STRUCTURAL GEOLOGY OF LITTLE SAN PASQUAL MOUNTAIN AND THE ADJACENT RIO GRANDE TROUGH

Submitted in partial fulfillment of the
requirements for the Degree of Master of
Science in Geology

By

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ABSTRACT

Surface mapping of Little San Pasqual Mountain in the central Rio Grande Valley shows that the mountain is a northeast trending anticline, composed predominantly of Pennsylvanian rocks, which has been deeply eroded on the western limb. To the north and south of the mountain the anticline is faulted and buried beneath Tertiary rocks.

The anomaly obtained during a gravity survey was matched by an anomaly derived by graphical methods from a structure model consistent with the known geology of the area. This interpretation indicates that Little San Pasqual Mountain is bounded on the west by two large normal faults and that the Rio Grande trough in this area is filled with approximately 7500 feet of Tertiary Santa Fe formation.

The geological control for the structure model is sufficient to consider the model essentially correct. Further changes in the geologic interpretation of this area may change the magnitude but not the basic structure.

INTRODUCTION

Scope of Work

The work described in this report was undertaken to determine the structural pattern of Little San Pasqual Mountain and its relationship to adjacent structural features (primarily the Rio Grande trough).

The methods used in this investigation were both geological and geophysical. Surface mapping determined the exposed structural relations of the area, and provided partial subsurface control for a subsequent gravity survey. The methods and results of both the geological and geophysical work are the subject of this paper.

Location, Accessibility, Economics

Little San Pasqual Mountain is in the Rio Grande Valley, approximately 13 airline miles south of San Antonio, New Mexico, and 1 mile east of the Rio Grande River (see Figure 1). The mountain lies within the Bosque del Apache National Wildlife Refuge and constitutes the extreme north central portion of the Val Verde 15 minute quadrangle. Figure 1 shows the area mapped for this work.

The area is accessible by two improved dirt roads which terminate at the now abandoned town of Val Verde. One road follows the Rio Grande River southward from highway 380, and passes about one mile to the west of the mountain. The second road, about 8 miles east of San Antonio on

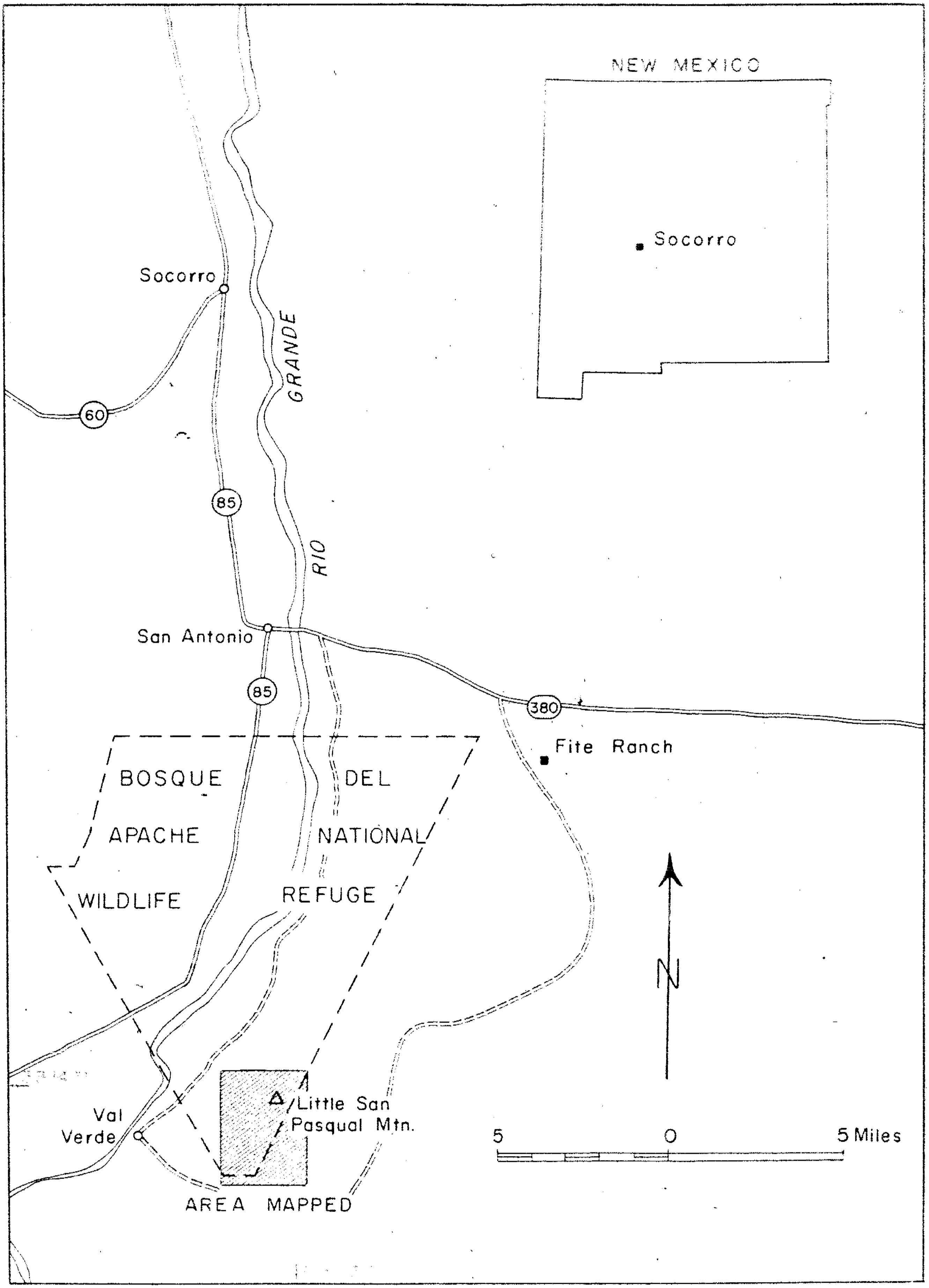


FIGURE 1. Location map of the area described in this report.

highway 380, winds through the Jornada del Muerto from Fite ranch headquarters and eventually passes two miles to the east of the mapped area. A service road for an airline beacon on top of the mountain furnishes access to the eastern edge of the mountain from this secondary road. Of the two roads, the one passing through Fite's ranch furnishes the best access. (See Figure 1.)

The area appears to have little economic value. Livestock grazing is by permit only and the numbers are limited. The mapped area is part of a federal migratory water fowl preserve and access, as well as development of any kind, is restricted. Numerous old prospect pits and shafts dot the area. Of all the prospects observed only one contained any mineralization--a small barite vein. One hundred feet away a second pit had been opened on the same trend without showing any mineralization. A sample of the barite was analyzed on the emission spectrograph which indicated a high strontium content with a trace of silver and a few other common elements.

Previous Work

The geologic map of the state of New Mexico published in 1928 by N. H. Darton shows Little San Pasqual Mountain to consist of Permian rocks. This is in error and has since been corrected by Kottlowski (1960).

Darton (1922, 1928) illustrates several cross sections through the Jornada del Muerto, extending from the Oscura and San Andres Mountains in the east to the Rio Grande river in the west. One of these cross sections is through Little San Pasqual Mountain and the section depicts the mountain as a simple anticline, however the texts of his reports contain no reference to the area.

Kottlowski (1960) describes the mountain as an east-southeastward tilted horst composed of Pennsylvanian rocks, however only a general description of the beds is given.

Dane and Bachman (1961) show the mountain to consist of Pennsylvanian rocks bounded on the west by a large fault. Their map is a compilation of many authors' work and it is believed that the geology of this area is that of Kottlowski.

Acknowledgments

I would like to acknowledge the help and advice of Dr. Clay T. Smith in the completion of this work and for originally suggesting the problem. I would also like to express my appreciation to Dr. Allan R. Sanford for his help and suggestions concerning the geophysical investigations.

I am especially indebted to Joseph Keeney and Viet Howard for their many hours spent in helping to complete the gravity measurements.

I would also like to acknowledge a grant received from the Roswell Geological Society which helped defray part of the expenses incurred in completing this thesis.

STRATIGRAPHY

General Statement

The sedimentary rocks exposed in the area mapped range in age from Pennsylvanian to Tertiary with most of the section assigned to the Paleozoic. Little San Pasqual Mountain is composed entirely of Pennsylvanian sediments with fringes on the west, east, southeast, and south of Permian rocks. On the north and northwest the Pennsylvanian rocks are in contact with the Tertiary Santa Fe formation (see Plate 1 in pocket). Included within the Santa Fe group is an andesitic lava which forms a purple soil cover and occurs as spotty outcrops. This lava unit was mapped separately from the Santa Fe as an aid to structural interpretation. To the northwest two dark reddish brown mesas occur which are composed of the Tertiary Baca formation. One small block of sandstone contained in the Santa Fe was tentatively identified as being derived from the Dakota sandstone. For detailed measurements and descriptions of the individual rock units in the mapped area see the appendix. Plate 2 is a geologic column of the rocks described in this report.

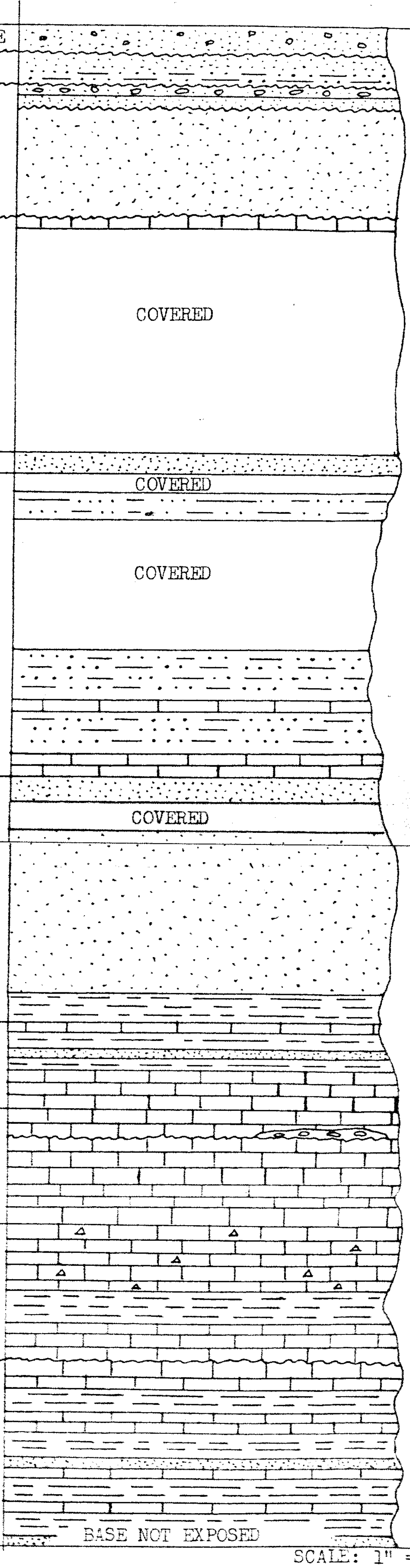
Pennsylvanian System

The Pennsylvanian system in New Mexico consists largely of marine limestones and is quite varied and widespread. The fact that the sequence is predominantly limey somewhat complicates mapping since it is difficult to identify a given bed within a group of

PLATE 2

SYSTEM	SERIES	FORMATION	THICKNESS (FEET)
QUATERNARY		ALLUVIUM	VARIABLE
TERTIARY		SANTA FE	100
		BACA	418.7
PERMIAN	LEONARD	SAN ANDRES	743.0
		GLORIETA	31.4
		YESO	935.7
	WOLFCAMP	ABO	753.1
PENNSYLVANIAN	UNIT 4 (VIRGIL?)		267.8
	UNIT 3 (MISSOURI?)	COUNCIL SPRINGS? ADOBE? COANE?	350.0 Coane
	UNIT 2 (DES MOINES?)		Cherty 413.9
	UNIT 1 (DERRY?)		571.7

GRAPHIC SECTION



SCALE: 1" = 400'

PLATE 2

limestones. For this work the nomenclature of Thompson (1942) was originally adopted; however it met with little success. The Pennsylvanian limestones in the mapped area in general cannot be correlated with Thompson's sections in the Oscura Mountains on a lithological basis. However, three of Thompson's units, the Coane limestone, the Adobe formation, and the Council Springs limestone, have been recognized. Most of Thompson's units are based on paleontological data and the requisite collections for evaluation were not made in the Little San Pasqual area.

Thompson (1942) defines four series for the Pennsylvanian system in New Mexico on a paleontological basis. These four series are from oldest to youngest; Derryan, Des Moinesian, Missourian, and Virgilian. On Little San Pasqual Mountain the Pennsylvanian was divided into four mappable units which herein are designated units 1, 2, 3, and 4. On a general lithological basis it is believed that these units correspond quite closely to the series units of Thompson.

