A GRAVITY STUDY OF THE
SAN LUIS BASIN, COLORADO

BY

GENE HOWELL DAVIS

A GRAVITY AND SUBSURFACE STUDY OF THE SAN LUIS BASIN, COLORADO

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THESIS

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ABSTRACT

The Rio Grande rift is a well-defined tectonic feature which dominates the north-south structural elements of central New Mexico and extends northward into south-central Colorado. The San Luis Basin constitutes the major structural element of this northward extension. A complete Bouguer gravity anomaly map of the San Luis Basin, based on about 5500 gravity stations, shows the basin to consist of two north-northwest trending grabens separated by a central and parallel horst. These features are bounded by faults or fault zones several kilometers wide. Thicknesses of Cenozoic sediments occupying the basin determined from gravity measurement and estimated or measured average rock densities, are typically about 1 km and reach a maximum of 2.9 km (9500 ft) immediately southwest of Crestone, Colorado. This maximum is substantially less than estimates from previous surveys and suggests that the San Luis Basin is not atypical, but instead typical in depth for basins associated with the Rio Grande rift. A broad gravity high can be distinguished from that caused by the intragraben horst and may indicate the presence of an upper crustal intrusive mass beneath the central and western portions of the San Luis Basin. This inferred intrusion occurs in an area of high measured heat flow and may be causally related. Finally, a positive correlation seems to exist between the eastern boundary fault(s) of the central horst within the San Luis Basin and the Pecos-Picuris fault as mapped by Sutherland (1963, 1972) and Mallory

(1960, 1972). This correlation suggests the presence of a zone of crustal weakness in this portion of the North American plate which may have influenced the development of the Rio Grande rift and the San Luis Basin.

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INTRODUCTION

Bryan (1938), who coined the term "Rio Grande depression" to describe the structural element through which the Rio Grande flowed, included the San Luis Basin as a part of this elongate feature. Forty years later, the Rio Grande rift (Fig. 1) is recognized as the structural feature which has dominated the late Cenozoic tectonics of south-central Colorado and central New Mexico. It extends southward from Leadville, Colorado, at least as far as El Paso, Texas (Chapin, 1971).

The San Luis Basin constitutes the major structural element of the Rio Grande rift in Colorado. Although its surficial physiographic boundaries are well defined, its subsurface configuration is incompletely known. A lack of deep oil and gas exploration has hampered geological studies of the subsurface structure, while only three publically available geophysical studies have been completed in the area. A gravity study conducted by Gaca and Karig (1965) produced earth models for profiles across the valley at various points, but their efforts were hampered by the lack of topographic mapping in the area at scales greater than 1:250,000. A seismic reflection study by Stoughton (1977) provided seismic reflection profiles in the extreme northern and east-central portions of the basin and a resistivity survey by Arestad (1977) has outlined some potential geothermal energy sites in the same areas. However, these two surveys are limited in their areal extent and have

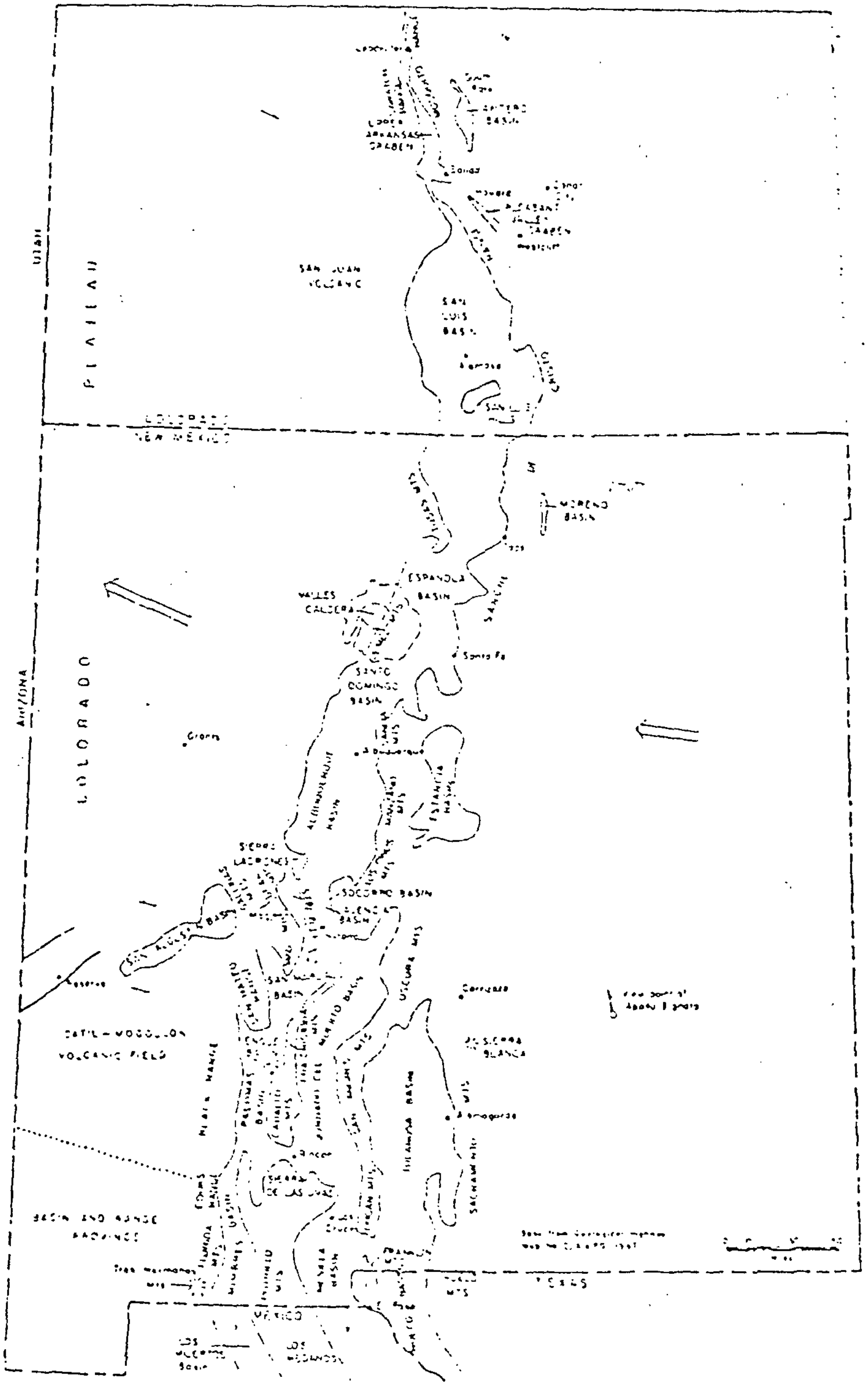

Figure 1. Generalized map of the Rio Grande rift (from Chapin, 1971)

not dealt with the remainder of the basin. An aeromagnetic map of Colorado (Zietz and Kirby, Jr., 1972) has been produced and shows the general structural grain of the basement rocks in the study area, but due to wide flight-line spacing does not lend itself to a detailed structural and subsurface analysis of the basin. Thus, a comprehensive understanding of the subsurface structure in the San Luis Basin and how it relates to the remainder of the Rio Grande rift is not available.

The purpose of this study is to present the results of a detailed gravity study conducted in the San Luis Basin and surrounding regions. By examining the Bouguer anomaly map and earth models produced utilizing these data, the subsurface structure of the basin and its relationship to adjacent areas has been analyzed. It is hoped that these results will further our understanding of this portion of the Rio Grande rift.

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LOCATION AND PREVIOUS WORK

The San Luis Basin is an elongate intermontane valley located in south-central Colorado and extreme northern New Mexico. Stretching approximately 240 kilometers (km) in a north-south direction, it is bordered on the west by the San Juan and Tusas Mountains and on the east by the Sangre de Cristo Mountains. Extending southward from Poncha Pass, the valley is only 10-12 km wide, but widens to approximately 70 km near Alamosa (Fig. 2). The valley floor, although appearing relatively flat, is built from the coalescence of alluvial fans sloping gently outwards from the mountain flanks towards the center of the valley. Fifteen kilometers south of Alamosa, this sloping terrain is broken by the San Luis Hills, a series of flat-topped, low-lying volcanic hills extending along a north-south trend to the Colorado-New Mexico border. Geographically the valley has been arbitrarily defined as terminating 15 miles south of the state line (Siebenthal, 1910). Upson (1939) however has noted that the valley is not a geological entity unto itself and instead merges southward into the Taos Plateau, an idea which has wide acceptance. Kelley (1956), meanwhile, has extended the San Luis Valley to include the Taos Plateau and gives its southern termination as the Embudo constriction near Santa Fe.

Initial reports on the geology of the San Luis Valley and the surrounding mountains were made by Hayden (1869) and Endlich (1877). A more detailed account of its geology and

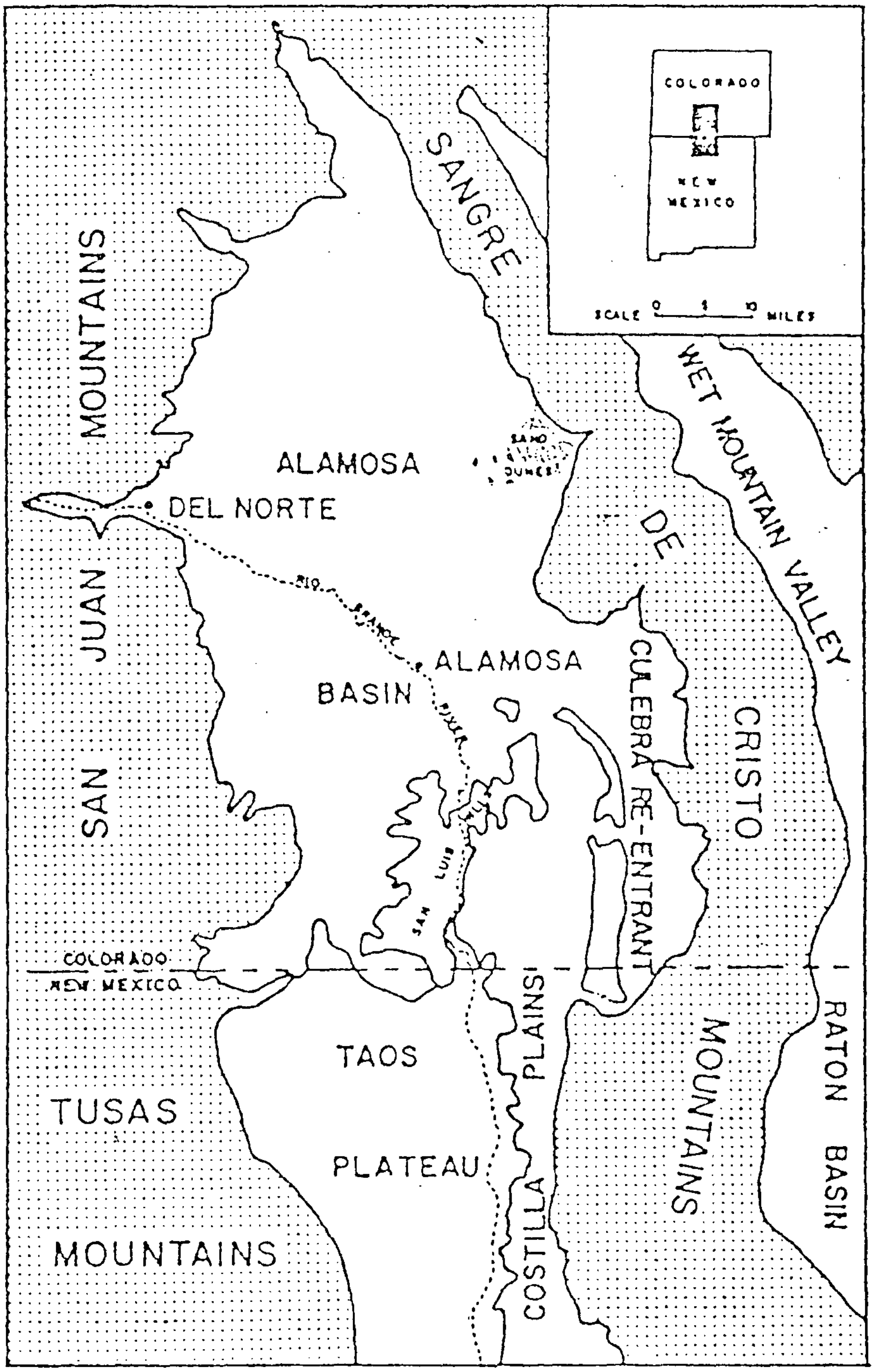


Figure 2. Physiographic subdivisions of the San Luis Valley, Colorado-New Mexico (modified from Upson, 1939)

