MORPHOLOGICAL STUDY OF GEOPHYSICAL MAPS BY VIEWING IN THREE DIMENSIONS

BY

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Stereo pairs of contour maps may be constructed by a process analogous to, but the inverse of, the process used to make contour maps from stereo pairs of aerial photographs. This construction can be carried out either manually or with computer plotting devices. The contoured stereo pairs are then viewed in three dimensions by a variety of methods: with lens or mirror stereoscopes, with bicolor anaglyphs in drafted, printed, or projected form, or by polarized light methods. Preferred techniques at present are 1) 5-inch wide prints viewed by the mirror stereoscope, and 2) anaglyphic rear projection on a 3×4 ft screen.

The advantages of studying complex contour maps in three dimensions are striking. The entire morphology of the map may be studied rapidly by the human optical system, the latter carrying out such functions as trend filtering, wavelength filtering, form and texture recognition, and location of linears almost simultaneously. Important features that are missed or seen with difficulty on the flat contour map become obvious in a three-dimensional view, and may be studied further in detail by manual or computer techniques.

The method appears to be a significant interpretational breakthrough, bringing us one step closer to a *total* interpretation, wherein all observable map features are correlated with their geological causes.

INTRODUCTION

At the Thirty-Fifth Annual Meeting of the Society of Exploration Geophysicists in Dallas in 1965, a commercial computer concern[1] had on display a three-dimensional anaglyph (bicolor stereo pair) of a gravity contour map. On viewing this display, the writer was immediately struck by the overall comprehension obtained of the map and how the many anomalies present could be quickly compared one with another. As an experienced photointerpreter, as well as a geophysicist, he realized that there are many types of features present in three-dimensional surfaces that can be more readily recognized and evaluated by viewing in three dimensions. Indeed, stereo viewing of the three-dimensional surfaces on aerial photographs has proven so effective an interpretational tool that almost all military and geological photo interpretation is now carried out under the stereoscope. This fact has prompted the author of one important text in the aerial photographic interpretation field (Lueder, 1959, p. 6) to state flatly, "A stereoscopic, or three-dimensional, view is essential to photo interpretation. No really effective interpretive use of aerial photography can be made without it." Subsequent work has shown that the application of stereo viewing to contour maps of geophysical data promises to be equally as effective.

Following the Dallas meeting in 1965, the writer embarked on a program of investigation and use of stereo contour maps of geophysical data that has gone on almost continually to the present time.

HISTORY OF STEREO VIEWING

Three-dimensional viewing of stereo pairs is 133 years old this year (1971); the technique ap-

[1] University Computing Company, Dallas.

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peared almost simultaneously with the invention of photography. The British physicist, Charles Wheatstone, discovered the principle of the stereoscope in 1838, and a French painter, Daguerre, and others announced the first successful photograph the following year. In the late 1800's and the early years of this century, the parlor stereoscope, showing exotic travel scenes of far away places, was to be found in nearly every comfortable living room in America. After the appearance of the airplane and the advent of aerial photography during World War I, stereoscopy found a proper and profitable home in commercial photogrammetry and aerial photographic interpretation. Most of the world's topographic maps are now prepared from stereo pairs of aerial photographs.

Stereo viewing of *contour maps*, on the other hand, has had a much shorter and less auspicious history. The earliest reference found was a paper by H. H. Blee (1940); Blee evidently was the first person to experiment with stereo viewing of contour maps. As an officer in the U.S. Army Air Corps after World War I, he developed stereo pairs of topographic maps for air crew briefing aids and was overwhelmingly enthusiastic as to their benefits and possibilities for future use. His paper contained a printed anaglyph of a topo sheet and color filters for viewing it. Three years later, H. T. U. Smith (1943) cited Blee's work, showed a black-line stereo contour map, and stated, "By far the most effective way of representing relief is by combining contours with stereoscopic perception . . . this type of contour map is still in the experimental stage, but gives promise of having great value in many fields of application." Yet, a search of the post-1943 literature shows no further mention of stereoscopic contour maps. Perhaps the greater effectiveness of vertical aerial photographs for viewing topography in three dimensions eliminated the need for stereo topo maps.

In the field of geophysics, stereo contour maps were first brought to public attention in 1965 at the annual SEG meeting.[1] The maps shown there were developed by geophysicist R. W. Wylie, who constructed them from a three-dimensional program superposed on a contour routine of gridded values. Wylie had learned of the idea from petroleum company exploration personnel, where the technique had been experimented with for at least two decades (as best the writer can determine). Trump and Patnode, for example, described the use and construction of stereo versions of geological structure contour maps in 1960.

The use of *physical relief models* to depict three dimensions in geophysics is probably nearly as old as the profession itself. In 1931, for example, E. D. Lynton published photographs of peg models and stacked celluloid profiles of magnetic surveys; these were later reproduced in the text by Heiland. Other types of three-dimensional models of geophysical data have been observed at various times by the writer during the past 20 years and may be considered uncommon, but not rare. Such past efforts, as well as the present one, point out the basic three-dimensional nature of geophysical data.

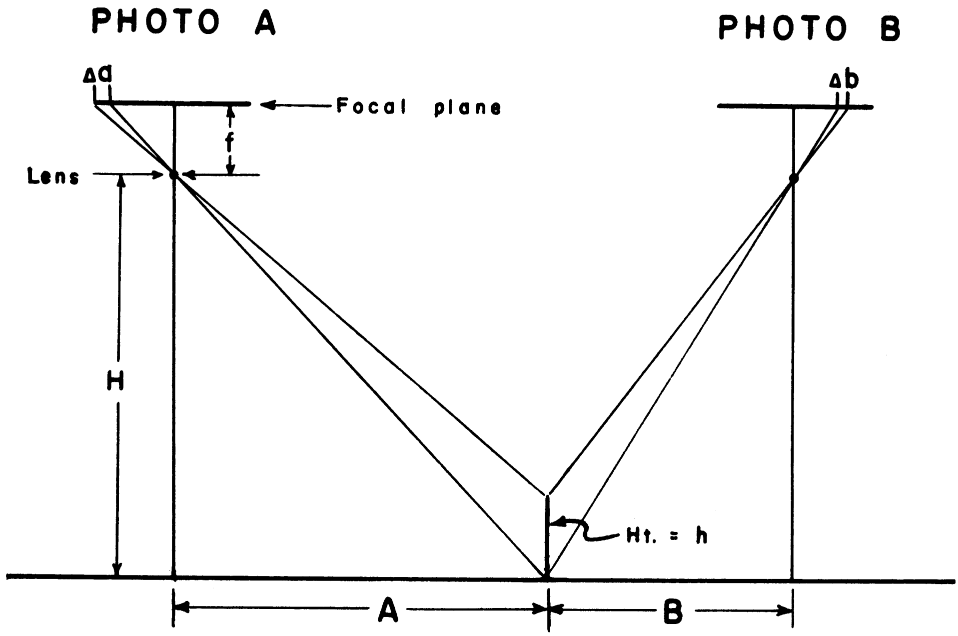
CONSTRUCTION OF STEREO PAIRS

The characteristics of stereo pairs are already known from photogrammetric theory. Figure 1 is the classical diagram of a pair of vertical aerial photographs recording an object of height h from two camera stations. The top and bottom of h appear at different points on the two photographs, and the total of the photo displacements, Δa and Δb, is termed the parallax of those points. It is this parallax which causes the top and bottom of the object to appear at different distances when the stereo pair is viewed by the binocular human optical system. The parallax may be measured directly on each photograph by a tube magnifier or indirectly on the stereo pair with a stereo parallax bar. It is related to h by the formula shown on Figure 1.

Whereas this relationship is useful for an understanding of stereoscopy in general, there is only a single simple characteristic of the vertical aerial photograph required for *construction* of stereo pairs of contour maps. That characteristic is the basic relationship between photoscale and camera altitude:

$$\text{Photoscale} = \frac{f}{H},$$

where f = the focal length of camera and H = altitude (Figure 2). Photoscale and altitude thus vary inversely, so that as the altitude decreases (points closer to camera station), the scale increases. This scale change takes place about the *principal point*, or center point, of the photograph, corresponding to the ground point vertically be-



1. Height of object = h

2. Height above datum = H

3. Separation, S = A + B

4. Focal length of lens = f

5. Parallax, $\Delta_p = \Delta_a + \Delta_b$

$$\Delta_p = \frac{Sfh}{H(H-h)}$$

FIG. 1. Diagram outlining one of the basic derivations of photogrammetric theory: the relationship between the photo parallax of a vertical object *h* and the other elements of vertical photo geometry.

neath the camera station. Also, since the focal plane, or photo negative, is flat and horizontal (by definition), a photograph of any flat horizontal surface has a constant scale, i.e., it is in reality a plan map of that surface. Since a contour line lies on such a surface, any given contour line has a constant scale; and this scale may be determined by the above formula. Contour lines of higher value (closer to camera station) have a larger scale.

