than could be made by closely-spaced traverses without the aid of photographs.

(g) *Physiographic data.* The photographs are very useful in studying glaciers, plotting boundaries of glaciers, and in spotting and plotting moraines and terraces, etc.

3. *Use in office compilation.* The chief use in this connection is in checking doubtful points and in renewing one's mental picture of structures, during final preparation of map and report.

In four-mile and reconnaissance mapping the application is similar, but photographs are even more useful because this work is done with a minimum of traversing, so that wider extrapolation and inference from photographs is justifiable. As the number of photographs covering a four-mile map area is much greater it is generally desirable to go over the photographs carefully before going to the field, and to take only those that show geological features.

Much of the mapping done by oil geologists in Alberta is done without the aid of base maps. They use the photographs instead of a base map, plotting all their information on them or on the back by pricking. Small, selected areas are surveyed by plane-table. Later, in the office, they make a map on the scale of the photos by tracing. Such a map has a good deal of distortion but gives a good picture of the geology. If this work indicates a really favourable area they will return and make an instrumental survey and more detailed geological map before locating a well-site.

AERIAL PHOTOGRAPHS AS AIDS IN STRATIGRAPHIC STUDIES

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INTRODUCTION

AERIAL photographs represent an invaluable, if not indispensable tool for geological investigations of the nature and distribution of stratified rocks—studies which comprise the branch of geology known as stratigraphy. Because stratified rocks are extremely widespread at the earth's surface and because their composition, thickness, sequence, and structure have a bearing on most types of engineering and economic geology, the work of the stratigraphic geologist is fundamental for many of the practical applications of geologic science. Insofar as photos aid this one branch of the science, they are indirectly of service to other branches as well.

Nature of stratigraphic studies. In any area where stratified rocks crop out or are concealed only by unconsolidated materials such as soil, loess, dune sand, glacial drift, and the like, the first objective of stratigraphic study is to determine the composition and arrangement of strata with respect to one another. First, it is necessary to determine the order of succession of the rock layers, and then to ascertain the thickness of each significant division of the succession. Commonly the layers of like composition and texture that occur together are grouped together and defined as a map unit called "formation," provided the similar strata have sufficient aggregate thickness to suit classification for mapping purposes on a selected scale. A formation also may include dissimilar kinds of rock layers, provided they represent essentially uninterrupted sedimentation or accumulation and accordingly do not include strata of greatly differing age. It is a task of the stratigrapher to classify and define these divisions, and for purposes of description or other reference to apply a geographic name to each recognized formational unit. In case formations have been differentiated by previous workers in an area being studied, the geologist who undertakes stratigraphic studies needs to identify the rock divisions already named, but he may revise classification if he deems previously-established units to be unsuitable.

Lithological characters of the strata and their content of fossils are all-important objects of stratigraphic study, whether an investigation in a given area constitutes initial exploration or follows previous work. These attributes of the rock layers are the means of distinguishing and tracing them.

Field work by the stratigrapher commonly includes careful observation and description in his notebook of all features relating to the exposed rocks that he thinks are significant. He measures the thickness of rock units and their subdivisions. He searches for fossils and, with a degree of effectiveness that varies with his training, experience, and skill, uses paleontological information as a guide in identifying and correlating the fossil-bearing beds. He maps distribution of formations so as to show the areas in which each is exposed or immediately underlies unconsolidated surficial materials.

Background for discussion of aerial photographs in stratigraphic studies. This paper is based wholly on my experience in using aerial photographs in my own stratigraphic field studies, supplemented in minor part by observations derived from acquaintance with projects of the U. S. Geological Survey and various aerial surveys made under auspices of the War Department. Many oil companies and other private organizations, as well as State Geological Surveys, are known to utilize aerial photographs extensively in exploration, both for reconnaissance and detailed stratigraphic studies. However, information is not available to me for review of their methods of work.

My experience in applying aerial photograph to stratigraphic studies includes (1) about one year of field and office work on areas of subhorizontal formations of late Paleozoic age in Texas and Kansas, (2) about three months' work on various areas of jungle-covered territory in South America, (3) several short-period studies of more or less strongly disturbed areas, including parts of the Arbuckle, Rocky, and Appalachian Mountains, and (4) surveys of rather extensive territory in northwestern Canada, Alaska, and some other areas assigned to me while on active military duty.