The basal Derryan is the most clastic of the four series described by Thompson. Unit 1 of this report is also highly clastic, composed largely of sandstones, and shales. The top of unit 1 is placed at an angular unconformity of about 10° magnitude. (See Figure 2.) This unconformity is believed to be the Derryan-Des Moinesian contact of Thompson. In Whiskey Canyon, northern Mud Springs Mountains, where Thompson described Derryan and Des Moinesian rocks, an unconformity is indicated by a faunal break. The clastic nature of unit 1 and the

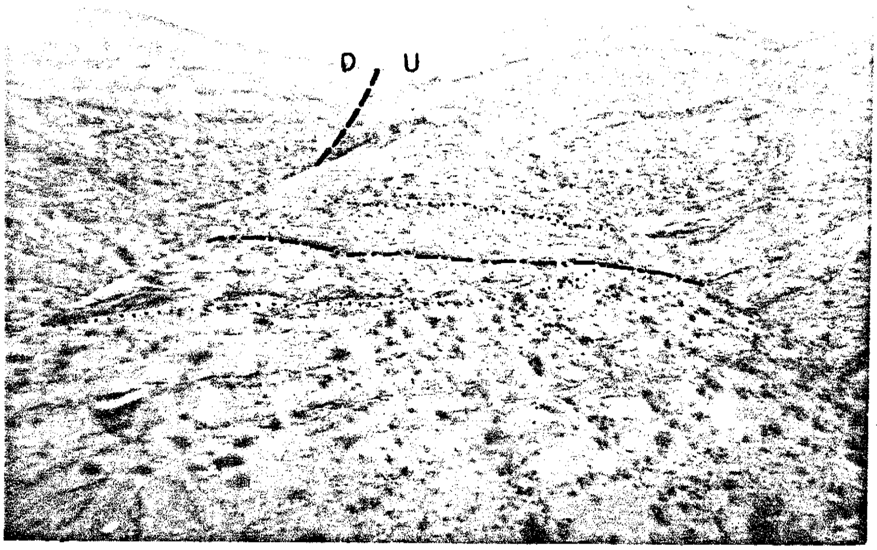


FIGURE 2. Looking east. The dashed and dotted line indicates the unconformity which separates unit 1 from unit 2 and is thought to be the Derryan-Des Moinesian boundary. A small normal fault higher in the section is shown with a displacement of approximately 20 feet. Dotted lines indicate bedding planes on either side of the unconformity.

pronounced unconformity at its top suggests that unit 1 is probably the Derryan equivalent. Measured thickness of unit 1 is 571.7 feet; however the base is not exposed.

Unit 2 corresponds closely to the Des Moinesian. It consists predominantly of very cherty limestones which are characteristic of the Des Moinesian in New Mexico. The chert is dark brown or black and generally occurs as bands or layers of chert lenses or as continuous thin beds. The lenses vary in size with the largest being approximately six inches long and one inch in thickness. The colors of the rocks of unit 2 vary, becoming darker as the top of the section is approached; they are almost black at the very top of the unit. Fossils are not common, however crinoid stems, corals, and a few fusulinids can be found scattered throughout the sequence. The base of unit 2 is the angular unconformity discussed above, the top is at the base of what has been tentatively identified as the Coane limestone. This contact is everywhere covered. Total thickness of unit 2 is 413.9 feet.

Unit 3 consists almost entirely of limestones. The base of unit 3 is the base of the limestone tentatively identified as the Coane limestone.

The limestones of unit 3 are generally more massive than those of the underlying unit 2. The basal member of unit 3, the Coane limestone, was tentatively identified by its massive cliff forming nature and its sequential relationship to an overlying massive but somewhat thinner cliff forming limestone tentatively identified as the Council Springs limestone. The Coane limestone contains very little chert and forms two almost vertical cliffs, the upper cliff being only one half as thick as the lower cliff (see Figure 5). The top of the Council Springs limestone is extremely silicified, locally becoming agate-like with pale blue, milky white, and black layered bands up to 1/4 inch in thickness. These beds (except for silicification) resemble those described by both Thompson (1942) and Kottlowski (1960). The identification of the Adobe formation follows since this unit separates the Council Springs limestone from the Coane limestone. From the top of the Council Springs limestone upward to the top of unit 3 the beds are only partially exposed. Where exposed, they usually consist of thin to thick bedded limestones with beds up to 6 feet in thickness. Approximately 50 feet from the top of unit 3 in NW 1/4 SE 1/4, Section 8, T.7S., R.1E., a lenticular, quartz and limestone pebble conglomerate occurs. Maximum thickness measured is 18 feet, however both the base and top are covered. Southward from the exposure the conglomerate thins rapidly and disappears beneath a soil cover. To the north the bed thins to 2 feet within a distance of 30 feet from the thickest part of the outcrop, then continues northward for 200 feet before it disappears under cover. This conglomerate is absent in all other areas where unit 3 is exposed. It is believed that this bed could possibly represent deposition upon a karst surface and that a period of emergence from the sea occurred during unit 3 time.

The entire unit is light gray to light brown in color with the upper half locally weathering bright orange to reddish brown. Fossils are more abundant in unit 3 than in unit 2, consisting for the most part of brachiopods and crinoid stems. Fusulinids are found only in the extreme upper portion of the Coane limestone.

The upper boundary of unit 3 was placed at the base of greenish gray, alternating thin bedded limestones and shales which provided an excellent marker bed. The equivalency of the unit 3-unit 4 boundary to the Missourian-Virgilian boundary of Thompson is not known. Thompson's section in the Oscura Mountains contains no such unit as described above so that no estimate can be made as to the actual boundary relationships. Total thickness of unit 3 is 350.0 feet.

Unit 4 consists of limestones in the lower part and grades upward into red clastics. The base of unit 4 consists of 35 feet of alternating greenish gray calcareous shales and greenish gray limestones with no individual bed being greater than 2 inches in thickness. Overlying this sequence are dark gray thin to thick bedded limestones which grade upward into a series of alternating gray limestones and red to purple shales. The thickness of the beds in unit 4 becomes greater upward from the base until the interbedded red clastics are reached, with the maximum thickness being 20 feet. The interbedded limes and red clastics of the upper portion of unit 4 vary in thickness, with one red shale bed being 51 feet thick. Fossils, where present, consist almost entirely of crinoid stems. Scattered fusulinids are found in the middle of the sequence with one massive limestone containing abundant fusulinids in the basal 2 feet.

The unit 4-Permian contact was arbitrarily placed at the top of the uppermost limestone just below a continuous series of red shales and fine grained sandstones. It appears that unit 4 actually is gradational into the Permian Abo formation and that no unconformity exists between the two units. Total thickness of unit 4 is 267.8 feet.

Permian System

The Permian system is best exposed in the southern portion of the mapped area. The Permian rocks delineated during the mapping are: Abo formation, Yeso formation, Glorieta sandstone, and San Andres limestone. The transitional Bursum formation, if present, was included with the Abo formation for mapping purposes.

Abo formation

The Abo formation consists of bright red to maroon and dark reddish brown fine grained sandstones and shales. A considerable thickness of the Abo is covered with sand dunes and could not be described in detail. In the Little San Pasqual area the Abo formation is 753.1 feet thick. The top of the Abo was placed at the base of a thick limestone with overlying red mudstones which are here considered correlatives of the Yeso formation.

Yeso formation

The Yeso formation is poorly exposed in the southern part of the mapped area. The Yeso consists primarily of red, yellow and brown mudstones and shales with a smaller amount of light gray limestone and an occasional red or brown sandstone. The Yeso for the most part is covered with soil. The limestones generally form good outcrops while the remaining beds are only occasionally exposed in the numerous gullies that cross the area. No gypsum was found to occur in the Yeso formation in this area.

The Yeso formation has apparently acted as an incompetent unit during folding and is quite brecciated. Local dip reversals are common and on the western margin of the Yeso outcrop area, where the Yeso is best exposed, numerous slump faults occur. Because of these complications the measured thickness of the Yeso formation is doubtful. The thickness of the Yeso is approximately 900 feet.

Glorieta sandstone

The Glorieta sandstone caps three low hills in the extreme southern part of the mapped area. Lithologically the Glorieta is somewhat variable. On the westernmost of these three hills the Glorieta is an extremely hard and dense dark brown quartzite. The Glorieta that caps the remaining two hills is a well indurated, fine grained, well rounded, light brown quartz sandstone, quite different in appearance from the Glorieta just described on the western hill. The thickness of this unit is 31.4 feet.

San Andres limestone

The San Andres limestone occurs as two low, parallel ridges southeast of Little San Pasqual Mountain. These two ridges trend northeast, are approximately 3 miles long, and have a total relief of about 40 feet. Outcrops are very poor except at the southernmost boundary of the unit where for a distance of about 200 feet a thin section of the San Andres is well exposed. The San Andres was identified as such by its stratigraphic relationship to the other rocks occurring in the area.

The San Andres where exposed is a thick bedded, granular, gray, very sparsely fossiliferous limestone, which weathers to a corroded surface. The thickness of this unit was calculated from map data as 743.0 feet.

Tertiary System

Baca formation

A large exposure of rocks in the area has been identified as the Baca formation. This identification is made by Dane and Bachman (1961) and is used in this report.

The Baca formation occurs in the northwestern portion of the area as two steep sided mesas. It consists of red and reddish brown sandstones with a conglomerate unit at the top. The sandstone is quite friable and in general is quite well sorted. A sieve analysis of a sandstone specimen near the top of the formation gave the following results:

Mesh Size (inches)	%
1/64	69
1/100	22
1/200	8

An angular unconformity occurs near the top of the Baca section which probably reflects intermittant faulting that is believed to have occurred in this area.

The Baca formation is, at least in part, considered to be Eocene in age (New Mexico Geological Society Third Field Conference Guidebook, 1952). The measured Baca thickness is 418.7 feet, however both the base and top are covered.

Santa Fe formation

The Santa Fe formation is exposed in the northern portion of the area and along the northwest facing front of Little San Pasqual Mountain. The Santa Fe beds dip very gently westward and are lithologically variable. The rocks consist of thin cross bedded, water laid sandstones and muds containing large limestone fragments. The beds are not well indurated and are generally covered by sand dunes. The exposed Santa Fe measures only 100 feet in thickness, but the base is not exposed and is known to be deeply buried so a total thickness of several thousand feet is probable.

A small block of medium to fine grained quartz sandstone occurs within the Santa Fe formation and has been tentatively identified as Dakota sandstone. This block is approximately 100 feet long and 9 feet in thickness. The sandstone, which is quite pure, extremely cross bedded, and badly brecciated, is probably a large slump block. It crops out along the western margin of the Pennsylvanian system outcrops.

Quaternary System

The remainder of the mapped area is covered by recent alluvium and sand dunes.

STRUCTURE

Folding

Structurally, Little San Pasqual Mountain is a gently arcuate anticline, concave westward and trending north-northeast (see Figures 3 and 4). The western limb of the anticline has been more deeply eroded than the eastern limb which leaves a steep scarp facing to the west. In the southern part of the area the anticline plunges 65° to the south. Map data indicates that at the north end of the area the anticlinal limbs start to converge and plunge to the north; however a northwest striking fault cuts off the Paleozoic rocks and forms the northern boundary of the exposed anticline.

On the eastern flank of the anticline is a monoclinal flexure. Rocks of unit 4 change abruptly in dip from approximately 35° to 75° within a distance of 200 feet. The flexure apparently flattens out rapidly beneath the alluvium of the Jornada del Muerto since gravity data does not indicate an easterly extension. If the rather flat lying San Andres limestone in the southeastern portion of the area is projected northeastward with the same attitude, it can be seen that the flexure must flatten out in a short distance to accommodate the rest of the stratigraphic section.

FIGURE 3. Looking northwest. The anticlinal nature of Little San Pasqual Mountain is clearly shown. In the middle background eroded beds of the western limb can be seen. The two dark mesas in the left background are composed of the Baca formation.

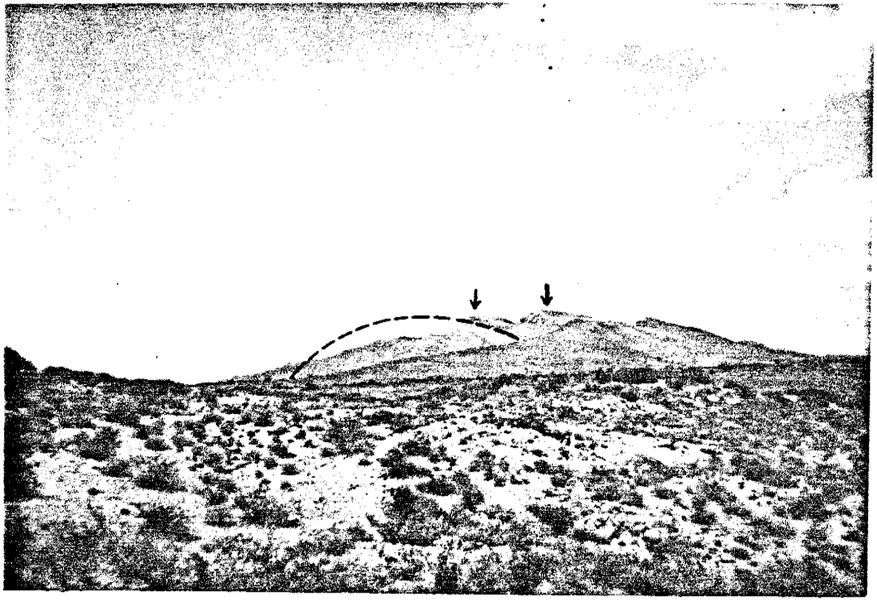


FIGURE 4. Looking north. The beds on the western limb of the anticline have been deeply eroded forming a west facing, steep scarp. The two peaks to the west indicated by arrows consist of basal beds of unit 3. Photo was taken while standing on beds of unit 4.

A small anticline occurs in the Abo formation in the southeastern portion of the area just below the Abo-Yeso contact. It disappears under sand dunes to the north and dies out rapidly to the south. The anticline is no more than 100 feet in width and is a very local structural feature.

Faulting

Numerous faults cross the anticline, most of which are approximately perpendicular to the trend of the fold. One normal fault however strikes approximately parallel to the axial trace of the fold. To the west of this fault the western limb of the anticline has been down-dropped forming part of the Rio Grande trough. Almost everywhere along this fault Santa Fe or alluvium rests against Pennsylvanian rocks. In one area however, Abo is exposed opposite the basal beds of unit 3. The stratigraphic position of this portion of the Abo is unknown, therefore the displacement along this fault can only be given within a certain range. The total displacement is somewhere between 1100 feet and 2400 feet as determined graphically. Stratigraphic displacement ranges from 600 feet to 1350 feet.

Another large normal fault trends diagonally across the anticline. (See Figure 5.) This fault is observed in the San Andres limestone and can be traced north-northwestward through the area to where it disappears beneath the Santa Fe. The displacement along this fault where easily observed is approximately 200 feet.

