retarded, and coarse-textured drainage with widely spaced channels develops.

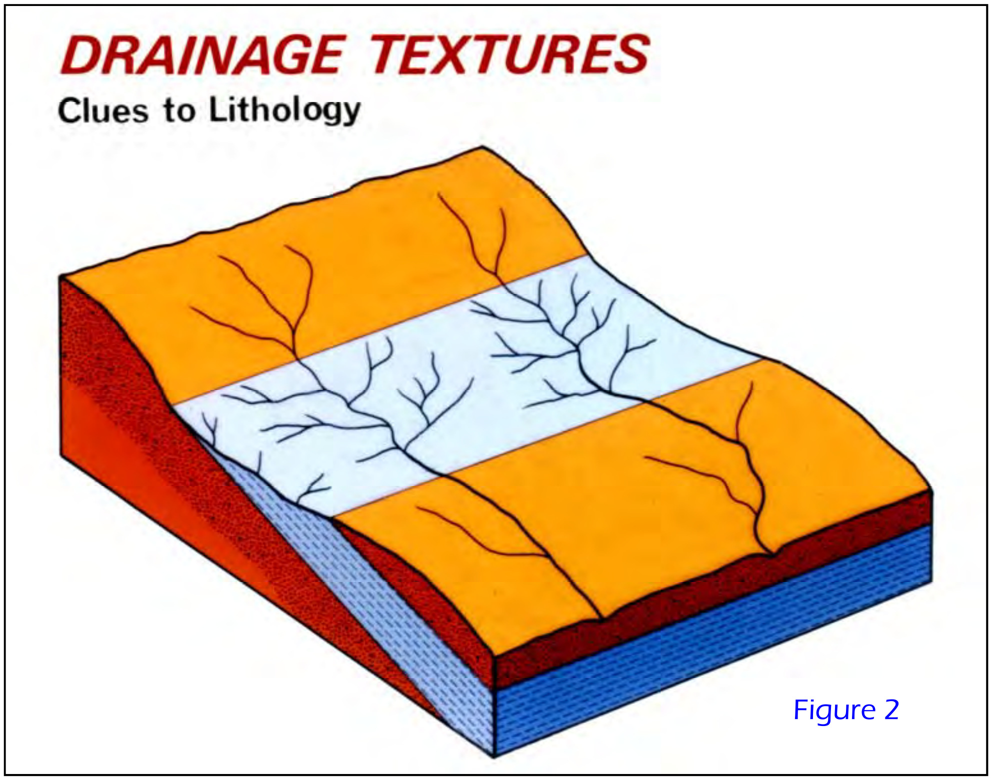



Figure 2 illustrates this principle, showing more streams per unit area developed on shale than on sandstone beds.

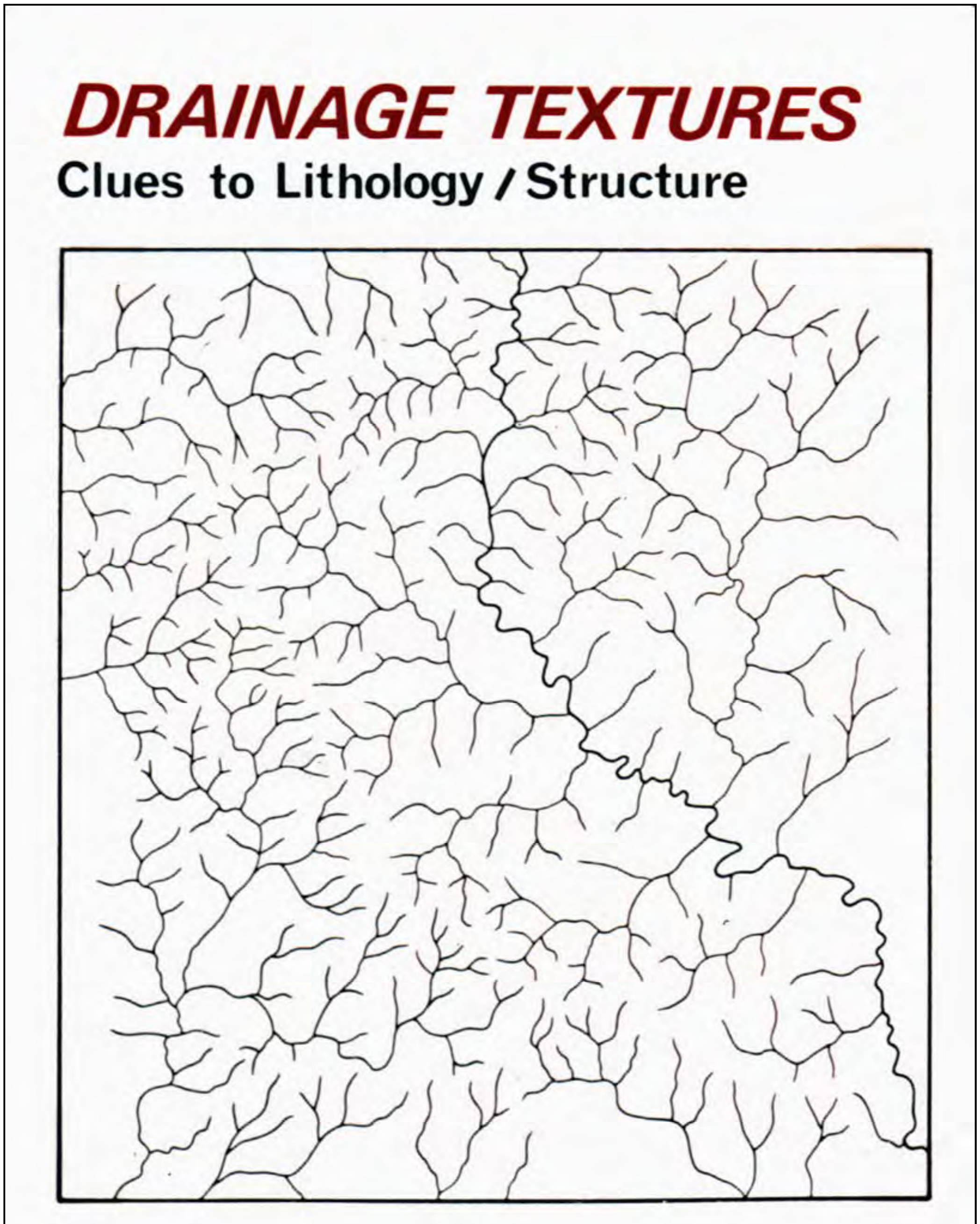
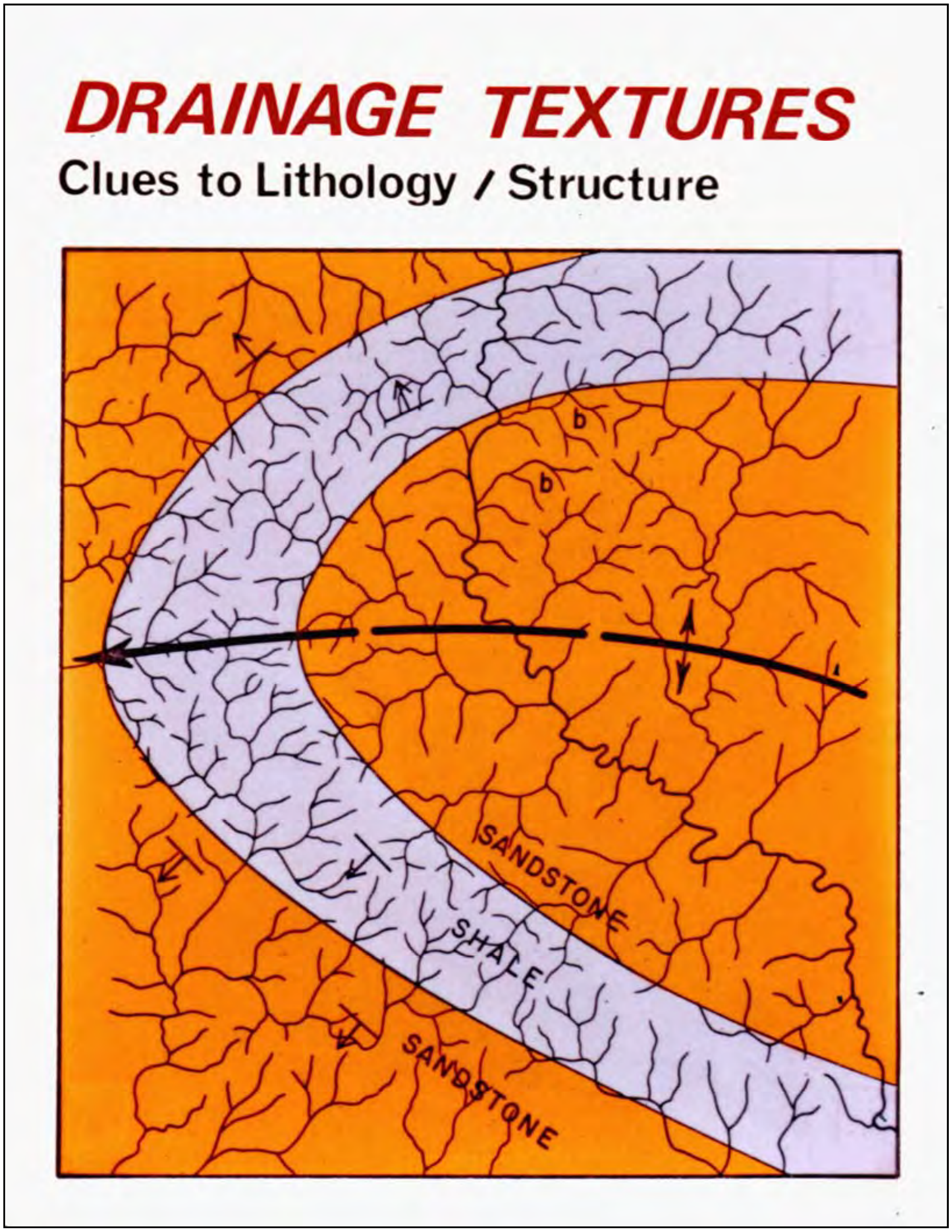



Figure 3

The usefulness of drainage textures as an aid to geologic mapping is depicted in Figure 3, a drainage pattern in the Ucayali basin of Peru. A belt of relatively fine-textured drainage, flanked by less dense streams, pointed the way to an anticlinal fold within this generally featureless, rain-forest jungle (Figure 4).