Thus, in order to construct a stereo pair from a contour map, we may simply follow the above rules pertaining to vertical aerial photography. Two hypothetical principal point locations are selected, one for the right view and one for the left; and the contours are enlarged or reduced successively about each point according to their value. If the principal points are located in the manner of vertical aerial photographs having the customary 55 percent overlap, they will fall slightly outside the map boundaries along the horizontal center line (see Figure 3). This type of stereo pair is herein termed the *classical*, or *variable-scale*, variety, since it is constructed in the manner of a classical stereo pair of vertical aerial photographs; and each contour value has a different scale. This principle was employed in the original program of stereo pair construction undertaken by the writer, but is now used only for special cases, as will be explained below.

For proper viewing of the classical stereo pair, the eyes should be located directly above the *photo-base*, that is, over the line connecting the principal points. Otherwise, highs in the upper half of the map, when viewed from directly above, will appear to lean artificially toward the top of

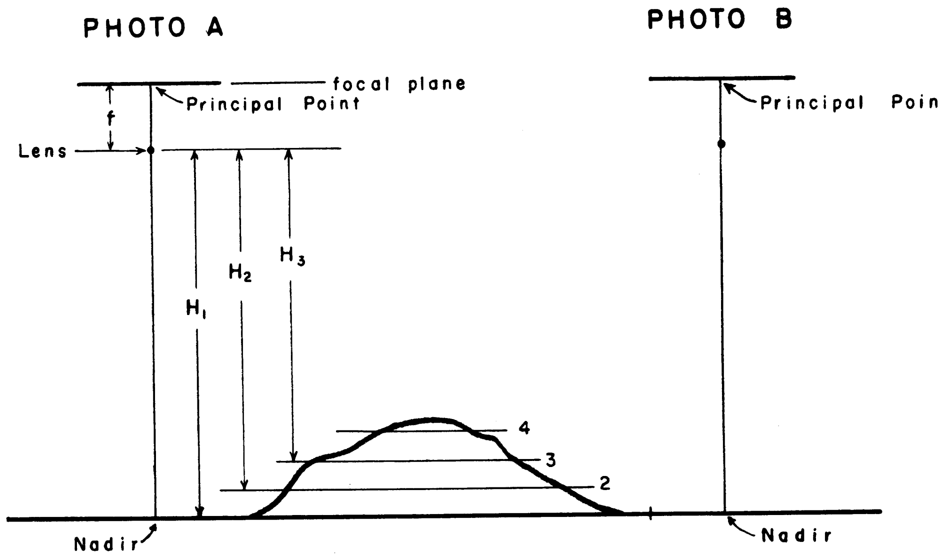


FIG. 2. Photoscale for planimetry on plane, $n = f/H_n$.

the map, and highs in the lower half, viewed in the same manner, will appear to lean toward the bottom half of the map. Lows will be tilted in the opposite direction to highs. This characteristic of stereo pairs is well explained by Miller (1961, p. 45–50); Miller's text is the only one found that explains this phenomenon.

However, usually for convenience and for ease of viewing, we examine each section of a stereo pair from directly above; airphoto interpreters have always done this in spite of the artificial leaning it produces. There is a special type of stereo pair, however, where the leaning phenomenon is absent; this case, as it happens, offers many advantages for artificial stereo pair construction. If we remove the hypothetical principal points to a great enough distance, right and left, along the center line of the map, in the resultant construction the scale change between different contours will be imperceptible, and the net effect will be a simple *translation* of contours right and left. The effect of stereo relief will be the

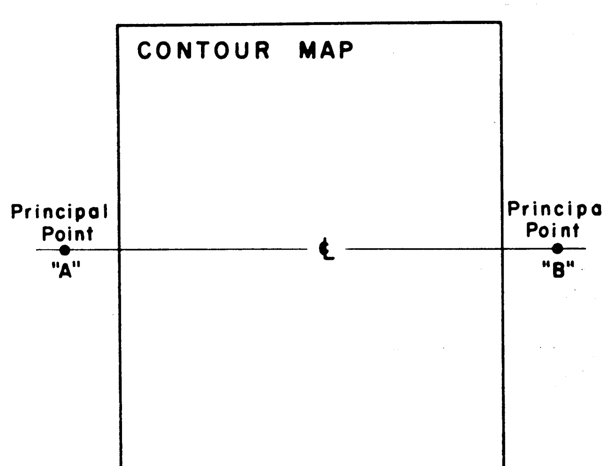


FIG. 3. Positioning of pseudo-principal points in construction of *classical* (variable-scale) stereo pair of a contour map.

same. The writer has termed this the *constant-scale*,[2] or *infinite photo-base*, stereo pair. All stereo pairs now constructed are of this variety, including the ones presented in this paper.

How do we determine the degree of stereo relief to be employed in artificial stereo pairs, i.e., the amount of enlargement or reduction which must be carried out in the variable-scale construction or the amount of translation in the constant-scale variety? Since an artificial three-dimensional surface is being created from units which are unrelated, that is, units of length in the x and y directions and gravity, magnetic, or other units in the z direction, there is a choice. The best answer is another question: "How much relief do we want?" Here we must be guided by empirical rules and must work between limits established experimentally. An upper limit is imposed by how much apparent relief a person's eye can accommodate; this varies with the viewer and with the viewing system. A lower limit is dictated by the smallest feature we wish to see in three dimensions.

In addition to the limitation on *total* relief, there is a limit as to the gradient, or apparent steepness of slope, which can be accommodated by the eye. Sometimes the peak contours of occasional sharp anomalies (either highs or lows) are omitted so as not to exceed the limitation on total relief. (See Figures 7b and 11b.) Another trick used is to introduce nonlinear relief, that is, subduing highs or subduing lows or subduing both highs and lows, while enhancing relief in the flatter parts of a map (Figure 11b was constructed in this fashion). Sometimes the first guess as to the desired relief factor is unsuitable, and it is necessary to construct a second stereo pair with a different relief factor. To date, stereo pairs have been constructed with the parallax between adjacent contours varying between 1/20th and 1/120th inch.

Both computer methods and manual techniques have been employed for stereo pair construction. In general, it has been found that manual techniques are more economical when we start with an undigitized contour map and the stereo pair is all that is desired. Where additional treatment of the map is required and this treatment can carry part or all of the digitizing cost, computer construction of the stereo pair becomes economically feasible.

[2] In actuality the map scale is constant only in the y direction perpendicular to the photo base, even though the scale of all the individual contour lines is the same.

VIEWING STEREO PAIRS

In viewing stereo pairs, the right hand image of the pair must be presented to and be seen by the right eye and the right eye only; and similarly, the left hand image must be seen only by the left eye. A number of methods have evolved over the years for accomplishing this separation. These methods may be divided into two basic categories, depending on whether the right and left hand images are physically separated for viewing or whether they are superimposed:

1. Separated Images
   a. Lens systems,
   b. Mirror systems,
   c. Combination lens and mirror sytems, and
   d. Direct viewing by voluntarily increasing the interocular angle;
2. Superimposed Images
   a. Polarized light systems,
   b. Anaglyphic (bicolor) methods,
   c. Image alternator, and
   d. Fluorescent inks.

Methods in the first category, physically separated images, were developed earlier and are perhaps still the most popular in terms of present day use. They are represented by the common lens and mirror stereoscopes (Figure 4) and by the magnifying mirror varieties, which are combinations of lenses and mirrors. Also, some skilled photo interpreters have the ability to view stereo pairs without any artificial aid by simply increasing the angle between the eyes so as to view right and left images placed close together. This may be done either with the eyes crossed or uncrossed.

In the second category, three methods have been developed for viewing stereo images which are superimposed one on the other. For the polarized light method, two superimposed images are projected from separate sources with the light polarized in mutually perpendicular directions and viewed through similarly polarized filters, so that each eye sees only the image intended for it. A special screen is required. Color three-dimensional movies employ this technique. Also, a technique for producing polarized light photo prints was developed a number of years ago under the trade name "Vectograph" (Kodak).