At both the north and south ends of the anticline, normal faults cut off the Paleozoic rocks. The fault to the north is quite clear

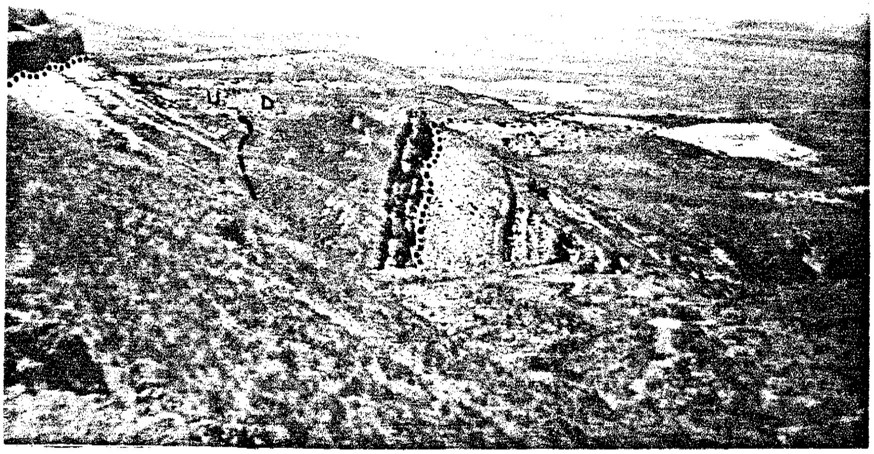


FIGURE 5. Looking south-southwest. A normal fault can be observed. The dotted lines are at the base of the bed tentatively identified as the Coane limestone, which is the boundary between unit 3 and unit 4 of this report. The small hill in the far left, middle background, is capped by Glorieta sandstone. The mountains in the far left distant background are the Fra Cristobals.

while the southern boundary fault is for the most part covered. Only at the southern end of the San Andres outcrop can this fault be observed. Displacements for these faults cannot be determined.

Several other faults strike northwest through the area; one has apparent reverse movement, while the remainder have apparent normal displacement. Displacements on these smaller faults range from 15 feet to 40 feet. The Baca formation which forms two small mesas to the northwest of the mountain is also cut by normal faults. No faults were observed within the Santa Fe formation.

Jointing

Joints are well developed in some of the rocks exposed in the mapped area, particularly in parts of the Abo formation. The limestones of the Pennsylvanian system occasionally have joints developed, however they usually do not form discernible sets. More often the fractures form an irregular pattern and are filled with veinlets of calcite. No attempt was made to map the joints where they do occur.

Structural History

The anticlinal Little San Pasqual Mountain is probably Laramide in age (see Figure 6). The thrusts and overturns of the Caballo and Fra Cristobal Mountains to the south and of the Joyita Hills and Manzano and Sandia Mountains to the north, all either in or bordering the Rio Grande Valley, are considered to be Laramide structures (Wilpolt, et al, 1946; Kelly and Silver, 1952). It is quite possible that the forces responsible for the deformation of the areas named above were also

257.54

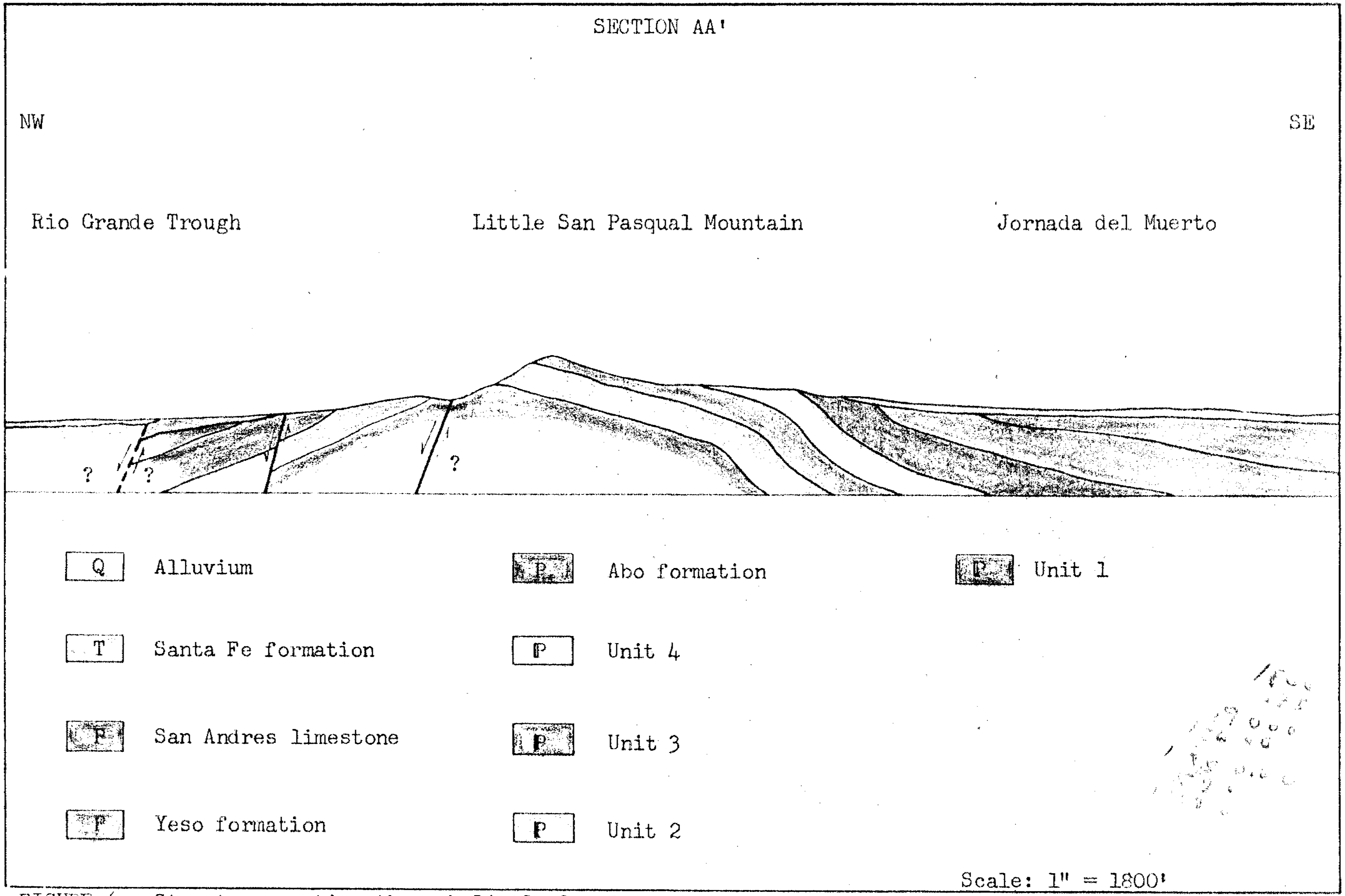


FIGURE 6. Structure section through Little San Pasqual Mountain. The Glorieta sandstone has been included with the San Andres limestone.

responsible for the folding of Little San Pasqual Mountain, although to a lesser degree. The steepening of dip on the eastern limb of the anticline could indicate the beginning of overturning and had the stresses continued for a greater length of time Little San Pasqual Mountain would have also become an overturned structure associated with thrust faulting.

The stresses that created the fold also caused joints to form, some of which later became the normal faults which cross the area, generally in a northwest direction. The formation of the west-bounding, northeast trending fault is probably due to a more general and deep seated unknown cause.

The time of formation of the large fault to the west of the mountain is not known; however, movement had begun no sooner than early Eocene. Movement occurred at least during the Eocene as evidenced by an angular unconformity near the top of the measured Baca formation, and by the tilted and faulted nature of the Baca beds. As faulting progressed the Rio Grande trough was continually receiving debris from surrounding elevated areas.

A younger limit can be placed on the movement occurring along this large fault. The Santa Fe formation along this fault is in depositional contact with the older, folded Pennsylvanian sediments. Since the Santa Fe formation is considered Miocene-Pliocene in age, the last movement on this fault occurred prior to deposition of the youngest Santa Fe beds (Kelly and Silver, 1952).

Subsequent erosion has stripped the Mesozoic and Permian rocks from the anticline and has deeply eroded the remaining Pennsylvanian sediments. Should the eroded section be restored, Little San Pasqual Mountain would be 4000 feet higher than its present elevation.

GRAVITY

General Statement

The gravity survey was undertaken in order to help define the structure of the area adjacent to Little San Pasqual Mountain and its structural relationship to the Rio Grande trough to the west. Interpretation of the gravity data gave a depth to the top of the Little San Pasqual structure where it is down faulted north of the exposed anticline; further, the interpretation suggested the displacement on the west bounding fault and whether more than one fault is present; and finally, the approximate depth of fill in the Rio Grande trough adjacent to Little San Pasqual Mountain was estimated.

Methods and Results

Forty-three ground stations were surveyed using a transit and stadia rod. Stations were spaced approximately four to a mile (see Figure 7). Distances and elevations were carried to the nearest tenth of a foot. The gravity traverse was made using a Worden gravity meter with a dial constant of 0.9385 milligals per division. Readings were taken to the nearest 0.1 scale division. The gravity instrument was returned to the base station at least once every three hours.

FIGURE 7. Map showing the location of gravity stations to the north of Little San Pasqual Mountain.

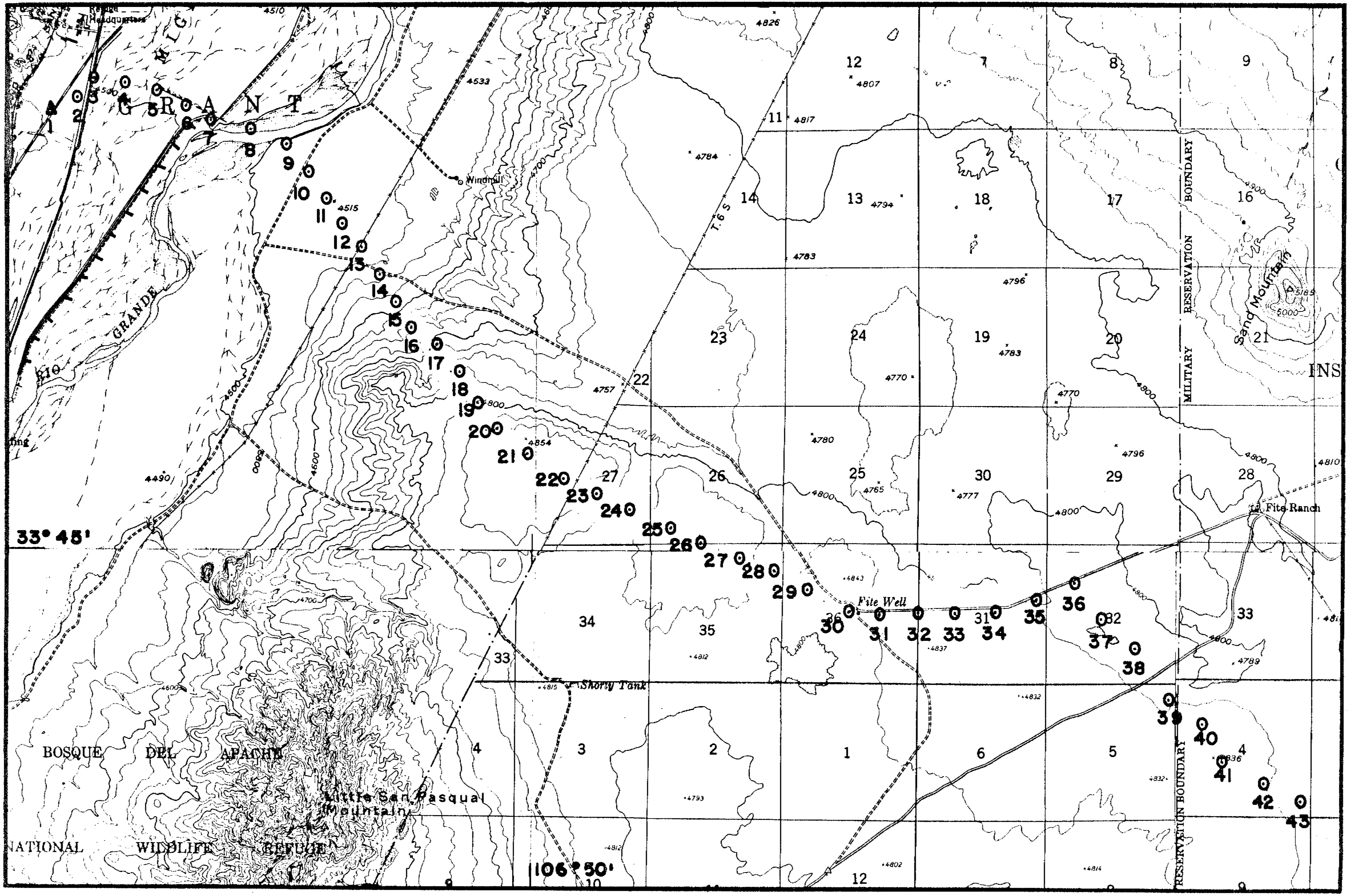

GRANT
RIO GRANDE
Headquarters
Windmill
T.6 S
Sand Mountain
MILITARY RESERVATION BOUNDARY
Fite Ranch
Fite Well
Shorty Tank
Little San Pasqual Mountain
BOSQUE DEL APACHE NATIONAL WILDLIFE REFUGE
33° 45'
106° 50'
1
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FIGURE 7

Station 1 is located approximately 1 mile south of the entrance to the Bosque del Apache wildlife refuge headquarters. Station 1 was USGS bench mark N230, established in 1950, and elevations were carried from this point. The eastward end of the gravity line extends several miles out on the Jornada del Muerto where no bench marks or other surveyed stations were available to check the accuracy of the survey. As a check on these elevations a Paulin surveying altimeter was employed. The altimeter was set using a bench mark near the entrance to Fite ranch and was taken to station 30. The difference between the elevations determined by the altimeter and the ground survey at this point was 4.0 feet. From this it is estimated that the maximum error in elevation at station 43 should be no greater than 6 feet.

