THE GEOMORPHOLOGY AND PHOTO-GEOLOGICAL STUDY OF THE "FLAT LANDS"

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INTRODUCTION

THE photo-geologist working in mountainous terrane of high relief has the opportunity to make frequent use of nearly all of the known techniques of photo study. For example:

Stereo-visualization of the strike of outcropping strata and estimation of the angle of dip.
Use of the well-known geomorphic models (or type situations) in the recognition of new structural anomalies.
Evaluation of the strike and dip of strata by detailed tracing of contact lines.
Evaluation of the significance of anomalies of rock hardness and color in the location of structural anomalies.

Other methods also may be used.
The stereoscopic study alone might take the form of

Naked eye study of the stereoscopic model
Use of magnifying prismatic stereoscopes of various kinds
Use of mirror stereoscopes either with or without magnification.

In the "flat-lands" however, the choice of methods of study in any one district is apt to be somewhat restricted, because of the flatter dips and because of the more obscure outcrops, which are in some areas entirely missing.

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GEOMORPHOLOGY OF THE "FLAT-LANDS"

By "flat-lands" is meant those relatively low-lying areas which are, of course, only relatively flat. The ones under discussion are of regional size and are underlain by sedimentary rocks. They consist of the following main geomorphic types, certain minor forms being omitted:

I. TRUE DEPOSITIONAL PLAINS

The coastal plains, such as the surface of the Beaumont formation in the coastal plain of Texas and Louisiana. They may be hundreds of miles long, but are not thus far known to be more than a small fraction of this in width.

The lake plains. Only the largest could be considered in this class.

The till plains. They are of continental dimensions, and the fine details of their geomorphology are not thus far very well understood.

Terrestrial alluvial plains. Only the largest, the "piedmont plains" or "aprons" should be mentioned here.

Sand dune plains. These should perhaps include the loess plains, which though well known are apparently rare in the uneroded stage.

II. THE TRUE DEPOSITIONAL PLATEAUS

These usually fall in one of the classes of depositional plains given above, especially the alluvial plain. Their geomorphology differs mainly in degree rather than in kind from that of the plains. In fact many so-called plateaus are also known as plains when seen from a different viewpoint. The "high plains" of Texas, Oklahoma, Kansas and eastern Colorado might be thought of as falling in this class.

III. THE LOW STRATA-BENCH LANDS

These are the regional expanses of outcropping, dipping bedrock strata, which have been deeply eroded, perhaps several times. The Osage Plains (a portion of the Permian and Pennsylvanian plains of Missouri, Kansas, central Oklahoma, and north-central Texas) belong in this class. The low strata-bench lands do not include the truncated bedrock regional surfaces which are covered by alluvium, by glacial till, or by other sediments, and which because of this cover fall in the class of "true depositional plains" mentioned above.

IV. THE HIGH STRATA-BENCH LANDS

Some of the plateaus of popular usage belong in this class. The Colorado plateau of Utah, Arizona, Colorado, and New Mexico probably is best thought of as a complex high strata-bench land, though it is, of course, very diverse in its geomorphic expression, and of different geologic history at different places. Such high surfaces differ mainly in *degree*, such as in amount of relief, rather than in *kind* from the low strata-bench lands.

STRUCTURAL INTERPRETATION

I. TRUE DEPOSITIONAL PLAINS

The determination of strike and dip of formations is ordinarily not possible in these plains, even though erosion may have dissected the recently-deposited beds to a noticeable degree. The geomorphologist must use drainage and other small-scale features for what they are worth. The drainage may be largely inherited from the time when the water was first receding from the plain surface, and it is likely to be very sensitive to the small-scale features of this surface.

If the base of the plain is structurally stable and immovable, the drainage may in certain cases have no relationship at all to buried structural features. If the sediments of the plain surface are thin, it is possible that the buried topographic features of an earlier cycle of erosion may be discernible in the variations of thickness and porosity of the covering deposits; thus buried structural anomalies may be brought to light to the extent that this topography reflects structure.

If the base of the plain cover is a tectonically active region, such as the salt basins of the Gulf Coast, one can expect the micro-drainage (as seen on the photos) and more rarely the major drainage, to show some effects of this movement. These effects are quite variable from one locality to another, and it would be very difficult at present to classify them or to illustrate them in the pages of a journal. A few years' experience with these micro-features will enable the photogeologist to interpret them with some confidence (Figure 1).

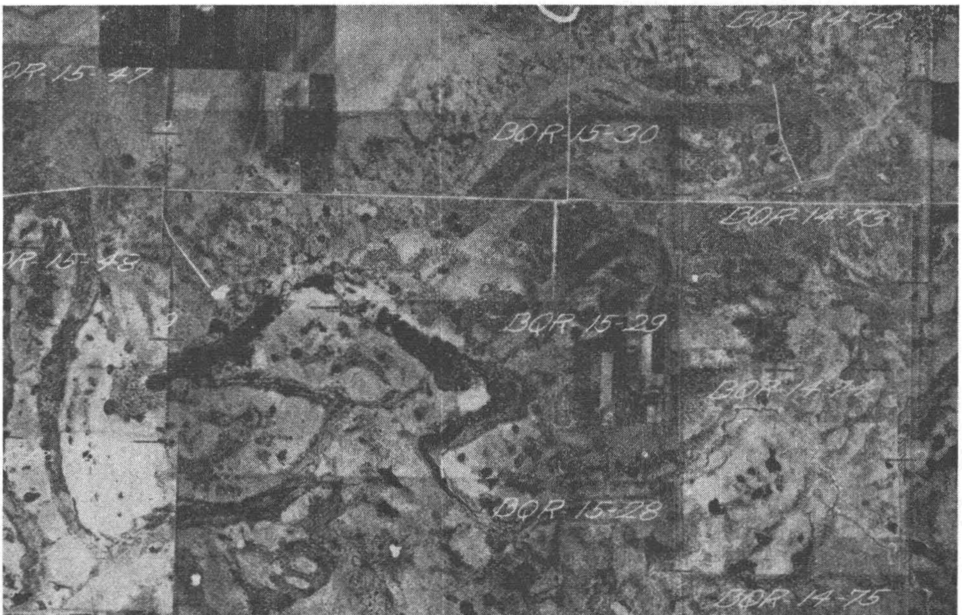

FIG. 1. A portion of the Beaumont surface (a true depositional plain) near Damon in Brazoria County, Texas. The abandoned meandering stream channel was probably a distributary emptying into the lagoons of Beaumont time which occupied the lower land to the north and south. Such coastal plains are usually narrow, but may attain great length along the margins of a continent. Stream erosion has only slightly modified this surface. (Photography in 1939 by the Production Marketing Administration of the U. S. Dept. of Agriculture.)

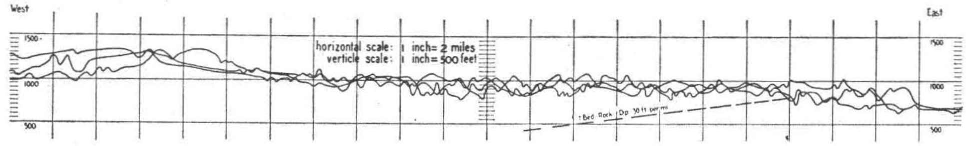

FIG. 2. Three profiles made along east-west lines one mile apart near Pawhuska, Oklahoma. The prominent accordance of summit level near 1,000 feet is the Pawhuska "peneplain" or "rock plain," an erosional surface, formerly extremely flat but now undergoing considerable dissection in a new cycle of erosion. It is a *low strata-bench land* and not a true depositional plain since the bed rock dips noticeably and is truncated by the elevated surface. The hills at the west are monadnocks on resistant cherty limestone marking the western edge of the surface. Such surfaces are very common in the flat lands of the world. Courtesy of Mr. W. E. Ham, Thesis for the M.S. degree, University of Oklahoma.

II. TRUE DEPOSITIONAL PLATEAUS

The problems of geomorphic interpretation of the true plateaus, which are not noticeably dissected by stream erosion, are not sufficiently different from those of the true plains to merit additional discussion here. Where they have been deeply eroded, however, there is the additional exploratory possibility of recognizing the strike and dip of the strata by stereoscopic study.

III. THE LOW STRATA-BENCH LANDS

Of those continental surfaces which are underlain by sedimentary rocks (as contrasted to metamorphic and igneous rocks) the greatest area lies in the class of *low strata-bench lands*.

Because all known examples of low strata-bench lands of regional size give ample proof that their drainage has been lately rejuvenated, and that earlier they were in a condition at least approximating peneplanation, it seems evident that generally speaking all major drainage lines in these regions should be thought of as "superimposed" or "superposed". An extensive low-level surface of stream erosion (such as a peneplain is thought to be at the end of the cycle of erosion that produced it) would undoubtedly in most cases be largely covered by a veneer, perhaps thin, of soil, alluvium, or wind-blown deposits. See Figures 2 and 3. Those streams that were able to persist through the rejuvenation terminating the cycle of peneplanation would find themselves "superimposed" on the dipping bedrock beneath. If the veneer were noticeably thick, the persisting streams would be said to be "superimposed from an unconformable cover." At all events such streams would be forced to erode down into and across gently-dipping rock formations of differing hardness and resistance to erosion.