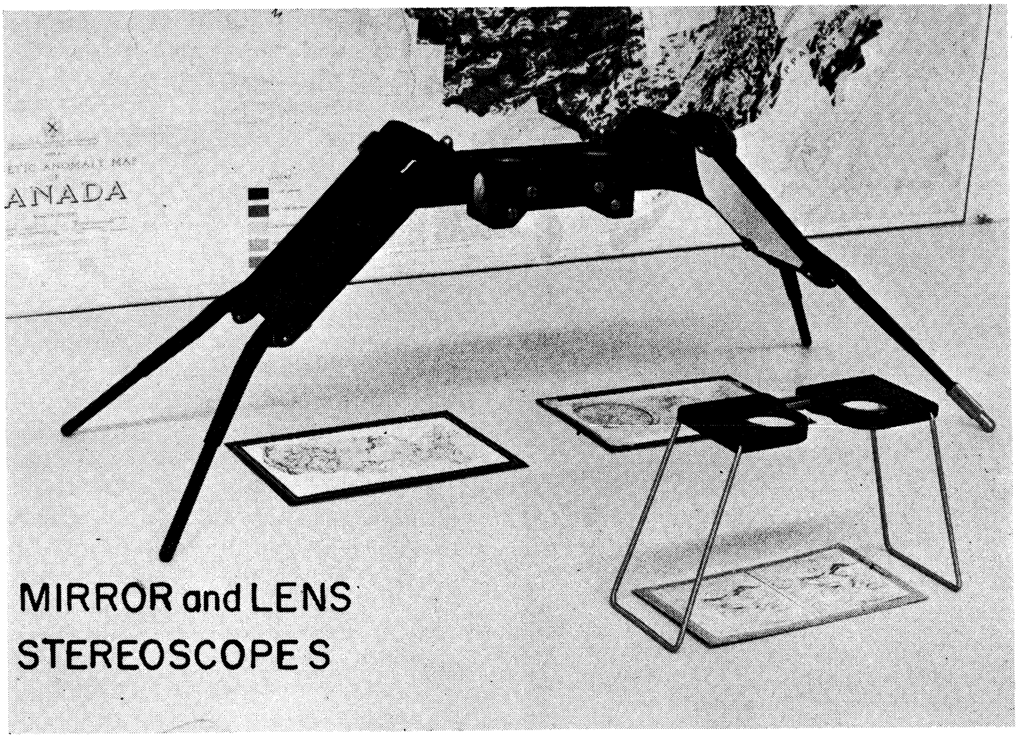


FIG. 4. Two common types of stereoscopes used by photo interpreters: 1) the lens, or pocket variety, and 2) the larger, mirror stereoscope.

In the anaglyphic method, right and left images are drafted or printed on paper in two mutually exclusive colors, such as red and green or red and blue, and viewed through like-color lenses. This method has been widely employed for producing stereo pairs on computer plotting devices but may also be employed for manually drafted stereo pairs.

The anaglyphic technique may also be applied to projected images in the manner of the commercial black and white three-dimensional movies prevalent a number of years ago. The Kelsh plotter, one of the more popular machines used in the photogrammetric industry for constructing topographic contour maps, has employed projected anaglyphs of aerial photographs for many years. By using photo *negatives* of black line stereo pairs, i.e. "bright-line" images, the writer successfully projected stereo contour maps in 1968 (for the first time, it is believed). It has been found since that positive transparencies, or ordinary black line images, may also be successfully projected; although this does not appear to be as effective for viewing as the bright-line technique.

The image alternator is a relatively new method for viewing superimposed stereo pairs that was perfected by personnel of the United States Geological Survey (Knauf, 1967). The stereo pairs are superimposed in space but not in time. Separate right and left images are flashed on a viewing area alternately several times a second while viewed through windows for right and left eyes that open and close in time with the light flashes. Persistence of vision ensures a steady nonflickering image. This system has not been tried for stereo contour map viewing.

A fourth method of viewing superimposed images also comes to mind: the use of contours drafted or printed with fluorescent inks and viewed through appropriate filters. Since many fluorescing materials have simple, single-peaked spectral curves, they should be easy to separate with filters; although this technique has never been tried to the writer's knowledge.

Perhaps all of the above methods will find a place in the viewing of stereo contour maps. The methods in category one are generally limited to viewing by one person at a time, or at most two

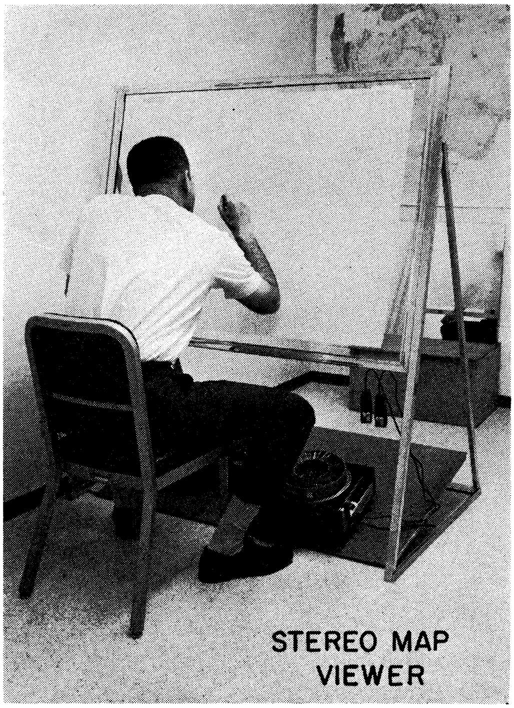


FIG. 5. Prototype of one design of rear-projection viewer for study and interpretation of stereo contour maps.

persons with some of the more advanced magnifying mirror stereoscopes. The projected systems can be viewed by both individuals and groups of people.

It has been found so far that *rear projection* by the anaglyphic method is the most effective viewing method for individuals or small groups, such as a two or three man geologist-geophysicist team. Compilation of the geological-geophysical interpretation is made on a piece of frosted mylar which serves as the viewing screen. The mylar is backed up by plate glass. One viewer of this type is shown in Figure 5. The scale may be readily adjusted to match any given map scale, such as that of a geological base map. Also, the base map can be reproduced on a mylar sheet, which can itself be used as a viewing screen, so that the base data and stereo contour map are viewed simultaneously.

Superposition of two three-dimensional images in stereo has also been accomplished. This was carried out with 1) aeromagnetic contours and 2) aerial photography by constructing a *classical* stereo pair of the aeromagnetics onto transparent material, using principal points coincident with those of the aerial photographs, and viewing the whole under the mirror stereoscope. The technique appears to be a powerful geological tool for certain interpretational problems. Geophysical and geological data (such as structural contours) similarly may be superimposed in stereo.

For the anaglyphic type of presentation, it is important that inks and filters be of mutually exclusive colors; otherwise, a ghost image of the wrong half of the stereo pair will exist for one or both eyes. Even a weak ghost hinders stereo fusion, and a moderate ghost destroys it altogether. Figure 6 shows spectral curves of some of the filters used so far, with the spectral response of the eye superimposed. Note the small amount of overlap of the filter curves in the color midrange. It has not been possible to find inks of comparable quality; although acceptable combinations have been located.

It would seem that we should be able to photograph a drafted bicolor anaglyph on color film and then view the projected image with filters. However, the dyes used in present day color films are not pure colors, and a strong ghost of the red lines results, making stereo fusion impossible. Commercial three-dimensional movies employ a special processing technique, but even here a moderate ghost is always present. Interestingly enough, the eye can tolerate a stronger ghost with continuous tone images (photographs) than with line images, such as contour maps.

NONCONTOUR STEREO MAPS

Experimentation has been carried out with stereo pairs 1) of point readings and 2) of profiles, as contrasted to the contour line stereo maps presented in this paper. The optical system readily fuses these pairs into continuous surfaces, provided that the density of data is great enough relative to the width of the anomalies being surveyed. This requirement points out that information is always added artificially in the construction of contour maps of geophysical data. Viewing point readings (such as gravity data) or profiles (such as aeromagnetics) in three dimensions would be the most rigorous way to study them, however, since this represents the raw, unbiased data.

Some organizations have used computers to construct stereo pairs of oblique, or isometric, views. Contours or vertical profiles, or both in

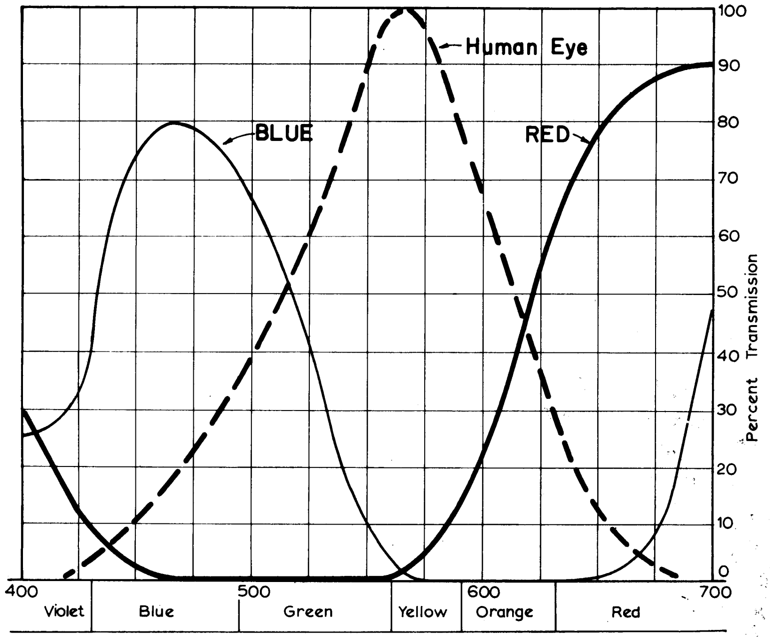


FIG. 6. Spectral response curves of currently used blue and red anaglyph filters.

combination, are presented in such views. Isometric views are similar to oblique aerial photographs and allow trends and linears along the line of sight to be more readily recognized. However, features behind prominent highs are not seen, nor are parallel features to right and left of the viewing point. Thus, vertical-view stereo pairs are considered superior in nearly all cases, since all areas of a map may be studied equally well with the one stereo pair. This same conclusion was reached years ago by aerial photo interpreters, and practically all photo interpretation is now carried out with vertical-view photographs only.