The geographical location of the stations was checked by plotting the stations on a topographic map of the area. Station 30 was located at Fite well (Figure 7) and the plotted location checks closely with this feature.

In considering the accuracy of the gravity survey two things must be taken into account, errors in latitude and errors in elevation. Since the sensitivity of the instrument is known, the limits within which these variations must be held can be calculated.

The change in gravity due to a change in latitude is given by the following formula (Nettleton, 1940).

(1.) $K = 1.307 \text{ Sin } 2\varphi$ (mg/mile),

Where K = change in gravity,

and φ = latitude of station in degrees.

φ here is approximately equal to 33° 45'. With the dial constant of the instrument being 0.9385 mg/division the ground survey must be true within 405 feet to stay within the sensitivity of the instrument. The actual error in latitude is not known, however it is believed that it is well within this limit.

The gravity error due to an error in elevation can be determined using the following elevation correction; (Nettleton, 1940) Change in gravity due to a positive change in elevation = -0.05960 mg/foot when a density of 2.7 is used. Using the sensitivity given above, the elevation from the ground survey should be within one foot of the true elevation to be within the instrument's sensitivity. Since the maximum error in elevation has been estimated at six feet the gravity survey is in error by no more than 0.3 milligals.

The absolute gravity at station 1 was determined by taking a gravity reading at a station just north of the Research and Development Division of the New Mexico Institute of Mining and Technology where the absolute gravity is known and then moving the instrument to station 1. After returning to the original station and taking a second reading the actual gravity at station 1 was determined. The value determined was 979180.15 mg.

Table 1 and Curve 1 of Plate 3 summarize the results of the gravity survey. Curve 1 is a graphical projection of the Bouger anomaly of each station to a line N60W through station 1. The projection is perpendicular to this line and approximately parallel

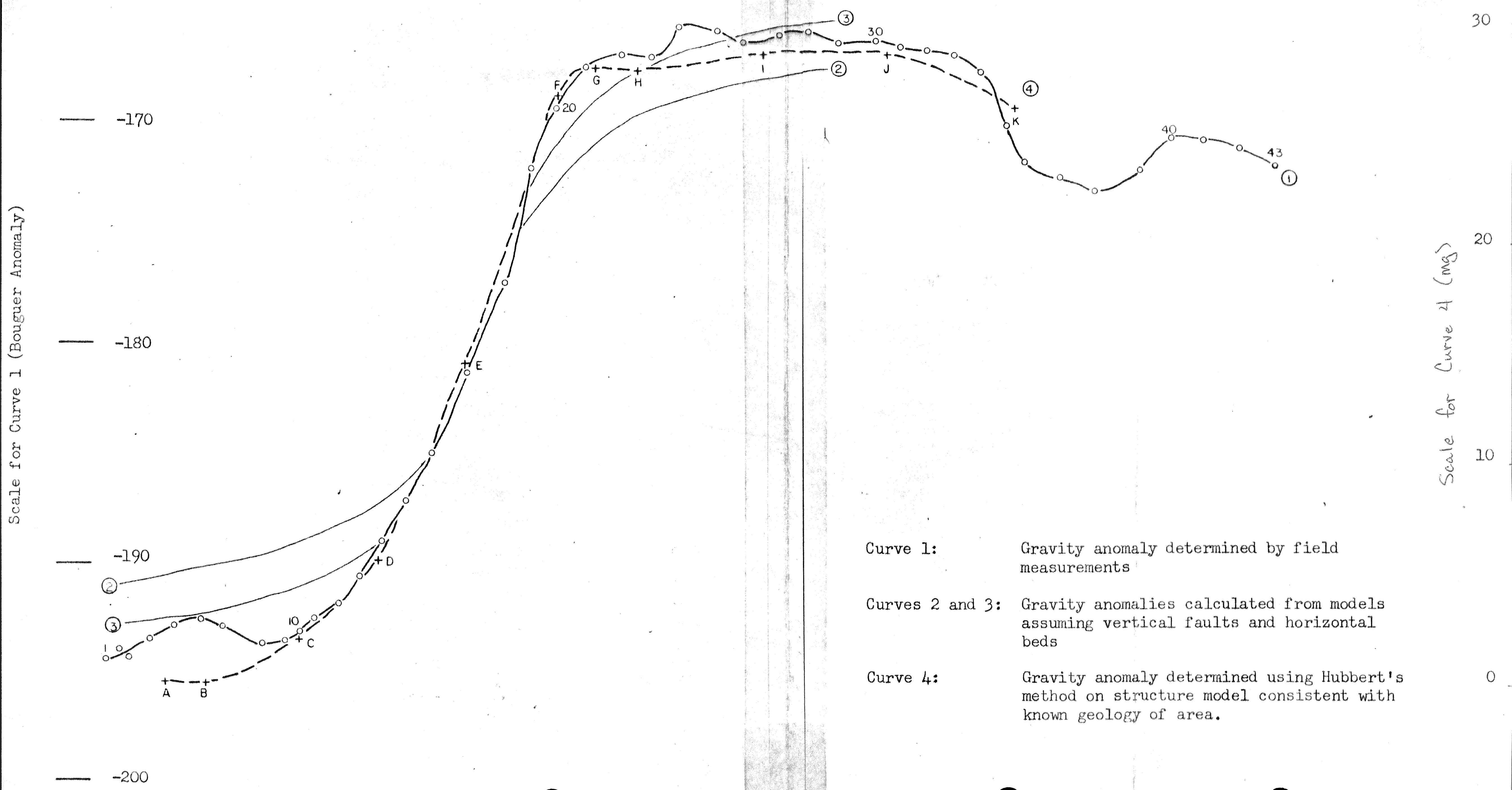
TABLE 1

GRAVITY DATA

STATION	DIFFERENCE IN LATITUDE FROM STATION 26 (FEET) (MINUS INDICATES NORTH)	ELEVATION (FEET)	OBSERVED GRAVITY (Mg)	BOUGUER ANOMALY (Mg)
1	-16890	4512.6	979180.15	-193.5
2	-17191	4504.4	181.06	-193.2
3	-17939	4509.8	180.85	-193.3
4	-17778	4511.7	181.46	-192.5
5	-17477	4514.4	181.80	-191.9
6	-16888	4514.6	181.86	-191.7
7	-16366	4518.5	181.25	-192.0
8	-15997	4509.0	181.14	-192.6
9	-15363	4515.9	180.58	-192.6
10	-14278	4515.1	181.31	-191.6
11	-13275	4519.1	181.56	-190.9
12	-12307	4517.8	182.67	-189.7
13	-11333	4530.8	183.40	-187.9
14	-10326	4548.7	183.75	-186.3
15	-9236	4587.6	183.26	-184.2
16	-8287	4656.7	181.55	-181.5
17	-7597	4723.5	179.47	-179.4
18	-6620	4787.9	178.42	-176.3
19	-5416	4809.1	182.07	-171.2
20	-4325	4850.2	182.15	-168.4
21	-3418	4857.1	183.45	-166.5
22	-2578	4850.8	184.10	-166.0
23	-1896	4831.2	185.07	-166.1
24	-1231	4826.2	186.59	-164.7
25	-509	4842.2	185.22	-164.9
26	0	4843.9	184.41	-165.5
27	581	4839.0	184.99	-165.1
28	1118	4817.2	186.43	-164.9
29	1652	4838.3	184.48	-165.4
30	2226	4839.0	184.31	-165.4
31	2191	4846.9	183.66	-165.6
32	2166	4842.8	183.66	-165.8
33	2162	4846.5	183.29	-166.0
34	2094	4849.2	182.47	-166.7
35	1458	4815.5	182.01	-169.3
36	974	4812.2	180.71	-170.9
37	2370	4807.5	180.01	-171.6
38	3583	4809.8	179.44	-171.7
39	5443	4819.2	179.06	-171.1
40	6455	4833.4	179.43	-169.7
41	8028	4831.9	178.94	-169.9
42	8801	4815.7	179.39	-170.2
43	9497	4805.5	179.05	-171.0

PLATE 3. Different gravity curves determined during the course of this work. Scales are given for curves 1 and 4. Curves 2 and 3 were located by placing the anomaly center over the anomaly center of curve 1. The determination of curves 2, 3, and 4 are described in a later portion of this report. Letters and numbers along curves 1 and 4 denote gravity stations..

Plate 3

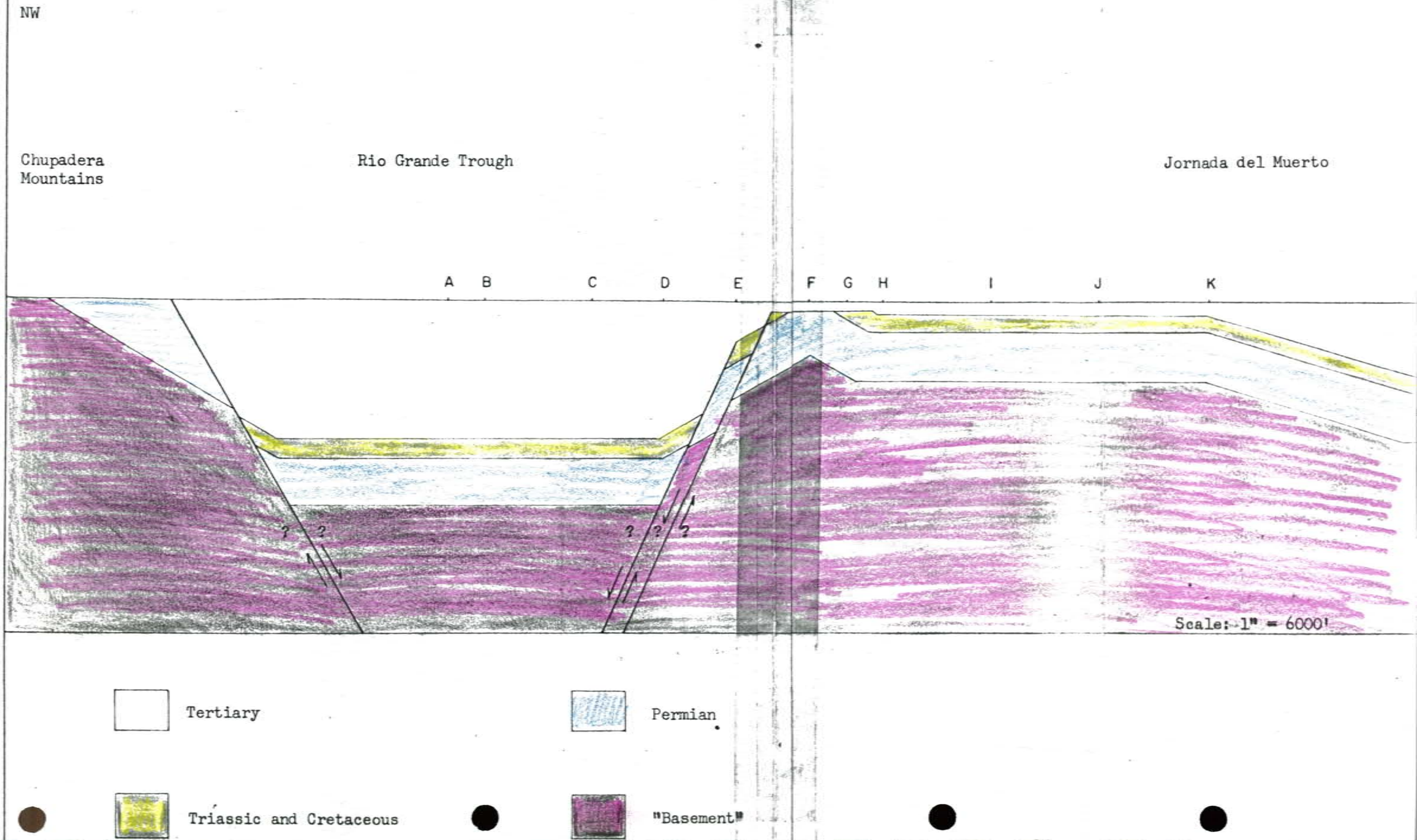


Curve 1: Gravity anomaly determined by field measurements

Curves 2 and 3: Gravity anomalies calculated from models assuming vertical faults and horizontal beds

Curve 4: Gravity anomaly determined using Hubbert's method on structure model consistent with known geology of area.

Plate 4


NW
Chupadera Mountains
Rio Grande Trough
Jornada del Muerto
A
B
C
D
E
F
G
H
I
J
K
?
?
?
?
?
Scale: 1" = 6000'
Tertiary
Permian
Triassic and Cretaceous
"Basement"

to the geologic structures mapped to the south of the gravity line. Sixteen stations lie to the south of the line of projection and twenty-six lie north of it.

In reducing the gravity data, free-air, Bouguer, and latitude corrections were applied. A terrain correction was not made. Terrain corrections were computed for stations 1 and 20, the two stations which are probably most influenced by the surrounding topography. The correction in both cases was less than 0.1 milligal. For this reason terrain effects were ignored. The free air and Bouguer corrections were combined into one correction factor (Nettleton, 1940). The factor used was 0.060 mg/foot which corresponds to a density of 2.67 for basement rocks.

The reference latitude chosen for the latitude correction was 33° 45'. A theoretical value of gravity for this latitude was determined to be 979640.57 mg using the method described by Nettleton (1940). The difference in theoretical gravity between the reference latitude and each station was calculated from equation (1), (page 26). The differences thus determined were then added to the value of theoretical gravity at 33° 45' for stations north of the reference latitude and subtracted for stations to the south. In this manner the theoretical value for g at each station was determined.

