REGIONAL GRAVITY SURVEY OF THE CARRIZO MOUNTAINS AREA, ARIZONA AND NEW MEXICO

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U. S. Geological Survey
Released to open file
May 8, 1958.

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Abstract

A total of 570 gravity stations were established within an area of about 1,000 square miles south of the common corner of Colorado, Utah, Arizona, and New Mexico. The Bouguer gravity anomaly pattern apparently is unrelated to the disposition of minette plugs inasmuch as there probably is little contrast in density between the conduit filling and the surrounding sedimentary rock. Gravity contours associated with an underlying dense mass within the Precambrian basement parallel the Boundary Butte anticlinal structure. The steep gravity anomaly gradient near the southeast corner of the area probably follows the buried, steeply dipping or faulted edge of the Defiance uplift.

Introduction

The gravity investigation in the Carrizo Mountains area extends the regional gravity survey of the Colorado Plateau begun in the Uravan area, Colorado during the summer of 1953 by the U. S. Geological Survey (Joesting, 1953, p. 55). The gravity survey is a part of the regional geophysical studies of the Colorado Plateau. These studies, "....involve the systematic collection of magnetic, gravimetric, geothermal, and subsurface data, and analysis of this data in terms of regional structural trends, basement topography and composition of the intrusive rocks" (Joesting, Byerly, and Plouff, 1955, p. 93). Most of the field work for the gravity survey was completed during October and November 1954 and May and June of 1955.

The gravity survey covered by this report comprises 570 stations established within an area of about 1,000 square miles of Navajo Reservation in Apache County, Arizona and San Juan County, New Mexico (fig. 1). Prominent landmarks of the area include the Carrizo Mountains near the center, Ship Rock to the east, and the Chuska Mountains to the south. Access to the area is via Shiprock, New Mexico (fig. 5).

Acknowledgments

H. R. Joesting, geophysicist-in-charge of the U. S. Geological Survey's Colorado Plateau regional geophysical studies, provided valuable guidance for many phases of this report. The Navajo Tribal Council kindly granted permission to work in the Navajo Reservation. In part the work was done on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

Geology

General

In general the area falls within the platform between the Defiance uplift, the Blanding basin, and the San Juan basin (fig. 1). The Carrizo Mountains dome interrupts the otherwise simple platform.

Sedimentary rocks that crop out in the Carrizo Mountains area range in age from the Permian to the Tertiary system (fig. 2). Oil wells drilled in the area extend the local geologic column to the Cambrian (?) (Bass, 1944). The discussion of geology in this report is limited to the general rock types, densities, and structure as related to their effect on the gravity pattern.

Precambrian rocks

The nearest exposure of Precambrian rock crops out in Quartzite Creek, about 25 miles south of the area covered by this report, two miles northwest of Fort Defiance, Arizona (Gregory, 1917, p. 17). About 800 feet of hard, well-bedded, intensely fractured quartzite occurs in two small exposures in this vicinity (Allen and Balk, 1954, p. 60). The Precambrian basement complex, however, is considerably more diverse than indicated by a single exposure. About 50 miles to the northeast more than 45 units have been mapped near the San Juan uplift, Colorado, and intrusive granitic rocks comprise almost half of the area of exposure (Cross, Whitman, and Larsen, 1935, p. 17-19). Similar diverse kinds of Precambrian rock are exposed in western Arizona near Grand Canyon where granite, schist, and gneiss, respectively, are abundant (Darton, 1910, p. 14), in west-central Colorado near the Uncompahgre Plateau schists and gneisses are most common (Shoemaker, 1956, p. 54), and in the Zuni uplift southeast of Gallup, New Mexico, where granites are exposed prominently (Darton, 1928, p. 148).

At present no wells have been drilled to Precambrian within the Carrizo Mountains area. Humble Oil Company drilled "No. 1-D Navajo" (New Mexico sec. 30, T. 26 N., R. 19 W.) about 7 miles southeast of the area to Precambrian rocks. The Phillips Petroleum Company "Navajo No. 1" well (New Mexico sec. 5, T. 30 N., R. 17 W.) reached gneiss and the Humble Oil Company "No. 1-C Navajo" well (New Mexico sec. 8, T. 31 N., R. 18 W.) reached probable meta-sedimentary rocks (J. E. Case, written communication, April 1958). Bass (1944, p. 13) reports two wells bottoming in schist near Mexican Hat, Utah about 30 miles northwest of the Carrizo area. The Amerada and Stanolind "Navajo-Black Mountain" well (Arizona sec. 26, T. 32 N., R. 23 E.), about 28 miles southwest of Round Rock, Arizona, also bottoms in Precambrian rocks.

Sampling of the Precambrian in other deep wells in this region undoubtedly will aid in giving direct information about rock types in the Precambrian. This is especially important for interpretation of gravity and magnetic anomalies. Near the Carrizo Mountains as in other areas the gravity pattern is strongly controlled by distribution of the various Precambrian rock types. Any data, then, pertaining to depth to basement and rock type within or near the area are a step toward solution of the basement configuration that most nearly fits the gravity anomaly pattern.