These changes aid in determining areas of differing lithologies, sometimes to a remarkable degree of accuracy, on the photographs. In areas of gently dipping sedimentary rocks, belts of differing lithologies become apparent though no outcrops are present. This interpreted "outcrop pattern" aids in determining regional and local structure.

## DRAINAGE PROFILES:

Drainage profiles are also important. Stereoscopic viewing of aerial photographs and satellite images permits the geomorphologist to study streams in three-dimensional profile. Cross-section profiles of gullies and stream valleys are useful indicators of surface soils and sub-soil lithologies (Figure 5); particularly in heavily cultivated or jungle areas. Shallow-rounded forms indicate cohesive, fine-grained materials. Deep-rounded or deep-rectangular forms indicate moderately cohesive materials (loess); V-shaped forms denote non-cohesive materials.

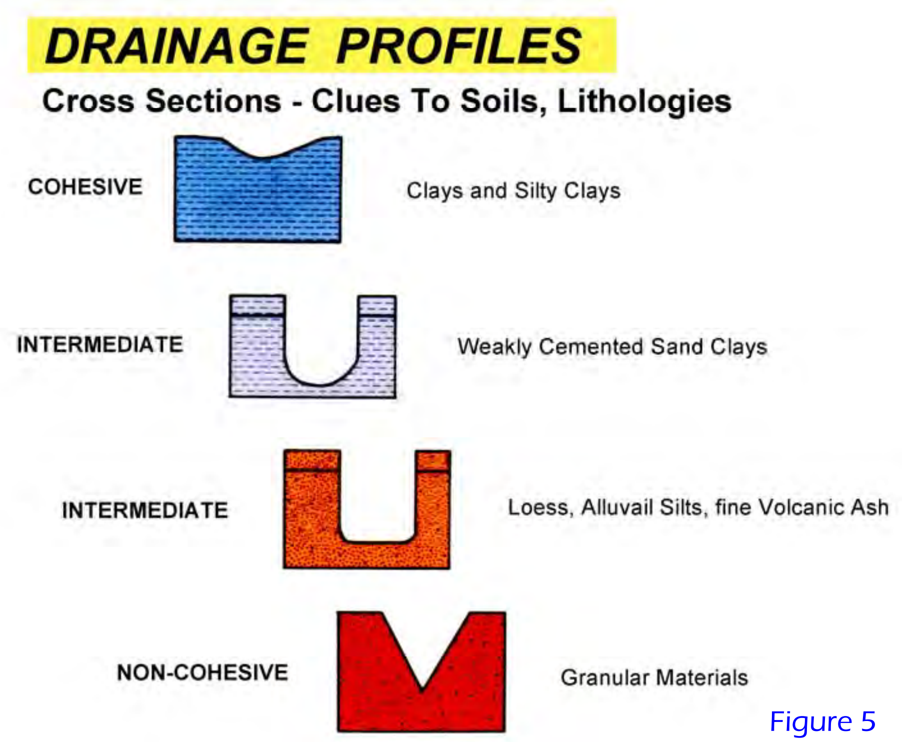
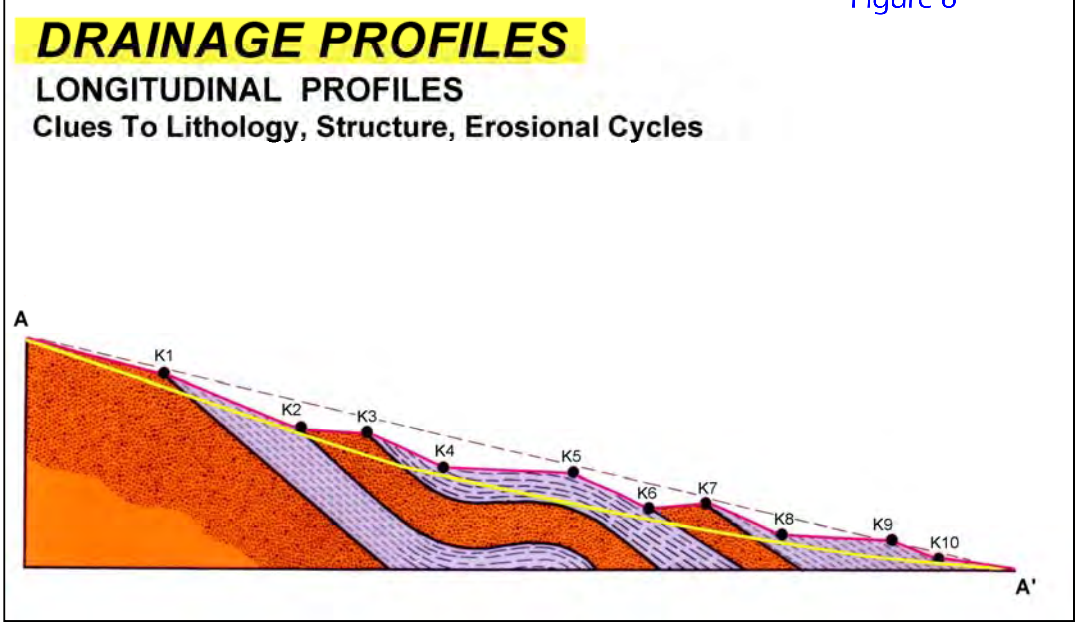


Figure 5

Longitudinal profiles are of significant interest to the geomorphologist. When studied in detail, they often furnish important information regarding lithology, structure and erosional history. The longitudinal profile of a graded stream, a profile of equilibrium, is never a straight line (as shown by dashed lines, Figure 6). It is generally pictured as a smooth, concave- upward hyperbolic curve decreasing in slope gradually down-valley (yellow line); however, this theoretical condition is seldom found. In reality, there are often graded and ungraded stretches along the stream course. The breaks between these stretches are often abrupt, and are called "knickpunkte" or, in English, nickpoints.

Figure 6



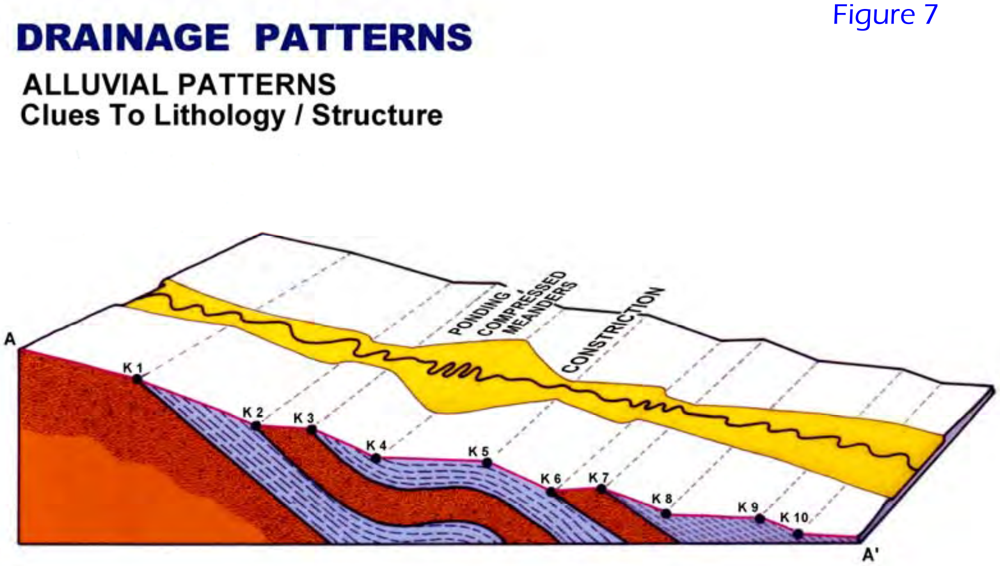

Nickpoints occur as a result of several factors. They are often found at the interface between resistant and non-resistant rock units. A hard sandstone for instance, encountered downstream from soft shale, will cause an abrupt reduction of gradient as shown at K2. The gradient will be increased again as a softer formation is crossed farther downstream, as at K3. Subtle nickpoints have been discerned in the vicinity of structural uplift, even where no noticeable change in lithology is observed, as at K4 and K5. Nickpoints related to structure and lithology are almost always temporary; that is, they will ultimately be breached by further erosion. In some cases, nickpoints are found which are not related to lithology or structure and are interpreted as the headward limits of successive periods of base leveling, as at K8, K9 and K10.

## DRAINAGE PATTERNS:

Insofar as lithology affects drainage texture and uniformity, structure has a dominant role in controlling the form and orientation of most drainage patterns. Only a few of the more significant ones are discussed here.

Alluvial patterns often have great significance (Figure 7). Under normal conditions, alluvial valleys broaden gradually downstream. Variations in this condition may indicate changes in bedrock or structure. Downstream narrowing of alluvial valleys often indicates the presence of a more resistant stratum, as at K2-K3, or the presence of local structure, as at K5. Anomalous alluvial buildups, sometimes referred to as "alluvial ponding", often occur immediately upstream from a lithologic or structural "barrier". These may be accompanied by zones of "compressed meanders", further indicating a reduction of stream gradient.

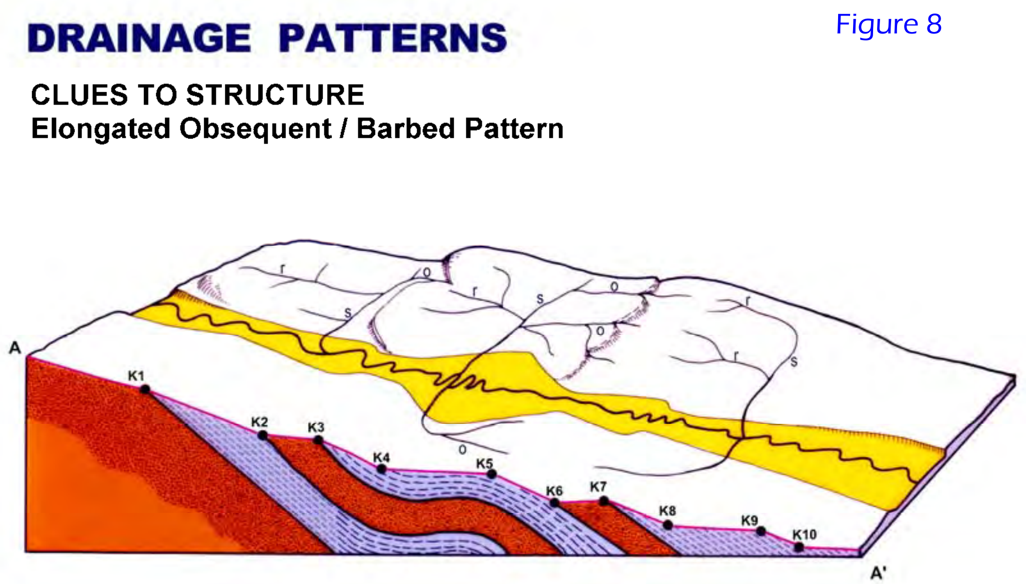
Figure 7



Nickpoints and anomalous alluvial patterns are simply "interruptions" to an accepted regional norm. When evaluating them as clues to hidden structure, they must first be studied in light of the probability that they reflect only changes in lithology or erosional cycles.