geologic history was made by Siebenthal (1910). Upson (1939) defined five physiographic provinces in the valley (Fig. 2) and described their topographic and surficial geologic features. The Cenozoic deposits of the valley were described indirectly by Bryan (1938) in his description of the Santa Fe Formation of the Rio Grande rift area. Powell (1958) described these formations in greater detail and gave descriptions from logs of wells drilled in the valley. Baltz (1965) also described the Cenozoic faulting and sedimentation in the northern portion of the San Luis Valley. Several studies of the tectonic history of the valley and the northern Rio Grande rift in general have been completed (Bridwell, 1976; Kelley, 1952, 1956; Chapin, 1971; Chapin and Seager, 1975; Knepper and Maars, 1971; Knepper, 1975; and others).

The San Luis Hills have been discussed briefly by various authors, including Atwood and Mather (1932), Upson (1939), and Larsen and Cross (1956), while a more complete analysis of the area has been presented by Burroughs (1971).

Numerous field studies have been completed concerning the geology of the Sangre de Cristo Mountains (Burbank and Goddard, 1937; Gableman, 1951; Litsey, 1958; DeVoto <u>et al</u>., 1971; and others). In addition, a number of unpublished theses by students of the Colorado School of Mines have dealt with the perplexing geology of the northern portion of the range.

A host of studies have been completed concerning the geology and geochemistry of the San Juan Mountains and the volcanic series exposed therein. These include Atwood and Mather's (1932) discussion of the Quaternary physiography and geology, and Larsen and Cross' (1956) study of the complex pre-Quaternary geology and petrology, especially that of the Cenozoic volcanic series. Lipman and others (1970, 1978), through the use of K-Ar dating and Pb and Sr isotope studies, respectively, have studied the volcanic history of the region and have postulated a petrologic evolution of this volcanic suite. The results of a gravity survey performed in the region by Plouff and Pakiser (1971) have indicated the possible presence of a near-surface batholith beneath the San Juan volcanic pile, a theory which has gained much support in recent years.

GEOLOGIC HISTORY AND TECTONIC SETTING

Precambrian

The Precambrian history of the San Luis Valley, although incompletely known, is apparently complex. The entire west flank of the Sangre de Cristo Range in Colorado and northern New Mexico, as well as portions of the Wet Mountains and the Tusas Mountains are composed of Precambrian rocks. Examination of these exposures suggests the following rather simplified geologic history. Numerous sedimentary sequences of probable early Precambrian age were tectonically deformed and intensely metamorphosed during middle Precambrian time into folded sequences of gneissic and schistose metasediments. These, in turn, were intruded by middle to late Precambrian (Hedge, 1972) plutons of silicic and intermediate compositions which were probably orogenically emplaced. Although evidence of uplift accompanying this supposed orogenic activity is sketchy, depths of erosion in the larger plutonic bodies do indicate extensive erosion (Boyer, 1962) and therefore uplift. Also, nonconformities are found to occur between the Precambrian crystalline basement and the overlying Paleozoic rocks (Litsey, 1958). Sutherland (1972) has documented approximately 23 km of Precambrian-age right lateral strike slip movement on the Pecos-Picuris fault in northern New Mexico. In fact, numerous faults which border the present Precambrian exposures have been suggested to have been tectonically active during Precambrian time (Tweto, 1975).

Early and Middle Paleozoic

At the close of the Precambrian era the study area was a part of a broad, relatively stable, positive element known as the Transcontinental Arch which, in Colorado, was composed of two highlands, Siouxia and Sierra Grande, bisected by a shallow trough, the Colorado Sag (Fig. 3). Pre-Pennsylvanian sedimentation was controlled by this tectonic feature. Relatively uniform accumulations of clear-water carbonate rocks and clean quartzose sandstones separated by disconformities indicate that epeirogenic events caused transgression and regression of the eastern and western epeiric seas across the area and accompanying periods of erosion. The absence of Silurian rocks in the area is probably due to one such period of widespread erosion during late Silurian to middle Devonian time (Haun and Kent, 1965) rather than to nondeposition (Fig. 4). The best preservation of pre-Pennsylvanian strata in the study area is in the Kerber Creek region of the northern San Juan Mountains where thicknesses of the section average between 200 and 350 meters (Knepper and Maars, 1971), and in the northern Sangre de Cristo Range where varying thicknesses of the same order are observed (Litsey, 1958). These two areas were located in a shallow trough, the Colorado Sag (Fig. 3), which probably received thicker accumulations of these pre-Pennsylvanian sediments. Broad regional uplift and widespread erosion occurred throughout the study area at the end of late Mississippian time and continued into the early Pennsylvanian.

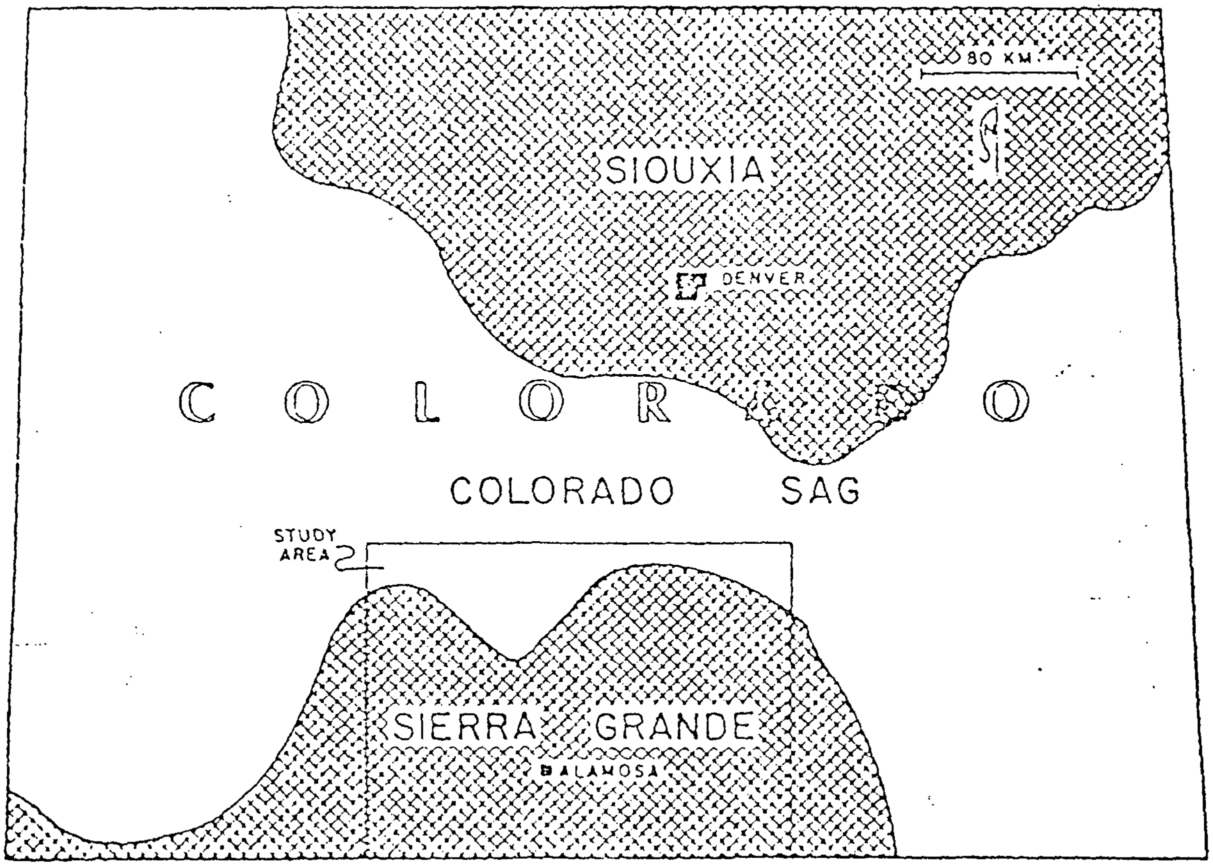


Figure 3. General outline of early Paleozoic highland areas in Colorado (modified from Berg, 1960)

AGE			UNIT	THICKNESS (IN FEET)
CENOZOIC	Quaternary	RECENT & PLEISTOCENE	Alamosa Fm.	0-5000?
			Servilleta Basalt	0-1000?
	TERTIARY	PLIOCENE and/or MIOCENE	Santa Fe Fm.	0-5000?
			Hinsdale Basalt	0-1000?
			Los Pinos Gravel	0-1300?
			Devils Hole Fm.	25-1300
		OLIGOCENE	Volcanics of the San Juan Mts.	
			Farisita Cong.	0-1200
		EOCENE	Huerfano Fm.	0-2000
			Cuchara Fm.	0-5000
		PALEOCENE	Poison Canyon Fm.	0-2500
			Raton Fm.	0-1700
MESOZOIC	CRETACEOUS		Vermejo Fm.	200-550
			Trinidad Ss.	0-300
			Pierre Sh.	0-2300
			Niobrara Fm.	500-630
			Carlisle Sh.	165-235
			Greenhorn Lm.	30-80
			Graneros Sh.	185-380
			Dakota Ss.	100-150
			Purgatoire Fm.	115-195
	JURASSIC		Morrison Fm.	200-400
			Ralston Creek Fm.	50-100
			Entrada Ss.	0-100
	TRIASSIC		Dockum Group	0-800
PALEOZOIC	PERMIAN		Sangre de Cristo Fm.	6300-9500
	PENNSYLVANIAN		Whiskey Creek Pass Fm.	150-300
			Minturn Fm.	2000-5500
			Sharpsdale Fm.	900-1200
			Kerber Fm.	100-300
	MISSISSIPPIAN		Leadville Lm.	210-330
	DEVONIAN		Chaffee Fm.	95-185
	ORDOVICIAN		Fremont Fm.	230-300
			Harding Ss.	60-116
			Manitou Fm.	90-225
	CAMBRIAN		Sawatch Qtzt.	0-20
PRECAMBRIAN				

Figure 4. Generalized stratigraphic column for south-central Colorado

Pennsylvanian and Permian

Orogenic activity manifested itself in Pennsylvanian and Permian time in the central United States with the vigorous uplift of the Ancestral Rocky Mountains. In central Colorado, these mountains consisted of two northwest-southeast trending highlands known as the Front Range Highland and the Uncompahgre Highland. These uplifts were separated by a narrow depositional basin, the Central Colorado Trough, a feature which has also been described as a graben (DeVoto and Peel, 1968). The study area was located on the eastern flank of the Uncompahgre Highland and was cleaved in two by its southeastern boundary, the Pecos-Picuris fault (Fig. 5).