The final gravity values obtained after adding a combined free-air and Bouguer correction and subtracting a theoretical value of gravity from the observed values of gravity are shown on Plate 3.

Values obtained in this manner are called Bouguer anomalies. The maximum difference in Bouguer anomalies is 28.8 milligals.

Interpretation

Once the Bouguer anomaly curve was determined the next step was to match this curve with theoretical curves for a geological structure consistent with the geology of the area as determined by surface mapping and other sources. From the shape of the gravity anomaly determined in the survey, the depth to the center of the uplifted block was estimated to be 2200 feet (Nettleton, 1940). With this figure in mind two first approximations to the observed gravity curve were calculated. A vertical fault bounded by horizontal beds of infinite extent was assumed in each case; one with 4000 feet displacement on the fault, the other with 5000 feet displacement. Figure 8 illustrates these models. The rocks bounding the vertical fault were those known or assumed from other evidence to be present in the area: Tertiary, Cretaceous, Triassic, Permian and Pennsylvanian. For purposes of calculation the Triassic and Cretaceous were combined into one unit.

The following equation was used in calculating the gravity anomaly:

$$g = 2K\Delta\rho h(\theta_2 - \theta_1), \tag{2.}$$

where g = gravity value at a given point,

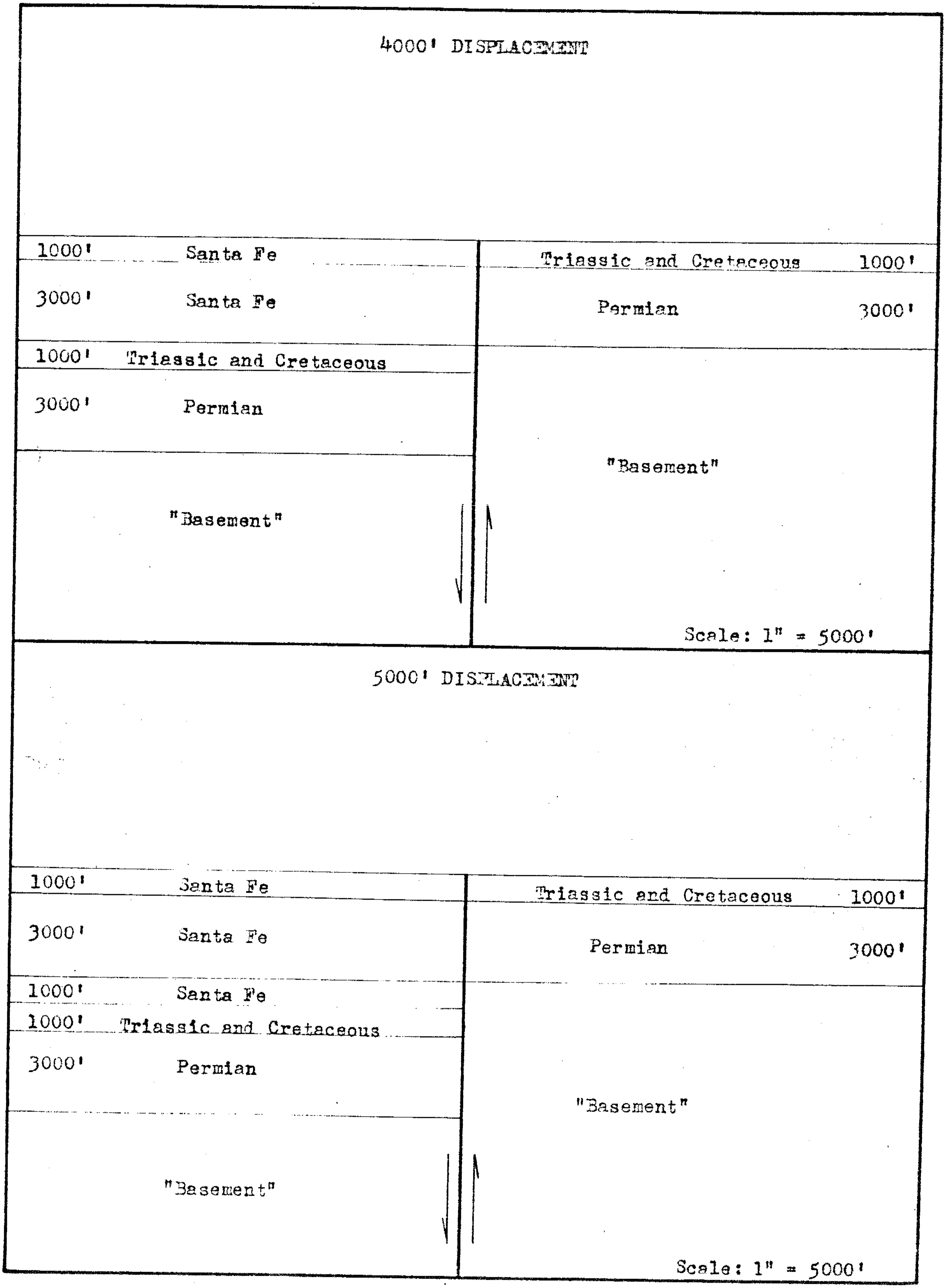
K = gravitational constant,

$\Delta\rho$ = density contrast of adjacent beds on either side of the fault,

h = thickness of bed.

FIGURE 8. Illustrations of the geologic models used in calculating gravity anomalies over vertical faults. The densities used for these models are: "Basement", 2.7; Permian, 2.6; Triassic and Cretaceous, 2.3; Santa Fe, 2.2. Details of the calculations can be found in the text of this report.

FIGURE 8


4000' DISPLACEMENT
1000' Santa Fe
3000' Santa Fe
1000' Triassic and Cretaceous
3000' Permian
"Basement"
Triassic and Cretaceous 1000'
Permian 3000'
"Basement"
Scale: 1" = 5000'
5000' DISPLACEMENT
1000' Santa Fe
3000' Santa Fe
1000' Santa Fe
1000' Triassic and Cretaceous
3000' Permian
"Basement"
Triassic and Cretaceous 1000'
Permian 3000'
"Basement"
Scale: 1" = 5000'

θ_2 is the angle, in radians, measured from a station to the center of the bed along the vertical fault. θ_1 is the angle from the same station to the center of the bed at its most distant point from the fault. Since the beds in this model are considered to be infinite, θ_1 is 0 and the equation becomes:

(3.) $$g = 2K\Delta\rho h\theta_2.$$

In making a gravity calculation of this nature two variables must be known. These are the thicknesses and densities of the rocks that are in contact along the vertical fault. For the calculations in this paper a hypothetical section was constructed from sediment thicknesses found in two Sun Oil Company wells (drilled in 1953) 18 miles south of Little San Pasqual Mountain; from stratigraphic sections measured near Carthage by Wilpolt and Wanek (1951); and in part from thicknesses measured in the mapped area. The thicknesses determined were:

Triassic and Cretaceous: 1016 feet
Permian: 2717 feet

All thicknesses for these two models were rounded off for convenience. This consisted of adding 283 feet to the Permian and subtracting 16 feet from the Triassic-Cretaceous. All pre-Permian rocks are lumped together as "basement".

The densities of the rocks were for the most part taken from the work of Anderson (1953). Anderson measured the densities of the Pennsylvanian and Permian rocks and calculated the density of the Santa Fe formation using geophysical means described by Nettleton (1940).

The density of the Triassic-Cretaceous unit was determined from values given in GSA Special Paper 36, Handbook of Physical Constants (Birch, et al., 1942).

The densities used for the various units are:

Tertiary	2.2
Triassic and Cretaceous	2.3
Permian	2.6
Pennsylvanian	2.7

The Pennsylvanian was assigned as basement since the density of these rocks corresponds closely to that of granite, or basement.

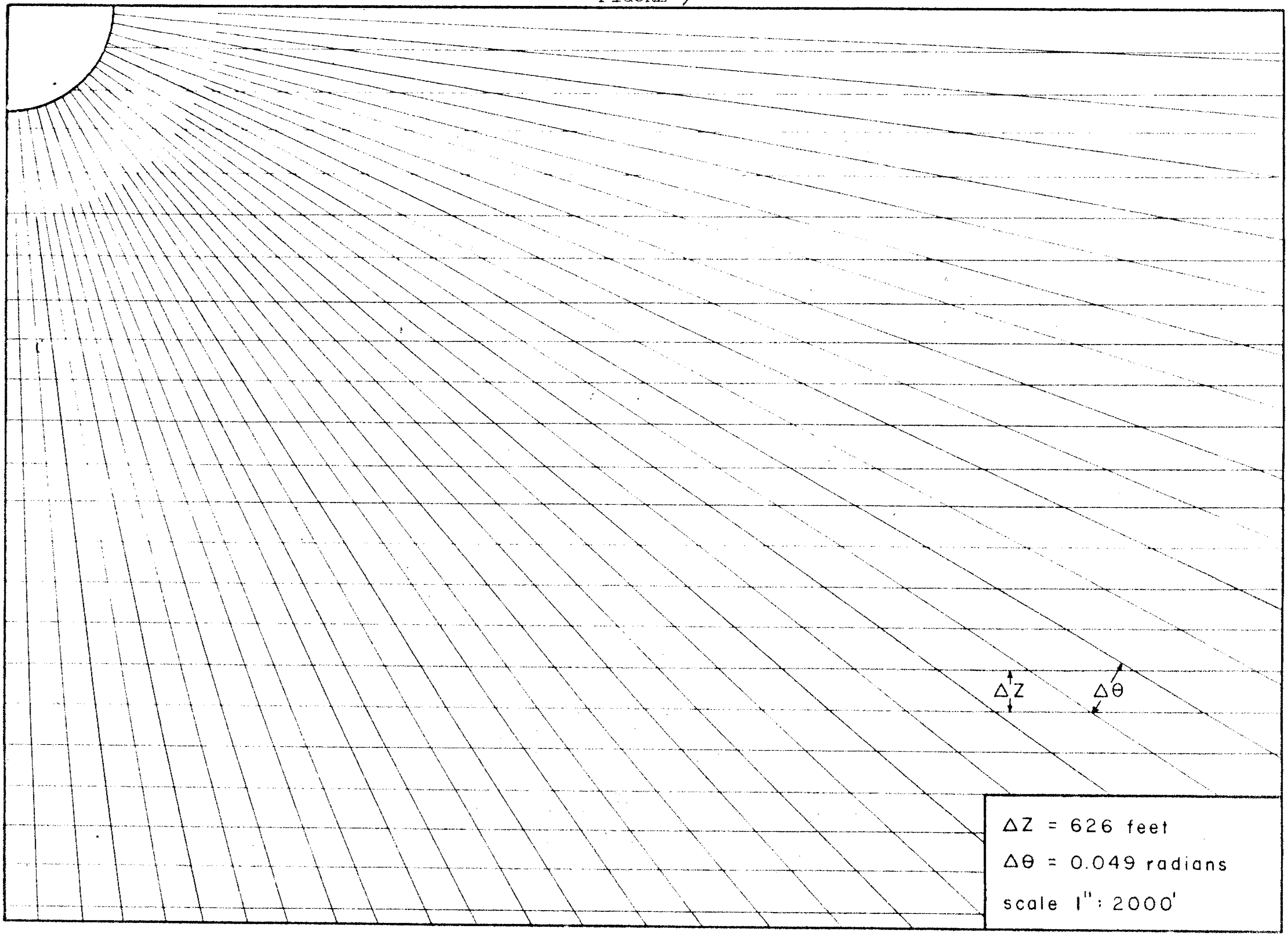
Curves 2 and 3 of Plate 3 show the calculated anomalies. The fault with 4000 feet displacement has an anomaly of 26.8 mg. while the 5000 foot fault has an anomaly of 32.6 mg.

In order to obtain a theoretical anomaly that would be closer to the observed anomaly the method of Hubbert (1948) was used. Briefly, this method consists of constructing a cross section of the geologic feature under consideration and then determining its gravity effect at a given point by placing a template, divided into solenoids of certain dimensions, over the cross section and counting the number of solenoids that fall within the body. With the gravity effect of each solenoid known, the total gravity effect can be easily calculated.

The template is constructed by drawing equally spaced horizontal lines on thin paper or celluloid at the same scale as the geologic cross section. Equally spaced radial lines are then drawn from one corner of the template. Figure 9 is a model of the template used in this work. The template is so constructed that for a given density each solenoid has the same gravity effect at the origin. The values

FIGURE 9. Model of the template used in determining the gravity anomaly over the structure model presented in this report. Each solenoid has a value at the origin, of 0.125 milligals when the solenoid is filled with material of density 1.0.

FIGURE 9



for the spacing on the template can be determined from the following formula (Hubbert, 1948).

(4.) $$g = 2K\rho\Delta\theta\Delta Z$$

where g = gravity effect of one solenoid

K = gravitational constant,

ΔZ = spacing of horizontal lines in feet,

$\Delta\theta$ = spacing of radial lines in radians,

ρ = density of the material within the solenoid.

For this work a value of 0.125 milligals was chosen for the value of each solenoid (for $\rho = 1.0$ c.g.s.), and 626 feet for the spacing of horizontal lines. Solving the above equation using these figures the value of $\Delta\theta$ is 0.049 radians.

The procedure used to calculate a theoretical anomaly was as follows. The origin of the template was placed on the cross section (the cross section will be discussed later) at ground level. The solenoids that covered the same density material were summed. The gravitational attraction of this material was then determined by multiplying the total number of solenoids by the gravitational effect of each solenoid. This was repeated for all rock units of different densities. The template was then reversed and the gravity calculated in the opposite direction. The total of all the gravity values determined at one station is the gravity value for that station. This procedure was followed at 11 stations across the cross section. The gravity anomaly was then determined by subtracting the lowest value obtained from the other 10 values. The final anomaly obtained is Curve 4, Plate 3. The magnitude of the anomaly obtained is 29.6

milligals, a difference of 0.8 milligals from the anomaly actually determined from gravity measurements.

