Geology and Mineralogy

This document consists of 55 pages, plus 3 figures.
Series A

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

REGIONAL GEOPHYSICAL INVESTIGATIONS OF THE URAVAN AREA, COLORADO*

By

H. R. Joesting and P. Edward Byerly

May 1956

Trace Elements Investigations Report 399

This preliminary report is distributed without editorial and technical review for conformity with official standards and nomenclature. It is not for public inspection or quotation.

*This report concerns work done partly on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

USGS - TEI-399

GEOLOGY AND MINERALOGY

Distribution (Series A)	No. of copies
Atomic Energy Commission, Washington	2
Division of Raw Materials, Albuquerque	1
Division of Raw Materials, Austin	1
Division of Raw Materials, Butte	1
Division of Raw Materials, Casper	1
Division of Raw Materials, Denver	1
Division of Raw Materials, Ishpeming	1
Division of Raw Materials, Phoenix	1
Division of Raw Materials, Rapid City	1
Division of Raw Materials, St. George	1
Division of Raw Materials, Salt Lake City	1
Division of Raw Materials, Washington	3
Exploration Division, Grand Junction Operations Office	6
Grand Junction Operations Office	1
Technical Information Extension, Oak Ridge	6
U. S. Geological Survey:	
Fuels Branch, Washington	1
Geochemistry and Petrology Branch, Washington	1
Geophysics Branch, Washington	6
Mineral Deposits Branch, Washington	1
P. C. Bateman, Menlo Park	1
A. L. Brokaw, Grand Junction	2
N. M. Denson, Denver	1
V. L. Freeman, College	1
R. L. Griggs, Albuquerque	1
W. R. Keefer, Laramie	1
M. R. Klepper, Spokane	1
A. H. Koschmann, Denver	1
L. R. Page, Washington	1
Q. D. Singewald, Beltsville	1
A. E. Weissenborn, Spokane	1
TEPCO, Denver	2
TEPCO, RPS, Washington, (including master)	2
	53

CONTENTS

ILLUSTRATIONS

REGIONAL GEOPHYSICAL INVESTIGATIONS OF THE URAVAN AREA, COLORADO

By H. R. Joesting and P. Edward Byerly

ABSTRACT

Aeromagnetic and regional gravity surveys have been conducted in the Uravan area as part of a study of the regional geology of the Colorado Plateau. Interpretations are based on available surface and subsurface geologic information as well as on geophysical data.

The Uravan area is in the east-central part of the Colorado Plateau physiographic province, and except for the Uncompahgre Plateau which bounds the northeast side, it lies within the Paradox Salt Basin, a sedimentary basin of Pennsylvanian age in southwest Colorado and southeast Utah.

Exposed rocks in the area include crystalline rocks of Precambrian age in the Uncompahgre Plateau, sedimentary rocks that range in age from Pennsylvanian to Quaternary, and a few small diorite intrusives of probable Tertiary age.

Devonian and Mississippian rocks have been penetrated in wells drilled in the area. Rocks of Cambrian age have been penetrated in adjoining areas and probably occur in the Uravan area.

The youngest Paleozoic and oldest Mesozoic rocks wedge out against the Precambrian rocks of the Uncompahgre Plateau, but the younger Mesozoic beds extend across the uplifted basement complex.

Structurally, the Uravan area is characterized by a major faulted monocline, which bounds the Uncompahgre Plateau on the southwest, by great salt piercement anticlines, and by gently dipping

strata between the larger features. The major structures strike northwest.

The larger magnetic anomalies are related to changes in the magnetization and probably in the composition of the basement rocks, and to faults involving large displacements of the basement. Prominent anomalies along the flank of the Uncompahgre uplift are associated with a belt of magnetic rocks which apparently occur in large fault blocks. Similar though less prominent anomalies along Disappointment syncline suggest an uplift resulting in a basement trough between Disappointment syncline and the Uncompahgre Plateau.

The major variations in gravity are related to variations in thickness of salt in the Paradox member and to changes in the density of the basement rocks. Large negative anomalies, associated with the Paradox Valley and Gypsum Valley salt piercement structures, suggest that the section from the top of the Chinle formation down to the Paradox salt is 8,500 to 10,000 feet thick between the valleys. There is no clear evidence of an appreciable thickness of salt near the flanks of the piercement structures, but the basement anomalies could obscure the effects of the salt. If there is no salt, then the thickness of the section is of the order of 10,000 feet. Gravity gradients suggest that except locally, basement relief is achieved gradually along the Uncompahgre front, perhaps because the major fault scarps have been reduced by erosion. Northeast of Nucla, however, there is evidence for the existence of a large fault scarp.

Magnetic and gravity trends are generally parallel to the northwest trending regional structures. South of Uravan, however, the regional gravity trend is normal to the present structural trend, probably because of rocks of high density within the basement.

INTRODUCTION

Geophysical surveys have been made in the Uravan area, in southwest Colorado, with the aim of providing information on regional geology, especially on those aspects that may not be apparent from surface evidence alone. Aeromagnetic surveys were made in 1952, and regional gravity surveys were made during the summers of 1953 and 1954. Figure 1 shows the area covered.

Information on surface geology was obtained from publications, from geologists working on the Colorado Plateau, and from personal observations. Subsurface information was obtained from commercial information services, from oil companies, and from the files of the Geological Survey.

From the assembled geophysical and geological data, it has been possible to gain additional information on several general and specific aspects of the geology of the Uravan area: on the configuration and major trends of the basement rocks; on the approximate thickness and structure of the sedimentary rocks; and on the migration of salt and the configuration of the salt anticlines of the Uravan area.

ACKNOWLEDGMENTS

The authors are grateful for the interest and advice of many geologists of the Geological Survey and the Atomic Energy Commission who are working on related problems on the Colorado Plateau. They also acknowledge with thanks the help of R. Clare Coffin, who has acted as geologic consultant for the work described here, of

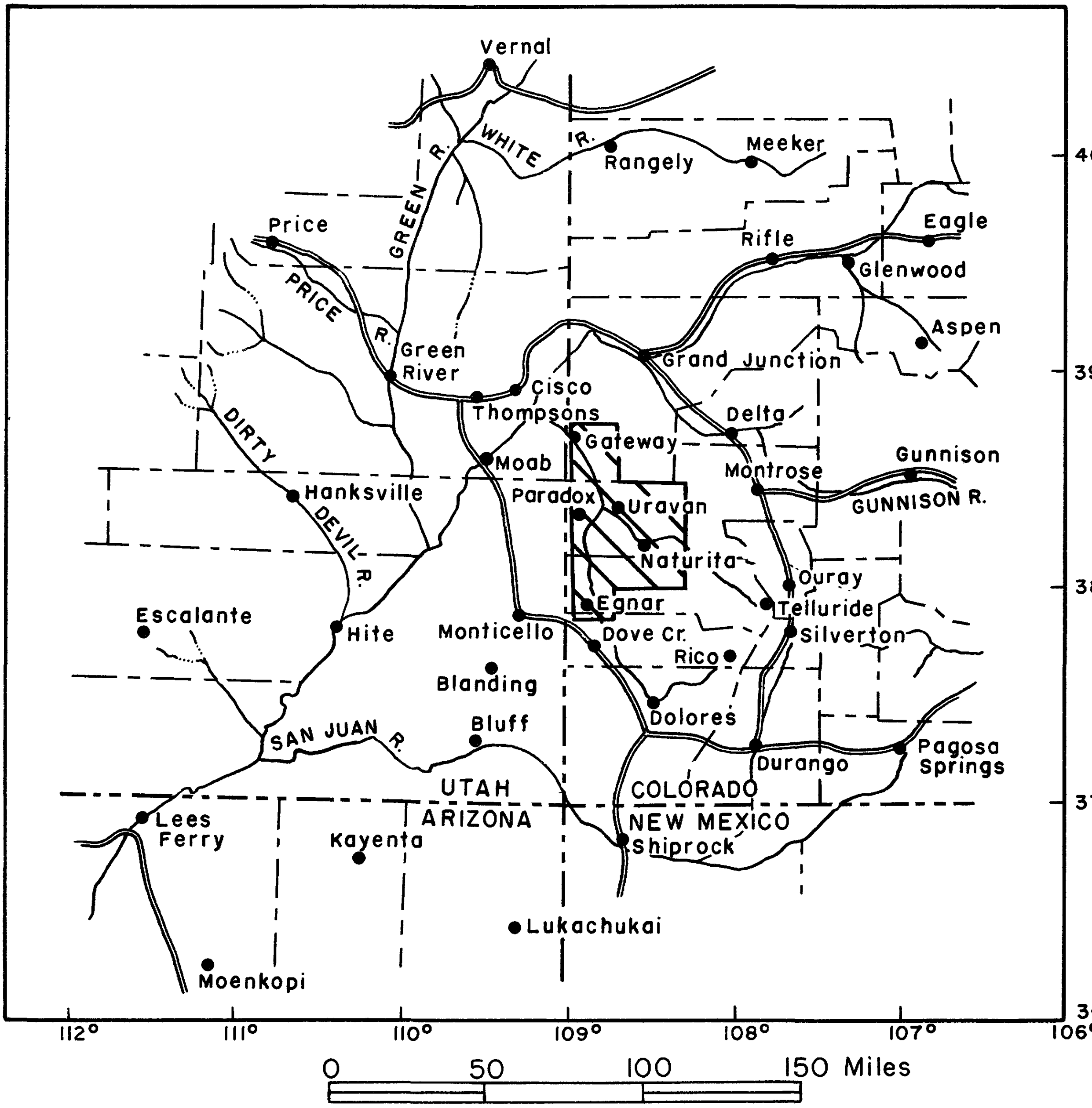


FIGURE I - LOCATION OF THE URAVAN AREA, COLORADO

Kenneth Smith of the Pure Oil Company and Max Hembree of the California Company for stratigraphic information, of Donald Davis of the Pure Oil Company for information that aided in planning and conducting the gravity survey, and of R. G. Henderson and Isidore Zietz of the Geological Survey on magnetic interpretation. In addition to geologic advice, E. M. Shoemaker and W. L. Newman of the Geological Survey furnished a number of specimens of crystalline rocks for determinations of magnetic susceptibilities and densities. Thomas Hopper and Winthrop Means assisted on the gravity survey, and Eugene Tassone computed several of the magnetic profiles. This investigation by the U. S. Geological Survey has been supported in part by the Division of Raw Materials of the U. S. Atomic Energy Commission.