AERIAL PHOTOGRAPHS AS BASIS FOR PLANNING AND CONDUCTING STRATIGRAPHIC SURVEYS

As for many other types of work, the first advantage of aerial photographs in connection with stratigraphic studies is their usefulness in furnishing information on how to find features that need to be examined on the ground. Few areas are mapped with such accuracy and detail as to show precisely the location of all roads and trails, streams and valleys, fences, houses, timbered areas, and many other features that one needs to know in finding his way about or in exactly spotting any desired position. Even a detailed, large scale topographic map may not reveal characters of the land surface such as gullies, thickets, bouldery and sandy areas and the like that affect travel. Aerial photographs are best suited to show both the things a geologist wants to see in the field and how to get there most expeditiously and painlessly.

An aerial mosaic or even a photo-index sheet may serve satisfactorily as a geographic base and for a comprehensive view of the main geological features in a region. Generally, however, stereoscopic examination of air photo pairs is needed for effective reconnaissance. It is extremely desirable to acquire facility in viewing aerial photographs stereoscopically with the unaided eyes, because this skill frees the worker from dependence on instruments that are ill-suited for use in the field, and greatly speeds his scanning of numerous pictures.

A reasonably careful inspection of air photos covering a region that is to be studied stratigraphically, supplemented by a rapid reconnaissance on the ground, furnishes the best possible basis for planning a program of work. It is likely to provide for the most effective distribution of available time, whether long or short, both for field and office work.

During progress of field work, the air photos need to be conveniently at hand whenever wanted. The geologist should be able to find any photograph, or pair

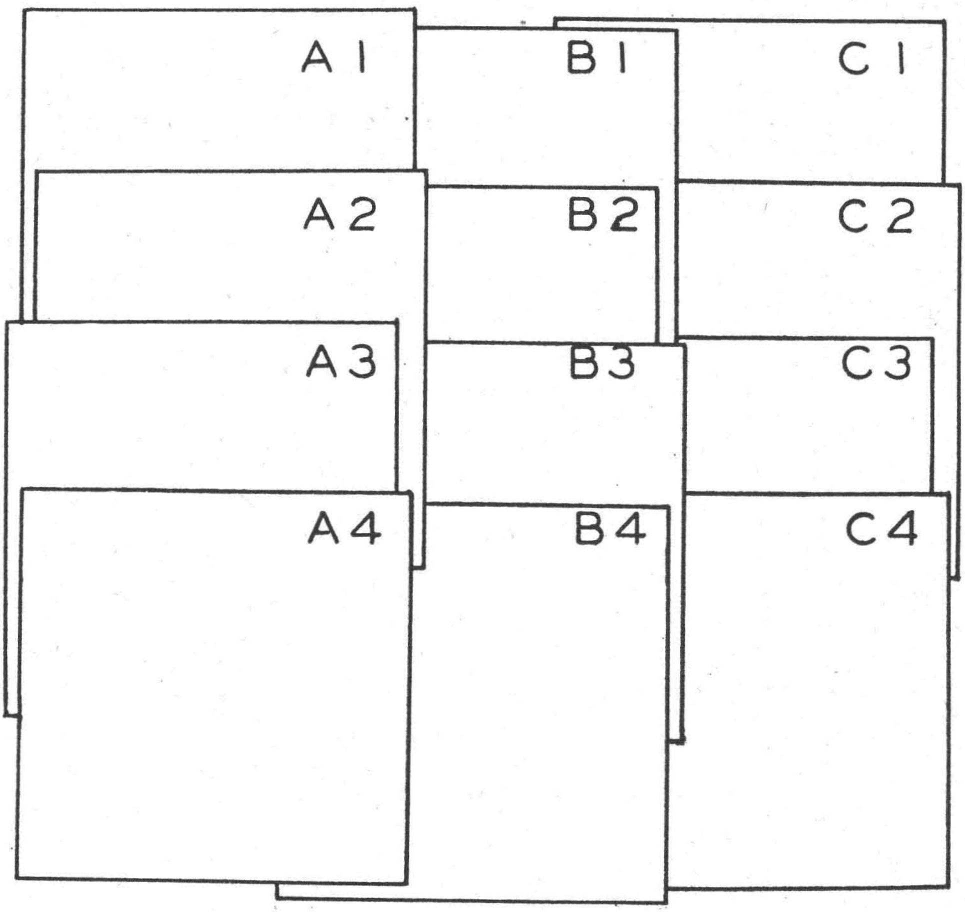

FIG. 1. Diagram showing uniform system for indexing air photos.