If during the process of regional uplift and rejuvenation, local uplifts occur,

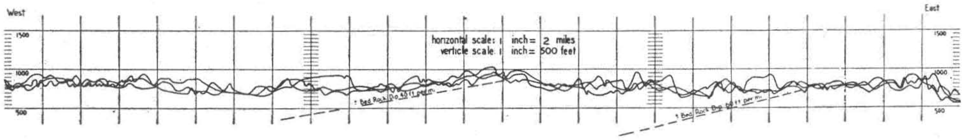

FIG. 3. Three profiles made along east-west lines one mile apart, near Wewoka, Oklahoma, showing a portion of a large *low strata-bench land*. The Pawhuska "peneplain" or "rock plain" (See Figure 2) though dissected, is still very evident. There may possibly be two or more regional erosion surfaces very close together in elevation. Considered as only one major peneplain, the Pawhuska rock plain extends with only slight changes of elevation from southern Iowa into north-central Texas. Its width in Oklahoma is in the neighborhood of 150 miles. Courtesy of Mr. W. E. Ham. Thesis for the M.S. degree, University of Oklahoma.

such as might be caused by faulting, some of the superimposed streams might be trapped flowing across the trend of a long and narrow uplift, and forced to erode downward into the rising uplift. Such a stream might be said to be *antecedent* to the local uplift. It should be kept in mind that such a stream could be antecedent at a particular locality, and still owe its existence *at that place as compared to some other place* to the process of superposition. In other words, the stream could be superimposed first, and later could be antecedent to the localized uplift; but the reverse could not be true—the stream could not be first antecedent and later superimposed at the same place without the occurrence of an intervening cycle of peneplanation and/or deposition. Thus it is conceivable that a certain percentage of the depth of a canyon might be due to antecedency and the balance to superposition.

There seems little reason to doubt that most of the major drainage of the high strata-bench lands likewise passed through a late cycle of superposition, just as in the case of the low strata-bench lands. The proof is not, however, so clear nor so widely known for these higher lands. It is perhaps too early to say

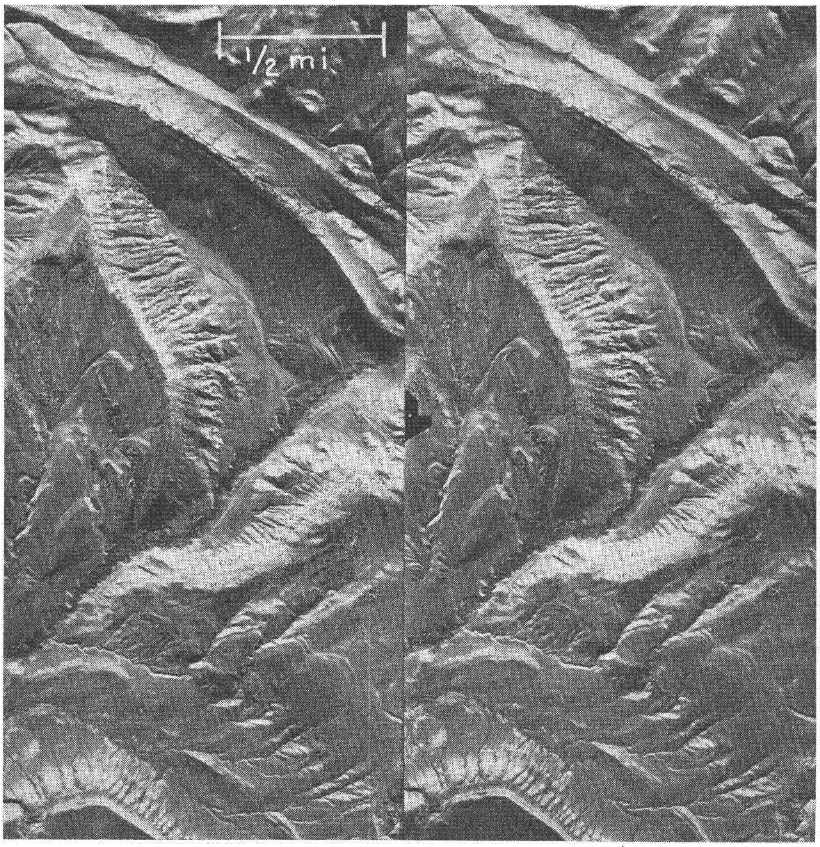

FIG. 4. Stereoscopic pair of vertical photographs showing a small anticline crossed by a stream, which is probably superimposed. Many of the streams intermediate between the smallest and the largest flow on the outcrop of weak rocks and may, to this extent, be said to be adjusted to rock structure. A valley follows the axis of the anticline for a short distance and then departs from it. Features of this type, but differing in scale and in detail, are common in the mountains and in the strata-bench lands of the world. Photography by the Production Marketing Administration of the U. S. Dept. of Agriculture.

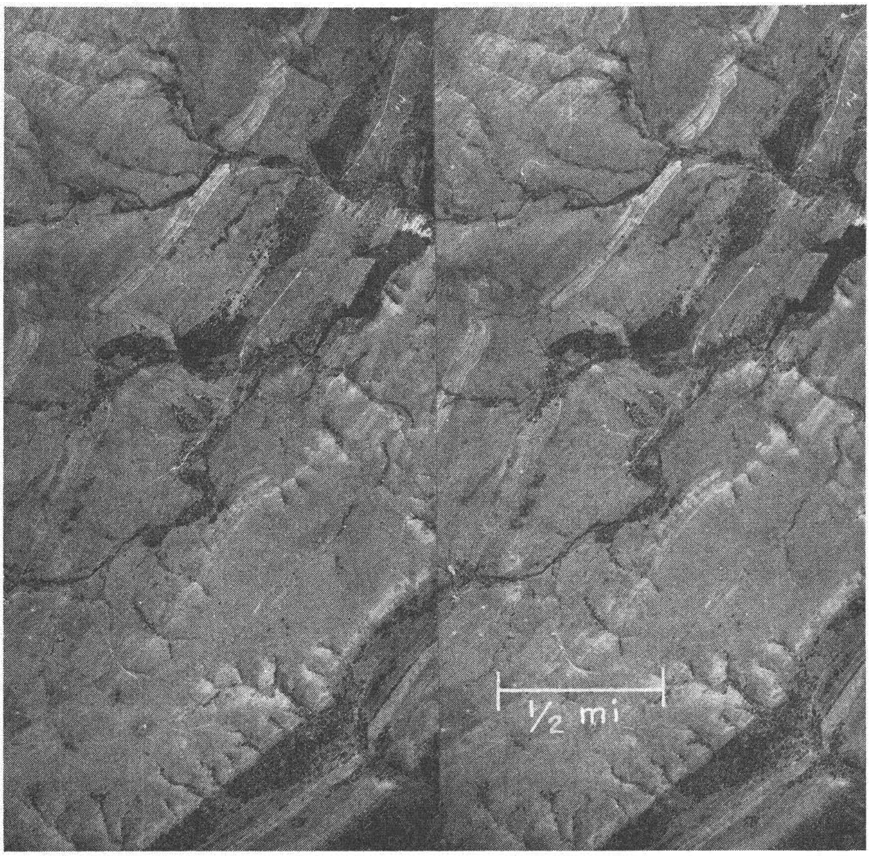

FIG. 5. Stereo pair of vertical photos showing a portion of the big monadnock of the Arbuckle mountain range of Southern Oklahoma. Southward-flowing streams have been superimposed across the strike of Paleozoic strata. Adjustment to structure is in process of attainment, but thus far has not attained noticeable perfection except perhaps in some of the smallest streams and in the largest one. Superposition is demanded by the geological history; the exact time when it occurred is not known, but there has been more than one time when it could have occurred. Conditions similar *qualitatively* to those shown here, but differing *quantitatively* (that is in details and in scale) are very common in the strata-bench lands of the world, as well as in the mountain ranges, where they have long been known. Photographs by the Soil Conservation Service, U. S. Dept. of Agriculture. Gift to the University of Oklahoma by Mr. C. W. Tomlinson.

that a history of regional superposition has been the prevailing history in the mountain ranges of the world, but there is plenty of evidence suggesting strongly that this may be the case in those ranges which are no longer tectonically very active. *Johnson* proposed this theory for the Appalachian drainage.* Local uplifts should perhaps be more common in the mountains than in the flat-lands with the result that a greater proportion of mountain drainage should have a late history of antecedency in addition to its earlier history of superposition.

The laws of geomorphology, especially those controlling the adjustment of streams to structure, shown so strikingly in the mountains of the world, are beautifully illustrated also in the high strata-bench lands, and are easily recognized in the low strata-bench lands (Figures 4 and 5).

* Johnson, D. W., "Stream Sculpture on the Atlantic Slope," 142 pp., Columbia University Press, New York, 1931.