GEOLOGY

The Uravan area is in the east-central part of the Colorado Plateau physiographic province. The entire area, with the exception of the Uncompahgre Plateau along the northeast side, lies within the Paradox Salt Basin, a sedimentary basin of Pennsylvanian age in southwest Colorado and southeast Utah (Wengerd and Strickland, 1954, p. 2158-9). Just west of the Uravan area are the La Sal Mountains, which have cores of intrusive rock of post-Mancos age (Shoemaker, 1954, p. 63; Kelley, 1955, p. 56).

Crystalline rocks of Precambrian age, sedimentary rocks that range in age from Pennsylvanian to Quaternary, and a few small sills of probable Tertiary age are exposed in the area. A generalized geologic section is shown in figure 2, and a generalized geologic map in figure 3. The rocks have been described in detail by

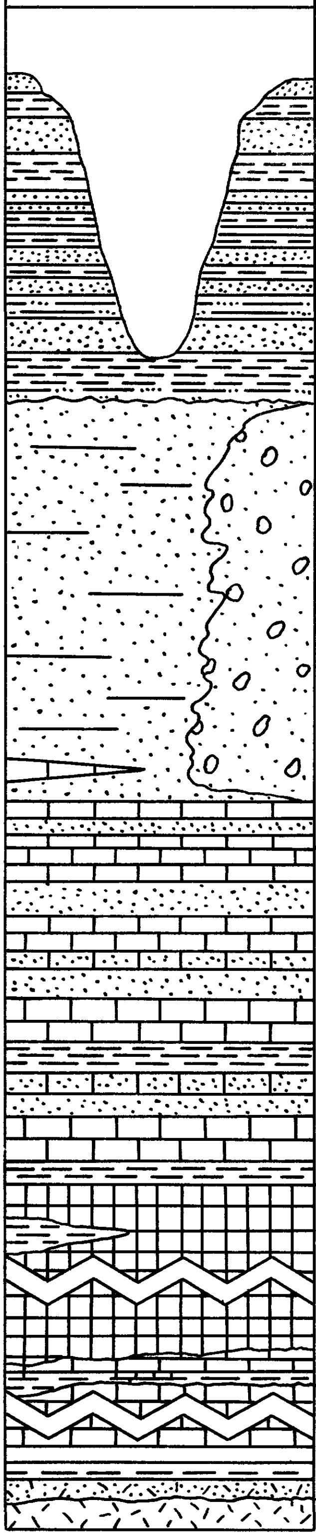
GENERALIZED SECTION	LITHOLOGIC CHARACTER	THICKNESS (FEET)	FORMATION OR GROUP		AGE
	SANDSTONE, SILTSTONE, & SHALE	300±	MESA VERDE FM. MANCOS SHALE DAKOTA SANDSTONE AND BURRO CANYON FM.		CRETACEOUS
		750±	MORRISON FORMATION		JURASSIC
		300±	SAN RAFAEL GROUP		JURASSIC
		675±	GLEN CANYON GROUP		JURASSIC AND TRIASSIC
		700±	CHINLE AND MOENKOPI FORMATIONS		TRIASSIC
	ARKOSIC CONGLOMERATE AND SANDSTONE (CUTLER) SANDSTONE LIMESTONE (RICO)	0-7800±	CUTLER AND RICO FORMATIONS		PERMIAN
	LIMESTONE, SANDSTONE, SHALE	1500-2400+	UPPER OR LIMESTONE MEMBER	HERMOSA FORMATION	PENNSYLVANIAN
	SALT, GYPSUM BLACK SHALE LIMESTONE	?	PARADOX MEMBER		
	LIMESTONE, DOLOMITE, INDURATED SANDSTONE AND SHALE	?	PRE-PARADOX SEDIMENTS		CAMBRIAN(?) DEVONIAN MISSISSIPPIAN

FIGURE 2 - GENERALIZED COLUMNAR SECTION OF THE URAVAN AREA

Coffin (1921), Stokes and Phoenix (1948), Cater (1954, 1955a, 1955b) and McKay (1955a, 1955b). Precambrian rocks crop out only along the flank of the uplifted Uncompahgre Plateau. The youngest Paleozoic and oldest Mesozoic rocks wedge out against the uplifted Precambrian rocks of the Uncompahgre Plateau, but younger Mesozoic rocks extend across the uplifted basement complex (Cater, 1954). Devonian and Mississippian sedimentary rocks were penetrated in the Continental 1 Nucla well northeast of the town of Nucla (fig. 3), but they are not exposed in the area and little published information is available.

As this investigation is concerned with relating gravity and magnetic anomalies to regional geology, the densities and magnetic susceptibilities of the rocks are of primary interest as guides to interpretation of the geophysical results. These properties and their relation to rock types are therefore emphasized in the following discussion.

Precambrian rocks

The Precambrian rocks of the Uncompahgre Plateau consist of complexly interrelated granites, gneisses, and schists. Similar rocks are assumed to underlie the sedimentary rocks in the remainder of the area. Because there are few exposures, only a few data on the magnetic properties and densities of this heterogeneous group of rocks have been obtained. Specimens of Precambrian rocks from regions bordering the Colorado Plateau - from the White River, Gunnison, San Juan, and Zuni Uplifts in Colorado and New Mexico, and from the Grand Canyon in Arizona - were made available by E. M. Shoemaker and W. L. Newman.

These, together with additional specimens from the Uncompahgre Plateau collected by the authors, and by E. M. Shoemaker and W. L. Neuman, probably are reasonably representative of the basement rocks of the Uravan area.

Magnetic susceptibilities of 23 samples of exposed Precambrian rocks from the Uncompahgre Plateau and from bordering regions range from about zero to 3.1×10^{-3} cgs units according to measurements made by R. A. Morgan, U. S. Geological Survey. As the samples were obtained from the surface, their susceptibilities may have been reduced somewhat by weathering, but otherwise they probably indicate the range of susceptibilities of the basement rocks in the Uravan area. The accompanying magnetic map (fig. 4) shows that the basement rocks are magnetically dissimilar and of low to moderately high susceptibility. No information was obtained on their remanent magnetization.

Saturated bulk densities of 13 samples of Precambrian rocks from the Uncompahgre Plateau and from bordering regions range from 2.60 to 3.07 g per cm^3, with an average of 2.71 g per cm^3. The wide range of densities indicates that relatively large gravity anomalies originate in the basement.

Pre-Pennsylvanian sedimentary rocks

Rocks older than Pennsylvanian do not crop out in the Uravan area. About 1,500 feet of pre-Pennsylvanian rocks, consisting mainly of marine sandstone, limestone, and dolomite, are believed to overlie the basement in the Uravan area, and to wedge out to the east and thicken to the northwest (Cooper, 1955, p. 59-65). The Continental 1 Nucla well, 6 miles northeast of Nucla, was drilled through more than 1,100 feet of Mississippian and Devonian rocks and bottomed in the Elbert formation of

Devonian age, but steep dips were recorded in the lower part of the section so the true thickness is unknown. Ordovician and Silurian rocks are believed absent, but rocks classed as Cambrian have been penetrated in wells in adjoining areas and are probably present in the Uravan area.

An apparent absence of pre-Pennsylvanian rocks at least locally, close to the Uncompahgre Plateau uplift, is indicated by the log of the Pure 1 Gateway well about 5 miles northwest of Gateway (shown on magnetic map, fig. 4). This hole entered the granitic basement directly after drilling through about 7,800 feet of Permian (?) and Pennsylvanian (?) arkose (Shoemaker, 1954, p. 61).

The pre-Pennsylvanian rocks have essentially no magnetic effect, as their magnetic mineral content is small. The contact between these rocks and the basement, however, provides a major contrast in magnetic susceptibility. Little direct information is available concerning densities, but measurements on cores from the Continental 1 Nucla well and the high proportion of calcareous rocks make it likely that the average density is close to that of the basement rocks. The average density is probably between 2.6 and 2.7 g per cm^3.

Pennsylvanian and Permian sedimentary rocks

Overlying the Mississippian rocks are the Molas and Hermosa formations of Pennsylvanian age; the Cutler formation of Permian age; and the Rico formation, which is considered to be transitional between the Hermosa marine deposits below and the Cutler continental deposits above. The deposits show many abrupt facies changes and much intertonguing of marine and continental clastics, evaporites, and marine carbonates. They are the result of environmental changes caused by major deformations in and along the edge of the Paradox Salt Basin (Wengerd and Strickland, 1954, p. 1258-1259; Turnbow, 1955, p. 66-68). Because of the complex stratigraphy there is considerable uncertainty concerning formational boundaries, but these problems have no bearing on this regional geophysical study.

The Molas formation consists mainly of sandstone, limestone, and shale. It is probably not more than 200 feet thick and has no effect on the geophysical measurements discussed here.

The marine facies of the Pennsylvanian and Permian rocks consist of a great cyclic series of limestone, salt, and other evaporites, shale, siltstone, and sandstone, which grade shoreward and upward into dominantly clastic sediments. Wengerd and Strickland (1954, p. 1277-78) estimate the maximum thickness of the lower Paradox salt member of the Hermosa formation (Bass, 1944) to be about 4,000 feet, except where there has been thickening of salt by flow. The maximum thickness of the predominantly limestone upper member is also estimated to be about 4,000 feet. A total of 6,326 feet of the Hermosa formation was logged in the Reynolds 1 Egnar well on the Dolores anticline (fig. 3) of which 4,809 feet, including 4,146 feet of salt, was assigned to the Paradox member. Baker (1933, p. 14) reports that about 3,900 feet of the salt series was drilled in the Shafer 1 well on Shafer Dome, at the Colorado River about 40 miles farther west. Some thickening of the salt due to flow is probable in both places. Toward the Uncompahgre Plateau the carbonates and evaporites grade into clastics, which finally wedge out against the Precambrian rocks.