of photographs, very readily. Virtually all aerial surveys provide photographs in parallel flight strips, with overlap both between successive pictures of each strip and between adjacent strips. The original photograph numbers are almost never such as to permit identification of map locations without reference to a photo index sheet which is large and cumbersone. Breaks in the sequence of numbers, which are frequent in some sets, add complications.

An indexing and filing scheme that I have tested thoroughly in field work avoids difficulties of finding any desired picture. Each flight strip is assigned an index letter and, without regard to the numbers assigned by the photographic laboratory, the pictures belonging to each strip are numbered with colored ink or crayon in a sequence arranged so that the same number is given to matching prints of parallel flight strips (Fig. 1). Thus, photo C15 should overlap laterally with B15 and D15. The fact that pictures of adjoining strips commonly are somewhat out of step, instead of matching exactly along their whole sides, offers no trouble, for it is easy to place C15 with B14 or D16 if these pictures provide a better match.

The photographs of each strip are placed in a suitable container, such as an open-ended manila envelope or letter file, and the containers are carried in a brief case or carton of suitable dimensions. In this manner any desired photograph can be located at a moment's notice without reference to an index sheet.

In my field work using aerial photographs it has been found desirable to enter directly on the photograph all essential locality data, such as places from which fossil collections are obtained, and outcrops used in preparing measured sections. A wax-base colored crayon is suitable for this sort of marking in the field but a more permanent record may be entered using colored ink. Either crayon or ink can be removed from the photographs easily if desired, preferably by use of a solvent.

Alternate photographs are employed as bases for plotting geologic data, which consist chiefly of the boundaries of rock formations and selected subdivisions. If such boundaries are placed on a picture at reference points identified in the field, using any discernible features of the photograph—a tree, bend of a stream, rock bench or the like—the extension of the boundary can be made either in the field or in the office by stereoscopic viewing of the picture with an overlapping neighbor picture. If desired, the photos that alternate with ones on which geologic boundaries are drawn, may be used to record special locality data, or these latter may be plotted also on the geologically-marked photographs.

STRATIGRAPHIC FEATURES SHOWN BY AERIAL PHOTOGRAPHS

Aerial photographs cannot show geological features that are nonexistent in some sort of surface expression, but good air pictures (Figs. 2 and 3) commonly reveal significant characters of topography, soil, rock outcrops and vegetation that are not apprehended by a geologist working on the ground. When his attention has been drawn to any of these features from study of the air pictures—and this almost invariably means stereoscopic study—the geologist is able to find the things shown by the photographs. Particularly important is the manner in which aerial photographs bring out many items of geological evidence otherwise overlooked, and, by their comprehensive coverage, show relationships that are not at all determinable when observation is confined to a small patch of ground. In this manner, rock units have been traced accurately across country where ground methods would have failed entirely.

Rock outcrops. Some geological formations are strongly expressed at the surface by their physical characters, such as hardness and resistance to solution. Outcrops may be numerous even in humid regions. Aerial photographs make delimitation of outcrop areas, including territory in which the rock is soil-covered, a task that is easily and accurately performed. Weak rocks are likely to be exposed only in places where erosion is active, or their outcrop may be represented by scattered loose fragments of one or more beds that are slightly more resistant than the rest. It is easy for a geologist driving along a road, or walking as he works, to overlook the stratigraphic significance of loose blocks or cobbles of rock strewn across plowed fields or lost to sight in grassy pastureland. On the air photographs these fragments are clearly seen to have a definite pattern in their distribution. In several places I have had the experience of seeing in the air photos what seem to be lines of outcropping rocks and then finding the outcrops on the ground. Traverses across the area prior to study of the photographs had missed these outcrops entirely.