The problem of the aero-geologist in the "flat-lands" is largely to interpret the effects which local structural anomalies have had on a superimposed stream. There is, of course, the "first cycle" drainage that has developed through headward elongation of valleys—the so-called *insequent* drainage of the textbooks—which, though it is popularly supposed to show no systematic influence on the direction of headward elongation or alinement, is actually controlled to a remarkable degree in many cases by such influences as the direction of the prevailing winds of some past time, or the direction of the rock fractures or "joints" in the bed rock. Such first-cycle drainage is usually the smaller and more local valleys or ravines, such as one might find on the face of a prominent scarp or

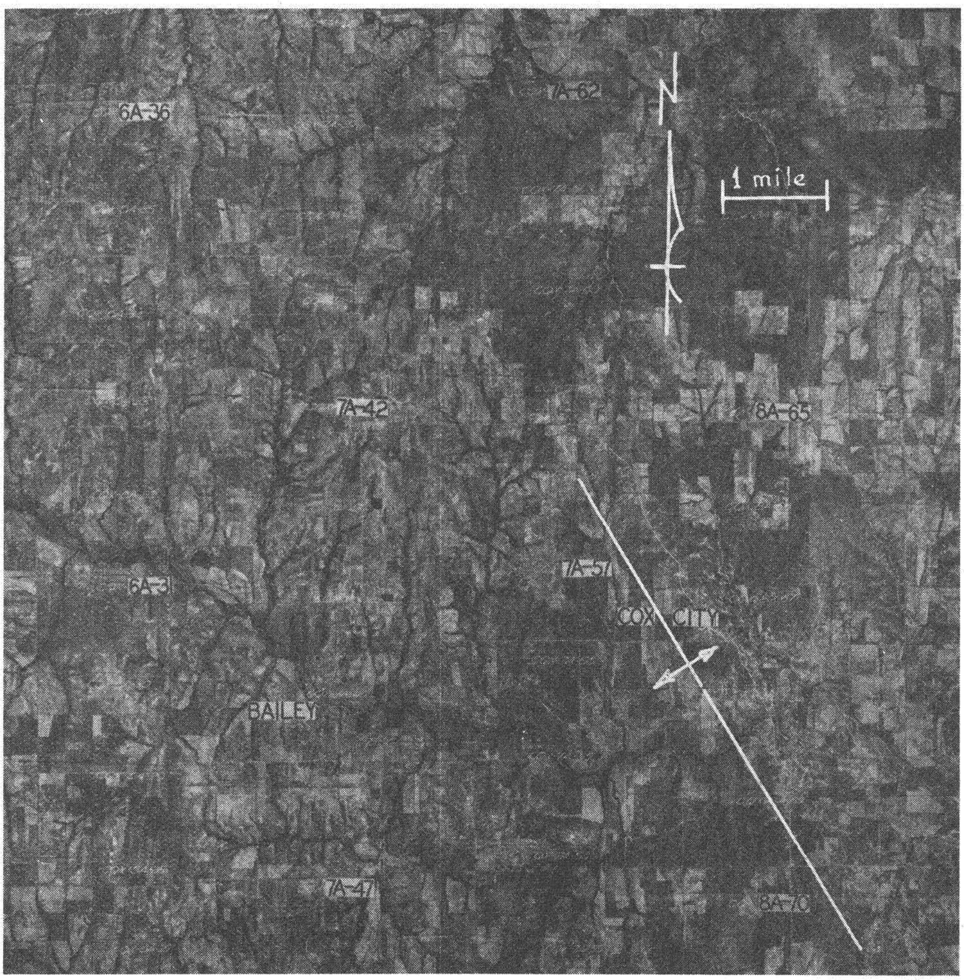

FIG. 6. A portion of a photo-index sheet showing 80 square miles on rocks of Permian age in southeastern Grady County, Oklahoma. The Knox oil field, an anticline, is shown. Rush Creek crosses this resistant barrier essentially perpendicular to the strike of the beds and of the axis. It was superimposed across the anticline probably in late Tertiary or early Pleistocene time. Tributaries of Rush Creek extending northeastward and southwestward are occasionally alined in what may be called "linears." They probably represent zones of jointing in the bed rock. Conditions similar *qualitatively* to those shown here, but differing *quantitatively* (that is in details and in scale) are common in the strata-bench lands of the world as well as in the mountains. Photography by the Production Marketing Administration of the U. S. Dept. of Agriculture.

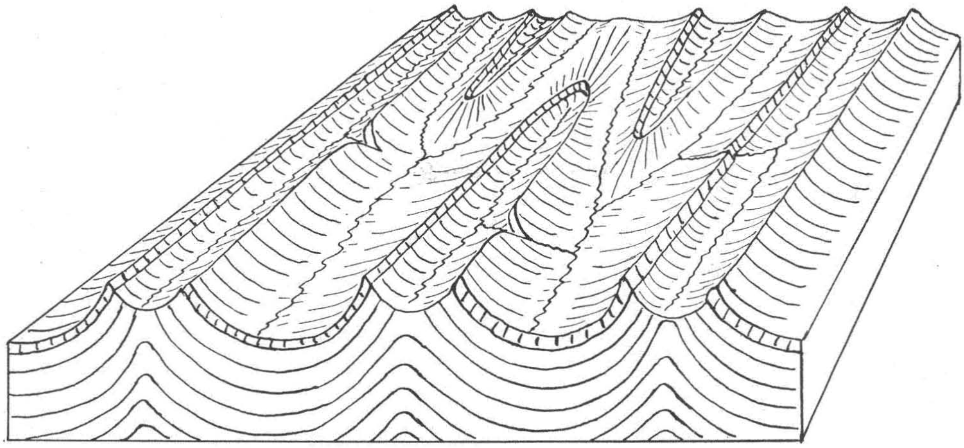

FIG. 7. Diagram representing a hypothetical stage in the erosion of a series of anticlines and synclines in a "folded" mountain range. The location of eroding streams parallel to, and directly on, the anticlinal axes is a supposed condition that has been a geological tradition for a long time. The Davis-Johnson school of geomorphologists have helped perpetuate this conception, which finds little support in the study of aerial photographs of either the flat-lands or the mountains of the world except in very special structural and geomorphic situations. (For the consultation of similar but more complete diagrams see von Engeln, "Geomorphology" Macmillan, New York, 1942, Chapter 15.)

mesa where the capping hard layer is underlain by soft, easily-eroded shales.

The aero-geologist working in the low strata-bench lands will find that the direction of plunge of an anticline, structural nose, or syncline is occasionally revealed by streams flowing around the strike of a resistant bed as is seen frequently in the mountains. Whether these "subsequent" streams are first cycle streams or superimposed streams may not be evident at first. Both take part in this kind of structural adjustment. Streams crossing the outcrop of the more resistant beds in the low strata-bench lands will in many cases tend to cross perpendicular to the strike, just as in the mountains, though perhaps not quite so straight, in spite of the fact that the "outcropping" strata may be completely soil-covered and invisible (Figure 6). There are many other resemblances between the geomorphology of the low strata-bench lands and that of the mountains.

There are, however, important differences. The bedding of the bed-rock is frequently entirely invisible over broad areas, a situation that occurs less frequently in the mountains. The axes of anticlines probably have a greater tendency to lie upon high ground in the low strata-bench lands than in the mountains where the rock formations are usually thicker and the dips steeper. At least it has been the writer's experience that anticlines are more often expressed by locally high ground than not. This of course is not in harmony with the time-honored textbook illustrations that show the geomorphic development of the folded mountain ranges of the Jura type. This older view, which was first developed extensively by *William Morris Davis*, and which is still given a certain amount of support by the Davis-Johnson school of geomorphologists* holds that the anticlines (of a range such as the Jura, with strongly differentiated hard and soft formations and with alternating folds) would rapidly be eroded to low ground by streams flowing along the axes of the anticlines, the synclines being left as the local high lands (see Figure 7). Such a sequence of events is of

* von Engeln, "Geomorphology." Macmillan, New York, 1942. Chapter 15.

course very far from the truth in most cases in the low strata-bench lands, and probably also in the mountains; though such a reversal of the more common elevation relationships of structural axes and topographic elevation does exist in certain restricted localities, as is well known. The sequence of erosional history in these cases probably involves peneplanation, perhaps several times. All of the well-known ranges and of course all of the high strata-bench lands give every indication of being in at least the second and perhaps in a higher numbered cycle of erosion. Space does not permit a detailed analysis of the geomorphic development of anticlinal ranges, but one may say that if rock formations of unusual resistance are present, their elevation relationship to the local base level of erosion is a controlling factor in the highness or lowness of the ground along the axis. It is more common to find somewhat random, or subsequent strike-following drainage on and near an anticlinal axis than it is to find a stream located parallel to the axis and directly on it. Perhaps the Jura or folded-Appalachian type of mountain range should be excepted from this generalization; but even in such mountains the correspondence of drainage lines with axes is not what a hoary geological tradition says it is.

SPECIAL FEATURES ENCOUNTERED IN THE FLAT-LANDS

The following special features are of smaller size than the regional features under discussion above, and do not belong in the same category with them. These should be mentioned, however, because they frequently are mistaken for some bed rock structural anomaly such as steeply-dipping beds, the rim syncline of a salt dome, etc. They occur in all parts of the world and in practically all of the large geomorphic features of regional dimensions discussed above. They may be more of a hindrance to structural exploration in the flat-lands than in the mountains, because generally speaking they are developed over larger areas in the flat-lands.

SAND DUNES

Sand dunes are of many kinds,* only a few of which are likely to be confused with bed rock features. They fall naturally into two classes—*complex* and *simple* the former being much the more common. Variable factors such as wind direction, depth of sand, irregularity of vegetal growth, etc. are responsible for the rarity of the simple dunes. It is only by first studying simple forms, however, that one can discern the origin and history of the surfaces of complex form. Following is a basic classification of simple dunes which is at the same time genetic and naturalistic. It is based on the assumption that the sand-moving wind blows with unvarying direction. It is important because of the large areas in the flat-lands that are covered by dunes in various stages of disintegration of weathering and erosion.

A. Base surfaces on loose sand.

I. *The barcan dune.* An isolated bare-sand hill on a non-sandy base. It is a migrating dune of crescent form, the wings pointing with the wind.

II. *The transverse dune series.* Formed on bare, loose sand of "unlimited" surface area and "unlimited" depth. Migrating parallel sand "waves" or ridges, the long dimension being across the wind direction (Figure 8.)