Because of its relatively low density, the Paradox member is the most important lithologic unit, from the viewpoint of its gravitational effect, in the Uravan area. The salt and associated material have intruded the overlying rocks to form the cores of the piercement structures of Paradox, Gypsum, and Sinbad valleys and have probably also migrated by plastic flow in other parts of the area.

Overlying the Pennsylvanian rocks in the Paradox basin, and forming a wedge between the Precambrian and the overlying Mesozoic rocks along the Uncompahgre Plateau uplift, is the Cutler formation of Permian age, of which the Rico marine facies is a basal part in the Paradox Basin. The Cutler formation consists mostly of arkosic conglomerate near the Uncompahgre Plateau and finer arkose to the southwest. About 7,800 feet of arkose, resting directly on granitic basement, was penetrated in the Pure 1 Gateway well (fig. 4).

The magnetic susceptibility of 44 specimens of Cutler arkose, apparently the most magnetic of all the sedimentary formations in the Uravan area, ranged from 0.006×10^{-3} to 0.070×10^{-3} cgs units, with an average of 0.025×10^{-3}. The computed maximum magnetic effect of a 7,000-foot wedge of arkose of average susceptibility is only a few gammas. The magnetic effect of the other sedimentary rocks is believed to be even smaller because of their lower content of magnetic minerals.

The gravitational effects of the Pennsylvanian and Permian rocks, on the other hand, are far from negligible, as these rocks consist of great thicknesses of salt and other evaporites with a density of about 2.2, and of limestones and clastics with different densities from those of the overlying Mesozoic rocks. Many of the large gravity anomalies shown on the accompanying gravity map (fig. 5) result from the large density contrasts between the salt and the adjacent rocks.

Density determinations were made on 30 samples of the Cutler formation collected near Gateway. The mean dry and wet densities were 2.50 and 2.58 g per cm^3, with standard deviations of $\pm$ 0.06 and $\pm$ 0.03 respectively. The wet density may be slightly low, as the samples were not placed in a vacuum before wetting.

Post-Paleozoic sedimentary rocks

Sandstone, siltstone, shale, and conglomerate of Mesozoic age overlie the Paleozoic rocks in most of the Uravan area. These rocks, with a total thickness of more than 5,000 feet, are well exposed in canyon walls and have been described by Coffin (1921), Cater (1954), and others. Their magnetic effect is nil; the average susceptibility of five specimens of the Wingate sandstone of Triassic age is only 0.006×10^{-3} cgs units. Susceptibilities of the other formations are likewise small, as indicated by their extremely small content of magnetic minerals.

The average density of the Mesozoic rocks from the Jurassic Morrison to the Triassic Wingate formations was found to be 2.50 g per cm^3 from gravimetric measurements at the top and bottom of the steep canyon of the San Miguel river, west of Uravan.

Relatively thin deposits of soil, alluvium, conglomerate and wind-deposited material are found in the valleys and other parts of the Uravan area. Although their density is comparatively low, their effect on gravity measurements is generally small, except possibly in the salt valleys, where residual and other unconsolidated deposits may be several hundred feet thick.

Intrusive igneous rocks

Small sills of diorite crop out between Disappointment and Gypsum Valleys in the southwest part of the area (Coffin, 1921, p. 122-123). They are unlike the intrusive rocks in the La Sal, Abajo, and other laccolithic mountains of the Colorado Plateau but are similar to some of the intrusives of the San Juan Mountains (E. M. Shoemaker, written communication). Physical properties of the sill rocks were not determined, but they are assumed to be of intermediate to high magnetic susceptibility and intermediate density, in line with those of the intrusive rocks from the nearby mountains.

Quartz monzonite was penetrated at a depth of 8,449 feet in the Fred Turner well about 7 miles south of Norwood (fig. 4). The rock is considered to be intrusive, because it contains schist inclusions and is in contact with metamorphosed sedimentary rock.

Regional structure

The geologic structure of the Colorado Plateau, including the Uravan area, has been discussed from various viewpoints by Baker (1935), Shoemaker (1954), Kelley (1955), Cater (1955a, 1955b), and others. Briefly, the Uravan area is characterized by a major faulted monocline, which bounds the Uncompahgre Plateau on the southwest, by three great salt anticlines (fig. 3) and by gently dipping Mesozoic strata between the larger features.

The Uncompahgre Plateau is a great uplifted block; it extends far beyond the limits of the area considered here. Along the southwest front of the uplift, the sedimentary rocks form southwest-facing monoclines which pass into steeply dipping faults, where they can be traced into the Precambrian rocks.

As impressive as the Uncompahgre uplift are the salt structures of Paradox, Gypsum, and Sinbad Valleys. Evaporites of the Paradox member have intruded many thousands of feet into the overlying rocks to form anticlines with predominantly salt cores. Solution and erosion have caused slumping and removed the crests of the anticlines, leaving the residuum of the intrusive evaporites and the overlying rocks.

In contrast to the salt anticlines and faulted monocline, the structure of the Mesozoic rocks, which cover most of the Uravan area, is relatively simple, except where they lap against the salt anticlines and the Uncompahgre Plateau. Folds are relatively gentle, and faults are small and normal. For the most part, the fold axes strike northwest, parallel to the regional structural trend.

The tectonic history and sedimentation of the Paradox Salt Basin involve considerable activity during late Paleozoic as well as during Laramide and later times. In some places pronounced and complex structures of the Paleozoic rocks may be partly or completely masked by the relatively flat-lying Mesozoic rocks.

Aeromagnetic surveys

Airborne magnetic surveys of the Uravan area were made in 1952, in connection with airborne radioactivity surveys. The magnetic data obtained were subsequently compiled and used in this report.

The magnetic measurements were made by a continuously recording AN/ASQ-3A magnetometer, installed in a multi-engine airplane flying at 150 miles per hour. East-west traverses were flown approximately two miles apart at a nominal height of 500 feet above the ground. Photomosaics were used for pilot guidance, and the flight path of the airplane was recorded by a gyrostabilized continuous-strip camera. The distance from plane to ground was measured with a continuously recording radio altimeter. The magnetic data were plotted and a contour map constructed on photomosaics. Flying and compilation were under the direction of J. L. Meuschke of the Geological Survey.

Because of operational limitations the accuracy of the resulting magnetic map is lower than that desirable for theoretical analysis. The accuracy of the magnetic measurements as affected by positioning was reduced by the requirement that the plane fly 500 feet above the ground - a difficult task over rough terrain - rather than at a constant barometric level. The necessity of using semi-controlled photomosaics, because suitable topographic maps of the area were not available at the time, has also resulted in positional errors. In addition, the two mile spacing of flight lines, while suitable for the broader magnetic features, is not sufficiently close to outline accurately the smaller, higher gradient anomalies. For these reasons, estimates of depths to sources of anomalies are subject to more than the usual uncertainty.

Gravimetric surveys

Gravimetric surveys were conducted in the Uravan area during the summers of 1953 and 1954. A few additional traverses were made in the summer of 1955. A total of 828 stations were established, including 13 stations outside of the area discussed here. These latter stations are on the Uncompahgre Plateau.

Satisfactory vertical and horizontal control for the regional gravity survey was obtained from the U. S. Geological Survey's multiplex topographic maps of the Uravan area, and from altimetric measurements. The topographic maps have a scale of 1:24,000 and a contour interval of 20 feet. This method made it possible for two and in some instances three men to carry out the field work. Because roads and trails cross almost all parts of the area, it was possible to attain a satisfactory distribution of stations, with a density of about one per square mile, almost entirely by use of a four-wheel drive vehicle.

Methods of surveying

All gravity stations are tied to the pendulum station of the U. S. Coast and Geodetic Survey designated "Egnar" near Egnar, Colo. The base stations are part of a net including Grand Junction, Gateway, Uravan, Bedrock, Paradox, Naturita, and Egnar, Colorado and Crescent Junction, Moab, La Sal, and Monticello, Utah. The closure error of the 370 mile external loop of this net is 0.3 milligal. The base lines were looped by the three-step method (Nettleton, 1940, p. 38-39) from Moab to Monticello, Utah and from Monticello, Utah to Egnar, Colo. Other legs of the base network were looped by the three-step method over about 50 percent of the total length. When looping between stations on one of these legs suggested no drift, or a small steady drift, either no drift or the extrapolated steady drift was assumed over the next succeeding station interval. The three-step process was then continued in the following interval. When drift was large, the three-step process was used exclusively. This procedure of incomplete looping was used to save mileage and time. Although the assumption of no drift or the extrapolation of drift curves is not to be recommended in general, it is believed that the majority of errors introduced in this net were small and of a random nature. The 0.3 milligal closure error, while perhaps fortuitously small, suggests this also. In rugged areas where roads are poor, and dense station coverage impracticable, except locally, a base net of this nature is satisfactory.

In the daily surveying a base station generally was occupied three times a day: at the beginning and end of the day's work, and around noon. Intermediate stations were repeated frequently. This procedure, combined with a general knowledge of the drift of the gravimeter, sufficed to construct a satisfactory drift curve for regional work.

Measurements were made with a Worden portable gravimeter with a scale constant of approximately 0.5 milligal per division. The range of the instrument was about 350 milligals and the maximum reading error was considered to be about 0.05 milligal.

Elevation control

Elevation control was provided by bench marks and spot elevations from multiplex topographic maps where available. About one-third of the elevations were determined by altimetric methods, including looping between bench marks with a single altimeter, single-base method, and two-base method. The majority of the altimetric elevations were determined by the single-base method. Two-base altimetry was used on several traverses between points with known difference in elevation of about 1,000 feet. These traverses were run only in the neighborhood of the Uncompahgre Plateau where the topography and lack of elevation control make anything but reconnaissance traverses impracticable.

From studies of the distribution of errors in the altimetric measurements it seems that the majority of the errors in the elevations determined by single-base work are about 5 feet or less, equivalent to errors in the anomaly of 0.3 milligal or less. Only a few errors as large as 0.6 milligal can be expected. The accuracy of the elevations determined by looping between bench marks with a single altimeter is considered to be 10 feet or less, corresponding to an error in the anomaly of 0.6 milligal or less. For the extended two-base traverses, the elevations on the line from Nucla to the Continental well northeast of Nucla are considered to be correct within 10 feet. The elevations of the stations along Indian Creek and on the traverse toward the Uncompahgre front between Shavano and Tabeguache Creeks are considered accurate within ± 20 feet.