Topography. Stereoscopic study of aerial photographs brings out most topographic features of the earth's surface very clearly. The detail of topographic delineation depends, of course, on the scale of the photographs, which

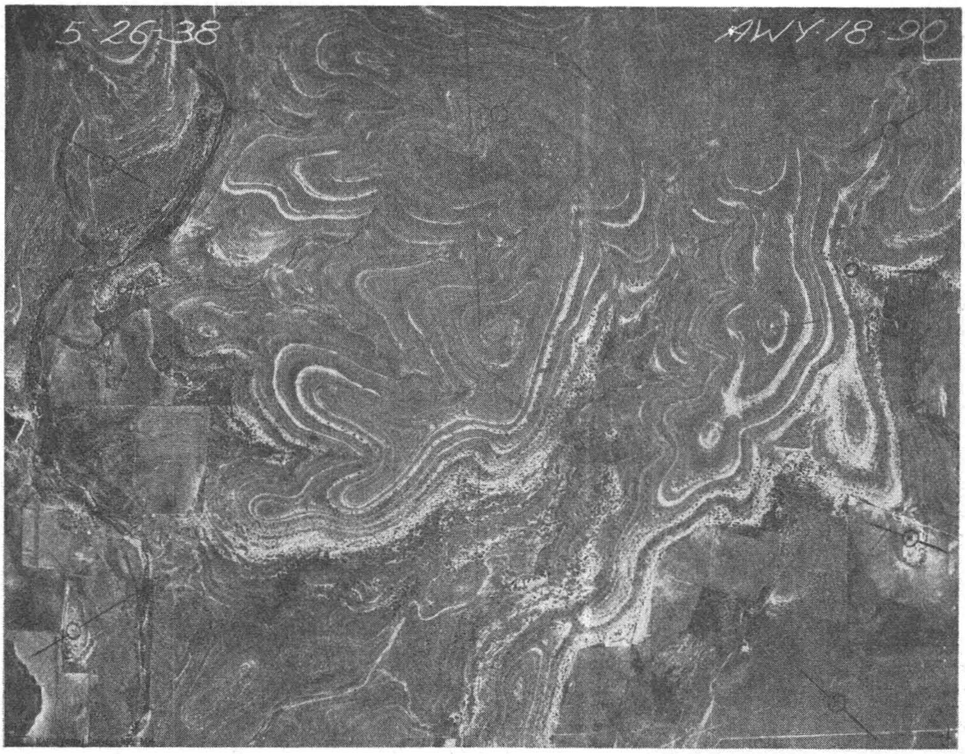

FIG. 2. Photo showing surface expression of subhorizontal strata in a hilly area in Coleman County, Texas. Each band represents the outcrop of a particular rock layer at the surface. Under the stereoscope, the prominent bands may be traced for long distances. USDA photo.

reflects the altitude from which the pictures were made. Exaggeration of vertical scale is afforded by the relatively large distance between the eye points represented by two air photos.

Topographic expression of outcropping rock formations plays an important part in stratigraphic studies that utilize air photographs, and commonly the significant features are more clearly seen on photos than on good topographic maps. Minor gullies and the pattern of minor prominences, both of which are related to characters of underlying rock strata, may show clearly on the photographs but are lacking on the maps.

Differences in steepness of slope, as seen in air pictures, may be utilized to determine the structural attitude of inclined rock layers and from this observation the order of succession of the strata can be determined. This is a fundamental stratigraphic relationship, and can also be ascertained on the ground. Photoreconnaissance stratigraphic studies of areas where work on the ground is not feasible however, may readily determine the order of rock succession and direction of dip, when air photos are available for examination. Even densely jungle-covered terrain which I have viewed in widely separated parts of South America by means of air photographs can be interpreted stratigraphically and structurally, but naturally one cannot collect fossils from the photographs and if information as to the geologic age of the outcropping beds is lacking, the extent of reliable geological conclusions derivable from the photos is limited.