III. *The isolated transverse dune ridge.* It is formed (frequently with human aid) from

* Melton, Frank A. "A tentative classification of sand dunes, its application to dune history in the southern high plains." *Jour. Geol.*, Vol. XLVIII, No. 2, 1940, pp. 113–145. This paper contains twenty-five aerial photo reproductions illustrating dunes.

bare, loose sand of "unlimited" surface area but of shallow depth. cf. certain parts of the "dust bowl" during 1934 to 1938.

IV. *Lee Dunes.*

1. Wind-shadow dunes. Formed from a continuing (unlimited) sand supply in the lee of a bed rock obstacle. The best examples in the United States are the extremely elongate straight dune ridges extending northeastward (leeward) from and behind the promontories at the west face of the Moencopi Plateau in northeastern Arizona. They have long been known as *longitudinal* dunes.

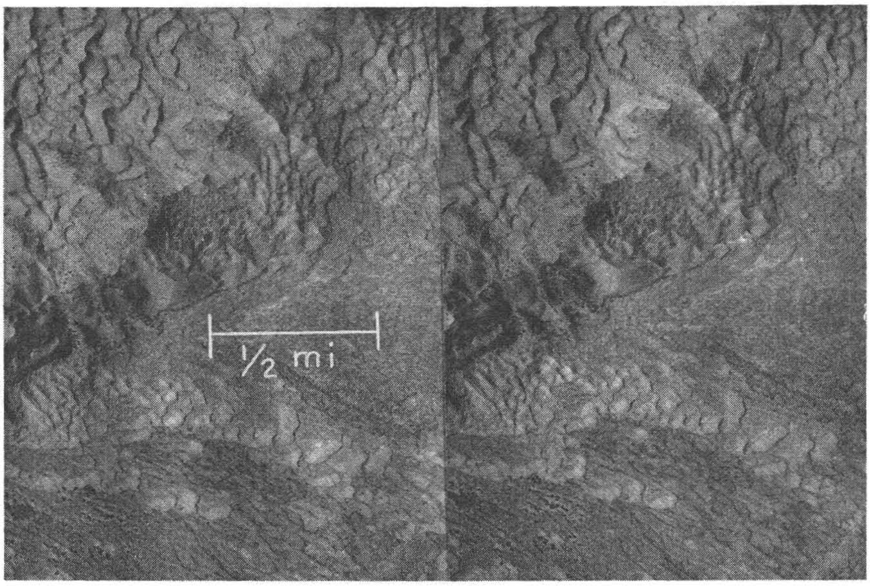

FIG. 8. Stereo pair showing active sand dunes in Utah. They are migrating toward the right, and are a complex of transverse dune series and individual barcan dunes. Similar developments of sand dunes cover extensive areas in the flat lands of the world. Photography by the Production Marketing Administration of the U. S. Dept. of Agriculture.

They do not migrate to any noticeable extent, except as they change their length. Small wind-shadow dunes may form behind clumps of vegetation.

2. Source-bordering lee dunes. Formed from a continuing (unlimited) sand supply, leeward from a source of sand of limited area, such as a stream floodplain, a beach, etc. These dunes may become a hundred feet or more in height, hundreds of feet wide, and miles in length near the beaches facing the Pacific Ocean in temperate latitudes. They are usually of small size to the lee of floodplains in the continental interior.

B. Formed by wind in conflict with growing vegetation.

I. *Shrub-coppice dune clusters.* Formed in, and to leeward from, bunch or clump vegetation such as mesquite bush on an unlimited and smooth surface of very shallow sand. These dunes are round or oval, are seldom more than ten feet high or more than one hundred feet across. They exist in great numbers in certain arid plains. They migrate very slowly.

II. (a) *Blowout or parabolic dunes.* Formed by gentle or moderately effective winds on deep sand with a shrub or grass-covered surface. These occur in countless numbers both as active dunes and as dunes anchored by vegetation. Most of them are less than three hundred feet across and are called "spot blowouts." The larger ones may be crescent-shaped with wings pointing *against* the wind. They do not migrate noticeably, except as migration is incidental to their growth and decay (Figure 9).

(b) Elongate-blowout and windrift dunes. Formed by strong winds, or else

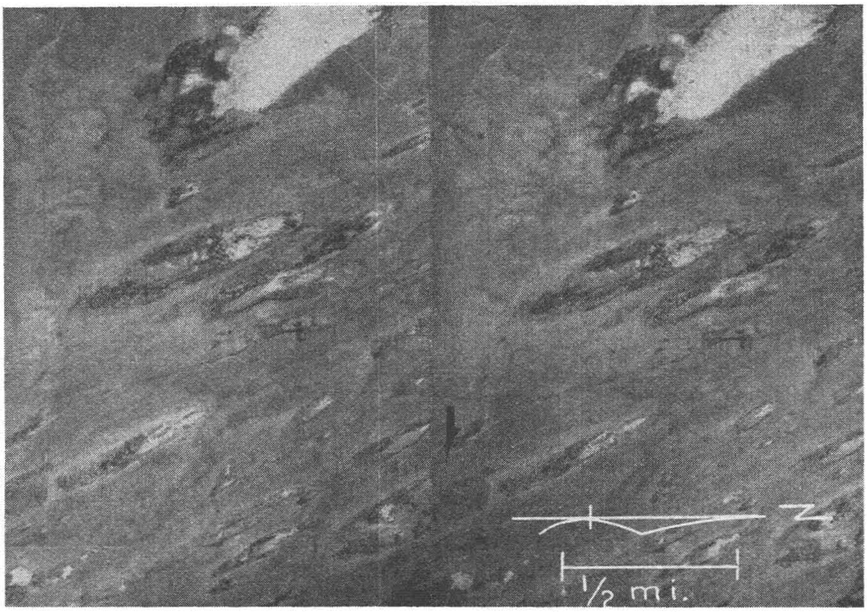

FIG. 9. Blowouts and blowout dunes formed by strong northwesterly winds in Umatilla County, Oregon. Prominent "ridging" of the ground caused by alignment of dunes may occasionally give a false appearance of steeply-dipping bed rock. Photography by the Production Marketing Administration of the U. S. Dept. of Agriculture.

by strongly-effective winds, on deep sand with shrub or grass-covered surface. These are hairpin-shaped ridges of grass covered sand opening toward the wind; occasionally they resemble a chevron. Where the hairpin or chevron has been cut in two ridges by wind scour, the name "windrift" is used. Their migration is probably confined to the period of growth. These are not being formed to any important extent today anywhere in the world outside of the Arctic, so far as yet known; though one should maintain reservations about portions of Asia and Australia which are not yet well-known to geologists. Yet in late Pleistocene or early Recent time they formed in considerable numbers in the southern High Plains and perhaps also in the Nebraska sand hill region (Figure 10).

Complex dune forms may be thought of as a combination of the simple forms just mentioned, with the exception of a few forms, the discussion of which space will not permit. In the main, the complex dunes on a large area of bare sand are a combination of forms resembling the barcan, the transverse ridge and sand peaks and basins. On deep sand with a shrub or grass vegetal cover the complex dunes consist largely of blowouts of various sizes, shapes and ages.

The photo-geomorphologist looking for structural anomalies in the aerial photographs, may be confused in certain places by the longitudinal dunes and by certain extreme developments of the windrift dune (Figure 11). Where these are in process of formation today or where they have been only lately formed, and still remain largely uneroded, they will not confuse any competent geomorphologist. But where these extremely elongate forms have been largely obscured by weathering and erosion, or where they may have advanced over rough country, as in portions of Arizona, New Mexico and southern Utah, remnants of these dune forms have been confused with outcropping, steeply-dipping bedrock. Confusion of this type may be resolved by newer photography made at a larger scale or made from a lower altitude.