In areas where bench marks or spot elevations were not available and where altimetric methods were not feasible, a few elevations were determined by interpolation between contours on the multiplex topographic maps. These elevations are less than 10 feet in error in gentle to moderate terrain with few trees, according to altimetric checks and to transit surveys made to locate drill holes by C. N. Brown, surveyor, U. S. Geological Survey. The few stations in relatively rough terrain depending on map elevations are in areas where the regional gradient of gravity is large. In these areas accuracy of elevation control is not so critical as in other areas.

Computation of Bouguer anomalies

The Bouguer anomalies were computed with an elevation factor of 0.062 milligal per foot, corresponding to a density in the Bouguer correction of 2.50 g per cm^3. This density was determined from gravimetric measurements in the bottom and at the top of the canyon of the San Miguel River, about one mile east of its junction with the Dolores River. The vertical distance separating the two measurements is about 800 feet.

Terrain corrections were made for about 450 gravity stations in rough topography. In general the corrections were discontinued at the zone for which the net contribution to the correction was around 0.2 milligal. This was generally zone "J" of Hammer's terrain correction tables (Nettleton, 1940). Near the edges of the area covered by topographic maps the extent of the correction was limited in some places by the topographic coverage.

Bouguer anomalies for a density of 2.50 g per cm^3 can be determined relative to the "International Formula" of 1930 for spheroidal gravity by subtracting 300 milligals from each contour value.

Accuracy of the Bouguer anomalies

The relative accuracy of the Bouguer anomalies at two gravity stations in the same local traverse can be estimated from the following sources of error:

Source	Estimated error
observed gravity	0 - 0.15 milligal
surveyed elevations	generally small
altimetric elevations	0 - 10 feet or
	0 - 0.6 milligal
latitude correction	0 - 0.1 milligal
terrain correction	probably generally small

From these estimated errors it is seen that, other things being equal, the error of the difference in the Bouguer anomaly between two stations in the same traverse at which elevations were surveyed should be about 0.3 milligal or less. In general the errors for the stations with altimetric elevations should be well below one milligal. These estimates do not include the few extended altimetric traverses because these are not representative of the body of the data. The uncertainty for stations on these traverses is largely in the elevations, and estimates of these errors have been presented. Sources of progressive rather than random errors in differences in the Bouguer anomaly for stations at considerable distances from one another are nonlinearity of the moving system of the gravimeter, nonrandom errors in the net of base stations, and regional terrain effects. A tie between the Green River, Utah and Egnar, Colorado pendulum stations and internal ties within the net of base stations suggest that the first two sources do not produce any significant error. Regional terrain effects may exist near the edges of the area surveyed, particularly in the area between Gateway and Uravan. The low along the canyon of the Dolores River (fig. 5) in this area is probably due to such effects.

DISCUSSION OF THE MAGNETIC AND GRAVITY MAPS

As already pointed out, the basement and intrusive rocks of the Uravan area are magnetically diverse, whereas the sedimentary rocks are essentially nonmagnetic. The accompanying magnetic map (fig. 4), therefore, yields information primarily on the basement and intrusive rocks - on their character, configuration and depth beneath the surface - and only indirectly on the sedimentary rocks, insofar as they are influenced by structural and other factors in the crystalline rocks that cause magnetic anomalies.

The gravity effects, on the other hand, are related to density contrasts and configuration of both the sedimentary and the crystalline rocks. Changes in thickness, facies, and configuration of the Paradox salt member are undoubtedly responsible for the largest gravity effects shown on the gravity map (fig. 5), but relief of the basement surface and density contrasts within the basement are also responsible for significant anomalies. The magnetic and gravity data are in general complementary.

The magnetic map

The magnetic map is characterized by a general northwest-southeast magnetic trend. A series of prominent, discontinuous anomalies occurs along the Uncompahgre front in the northeast part of the area, and a similar, though less prominent, series occurs southwest of Gypsum Valley, in the southwest part of the area. In the area between the Uncompahgre uplift and Gypsum Valley, there are low-gradient, broad anomalies, in contrast to the higher-gradient discontunuous anomalies to the northeast and southwest. There is a cluster of small, high-gradient anomalies east of Dry Creek in the southeast part of the area, and a similar anomaly 10 miles west, at the head of Gypsum Valley.

Regional trends

The northwest-southeast magnetic trend parallels the Uncompahgre front, the Paradox and Gypsum Valley salt anticlines, and the axes of the broad folds in the Mesozoic rocks. Thus the regional trends of the underlying crystalline rocks, as reflected by the magnetic trends, are generally parallel to the major structure of the sedimentary rocks.

Uncompahgre uplift

The zone of prominent magnetic anomalies in the Gateway-Nucla-Norwood area lies along the southwest-facing Uncompahgre uplift. (See figs. 3 and 4.) They mark an abrupt change in the magnetization and probably in the composition of the underlying crystalline rocks, as well as in their depth beneath the surface. The change occurs for the most part along the flank of the uplift, several miles and more southwest of the structural crest. Two of the anomalies on the flank indicate that the basement rocks are at a relatively shallow depth. They are the prominent magnetic high about 8 miles southeast of Gateway, and the high about 7 miles northeast of Nucla, where the indicated depths are only about 2,000 feet beneath the surface. The sources of these anomalies are rocks with relatively high apparent magnetic susceptibilities—on the order of 0.002 to 0.003 cgs units. (Estimates of depths to sources of anomalies and of magnetic susceptibilities were made according to the method of Vacquier and others, (1951), whereby observed magnetic effects are compared with the computed effects of bottomless rectangular prismatic models with vertical sides, and with uniform magnetization induced by the earth's field. The accuracy of these depth estimates depends on the accuracy of the magnetic measurements and on the degree to which the observed and computed effects correspond. Zietz and Henderson (1955) have shown that the errors may be less than 10 percent under favorable circumstances, but they may of course be much greater.)

In some places, the anomalies along the flank of the Uncompahgre front coincide approximately with surface traces of faults of relatively small vertical displacement: for example, northeast of Nucla and at the head of Atkinson Creek. In other places, the anomalies coincide with steep dips or faults in the Paleozoic rocks, although the overlying Mesozoic beds are relatively flat. Steeply dipping beds of Pennsylvanian and Devonian age under gently dipping Mesozoic rocks were found in the Continental 1 Nucla well, 2 miles west-northwest of the Nucla magnetic high; and repetition of Pennsylvanian and and Mississippian beds in addition to steep dips were recorded in the Park Holbert 2 and the Penrose and Tatum 1 Federal wells, 12 miles to the southeast (extreme eastern edge of the magnetic map, fig. 4). The latter wells are on the east flank of a prominent magnetic high.

Although the major magnetic anomalies along the Uncompahgre front may coincide with faults in which the basement was involved, they are in general caused mainly by contrasts in magnetization rather than by displacement of the surface of basement. Large-scale displacement of the basement may be responsible for the contrasts by bringing rocks of contrasting susceptibility into contact. It seems likely, in fact, that the major faulting took place during late Pennsylvanian and

Permian times (Cater, 1954), and that the resulting fault zone outlines the main blocks of rocks of contrasting magnetization. As already shown, there is subsurface evidence of steep dips and faults in the Paleozoic rocks along the edges of the magnetic highs northeast of Nucla and 10 miles farther southeast.

Figure 6 shows a magnetic profile across the complex anomaly southeast of Gateway, compared with a profile that would result from a two-dimensional prismatic body magnetized in the earth's field. The effects of residual magnetization were ignored. The top of the prism was placed 2,000 feet below the surface in accord with the estimated depth to the source of the observed anomaly. In order to obtain reasonably good agreement with observed profile, it was necessary to assume a moderately high susceptibility contrast of 0.0027 cgs units. It is doubtful if the observed profile could be caused by any conceivable vertical displacement of the surface of a uniformly magnetized basement.

Although differences in magnetization within the basement seem to be the main cause of the larger magnetic anomalies along the Uncompahgre front, vertical relief of the surface of the basement may also be a significant contributing cause in some places. For example, both drilling information and magnetic and gravity data indicate the basement slopes steeply to the southwest, northeast of Nucla, possibly the result of faulting. The basement relief is estimated to be about 7,000 feet between the magnetic high and the Continental 1 Nucla well. (The elevation of basement at the magnetic high is about 5,800 feet above sea level, according to magnetic depth