Soil. The nature of soil, in many circumstances, is closely related to the

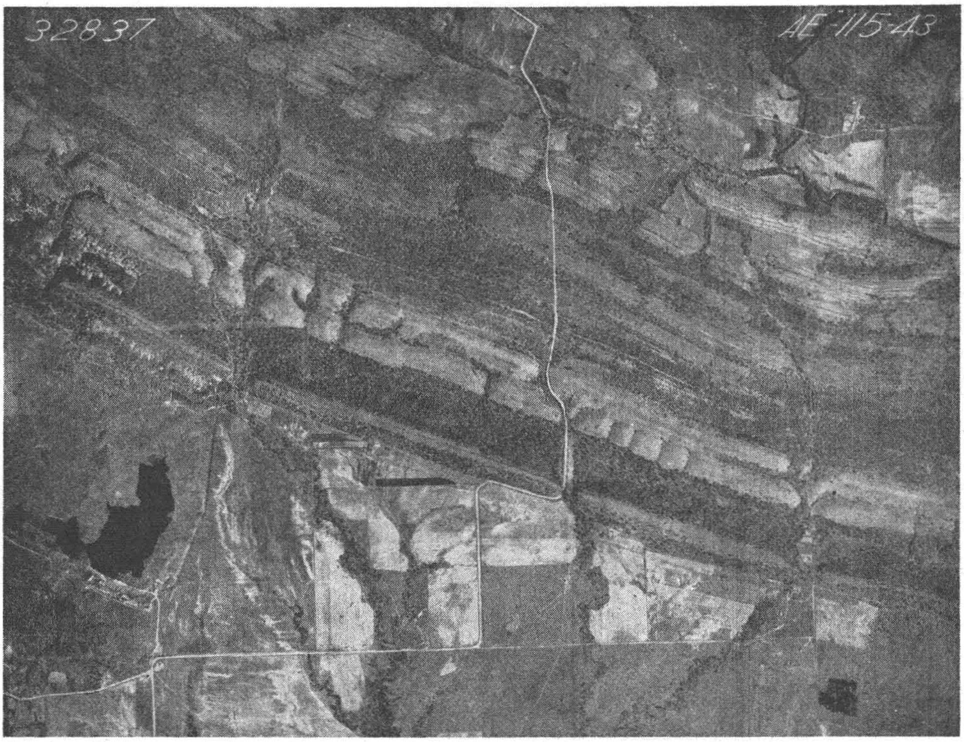

FIG. 3. Photo showing surface expression of steeply dipping beds of limestone, sandstone, and shale in the Arbuckle Mountain area of Oklahoma. The banded pattern of the vegetation reflects the outcrop pattern of the rocks. USDA photo.

character and structure of underlying bed rock. The chief differences in soils of residual origin are found in their color, texture, and composition. The variation in color of soils is reflected by shades from near-white to black as shown by air photographs and, of course, such record of soil colors is best given in photographs showing many newly plowed fields, or at least areas not densely clothed with vegetation. Air photographs in natural color, which may be available at some future time, will be a very great aid to stratigraphic investigations because of the manner in which slightly varying shades of soil and bed rock will be observable. Composition and texture of soils are likely to be expressed in various ways, as in ready yielding to erosion that produces gullies.

Vegetation. The dependence of many sorts of plants on the nature of the soil or bare rock on which they grow is very well known. Some variations of this sort are readily observed by a geologist working on the ground but most geologists are insufficiently trained in botany to make full use of vegetation as a stratigraphic tool.

The study of air photographs frequently reveals a pattern in the nature of vegetation that may be inferred to have geological significance. What the plants may be that follow a given outcrop belt generally is not determinable from the photographs, but differences between the vegetal cover of adjacent belts is easily detected. In conjunction with other evidence, the nature of the vegetation can furnish important information to the stratigrapher, and the regional distribution of vegetation can be seen better from study of the air photographs than by observation on the ground.

Facies changes. A situation in which use of aerial photographs has maximum value to the stratigraphic geologist is that presented by changing facies. This refers to changes in the nature of sedimentary deposits formed contemporaneously as they are traced from place to place. Thus, sandstone is found to grade laterally or interfinger with beds of shale; limestone changes laterally into calcareous shale or shale interbedded with layers of limestone. It is extremely difficult by ground methods to trace details of such variations of formations, whereas they are likely to be readily identifiable on photos if exposures or characters of vegetation and topography reflect features of the bed rock reasonably well. Changes of facies are well shown in some of the Cretaceous deposits of the western United States, late Paleozoic rocks of the midcontinent region, and Paleozoic rocks of the Appalachian Mountains. Such features may have much economic importance, as in furnishing underground conditions favorable for entrapment of oil and gas.