E. M. Shoemaker of the U. S. Geological Survey has collected a number of samples of xenoliths of Precambrian crystalline rock from diatremes on the Navajo and Hopi Reservations in Arizona, New Mexico, and Utah. A large variety of crystalline rock types is indicated by 8 samples collected in the Carrizo Mountains area and 19 samples within 20 miles from the area. The average dry bulk density measured from the collection is 2.73 gm/cm^3 over a range from 2.51 to 2.94 gm/cm^3. These samples show little effect of weathering or alteration (E. M. Shoemaker, oral communication, 1957); hence 2.73 gm/cm^3 may be fairly representative of the overall density of the complex Precambrian crystalline rocks underlying this area within the limits of accuracy of the small number of samples. Density contrasts of as much as 0.3 gm/cm^3 among the basement rock units may be expected.

As far as average rock type is concerned, V. C. Kelley (1950, p. 53) estimates that Precambrian rocks underlying the nearby San Juan basin consist of varying combinations of about 45 percent granite, 30 percent schist and gneiss, 15 percent quartzite and phyllite, and 10 percent greenstone. Quantitative data, such as provided with a study of samples from wells and xenoliths, helps in the interpretation of gravity anomalies originating from rock units of contrasting density in the basement.

Pre-Permian sedimentary rocks

Examination of data from 18 deep wells drilled in and near the Carrizo Mountains area indicates that 2,400 to 3,100 feet of pre-Permian sedimentary rocks underlie most of the northern and eastern part of the area. More than half this thickness consists of the Hermosa formation (Pennsylvanian) and the gradational Rico formation (Pennsylvanian and Permian?). This section undoubtedly thins southward toward the Defiance uplift, inasmuch as a thickness of about 1,450 feet appears in the Humble "No. 1-D Navajo" well southeast of Beautiful Mountain, and no pre-Permian sedimentary rocks crop out over the Precambrian 25 miles south of the area (Gregory, 1917, p. 17).

This sequence of rocks consists chiefly of carbonates (table 1). However, appreciable thicknesses of shale are present in the Molas formation (Pennsylvanian) and sandstone is common in the Cambrian (?) and Devonian systems. Density measurement data are insufficient to assign an accurate average density for the pre-Permian section in this area. The range of densities for the carbonate section is about 2.65 to 2.8 gm/cm^3, while that for the clastics is about 2.5 to 2.6 gm/cm^3. A density of 2.65 gm/cm^3, the same order of magnitude as the density of lighter Precambrian rocks, probably typifies the pre-Permian sedimentary section.

Table 1.--Generalized section of the sedimentary rocks in the Carrizo area.

System	Formation or group	Approximate complete thickness in area (feet)	Predominant kind of rocks
Tertiary	Chuska	500 - 1,400	Sandstone
Cretaceous	Mancos (upper member)	up to 600	Shale
	Gallup (Mesaverde group)	0 - 150	Sandstone
	Mancos (lower member)	700 - 850	Shale
	Dakota	100 - 300	Sandstone
Jurassic	Morrison	700 - 900	Sandstone, mudstone
	San Rafael group	100 - 350	Sandstone and siltstone
Jurassic(?)	Navajo	0 - 200	Sandstone
	Kayenta	0 - 60	Sandstone and shale
Triassic	Wingate	400 - 1,100	Siltstone and sandstone
	Chinle	900 - 1,500	Sandy claystone
Permian	Cutler	1,000 - 2,000	Red clastics
Pennsylvanian and Permian(?)	Rico	200 - 500	Clastics, limestone
Pennsylvanian	Hermosa	1,000 - 1,700	Limestone
	Molas	80 - 170	Shale
Mississippian	Leadville-	200 - 700	Carbonate
Devonian	Ouray		
	Elbert		Sandy carbonate
Cambrian(?)	Ignacio(?)	100 - 200	Sandstone

Permian and younger sedimentary rocks

The Permian and younger sedimentary section consists primarily of clastic rocks ranging from shale to sandstone. J. D. Strobell, Jr. picked a number of formation contacts for wells within and near the Carrizo area to contribute to the following general measurements. The complete thickness of the Permian Cutler formation, consisting mainly of red clastic beds, ranges from 1,100 to 1,900 feet in eight wells. Seven wells show 1,650 to 2,000 feet of sandy claystone and fine sandstone in the Triassic system. Three wells show 950 to 1,150 feet of Jurassic rocks ranging from mudstone to sandstone. The full Cretaceous section does not crop out within the area. Assuming saturation of pore space and compaction with burial, the average density of this section probably is between 2.4 and 2.55 gm/cm^3.

Igneous rocks

Sills and laccoliths

The Carrizo Mountains, rising to 9,412 feet above sea level and covering 100 square miles, dominate the area, much like an "island in the middle of a sedimentary sea" (Holmes, 1877, p. 274). Typical sills and laccoliths are exposed at the surface and implied by structure (fig. 3). Thicknesses of exposed sills and laccoliths are 500 feet or less (J. D. Strobell, Jr., oral communication, July 19, 1957).