Perhaps the most significant drainage pattern "interruption" in low-dipping homoclinal beds is the presence of "elongated" obsequent streams (Figure 8).

Figure 8



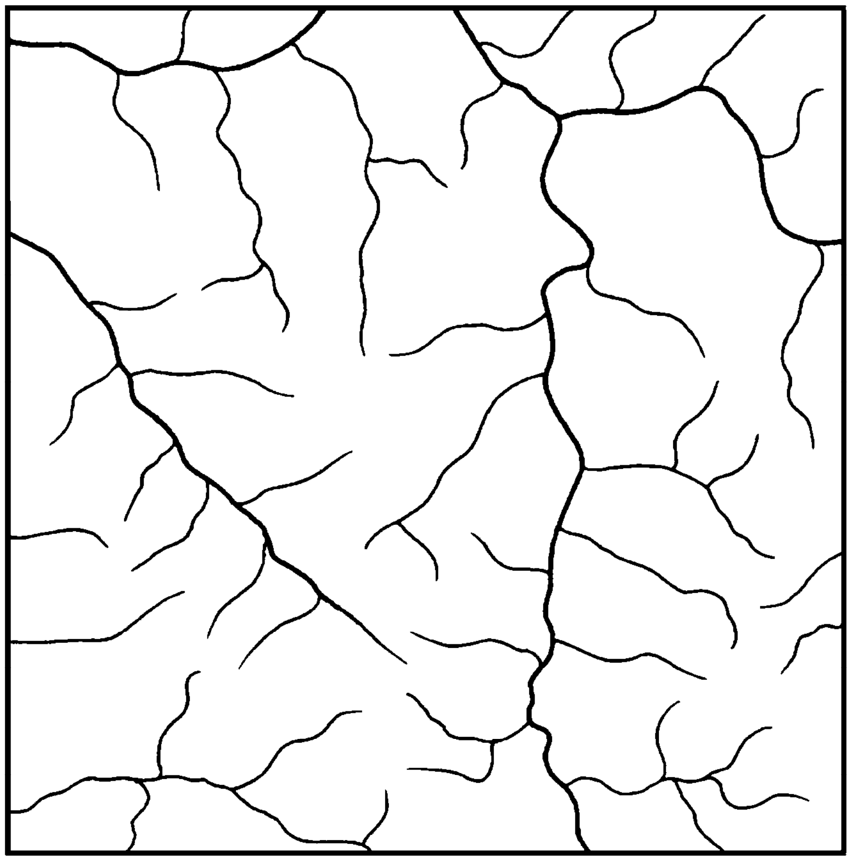

"Dip-slope" resequent streams are typically longer than their obsequent counterparts. Where this condition is reversed, and the obsequent drainages are abnormally lengthened, the presence of local uplift is strongly suspected. The elongated obsequents flow in a direction opposite to the major consequent drainages and often enter these in "boathook" bends, a pattern referred to as "barbed" drainage. The topographic forms associated with elongated obsequents are often recognized to be anomalous. This "reverse" topography condition is a useful and supportive criterion for discerning buried structure.

Uniformity of drainage patterns is an important indicator of lithologic control. For example, a dendritic pattern (Figures 9, 10) implies a uniform or homogeneous lithologic character of the underlying rock, and a general lack of structural control. This pattern is characterized by irregular branching and re-branching of tributaries in all directions and at any angle, but normally at less than a right angle.

DENDRITIC PATTERN IN SHALE

Figure 9

A change in the uniform pattern, i.e., an increase in angularity, parallelism, and angle of confluence sometimes indicates a change in lithologic character or increase in structural control.

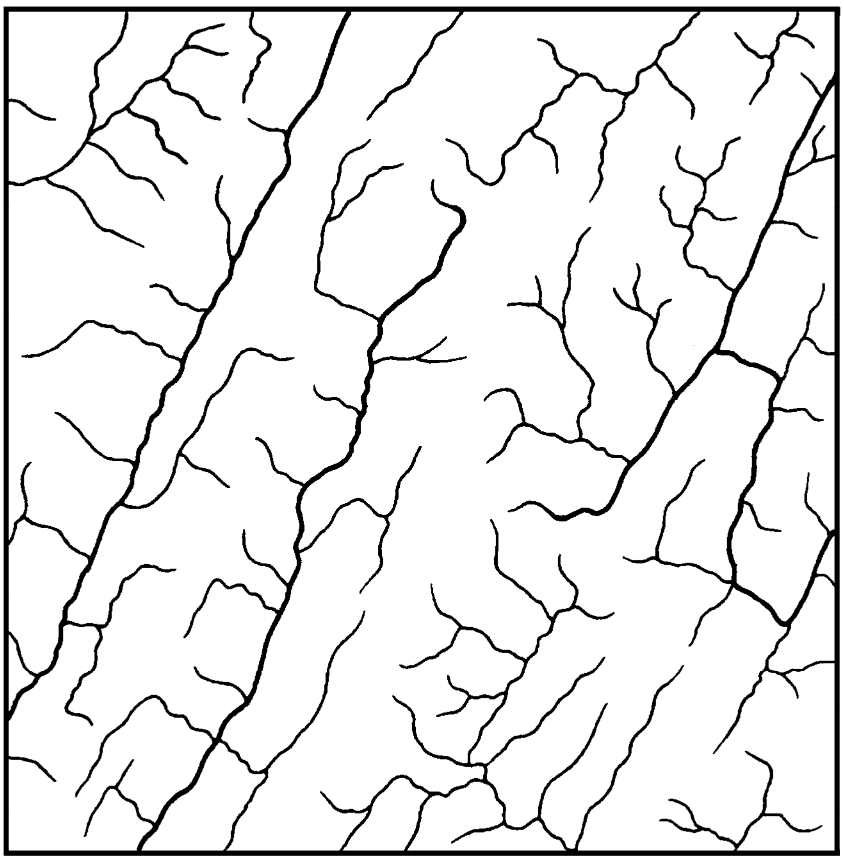


DENDRITIC PATTERN IN LIMESTONE

Figure 10

## SUMMARIES OF OTHER TYPICAL DRAINAGE PATTERNS:

**Trellis drainage** (Figure 11) displays a pattern of parallel or subparallel streams joined at right angles by shorter tributaries which are parallel or subparallel to each other. The longer streams are aligned along the strike of strongly folded or dipping rocks.



TRELLIS DRAINAGE PATTERN

Figure 11

Rectangular drainage (Figure 12) reflects fault or fracture control. It is characterized by right-angle bends of the main and tributary streams.

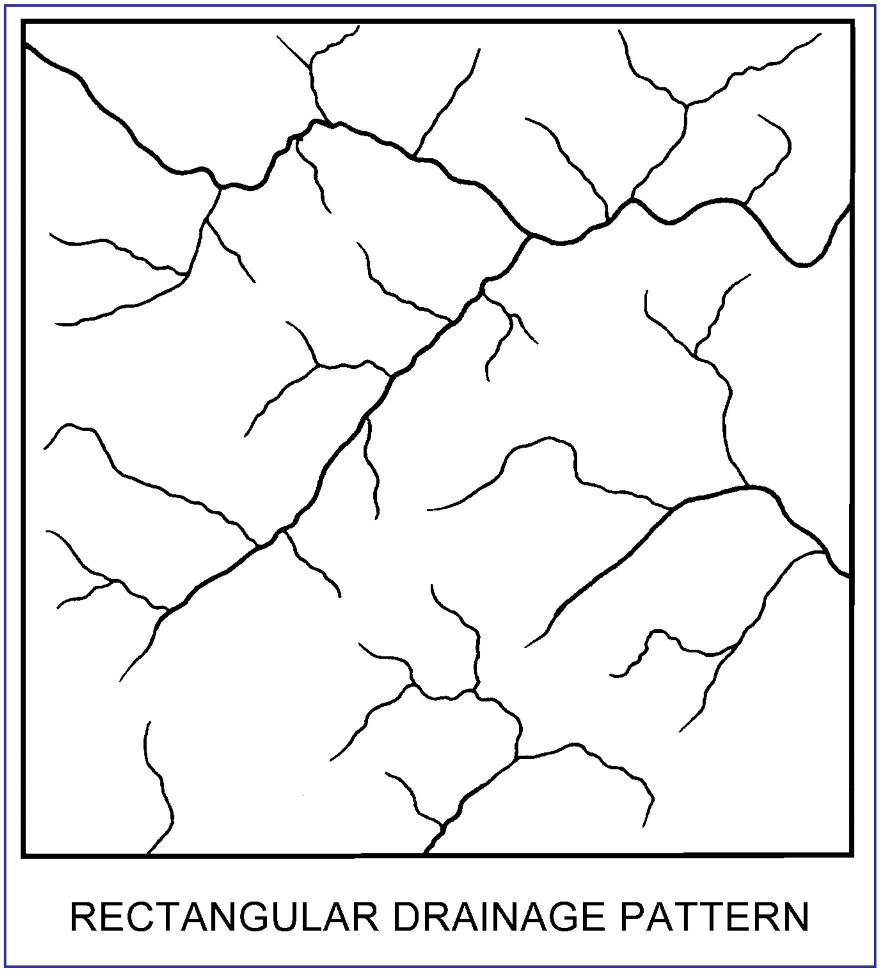
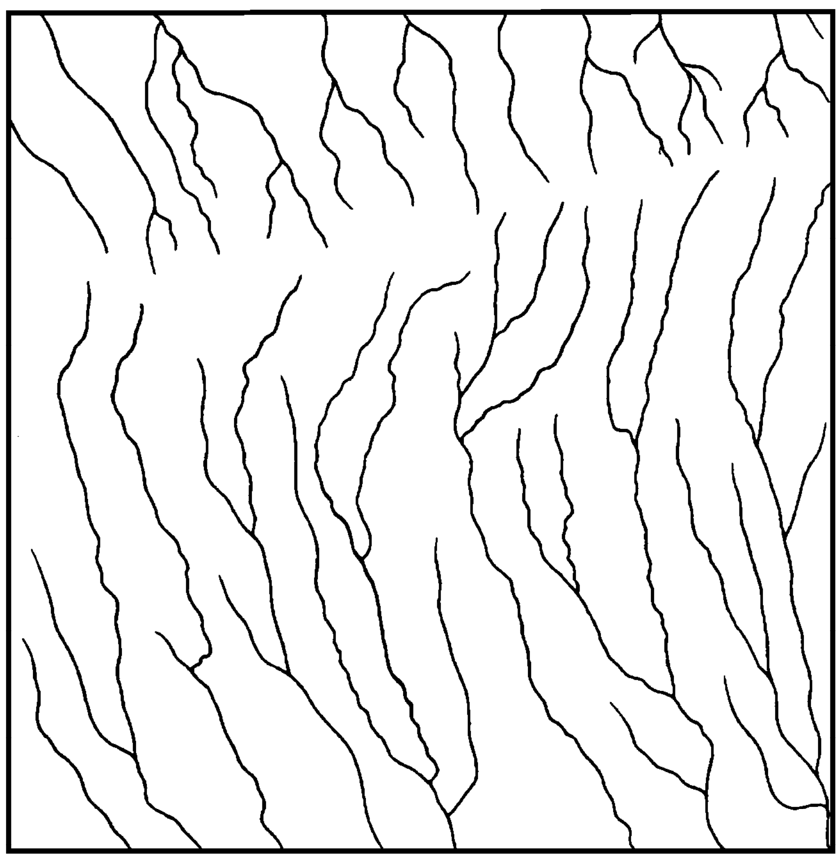