MEASURING STRATIGRAPHIC SECTIONS BY MEANS OF AERIAL PHOTOGRAPHS

A method of rapid, accurate measurement of stratigraphic sections, utilizing air photos, and adapted both to subhorizontal and inclined rock strata, has been employed by me. This takes advantage of the multitudinous identifiable surface features seen on photos, all of which, with minor qualification, are shown with reasonable accuracy to scale on a given photograph. The equipment required comprises a light plane table and alidade, to be used for measurement of vertical angles. The photograph being used may be fastened to the plane table with scotch tape and oriented by sighting on features such as fence lines or roadways shown in the photograph. It is advisable to check the scale of the photograph being used, employing any sort of available control for this purpose or making determinations with stadia rod. After the scale is satisfactorily established, the alidade may be located at any point identifiable on the photograph and elevations computed from vertical angles read to any visible points (also definitely identifiable on the photograph). Distance between the instrument station and point sighted may be scaled directly. The advantage of this procedure lies in the elimination of ground surveying techniques for measuring horizontal distances, and in the ease with which the work may be carried on by one man without a rodman or other helper. Also important is the rapidity with which vertical control of stratigraphic datum points may be obtained. Traverses many miles long can be run by shifting from one photograph to the next as successive points are located. A 60-mile traverse made by me in less than one day served to locate many vertical positions along the route, and tie-in at the end of the run with an error of only 4 feet as checked against a bench mark.

Accurate graphic sections of subhorizontal strata can be constructed from data derived in the manner just described, if control shots are obtained to indicate dip of the beds.

The plane-table-and-alidade method in conjunction with air photographs is applicable equally to measurement of more or less steeply inclined strata. Horizontal measurement should be scaled at right angles to the strike of the beds and elevations of hogback crests should be located along the same selected line. It is necessary in addition to make dip readings, by Brunton compass or by alidade measurement of two or more points on the same stratum. The data are then used for construction of a graphic section and thicknesses of formational units may be scaled from the section. The aerial photograph aids in obtaining a more detailed and accurate section than can be made otherwise without surveying work on the ground, which is likely to be slow and difficult.

CONCLUSION

Aerial photography is a new tool having value to stratigraphic geology in approximately the manner and almost the degree that a telescope serves astronomy. Although geologists studied, described, classified, measured, and mapped rock formations before the airplane was invented, just as astronomers studied heavenly bodies before the days of Galileo, few geologists or astronomers today would care to dispense with the modern equipment at their command.

AERIAL PHOTOGRAPHS IN GEOLOGY

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AERIAL photographs have been used for field mapping in this country only since the late '20's, and their utilization by geologists has continued down to the present. The aerial photograph as a base map has largely supplanted the topographic map and doubtless will continue to be one of the most effective tools available to the field geologist. Advantages of ease of location, wealth of detail, up-to-dateness of cultural features and representation of soil and lithologic differences by differences in shading far outweigh disadvantages of distortion and the handling of large numbers of prints in the field and office.

Several papers and books have appeared recently that are concerned with the interpretation of geologic features shown on aerial photographs (see references 1–16). Very few of these articles discuss the use of aerial photographs in the field; most of them describe photo-interpretation, or photogeology (Rea, 14), as a means to an end by itself.

To my mind this is putting the cart before the horse. It seems to me the fundamental use of aerial photographs is a base for field mapping. For this purpose they are unexcelled; used by themselves in the office as a substitute for field work their use can sometimes lead to serious errors in interpretation almost as well as to the truth.

AERIAL PHOTOGRAPHS IN FIELD MAPPING

When aerial photographs are used in the field as a base map for plotting dips, strikes, attitudes of joints, faults and contacts, their utilization involves few problems additional to those encountered in using a topographic or planimetric base. In fact, it has been my experience in the war and in teaching students in field geology that most people have less difficulty in visualizing terrain from an aerial photograph than they do from a conventional map.