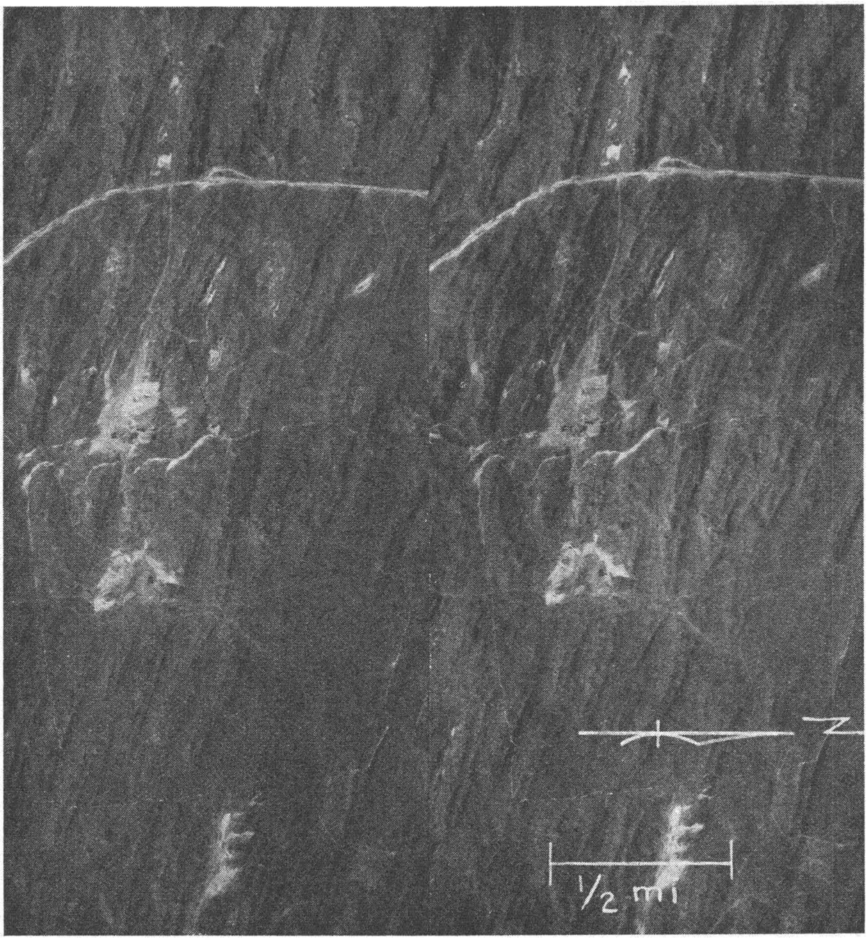

FIG. 10. Stereo pair near Halsey in the sand hill region of Nebraska, an area of deep sand covering most of the surface in several counties. The hairpin ridges and pairs of ridges give conclusive evidence that the sand-moving wind blew from the northwest toward the southeast. Most of the dune surface is covered by grass and shrubs, but certain areas of bare sand have been uncovered by wind activity, helped by the white man, in historical time. The ancient elongate pairs of ridges may be called *elongate blowouts and windrift dunes*. The small pits are spot blowouts formed at some time after the formation of the elongate blowouts and windrifts, but probably before the white settlement of North America. The swales between the paired ridges are quite broad and deep in comparison to the small size of the ridges themselves. An explanation for this conditions has not thus far been offered, but may lie in one of three or more field hypotheses. (1) There may have been an earlier generation of southeast-trending ridges (formed by wind action or by running water directed by a still earlier wind effect, on top of which the present paired ridges were later excavated and constructed by wind. (2) The snow and ice conditions in the late Pleistocene time may have withheld sand movement in the lower swales, but not on the summits of the sandier ridges, which then became subject to wind activity. (3) Deflation (complete removal) from the swales of much sand and dust during or after the formation of the paired dune ridges. Hypothesis (1), assisted by (2), is favored by the author. The hairpin and paired ridges are believed to have been constructed on the summit of earlier and larger ridges of similar origin either by wind or by running water directed by still earlier wind-formed ridges. Photographs by the U. S. Forest Service.

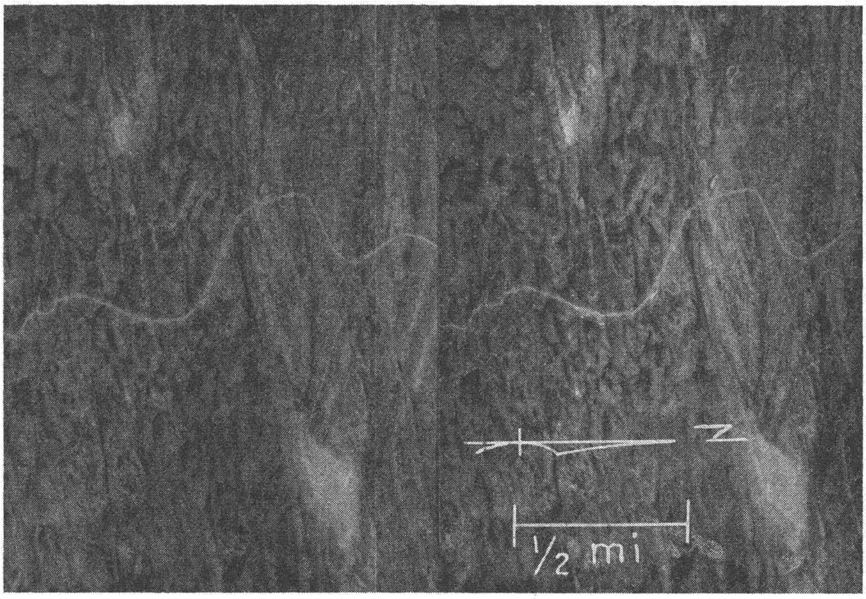

FIG. 11. Sand dunes (blowout, elongate-blowout, windrift, and perhaps longitudinal lee dune types) near Seminole Dam in Carbon County, Wyoming. Most of the dunes are anchored by vegetation and were moved toward the lower right by the prevailing westerly winds. The reader should notice how easy it would be to confuse the dune ridges of steeply-dipping beds, which trend lightly south of east and north of west. Photography by the U. S. Forest Service.

FLOODPLAINS*

There are two main classes of floodplain streams and of floodplains: those which do only one type of geological work when they are in flood and which hence have a relatively simple floodplain; and those which have two kinds of floods and which consequently do two kinds of geological work. The former are called *single-crest* streams and the latter are called *double-crest* streams. The features of floodplains are so well known that they will not be discussed in detail here (Figures 12 and 13).

Why is it important for the geomorphologist working with aerial photos to know about floodplain features? Almost any geologist will recognize an uneroded floodplain of recent origin, regardless of the type of floodplain. Remnants of floodplains or terraces remaining after considderable erosion has taken place, or after some geological process has obscured them, are not so easily recognized and occasionally have been interpreted as local structural anomalies. For example the giant oxbows of ancient origin in the lower Mississippi floodplain may in places be confused with rim synclines of the salt domes; they are much the same order of size. Likewise, the relatively straight scarps found at the margins of many floodplains in the mountainous regions have on occasion been interpreted as fault scarps, even though their origin was due merely to the down-valley migration of meander-loops which thus trimmed the valley walls to a straight line.

JOINTING

Jointing is a type of rock fracture that is found in hard rocks of all types and of all ages including the Recent time, though the origin may not necessarily be

* Melton, Frank A. "An empirical classification of floodplain streams." *The Geographical Review*, Vol. XXVI, No. 4, October, 1936, pp. 593–609. Eleven plates illustrating floodplains.

the same in all types of rocks. In hard, nearly flat-lying sedimentary rocks the joints will ordinarily be perpendicular to the bedding of the hard beds and accordingly nearly vertical in attitude. They are spaced in a more or less regular manner depending upon the thickness of the hard bed, its geological age, and other factors not all of which are understood. They are related in origin to some of the fault systems that cut sedimentary rocks, and near these related faults, the joints will usually be more closely spaced. Different systems of joints cross each other at angles which vary from place to place in a manner that in some places at least is systematic.

Sedimentary hard rock joints of this type may in places be related to local anticlinal uplifts. They are sometimes made visible in aerial photos by selective

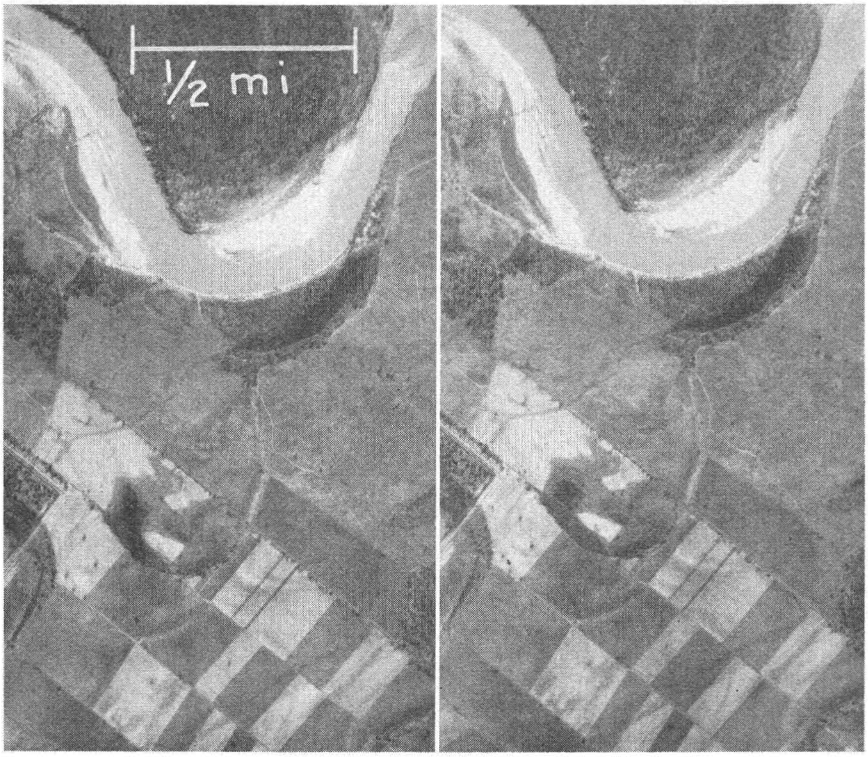

FIG. 12. A portion of the floodplain and meandering low water channel of Brazos River in central Texas. Note floodplain markings of earlier meander loops, and also the straighter sloughs made during flood time. In certain places in the Gulf "coastal plain," floodplain features may be confused with structural effects caused by the rising salt domes. Courtesy of the Edgar Tobin Aerial Surveys, San Antonio, Texas.

weathering and lines of vegetation along them, but not often enough to make their observation of much use in geomorphic studies.

The unconsolidated sediments of the Gulf Coast geosyncline are probably jointed or fractured in some manner comparable to those just mentioned, though it is difficult to visualize how fracturing of the same kind could occur. Alinements of vegetation in certain areas seem to demand this explanation,though neither of the terms of jointing or fracturing seem quite suitable. Whether they are caused by movements of the salt or of the entire geosyncline is not known, but the writer feels fairly confident that they have some observable relationship to the larger structural anomalies. Just what the relationship is, it is not yet possible to say. These features are so small that they cannot be reproduced by half-tones, hence no illustration of them can be shown here.