Figure 12

Parallel drainage (Figure 13) describes a system of streams that flow parallel to one another in the direction of the slope of the land surface. This is a common "youthful" pattern seen in alluvial fans bordering mountain ranges.



PARALLEL DRAINAGE PATTERN

Figure 13

Centripetal drainage (Figure 14) lines converge into a central depression. This pattern is frequently characteristic of synclines and other structural depressions.

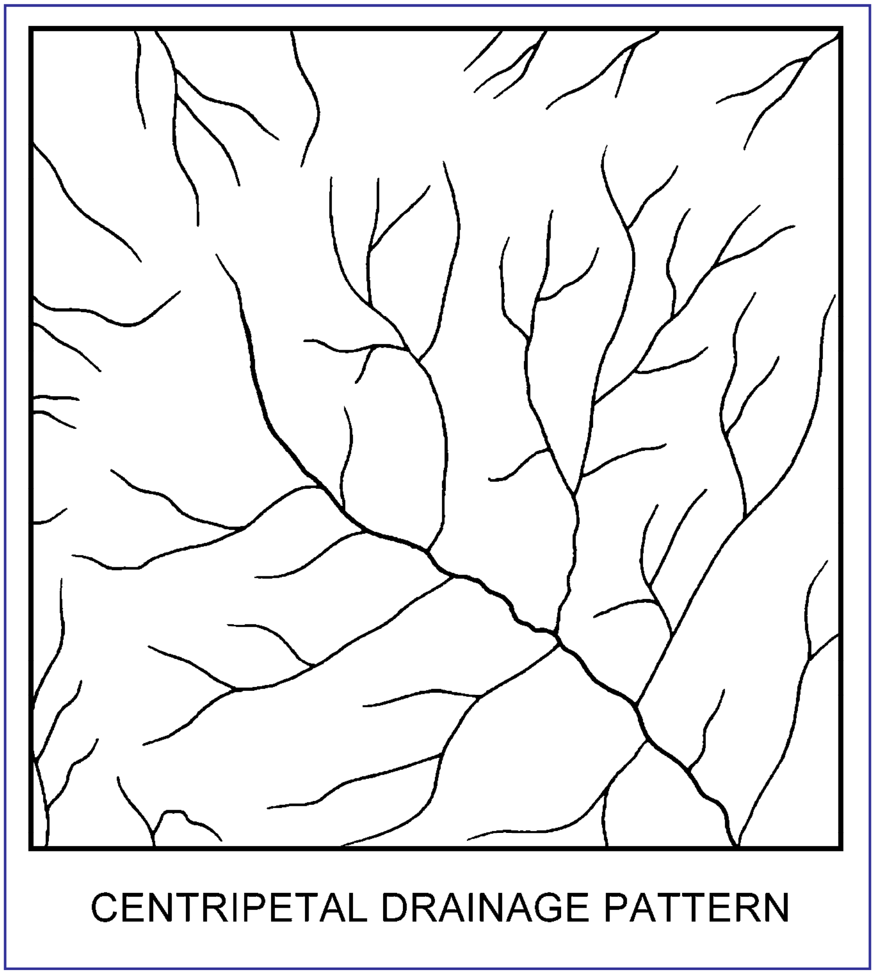
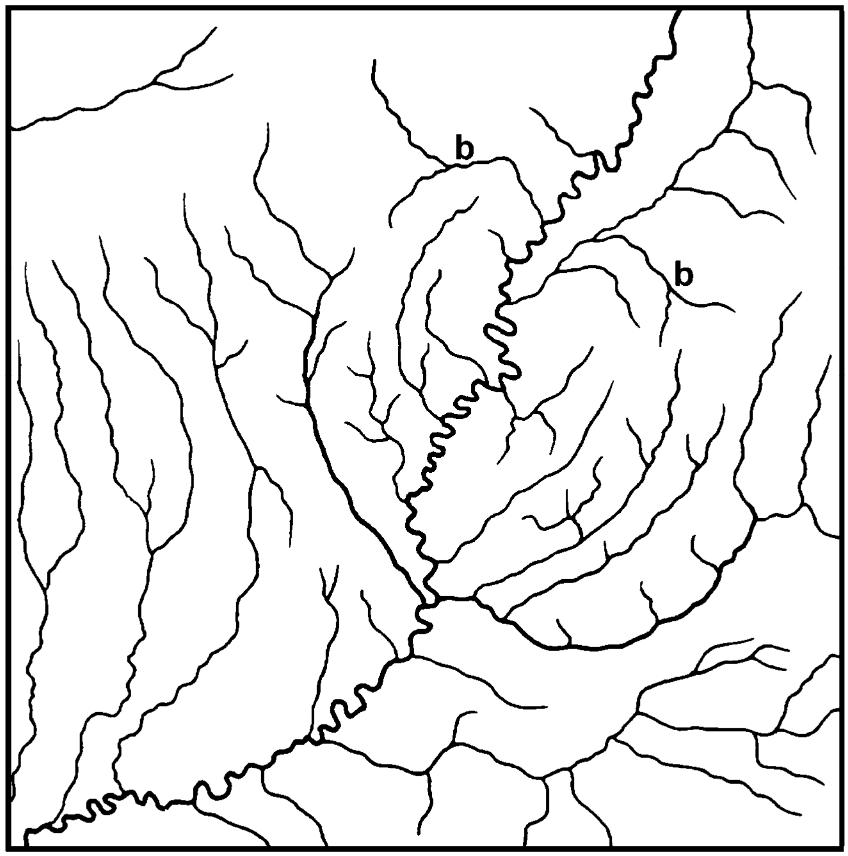



Figure 14

**Annular drainage** (Figure 15) exhibits arcuate subsequent streams which tend to encircle a domal or anticlinal uplift..




ANNULAR DRAINAGE PATTERN

Figure 15

Barbed drainage (Figure 16) refers to tributaries entering larger streams in "boathook bends" which point upstream. This pattern may reflect structural uplift, but is commonly caused by stream piracy.

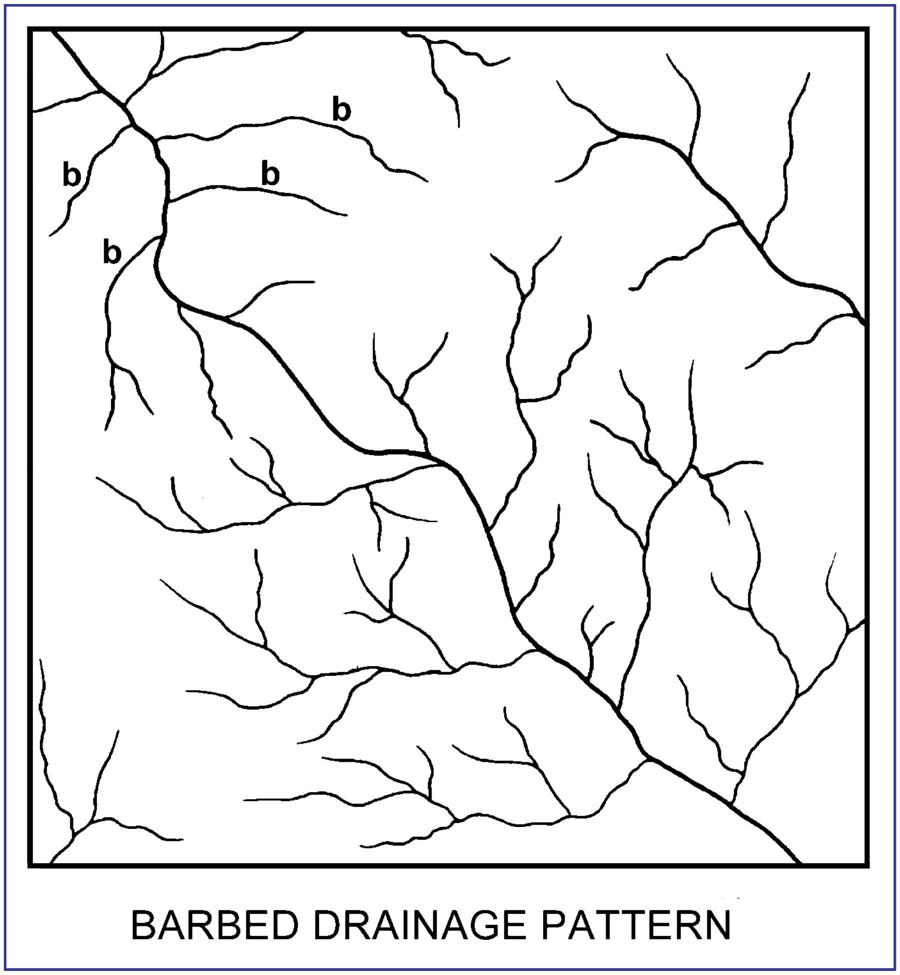
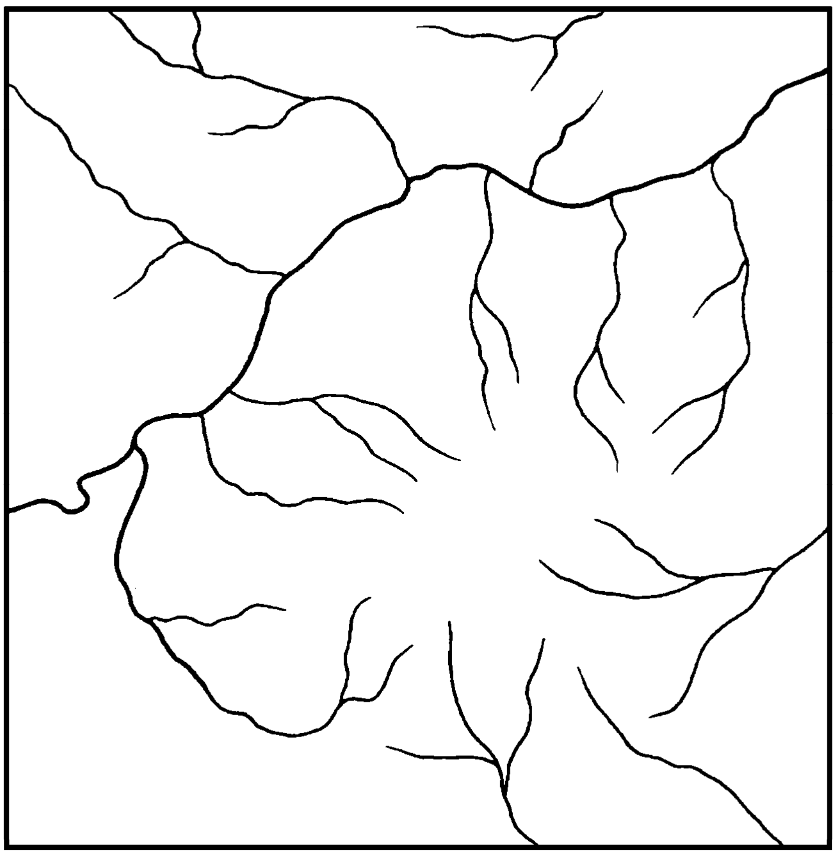