A mixture of fluvial sediments grading upward into shallow-water carbonates dominated initial sedimentation in the Central Colorado Trough. By Atokan time, pronounced uplift of the Uncompahgre Highland resulted in the exposure of the Precambrian crystalline basement and the widespread deposition of red arkosic alluvial deposits within the Central Colorado Trough (DeVoto and Peel, 1972). Relief on this Pennsylvanian uplift may have been as great as 3 km (Mallory, 1972). Late Pennsylvanian deposits were largely influenced by this earlier faulting, with thicknesses varying laterally along the trough. Rocks of this age indicate a shallow coastal plain environment (DeVoto _et al_., 1971).

Renewed uplift of the Uncompahgre Highland in early Permian time drastically changed sedimentation in the adjacent

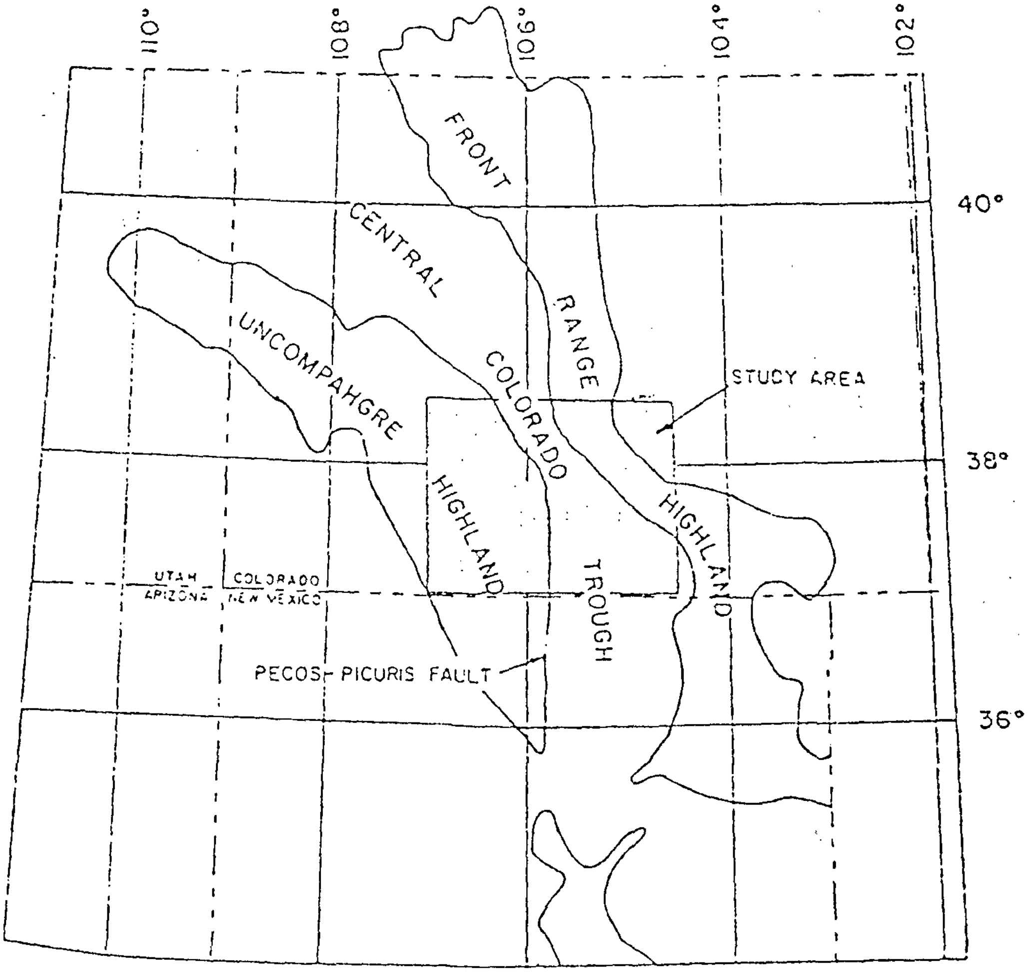


Figure 5. General outline of major Pennsylvanian and Permian highland areas in Colorado

basin. Rapid erosion of the rising Precambrian massif developed thick deposits of continental arkosic sandstones and conglomerates. Repeated movements along the bounding fault(s) triggered periods of vigorous erosion of the upland, thereby imparting a cyclic character to the deposits. Deformation of this nature continued until late Permian time when the basins, filled with detritus, encroached on the adjacent uplifts and reduced their topographic relief (DeVoto and Peel, 1968). In all, an average of 4500 meters of Pennsylvanian and Permian sediments were deposited in the Central Colorado Trough.

Mesozoic

Rocks of Mesozoic age do not occur in the San Luis Valley. However, the presence of a thick Mesozoic section in the neighboring Raton Basin and the San Juan Mountains, as well as scattered outcrops in the southern Wet Mountains and central Sangre de Cristo Range (Baltz, 1965), indicate that Mesozoic sediments once covered the study area but have been removed by widespread erosion associated with uplift of the region during the late Cretaceous-early Tertiary Laramide orogeny (Knepper and Maars, 1971).

At the close of Permian time, the once-towering uplifts of the Ancestral Rocky Mountains existed only as erosional remnants. Regional stratigraphic evidence supports the existence of these remnants until late Jurassic time when Morrison age, continental fluvial sediments finally buried them (Oriel and Craig, 1960). Early Cretaceous time saw the encroachment of an epeiric sea from the east which continued to transgress westward across the study area through middle and early late Cretaceous time, depositing as much as 1500 meters of marine sediments in the region (Haun and Weimer, 1960). Sedimentation of this nature ended with the initiation of the Laramide orogeny in late Cretaceous time.

Laramide Orogeny

In southern Colorado, the Laramide orogeny began in the late Cretaceous (Fox Hills time) and lasted into the late Eocene (Haun and Kent, 1965). The structural development of this region has been described as being the result of a few distinct phases of deformation; however, Tweto (1975) has characterized the orogeny as the northeastward advance of an irregular orogenic front across south-central Colorado, with uplift occurring "along a central axis and expanding outward as it extended upward." Many of the present structural elements existing in the southern Rocky Mountains were formed by this orogenic activity.

In the study area, the initial manifestation of the Laramide orogeny was the emergence of a highland located in the area of the southern San Luis Valley, Sangre de Cristo Mountains, and San Juan Mountains. This uplift, here called the San Luis Uplift, coincided with the southeastern extension of the Late Paleozoic Uncompahgre Highland and was most probably a rejuvenation of this tectonic feature (Tweto, 1975). Sediments eroded from this highland were deposited in subsiding basins which flanked it, the San Juan on the southwest and the Raton on the east (Baltz, 1965; Tweto, 1975). Laramide tectonic features of Paleocene age (Tweto, 1975) exposed along the eastern flank of the Sangre de Cristo Range and its bordering basins; the Wet Mountain Valley, Huerfano Park, and the Raton Basin (Fig. 6), illustrate that as uplift of the San Luis Highland spread laterally, folding of the sedimentary rocks exposed on the flanks gave way to steep reverse faulting, overthrusting, and folding of the thrusts (Tweto, 1975; Burbank and Goddard, 1937; Briggs and Goddard, 1956). By middle Eocene time, Laramide orogenic activity had ceased and by late Eocene time an erosional surface of low relief which truncated all major Laramide structures, had developed in the region north of the San Luis Valley (Epis and Chapin, 1975). This erosional surface probably existed in the study area as well, as is suggested by the fine-grained nature of the Huerfano Formation in the Raton Basin, and is probably hidden beneath the subsided San Luis Basin.

Middle and Late Cenozoic

Following the end of Laramide orogenic activity in late Eocene time, large scale volcanism and plutonism occurred during a time of neutral stress (Chapin, 1974) in the area of the southern Rocky Mountains. The existence of an enormous

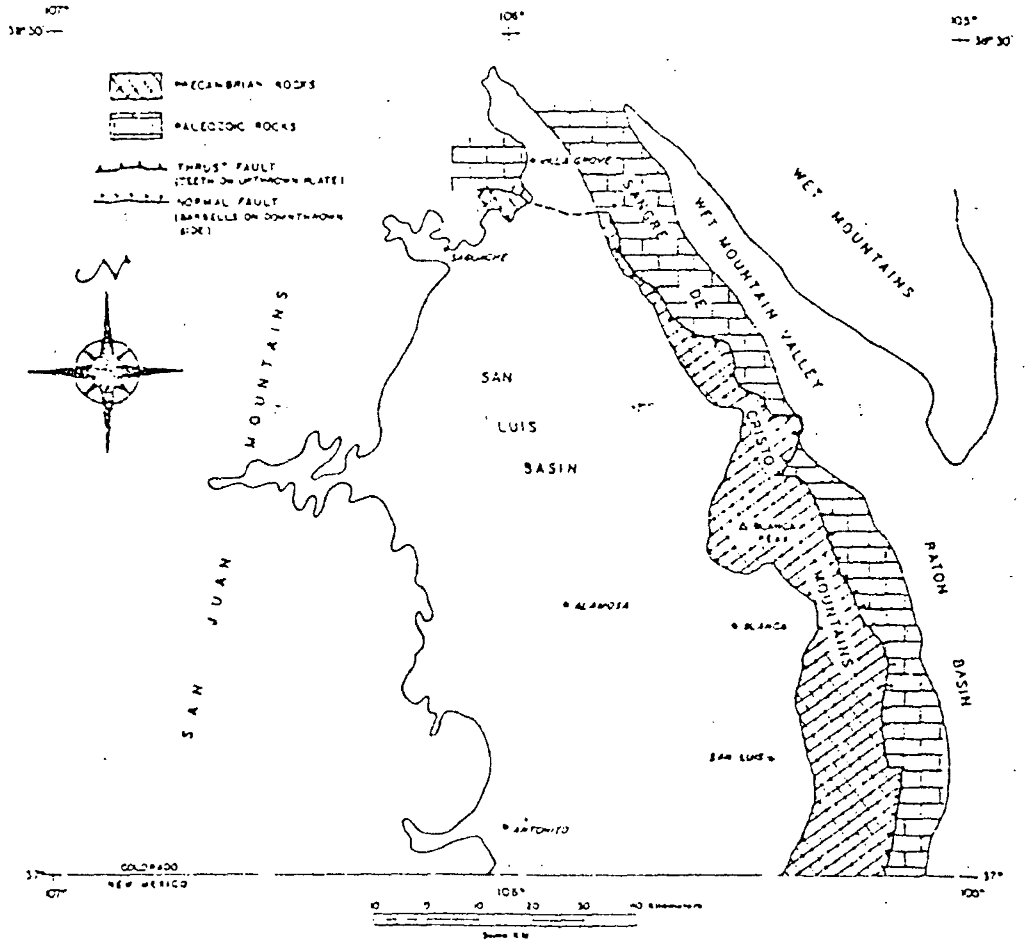


Figure 6. Map showing Laramide boundary between Precambrian and Paleozoic rocks exposed in the Sangre de Cristo Mountains, Colorado

Oligocene volcanic field in south-central Colorado built upon the late Eocene erosional surface mentioned above has been postulated by Steven and Epis (1968) and Steven (1975). This field can be envisioned as a composite volcanic plateau composed of central volcanoes of intermediate composition with associated lavas, breccias, and volcanoclastic rocks which were modified by the eruption of voluminous ash-flow sheets from large calderas (Lipman and Mehnert, 1975). This volcanic terrain has been suggested to extend from the western rim of the San Juan Mountains to the western edge of the Great Plains (Steven, 1975). In the study area, evidence for the existence of this continuous volcanic field is obscured beneath the subsided San Luis Valley, but is supported by the existence of remnant volcanics overlying early Tertiary sediments in the Culebra Reentrant (Fig. 2) of the eastern San Luis Valley (Upson, 1939), by Oligocene-Miocene paleovalleys on the eastern slope of the northern Sangre de Cristo Range (Taylor, 1975), and by volcanics encountered in drill holes at various locations within the valley.