If it is important to view the map along different lines of sight, and it sometimes is, the vertical stereo pairs may be rotated and viewed at any angle. When this is done, however, the relief becomes less and less as a 90-degree angle of rotation is approached and finally disappears when the stereo images are oriented at right angles to the photo-base. A second vertical stereo pair, preferably with the photo-base at right angles to the first, would be required for viewing along all possible lines of sight.

Many types of two-dimensional *perspective* maps have been touted as three-dimensional (e.g., Jenks, 1966), but only 1) physical relief models or 2) stereo maps offer a truly three-dimensional image.

EXAMPLES OF STEREO CONTOUR MAPS

Five stereo map interpretations are presented. For each of them, there is an original and a stereo pair. For some maps, the interpretation is annotated on the original; for others, on a separate copy. The stereo pairs are reproduced for viewing with an ordinary lens, or pocket stereoscope. There was a slight loss of detail in the reproduction of the stereo pairs for printing in this journal, and some of the advantages of stereo viewing cited herein would be clearer on the original photoprints, or better yet, with a rear-projection viewing system.

FIGURE 7: AEROMAGNETIC MAP OF THE SAN FRANCISCO MOUNTAINS AND VICINITY—SOUTHWESTERN UTAH (GP-598, USGS, 1966)

Interpretation of original map (*Figure 7a*)

The large 3400 gamma magnetic high in upper left center arises from an intrusive body near the south end of the San Francisco Mountains. The Horn silver mine, record-holding silver producer in the U. S. earlier in this century, and the Cactus copper mine lie on the flanks of this anomaly. The

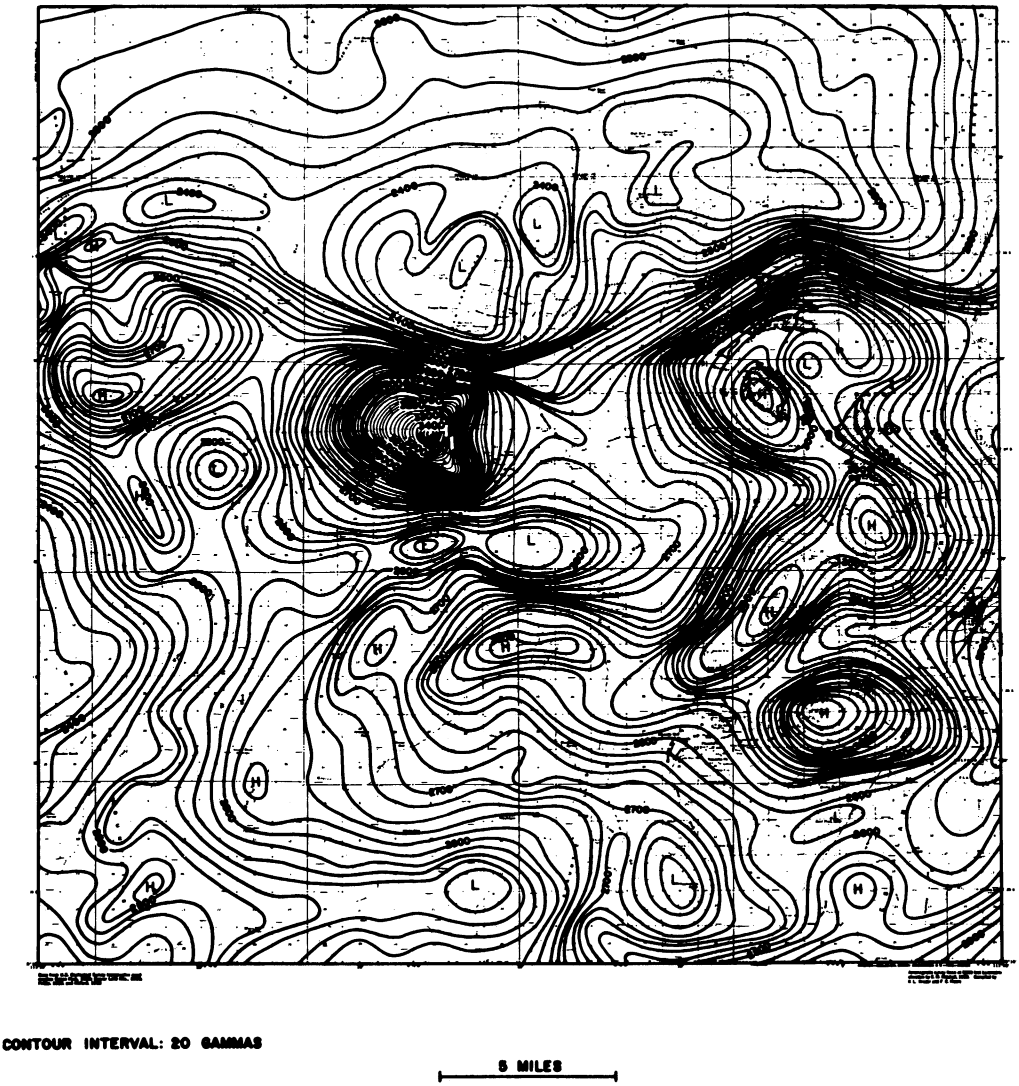


FIG. 7a. Aeromagnetic map of San Francisco Mountains and vicinity, southwestern Utah.

large high directly east is the locus of the O.K. mine and of numerous lesser mines in the Beaver Lake Mountains. The three highs south of this anomaly are the locus of most of the mines of the Star Range. Thus, the majority of the mines on this map lie on the crests or flanks of the large magnetic highs. These highs have been interpreted as arising from monzonitic or dioritic intrusive bodies. The steep gradient trending east-west across the map just north of the highs marks the northern edge of the east-west belt of intrusives coinciding with the Wah Wah-Tushar mineral belt. The long east-west lows in center and bottom of map are thought by some to be altered zones. They have been the site of exploration for disseminated copper porphyry bodies.

This is a high altitude aeromagnetic map flown at 9000 ft above sea level, and little reflection of topography has been noted in the contours. The prominent San Francisco Range trends right across the 3400 gamma high and the low north of it. Anomalies from volcanic rocks, which evidently do not extend to great depth, are also much subdued.

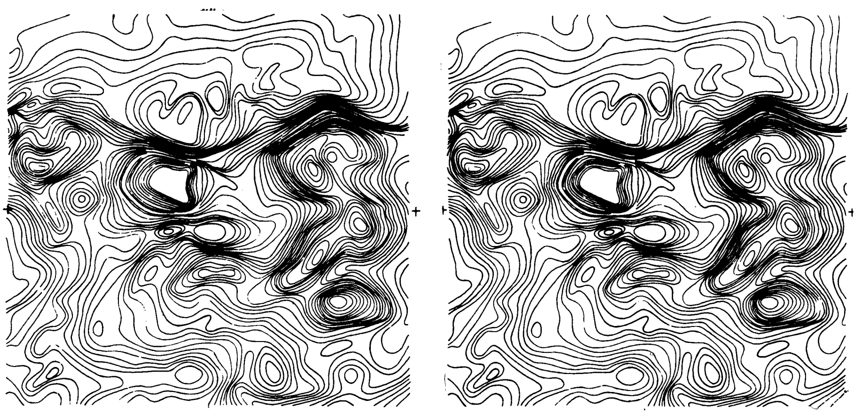


FIG. 7b. Stereo pair of map of Figure 7a.

Stereo interpretation (Figure 7c)

1. Closures. The small circular closures are seen to be simply the culmination of large, broad highs. On the original map, one tends to place excessive emphasis on the circular "bullseyes."
2. Anomaly *C*. This is seen to be a "doughnut" shaped anomaly. The central low is due to a zone of deep, intense hydrothermal alteration. One western copper porphyry deposit shows this same type of anomaly.
3. "Bulge" at *J*. The contours here form a nose that is on trend with the high to the northeast, perhaps indicating a buried extension to the intrusive.
4. Anomalies *D*, *E*, *F*. Colinearity of these anomalies is very obvious in three dimensions. Perhaps they arise from a basic dike swarm beneath alluvial and volcanic cover.
5. Line *B*—*B′*. The north limit of this low is seen to be extremely linear and to trend clear across the map—something not noticeable on the original map. The western half of this line coincides with an altered zone in volcanics mapped in surface geology.
6. Line *A*–*A′*. Similar to *B*–*B′* and the north limit of a prominent low. Note, however, that the southern limits of the two lows are not as well developed on the contour pattern as the northern limits. The lows may represent alteration on the hanging wall of south dipping faults which correspond to the lineaments.
7. *G*–*G′*. This "linear" is perhaps one of the most significant geological features on the map; it is doubtful if it would ever have been noted except on the stereo maps. The linear is interpreted as a possible block fault, downthrown on the west, separating a tilt block corresponding to the San Francisco Mountains on the west from a tilt block of the Beaver Lake Mountains on the east. *H*–*H′* may be a shorter segment of a similar fault.