Figure 16

Radial drainage (Figure 17) emanates from a topographically high area, and is significant when developed in association with a structurally high area. This pattern generally will not stand alone as the determining evidence of structure, as it may be developed on topography unrelated to structure.



RADIAL DRAINAGE PATTERN

Figure 17

Deflected drainage (Figure 18) refers to streams that have been abruptly diverted from their normal course, usually indicative of structural control by a fault, fold or lithologic barrier.

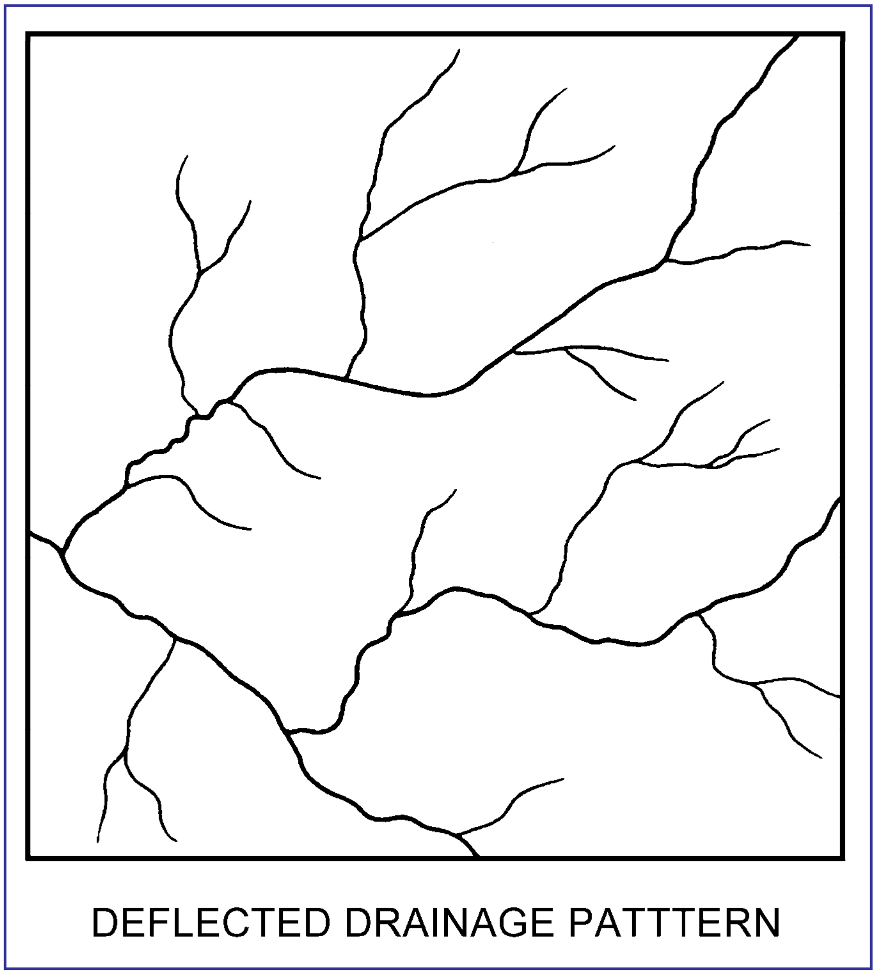



Figure 18

Climate, age and erosional position have significant modifying effects upon the development of drainage patterns. The greater precipitation of an area in a humid climate results in more intensive sub-aerial erosion, finer textures and more completely integrated patterns than an area of similar lithology in an arid climate. A relatively young, underdeveloped pattern will be less useful for interpretive purposes than an older pattern which is "adjusted" to the lithology and structure of the underlying rocks. A very low erosional position may result in a characteristic "constructional" pattern, whereas a higher position in similar lithology would result in the normal "destructional" drainage pattern.

## LANDFORM ANALYSIS

It is not possible to separate detailed landform analysis from drainage analysis, because the two subjects are closely interrelated. Landforms, products of sub-aerial erosion of which stream action is a major factor, bear a distinct correlation to the characteristics of the sculpturing agents that have acted upon them.

A landmass can be thought of as passing through several stages of development, much like that of a stream. The initial state of dissection, although seldom found, represents that period when the block is relatively undissected and drainage has just begun to develop. The youthful state is that early period of active stream development and dissection characterized by steep slopes and V-shaped valleys. Yet much of the original surface remains. The mature state is characterized by more moderate slopes and near complete removal of the original landmass. The old age stage is represented by very low topography with only isolated hills rising above the featureless plain. Much of the lower topography is now adjusted to the new base level.

Landform analysis, like drainage analysis, is most effective when the area has reached the mature stage of the geomorphic cycle, where the terrain and drainage system have developed in sensitive response to the lithologic and structural peculiarities of the underlying bedrock. In the initial and early youthful stages, the topography and streams have not had time to carve their geologic impact on the landscape. In old age, much of the lower topography is a "constructional" plain which tends to mask many of the details of the underlying geology.

In some regions, the prevailing topography is generally concordant with the geologic structure. Some of the principal examples are anticlinal mountains and synclinal valleys, seaward-dipping coastal plains, and lava-capped plateaus. Landform interpretation in these regions is relatively simple.

In most regions however, the land surface does not precisely coincide with the underlying geologic structure. In some areas of "inverted" topography, geologic structure and topography are exactly reversed. This is generally the result of relatively strongly folded alternating resistant and nonresistant sedimentary rocks where the older units are less resistant than the younger. For most areas however, rock units extend across various topographic forms and intersect them in a variety of ways. Landform interpretation in these areas is more difficult and is dependent upon the geomorphologist's diligence and experience.

In areas of limited erosion, some geologic features can be discerned by their shape alone. These include sand dunes, alluvial fans, cinder cones, lava-capped plateaus, glacial moraines and uneroded structural domes. After their original form has been modified by erosion, interpretation is often more difficult.

However, sub-aerial erosion is an important aid, and not a detriment, to landform interpretation. Differential erosion, by progressively removing the less resistant rocks more rapidly than the resistant units, tends to etch the lithologic and structural imprint on the landscape in a vivid manner. The geomorphologist needs to recognize the subtle as well as the obvious products of differential erosion.

## TYPICAL FEATURES PRODUCED BY DIFFERENTIAL EROSION

*strike ridges* - often represent the key to unraveling the geology in heavily vegetated or mantled areas. Usually accompanied by angular drainage, parallel or sub-parallel subsequent streams. The trend and continuity of ridge lines are most important, particularly when it is determined that the ridges are strike ridges. Disruptions in trend and continuity often reflect abrupt structural changes (faults, sharp folds, etc.).

*dip slopes* - hogback patterns where dip is steep, cuestas where dip is gentle. "Slope asymmetry" is one of the most important factors in landform analysis. The geomorphologist must be sensitive to the relative slopes on opposite sides of a ridge as well as to the erosional and drainage differences. These provide clues to whether one of the slopes is a dip slope and which one reflects the dip of the strata. In most gently dipping areas, the obsequent slope is usually greater than the resequent slope, the streams are shorter and more angular, and the topography is more rugged and irregular. In areas of steep dip however, the resequent slope (dip slope) might be as steep or steeper than the obsequent. Also, some of the other criteria might also be reversed; therefore, slope asymmetry should not be considered to be an infallible criterion for dip determination.

*zig-zag (or looping) ridges and valleys* - often reflect plunging anticlines and synclines.

*parallel ridges* - often reflect non-plunging folds. These can also reflect simple strike ridges in homoclinal regions.

*circular hills or mountains* - might represent volcanic necks or plugs, or structural domes. Also might represent isolated erosional remnants underlain by horizontal strata.

*linear wall-like ridges* - might represent igneous dikes or resistant veins where host rock is more easily eroded. If the reverse is true, linear depressions will often result. Sometimes (rarely) dike-like ridges are the result of faulting.

*sharp linear topographic breaks* - might reflect the presence of a fault. Often accompanied by incised subsequent stream. These are more easily detected if they intersect or offset the regional topographic patterns.

Thus, landform analysis is an important aspect of detailed geomorphic analysis. The geomorphologist must be particularly concerned with topographic shape and form, asymmetry or lack of it, continuity and trend of ridge lines, and the myriad of accompanying erosional and drainage characteristics. It is absolutely necessary that he begin his study by developing a regional understanding of the relations between morphology and geology so that he will be able to recognize an "anomaly" when he sees it.

## FRACTURE PATTERNS ANALYSIS

Fracture patterns analysis is an integral part of detailed geomorphic analysis, and is fundamental to any comprehensive photogeologic-geomorphic study for petroleum and mineral exploration. Because there is a great diversity of opinion among exploration geologists regarding the meaning and importance of fractures, a brief discussion of terminology is in order.