Geophysical studies (Plouff and Pakiser, 1972; Tweto and Case, 1972) and the presence of numerous intermediate and silicic stocks of Oligocene age within the source areas of the proposed volcanic field indicate the existence of a shallow batholith beneath the large volcanic pile. This volcano-plutonic association of predominantly intermediate compositional types has been interpreted to reflect the innermost expression of convergent plate tectonic interactions between the American and Farallon plates during early and middle Cenozoic time (Lipman *et al*., 1972).

In late Oligocene or early Miocene time, a major change in volcanic associations and their tectonic settings occurred in the study area. A transition from a neutral stress field (Chapin, 1974) to one of extensional faulting and fundamentally basaltic volcanism (Christiansen and Lipman, 1972) brought about the initiation of normal faulting in the San Luis Valley region and the inception of the Rio Grande rift. This change in tectonic setting has been correlated with the collision of the East Pacific Rise with the American plate and their contact along a right-lateral transform fault (Atwater, 1970; Christiansen and Lipman, 1972; Lipman and Mehnert, 1975).

Bryan (1938) originated the concept of the Rio Grande rift when he suggested that the basins through which the Rio Grande flowed were a structural depression, and he included the San Luis Valley as a part of this elongate feature. Kelley (1956) modified the structural depression concept, describing it as a series of linked, en-echelon grabens with a northerly trend. Chapin and Seager (1975) have described the rift as an intracratonic continental rift which has been superimposed on a north-trending tectonic belt which had been deformed during Laramide, late Paleozoic, and probably late Precambrian time. Chapin (1971) has proposed a possible tectonic model for the Rio Grande rift which is described below.

The plate west of the rift is moving westward at a faster ra than the continental interior, resulting in the splitting of the Colorado Plateau block from the Great Plains at the site of a mantle bulge. As the eastern block overrides this bulge it develops greater structural relief than the western block. Crustal extension on the western side of the rift develops normal faults which relieve subcrustal pressures and provide avenues for the ascent of magmatic material which explain the prevalence of post Oligocene volcanic eruptions on the wester side of the rift. Normal faults developed on the eastern sid of the rift are kept tight and therefore free of volcanism by northwestward drift and rotation of the Colorado Plateau. Lipman (1969), in studying the petrologic evolution of the basalts exposed in the rift and along its borders, has provid evidence supporting Chapin's model. However, Christiansen an Lipman (1972) feel that the driving force for opening of the rift has been an oblique release of tensional forces built-up along the San Andreas transform fault zone.

The San Luis Valley is the major element of the Rio Grande rift in southern Colorado, and thus is the key to understanding the history of the rift in this area. Siebenthal (1910) first suggested that widespread volcanism and uplift of the mountains adjacent to the San Luis Valley occurred in Miocene time. Kelley (1956) restated this opinion and attributed the initial development of the Rio Grande rift to late Miocene structural movements. Lipman and Mehnert (1973, 1975) described the basalt chronology of the San Juan Mountains of southwestern Colorado and have demonstrated that basalts of earliest Miocene age (26 m.y. old) are found to overlie a late Oligocene erosional surface developed on 27 m.y. old tuffs. These tuffs were deposited uniformly across the positions of later normal faults associated with the subsidence of the San Luis Valley. Moreover, they show that similar basalts overlie and interfinger with volcanoclastic and alluvial fan deposits which accumulated in the subsiding basin. Therefore, subsidence of the San Luis Valley, at least along its western edge, can be identified as beginning in earliest Miocene time.

Unfortunately, the uplift of the Sangre de Cristo Mountains is not so well documented. The range is largely formed by a Precambrian crystalline massif which has been upthrust by Laramide tectonic events against rocks that were deposited in the late Paleozoic Central Colorado Trough. This range was probably a part of the eastern flank of the Laramide San Luis Uplift and has been split from that feature by the present steep western boundary fault(s) of the range. Taylor (1975) has postulated that the present Sangre de Cristo Range is a horst between two grabens, the San Luis Basin and the Wet Mountain Valley (Fig. 2). Structural relief of this horsted block may be as great as 8 km on the west (Gaca and Karig, 1965), and as great as 3 km on the east (Taylor, 1975). Baltz (1965) and Tweto (1975), meanwhile, have set a middle Miocene age for uplift of the range while Taylor (1975) has indicated that uplift could occur no later than 29 m.y. ago. In view of the tectonic setting of the San Luis Valley, it would not seem unreasonable to expect a similar age for subsidence of the eastern portion of the basin as for the western portion. However, recent palynologic data from the Amoco Mapco State 1-32 well (Fig. 7) suggest that the sediments penetrated by drilling record a single, relatively uninterrupted period of alluvial deposition from Paleocene to Pliocene time (Huntley, 1979). This data suggests an early Cenozoic date for the initiation of subsidence in the San Luis Valley and reflects the uncertainty present in forecasting the time of the inception of rifting along the eastern edge of the San Luis Basin. Fault scarps on either side of the range are largely obscured by Quaternary alluvial fans, but recent movement along the western boundary fault in the extreme northern portion of the San Luis Valley has been documented (Knepper and Maars, 1971).

Therefore, the San Luis Valley is a north-trending graben which has been filled by Miocene-Pliocene volcanoclastic sediments and interlayered basalt flows and Quaternary alluvial fan deposits (Baltz, 1965). Gaca and Karig (1965) have shown that the basement configuration of the valley consists of a series of subparallel, north-trending horsts and grabens. These features are mantled by volcanic rocks of Oligocene age which covered the area prior to subsidence. A narrow fault-bounded trough extended northward from the San Luis Valley into the Arkansas Valley in middle Miocene time (Van Alstine, 1968,

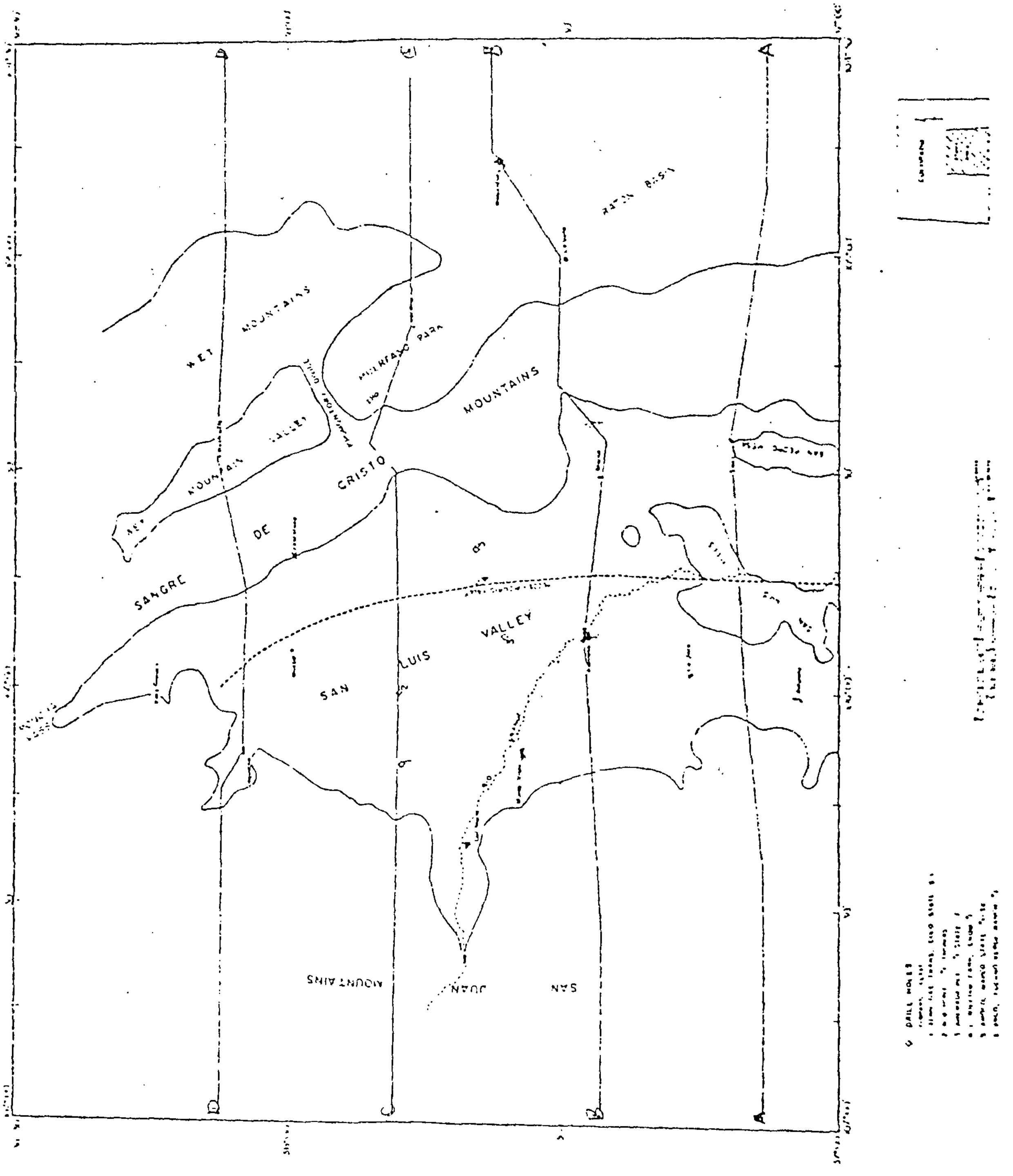


Figure 7. Map of San Luis Valley and adjacent areas showing location of major physiographic provinces, principal cities and rivers, drill holes, gravity profiles, and the Pecos-Picuris fault as suggested by Mallory (1972)

1970) and was filled with sediments of the Dry Union Formation, an equivalent to the Santa Fe Formation of the Rio Grande rift of southern Colorado and northern New Mexico (Van Alstine, 1970). However, this trough was fragmented by Pleistocene movement along transverse faults in the vicinity of Poncha Pass (Knepper and Maars, 1971) which has left the Arkansas Valley and the San Luis Valley as separate geographic entities, although their mode of origin was probably the same (Tweto and Case, 1972).