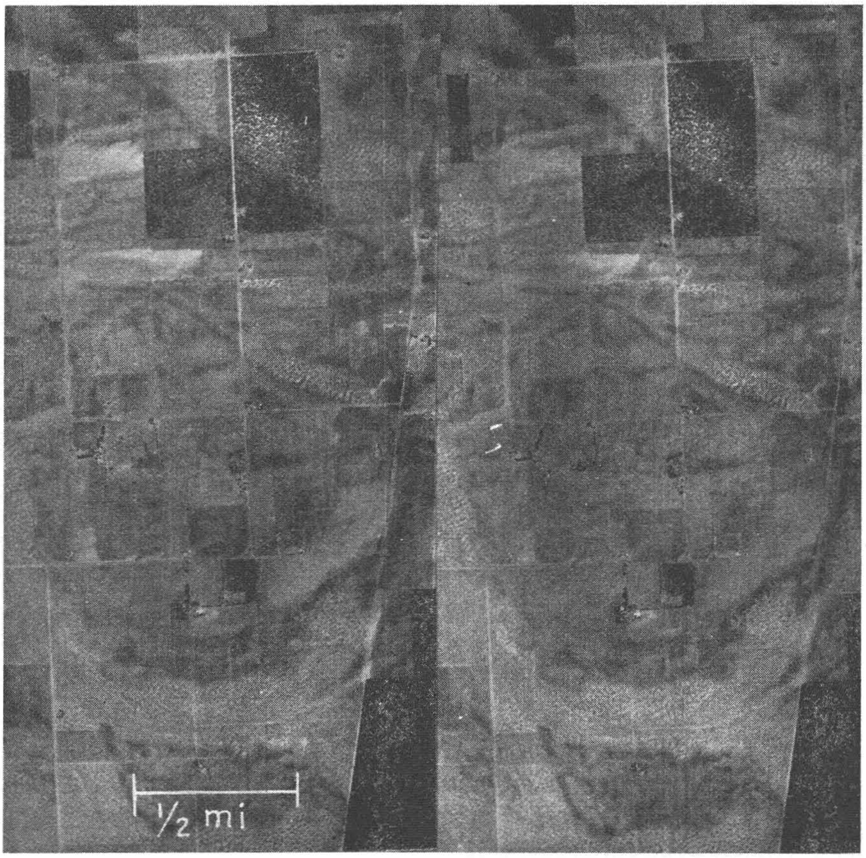

FIG. 13. Portion of the floodplain or a low terrace of the Rio Grande River or one of its distributaries in Willacy County, Texas. Note the traces of former meandering activity of the low water channel. In floodplains of great width, features of this type may on occasion be confused with bedrock structural anomalies. Photography by the Production Marketing Administration of the U. S. Dept. of Agriculture.

LINEARS

These features are prominent alinements of surface drainage usually in the actively eroding headwaters of a drainage system though the lower courses of larger streams may be affected also. Several small streams usually take part in the alinement which may extend from a few miles to twenty miles and perhaps farther (see Figure 6). They occur in the true depositional plains and plateaus, and also in the strata-bench lands. There is usually no visible faulting or other structure of comparable dimensions, though small surface faults, anticlines and anticlinal noses may in certain cases be associated with them. It is not yet evident just what is the significance of the linears in the low-lying regions of sedimentary rocks. It is the writer's belief, however, that they represent zones of jointing. These zones of jointing, it is believed, are associated with deep-seated faulting in the basement complex, which in the flat lands of North America is ordinarily composed of Pre-Cambrian rocks. Similar features of much greater size have lately been described in the Pre-Cambrian shield of Canada, where they are believed by some to be major fault lines associated with mountain systems.*

Derangements of normal surface geomorphic features by vertical movements associated with salt domes have been discussed and illustrated by *De Blieux.*† They are largely derangements of surface drainage, the recognition of which requires a clear understanding of the local geomorphic processes.

GEOLOGICAL EXPLORATION BY MEANS OF STEREOSCOPIC VISION

THE SHADOW EFFECT**

It is a common belief that in viewing aerial photographs of hilly country those hillsides in the sun-shadow must be oriented so that the sun appears to be above the observer's head. Failure to do this when one is viewing a single photo may lead inexperienced observers to "sense" the topography in reverse. More rarely it may cause the beginner when viewing a stereo-pair to imagine that he sees even the stereoscopic image in reverse. However, those accustomed to using aerial photos will soon discover that, except in extremely rugged topography, the direction of the sun-shadow makes no appreciable difference. In fact, the full-time student of aerial photos, for ready comparison with maps, must frequently study them with the north direction "up" regardless of the direction of sun-shadows.

The vegetal growths on the protected north-facing hillsides (the "vegetal sun-shadow"), because they appear as dark areas, act much as a true sun-shadow in their effect on aerial photo study.

STEREOSCOPIC VISION

One of the great innovations of modern geology is the use of aerial photographs for stereoscopic vision. Human bioptic vision is of course stereoscopic vision, wherein each eye supplies the brain with its own separate retinal image of the same field of view as seen from the two positions of the two eyes. A similar arrangement of two photographic images of the same field of view, as seen by the aerial camera from two different positions, supplies the brain with the stereoscopic pair of images needed for aerial stereoscopic vision. The beauty and significance of stereoscopic vision of geomorphic features cannot be described in words, it can only be experienced. The writer believes that the use of aerial photographs and stereoscopic vision is the major advance of geologic science of the past one-half century. But geomorphologists must be interested in the faults of stereoscopic vision as well as in its perfections.††

COMMON FAULTS

All students of aerial photos have noticed the concave, bowl-shaped aspect of the stereo-model produced by nearly all the available photographs. Photo-engineers claim this is the result of inadequate lenses. Though sufficiently good

* Wilson, J. Tuzo. "Some aspects of geophysics in Canada, etc.," *Amer. Geophysical Union, Transactions*, Vol. 29, No. 1, pp. 1–12, 691–726. 1948.

† De Blieux, Charles. "Photogeology in Gulf Coast Exploration," *Amer. Assoc. Petroleum Geologists*, Bull. 33, No. 7, pp. 1251–1259, July, 1949.

** Melton, Frank A. "Preliminary observations on geological use of aerial photographs." *Amer. Assoc. Petrol. Geol.*, Vol. 29, No. 12, Dec. 1945, p. 1761.

†† Melton, *op. cit.*, p. 1757.

lenses may have been designed, they are not yet in common use. For geological purposes, aerial photos should not utilize the entire field of the lens unless it is understood that a considerable part of each photograph must be cut off. By proper cutting, a less distorted central part of each photograph may be made accessible for close study with a magnifying stereoscope. But unless the overlap has been planned to make this possible, certain parts of the photographed area may thus be lacking for closely detailed stereoscopic study. The best geological interpretation requires that only the central part of photographs be used, and that the lens have relatively long focal length—10 or 12 inches or even more if cost will permit.

Photos with $8\frac{1}{4}$ inch focal length are in common use, but in the flat lands discussed here they are inadequate for good stereoscopic work.

DISTORTION OF THE PERSPECTIVE

The correct relative position of a stereo-pair of aerial photographs to give the best possible stereoscopic model is a problem worthy of discussion. It has been stated in textbooks and articles on photogrammetry, that the only "correct" orientation of contact prints for stereovision is the "line-of-centers" orientation. In this method, the observer places a stereo-pair of overlapping photos in such a position that the ground-images at center-points of the photos, together with the observer's eyes, fall in a single plane. In other words (if perfectly regular conditions be assumed, such as straight flying, freedom from tilt of camera axis, et cetera), the "line of flight" on the photos and the eye of the observer should fall in the same plane. This is general practice and is, indeed, the only satisfactory method to use in geologic interpretation or other types of map work with stereoscopic pairs of aerial photos.

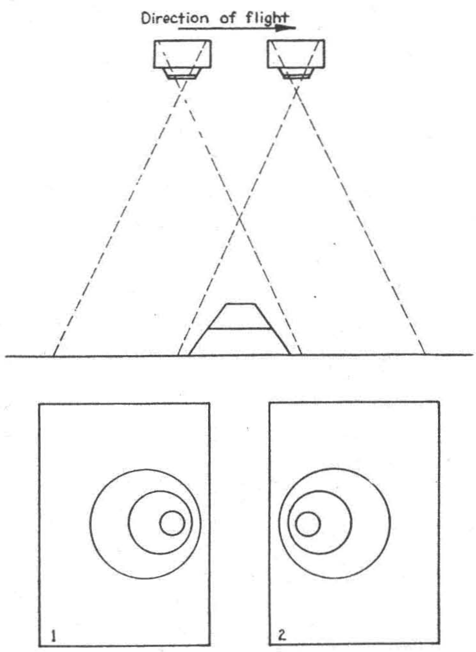

FIG. 14. Showing the geometric relationships of the perspective of a symmetrical flat-topped hill, marked by contours at the top middle and base, when it is photographed from above by two consecutive vertical aerial photographs. See Figure 15.

However, it should be pointed out that so far as the stereoscopic image or model alone is concerned, the "line of centers" or (under ideal conditions) the "line of flight" may be disregarded. Figures 14 and 15 illustrate the "distortion of the perspective" which is under discussion. Figure 14 shows the geometric relationships of the perspective of a symmetrical flat-topped conical hill marked by contours at the top, middle, and base. If the hill lies in the marginal area of two consecutive vertical photos, its photographic images on the contact prints will be asymmetrical because of the perspective or obliquity at the margin.