### TERMINOLOGY

*Fracture* - "a general term for any break in a rock, whether or not it causes displacement, due to mechanical failure by stress." For the purpose of this report, "fracture patterns analysis" is meant to include, not only fractures (rock breaks) but "lineaments" and "alignments."

*Lineaments* - "straight or gently curved, lengthy features of the earth's surface, frequently expressed topographically as depressions or lines of depressions; these are prominent on relief models, high-altitude aerial photographs, satellite imagery and radar imagery. In this report lineaments are regarded as "long linear geomorphic features having probable structural significance." Some authors use other terms (correctly or incorrectly) to refer to these features, such as "linears," "lineations" or "photolinears," and others.

*Alignment* - a colloquial (among photogeologists) term to refer to a short lineament (less than 8 km in length).

## SIGNIFICANCE

Many fractures and lineaments no doubt reflect lines or zones of crustal weakness. Some of these might represent shallow features of limited areal extent, whereas others might reflect regional basement lines of weakness. Experience has shown that generally, the longer the fault or lineament, the deeper its roots. These are likely reflections of basement faults which might have been recurrently active throughout much of geologic time.

The advent of space photography has enlarged the geologist's perspective so that he is able to discern many of the continental-size structural elements associated with the plate tectonic model. By using a combination of space imagery and large scale aerial photography, it is now possible to develop a comprehensive fracture patterns map, which can provide clues to the presence and significance of the regional tectonic features which might have exerted control on the genesis and development of basins, uplifts and associated subsidiary structural features. By integrating these data into the other elements of the photogeologic-geomorphic analysis, the resultant patterns should provide the basis for formulating a tectonic model for understanding the chronology of structural events affecting the region, and assist in localizing the most prospective areas for petroleum and mineral accumulations.

## METHODOLOGY

To achieve an effective study, two separate tasks are involved, detection and interpretation.

*Detection:* - Since the early days of photogeology, the task of mapping fractures and lineaments on aerial photography has been a controversial one. No doubt there has been as much "art" as science involved in this sometimes esoteric exercise. This is because linear features are manifested in so many different ways across the modern landscape. Sometimes the most subtly expressed features turn out to be reflections of the most important deep seated faults.

Stereoviewing is critical to effective fracture mapping. Many sharp topographic lineaments are not readily discernible on "monoscopic" images because of heavy vegetation, poor sun angle, etc. Moreover, without "stereo", it is virtually impossible to perceive offset relations which are necessary for the proper interpretation of fault types, direction and amount of throw, etc. In recent years many "monoscopic" lineaments studies have been accomplished using various satellite imagery. The results of a good number of these studies have been less than adequate, and could have been vastly improved if stereoviewing methods were used.

Obviously, experience is an important factor in discerning and mapping valid lineaments and other fractures. The experienced geomorphologist will have no trouble with the cultural features and will be better able to discern the presence of subtle lineaments in difficult terrains.

All visible rock breaks should be delineated on the imagery first, and proper symbols used to denote faults or joints. If the break is a fault, the sense of movement should be noted if possible; this might not be possible until the latter stages of the interpretation.

The mapping of lineaments (or alignments) is obviously a more difficult task. These may be expressed on the imagery as one or combinations of sharp topographic breaks, linear drainage lines, abruptly deflected drainage, aligned depressions or sink holes, zones of aligned local structural features, linear tonal/ color/vegetation breaks, etc. One of the most difficult tasks is to discern the presence of faults or lineaments, which are aligned parallel with the regional strike or structural/geomorphic grain of the area. In these cases, the interpreter must use other geomorphic clues.

The interpreter needs to be alert to structural or geomorphic lines that trend at an angle to the regional structural or geomorphic patterns. These important features will sometimes be reflected by a geomorphic or structural discordance across a very subtle lineament. This aspect sometimes becomes apparent only in the latter stages of interpretation, at the formlining or regional interpretation phase.

*Interpretation:* After the detection (mapping) of all visible faults, joints, lineaments and alignments, the next task is to interpret their significance. It is our view that this phase should not involve the fracture patterns alone, but should be accomplished in the context of all the structural, stratigraphic and other geomorphic criteria gathered in the overall photogeologic-geomorphic study.

It is possible that the longest and even the moderate-length zones might reflect important older, basement lines of weakness. Thus, it is necessary to study all the photogeologic information, stratigraphic trends, fold patterns and fracture/lineament systems to reconstruct the tectonic history and develop the overall geologic model for the area.

In addition to the regional analysis, several specific patterns are important.

*Zones of fracture intersection* - the intersection of prominent fracture/lineament trends in some areas is considered to have possible importance for petroleum and mineral accumulation.

*Zones of fracture concentration* - these often occur at the crest or along the margin of buried anticlinal folds; also, they might represent subsurface zones of fracture porosity development. In addition, these lines of weakness might be indicative of potential conduits for mineralization and(or) groundwater accumulations.

If these zones occur along long linear trends, they might represent older basement zones of weakness which have persisted throughout much of geologic time and along which strike/slip movements might have occurred. Accordingly, they might have had important influence on basin development and depositional trends.

## PHOTO TONAL (OR COLOR) ANALYSIS

Tonal analysis, when using black and white photography or imagery, is the term applied to the detailed study of numerous shades (or tones) of gray, ranging from black to white recorded on the photographs or imagery. Photo tonal characteristics are influenced by a myriad of factors many of which are geologically significant; among these are lithology, porosity, permeability, the chemical content of the surface materials, and the type and density of vegetation. Anomalous photo tonal characteristics, therefore, often reflect subtle structural anomalies.

Color analysis involves a similar interpretive approach, but is applied when viewing color photography or imagery. Color is especially useful in lithologic discrimination.

In areas of exposed bedrock the individual formations can often be distinguished by their distinct color or photo tone (shade of gray). The color or tone will change from place to place as a result of weathering. Photo tones will generally be darker for rock units that weather into irregular or mottled surfaces, than for those which weather into smooth textured surfaces.

If the bedrock is covered by thick soil or mantle, the resultant color or tone may or may not reflect the lithologic characteristics of the underlying rock units. This occurs because the development of soils is dependent upon many other factors; including climate, drainage, erosional position, vegetation and time. Therefore, care must be taken in studying variations in soil color, composition and texture as an indicator of underlying lithology. Cross-section drainage analysis is often very useful in this context.

The moisture content of the surface materials is most important. Relatively dry materials appear lighter toned than wetter ones. Since in a given area the amount of rainfall should be constant, the relative amount of moisture as indicated by tone is most important. While moisture also affects vegetation, it generally produces the same effect in regard to photo tones, i.e., an increase in moisture causes an increase in vegetation and a corresponding increase in darker tones.

Vegetation may help or hinder photogeologic analysis. Distinct changes in vegetation type occur along soil or rock contact zones, generally as a result of the changes in porosity, moisture and chemical content of the various surface materials. Therefore, vegetation patterns can be a helpful indicator of changes in underlying geologic conditions.

Thus, anomalous photo tonal or color characteristics can often be subtle reflections of subsurface structural anomalies such as anticlines, domes or faults. Distinct color or tonal changes are often indicators of altered rocks in association with mineral deposits. More often than not however, a valid color/tonal anomaly is often accompanied by anomalous drainage, landform or fracture patterns characteristics as supporting evidence.

"False color" images are the typical product of computer enhanced digital data (Landsat, Thematic Mapper). Subtle distinctions between bedrock lithologies and soil types and the identification of local mineralized zones are greatly enhanced by these products. However, effective interpretation of these images requires an understanding of the wave-length bands used and the processing techniques involved.

## SPECIAL TYPE AREAS

Due to special conditions in certain type areas, detailed geomorphic analysis must necessarily be studied with special reference to the unique geologic setting. The following examples will illustrate this principle.

### DESERT OR SAND DUNE ANALYSIS

Geomorphic interpretation, in search of clues to subsurface geologic conditions in the great deserts of the world, is most difficult. Many geologists believe it is nearly impossible. This is easy to understand.

Outcrops are sparse. In these seas of sand, the dunes are waves and outcrops are islands. Surface drainage is virtually non-existent due to the porous nature of the surface materials. The topographic forms are considered to be products of surficial processes (wind) having little to do with subsurface geologic conditions. In many desert regions photogeologic analysis reveals however, that when studied in light of applied geomorphic analysis, the surface offers numerous clues to subsurface geologic conditions.

As stated earlier, effective geomorphic analysis requires an understanding of "normal" sand dune patterns, and interruptions to that "norm" might reflect underlying geologic anomalies.

First it is necessary to distinguish between the various sand dune types in the region. For many areas, five types of dunes can be identified. These are (1) linear (longitudinal, sief), (2) crescentic (barchan), (3) parabolic, (4) star; and, (5) dome shaped dunes. The boundaries between the different type dunes, particularly if they are abrupt, often indicate changes in topography (and thus possibly geology) of the bedrock below.

In many places, distinctive surface alignments can be mapped where abrupt changes in dune pattern occur. These are easiest to map where the change takes place at a strong angle to the dunes themselves. These features are interpreted to possibly reflect faults, fractures, etc. or strike or "grain" of the underlying formations.

Dune deflections and abrupt local changes in dune direction are often noted to reflect changes in underlying topography (and hence geologic) conditions.

## GLACIAL ANALYSIS

It is commonly thought that there are no definitive relationships between glacial features and bedrock structure. Contrary to popular belief, continental ice sheets do <u>not</u> characteristically plane down all the pre-glacial topography and obliterate all relief features encountered in their paths.

While being modified by glaciation, the pre-glacial surface often exerts considerable influence on the ice movement. Rather than being essentially destroyed by the glaciation, the pre-glacial surface of many areas is only modified by the repeated advances of glacial ice. Modifications of a destructional nature take the form of streamlining the more prominent topographic features and subduing their relief to varying degrees. Modifications of a constructional nature result from deposition of glacial materials onto the pre-glacial surface. The resultant glacial topography has much in common with the pre-existing topography, the former being a subdued representation of the latter.

Glacial analysis is concerned with establishing relationships between glacial features (and associated surface phenomena) and bedrock geologic conditions. In order to establish definitive relationships, it is first necessary to gain a thorough understanding of the regional glacial history. All previously published reports and maps are studies for background information regarding chronology of glacial events, and the extent, duration, and effects that glaciation has had on the subject area.