Hubbert's method (1940) was originally meant to be used on bodies finite in cross section such as a high density ore deposit surrounded by low density material. A glance at Plate 4, the model arrived at after several adjustments in the geology, indicates that this structure is not finite and this introduces an error into the determination of the gravity anomaly. The template actually used for this work considered only the material within slightly more than 5.7 miles on either side of a station. The omission of the material outside of the template causes only a small error in the final anomaly. The solenoids become larger and larger with increasing distance from the station under consideration, therefore a single solenoid at a long distance from the origin covers a large amount of material and can be omitted without serious error. Failure to consider gravitational effects of several solenoids from any one station could cause a significant error in the calculations; however, since at all stations gravity effects beyond 5.7 miles were ignored, the error is quite small.

The total number of solenoids at every station was 1034. To check the accuracy of the count at each station, the number of solenoids falling on each different unit of the cross section were summed. In all cases the difference between the number counted and the number actually present was not greater than two. Using the highest density utilized in the calculations, 2.7, the maximum error from miscounting the total number

PLATE 4

of solenoids is 0.34 milligals. One other source of error is possible in determining the anomaly. This is the shifting of solenoids from one unit to another by miscounting fractional parts of solenoids. The counts on individual units are believed to be within at least 3 solenoids of the true number. If 3 solenoids were shifted from the unit with density 2.7 to the unit with density 2.2, the most extreme case, the resulting error would be approximately 0.2 milligals.

From the above considerations it is believed that the gravity anomaly determined by Hubbert's method over the structure section presented is accurate to ± 1.0 milligals.

The structure model shown in Plate 4 is the one used in calculating Curve 4 on Plate 3. This model was arrived at by the trial and error method, utilizing the known geology in the area. In the structure section all pre-Permian rocks have been combined as basement. It is believed that the oldest rocks in the area above the pre-Cambrian are Pennsylvanian sediments. The two Sun Oil wells to the south of the area passed through a thin section of pre-Pennsylvanian rocks, however the pre-Pennsylvanian section in the San Andres and Oscura Mountains to the east and southeast as shown by Dane and Bachman (1961) pinches out northward and is absent at the latitude of the mapped area. Should any pre-Pennsylvanian rocks be present in this area they are probably quite thin.

The densities used for this structure section are the same as those used in determining the curves over the vertical faults. The thickness of the Triassic-Cretaceous unit shown on Plate 4 is 1000 feet, that of the Permian is 2700 feet.

In justifying the structure model the first point to be made is that the observed anomaly and the theoretical anomaly for the model are quite similar, both in shape and magnitude. It should be pointed out, however, that this is not a unique solution, a narrower and deeper structure with the same configuration as that shown in the model could produce a similar curve, or the structure could be entirely different and produce the same curve as calculated. The geology of the area however indicates that this is the most probable interpretation.

The western edge of the structure model shows "basement" outcropping in the southern portion of the Chupadera Mountains. The "basement" indicated on the structure section is Pennsylvanian and pre-Cambrian. These rocks actually outcrop at the point shown (Dane and Bachman, 1961). On the model section Permian rocks are shown as outcropping in the same area, however this has not been observed in the Chupadera Mountains. The placement of the westernmost bounding fault would actually determine whether the Permian is present (under cover) or not. This fault was placed in its present position in order that the calculated gravity curve would flatten out across the Rio Grande trough in approximately the correct position.

The west bounding fault is shown as a single fault with a large displacement. There may be more than one fault in this location, however this configuration was used for convenience in calculations.

The thickness of the Santa Fe formation within the Rio Grande trough was determined to be 7500 feet. This figure, although large, is not unreasonable. Humble Oil & Refining Company in 1956 drilled a well east of Belen, New Mexico, and encountered 9800 feet of Santa Fe above the Cretaceous section. Sullivan (1960) using geophysical means determined the Santa Fe to range from 5900 feet to 27,000 feet in thickness, also near Belen. Anderson (1953) using gravity methods determined the Santa Fe to be up to 5900 feet in thickness a few miles north of Socorro. Finally, three oil wells drilled in 1927-29, approximately 5 miles northwest of gravity station 1 of this report, all bottomed in Santa Fe, the deepest well being over 4200 feet.

The eastern edge of the Rio Grande trough is bounded by two normal faults in the structure model. To the south of the gravity traverse, in the area mapped for this work, the Abo formation is faulted against the lowermost beds of Pennsylvanian unit 3. This fault trends northeast along the western edge of Little San Pasqual Mountain and cuts the gravity line at approximately right angles. The exact displacement on this fault cannot be determined; however, the minimum and maximum displacements are 1100 feet and 2400 feet respectively. Such displacements are not large enough to allow 7500 feet of Santa Fe to accumulate in the Rio Grande trough. (The Abo, at the center of the trough, is approximately 11,000 feet below the surface using the configuration shown in the structure model.) In order to achieve this amount of Santa Fe a second normal fault is indicated. The true angle of dip of the faults is not known; a value of 65° was used in constructing the model section.

The anticline shown in the model is truncated for three reasons. First, the anticline mapped to the south is deeply eroded with middle Pennsylvanian beds topographically the highest layers exposed. It is assumed that some erosion took place on the northern part of the anticline before it was faulted and buried by Tertiary sediments. The second reason for the truncation was to achieve a broad flat curve over the top of the buried hypothetical structure that corresponded closely to the observed gravity curve. The third reason for truncation was to bring high density material close to the surface to achieve the correct magnitude for the total gravity anomaly. It should be remarked here that by restoring the Triassic-Cretaceous unit over the anticline and deepening the Rio Grande trough to the west a similar gravity curve could be obtained. The thickness of the Santa Fe over the crest of the anticline is arbitrary. In one of the Sun wells on the eastern margin of the Rio Grande trough the Santa Fe is only 154 feet thick. The log of the second well did not separate the Santa Fe from the Cretaceous section; however, the base of the Cretaceous is shallow enough to allow only a small amount of Santa Fe to be present.

To the east of the anticline the beds are flat lying or dip gently to the east. This configuration is required to keep the gravity curve from dropping off too rapidly to the east. Geologically this is reasonable. The San Andres limestone which outcrops to the southeast of Little San Pasqual Mountain dips quite shallowly to the southeast. Dips vary from 7° to 20°. If this unit is projected northeastward, these beds will be quite close to the surface southeast of the area under consideration.

The map of the pre-Cambrian in New Mexico (Foster and Stipp, 1961) indicates that the pre-Cambrian rises rapidly in the subsurface from south to north, beneath the Jornada del Muerto. The map is not complete but does indicate a pre-Cambrian high to the east of and probably underlying Little San Pasqual Mountain. The beds shown in the model are assumed to lie on this pre-Cambrian high and thus have a shallow dip to the southeast.

Thus the structure model of the Rio Grande trough and adjacent areas given in this paper is based on geological evidence supplemented by geophysical work and is not merely the result of "fitting" a theoretical curve obtained without geologic information to the gravity curve that was actually observed.

CONCLUSIONS

Little San Pasqual Mountain is an anticline that has been faulted to the north, west, and south. The anticline apparently continues northward under a cover of Tertiary, Santa Fe sediments as indicated by a structure model determined from geological information in the area and then adjusted to fit an observed gravity curve. It is believed that the structure model in this report closely approximates the actual structure present in the Little San Pasqual area and that any changes in the model will be those of dimensions and not of basic structure.

LOCATION OF MEASURED SECTIONS

The land office survey covers only a small portion of the mapped area, the remainder of the area being grant land. If, however, the survey is projected through the area the locations of the measured sections can be given.

Units	Location of Measurement
Units 1, 2, and 3	S 1/2 S 1/2, Sec. 5, T.7S., R.1E.
Unit 4; Abo formation	N 1/2 S 1/2, Sec. 18, T.7S., R.1E.
Yeso formation; Glorieta sandstone	NW 1/4, Sec. 19, T.7S., R.1E.
Baca formation	NE 1/4, Sec. 31, T.6S., R.1E.

DETAILED STRATIGRAPHY

PENNSYLVANIAN SYSTEM

Pennsylvanian; Unit 1 Total Thickness: 571.7

Top	Thickness (feet)
Limestone; massive, light gray, weathers to a pitted surface with brown streaks; abundant corals; a few chert lenses.	12.0
Slope; poorly exposed gray, buff, and maroon shales.	43.0
Limestone; shale partings; limestones form beds up to 1 foot thick; red to brown; weathers black.	4.3
Limestone; black, sandy, with interbedded black shale; weathers buff.	2.0
Covered; small patch of maroon shale exposed in gully.	7.0
Limestone; light gray, badly brecciated; weathers orange; fossiliferous.	5.5
Mixed; gray shales and limestones, brown sandstones; beds up to 6 inches in thickness; abundant brachiopods in the limestones.	10.9
Shale; light gray and olive drab; near top are several 2 inch thick beds of fine grained sandstones.	15.3
Limestone; platy; gray; weathers orange; fossiliferous.	2.3
Shale; calcareous; dark gray and olive drab.	13.5
Limestone; sandy; dark brown; center of bed is platy; weathers yellow-brown; fossiliferous.	2.3
Shale; slope; poorly exposed, gray and brown shales; near center of unit shales alternate with 2 inch thick beds of fine grained micaceous sandstones.	46.9
Limestone; very dense; black; weathers orange; occasional crinoid stem.	1.3
Covered;	14.4

Limestone; dense, light gray; weathers light gray with a pitted surface; occasional band of chert; abundant fusulinids.	18.0
Shale; poorly exposed gray and maroon shales; occasional thin limestone interbed.	23.2
Limestone; platy, dense, sandy, black; weathers orange and brown; non-fossiliferous.	5.5
Shale; slope; poorly exposed gray and purple shales; with an occasional thin limestone or sandstone.	27.5
Limestone; dense, light gray, weathers to a pitted light brown surface; numerous corals; a few fusulinids.	5.2
Covered;	24.4
Limestone; dark gray, weathers brown; abundant crinoid stems.	1.2
Covered;	7.5
Limestone; dark gray, thin bedded, weathers brown; sparingly fossiliferous.	1.3
Covered;	52.7
Limestone; dense, sandy, dark gray; weathers pale brown; sparingly fossiliferous.	3.0
Shale; dark gray.	4.7
Covered;	48.6
Shale; gray, brown, and black calcareous shales.	26.0
Sandstone; fine grained; thin bedded; light brown; micaceous.	2.0
Shale; gray shale poorly exposed on slope.	13.5
Sandstone; dark gray; well rounded, fine grained sandstone.	18.0
Shale; light greenish-gray with a few thin sandstone beds.	18.0
Sandstone; dark reddish brown; fine grained, well rounded quartz sandstone.	3.5
Covered;	3.6
Limestone; light gray; fossiliferous; a few chert nodules.	3.3

Covered;	27.3
Sandstone; red yellow and brown, coarse to very coarse angular quartz sandstone.	11.0
Covered;	11.0
Sandstone; medium grained, gray.	1.3
Covered;	1.5
Sandstone; dark brown, medium grained, rounded to sub-rounded quartz sandstone.	1.5
Covered;	3.0
Limestone; dense, brown.	1.7
Limestone; olive drab to brown, coarsely crystalline.	8.0
Covered;	4.0
Sandstone; dark brown, medium to coarse grained; badly weathered.	10.0

Base of Pennsylvanian not exposed, section begins at a large fault.

Pennsylvanian; Unit 2 Total Thickness; 413.9

Top	Thickness (feet)
Covered;	4.0
Limestone; dense light gray, weathers to a rough, light brown surface; extremely cherty; non-fossiliferous.	19.2
Limestone; dark gray, dense, thin bedded limestones, beds 2 inches to 4 inches in thickness; non-fossiliferous.	28.8
Covered; occasional thin, dark limestone.	83.2
Limestone; dense, massive, light gray limestone; weathers to a rough gray and brown surface; extremely cherty.	69.1
Limestone; slope; poorly exposed; thin bedded dark limestone, 2 inches to 2 feet in thickness.	36.8
Shale; poorly exposed; interbedded dark shales and limestones.	27.7
Limestone; bedded, 1 inch to 4 inches in thickness; dense, medium gray, weathers gray and brown; fossiliferous.	9.2
Covered; basal 5 feet has small exposure of olive drab shale in gully.	13.8
Sandstone; coarse grained sandstone made up of rounded calcite grains; contains crinoid stems and other fossils.	1.1
Limestone; crystalline, light gray, weathers brown; non-fossiliferous.	1.8
Covered;	6.0
Limestone; massive, dense, pale gray; weathers to a very rough, light brown surface; upper 3 feet is separated from remainder of bed by a bedding plane; contains crinoid stems and corals.	9.2
Covered;	8.5
Limestone; massive crystalline, pale gray; weathers to light brown.	1.7
Covered;	5.0
Limestone; dense, massive, pale gray; weathers to a rough gray and brown surface; fossiliferous.	10.4

Limestone; bedded, beds 1 inch to 2 feet in thickness, 2 feet of gray shale exposed 12 feet from base; beds weather to a round, knobby surface; top 8 feet contains a small amount of chert; fossiliferous.	43.0
Limestone; dense, massive, medium gray, weathers to dark gray; sparingly fossiliferous.	2.7
Covered;	6.0
Limestone; platy, medium gray; weathers brown; fossiliferous.	4.3
Covered;	9.2
Limestone; dense, dark gray, sandy; weathers light brown; fossiliferous.	1.0
Covered;	9.2
Limestone; dense, massive, light gray; weathers brown; abundant chert; abundant corals.	3.0

Base of Pennsylvanian Unit 2; section begins at an angular unconformity.