The sills and laccoliths of the Carrizo Mountains are almost wholly diorite porphyry, generally consisting of one-third to one-half phenocrysts of hornblende and andesine in a groundmass of quartz and orthoclase (Emery, 1916, p. 355; Williams, 1936, p. 155). G. V. Keller of the U. S. Geological Survey measured the bulk densities and fractional water content at saturation for 25 samples of diorite porphyry from various sills and laccoliths of the Carrizo Mountains (written communication, August 1955). The average dry and saturated bulk densities of these samples are 2.60 and 2.63 gm/cm^3, respectively. The standard deviations for these measurements are ± 0.06 gm/cm^3.

The average grain density, as defined by Spicer (1942, p. 17), of this set of samples is 2.68 gm/cm^3 with a standard deviation of ±0.03 gm/cm^3. The average dry bulk density of 11 other diorite porphyry samples from the Carrizo Mountains is 2.60 gm/cm^3 (standard deviation ±0.05 gm/cm^3). From these data it is estimated that the average overall density of sills and laccoliths in the Carrizo area is about 2.63 gm/cm^3.

Plugs and dikes

A number of exposed volcanic rocks form a conspicuous part of the landscape south and east of the Carrizo Mountains (fig. 2). Ship Rock is the most prominent of the group (fig. 4). Ship Rock, rising 1,700 feet above the floor of the surrounding valley, typically consists of minette tuff breccia admixed with fragments of sedimentary and plutonic rocks (Williams, 1936, p. 136) filling a funnel-shaped vent originally drilled by explosion (Shoemaker, 1956, p. 180). The other smaller plugs exposed south and east of the Carrizo Mountains are composed of varying amounts of tuff, basalt, and macrobreccia. In one locality a neck of minette is surrounded by a vent agglomerate of sedimentary materials (fig. 2).

Igneous dikes are common throughout the area. A number of diorite porphyry dikes are found along the flanks of the Carrizo Mountains. Minette dikes radiate from igneous plugs or crop out with apparent independence. Most dikes, though as much as 1 to 2 miles long, are less than 20 feet thick (J. D. Strobell, Jr., oral communication, July 1957) and, consequently, have little effect on the regional gravity pattern.

The dry bulk densities of 35 samples of minette collected by E. M. Shoemaker from the Navajo Reservation were measured by G. V. Keller of the U. S. Geological Survey The average density of the group is 2.70 gm/cm^3 with a standard deviation of ±0.18 gm/cm^3. This high value undoubtedly does not represent the overall density of plugs, since the plugs ordinarily are not filled by solid igneous material but, as illustrated by Ship Rock (fig. 4), contain appreciable amounts of minette in the form of less dense tuff breccia.

Structure

Geologic structure influences the gravity anomaly pattern, in bringing rocks of contrasting densities into juxtaposition. The more prominent structural features of the area will be discussed briefly.

The broad domal uplift of the Carrizo Mountains (fig. 3) is the result of the physical injection of diorite porphyry in the form of a discordant stock (Emery, 1916, p. 361; Hunt, 1942, p. 199) and additional thickening by radial sills and laccoliths between the sedimentary strata (Holmes, 1877, p. 274). C. B. Hunt (1953, p. 140) found that the conical surface area of the uplifted strata of many laccolithic domes is equal approximately to the sum of the area of the circular base of the disturbed strata, the circular area of the stock, plus a corrective area allowing for maximum stretching of the strata without rupture. The brecciated area near the center of the Carrizo dome (fig. 2) conforms closely in size to the diameter of a stock--3,900 feet--expected from applying Hunt's empirical criterion.

Bitlabito dome, south of Bitlabito trading post, interrupts the regularity of the structure along the east flank of the Carrizo Mountains dome (fig. 2). The presence of the 400-foot structural high (Winchester, 1933, p. 81) may be attributed to an underlying igneous intrusion. However, the Continental well near the structural center penetrated about 4,840 feet of normal sedimentary rocks (Strobell, 1956). Supplementary gravity stations were established in this vicinity to investigate the possibility of an underlying igneous intrusion extending only to the top of the Precambrian basement or offset from the mapped surface structure.

In general the surface structure is only very slightly disturbed by the protrusion of minette plugs through sedimentary strata in the Carrizo area. Black Rock (also known as Walker Peak), however, coincides with a structural closed high, the vicinity of Mitten Rock exhibits irregular dips (Beaumont, 1954), and Ship Rock falls in a broad low. To investigate the relation, if any, between the disposition of diatremes and geologic structure, additional gravity stations were established in the vicinities of Black Rock and Ship Rock.

The Boundary Butte anticline (fig. 1) plunges southeast into the Carrizo Mountains area near Red Mesa trading post (fig. 2). The apex of the 400-foot closed structural high is located in Utah about 5 miles northwest of Red Mesa (Spragg, 1952, p. 104). The trend of a major magnetic anomaly closely parallels the structure (Whelan, 1952, p. 126; Strobell, 1956).