This research is followed by detailed mapping of the various glacial deposits and study of their composition, thickness, areal patterns and distribution. During this phase of the evaluation, the other facets of geomorphic structural analysis, i.e., drainage, land form, fracture pattern and photo tonal analyses, are applied to the problem.

The next phase of analysis is concerned with determining the degree of influence that the pre-glacial bedrock surface had on regional glaciation. This requires a knowledge of (1) the lithologic characteristics of underlying bedrock, (2) the regional structure of the underlying bedrock, (3) the degree (stage) of dissection of the underlying bedrock, and the (4) pre-glacial drainage patterns that existed prior to the advance of the earliest ice sheet. This information is obtained by study of all published reports and maps in light of the detailed data revealed by the photogeologic-geomorphic evaluation.

The final phase of the evaluation is the interpretive stage. This involves a logical determination of which anomalous surface features can be reasonably classified as indications of bedrock structural and(or) stratigraphic anomalies, and which are indicative of surficial, geologically unimportant, conditions.

Thus, the geomorphic evaluation is essentially an exhaustive study in applied glacial analysis, with the main objective being to determine as much as possible about subglacial bedrock geologic conditions.

The following example illustrates the extent of control pre-glacial surfaces exert on the movement of continental ice sheets. Figure 19 was taken from the colored map showing the glacial deposits in the northern and western part of Ohio. The purple colored area in the southern and south-central areas is Illinoian deposits. The remainder of the shaded area is Wisconsin glacial deposits. The dark bands are end moraines, occurring as long linear belts of thicker till rising above the ground moraine. These were formed when the rate of advance of the ice sheet equaled the rate of melting. The advancing ice

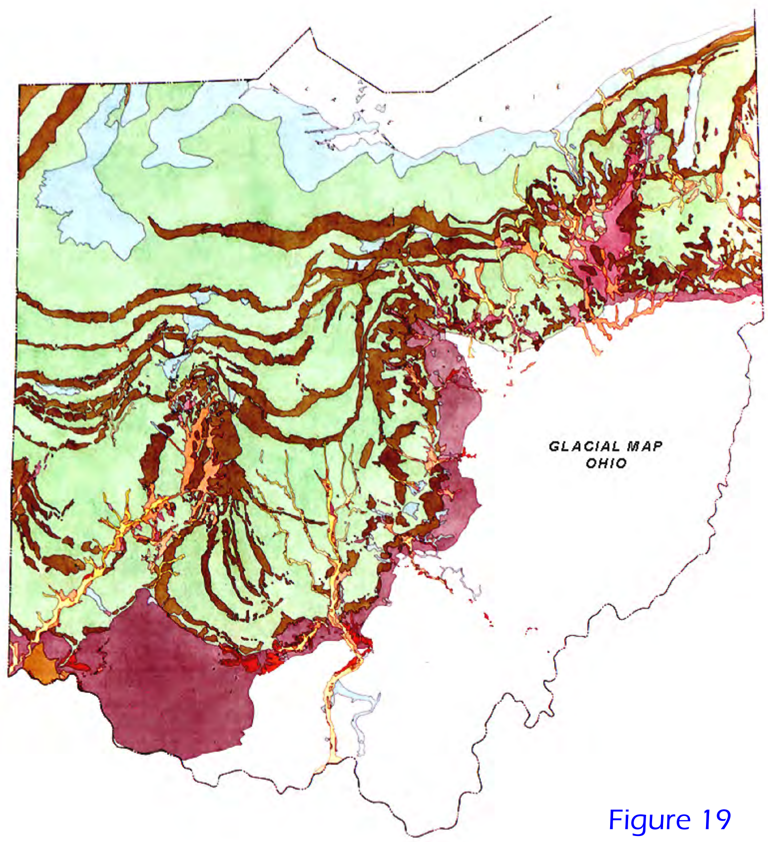


Figure 19

continued to transport debris to the melting edge, resulting in a hummocky buildup of material. These moraines clearly mark the position and direction of the ice advances into Ohio.

The glaciers advanced from a major center in Labrador, moved through the Erie Basin and spread southward in a series of lobes controlled by the position of the highland and lowland areas, moving farther south in the areas of lower relief. Two major lobes are recognized in southwest Ohio, the Miami lobe and the Scioto lobe. The points of intersection of these lobes, or where their pattern forms an inverted U, convex northward, marks the axis of a low, pre-glacial divide, which is precisely <u>coincident with the axis of the subsurface Findley Arch!</u> (See figure 20).

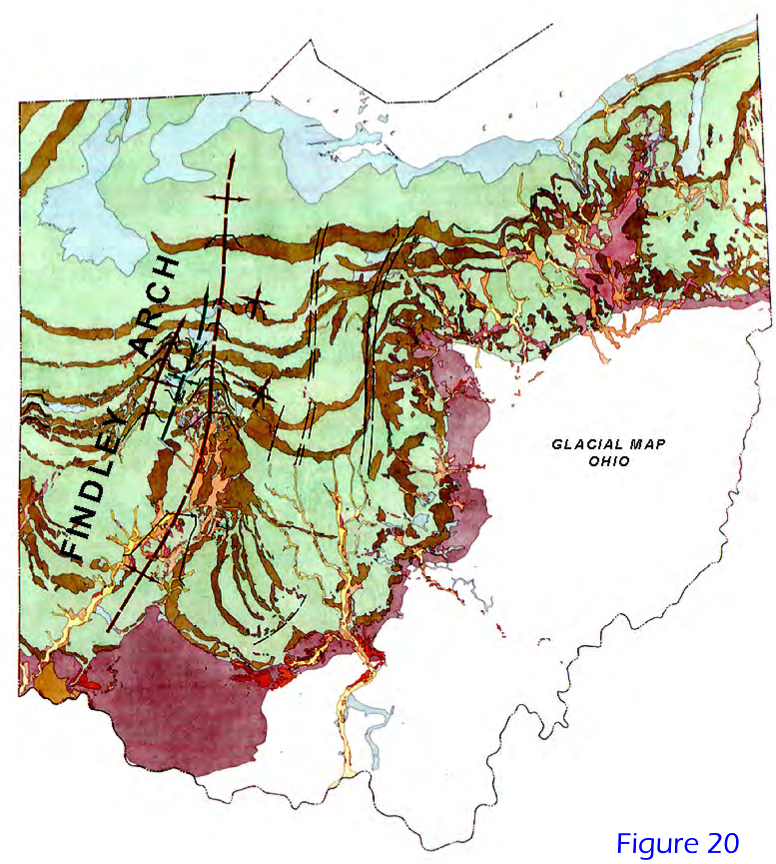


Figure 20

A similar pattern a short distance west revealed the presence of a known but unnamed subsurface anticline. The intervening synclinal axis is clearly marked at the surface by the presence of a series of irregularly-shaped glacial lake deposits.

Farther east, the easternmost edge of the Scioto lobe is abrupt and anomalously straight-lined, suggesting the presence of a subglacial escarpment that acted like a rudder in controlling the flow of the glacial ice. The profound, straight-lined orientation of this escarpment is interpreted to reflect a zone of monoclinal steepening in the bedrock, which coincides with the basin edge of a deep buried feature known as the Waverly arch! A similar hinge line is postulated between this feature and the Findlay axis on the basis of the alignment of several abrupt deflections in the end moraines.

Glaciated areas then are no exception. When regional relationships between morphology and geology are established, local interruptions to an understood "norm" take on profound importance as clues to buried structure. Note some of the minor interruptions here. What do you think they mean?

To further illustrate this point, I refer you to the glacial map of North Dakota (Figure 21).

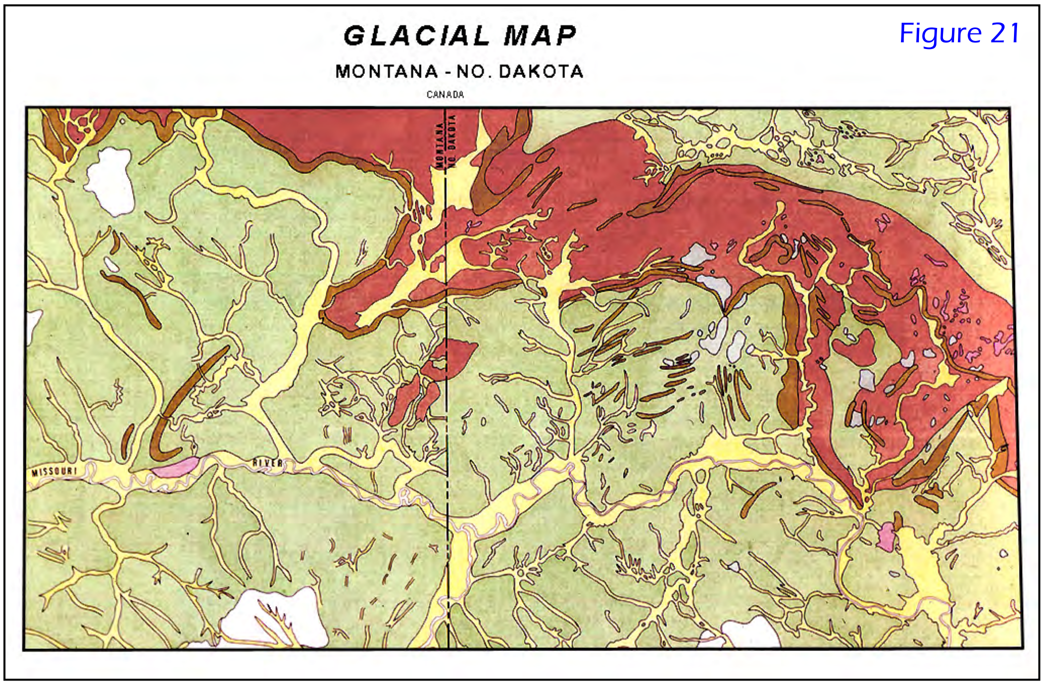


Figure 21

Study this and see how the end moraines outline perfectly the axis of the Nesson anticline (Figure 22).