FIGURE 8: AEROMAGNETIC MAP OF AN AREA IN SOUTHEASTERN MISSOURI

Interpretation of original map (Figure 8a)

The magnetic pattern seen here arises from the Precambrian basement in southeastern Missouri. Up to 2000 ft of horizontal to gently dipping Paleozoic sediments, principally carbonates, overlie the basement, which crops out as a series of knobs at places in the lower right quadrant. Rock here is "felsite," or metamorphosed volcanics, about which little has been deciphered. In fact, the geology of the Precambrian in Missouri is quite poorly known due to the small area of exposed outcrop and the widely scattered spacing of drill holes which intersect it.

Recognizing knobs on the magnetic map is of prime importance to exploration because the flanks of some knobs are the site of lead orebodies. Some of the magnetic highs coincide with knobs, but others arise from lithologic changes within a flat basement. Separating the two has not been possible to any degree of certainty, even after considerable interpretation by many organizations, interpretation which included the application of residual, second derivative, and continuation methods.

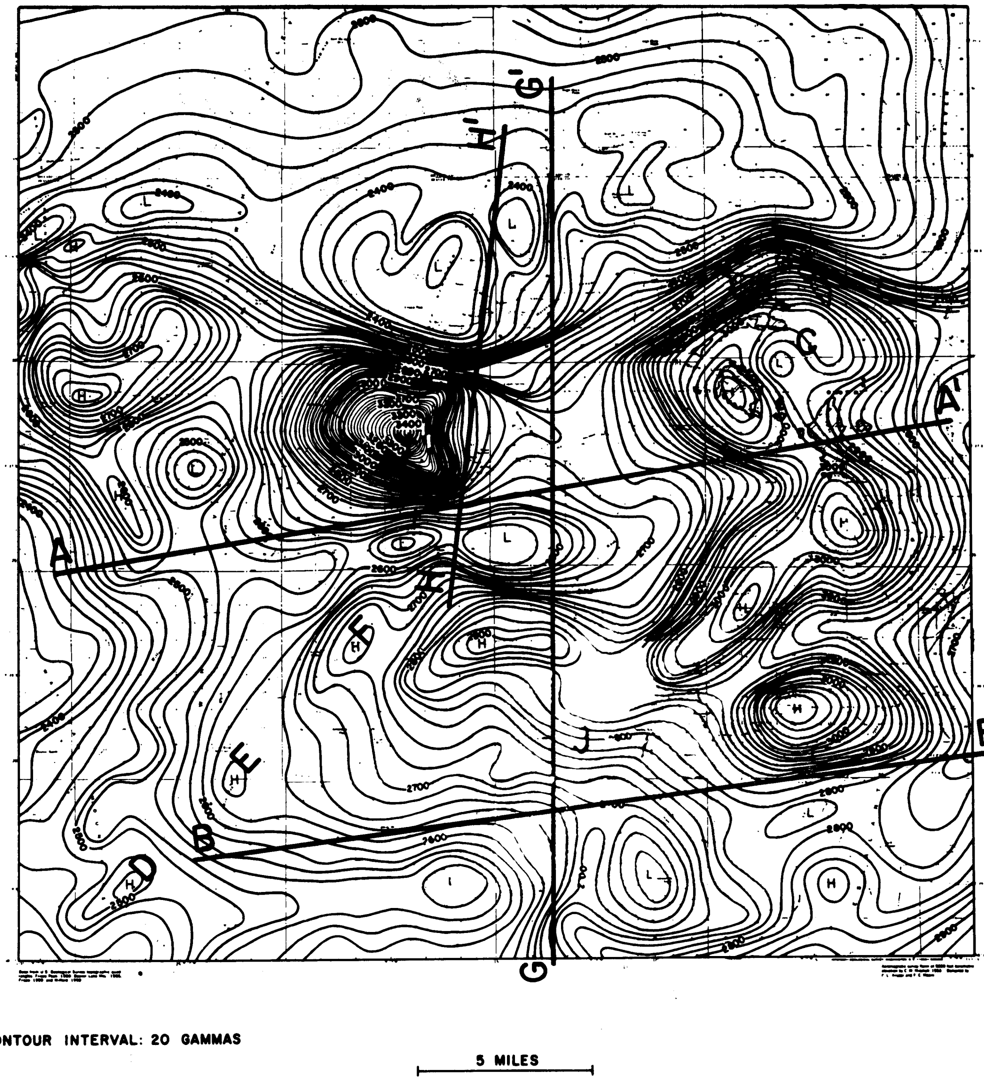


FIG. 7c. Annotated version of Figure 7a, showing features interpreted from stereo viewing of Figure 7b.

Stereo interpretation (*Figure 8c*)

1. Line *H–H′*. A textural and level change takes place across this line, with anomalies being more subdued and at a lower level on the north. The change in texture seems obvious in Figure 8c, but was more subtle on the original full scale map. Possibly, it represents a change in rock type or in depth to basement.
2. Southeast quadrant. Most of the highs here correspond to outcropping Precambrian knobs, or structural highs in the Paleozoics. A dominant northwesterly strike is immediately seen in the stereo pair, but is not obvious on the original map. This is probably the strike direction of the Precambrian volcanic rocks which compose the knobs. It had been noted that the highs here often have auxiliary lows to the northeast, but this was previously ascribed to remanent magnetism. Now it is seen that the position of the lows is due to the northwesterly strike of the anomalies.
3. Magnetic low in southwest quadrant. This has been interpreted as arising from a granite intrusive, a feature common in Missouri. If

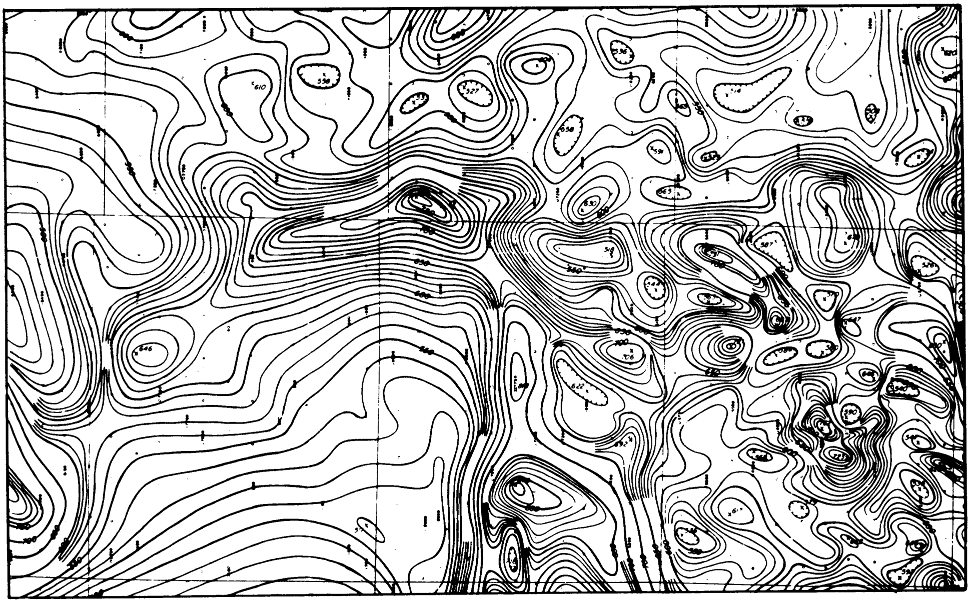


FIG. 8a. Aeromagnetic map of an area in southeastern Missouri.

this interpretation is correct, the belt of anomalies *A–B–C* may arise from a magnetite-rich contact zone around the intrusive. Anomaly *B* has been drilled and found to occur over a flat basement, which substantiates that idea. Note the similarity of *A*, *B*, and *C* as to form, width, and amplitude. Probably they have a common origin and all occur over a flat basement. Such an interpretation thus separates them from the knob anomalies in the southeast quadrant—a significant step forward in Missouri aeromagnetic interpretation.

4. Linear *D–D′*. Note this well defined linear in the three-dimensional display. Study of the original map over a period of weeks failed to locate this feature. Parallel linears can be noted at *E–E′* and possibly at *F–F′*. Are they faults? Other more subtle linears may be present. A closer flight line spacing would have facilitated their detection.
5. Line *G–G′*. Note linearity of the north-south trending east boundary of the low with other features to the north. Is this a preintrusive bounding fault? Possibly, it is the fault that controlled emplacement of the intrusive.

FIGURE 9: GROUND MAGNETIC SURVEY NEAR CEDAR CITY, UTAH

This survey was carried out over a buried laccolithic intrusive dome of quartz monzonite apexing at 1700 ft subsurface. The overlying rock is a sequence of gently dipping Mesozoic sediments. The stereo pair immediately shows a

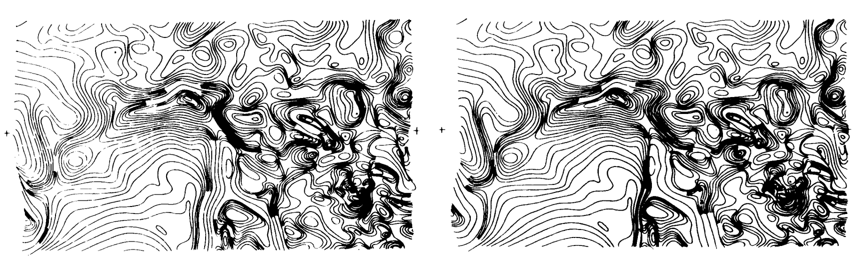


FIG. 8b. Stereo pair of map of Figure 8a.