Pennsylvanian; Unit 3 Total Thickness: 350.0

Top	Thickness (feet)
Limestone; dense, pale brown; weathers to a corroded, light gray surface; generally massive, basal 2 feet bedded, beds 4 inches to 6 inches in thickness; considerable chert; fossiliferous.	6.9
Covered; slope;	9.1
Limestone; dense, brown; weathers to a mottled yellow and brown pitted surface; thin bedded, 3 inches to 12 inches in thickness; considerable chert; abundant brachiopods.	10.2
Shale; poor exposure; olive drab shale present in a gully.	7.0
Limestone; massive at top, bedded at base; beds 8 inches to 6 feet in thickness; dense, black on fresh surface, weathers to a brown pitted surface; fossiliferous.	28.0
Covered; slope;	27.3
Limestone; dense, medium gray; in part conglomeratic; bedded, beds 6 inches to 1-1/2 feet in thickness; weathers to a medium gray, has a sandy appearance. Stratigraphically equivalent to conglomerate 1/4 mile southward. Conglomerate consists of limestone and quartz pebbles with coarse sand matrix, appears to be a bed deposited on a karst surface.	5.5
Covered;	11.4
Limestone; dense, black, platy; weathers to medium brown; sparingly fossiliferous.	9.1
Covered; slope;	22.8
Limestone; very dense, light gray, breaks with a conchoidal fracture; platy, beds up to 2 feet in thickness; weathers to yellow and gray streaks; sparsely fossiliferous, a few crinoid stems.	18.2
Limestone; brown, sandy; weathers to a pale gray; abundant chert; fossiliferous.	2.1
Limestone; dense, dark gray, platy; beds 1/4 inch to 2 inches in thickness; weathers to a mottled yellow and gray; fossiliferous.	11.4
Covered; slope;	9.6

Limestone (Council Springs?); dense, light gray; weathers to a light brown pitted surface; massive in upper half, bedded in lower half; contains many solution cavities with calcite or quartz crystals; extremely silicified in upper part.	43.4
Covered;	5.0
Limestone; dense, light gray; weathers to a pitted surface with a sandy appearance; abundant chert; fossiliferous.	9.6
Covered;	14.4
Limestone; dense, massive, light gray; weathers to a rough pitted surface; locally silicified in upper part; fossiliferous.	8.0
Covered;	5.0
Limestone; dense, massive, medium gray; weathers to a rough mottled yellow and gray surface; a few chert nodules; fossiliferous.	20.0
Covered;	3.0
Limestone (Coane?); light gray, dense, massive limestone; weathers to a pitted, light gray surface; forms two cliffs, lower cliff twice as thick as the upper; both cliffs contain chert bands in upper portion; fossiliferous.	63.0

Base of Unit 3 begins at the base of a massive, light gray, cliff forming limestone. The contact with the underlying rocks is covered by talus.

Pennsylvanian; Unit 4 Total Thickness: 267.8

Top	Thickness (feet)
Limestone; brown, very dense, sandy; weathers dark brown; slightly fossiliferous.	8.4
Covered;	15.6
Sandstone; dark gray, calcareous, medium grained, sub-rounded grains; weathers black; fossiliferous.	3.0
Covered;	5.2
Sandstone; arkosic, fine grained, platy; weathers purple; grades upward into mudstone.	9.8
Covered;	4.0
Limestone; light gray, dense; weathers to a light brown, pitted surface; fossiliferous.	5.0
Shale; purple.	20.3
Limestone; bedded, beds 6 inches to 12 inches in thickness; dense, pale gray; weathers dark brown; sparsely fossiliferous.	4.0
Shale; red and purple; two thin, gray limestones and a purple sandstone occur near the middle in beds less than 1 foot thick.	51.0
Limestone; thin bedded, beds 4 inches to 1 foot in thickness; dense, light brown; weathers pale gray; abundant fossils.	8.0
Covered;	8.0
Sandstone; dark gray, platy, fine grained; weathers brown.	6.0
Covered; slope; a few poor outcrops of gray limestone.	23.8
Limestone; thin bedded, beds 1 inch to 6 inches in thickness; dense, pale gray; weathers dark gray; sparsely fossiliferous.	5.0
Covered;	4.0
Limestone; massive, dense, light gray, weathers to a light gray, rough surface; numerous crinoid stems.	27.2

Covered;	15.2
Limestone; bedded, beds 6 inches to 1 foot in thickness, pale gray, crystalline, weathers to a brown corroded surface; fossiliferous.	9.8
Shale and limestone; greenish gray, interbedded limestones and shales; individual beds less than 2 inches in thickness.	34.5

The base of Unit 4 begins at the base of a series of alternating, thin bedded, greenish gray limestones and shales. The contact is locally well exposed and appears to be conformable to an underlying dense, brown limestone.

PERMIAN SYSTEM

Abo formation Total Thickness: 753.1

Top	Thickness (feet)
Sandstone; medium to fine grained; usually pink but has been locally bleached white or brown; platy; thin bedded.	8.0
Sandstone; occasionally thin bedded but usually massive; fine grained, brick red to dark red although laterally it may be white yellow or brown due to bleaching.	76.5
Covered; red and brown sandstone pebbles on slope.	28.0
Sandstone; red; thin bedded to massive.	7.8
Covered; red sandstone pebbles on slope.	55.7
Covered; sand dunes, dunes covered with red sandstone pebbles.	151.0
Shale; red and blue-green sandy shales; grades upward into thin to thick bedded, cross bedded, red sandstone; beds 1/2 inch to 4 feet in thickness; this section is approximately one half shale and one half sandstone.	32.0
Covered; occasional poor exposure of red sandstone and shale on slope.	81.6
Sandstone; poor exposure of reddish-brown sandstone.	5.0
Covered;	22.7
Sandstone; dark red; conglomerate bed one foot thick at base; conglomerate contains limestone and red sandstone pebbles up to 1 inch in diameter, dense reddish matrix; sand is thin and cross bedded.	4.8
Covered;	10.5
Sandstone; thin bedded, reddish-brown, fine grained, cross bedded.	5.8
Slope; mostly covered; red sandstone outcrops in small patches; maroon shale exposed near top.	37.7
Conglomerate; yellow-brown; limestone pebbles only, up to 1 inch in diameter; matrix is a fine grained, reddish brown sand.	3.0

Covered;	17.8
Sandstone; very fine grained, reddish brown; weathers dark reddish brown to black.	1.4
Covered; two small exposures of red sandstone on slope.	34.4
Sandstone; poor exposure of red sandstone; medium grained, angular to sub-angular, cross bedded; weathers almost black.	4.5
Covered; red shale exposed near base; slope covered with slabby red sandstone fragments.	61.8
Conglomerate; red; contains limestone and red sandstone pebbles up to 1/2 inch in diameter; fine sand and mud matrix.	2.8
Covered;	18.6
Sandstone; fine grained, dark reddish brown, slabby, cross bedded.	12.6
Slope; mostly covered; bright red shales and muds exposed at base; slope covered with slate-like pieces of fine grained, reddish sandstone.	69.1

The base of the Abo was placed at the top of a dense brown limestone, just below a thick sequence of red sandstones and shales. The contact is arbitrary and it appears that unit 4 grades into the Abo formation.

Yeso formation Measured Thickness: 935.7

Top

	Thickness (feet)
Covered, slope; lower 138.0 feet has occasional red mudstone exposed in gully; upper 111.0 feet covered by Glorieta talus.	249.0
Sandstone; fine grained; white on fresh fracture, weathers brown.	5.0
Mudstone; yellow, changes color upward to brown and then to gray; shaly in upper part.	21.9
Covered; limestone float on surface; red muds and shales poorly exposed locally.	437.3
Limestone; brown; poorly exposed; badly brecciated.	39.2
Covered;	27.4
Limestone; dense, dark gray, weathers to a light gray, corroded surface; thin bedded, beds 1 inch to 18 inches in thickness.	12.0
Mudstone; yellow and brown; becomes shaly at the top.	4.2
Shale; blue gray.	0.9
Limestone; dense, pale gray; bedded, beds 1 foot to 2 feet in thickness; non-fossiliferous.	8.0
Covered; red and blue-green shales and red mudstones poorly exposed in side of gully; one thin bed of red sandstone exposed near middle of section.	114.0
Limestone; dense, dark gray; weathers to a light gray; thin, irregularly bedded, beds 1/2 inch to 6 inches in thickness; shaly in lower part; fossiliferous.	16.8

The base of the Yeso formation was placed at the contact between a pinkish, fine grained sandstone and an overlying dark gray limestone. The contact is only poorly exposed and depositional relationships could not be determined.

Glorieta sandstone Minimum Thickness: 31.4

Top of Glorieta forms present erosion surface.

Varies within the area; dense, hard quartzite, weathers dark brown to black; also medium to fine grained, well rounded, quartz sandstone. Quartzite facies only on western most of three hills in southern portion of mapped area.

The Yeso-Glorieta contact is everywhere covered by Glorieta talus. For mapping purposes the contact was placed at the base of the exposed Glorieta where an abrupt change in slope angle was observed to occur.

San Andres limestone

Top: Covered

Very poorly exposed and only in upper part; weathers medium gray; gray on fresh surface, granular; slightly fossiliferous where exposed; thickness calculated from map data. 743.0

Base: Covered

TERTIARY SYSTEM

Baca formation; faulted and difficult to measure. Measured Thickness: 418.7

Top: Covered

	Thickness (feet)
Conglomerate; pebbles in basal part rarely reach 1 inch in diameter, pebbles in upper part up to 3 inches in diameter; pebbles are red sandstone, limestone, andesite, and an occasional quartz pebble; sandy zones in upper part, top 8 feet is mostly sandstone; pale purple in color; matrix is poorly sorted sand; top is covered with dune sand.	24.0
Sandstone; pale red, thin bedded, fine grained, poorly sorted and sub-rounded; friable.	17.1
Covered; angular unconformity occurs in covered area.	8.0
Sandstone; brick red; bedded; well rounded, medium well sorted quartz sandstone; friable.	41.0
Covered;	4.5
Sandstone; weathers to a dark reddish brown knobby surface; poorly sorted; fine to medium grained; sub-angular grains; friable.	5.7
Covered; exposure of red sandstone in road.	50.0
Sandstone; dark reddish brown, medium to fine grained, well sorted, sub-rounded; thin to massive bedded, cross bedded; weathers to a round knobby surface; weathers black on joint surfaces; friable.	227.0
Sandstone; light reddish brown, thin bedded to massive, cross bedded, friable, poorly sorted, sub-rounded quartz sandstone; lowest exposure begins 75 feet up a talus covered dune slope.	41.4

Base: Covered

Santa Fe formation

Up to 100 feet
exposed

Lithologically quite variable; ranges from thin, cross bedded, "salt and pepper" sandstone to red, yellow, and brown conglomeratic mudstones; usually covered by blow sand.

A large talus block of sandstone embedded within the Santa Fe has been tentatively identified as the Cretaceous, Dakota sandstone.

Dakota sandstone;

Well sorted, fine grained, sub-rounded quartz sandstone; weathers yellow to buff, almost white on fresh surface; extremely cross bedded and brecciated.

QUATERNARY SYSTEM

Alluvium and large shifting sand dunes cover the lower portions of the Little San Pasqual area and constitute the most recent material to accumulate in this region.

BIBLIOGRAPHY

Anderson, R. C., (1953), *A Gravity Survey of the Rio Grande Valley near Socorro, New Mexico*, Unpublished Masters Thesis, New Mexico Institute of Mining and Technology

Billings, M. P., (1955), *Structural Geology*, Prentice-Hall, Inc., New York

Birch, F., et al., (1942), *Handbook of Physical Constants*, Geological Society of America, Special Paper 36

Dane, C. H., and Bachman, G. O., (1961), *Preliminary Geologic Map of the Southwestern Part of New Mexico*, Miscellaneous Geologic Investigations Map I-344, USGS

Darton, N. H., (1922), *Geologic Structure of Parts of New Mexico*, USGS Bull. 726-E

______, (1928), *"Red Beds" and Associated Formations in New Mexico*, USGS Bull. 794

De Sitter, L. U., (1956), *Structural Geology*, McGraw-Hill Book Company, Inc., New York

Dobrin, M. B., (1960), *Introduction to Geophysical Prospecting*, McGraw-Hill Book Company, Inc., New York

Foster, R. W., and Stipp, T. F., (1961), *Preliminary Geologic and Relief Map of the Pre-Cambrian of New Mexico*, New Mexico Bureau of Mines and Mineral Resources, Circular 57

Heiland, C. A., (1946), *Geophysical Exploration*, Prentice-Hall, Inc., New York

Hubbert, M. K., (1948), *A Line-Integral Method of Computing the Gravimetric Effects of Two-Dimensional Masses*, Geophysics, Vol. 13

Johnson, R. B., and Read, C. B., (1952), Editors, *Stratigraphy of Paleozoic, Mesozoic Rocks in parts of Central New Mexico*, New Mexico Geological Society Guidebook, Third Field Conference, Rio Grande Country, Central New Mexico

Kelly, V. C., and Silver, C., (1952), *Geology of the Caballo Mountains*, The University of New Mexico Press, Albuquerque, New Mexico

Kottlowski, F. E., (1960), *Summary of Pennsylvanian Sections in Southwestern New Mexico and Southeastern Arizona*, New Mexico Bureau of Mines and Mineral Resources, Bull. 66

_________, Flower, R. H., Thompson, M. L., and Foster, R. W. (1956), *Stratigraphic Studies of the San Andres Mountains, New Mexico*, New Mexico Bureau of Mines and Mineral Resources, Memoir 1

Nettleton, L. L., (1940), *Geophysical Prospecting for Oil*, McGraw-Hill Book Company, Inc., New York

Skeels, D. C., (1947), *Ambiguity in Gravity Interpretation*, Geophysics, Vol. 12

Sullivan, W. D., (1960), *A Telluric Current Survey of the Rio Grande Valley near Belen, New Mexico*, Unpublished Masters Thesis, New Mexico Institute of Mining and Technology

Thompson, M. L., (1942), *Pennsylvanian System in New Mexico*, New Mexico Bureau of Mines and Mineral Resources, Bull. 17