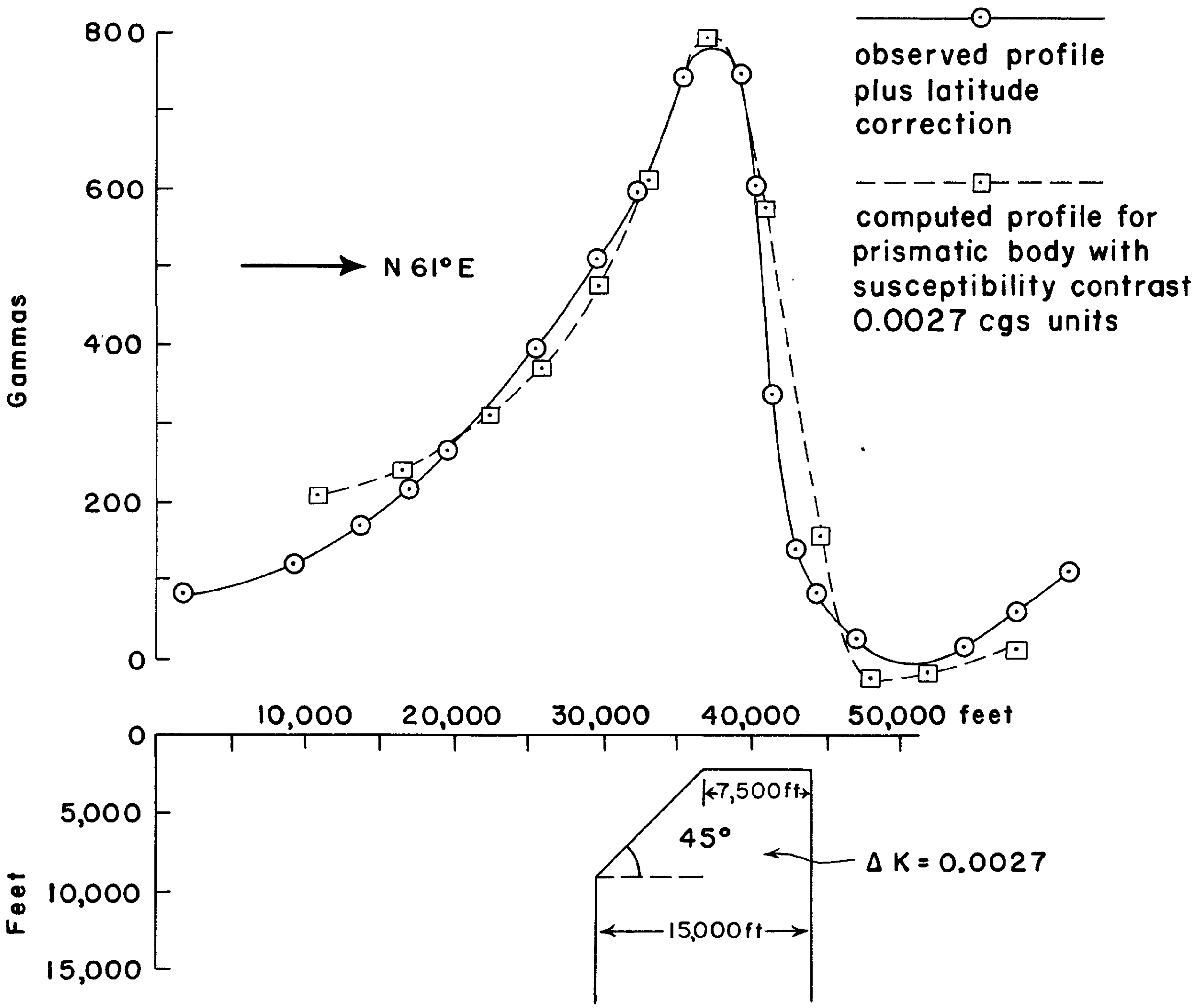


FIGURE 6 - MAGNETIC PROFILES ACROSS THE UNCOMPAHGRE UPLIFT NEAR GATEWAY

1276

estimate, and at the Nucla well is estimated to be about 1,000 feet below sea level.) This well penetrated the Elbert formation of Devonian age at a depth of 7,316 feet, or about 200 feet below sea level. The top of the basement is estimated to be about 800 feet deeper. The total magnetic anomaly resulting from such a basement scarp would be about 150 gammas, or approximately half of the observed effect, if a reasonable, uniform susceptibility of 0.001 cgs units is assumed. Doubling the susceptibility would double the magnitude of the anomaly, but a reasonably close fit with the observed anomaly would require contrasting susceptibilities.

According to Cater (1954), fault scarps probably bounded the southwest flank of the Uncompahgre uplift during Late Pennsylvanian and Permian time. The structure near Nucla is presumably such a scarp. Evidence of steep scarps along other parts of the uplift in the Uravan area is lacking, possibly because the scarps were largely removed during the vigorous erosion that accompanied the uplift.

Near Gateway, relief on the surface of the basement is about 11,000 feet between the Pure 1 Gateway well 4 1/2 miles north-northwest of Gateway and the structural crest of the Uncompahgre Plateau. The total relief is evidently even greater, as the well was drilled on the flank of the uplift. The well went through granite wash, overlying basement at a depth of about 7,900 feet. Between the magnetic high east of Gateway, where the basement is estimated to be about 2,000 feet beneath the surface, and the down-dropped side of the structure, relief may be at least 9,000 feet. Though basement relief is great, the slope is probably gentler than at the Nucla structure, as erosion has probably modified the fault scarps; at least there is no geophysical evidence for large, steep fault scarps. If there is a uniform susceptibility of 0.001 cgs units, there would be a magnetic anomaly of only about 125 gammas attributable to a basement surface with a surface sloping downward to the southwest at 20 degrees from the horizontal. The computed amplitude of the anomaly is thus about one-third the observed amplitude.

Southwest of Gypsum Valley

Southwest of Gypsum Valley the relatively uniform, low-gradient magnetic pattern changes to one of discontinuous, higher gradient anomalies. The general appearance of the anomalies is similar to those over the Uncompahgre uplift. Similarly they are interpreted to reflect a change in both the character and depth of the underlying crystalline rocks: from comparatively uniform deep-lying basement rocks in the central part of the area to shallower, magnetically dissimilar material southeast of Gypsum Valley.

Depths to the sources of the closed anomalies at Disappointment syncline and at Coyote Wash were estimated by the method of Vacquier and others (1951) to be of the order of 6,000 to 7,500 feet beneath the surface. These estimates must be considered only rough approximations because of the wide spacing of flight lines, the departure of the observed anomalies from ideal configurations, and the availability of only two anomalies reasonably suitable for depth estimates. Nevertheless the available evidence indicates the sources of anomalies southwest of Gypsum Valley are at considerably smaller depths than to the northeast.

Recent drilling has partly confirmed the existence of a shallower basement southwest of Gypsum Valley, though the amount of uplift is much less than indicated by the magnetic data. The Reynolds 1 Egnar well, completed late in 1955 on the Dolores anticline, was drilled through the base of the salt in the Paradox member of the Hermosa formation at a depth of 9,579 feet below the surface, or 2,370 feet below sea level. The top of the Molas formation was entered at 2,555 feet below sea level and of the Leadville formation at 2,714 feet below sea level. The well was bottomed in the Leadville formation at a depth of 10,220 feet or 3,011 feet below sea level. If the thickness of pre-Pennsylvanian sediments is approximately that estimated by Cooper (1955, p. 59-65), the Precambrian surface lies about 4,000 feet below sea level under the Reynolds 1 Egnar well.

In Paradox Valley, on the other hand, the American Liberty 1 Government well bottomed in salt at a depth of 10,847 feet, or about 5,300 feet below sea level. If the well bottomed near the base of salt and the thickness of the pre-Paradox rocks is about the same in both places, the basement surface is on the order of 3,000 feet higher under the Dolores anticline than under Paradox Valley.

As already stated, magnetic data indicate depths to crystalline rocks on the order of 6,000 to 7,500 feet under the magnetic highs at Disappointment syncline and Coyote Wash, whereas stratigraphic evidence indicates depths of about 11,000 feet at the Dolores anticline, about five miles southwest. Much of the difference may be attributable to inadequacies in the magnetic data and the departure of geologic conditions from the simplified conditions that are assumed in making estimates of depths to magnetic sources. Yet in view of the size of the difference, part of it may be real; in other words the depths to the magnetic sources at Disappointment syncline and Coyote Wash may be considerably less than the depth to the basement at the Dolores anticline.

The indicated shallow depths may be due to relatively magnetic intrusives rising above the level of the Precambrian basement, to relief on the basement surface, or to structural uplifts. The Triassic beds, the oldest exposed near the anomalies, show no structural indication of large underlying intrusives. So far as is known, there is no record of Paleozoic intrusive rocks in the region. Relief on the basement surface is entirely inadequate to produce the observed anomalies, though they could of course be caused by a fortuitous coincidence of topographic highs and high susceptibilities. Uplifted portions or blocks of relatively magnetic basement rocks, possibly similar to the uplifted segments of the Uncompahgre Plateau, seem to be the most plausible explanation. Any such uplifts would of necessity be pre-Triassic, or older than the lowermost rocks in the vicinity, and would possibly be related in time to the Pennsylvanian and Permian tectonic activity along the Uncompahgre front.

Figure 7 shows a magnetic profile across the Disappointment syncline - Gypsum Valley anomaly compared with two profiles that would be caused by two prismatic bodies magnetized in the earth's field. A latitude correction of 8.5 gammas per mile was added to the observed profile to permit comparison with the computed profiles.