DATA REDUCTION

During this study, approximately 1200 gravity readings were made in the San Luis Valley and surrounding areas (Fig. 7) during the 14-month period from September 1976 to November 1977. Three different Worden, Educator model, gravity meters were used during the course of the survey; Worden #229, owned by the University of Texas at El Paso, and Worden #393 and Worden #90, both on loan to the University from the U. S. Geological Survey. Eighty-five percent of these readings were made with Worden #393.

A Department of Defense gravity base station located at the Blue Peaks Learning Center in Alamosa, Colorado (IGB, 11975B), which is a part of the International Gravity Standardization Net 1971, functioned as the primary base station for the entire survey. Supplementary base stations were established at Westcliffe and LaVeta, Colorado (Appendix A) with gravity values determined relative to the Alamosa base by averaging meter readings from multiple occupations. These base stations are believed to have an accuracy of approximately 0.1 mgal (milligals) relative to the Alamosa base.

Field procedure was to occupy the same base station at the beginning and end of each gravity traverse. These traverses normally lasted an entire day, usually from shortly after sun-up till sundown. Whenever possible, a tie with a previous traverse, a repeat within the traverse, or an occupation of a supplementary base station was included in each traverse in order to maintain internal control. Instrument drift and earth tidal effects were considered together, and generally ranged from 0.1 mgal to 0.6 mgals per traverse. This drift was assumed to be linear after repeats within the first traverse of each field expedition showed deviation from linearity to be minimal.

Gravity stations were established at benchmarks and at photogrammetric elevations such as road intersections, fence lines, and wells that were located from and plotted on 7.5 minute, or when necessary, 15 minute topographic quadrangles. Horizontal location of the gravity stations then is considered to be correct to within 50 feet for most stations and vertical accuracy is within five feet. Precise latitudes and longitudes for each station were determined using a Calma 450 VIP digitizer with an accuracy of 0.005 of an inch. A station spacing of approximately two miles was maintained wherever possible, but the spacing was generally less dense in the more rugged portions of the study area. Raw data recorded at each station consisted of a station identification number, elevation of the station, meter reading in dial units, and elapsed time from initial base station occupation.

Reduction of the raw data was accomplished in three stages. Calculations of gravity anomaly values were made at the University of Texas at El Paso using standard gravity reduction techniques. For the sake of standardization, these calculations were repeated at the facilities of the U. S. Geological Survey in Denver, Colorado, using:

a. A Bouguer density of 2.67 gm/cc;

b. Values of theoretical gravity calculated using the International Gravity Formula of 1967; and

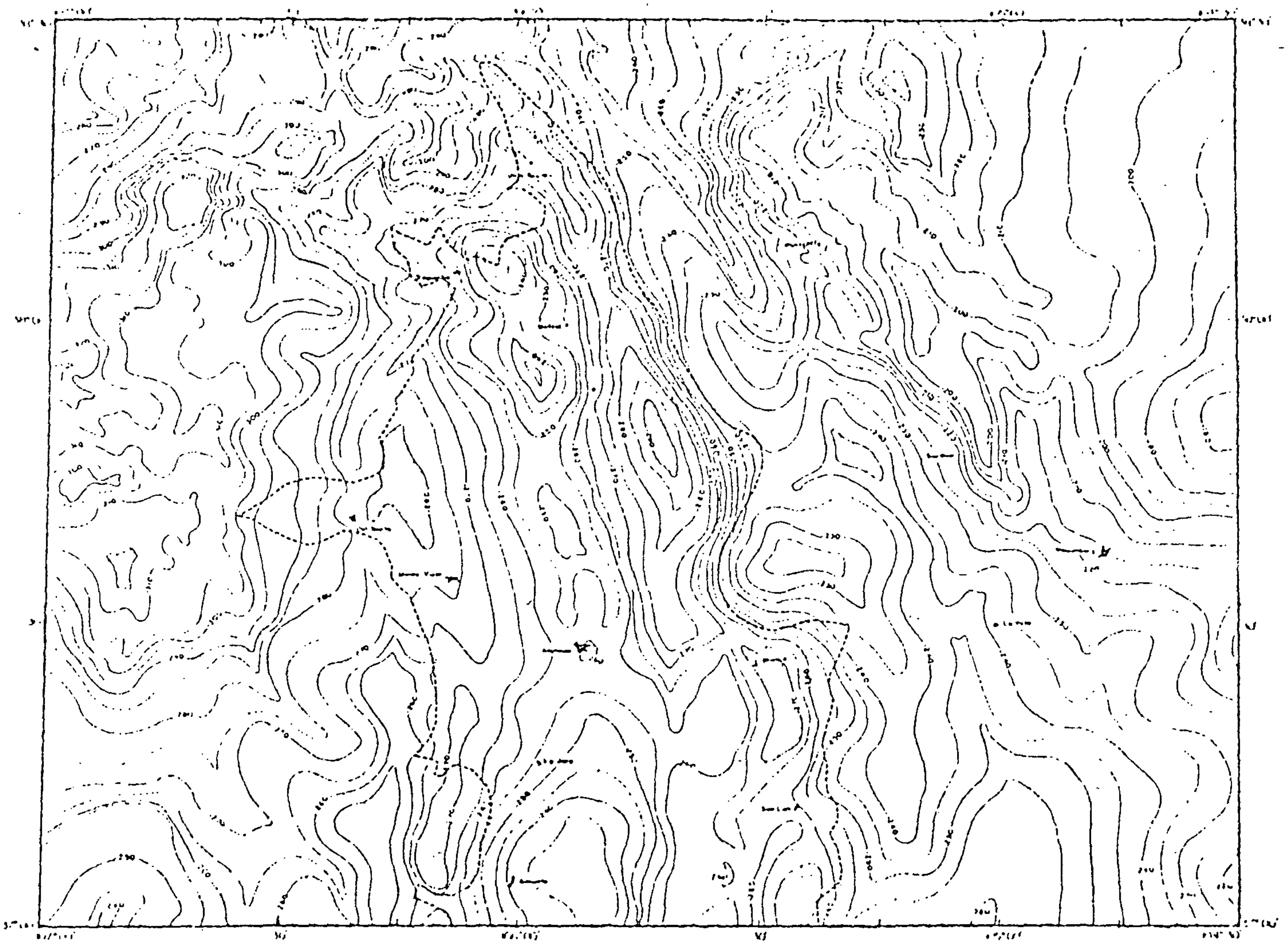
c. A curvature correction using the formula shown below:

$$cc = \text{elev.}*(1.4639108e - 3 + \text{elev.}*(4.449648e - 14 * \text{elev} - 3.5327153 - 7)).$$

Final reduction to complete Bouguer gravity values was accomplished by calculating terrain corrections for each station for regions within a radial distance of 166.7 km.

This final step was carried out in two stages. First, inner zone terrain corrections were hand calculated using the template method of Hammer (1939). Inner zones are defined as Hammer's (1939) zones A to H (radial distance 0 to 2.7 km). After calculating this correction for 50 stations made in the San Luis Valley, it was determined that the average correction for stations made anywhere on the valley floor was less than 0.01 mgal because of the extremely flat topography. This value is insignificant; thus, inner zone terrain corrections were calculated only for stations in regions of rugged topography. Secondly, outer zone (2.7 to 116.7 km) terrain corrections were calculated for all stations using a computer routine devised by Plouff (1966). The inner and outer zone corrections were then added to the simple Bouguer anomaly value to give a complete Bouguer anomaly value. Principal facts for all stations taken by the author are included in Appendix B.

Approximately 3500 gravity readings were carefully selected from the files of the Department of Defense gravity library and combined with the almost 1200 readings made during this survey to produce a file of gravity values for the area bounded by the longitudes and latitudes 104°W and 107°W and 37°N and 38°30'N, respectively. These additional stations were also corrected for outer zone terrain effects using Plouff's (1966) method, and a few critical ones were corrected for inner zone effects. The final step in computer reduction and processing of the data was to produce a complete Bouguer gravity map of the above area using this large data file (Fig. 8).



BOUGUER GRAVITY MAP OF THE SAN LUIS VALLEY AND ADJACENT AREAS, COLORADO

by Gene Howell Davis

[illegible]

Sea Level Datum

Contour Interval 5 milligals

Bouguer Density 2.67 gm/cc.

Figure 8. Bouguer gravity map of the San Luis Valley and adjacent areas, Colorado

REGIONAL ANOMALIES

Figure 7 illustrates the principal cities, rivers and physiographic-geologic provinces located in the study area. This figure is meant to be an underlay to the complete Bouguer gravity map shown in Figure 8, and can be visually superimposed by aligning the outline of the San Luis Basin. Each of the major geologic features located in the study area is represented by major Bouguer gravity anomalies which are described below.

A large, subcircular gravity minimum of up to 30 mgal is associated with the San Juan Mountains. The outline of this anomaly can be drawn along the -290 mgal contour on Figure 8. Plouff and Pakiser (1972) attributed this anomaly to a mid-Tertiary igneous complex of batholithic proportions whose depth beneath the surface is between 2 and 7 km. Case (1966) and Tweto and Case (1972) have suggested the existence of a similar batholithic body of composite Laramide and mid-Tertiary age to underlie the Colorado mineral belt and the southern Sawatch Range. Steven (1975) has postulated that this mid-Tertiary batholith indeed extends from the San Juan Mountains northeastward beneath the Sawatch Range, thereby forming a subsurface buttress to the San Luis Basin on the north and west. If the -290 mgal contour is outlined on Figure 8, as suggested above, the shape and position of this mid-Tertiary batholith becomes clear and supports Steven's (1975) hypothesis.

The eastern flank of the San Luis Basin is bordered by the Sangre de Cristo Range, which is the northern segment of the Sangre de Cristo Mountains. The structure of the range is complex and inadequately studied, but its gross physiographic expression is that of a horsted block. Precambrian rocks crop out along the western edge of the range, while Paleozoic rocks, especially a thick section of Pennsylvanian and Permian sedimentary rocks, crop out along the crest and eastern flank of the range. The width of the Precambrian exposures increases to the south, where the character of the gravity anomaly associated with the range also changes.

On the gravity map (Fig. 8), the Sangre de Cristo Range is discernible as an arcuate gravity high, convex to the east, with a maximum closure of 15 mgals which can be divided into two distinct segments by a line drawn from Westcliffe to Blanca. The northern half of the range is a narrow, linear feature bounded on either side by steep gravity gradients of 5 mgals/km. These gradients indicate the location of the major boundary faults of this portion of the range, the Sangre de Cristo fault on the west and the Alvarado fault on the east (Taylor, 1975), both of which are steep normal faults. The southern half of the range is somewhat broader than the northern half owing to the broadening exposure of Precambrian rocks. A closed high of 15 mgals, which is centered around the Blanca Peak Precambrian massif and extends 70 km to the south, exemplifies this broadening. The western margin is still marked by the Sangre de Cristo fault, but the gravity gradient associated with it lessens to 2 mgals/km. The eastern margin becomes somewhat diffuse in the southern half of the Sangre de Cristo Range. This is caused by the juxtaposition of a thick Pennsylvanian-Permian sedimentary section on the eastern flank of the range and the thick Mesozoic-Paleozoic sedimentary section in the downfaulted Raton Basin.