The Defiance uplift (fig. 1) is a major tectonic element of the Colorado Plateau. The Carrizo Mountains area probably includes the northernmost extension of this feature. The east boundary of the uplift, the Defiance monocline, evidently strikes north near Mitten Rock (fig. 2).

Field survey

Station location

U. S. Geological Survey 7-1/2 minute (1:24,000) and 15 minute (1:62,500) topographic quadrangle maps were used for the field location of gravity stations. These maps, contoured at 20-foot or 40-foot intervals, provide an excellent means of horizontal location. Numerous Indian-built roads, mine access roads, and roads constructed for petroleum geophysical prospecting made possible a close approximation of a proposed one and one-half mile station interval.

Equipment

The use of a Worden gravity meter with a constant of about 0.50 milligal per dial unit proved well suited for the field measurement of gravity. The instrument was carried in a station wagon equipped with four-wheel drive. Two Wallace and Tiernan altimeters provided auxiliary elevation control.

Elevation control

Numerous benchmarks and unlisted elevations along third order level lines surveyed in 1933, 1934, and 1950 by the U. S. Geological Survey were used for control of altimetry. A total of 65 stations were established at these points. Numerous prominent features have been assigned "spot elevations" determined by aerial photographic interpretation or ground survey. The elevations of most of the 63 stations established at these points showed consistent agreement to within five feet when correlated with altimetry.

Inasmuch as a complete plane table or level survey was not practical, the remaining 433 stations required elevation control using procedures of altimetry. Continuous readings at a single base altimeter station were used for control in establishing 54 gravity stations. A procedure of frequent repeat readings and occupation of known or previously established elevations plus emphasis on field work before 11 A.M., when the barometric gradient usually began to increase rapidly, sufficed to establish elevations for the rest of the stations. The elevations of most of the stations are accurate to within about 10 feet. The station elevations range from 4,662 near the San Juan River to 9,412 feet above sea level at a benchmark on top of Pastora Peak in the Carrizo Mountains.

Gravity measurement

A procedure of three-step loop repetition (Nettleton, 1940, p. 38) was used to establish 28 gravity base stations distributed along main roads throughout the area (table 2). The error of closure of a 135-mile closed loop including 22 bases within the area is 0.1 milligal. The 350-mile loop, including Blanding, Utah, Mexican Hat, Utah, and Cortez, Colorado, joining the Carrizo area to the absolute datum of the pendulum gravity station at Egnar, Colorado, yielded a closure error of 0.2 milligal.

Five checks against a 73-milligal loop for instrument calibration near the Colorado National Monument, Mesa County, Colorado, varied on the average less than 0.07 milligal from the established gravity difference. Combined diurnal instrument drift and tidal effect, for which all observations were corrected, ranged from 0.15 to 0.80 milligal with an average of 0.44 milligal. The maximum expected error in observed gravity for a station within the Carrizo area is about 0.3 milligal.

Table 2.--Principal facts for gravity base stations of the Carrizo Mountains area, Arizona and New Mexico