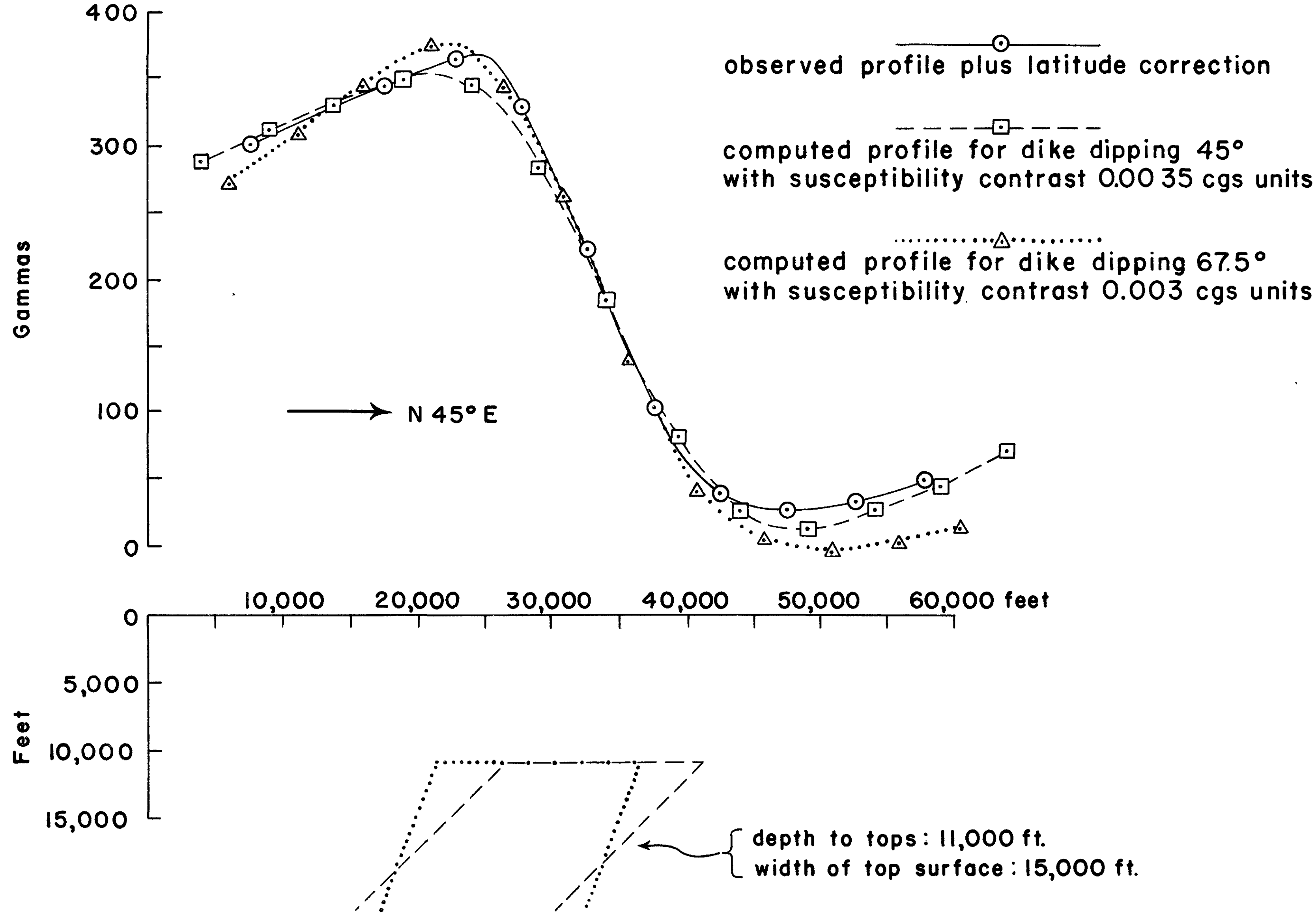


FIGURE 7- MAGNETIC PROFILES ACROSS DISAPPOINTMENT SYNCLINE AND GYPSUM VALLEY

1276

The correction was obtained from U. S. Coast and Geodetic Survey values of horizontal and vertical magnetic intensity for Colorado.

When the tops of the prismatic bodies were placed 11,000 feet beneath the surface, which is the probable approximate depth to basement at the Reynolds 1 Egnar well on the Dolores anticline, good agreement of the computed and observed profiles was obtained when the bodies were inclined and assigned relatively high contrasting susceptibilities, as shown in the figure. Profiles computed for vertical dikes at the assumed depth did not compare satisfactorily with the observed profile. Good agreement could be obtained at depths shallower than 11,000 feet, using other geometries and susceptibilities, but agreement at much greater depths would require assuming bodies with unreasonably high susceptibility contrasts and smaller dimensions. Thus, although no unique solution can be obtained, 11,000 feet may be considered a probable maximum depth to the source of the anomaly.

The existence of shallow basement or other crystalline rocks under Disappointment syncline, indicated by the magnetic data, is not supported by structural evidence at the surface, as the Mesozoic rocks are more than 2,500 feet lower in the trough of the Disappointment syncline than on the Dolores anticline. Stokes and Phoenix (1948) attribute the formation of the broad folds in the Uravan area, including the Dolores anticline and the Disappointment syncline, to widespread tectonic compression near the end of the Cretaceous period. Normally the basement would be involved in broad regional warping, but the magnetic evidence indicates either that there is no direct relation between the folds at the surface and the depth to the basement, or that the effect of concordant warping is obscured by an earlier uplift of the basement under Disappointment syncline.

Central area, between Uncompahgre uplift and Gypsum Valley

The relatively uniform, open magnetic pattern in the central area between the Uncompahgre Plateau and Gypsum Valley is believed to be caused in part by relatively uniform magnetization of the basement, and in part by a greater depth to the basement. Subsurface evidence tends to confirm the postulated greater depth; and estimates of depths to sources of anomalies indicate that the magnetically uniform central area is bounded to the northeast and southwest by shallower crystalline rocks of higher magnetization.

The positive gradient northeastward from Gypsum Valley to the Uncompahgre front is due in part to the northward increase in the magnetic field, which has been computed from U. S. Coast and Geodetic Survey smoothed values of vertical and horizontal intensity as about 8.5 gammas per mile in the Uravan area, but a small gradient remains after subtracting the latitude gradient. The positive northeastward gradient immediately adjoining Gypsum Valley is mainly the result of "tailing out" of the anomaly associated with the postulated structure between Gypsum Valley and Disappointment syncline, as shown in figure 7. Similarly, most of the gradients that extend southwestward from the Uncompahgre Plateau are apparently associated with the large displacement of basement along the flank of the uplift. An exception may be the prominent gradient which extends southwest from

Redvale and Norwood, and which may be related to gradational changes in the susceptibility of the basement rocks, or to deep-seated changes within the basement.

The small, high-gradient anomalies east of Dry Creek and a similar anomaly at the southeast end of Gypsum Valley are probably caused by shallow, relatively magnetic rocks, similar to the diorite sills described by Coffin (1921, p. 122-123). Closer spacing of flight lines would be required to define these anomalies accurately. The broader high about 10 miles east of Dry Creek may be related to a quartz monzonite intrusion penetrated in the Fred Turner 1 well at a depth of 8,449 feet.

The remaining anomalies of small amplitude and low gradient in the central area may be related to several causes: to small contrasts in the magnetization of the basement rocks, to basement relief, or to deeper seated causes. There is no unique cause-and effect relationship. The magnetic features associated with Paradox and Sinbad Valleys fall into this category; but a relationship between the basement and salt structure is suggested at the head of Paradox Valley, west of Naturita. There the axis of the salt structure is offset to the north about a mile, and the magnetic contours are similarly offset to curve around the broad high in Dry Creek basin.

Bouguer anomaly map

General description

The most striking features of the Bouguer anomaly map are the negative anomalies along Paradox and Gypsum valleys. The residual anomaly over the eastern part of Paradox Valley is about -30 milligals. Along the southwest side of the valley, near Bedrock, the gradient is approximately 20 milligals per mile. A large negative anomaly is associated with Sinbad Valley also, although the gravity coverage in this area is insufficient to determine details of the anomaly.

The anomalies in Paradox and Gypsum valleys evidently are superposed on a strong regional trend with a trough-like minimum, which passes through Naturita, the saddle in the contours in Dry Creek Basin, and the minimum in Gypsum Valley. The regional trend of the contours between Gypsum Valley and the broad gravity high centering near Uravan seems to be approximately south-southwest, roughly at right angles to the observed structural trends. North of Egnar this regional trend strikes roughly east-west, and the results of recent surveys to the west of the area covered by this report indicate that this trend continues for some distance. There is thus no gravitational evidence of any great local thickening of salt in the Dolores anticline north of Egnar, for the contours show no major flexures in crossing the axis of the structure in this area.

The nose formed by the contours southwest of Gypsum Valley is probably due in part to the withdrawal of salt into the Gypsum Valley piercement structure. The Reynolds 1 Egnar well, about 6 miles north of Egnar, penetrated about 4,100 feet of Paradox salt and was bottomed in pre-salt beds. An anomaly of approximately + 6 milligals would be produced by the withdrawal, at the depth of the salt in this well, of a body of salt with the following properties: (1) cross-sectional area roughly one half of the estimated thickening in the Gypsum Valley structure, (2) maximum thickness 2,000 feet, (3) density contrast 0.35 g per cm^3 (data on densities are discussed in a subsequent section). The anomaly is of the right shape to fit profiles of the observed gravity across the nose. Of course, the withdrawal of larger amounts of salt would mean that an even larger positive anomaly than that calculated should be present. It is thus likely that the post-salt Paleozoic section is appreciably thicker along the axis of this nose than on the Dolores anticline, because there is no evidence of a major thickening in the overlying Mesozoic rocks.

The gravity relief across this nose seems to increase toward the southeast in the same direction as the increase in structural relief of the Mesozoic rocks between the Dolores anticline and Disappointment syncline. It is uncertain how much of this gravity pattern is due to the migration of salt and how much may be due to a flexure in the contours caused by other masses. The axis of the gravity nose lies 1 1/2 to 2 miles south of the axis of the Disappointment syncline in the area mapped. This shift is rather more than could be accounted for by the tailing-off of the anomaly due to the Gypsum Valley piercement structure. A near coincidence of the axis of the gravity anomaly and the axis of Disappointment syncline would suggest post-Mancos migration of salt, perhaps partly into the Dolores anticline east of Egnar. The contours of the Bouguer anomaly do not correlate particularly well with the structural relief of the Mesozoic rocks in this area. Although there is a suggestion of salt thickening southeasterly along the Dolores anticline, it appears that most of the movement of salt northeast of Egnar occurred in pre-Mancos time.

Some rather strong anomalies in the Uravan area are due to intrabasement density contrasts. This is apparent from the magnitudes of the anomalies and suggested by the marked discordance between the trends of the contours and the major structural trends. The broad high centering near the junction of the San Miguel and Dolores Rivers is of the same magnitude as the Bouguer anomaly on the structurally higher Uncompahgre Plateau near the head of Atkinson Creek. Terrain corrections for the stations on the Plateau northeast of Uravan were carried to considerable distance so that the terrain effects in the anomalies are probably relatively small. Similarly the Bouguer anomalies in the vicinity of Wray Mesa are considerably more positive than those near the head of Atkinson Creek. The high values of gravity at Wray Mesa and at the junction of the Dolores and San Miguel rivers cannot be due to changes in thickness of a homogeneous sedimentary section alone. The high anomalous gravity in the vicinity of Wray Mesa is certainly the result of high-density masses within the basement. The high near Uravan is evidently due to the superposition of the effects of the withdrawal of salt, into Paradox Valley and the Roc Creek area, upon a broad intrabasement anomaly. As the Paradox salt presumably feathers out to the northeast between Uravan and the Uncompahgre Plateau, it is difficult to say how much of this anomaly is due to the withdrawal of salt. In particular it does not seem possible that the gradient along Atkinson Creek can be attributed to the return to local "normal" thickness of the salt away from Paradox Valley, for there is no gravimetric evidence of feathering out farther to the east. In fact it seems that a strong intrabasement trend has obliterated any gravitational effects of the thickening of sediments off the Uncompahgre front in this area. The ridge in the contours near the Uncompahgre front along Atkinson Creek may be due to the superposition of the effects of a local shallowing of the basement off the front on the postulated basement anomaly. However, this is purely a speculation. It is likely that there is little salt left in this general area and that the Uravan high is largely the result of basement density contrasts.