A small gravity high appears to connect the gravity high of the Sangre de Cristo Range to that of the Wet Mountains at the approximate location of Promontory Divide (Fig. 7), the physiographic divide between the Wet Mountain Valley and Huerfano Park. This gravity ridge may indicate an upwarp of Precambrian and/or Paleozoic rocks which acts as the northern boundary of the Raton Basin and serves to separate the Miocene Wet Mountain Valley from the Laramide Raton Basin.

A linear gravity high of up to 20 mgals, 85 km in length and 25 km in width, defines the outline of the Wet Mountains and DeWeese Plateau (Fig. 7). This range is composed of Precambrian basement rocks and scattered outcrops of Oligocene volcanic rocks which were uplifted in late Tertiary time. Steep gravity gradients mark the east and west flanks of the range and coincide with the postulated positions of the Wet Mountain and Westcliffe faults (Taylor, 1975; Tweto, 1976), respectively. A steep gradient at the northern terminus of the Wet Mountain-DeWeese Plateau anomaly coincides with the approximate location of the Arkansas River and may indicate the juxtaposition of two significantly different density units, possibly along a faulted contact.

Huerfano Park, which merges southward into the Raton Basin, is characterized by a semicircular gravity anomaly, open to the south. This small basin is associated with a maximum closure of 10 mgals which is centered just west of Gardner. The interconnecting nature of these two basins can be seen by the arcuate low which extends southward from Huerfano Park into the Raton Basin. This low becomes more pronounced to the south, indicating a deepening basin.

The San Luis Basin, which is the main focus of this study, occupies the central portion of the study area (Fig. 7) and, as has been described above, is bounded on the north and west by the San Juan Mountains and on the east by the Sangre de Cristo Mountains. Its gravity signature is that of three north-northwest trending anomalies, two lows flanking a central high. Each of these anomalies is composed of distinct en-echelon segments and they have been interpreted as the signature of two grabens flanking a central horst (Gaca and Karig, 1965).

The easternmost low is composed of four en-echelon closures and is slightly offset to the west along a line extending from Alamosa to Blanca (Fig. 8). This low extends southward from Poncha Pass (Fig. 7) into northern New Mexico

(Cordell, 1978, personal communication). Its maximum closure is 20 mgals and its total relief ranges from 20 mgals to a maximum of 60 mgals near Crestone and Moffat (Fig. 8). Gravity gradients bounding it range from 2 mgal/km to 5 mgal/km. At its northern end, this low is terminated by a linear gravity high near Poncha Pass which corresponds to a Neogene fault separating the San Luis Basin from its northern extension, the upper Arkansas Valley (Van Alstine, 1968, 1970; Taylor, 1975). The eastern flank of this low is bounded by the late Tertiary Sangre de Cristo fault and the strong gravity gradient present suggests the presence of large scale faulting.

Parallel and west of this low is a pronounced gravity high which is separated into two segments by a saddle centered at Alamosa. The first segment (north of Alamosa) is composed of three distinct closures. Maximum closure of this high is 25 mgals with a maximum relief of 55 mgals on the east and 45 mgals on the west. The southern segment, centered just east of Antonito and underlying the San Luis Hills (Fig. 7), is a high with a maximum closure of 20-25 mgals and a relief of 30-35 mgals. The gradients bounding the entire length of this central high range from 2 mgal/km to 5 mgal/km and suggest a faulted contact between it and the adjacent lows. This central high ends abruptly to the north where it abuts the large low associated with the mid-Tertiary batholith of the San Juan Mountains.

Another linear low comprised of two closures is located to the west of this central high. This composite low pinches out just north of Del Norte between the edge of the San Juan Mountains and the central gravity high of the San Luis Basin. Maximum closure of this low is only 5 mgals but its relief is between 30-35 mgals with gradients along the flanks of 2-3 mgals/km. These values suggest that this low is also fault bounded but is shallower than the eastern graben.

SUBSURFACE GEOLOGY AND DENSITIES

During this study, it was necessary to conduct an extensive search of the literature pertaining to the geology of south-central Colorado in order to derive some insight into the possible subsurface geologic configurations of the San Luis Basin. This information was supplemented by examining data from oil and gas exploration wells in the study area. This information, especially that concerning lithologic variations and basement depth, was used extensively as constraints for the gravity modeling and interpretation. A generalized description of the basement and overlying units is given below and a generalized stratigraphic column is shown in Figure 4.

The Precambrian basement complex which underlies the San Luis Basin appears to be quite varied. Precambrian rocks are exposed in all of the mountain ranges surrounding the San Luis Basin, and their lithology ranges from granite to diabase and includes metamorphic rocks such as granite gneiss, schist, and amphibolite (Larsen and Cross, 1956; Burbank and Goddard, 1937; Litsey, 1958; and Montgomery, 1953, 1963). Two wells drilled in the San Luis Valley have encountered the Precambrian basement. Amerada Petroleum drilled the #1 State F Well approximately 40 km north of Alamosa (Fig. 7) and encountered basement rocks at 5408 feet (1650 meters) beneath the surface. Tennessee Gas Transmission Company drilled the #1 Colorado State B well near Del Norte (Fig. 7), and encountered "granite" at 9940 feet (3030 meters) beneath the surface. These wells demonstrated that the configuration of the Precambrian basement in this portion of the San Luis Basin is complex. However, no density information was available for these two wells. Tweto and Case (1972), in a gravity study of the Arkansas graben near Leadville, Colorado, used a weighted average of densities calculated for samples of Precambrian rocks exposed in the nearby mountains to arrive at an acceptable density value for the Precambrian basement in that region of Colorado. The value they derived was 2.76 gm/cc (grams per cubic centimeter). Cook (1960) reported the density of a biotite granite gneiss which crops out in the San Juan Mountains immediately northeast of Saguache as 2.7 gm/cc. Assuming that most of the San Luis Basin is underlain by rocks of similar composition to this gneiss, and ignoring possible variations from this due to zones of more mafic composition, a 2.7 gm/cc density value has been assigned to the Precambrian basement for modeling purposes. However, the results of Tweto and Case (1972) suggest this is a minimum value.

The lack of subsurface geologic information in the San Luis Basin has caused much speculation concerning what exactly mantles its Precambrian basement. A review of the geologic history of this portion of south-central Colorado reveals that the region which is now the San Luis Basin existed as an uplifted highland during both Pennsylvanian-Permian (Fig. 5) and Laramide (Fig. 6) time. Furthermore, during these orogenic episodes, vigorous erosion bared the underlying Precambrian terrain by removing thick sections of Paleozoic and Mesozoic sedimentary rocks (DeVoto and Peel, 1968; DeVoto et al., 1971; Tweto, 1975). Therefore, at the end of the Laramide orogeny in early Eocene time, an erosional surface developed on Precambrian basement rocks exposed in the area which is now the San Luis Basin. This surface was covered in Oligocene time by an extensive volcanic field. This field was composed of central volcanoes of intermediate composition which were modified by eruption of voluminous ash-flow sheets and caldera development and covered much of south-central Colorado (Steven, 1975). This relationship is seen along the western flank of the Sangre de Cristo Mountains north and east of the town of San Luis (Tweto, 1976). The San Luis Hills, which rise above the valley floor south of Alamosa and east of Antonito (Fig. 7), are composed of andesitic to rhyodacitic flows, breccias, and intrusives that have been correlated with the Conejos Formation, the lowermost and most widespread unit of this Oligocene volcanic field (Burroughs, 1971). Similar volcanics crop out within the valley immediately north and east of Saguache. These two occurrences, coupled with the presence of similar felsic volcanics recognized in the few deep drill holes drilled within the San Luis Basin, suggest this volcanic unit is widespread beneath most of the subsided basin, and this relationship has been assumed in modeling. A density value of 2.6 gm/cc for these volcanics was obtained from a bulk density log measured in the Amoco Production Company Mapco 1-32 State well (Fig. 7). This value coincides with an average value for andesite given by Telford et al. (1977) and has been used to represent the buried volcanics in the San Luis Basin.

In early Miocene time, the Oligocene volcanic field described above was fragmented by the inception of rifting in south-central Colorado. This tectonic activity continued into recent time and has created the San Luis Basin. As the basin subsided, the Oligocene volcanics were covered by alluvial fan deposits, volcanoclastic sediments, interlayered basalt flows, and sediments produced by mass wastage. The thickness of these Miocene to Recent basin fill deposits varies with the amount of subsidence within the basin itself. Data from drill holes show it to be as thin as 300 feet (100 m) and as thick as 8620 feet (2630 m). A bulk density log measured in the Amoco Mapco 1-32 state well, as mentioned above, provides a detailed measurement of the density stratification among the sediments, with the density increasing approximately linearly with depth. This increase could be attributed to many factors such as differential compaction and variation in the dominant lithology of detrital material composing the fill sediments through time. Three density units within the basin fill were delineated from this log: a 1.9 gm/cc unit extending from the surface to 1850 feet (570 m), a 2.1 gm/cc unit extending from 1850 feet (570 m) to 4340 feet (1325 m), and a 2.3 gm/cc extending from 4340 feet (1325 m) to the top of the Oligocene volcanic unit.

These density values are an average value computed over the thickness of the unit. This density stratification was used to represent the basin fill in only one profile, C-C'. An average density of 2.1 gm/cc was used in the other profiles. Basalt flows of the Hinsdale and/or Servilleta Formations are interbedded with these basin fill sediments in the southern half of the basin. These units have been assigned a density of 3.0 gm/cc which is an accepted average density for basalt (Telford _et_ _al_., 1977).

A thick, late Paleozoic-Mesozoic sedimentary section is exposed along the central and eastern flank of the Sangre de Cristo Mountains. This same sedimentary section is buried beneath the Cenozoic sedimentary cover in the Raton Basin and records tectonic activity from early Pennsylvanian to Oligocene time. The sedimentary units are composed of rocks varying from conglomerate to deep-water carbonate. A compensated neutron-formation density log measured in the Atlantic Richfield Company Cuerno-Verde Ranch -1 well suggests an average density of 2.55 gm/cc for the sedimentary section buried in the northern Raton Basin. This value has been used in modeling to represent these thick sedimentary units.

COMPUTER MODELING

In order to facilitate interpretation, four east-west profiles of gravity readings were constructed. These profiles were analyzed using the two-dimensional modeling technique of Talwani et al. (1959), which calculates theoretical gravity values for a given geological model. By modifying the configuration of the geologic model, an acceptable fit between observed and theoretical gravity values can be obtained. The error produced by the two-dimensional assumption is negligible as long as the structure being modeled is several times longer in the direction perpendicular to the line of the profile than it is parallel to the profile. An examination of the complete Bouguer gravity map of the study area in Figure 8 shows the study area to be ideally suited for the use of this modeling technique.