Station	USGS 15' quad.	Latitude	Longitude	Elev. (feet)	Terr. corr.	Observed gravity	Description
CB-10	Chimney Rock	37° 00.0'	108° 44.9'	5122	0.2	979.4215	4 ft. higher than BM on east headwall of cattle crossing.
CB-11	Chimney Rock	36° 51.6'	108° 42.2'	5003	0.1	979.4159	Level of east abutment of bridge.
CB-12	Chimney Rock	36° 46.8'	108° 41.7'	4921	0.1	979.4057	First intersection south of river bridge; old road to west.
CB-13	Rattlesnake	36° 46.0'	108° 48.6'	5325	0.1	979.3784	Intersection.
CB-14	Rattlesnake	36° 49.1'	108° 54.8'	5063	0.5	979.4023	100 ft. north of BM remnant "5058"; over culvert.
CB-15	Pastora Peak	36° 50.4'	109° 00.9'	5567	0.8	979.3677	Over site of BM; intersection.
CB-16	Pastora Peak	36° 51.8'	109° 02.5'	5642	1.3	979.3682	Over BM 1-12.
CB-17	Pastora Peak	36° 55.4'	109° 06.4'	5133	0.8	979.4129	Over BM 1D.
CB-18	Pastora Peak	36° 55.7'	109° 12.4'	5423	0.7	979.3996	At intersection.
CB-19	Toh-Atin Mesa	36° 57.3'	109° 17.3'	5305	0.2	979.4188	At BM 7D, intersection.
CB-20	Toh-Atin Mesa	36° 57.9'	109° 23.5'	5392	0.1	979.4121	Over BM 82D.
CB-21	Toh-Atin Mesa	36° 59.3'	109° 29.5'	5236	0.0	979.4253	At BM 85D.
CB-23	Toh-Atin Mesa	36° 54.5'	109° 20.6'	5817	0.4	979.3716	At BM 9D.
CB-24	Toh-Atin Mesa	36° 50.7'	109° 24.4'	5501	0.1	979.3782	Over BM 12D.
CB-25	Toh-Atin Mesa	36° 49.4'	109° 29.6'	5287	0.1	979.3960	East of BM 15D.
CB-27	Toh-Atin Mesa	36° 54.2'	109° 15.7'	5593	0.7	979.3833	Between stream crossing and road; 1 ft. above stream.
CB-28	Toh-Atin Mesa	36° 51.0'	109° 19.5'	5825	0.4	979.3574	Road intersection; 1.5 ft. higher than road.
CB-29	Los Gigantes Buttes	36° 44.8'	109° 28.9'	5902	0.2	979.3523	Over BM 76D.
CB-30	Los Gigantes Buttes	36° 43.8'	109° 25.2'	6210	0.6	979.3284	Over BM remnant 73D.
CB-31	Kirtland (30')	36° 39.3'	108° 42.5'	5283	0.0	979.3655	Intersection of U.S. 666 and main road west to Cove School.
CB-32	Ship Rock	36° 38.5'	108° 46.8'	5466	0.1	979.3497	Over BM MM2.
CB-33	Ship Rock	36° 37.1'	108° 53.3'	5527	0.2	979.3407	Over iron stake, north of highway intersection; 7 ft. east of phone pole.
CB-34	Ship Rock	36° 35.6'	108° 58.2'	5912	0.4	979.3234	East of intersection; 25 ft. south of road; over 1 ft. sandstone block.
CB-35	Redrock Valley	36° 36.4'	109° 03.8'	5725	0.4	979.3604	185 ft. east of stream culvert; near sign 30 ft. south of road.
CB-36	Redrock Valley	36° 35.1'	109° 07.5'	6057	0.6	979.3471	27 ft. south of road; over culvert.
CB-37	Los Gigantes Buttes	36° 39.5'	109° 15.7'	6793	1.6	979.2964	At BM 67D.
CB-38	Redrock Valley	36° 37.9'	109° 10.7'	5989	0.4	979.3504	Over BM 63D.
CB-39	Los Gigantes Buttes	36° 39.5'	109° 18.4'	6260	0.9	979.3266	Over BM 68D.
CB-40	Los Gigantes Buttes	36° 39.3'	109° 22.5'	6251	0.5	979.3190	Over BM 71D.
CB-41	Redrock Valley	36° 33.6'	109° 13.0'	6446	1.4	979.3187	5 ft. north of fence corner, at intersection.
CB-42	Redrock Valley	36° 32.5'	109° 03.7'	6219	0.8	979.3141	Over BM 57D.
CB-43	Redrock Valley	36° 40.4'	109° 03.5'	5577	0.5	979.3771	Midway along road curve; wide spot.

Reduction of data

Standard methods of computation were used to reduce the station data to the final Bouguer gravity anomaly (fig. 5). U. S. Coast and Geodetic Survey charts based on the International Formula provided the value of mean sea level theoretical gravity at mean sea level for the latitude of each station.

In agreement with the U. S. Geological Survey regional gravity studies of the central Colorado Plateau, a value of 2.5 gm/cm^3 (Joesting and Byerly, 1954, p. 50) has been assumed for the average rock density to sea level for use in the elevation correction. A brief study of densities of nearby well and surface samples, as discussed previously, gave reasonable agreement with this value.

An error of as much as 0.1 gm/cm^3 in density corresponds to a change of 6.1 milligals of the Bouguer gravity anomaly difference between the highest and lowest gravity stations of the gravity survey. The assumption of 2.5 gm/cm^3 for the density of near-surface rocks was partly substantiated, inasmuch as a close study pointed out no systematic deflection of the gravity contours among adjacent gravity stations with large elevation differences.

Terrain corrections carried out to about 45 miles (Hammer, 1939, p. 190-191 and extrapolation) were applied to all stations. A value of 2.5 gm/cm^3 was assumed for the density of near-surface rocks. Since the average terrain correction is about 1.3 milligals per station, an actual near surface rock density as low as 2.2 gm/cm^3 would introduce an error of only 0.2 milligal in this correction. The terrain correction for the station on the top of Pastora Peak is 13.1 milligals. In this case the surrounding terrain, sedimentary rocks and diorite porphyry, probably has an average density of no less than 2.4 gm/cm^3, equivalent to an error of 0.5 milligal. This error will not appreciably change the gravity pattern, inasmuch as the Bouguer anomaly at nearby stations also would be reduced proportionately.

The error due to mislocation of the station is undoubtedly less than 0.2 milligal, since certainty of location was a prerequisite in the field. The value of observed gravity is accurate to about 0.3 milligal. The largest error, ranging from 0.2 to 1.0 milligal, corresponds to the expected error in elevation. Assuming 5 percent accuracy for terrain correction yields a maximum error of 0.6 milligal. Hence, the overall expected error of the Bouguer anomaly is probably less than 1.0 milligal.