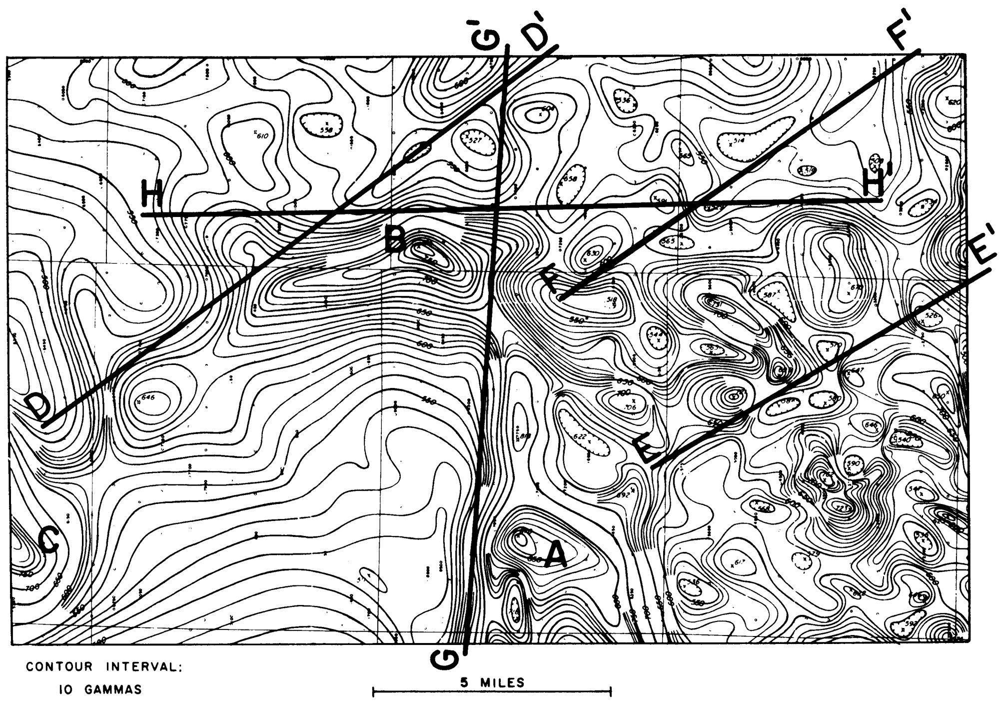


FIG. 8c. Annotated version of Figure 8a, showing features interpreted from stereo viewing of Figure 8b.

domal shaped anomaly, as did the original airborne survey of this area, whence the anomaly was found. However, the ground magnetic survey is complicated by a series of sharp, local anomalies arising from magnetite concentrations in stream beds. The magnetite has been eroded from iron ore deposits that outcrop upstream. The sharp anomalies completely obscure the broad domal pattern in the left side of the map and make it difficult or impossible to recognize. Drawing profiles across the map would reveal the domal pattern, but when we are dealing with a large area, how many profiles do we draw and where? Computer treatment, such as wavelength filtering, polynomial fitting, or upward continuation, would reveal the anomaly, of course; but the broad wavelengths would be separated from the narrow ones and altered by them; and two or more maps would be necessary to see both the narrow and wide anomalies. Here we see both classes of anomalies and can study them together on the same presentation.

FIGURE 10: AEROMAGNETIC MAP OF THE BOULDER BATHOLITH AREA, SOUTHWESTERN MONTANA (GP-538, JOHNSON, ET AL, USGS, 1965)

There are a great many features of interest on this map, but only a few will be mentioned. It was impossible to reproduce all the detail on the 2.5 inch wide stereo images in Figure 10b. The larger original (Figure 10a) is actually one side of the stereo pair.

The large oblong-shaped northeast-trending area of high magnetics, which dominates the map, outlines the Boulder Batholith. Related outlying intrusives are found at Philipsburg (upper left) and Radersburg (right center). The area of different magnetic texture in the lower right corner is part of the Stillwater Complex. Butte, Montana, one of the most prolific mining districts in the United States, is located at *B*. Note that *B* coincides with a magnetic low lying adjacent to what, to the writer, is the most prominent aeromagnetic lineament on the map (indicated by arrows). Whereas this lineament is visible in the two-dimensional version (Figure 10a), it is more pronounced in stereo. Just what relationship this lineament has to the Butte intrusive or to the metallic mineralization is unknown. However, lineaments of this type cutting intrusives occur frequently in the maps studied to date.

A series of shorter parallel lineaments striking N60°E are found a few miles south of Butte. These coincide with a prominent lineament of the

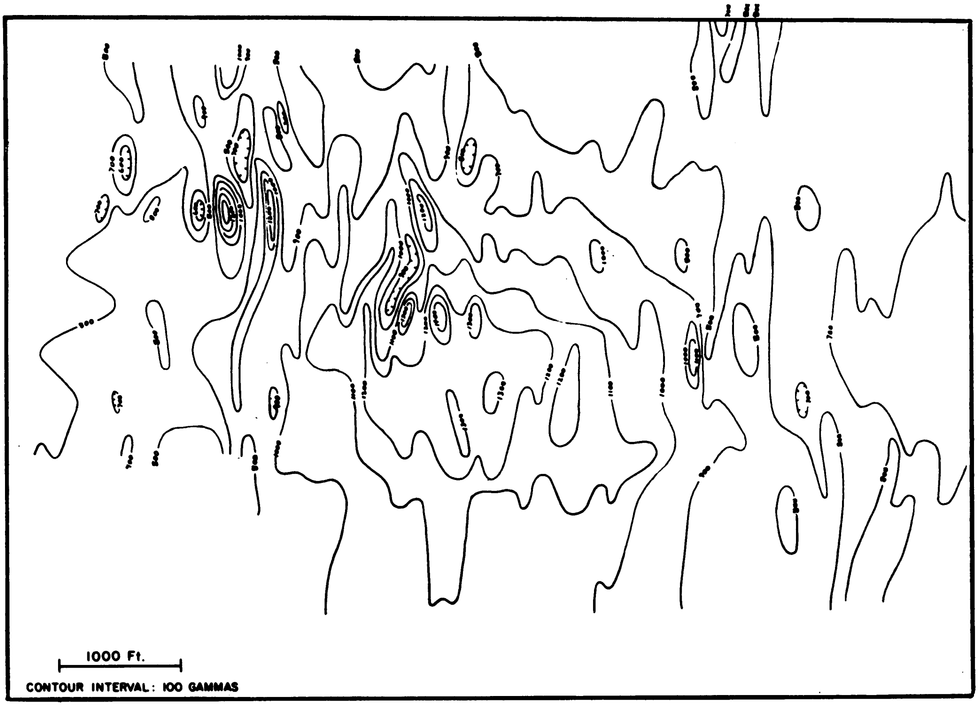


FIG. 9a. Ground magnetics over an anomaly near Cedar City, Utah.

same strike visible on the gravity map of the United States (Woollard, 1964). The gravity lineament is over 700 miles long.

FIGURE 11: AEROMAGNETIC MAP OF AN AREA IN NORTHEASTERN MINNESOTA

There are many, many features of interest visible on this map, both in the original version and in the stereo pair. However, only two will be mentioned. The first of these, the most prominent geophysical break on the map, was missed after hours of careful study by two skilled geophysicists on an intricately color-coded version of the original. That break is the line A–A', which abruptly separates an area of high magnetic relief on the south from an area of low magnetic relief on the north. The high magnetic relief is evidently due to a series of basic Precambrian dikes and sills that have invaded older Precambrian rocks. These dikes and sills are genetically related, it is believed, to the famed Duluth Gabbro, which lies to the southwest of the area.

The most important *geological* break on the map was also missed in the study of the original map. That is a subtle lineament which trends from B to B'. This break corresponds to the contact between the Precambrian Lake Superior volcanic series on the south and the overlying, conformable Rove slates on the north. It was picked out immediately in the stereo version by

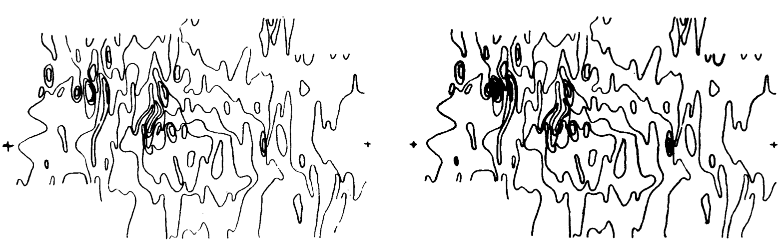


FIG. 9b. Stereo of pair of map Figure 9a.