Wilpolt, R. H., et al., (1946), *Geologic map and stratigraphic sections of Paleozoic rocks of Joyita Hills, Los Pinos Mountains, and Northern Chupadera Mesa, Valencia, Torrance, and Socorro Counties, New Mexico*, Oil and Gas Investigations Preliminary Map 61, USGS

_______, and Wanek, A. A., (1951), *Geology of the Region from Socorro and San Antonio east to Chupadera Mesa, Socorro County, New Mexico*, Oil and Gas Investigations Map 121, USGS

This thesis is accepted on behalf of the faculty of the Institute by the following committee:

Frank E. Kottlowski

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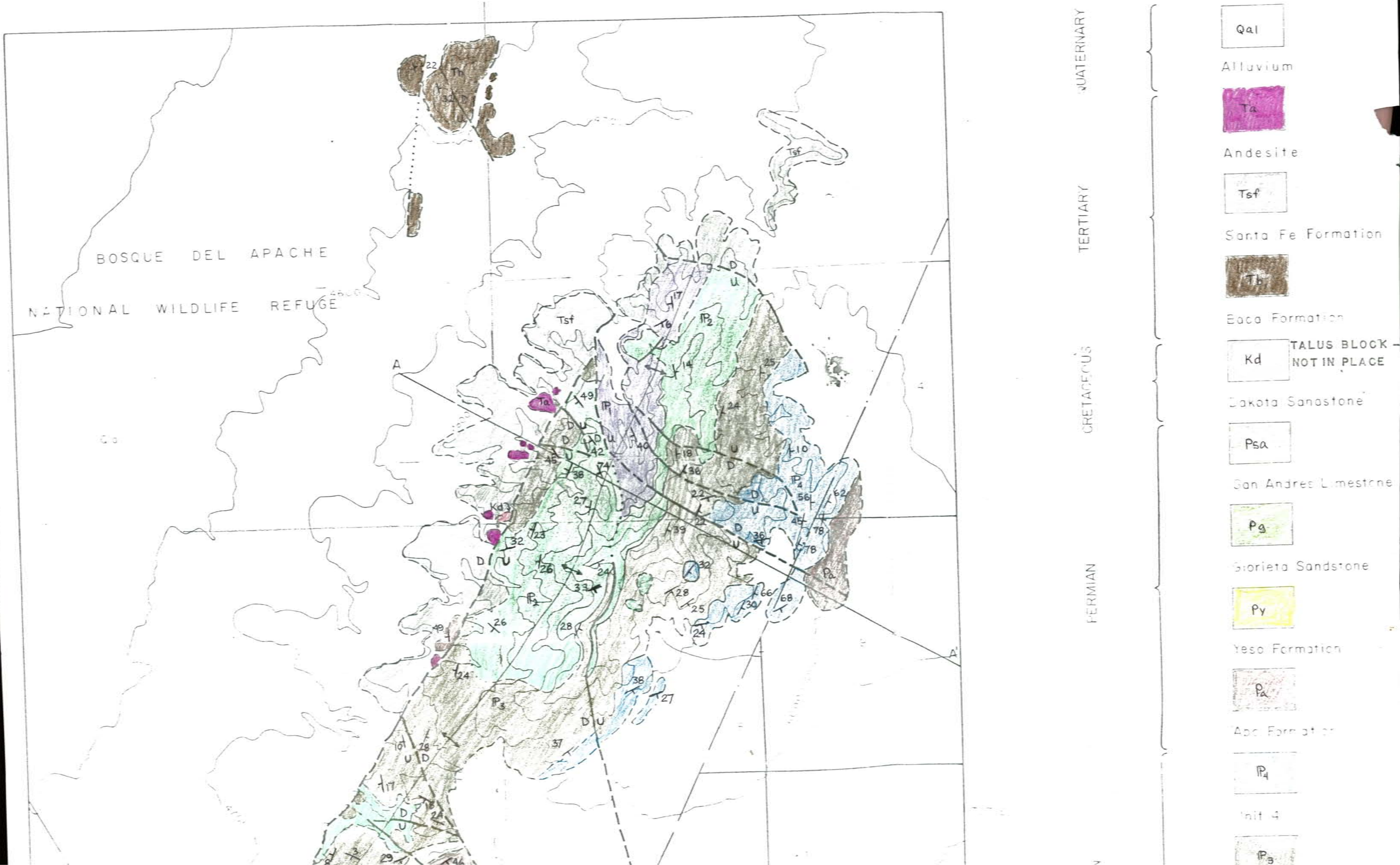
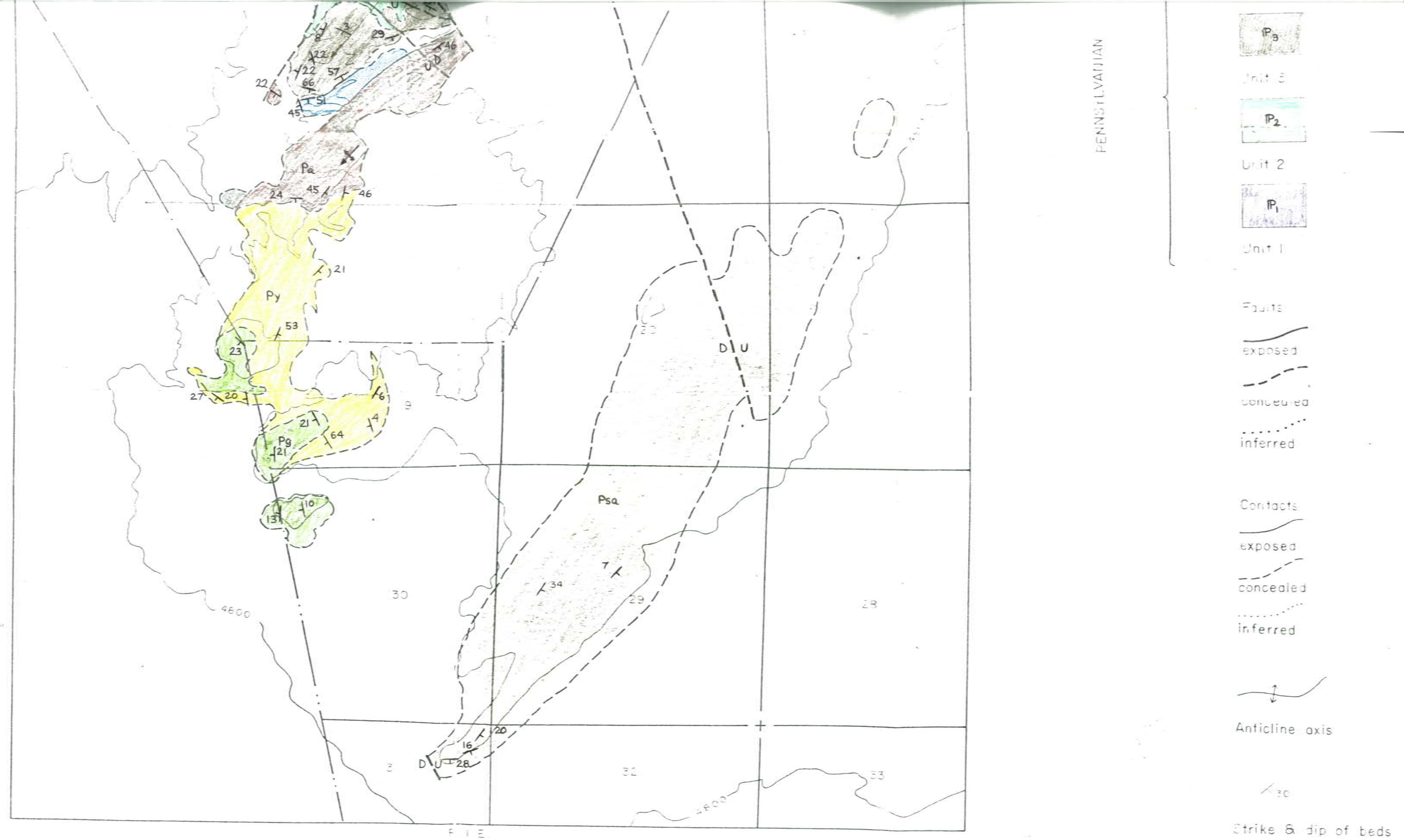
Clay T. Smith

Date: April 29, 1963

PLATE I

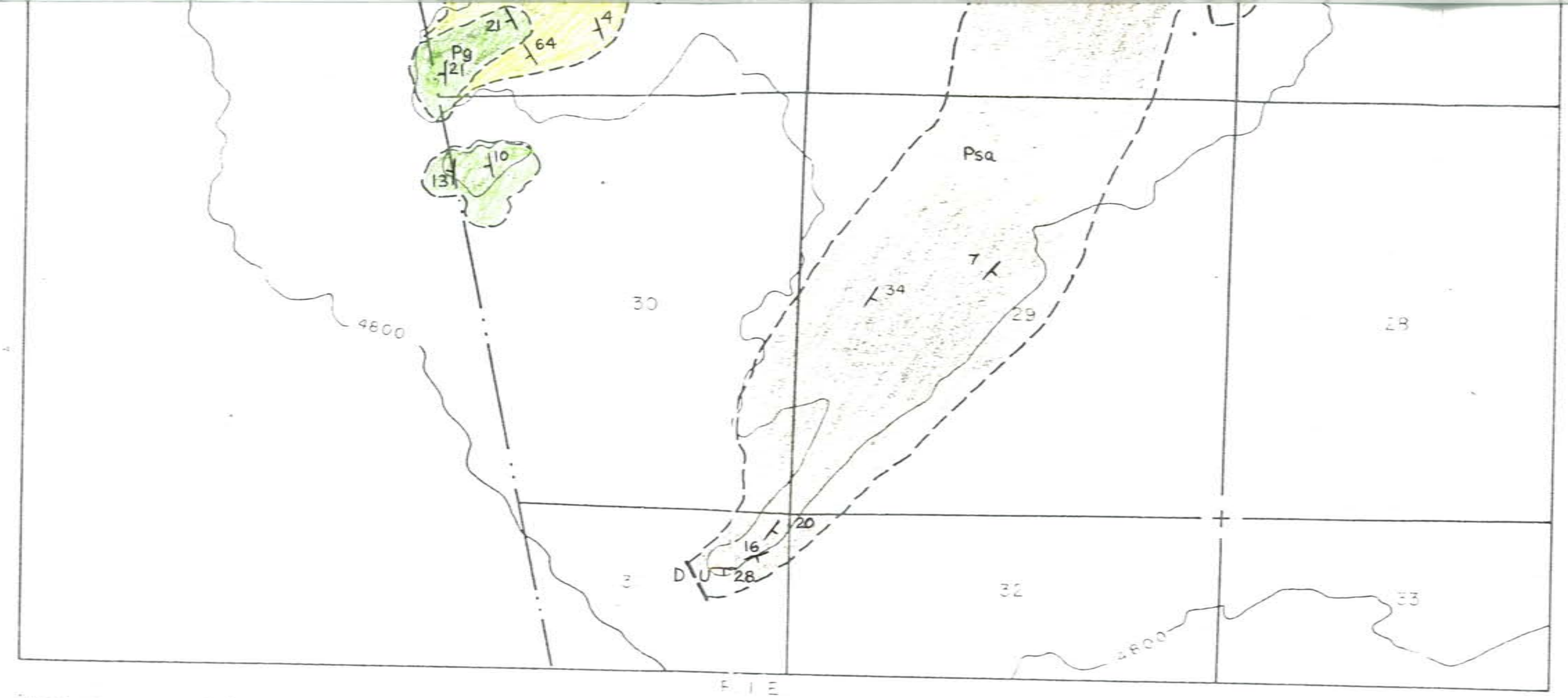

BOSQUE DEL APACHE
NATIONAL WILDLIFE REFUGE
A
A'
Tsf
Ta
Tb
Kd
Pa
P_1
P_2
P_3
P_4
D
U
QUATERNARY
TERTIARY
CRETACEOUS
PERMIAN
Qal
Alluvium
Ta
Andesite
Tsf
Santa Fe Formation
Tb
Baca Formation
Kd
TALUS BLOCK - NOT IN PLACE
Dakota Sandstone
Psa
San Andres Limestone
Pg
Glorieta Sandstone
Py
Yeso Formation
Pa
Abo Formation
P_4
Unit 4
P_3



Base map enlarged from
U. S. Geol. Survey
Val Verde 15' quadrangle

Geology by R. W. Geddes, 1962

EXPLANATION



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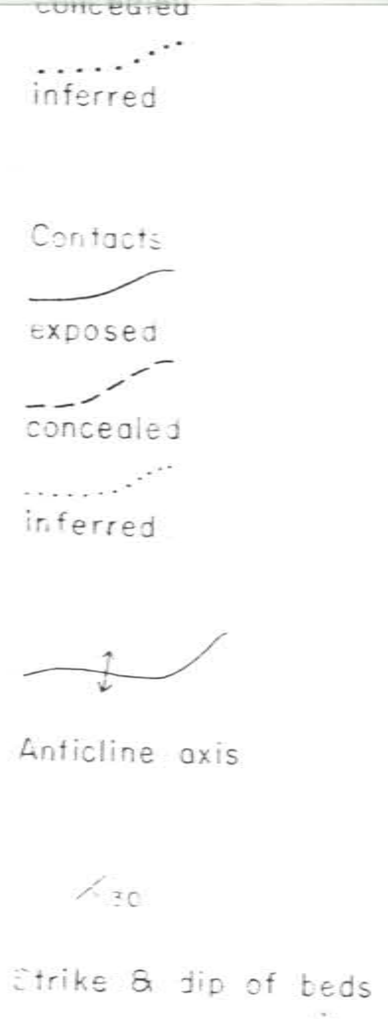

EXPLANATION

GEOLOGY OF LITTLE SAN PASQUAL MOUNTAIN