Figure 15 illustrates the sequence of changes in stereoscopic and non-stereoscopic, though binocular, vision of this ideal stereo-pair, as each print of the pair is rotated toward the

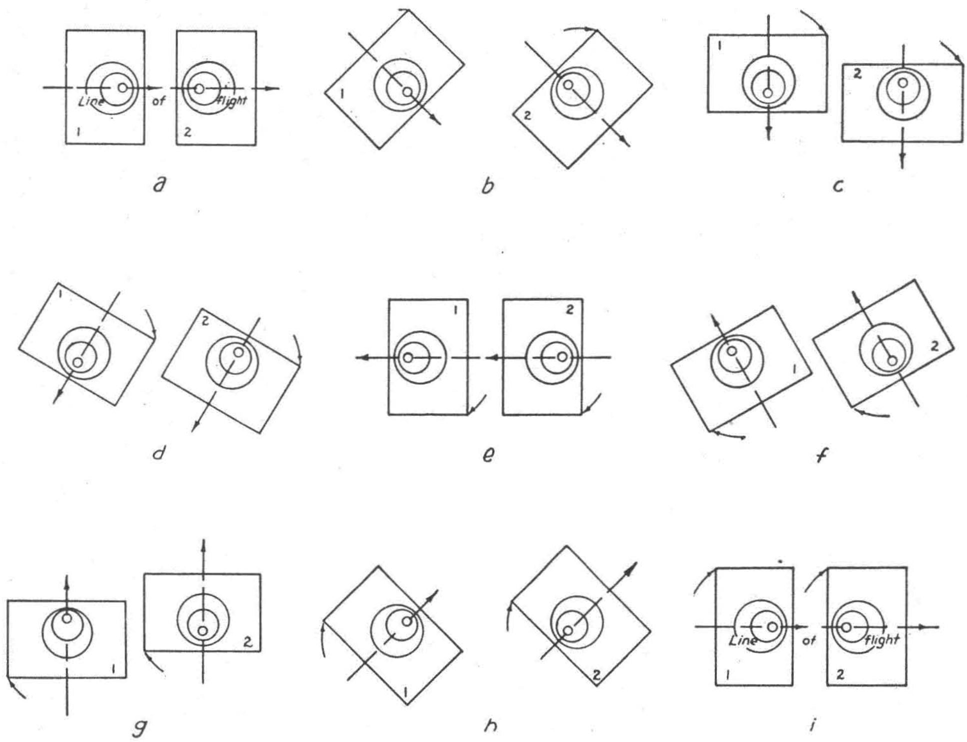

FIG. 15. This illustrates the sequence of changes in stereoscopic and non-stereoscopic, though binocular, vision of the ideal stereoscopic pair of vertical photographs in Figure 14. Each print of the pair is rotated toward the right maintaining stereoscopic vision with suitable optical aids. See text.

right, retaining binocular stereoscopic vision with suitable stereoscopic instruments. The following list will clarify the diagrams; it represents *all the possible* positions in which a stereo-pair may be held for stereo-vision.

a. Relative position of the ideal stereo-pair for stereoscopic vision with normal relief. This is the correct position for stereoscopic work, but not the only position.
b. The stereoscopic image begins to disappear for most observers between 30° and 60° of rotation toward the right or left.
c. With 90° rotation the stereoscopic image cannot be seen but a "pseudo-stereoscopic" image is clear and distinct. In other words a clear picture is visible but there is no stereoscopic relief. This is one of two positions of "extinction" for the stereoscopic image. See diagram "g" for the other position.
d. With further rotation to 135° from the starting position (±15°), a stereoscopic model begins to appear in reverse relief. This is one of the limiting positions for stereoscopic vision with reversed relief. The other limit is the position 225° (±15°). See diagram "f".
e. The rotation is 180°. This is the optimum position for stereoscopic vision with reversed relief. It is the direct opposite, both in orientation and perception, of the correct position for stereoscopic vision with normal relief shown in diagram "a". Reverse relief is as easily seen by an experienced observer as normal relief; it is, in fact, on rare occasions useful to the geologist.
f. With further rotation to 225° from the starting position (±15°), stereoscopic vision with reversed relief begins to disappear. This is one of the limiting positions for stereo-vision with reversed relief. The other limit is the position 135° (±15°). See diagram "d".

g. The rotation is 270°. This is one of the two positions of "extinction" for the stereoscopic image and for the appearance of the pseudo-stereoscopic image. See diagram "c" for the other position.
h. The stereoscopic image with normal relief begins to reappear for most observers between 30° and 60° to the left of the starting position. This is 315° (±15°) of rotation toward the right and 45° (±15°) of rotation toward the left of the starting point.
i. The starting position. See diagram "a".

"Distorting the perspective" of a stereo-pair, by rotating both photos far toward the left and toward the right, does not noticeably distort the stereoscopic model. Nevertheless, for reasons of uniform and rapid handling of photos as well as easy perception of the stereoscopic image, the customary orientation of aerial photos is best.

PARALLEL VISION, CROSSED VISION, AND REVERSED RELIEF

If two overlapping aerial photos are held in their correct position with respect to one another and viewed stereoscopically, with the line of flight parallel to the line between the eyes (the eye base), normal relief is seen though in somewhat exaggerated steepness (see Figures 4, 5). If the photos are crossed, the one that was on the right being now on the left side (Figure 16), and if they are viewed stereoscopically, say with a mirror stereoscope, the relief will appear as distinct as before only it will be in reverse, with the valleys appearing as ridges (cf. Figure 13, e). There may be times when this type of stereovision is useful for the geomorphologist, especially during the interpretation of faulty photographs.

If one takes the crossed photos from the mirror stereoscope and views them with crossed eyes, holding the photos at arm's length, the normal relief is once

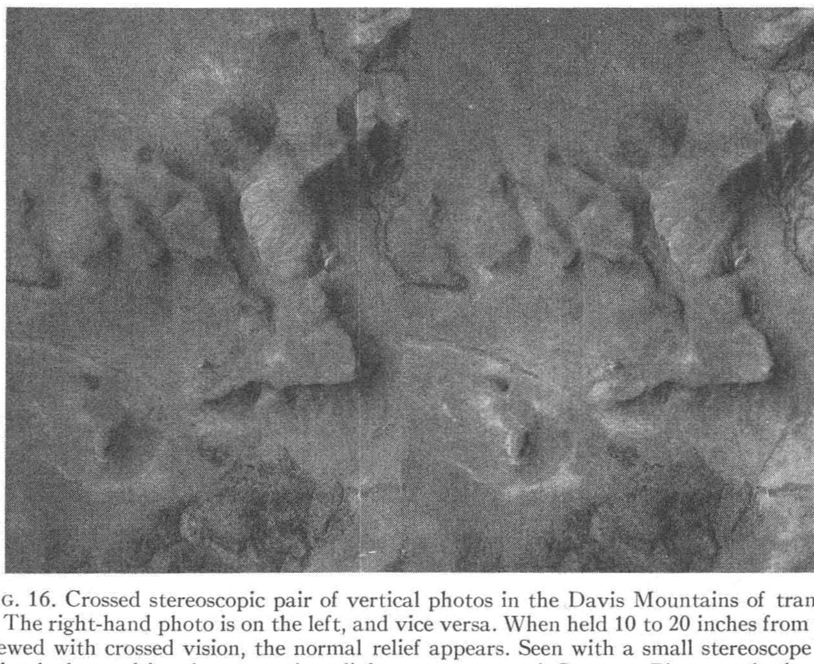

FIG. 16. Crossed stereoscopic pair of vertical photos in the Davis Mountains of trans-pecos, Texas. The right-hand photo is on the left, and vice versa. When held 10 to 20 inches from the face and viewed with crossed vision, the normal relief appears. Seen with a small stereoscope or with parallel naked eye vision, however, the relief appears reversed. See text. Photography by the Soil Conservation Service of the U. S. Dept. of Agriculture.

more visible. If one puts the photos once more in their correct relative position with respect to each other and still views them with crossed vision, the relief will once more appear to be reversed. Aerial photographs and stereoscopes being what they are (of varying degrees of excellence and of varied design), there will be times when the student of aerial photos will find these various techniques useful.

In examining aerial photographs from different lines of flight, or photographs made under difficult flying conditions, one must be careful not to hold the photographs in the position indicated by (c) and (g) or (b) and (h) in Figure 13. One would see a clear photograph in most cases but the relief would not be visible or would be visible only with difficulty. It would not be stereoscopic vision but *pseudo-stereoscopic vision.** Failure to recognize it for what it is might introduce errors into the geological map.

PARALLEL VISION AND NORMAL STEREO RELIEF

The following points cannot easily be illustrated in a journal article because of the loss of detail in half tone printing. The reader with access to any representative file of aerial photographs, however, will be able to find suitable illustrations without trouble.

Naked-eye stereovision (parallel and with normal relief) has certain advantages as well as disadvantages. In certain types of large-scale or coarse-textured terrane of high relief there may be less apparent distortion of the dip of gently sloping beds than when magnifying prismatic lens stereoscopes are used. This is probably due largely to the prism in the lenses, though the spherical correction (the magnification) may have something to do with it also, as does the distance from the eye to the pictures under observation. In most areas, however, naked-eye vision is not adequate because not enough of the geomorphic detail can be seen to evaluate it properly. For example, in most terrane of ordinary relief it will usually be possible to form a more accurate visual estimate of the position of the local base level of stream erosion with magnifying stereoscopes than with the naked eye, because with magnification one can better see the stream channels. Thus magnification may outweigh the disturbing effects of the prismatic component of the lenses.