Presumably the area of relatively low anomalous gravity near and to the east of the Dolores River and north of the Uravan high, is related to the thickening of the sedimentary section off the Uncompahgre front. At any rate, decreasing values of the Bouguer anomaly are to be expected away from the Uncompahgre front as the sedimentary section thickens. One might expect that this low would extend to the south or southeast, were it not for the interference of the basement anomaly near Uravan.

The two traverses toward the Uncompahgre front east of Gateway and Uravan suggest that the basement slopes away in varying degree from the Uncompahgre front on the downthrown side. Only northeast of Nucla is there evidence of an abrupt increase in the depth to crystalline rock. Two closed traverses were run northeast of Nucla, crossing the region where there is a sharp gradient in the contours.

Although this gradient could be produced by a shallow, dense intrusion, there seems to be no supporting structural evidence for this possibility in the local Cretaceous and Jurassic rocks. No periods of Paleozoic or early Mesozoic intrusion have been recognized in this general area. The gradient is presumably due to a major fault, with a displacement of several thousand feet. The gravity anomaly coincides with a surface fault of relatively minor displacement, but the major displacement must have occurred during the uplift of the ancestral Uncompahgre Plateau. The absence of a sharp gradient on the traverse toward the Uncompahgre front to the northwest of this area suggests that either the fault must strike roughly north, to the northwest of the traverse revealing the fault, or it must die out in the six miles between traverses. The basement must be close to the surface on the north side of the fault, because of the sharpness of the gradient. This is in qualitative agreement with a depth of about 2,000 feet, estimated from a magnetic anomaly.

No salt was logged in the Continental 1 Nucla well, about 6 miles northeast of Nucla (fig. 3) on the south side of the fault, and this indicates that the density contrast involved is that between crystalline and sedimentary rocks. The log of this well indicates that there is 3,700 feet of granite wash overlying the Hermosa formation. The well was bottomed in Devonian beds at a depth of 7,616 feet.

This fault suggests that local fault blocks, related to the ancestral Uncompahgre uplift, extend some 2 miles farther south than the present surface faulting north of Tabeguache Creek.

Area north of Uravan

The negative anomaly along Roc Creek is doubtless associated with the vertical migration of Paradox salt. The Paradox member crops out in at least four places on Roc Creek, and the circular structure in this area shown on the geologic map is a salt dome (Shoemaker, 1955). Because there are no gravity stations between Roc Creek and Sinbad Valley, the contours between these two areas cannot be joined. The geologic evidence (Shoemaker, 1954) suggests that there is a distinct closed minimum in the vicinity of the Roc Creek dome.

Terrain effects are greatest in the area north of Uravan, particularly for the stations in the bottom of the canyon of the Dolores River and in Roc Creek canyon. Evidently the anomalies show some distortion attributable to terrain effects along the Dolores River. The low following the Dolores River is probably due to the relatively large effects of distant terrain on stations in canyons.

The traverse across the Ute Creek graben reveals a small negative anomaly associated with this structure.

Paradox Valley and vicinity

The Paradox Valley piercement structure gives rise to a large negative gravity anomaly. Two interpretations of this structure along profile AB (fig. 5) are shown in figure 8. The residual anomaly shown is due largely to the intrusion of salt. The residual was determined by smoothing the regional trend of the contours across the valley, and subtracting this smoothed regional trend from the observed gravity.

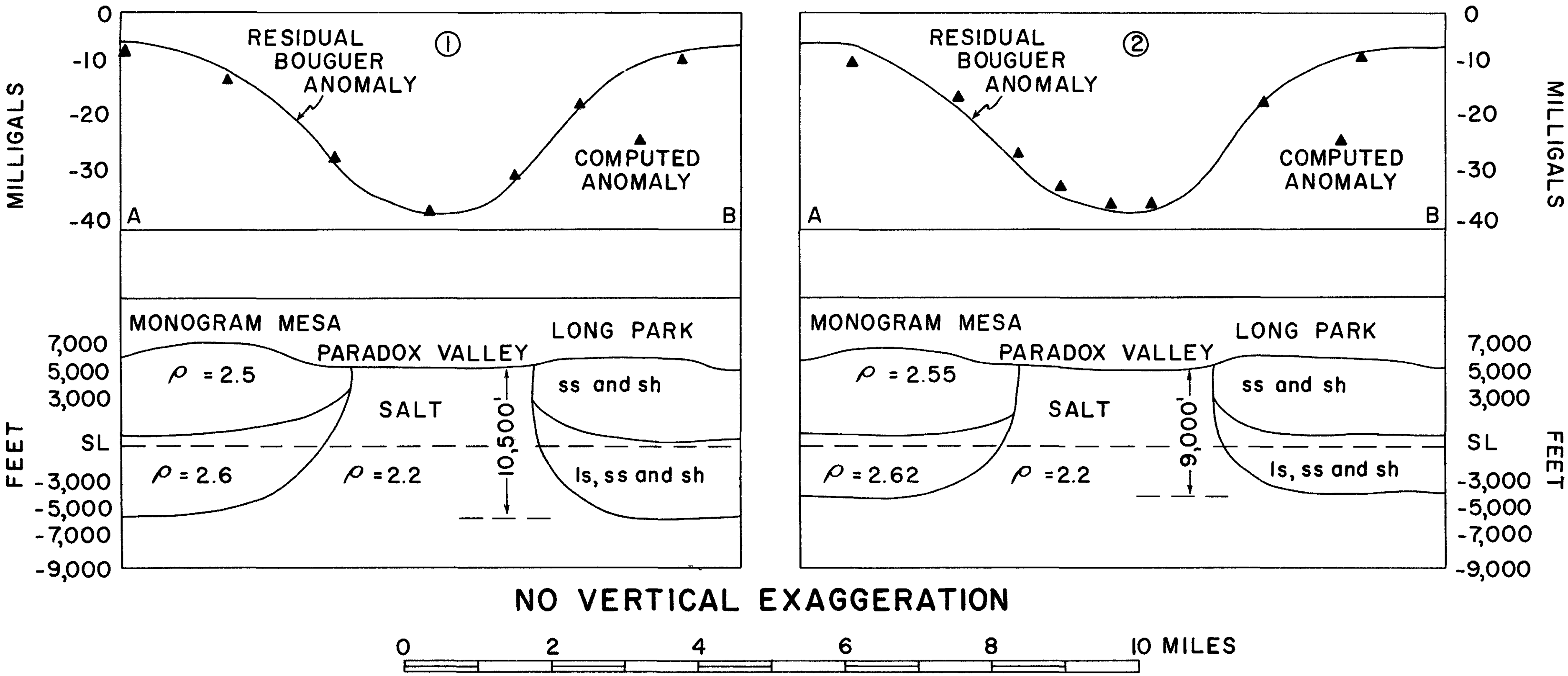


FIGURE 8- INTERPRETATIONS OF THE PARADOX VALLEY GRAVITY ANOMALY

1276

The calculated distributions of mass are for a two-dimensional body, that is, one long compared to its width.

In the American Liberty 1 Government well, near the middle of Paradox Valley and approximately on the line of section AB, drilling stopped in salt at a depth of 10,847 feet. According to well logs the salt was first penetrated at a depth between 1,090 and 1,230 feet. The material above the salt is described as alluvium and gypsum, black shale, sandy shale, and anhydrite. The ground level of this well is approximately 5,540 feet.

Stratigraphic information for the southwest flank of the valley is available from the Chicago 1 Ayers well. This well is on the Dolores River about two miles south of Bedrock and about a mile southwest of the beginning of the complex fault zone bordering Paradox Valley. The ground level of the well is 5,000 feet and the well was bottomed in the Hermosa formation at a depth of 6,860 feet. There is considerable variation in the interpretations of the depths to the tops of various formations in this well. In figure 8 the elevations approached by the top of the limestone-sandstone-shale section away from the salt cores are within 350 feet of several estimates of the top of the Hermosa formation in the Ayers well.

It is not implied that these figures indicate accurately the top of the Hermosa formation. Large dips are to be expected on the flanks of Paradox Valley. The sections merely indicate distributions of mass that make it possible to obtain a reasonable fit between the calculated anomaly and the observed anomaly. The maximum thickness of the Cutler formation and, therefore, the maximum depth to the top of the Hermosa, is presumably somewhere near the middle of the area between Paradox and Gypsum Valleys, or roughly two to three miles southwest of the Ayers well. Thus the position of the density contrast away from the salt cores is presumably somewhat too high in the section. Other things being equal, the figures as shown will yield conservative estimates of the thickening of salt in the Paradox structure.

A density of 2.2 g per cm^3 has been used for the core of the structure. This density is used commonly in the calculation of the gravitative effects of salt structures. According to Parker and McDowell (1955, p. 2389) most salt masses of the Gulf Coastal Plain consist of at least 90 percent sodium chloride, with anhydrite the dominant impurity. The density of halite is 2.135 (Birch, Schairer, and Spicer, 1942, p. 10). A density of 2.2 corresponds to a mass composed of approximately 93 percent halite and 7 percent anhydrite. On the other hand, if the salt mass is composed of 90 percent halite and 10 percent clastic material of density 2.4 to 2.5 g per cm^3, the effective density is 2.17 to 2.18 respectively, for material distributed or admixed to a suitable degree. These figures can be kept in mind in comparing the interpretations in figure 8. For example, the anomaly in part 2 of figure 8 is the same as the anomaly with densities of 2.18, 2.53, and 2.60 replacing 2.2, 2.55, and 2.62 respectively.

It is likely that the density of part of the first thousand feet of the Paradox structure is more than 2.2. The density of gypsum, for example, is about 2.32 (Birch, Schairer, and Spicer, 1942, p. 10).

On the other hand, the fraction described as alluvium is certainly less dense, perhaps 1.9. Probably the material as a whole is more dense than 2.2. In this case calculations based on a density of 2.2 g per cm^3 will yield conservative estimates of salt thickening.