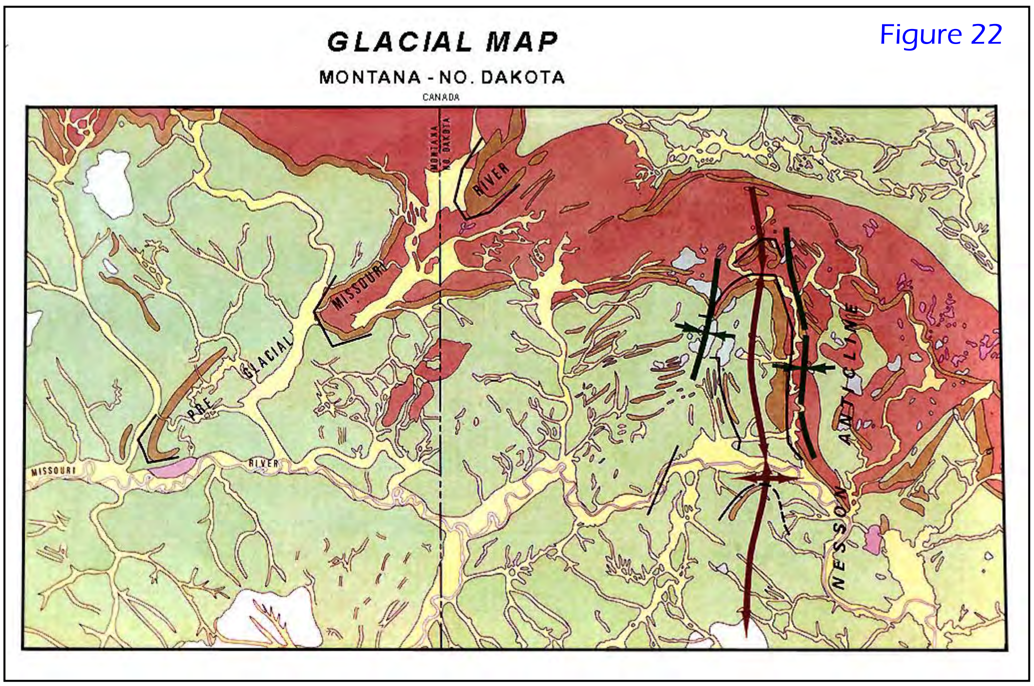


Figure 22

## BATHYMETRIC ANALYSIS

Another environment where geomorphic analysis has proven useful is in the offshore continental shelf areas. As topographic maps are an invaluable geomorphic aid in land areas, a geomorphic interpretation of the continental shelf regions is made possible through the use of bathymetric maps, the marine counterparts of topographic sheets. To be effective geomorphic principles must be applied in the context of the marine geology of the area.

## SUGGESTED PROCEDURE FOR CONDUCTING OFFSHORE BATHYMETRIC ANALYSES:

1) Construction of Contoured Bathymetric Maps:

   Contoured bathymetric maps should be constructed using the smallest feasible contour interval (in fathoms or meters). Every fifth contour should be in a heavy line. These maps can be accomplished by hand or computer contouring of bathymetric soundings plotted from available bathymetric charts. If computer facilities are available, a residual or derivative map is also useful for removing the regional slope. The bathymetric charts should show an appreciable part of the adjacent continent land area.

2) Plot Known Geology:

   Major geologic features known on the adjacent land map should be plotted and extended as far as possible onto the continental shelf.

3) Recognition of Recent Marine Features:

The bathymetric maps should be studied next in order to recognize and outline in light pencil all typical marine erosional and depositional features. These represent "noise" and must be mentally removed in order that the interpretation yield valid clues to older geologic features. Some of these are:

a) Depositional features - barrier bars, offshore bars spits, peninsulas, islands (some, not all, will be easily recognized as depositional features). These will be more abundant within littoral (wave action) zone along emergent-type coast lines.

b) Erosional features - some are typically erosional in associated patterns which probably do not reflect structure, i.e., marine canyons, etc.

4) Geomorphic Structural Mapping

a) Alignments - possibly faults and fault zones. Will reflect regional structural "grain" and often parallel shoreline; will generally be characterized by steeper edge toward the basin deep (often reflects gravitational faulting and(or) adjustment); asymmetry toward continental margin generally reflects antithetical faulting and probable uplifting on other edge – (detailed analysis of raw contour map in conjunction with residual map is very important here); detection of cross-grain alignments very important – helps determination of structure/age relationship of main elements; basement fault control.

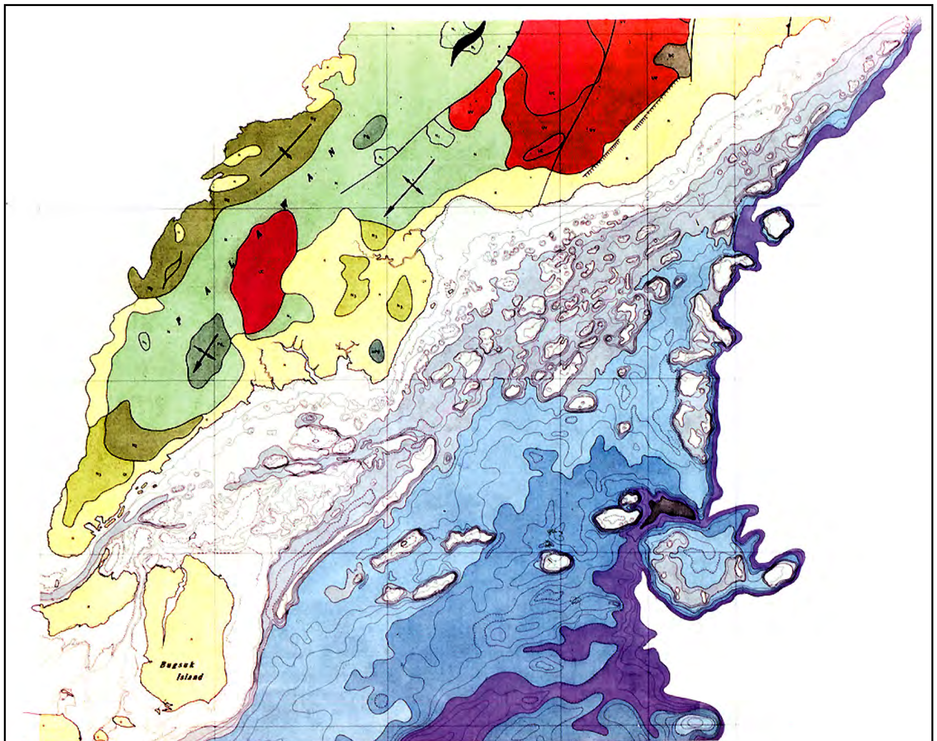
b) Topographic Patterns - "Asymmetry" is most important (residual and raw contour maps needed together). "Shape" of sub-aqueous topographic features is a clue to their structural- lithographic make-up. Topographic highs often reflect structural highs - not necessary so within littoral zones; very linear ridges and swales likely reflect gravitational faults - close linear patterns suggest faults along edge of uplift (the point here is that the very linear ridges are not the target, but rather the broader platform-type feature flanked by linear ridges) – some irregular patterns can be recognized as reflecting different-type lithology, rather than changes in structure.

5) Correlation Interpretation:

The final phase includes interpretation and correlation with all available additional data such as gravity, seismic, bottom sample information, etc.

## BATHYMETRIC ANALYSIS EXAMPLE:

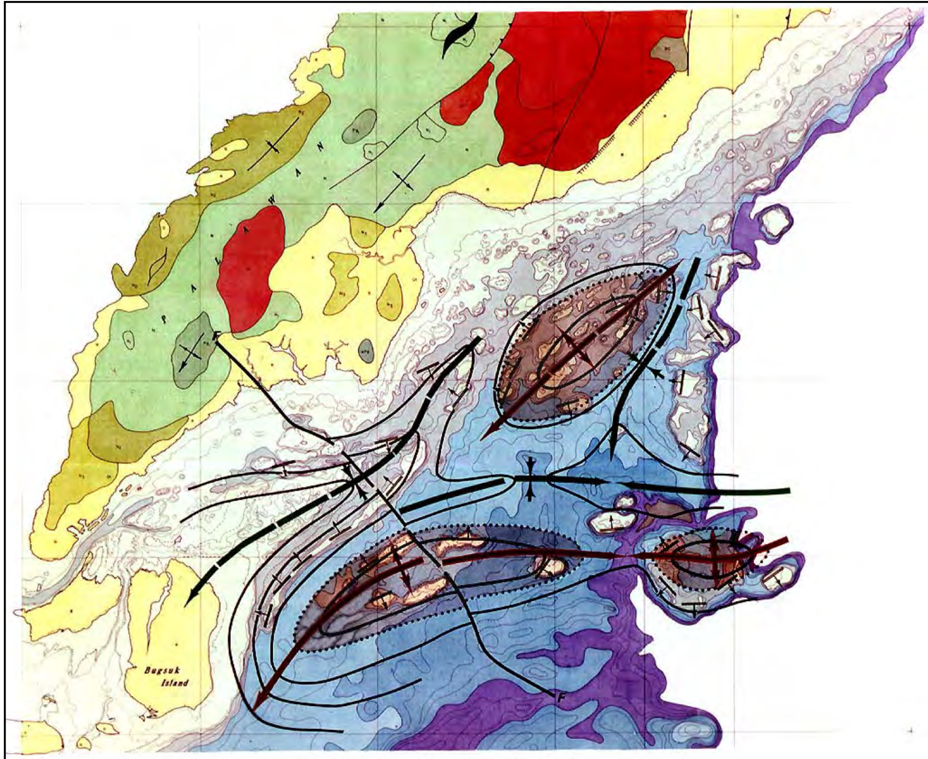
An excellent example of offshore geomorphology occurs along the shelf adjacent to an island anticlinorium in the Philippines (Figure 23). The morphology of the shelf here reveals the



OFFSHORE GEOMORPHOLOGY
PHILIPPINES

Figure 23

presence of several pronounced structural features that appear to parallel the structural configuration of the island uplift – notably a pronounced syncline and several companion anticlinal structures. The patterns here exhibit a reversal of topography and structure. The higher subsea ridges outline the syncline, and the deeper, broken areas point up the "breached" anticlinal folds. The asymmetry of topographic form along the major scarps denotes the direction of dip of the underlying beds. Faulting is indicated along the trace of offsets in the major scarps (Figure 24).




OFFSHORE GEOMORPHOLOGY
PHILIPPINES

Figure 24

## CONCLUSIONS

Thus, "applied geomorphology" is absolutely necessary for conducting a comprehensive analysis of large areas… because so much of the earths' surface is obscured by surficial deposits and or vegetation.

This will be especially true for the very near future when we will be able to obtain very High Resolution Imagery*, which will open clearly for the first time, our "Eyes" to the geologic-geomorphic details of huge heretofore inaccessible regions of the globe.

* Currently there are numerous programs which are scheduling launches of 1-10 meter satellites.

## CONTACTING

Should you have any questions or comments, or you require additional information regarding Trollinger-Marsh Resources, Inc., please visit our web page at www.PHOTOGEOLOGY.com. This site contains information on where we currently have available photogeologic-geomorphic mapping around the world.

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