The locations of the profiles which were modeled are shown on Figure 7 (A-A', B-B', C-C', and D-D'). These locations were chosen so as to traverse the major gravity anomalies and associated structural features. Areas well beyond the main study area were modeled in order to examine the regional structural relations of the San Luis Basin. For all four profiles, the observed complete Bouguer gravity values were taken from gravity stations lying either immediately on the line of the profile or within 1.6 km from the line of the profile.

Inspection of Figure 8 reveals strong east-west regional gravity gradients in the San Luis Basin area. These long wavelength features are due to deep crustal and upper mantle variations which were not of interest in this study. In order to remove these regional effects, a linear surface was fitted to the observed data and residual values were calculated (Agocs, 1951). Figure 9 is a Bouguer gravity map of the study area with this linear regional removed. A similar linear surface was removed from the individual gravity profiles and these residual values were then used in the modeling process (Fig. 10a and b).

As the first step in the modeling process, an initial earth model along the line of each profile was constructed using available geologic and well data to locate subsurface positions for the various geologic units. Each geologic unit was then assigned its calculated density value which was held fixed throughout the modeling process. Any changes in this geologic model necessary to obtain agreement between observed and theoretical values were accomplished by moving boundaries of the geologic units within the constraints provided by the geologic and well data.

After numerous iterations of the modeling process, the earth models shown in Figures 11 through 14 were derived. Although inherently nonunique, these models satisfy all available geological and geophysical data. A datum of 7000 feet (2135 m) above sea level was used for each profile. Therefore, the

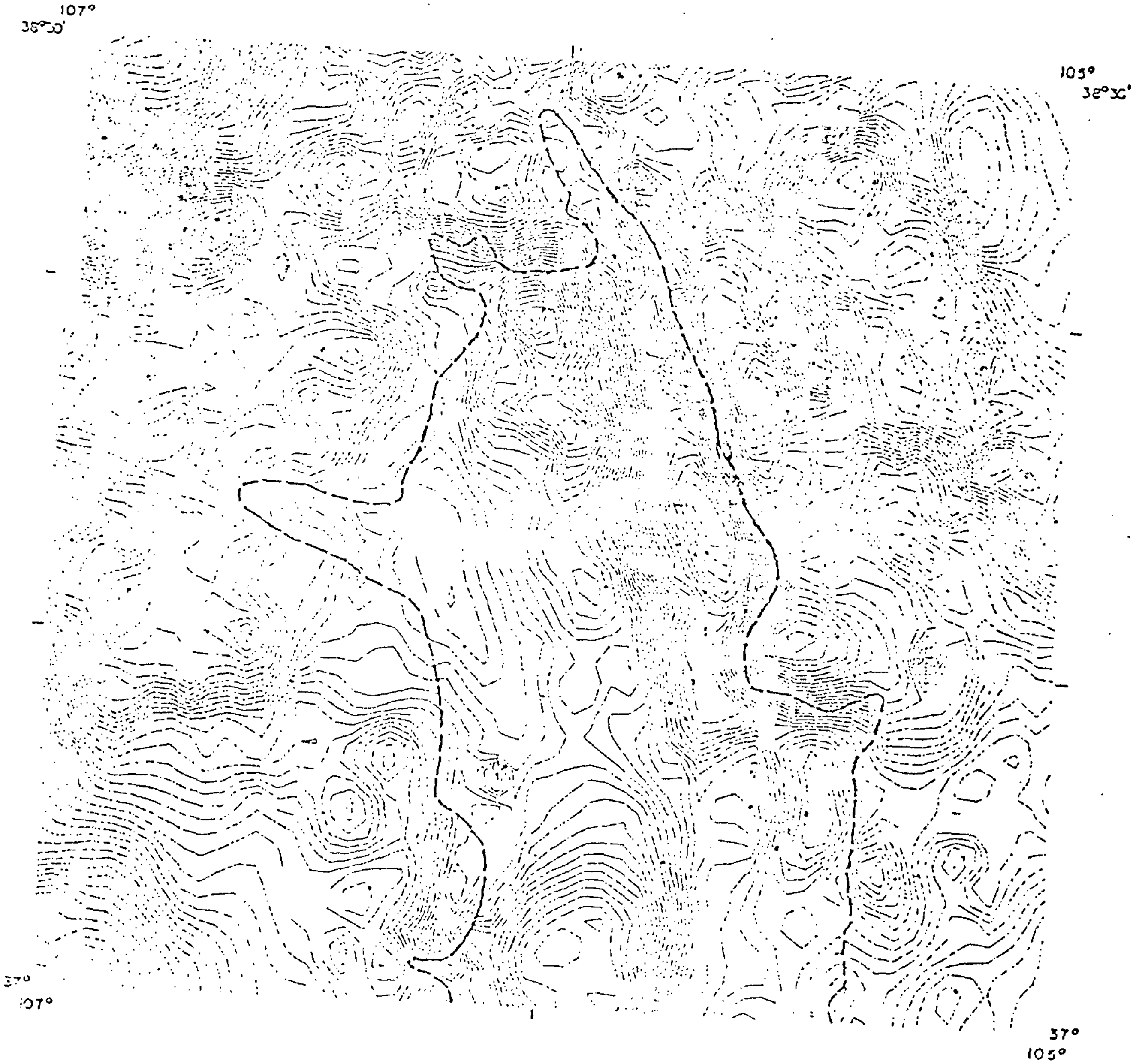


Figure 9. Residual Bouguer gravity map of study area; linear regional field removed

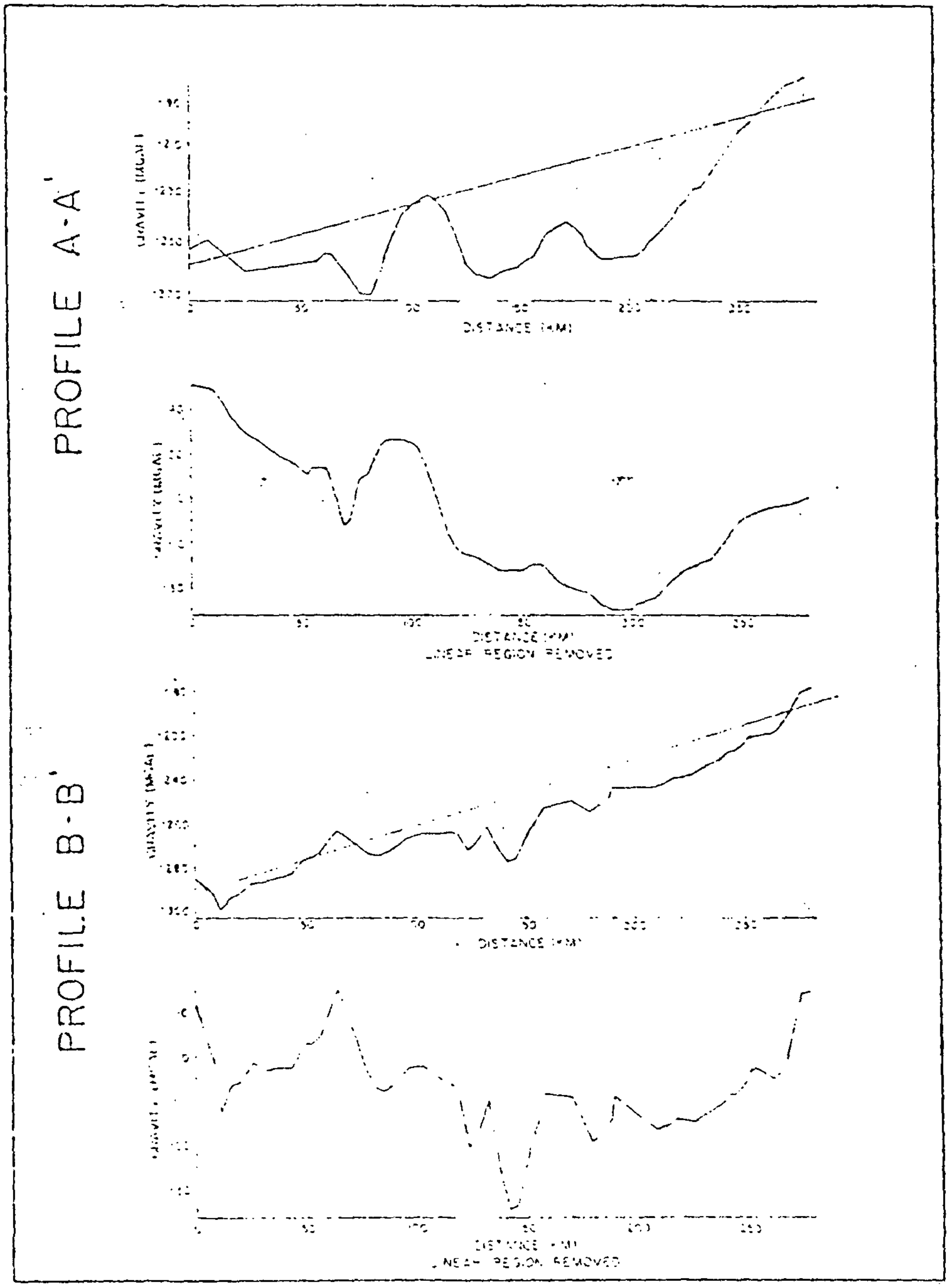


Figure 10a. Individual gravity profiles used in modeling showing effect of removing a linear regional field, lower profile in each case used in modeling procedure as described in text: Profiles A-A' and B-B'