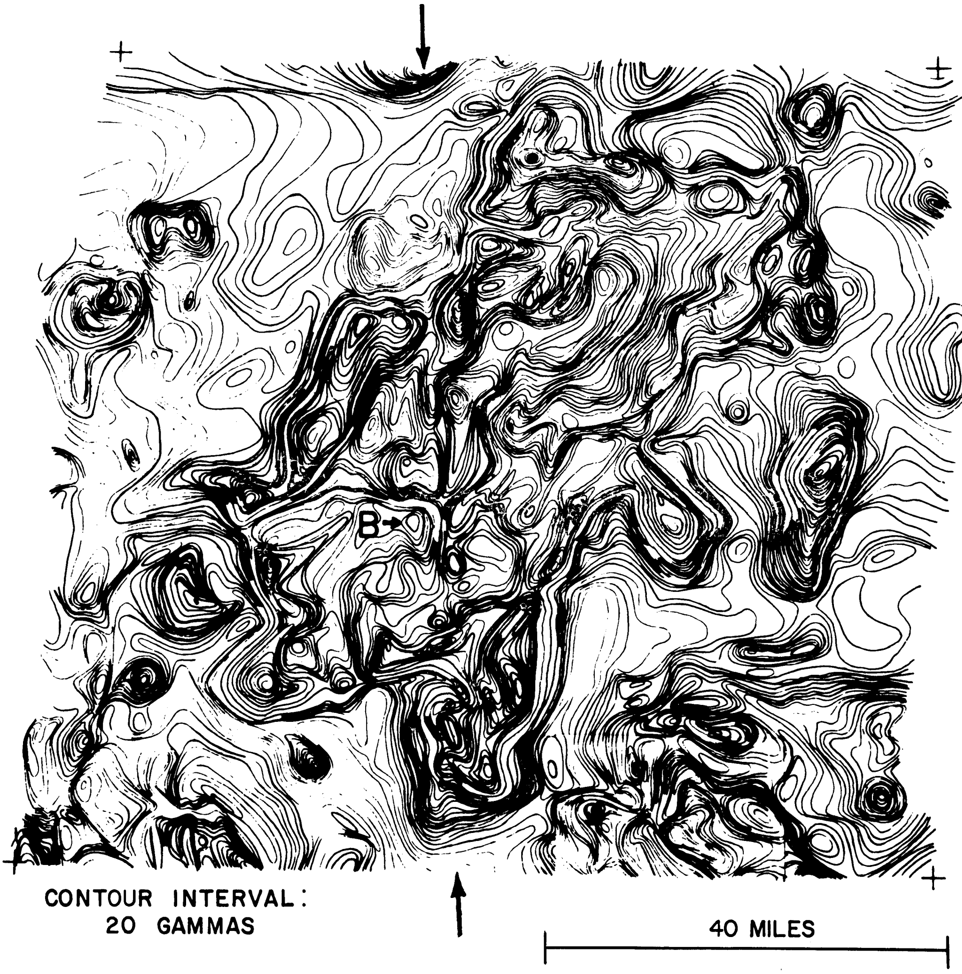


FIG. 10a. Aeromagnetic map of the Boulder Batholith area, southwestern Montana.

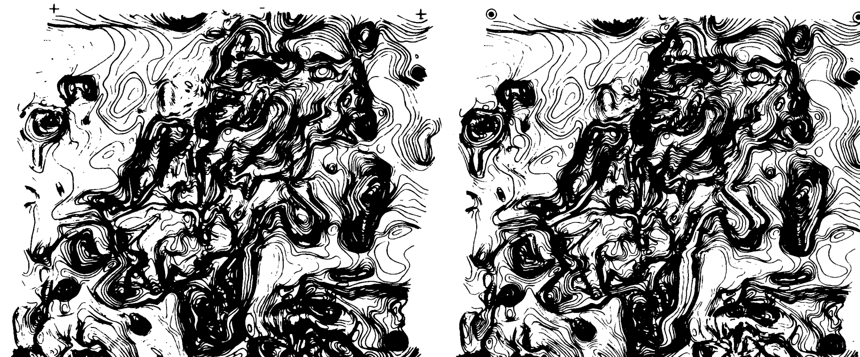


FIG. 10b. Stereo pair of map of Figure 10a.

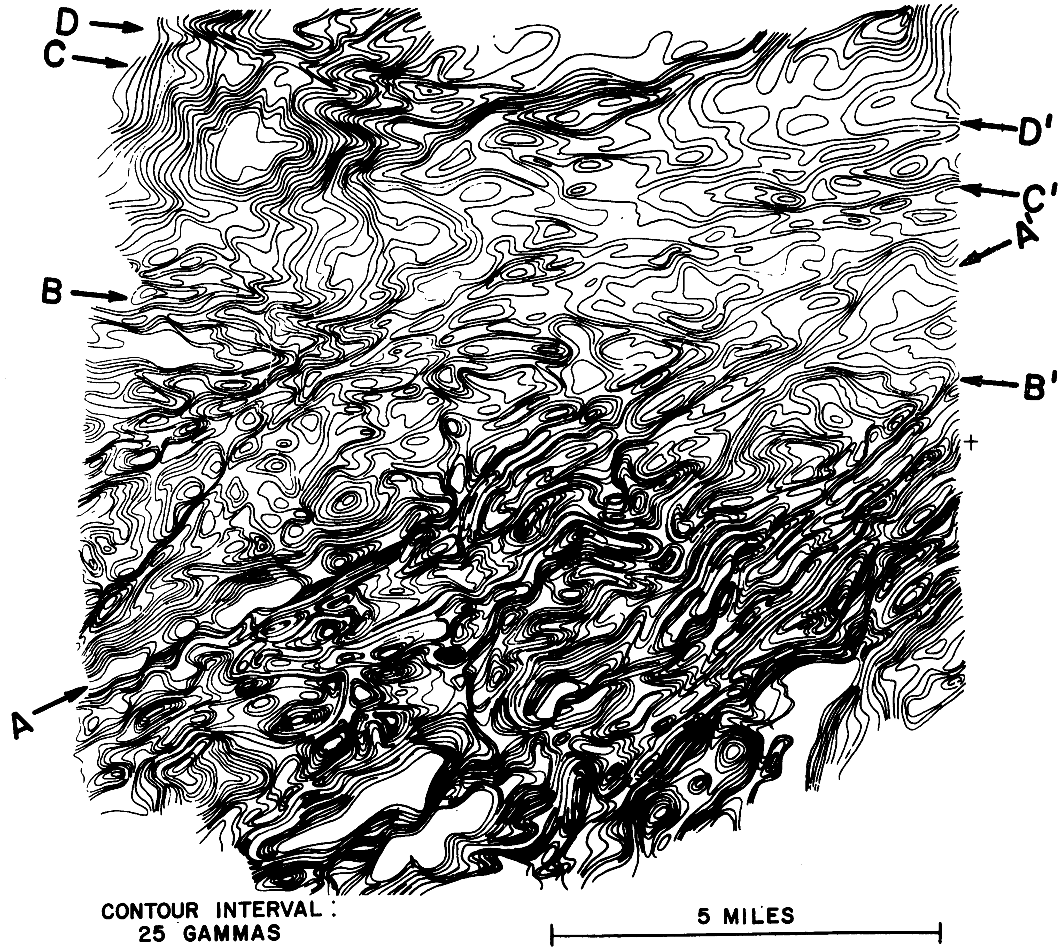


FIG. 11a. Aeromagnetic map of an area in northeastern Minnesota.

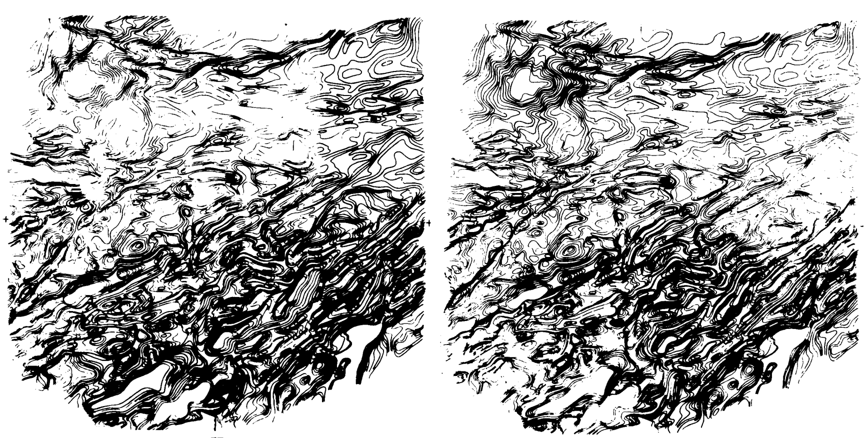


FIG. 11b. Stereo pair of map of Figure 11a.

several interpreters, but is difficult to trace on the original map, even when we know approximately where to look. Two linear trends at C–C' and D–D', that are parallel to B–B', are interpreted by the writer as volcanic members of the Rove slates.