Interpretation

The large gravity anomalies (fig. 5) dominating the area are principally the expression of rock units of different densities within the underlying Precambrian basement. Gravity anomalies on the order of a few miles in diameter apparently overlie rocks of uniform overall densities within the basement. The large gravity lows near Ship Rock, Bitlabito, and east of Sweetwater as well as the highs near Red Mesa and south of Black Rock most likely outline deep underlying domains of rock whose average density contrasts with that of the surrounding basement rocks. Gravity contours west of Segi Ho Cho Mesa, though not forming a closed pattern as in the preceding examples, in their lack of definite gradient probably indicate associated basement rocks of relatively uniform density.

A 3-milligal closed gravity high (fig. 5) roughly coincides with the Carrizo Mountains dome. An appreciable part of this closure may be due to the excess mass of the diorite porphyry intruded into the dome formed by the less dense sedimentary rocks. If the upwarped section consists of diorite porphyry rather than sedimentary rock (assuming a density contrast of +0.15 mg/cm^3), this would account for an anomaly of only 5 milligals. However, sills and laccoliths make up only a subordinate part of the mountain mass, so that an anomaly of 2 milligals or less probably is due to igneous material in the upwarped sedimentary section, while the remainder of the anomaly is due to relatively dense rock within the underlying Precambrian basement.

The 3-milligal gravity closure over the Carrizo Mountains lies within a larger north-plunging gravity nose. In profile view (fig. 3) the nose has a relief of about 20 milligals relative to the nearby regional lows to the east and west. This probably represents an extensive mass of rock on the order of a few miles deep that contrasts positively in density with the basement rock to the east and west. There is insufficient evidence to show whether the deep mass causing the anomaly is genetically related to the origin of the intrusion, to an extension of a dense basement mass related to the Defiance uplift, or simply to the normal basement between two prominent low density domains.

The gravity anomaly pattern apparently bears no relation to structure near Bitlabito dome. There is no hint of a connection between this dome and the Carrizo Mountains on the basis of the Bouguer gravity anomaly map. The magnetic anomaly map of a ground magnetic survey (H. R. Joesting personal communication) over the same stations within the dome likewise shows no relation to structure. If the structure is related to igneous intrusion, either offset from the domal center or near the Precambrian surface, the intrusive body is too small, too deep, or has too small a density contrast with the surrounding rocks to be detected as a gravity anomaly.

Additional gravity stations were also established near Ship Rock and Black Rock. The Bouguer gravity anomaly map fails to indicate a comparable gravity low or a high in the vicinity of Ship Rock or Black Rock. Similarly, Mitten Rock and other smaller minette plugs and dikes show no correlation to the Bouguer gravity anomaly pattern. The close spacing of stations minimizes the possibility of missing gravity anomalies corresponding to features of small areal extent. Undoubtedly the tuffaceous and brecciated character of the igneous material (fig. 4) results in a reduction of the overall density of the plugs below the 2.7 gm/cm^3 for solid minette. Inasmuch as the gravity anomaly contours are not noticeably deflected in the vicinity of the plugs, the overall density of the plugs is probably close to that of the enclosing sedimentary rock.

The Bouguer gravity anomaly contours near Boundary Butte anticline roughly parallel the mapped geologic structure. The magnetic anomaly shows a similar trend (Whelan, 1952, p. 126). Undoubtedly an extensive body of relatively dense rock underlies the Boundary Butte anticline. Logs of nearby wells indicate that this dense rock probably does not occur in the sedimentary section. The maximum depth to the center of this relatively dense mass, according to measurements of the half-width of the anomaly (Nettleton, 1940, p. 123, 224), is about 5 miles.

A gravity gradient of about 6 milligals per mile east of Red Rock (fig. 5) parallels the east boundary of the Defiance uplift. The steeply-dipping or faulted edge outlining the east edge of the rather high density mass underlying the Defiance uplift is located within the basement approximately between the 120 and 125 milligal contours near Red Rock, i.e., offset to the west of the monoclinal structure at the surface. Less than 5 milligals of the gravity gradient can be attributed to the estimated 2,500 to 3,000 feet of relief on the top of the Precambrian basement. The principal part of the anomaly, then, is due to the contrast along a rather sharp contact of a large-scale dense basement mass beneath the Defiance uplift and the less dense basement to the east. The west boundary of the uplift probably blends less markedly into the normal section, which lies west of a line along the three gravity lows west of the Los Gigantes Buttes, southeast of Walker Butte, and west of the Carrizo Mountains.