On the other hand, the disadvantages of the small folding magnifying and prismatic stereoscopes in wide use include the uncomfortable and cramped position the operator must assume—a disadvantage when it must be maintained for long periods of time. Likewise it is occasionally a disadvantage to be able to see only a small portion of the stereo-image at one time; though, if the photographic image is sufficiently fine-grained to stand magnification, the use of a magnifying stereoscope may have a compensating advantage.

Mirror stereoscopes have an advantage when the observer is looking especially at the outcrop of thick formations, or when he is interested in other large-featured aspects of the geomorphology that are also easily seen. Mirror stereoscopes whether silvered on the front or back sides have the disadvantage of placing the observer at a considerable distance from the photos; they thus obscure considerable detail. They eliminate distortions inherent in magnifying prismatic lenses, but do not eliminate the distortions inherent in the film, in the prints and in the human eye. In addition the mirror surfaces are occasionally uneven, thus introducing their own type of error.

* "Pseudoscopic" vision is a term that many have used for the reversed image described above. The writer does not believe that "pseudoscopic" is a proper scientific name. He does feel, however, that there is a need for the name *pseudostereoscopic* in the usage given above.

So much has been written about stereoscopes that it seems fitting for the writer to present the results of his experience with their geological use in the form of a list.*

a. The geologist will want magnification in his stereoscopes, within the limit set by the size of grain in the pictures. It is true that in certain geological terrane, the formations and the structures are of such dimensions that they are clearly visible to the naked eye; yet in nearly every case certain important details will be visible only with magnification.
b. The geologist will need lenses of the highest quality. Since he will spend much of his time searching the photos for geological features near the limit of visibility, even the slightest irregularities and imperfections will introduce relatively great distortions. So far as the writer has been able to learn, lenses of high quality are not in common use.
c. The geologist will want bright illumination; and, during much of his study, will want to view the photos as close to the eye as is possible, consistent with clear vision. The reasons for these conclusions are the same as those supporting the foregoing statement ("a") about magnification.
d. The geologist will need a stereoscopic-aid which is adjustable, or which has interchangeable lenses to compensate in part for the varying width of overlap found in existing aerial photographs and for other irregularities.
e. The geologist must have stereoscopes that can be used for many hours daily without undue physical or ocular strain. Stereoscopic spectacles remove much physical strain, such as that caused by prolonged bending over a table; but they may introduce certain distortions if the lens mount is flexible.

It seems clear that stereoscopes designed for geological use have not yet been developed. Many of the existing magnifying stereoscopes either are not of sufficiently high quality or are not adjustable for varying ocular width. The available mirror stereoscopes place the observer too far from the photos and do not permit adequate illumination.

CAUSES OF STEREO-IMAGE DISTORTION AFFECTING THE PHOTO-GEOLOGIST

In the writer's opinion the following factors affect and distort the stereoscopic image. They are arranged in a loose "order of importance" based on the writer's own estimate of the degree a horizontal surface would be deranged by the distortion. That other geologists will want to change the order is understandable, because the human eye is a varying instrument from person to person, and from time to time in the same person, and also as the stereoscopic image is itself an optical illusion seen with varying degrees of clearness and intensity by the same person under different conditions of illumination and fatigue.

1. Focal length of the camera lens. The longer focal lengths give a truer and less distorted stereoscopic image than the shorter ones, other qualities being equal. Perhaps with the theoretical ideal lenses this should not be so; but with the lenses that have been used thus far this statement can hardly be questioned.
2. The use of cameras that take the total visual field of view of the lens. Regardless of the type of lens the marginal portions are likely to be inferior. Then too when this factor is combined with short focus lenses, as has been done, the marginal portions of the stereo-image will be greatly distorted. Also the shape of the usable portion of the photos is circular and of small size—and is not convenient for geological work. For the study of gross drainage or for the production of base maps of hitherto unmapped terrane, such photographs may be satisfactory; but for close geological study in the flat-lands of the world they are nearly useless.

* Melton, *op. cit.*, p. 1761.

3. Differences in the altitude of the plane when making successive overlapping photographs—i.e. differences in scale of overlapping photographs. This results in a pronounced tilt of the stereoscopic image, thus introducing slopes that do not exist on the ground.
4. Lens imperfections. These are by no means as common as they were a few years ago, but imperfect lenses are still occasionally used. They may introduce stereo-slopes that are unreal.
5. Unequal shrinkage or expansion of the film and/or paper. This accounts for much distortion near the margin of the photos and more rarely for large distortions near the center.
6. Tipping or tilting of the stereo-image caused by failure to view it directly perpendicular to the photographs. This introduces stereo-slopes that do not exist.
7. Tilt of the plane and the camera at the time of making the photograph. This is not such a great source of stereo-distortion as many believe though it is a source of error.

There are other causes of distortion of the stereoscopic image that are more uncertain and variable in their effects. For example the writer has long suspected that there may be such a thing as a "cliff effect," which is sometimes, though not always, noticeable in large cliffs at the edge of mesas and plateaus, whereby the supporting strata are made to appear to dip toward the mesa, or to dip more steeply than they really do. It would be instructive to have the opinion of others as to whether they have or have not seen such an "effect."

Stereoscopic vision depends to a certain extent on the recognition or perception of detail. Stereo-pairs of aerial photos have occasionally been made of heavily wooded areas with all relationships normal except that one photo was made in the forenoon and the other in the afternoon. This caused the tree shadows in the stereo-pair to fall in two directions, nearly perpendicular to each other. In such a stereo-pair, it may be impossible to resolve the topography into a stereoscopic model, even though the per cent of overlap may be normal, tilt and "crab" may be absent, and even though the scale of the two photos may be the same. Unless the hill-form is large and striking, it may be obscured by the divergent tree shadows.*

The two human eyes may not be equally effective in visualizing the optical image, and may thus give rise to a so-called "one-handedness" in its perception. One can see what this may amount to (if he is subject to it at all) by viewing a pair of photos stereoscopically, then fastening them together and rotating the pair 180 degrees about the line of sight so that stereovision may also be secured in the new position. The stereo model may not appear the same in the two positions regardless of shadow effects or other tangible causes of distortion.

In extreme cases, stereo-distortion can be recognized by the appearance of the drainage lines. For example some of the streams may appear to run up-hill. But in most stereo-pairs the degree of distortion is so slight that it is unrecognizable without the elevation control furnished by bench marks.

THE PHOTOGRAPHS

Increasingly good photographs are being made by aerial photographers. So many factors are involved and so much has been said about the causes of good and bad photographs that the writer does not want to add more, except as his own experience as a consulting geologist prompts him to do so.

Everyone now understands that geologists need clear photos, flat-lying

* Melton, *op. cit.*, pp. 1757–1758.

paper, and the finest possible emulsion grain in order that magnification may be used. The best photographs for geological use, however, depend upon the nature of the terrane to be studied; in coarse-textured terrane of high relief where the structural anomalies are of large size, one can usually employ shorter focal length photos than in the flat-lands under discussion here. As stated above, the widely used $8\frac{1}{2}$ inch focus lens has produced most of the photographs available today. It is practically at the limit of usefulness for stereoscopic study of strike and dip in the flat lands. A longer focus would be better in those regions. Any undertaking with the great possibilities of aerial photographic exploration and mapping will not be handicapped by lack of proper photographs for long.

In addition to evaluating the significance of the larger features, geologists will probably always be searching for signs of bedding and other features up to the limit of visibility of the photographs. Professional photogrammetrists could no doubt do a much better job of estimating dips and strikes than the photogeologists; but the surveying work, the time and the effort necessary to do it, and the possibility of confusion arising in the recognition of bedding would make the undertaking prohibitively expensive for geological exploration. The photogeologist can work many times as fast. Any new improvements in quality of photographs and in the variety of photographs available in oil-bearing regions will be to the benefit of exploration companies and photographers, as well as to geologists.

PHOTO-INTERPRETATION OF CORAL REEFS

Curt Teichert, University of Melbourne and R. W. Fairbridge, University of Western Australia

INTRODUCTION

THERE can be few branches of geology where aerial photographs are more useful than in the study of coral reefs. Because reefs are either partly or wholly submerged, most reefs can only be visited in parts, and many reefs are entirely inaccessible. The first more comprehensive studies of aerial photographs of restricted coral reef groups were made in the East Indies by *Umgrove* (1928, 1929) and in the Great Barrier Reef of Queensland by *Stephenson* et al. (1931); but both used aerial photos as a check on ground observations and not as independent sources of information.

During World War II the coral reefs of the western Pacific area, including those of Indonesia, New Guinea and northern Australia were extensively photographed from the air. An almost inexhaustible source of information on coral reef structures is thus now available. Subsequently there have appeared a number of coral reef studies in which extensive use has been made of aerial photographs (*Nugent*, 1946, 1948; *Tracey, Ladd* and *Hoffmeister* 1948, *Fairbridge* and *Teichert* 1947, 1948; *Teichert*, 1947; *Fairbridge*, 1948, 1950 b) and one which is entirely based on photo-interpretation (*Teichert* and *Fairbridge*, 1948). Some future possibilities in this direction were outlined to the Great Barrier Reef Committee by *Fairbridge* (reported on by *Steers*, 1945).

REQUIREMENTS FOR CORAL REEF PHOTOGRAPHY

The photography of coral reefs poses special problems, mainly because of the fact that some of the features to be photographed and interpreted are situated in the surf zone or below sea-level.

For detailed determination of reef features the scale of verticals should not