It is interesting to speculate on the reasons why the prominent geological-geophysical break A–A' was missed in the original interpretation. Partly, it is due to the fact that this break, which is actually a magnetic low, increases in value from southwest to northeast; and the colors on the color-coded map changed along its length, actually wrapping across the break on the right hand side of the map. Color-coding, in this case, served to obscure the feature rather than enhance it. This is significant in that color-coding is used so extensively and is so greatly favored by a large number of geophysical interpreters.

DISCUSSION

The foregoing examples illustrate many of the features which stereo viewing enhances for the interpreter of geophysical data. Summarizing, we see that these include 1) proper perspective of all highs and lows on any map at a glance, 2) detection of subtle changes in *level* from one area of a map to another, 3) detection of subtle changes in *texture* or *fabric* of the contour patterns—an altogether neglected, but important, subject in interpretation, 4) correlation of subtle anomaly trend directions in different areas of a map, 5) recognition of broad, hidden anomalies which are obscured by complex patterns of sharp local anomalies, and most importantly, 6) the detection of lineaments, which it is now realized, are prominent on most geophysical maps. These lineaments evidently coincide with faults, which may or may not be known from geological study; and many of them are of regional or even continental proportions.

Other important interpretational advantages of stereo viewing, not shown by the foregoing examples but which have been put to use in interpretation, are 7) the recognition of sharp local anomalies superimposed on broad anomalies from deep sources, an advantage which is the inverse of 5, 8) the recognition of magnetic lows due to reversed remanence, a near-diagnostic characteristic of volcanic rocks in some areas, 9) instant comparison of gravity anomalies as to excess mass, which by Gauss's theorem is in direct proportion to the volume of the anomaly observed in three dimensions, and 10) recognition and comparison of anomalies having a characteristic shape. With regard to 7) above, gentle basement terrain anomalies in the midcontinent area have been recognized on the crests of broader anomalies arising from basement lithology; and shallow magnetic tactites have been recognized from perched anomalies on the crest of broader anomalies over igneous intrusive bodies. With regard to 10), aeromagnetic coverage of many thousands of square miles has been successfully scanned in a matter of minutes to locate anomalies of a characteristic *shape* corresponding to anomalies over known ore deposits. This latter function is three-dimensional crosscorrelation.

After extensively studying contour maps in three dimensions, the writer has come to realize that not only do we miss many of the features described in 1) through 10) above when viewing contour maps in the standard two-dimensional manner, but that flat maps suffer from a number of even more basic defects that impair interpretation. The following axioms of two-dimensional viewing were coined to describe some of these defects:

1) On flat contour maps, bullseyes (i.e., closures), either high or low, assume an importance out of all proportion to their true value, at the expense of other features on the map.
2) Different bullseyes on flat maps tend to assume equal importance, regardless of their true amplitude.
3) The physical process of contour line drawing itself tends to *equal density of contour lines in all areas of the map*, which obscures the true morphological pattern of the map. (Contour lines are skipped in areas of steep gradient and added in areas of gentle gradient.)
4) Flat contour maps of the same geophysical data constructed with different datum planes (such as different aeromagnetic maps of the same area) emphasize *differences* in the data which are not real. Stereo maps of the same data with different base levels emphasize the *similarities* of the data.

Additional axioms might be set down for describing other such truisms of contour map interpretation.

In addition to interpretational advantages, three-dimensional viewing vastly increases the *speed* of interpretation—by as much as several hundred percent in some cases. This is particularly important where large volumes of geophysical coverage suddenly become available, such as the aeromagnetic maps of Canada or the recently released aeromagnetic map of Arizona. Also, the speed with which an interpreter can evaluate a geophysical map is intimately linked with the *reliability* of the interpretations or the *confidence* the interpreter has in his analysis. For example, we could spend a whole day on a single subtle feature on a map merely trying to decide if it were valid. This statement applies, in particular, to lineament recognition. The increased speed of interpretation is thus, in many cases, due to the interpreter's increased level of confidence in his interpretations when carried out in three-dimensions.

Then, there are some features which could never be recognized at *any* level of confidence on a flat two-dimensional map; at least so the writer feels. Lineaments *G–G′* in Figure 7c and *B–B′* in Figure 11a are examples. Stereo contour maps make possible the recognition of such features for the first time. Indeed, the first several maps interpreted by the writer were reinterpretations of prior data; and in all cases, the original reports were discarded after the new interpretations based on stereo viewing were completed.

In support of the above statements, during a recent interpretation of an aeromagnetic map in Nevada, four out of seven lineaments of a parallel set that were picked without recourse to geological maps coincided with mapped Basin Range faults. The lineaments were considerably longer than the mapped portions of the faults; this disclosure extended the known geology. The remaining three lineaments were located in alluvial covered areas; one of these was the most prominent lineament of the set and evidently defined the edge of a broad pediment. This type of information is useful to the exploration geologist and is, in fact, the type of information generally sought in aeromagnetic surveying.

In other instances, known ore deposits have been found aligned along prominent aeromagnetic lineaments, and intrusive masses associated with ore bodies have been found to be cut by prominent lineaments. The importance of aeromagnetic and gravity lineaments to ore occurrence has yet to be properly and fully assessed. In the writer's opinion, this is an exciting field for future study.

A number of lineaments of *regional* proportions have been recognized in studies to date, indicating that an interconnected continental fracture system may exist. Knowledge of such a fracture system would contribute substantially to understanding the new plate tectonics. Indeed, we will fully understand plate tectonics only when existing regional fractures have been mapped. Since the most characteristic signature of regional fractures have been found to be gravity and magnetic lineaments, any technique which aids in their recognition will prove invaluable, especially as more wide scale geophysical coverage of continental regions become available in the years to come. It was, in fact, the recognition of magnetic lineaments in the ocean basins that paved the way for current acceptance of the previously defunct theory of continental drift. The revised gravity map of the United States that is forthcoming and an aeromagnetic map of the United States proposed to the federal government by a number of professional organizations (including the SEG) will both be of enormous benefit in recognizing lineaments of regional or continental proportions.

In the past, geophysicists have attempted to enhance many of the interpretational features listed in the first part of this section by residual and second derivative methods and more recently by polynomial fitting and the various filtering techniques carried out by computer. However, it appears that optical three-dimensional viewing can perform a number of these functions better than computer processing methods. Polynomial fitting and wavelength filtering, for example, attempt to carry out functions 2), 5), and 7) above, but stereo viewing performs the functions better, as anomalies of all wavelengths are visible at once and it is not necessary to turn out different maps for different wavelengths. Function 10) is correlation (autocorrelation or crosscorrelation), which has not been carried out in three dimensions on contour maps to the writer's knowledge. Function 4) is trend or fan filtering, which has not proven useful for contour maps so far. And 6), the detection of lineaments, has never been attempted by computer methods because of the difficulty in mathematically defining a lineament. To the writer, a lineament is a *disruption* in the contours, that is, a line against which other anomalies terminate. It *may* be a high or a low as well.

In addition to the above shortcomings of computer filtering methods, resolution is lost at the edge of a map, and the data are generally cut off a certain distance inside the edge, leaving a wide blank zone around the border. This does not occur in optical stereo analysis, which proceeds uninterruptedly clear to the edge of the map.

It has been interesting to observe the surprise and even disbelief expressed by some people when the statement is made that optical three-dimensional viewing of geophysical data is superior in many instances to computer processing techniques. Yet, the human brain is universally pointed out as the *ultimate* computer even by computer experts, at least for certain functions, such as correlation methods and filtering. Stereo viewing is simply a way of putting the brain to work on the problem. The stereo pair may be considered the program. The apparent simplicity of this program does not negate a superior result. Quite the contrary. The results, of necessity, *must* be superior in many instances to computer processing techniques because of the extreme sophistication of the computer which we put to use in optical three-dimensional analysis.

As an example of this superiority, consider wavelength filtering discussed above. Wavelengths of two or more frequencies can be observed and studied simultaneously by three-dimensional viewing. Computer processing produces two or more simplified two-dimensional maps—bullseye maps, if you will. A generalization may here be made: computer processing tends to greater and greater simplification of the data for presentation in the outmoded two-dimensional form; stereo viewing demands more and more complex data for effective interpretation. However, a combination of computer processing and stereo viewing would undoubtedly be superior in some cases to either method alone. One example of this combination would be the recognition and location of lineaments on the stereo pair, and the subsequent construction of average profiles of these lineaments by computer.

Another comment that has met with resistance is the statement that through the use of stereo contour maps, the "interpretation of gravity and magnetic data, particularly aeromagnetics, may now become principally the domain of the geologist rather than the geophysicist." A review of functions 1) through 10) in the first part of this section reveals not a single one that requires geophysical training. True, some geophysical knowledge is useful for all of them, but it is secondary to geological knowledge in assessing the *significance* of the features recognized. *Recognition* of the important features visible in stereo require *no* geophysical training at all and is, in fact, more readily carried out by photogeologists than by geophysicists, since photogeologists are already accustomed to working with three-dimensional data. Source body analysis—the study of individual anomalies for determining source body configuration—remains, of course, the domain of the geophysicist.

The closing thought of this paper is this: a contour map is a representation of a three-dimensional surface. What better way to study it than in three dimensions?

ACKNOWLEDGMENTS

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