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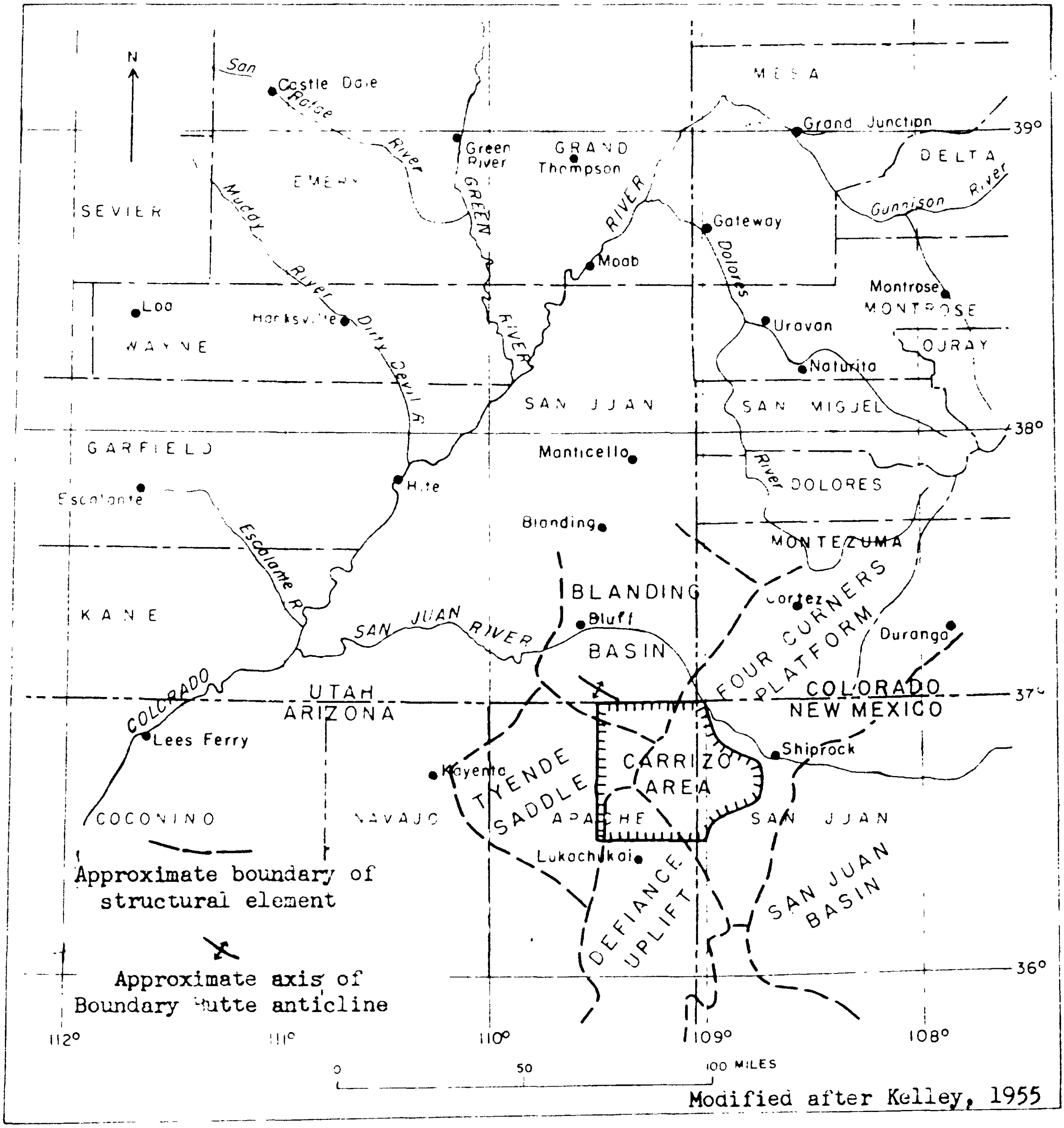

Figure 1.—Index map showing location and structural setting of the Carrizo area, Arizona and New Mexico.

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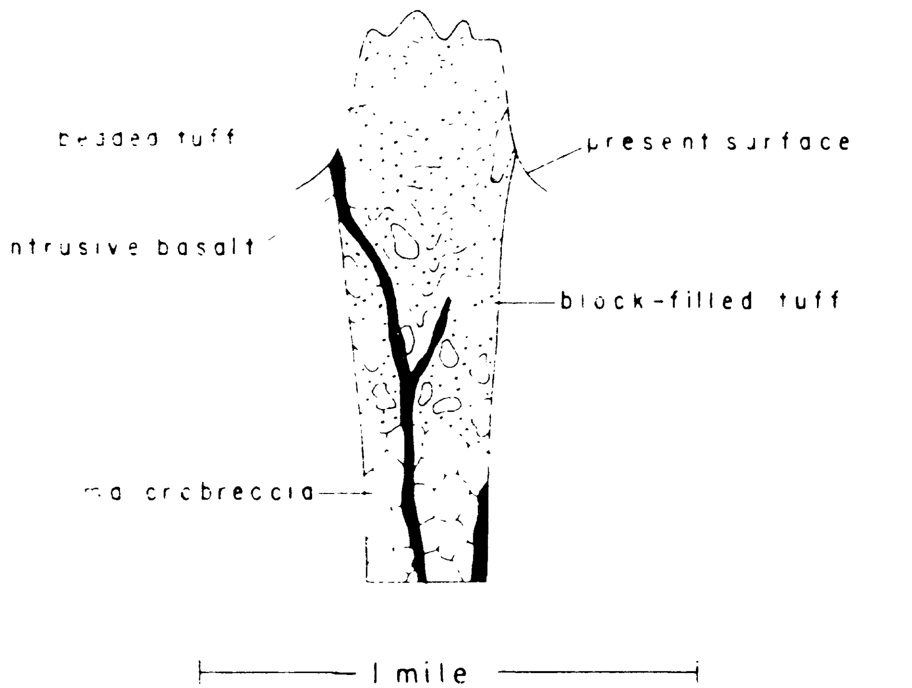

Figure 4.—Diagrammatic section of Ship Rock diatreme and hypothetical extension to depth.