In one interpretation the density 2.6 has been used for the Hermosa formation and 2.5 used for the post-Hermosa formations. The first density is purely a guess, based on the lithology of the formation. The second was determined gravimetrically as the average density of the upper Mesozoic rocks exposed in the canyon of the San Miguel River. In the second interpretation, 2.55 g per cm^3 is the density of the the Cutler formation when approximately 50 percent saturated with fresh water, as determined from 30 surface samples collected near Gateway, Colo. The density 2.62 is an average effective density for the Hermosa determined by weighting the thicknesses of sandstone and shale and of limestone, in drillers' logs of this formation in the Moab area, with the densities 2.55 and 2.65 respectively. The latter density is based upon 8 samples of limestone from a measured section of Hermosa near Big Indian Wash, Utah.

The Paradox Valley piercement structure is evidently large enough vertically that it is difficult to fix this dimension. Small variations in the densities may alter the calculated depth of the structure by 1,000 feet or so. It seems reasonable to expect that the actual or equivalent density contrasts are included in the range shown in figure 8.

If it be presumed that the base of the salt is not much deeper than the depth of the American Liberty well, namely 10,847 feet, the interpretation in part 1 of figure 8 suggests that there is little salt left on the flanks of Paradox Valley. There is no good gravimetric evidence of the presence of any appreciable thickness of undisturbed salt on the north flank of Paradox Valley; but, because of the interference of intrabasement trends in this area, it is impossible to make a positive statement.

The second interpretation (fig. 8) suggests that either there are at least 2,000 feet of salt between Gypsum and Paradox Valleys or that the base of the salt is deeper under Paradox Valley.

Either of these interpretations is reasonable, but it seems unlikely that there are as much as 2,000 feet of "undisturbed" salt remaining. Although the pre-Morrison formations thin out against the flanks of Paradox Valley, the Morrison formation was deposited continuously across the valley (Cater, 1954). Presumably the Paradox Valley piercement structure is of the order of 10,000 feet or so in vertical extent and the combined thickness of the section from the top of the Chinle formation to the top of the salt, between the valleys, is of the order of 9,500 feet or so. The assumption is made here that the elevation of the top of the Chinle formation is roughly 5,000 feet, between Paradox and Gypsum valleys.

This estimated thickness can be compared with a thickness of approximately 4,000 feet for a presumably analogous section from the Reynolds 1 Egnar well on the Dolores anticline, about 6 miles north of Egnar. The absence of the Cutler and Chinle formations and Wingate sandstone from the list of tops of formations in this well is curious. The thickness of the interval described as Moenkopi is approximately 1,800 feet. Presumably the Cutler and Chinle, or their equivalents lie in this interval. The figure 4,000 feet is approximately the interval between the top of the salt and top of the Moenkopi in this well. The figure includes approximately 500 feet of what is described as Paradox.

Just how the northeastward thickening of this section is distributed is uncertain. It may be largely within the Cutler formation. It is not unlikely that both the Cutler and the upper Hermosa thicken considerably.

SUMMARY OF CONCLUSIONS

Regional magnetic trends in the Uravan area indicate that the major basement trends are parallel to the northwest-striking regional structures of the overlying sedimentary rocks. Regional gravity and structural trends are generally parallel along the Uncompahgre uplift. South of Uravan the regional gravity trend, excluding the effect of salt, is normal to the present structural trend, probably because of intrabasement rocks of high density that cross the present structural trend.

On the basis of magnetic patterns the area is divisible into three distinct parts: the Uncompahgre uplift to the northeast, the part southwest of Gypsum Valley, where the basement has apparently been uplifted, and the central part, where the basement rocks lie at greater depths.

The prominent, discontinuous magnetic anomalies along the flank of the great Uncompahgre uplift are caused mainly by a discontinuous belt of relatively magnetic rocks. Some, and perhaps all of these magnetic masses are bounded by faults; thus the magnetic anomalies may indicate the outlines of faulted blocks along the uplift.

The gravity patterns suggest that basement relief is generally achieved gradually along the flanks of the Uncompahgre Plateau; the major displacements along the faults are within the basement. Evidence of steep basement fault scarps is found locally, northeast of Nucla.

Southwest of Gypsum Valley the magnetic pattern resembles that over the Uncompahgre uplift, though the anomalies are broader because of the greater depth of burial of the basement rocks. The depth of the basement rocks at the Dolores anticline is probably about 11,000 feet, according to available stratigraphic evidence; but crystalline rock is estimated to be only about 6,000 to 7,500 feet deep in the Disappointment syncline, about six miles to the northeast, on the basis of magnetic data. Much of the difference may be due to inadequacies in the magnetic data; yet it seems likely that the magnetic indications of shallow basement or intrusive rock are partly real. Structural uplift of a segment of magnetic basement rocks is considered the more plausible cause, though intrusives of igneous rock cannot be ruled out.

Both magnetic data and geologic evidence indicate that the basement lies at comparatively great depth in the central part of the area, between the Uncompahgre front and Gypsum Valley. Magnetic indications of greater depth northeast of the Gypsum Valley - Disappointment syncline anomaly are substantiated in part by subsurface evidence, which suggests that the sea level elevation of basement under Paradox Valley is about 3,000 feet below that at the Dolores anticline. Surface structure likewise suggests a downwarp of about 3,000 feet, though about 5 miles south of the magnetic indication. The low gradients and regularity of the magnetic pattern in the central part indicate that the basement is relatively nonmagnetic and of uniform composition, in contrast to the magnetically dissimilar basement, to the northeast and southwest.

The large negative gravity anomalies associated with the Paradox and Gypsum Valley salt piercement structures indicate a considerable thickening of the post-salt Paleozoic rocks between these structures. The thickness of rocks above the salt, to and including the Chinle formation in the area between Gypsum and Paradox valleys is probably about 9,500 feet. It is likely that these rocks also thicken considerably along the south flank of the Gypsum Valley piercement structure. There is no definite gravitational evidence that appreciable thicknesses of salt remain in the neighborhood of Gypsum and Paradox valleys, but the obscuring effects of basement anomalies make it impossible to say with assurance that there is no salt.

No basement effects that might exert structural control can be related with certainty to the salt anticlines, though a relationship is suggested by gravity and magnetic trends that correlate with offsets of the Paradox and Gypsum Valley structures.

Several gravity and magnetic features correlate rather closely in position, notably the anomalies along the Uncompahgre front, the highs along Atkinson Creek, the lows along the Dolores River, south of Gateway, and the broad highs in Dry Creek Basin. They are probably related mainly to variations in the properties of the basement rocks rather than to topography, though these effects cannot be distinguished.

LITERATURE CITED

Baker, A. A., 1933, Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, 95 p.

__________, 1935, Geologic structure of southeastern Utah: Am. Assoc. Petroleum Geologists Bull., v. 19, no. 10, p. 1472-1507.

Bass, N. W., 1944, Paleozoic stratigraphy as revealed by deep wells in parts of southwestern Colorado, northwestern New Mexico, northeastern Arizona and southeastern Utah: U. S. Geol. Survey Oil and Gas Inv. Prelim. Chart No. 7.

Birch, Francis, Schairer, J. F., and Spicer, H. Cecil (editors), 1942, Handbook of physical constants: Geol. Soc. America Special Paper no. 36, 325 p.

Cater, F. W., 1954, Geology of the Bull Canyon Quadrangle, Colorado: U. S. Geol. Survey, Geol. Quad. Map GQ 33.

__________, 1955a, Geology of Gateway Quadrangle, Colorado: U. S. Geol. Survey, Geol. Quad. Map GQ 55.

__________, 1955b, Geology of Pine Mountain Quadrangle, Colorado: U. S. Geol. Survey, Geol. Quad. Map GQ 60.

Coffin, R. C., 1921, Radium, uranium and vanadium deposits of southwestern Colorado: Colo. Geol. Survey Bull. 16, 231 p.

Cooper, J. C., 1955, Cambrian, Devonian and Mississippian rocks of the Four Corner area: Four Corners Geol. Soc., Field Conference Guidebook, p. 59-65.

Kelley, V. C., 1955, Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium: Univ. N. Mex. Pub. in geology, no. 5, 120 p.

McKay, E. J., 1955a, Geology of the Atkinson Creek Quadrangle, Colorado: U. S. Geol. Survey, Geol. Quad. Map GQ 57.

____________, 1955b, Geology of Red Canyon Quadrangle, Colorado: U. S. Geol. Survey, Geol. Quad. Map GQ 58.

Nettleton, L. L., 1940, Geophysical prospecting for oil, p. 38-39, New York, McGraw Hill Book Co.

Parker, T. J., and McDowell, A. N., 1955, Model studies of salt-dome tectonics: Am. Assoc. Petroleum Geologists Bull., v. 39, no. 12, p. 2384-2470.

Shoemaker, E. M., 1954, Structural features of southeastern Utah and adjacent parts of Colorado, New Mexico, and Arizona: Utah Geol. Soc., Guidebook to the geology of Utah, no. 9, p. 48-69.

____________, 1955, Preliminary geologic map of the Roc Creek Quadrangle, Colorado: U. S. Geol. Survey Mineral Field Inv. Map MF 23.

____________, 1956, Geology of the Juanita Arch Quadrangle, Colorado: U. S. Geol. Survey, Geol. Quad. Map GQ 81.

Stokes, W. L., and Phoenix, D. A., 1948, Geology of the Egnar-Gypsum Valley area, San Miguel, and Montrose Counties, Colorado: U. S. Geol. Survey Oil and Gas Inv. Prelim. Map 93.

Turnbow, D. R., 1955, Permian and Pennsylvanian rocks of the Four Corners area: Four Corners Geol. Soc. Field Conference Guidebook, p. 66-68.

Vacquier, Victor, Steenland, N. C., Henderson, R. G., and Zietz, Isidore, 1951, Interpretation of aeromagnetic maps: Geol. Soc. America Mem. 47, 151 p.

Wengerd, S. A., and Strickland, J. W., 1954, Pennsylvanian stratigraphy of Paradox Salt Basin, Four Corners region, Colorado and Utah: Am. Assoc. Petroleum Geologists Bull., v. 38, no. 10, p. 2157-2199.

Withington, C. F., 1955, Geology of the Paradox Quadrangle, Colorado: U. S. Geol. Survey, Geol. Quad. Map GQ 72.

Zietz, Isidore, and Henderson, R. G., 1955, The Sudbury aeromagnetic map as a test of interpretation methods: Geophysics, v. 20, no. 2, p. 307-317.