FIGURE 2.— GENERALIZED GEOLOGIC MAP OF THE CARRIZO AREA, ARIZONA AND NEW MEXICO

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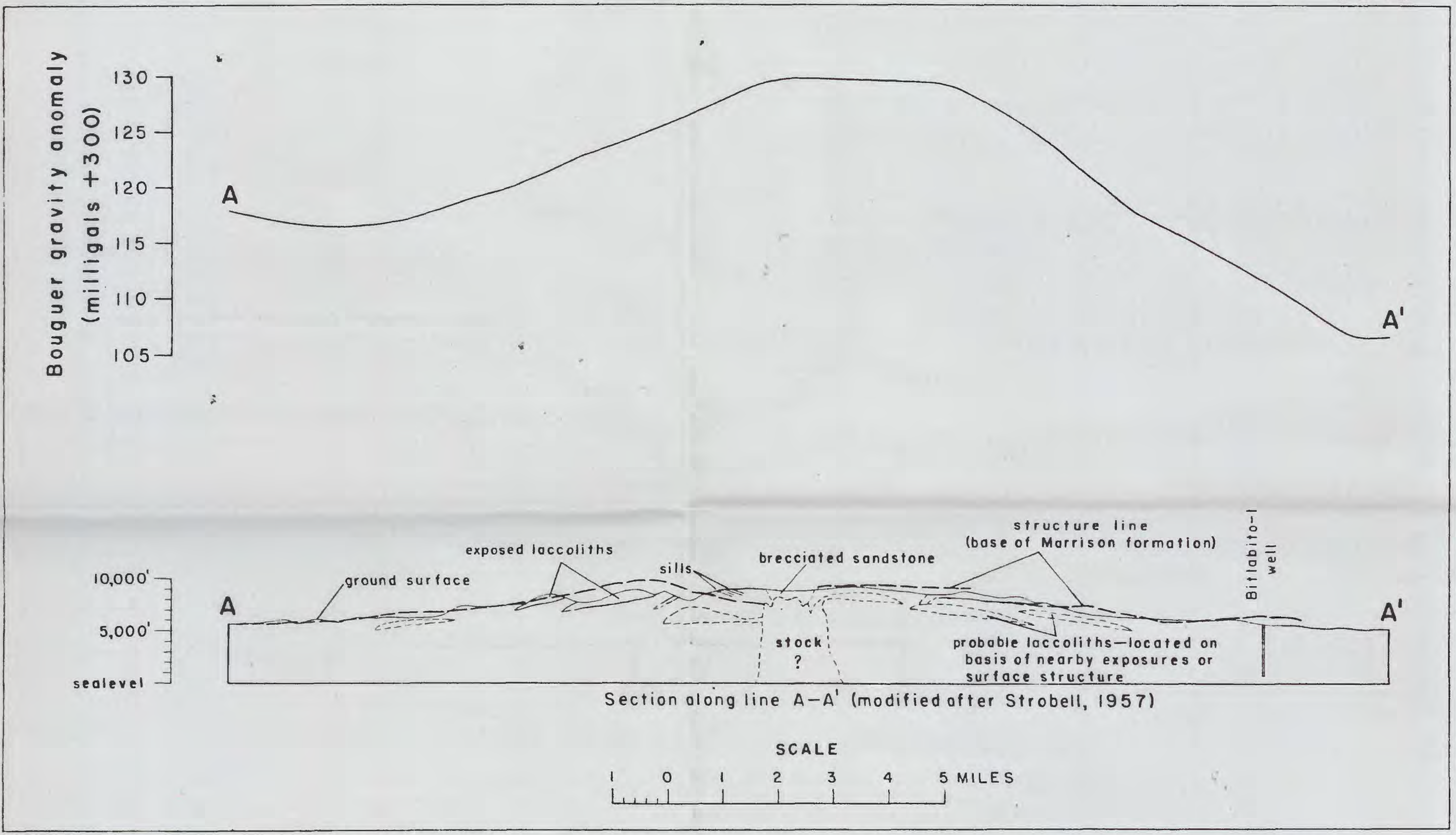

Figure 3.— Gravity and geologic profiles along line A—A' showing known and inferred intrusives and hypothetical relations at depth.

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FIGURE 5.— BOUGUER GRAVITY ANOMALY MAP OF THE CARRIZO AREA, ARIZONA AND NEW MEXICO