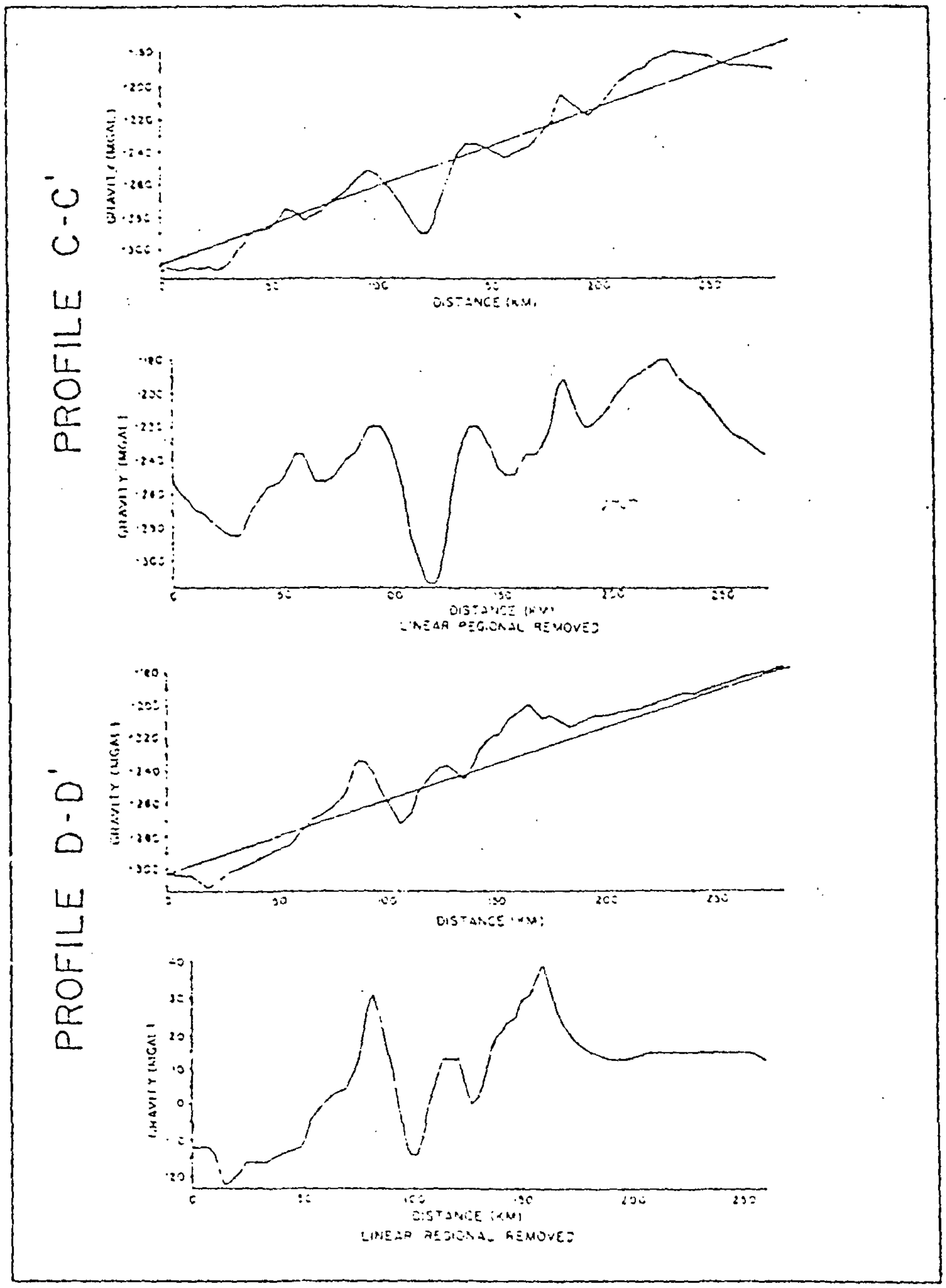


Figure 10b. Individual gravity profiles used in modeling showing effect of removing a linear regional field, lower profile in each case used in modeling procedure as described in text: Profiles C-C' and D-D'

value of 0 kilometers on the depth bar scale on each profile is equivalent to this value (Fig. 11-14).

In construction of the initial earth models associated with each profile, it became obvious that there was a severe lack of data concerning the thickness of the Oligocene volcanics which underlie much of the San Luis Basin. Although two drill holes had completely penetrated this unit, its thickness had not been recorded on the well completion reports available to the author. It was therefore necessary to rely on geologic data and cross-sections from the eastern San Juan Mountains (Larsen and Cross, 1939; Lipman and Mehnert, 1975) for aid in determining a usable thickness for the modeling of this unit. Three assumptions were made concerning this volcanic unit: 1) it was deposited on a surface of low relief; 2) it thinned outward from its eruptive centers which were located in the present San Juan Mountains area; and 3) it was relatively uniform in composition. With these assumptions in mind, 3900 feet (1200 m) was determined as a maximum thickness for this unit beneath the San Luis Basin and that it thinned to between 1950 feet (600 m) and 0 feet along the eastern margin of the basin. These values should be interpreted as average values suitable for modeling purposes because local thinning and thickening most certainly occurred.

Profile A-A'

Profile A-A' (Fig. 11) is the southernmost of the four profiles shown in Figure 7. The physiographic San Luis Basin occupies the central portion of the profile, extending from 86 km to 164 km. However, the profile indicates the presence of an additional portion of the basin buried beneath the late Tertiary Los Mogotes volcanic field, which extends from 56 to 86 km. A steep fault at 74 km, with a throw of 800 meters (2560 ft), marks the western boundary of the San Luis Basin. This fault also acts as the western boundary fault of a narrow but deep graben situated between 74 and 83.5 km. This graben shows up as a well-defined linear gravity low along the western flank of the San Luis Basin on Figure 8. Two steep faults mark the eastern edge of this graben, the first at 83.5 km and the second at 105 km. This graben is filled with basin fill which has slightly higher density than the accepted average basin fill density of 2.1 gm/cc described above. This fill belongs to the Los Pinos Formation (Lipman and Mehnert, 1975; Butler, 1971) and is composed of interbedded sand, gravel and basalts of the Hinsdale Formation. These basalts also form the shield volcano of Los Mogotes and dip beneath the valley as shown in the model. For modeling purposes, the density of the basin fill has been increased to 2.3 gm/cc to account for the thin (25 - 50 m) interbedded basalts. From 86 to 105 km, a relatively thick (approximately 200 m) layer of Hinsdale Formation basalts is shown to exist near the valley surface. This

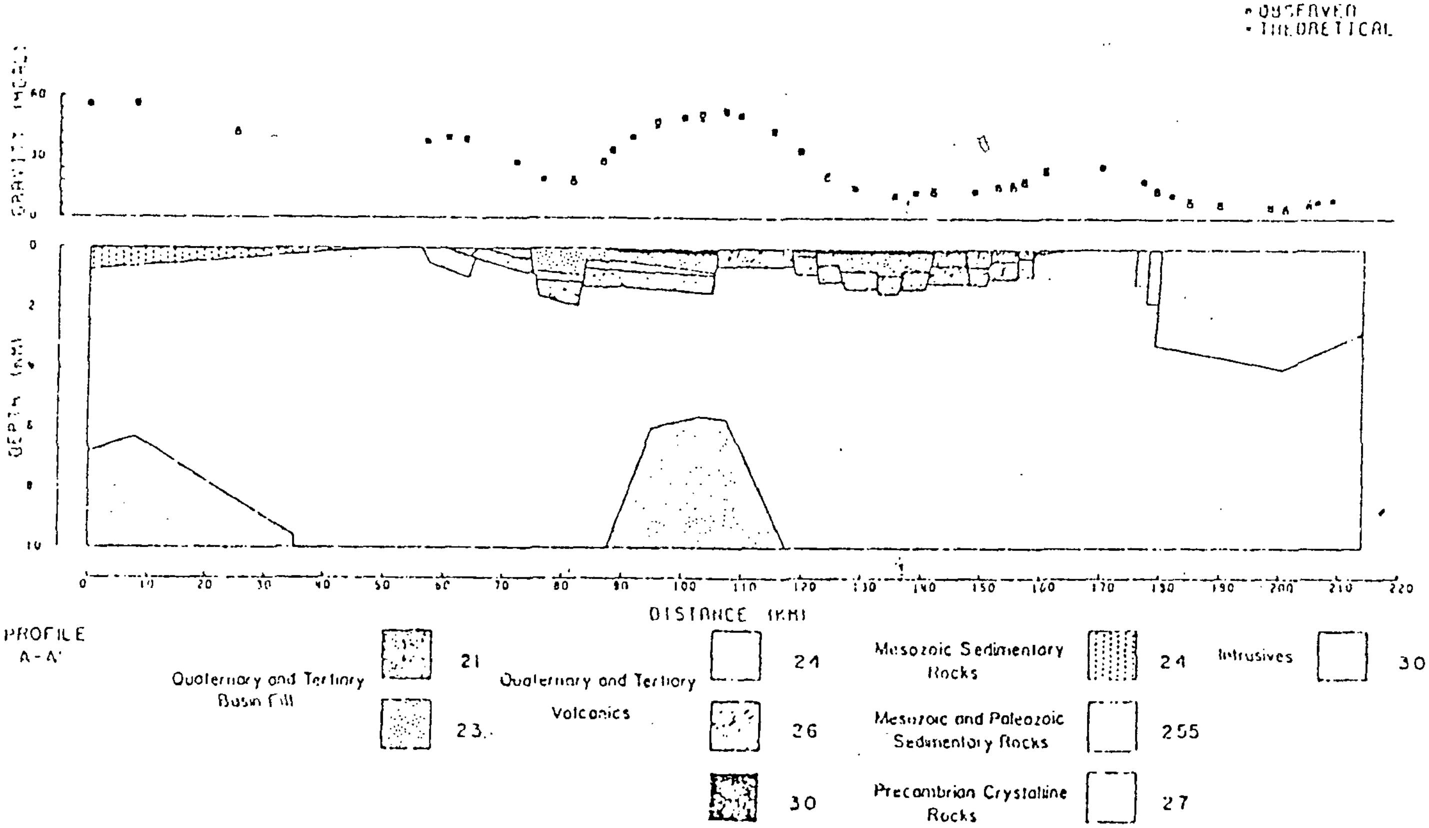


Figure 11. Gravity Profile A-A'

unit represents flood basalts from the Los Mogotes shield volcano which are penetrated by shallow (< 100 m) water wells in the area (Powell, 1958). Its thickness is meant to represent a cumulative thickness rather than the presence of a single, thick flow.

The San Luis Hills are located between 105 and 118 km on the profile and are represented by a distinct gravity high on Figure 8. These low lying hills sit astride an apparent horst which extends the length of the San Luis Basin (Fig. 8). The Conejos Formation crops out in these hills as described above and is modeled as being 600 meters thick. This volcanic unit is shown to extend throughout the subsurface on either side of this horst and maintains this average thickness. An additional volcanic unit of density 2.4 gm/cc is shown to exist along the western flank of the basin. This unit represents ash flows originating in the Platoro Caldera and which are shown to dip beneath the valley floor by Lipman and Mehnert (1975). These ash flows thin dramatically toward the center of the valley and are shown to be less than 100 meters thick at their distal edge.

A broad gravity low centered at approximately 130 km has been interpreted as a complex graben. This graben is shown to extend from 118 to 164 km, spanning the distance from the San Luis Hills to the Sangre de Cristo Mountains. Its gravity signature implies a number of small, step-like faults along both flanks of this graben instead of a single, steeply dipping boundary fault. Within the graben, a total vertical displacement of 900 meters is indicated. A thin unit of basalt is shown to lie at or near the surface within the confines of this graben and corresponds to basalt flows of the Servilleta Formation.

A gravity high between 164 and 176 km marks the outcrop of Precambrian basement rocks in the Sangre de Cristo Range. The absence of a major boundary fault along the western flank of this range contrasts sharply with the profiles to the north and suggests that the rifting in this portion of the San Luis Basin was less vigorous. Steeply dipping faults at 176, 178, and 180 km mark the western edge of the Raton Basin, which is shown to have a depth of 3.8 km.

A good fit of observed versus theoretical values was easily obtained along most of the profile. The exception was the region between 87.5 and 118 km, where a narrow gravity high seemed to be superimposed on the near surface gravity effects. In order to fit the gravity data, an intra-basement body of density 3.0 gm/cc had to be added to the model. Near surface density units were manipulated within their geologic constraints as much as possible before resorting to the addition of this feature. Therefore, the presence of an intracrustal intrusive mass is suggested to underlie the central and western portions of the San Luis Basin. An analogous anomaly appears in the southern portion of the Rio Grande rift and has been interpreted as a mantle upwarp (Ramberg et al., 1978; Decker and Smithson, 1975). However, the short wavelength character of the anomaly in the San Luis Basin suggests a more localized intracrustal feature similar to a model proposed by Bridwell (1976) for the northern Rio Grande rift. The ultimate source of this feature may be in partial melting of lithospheric mantle associated with rifting (Lipman and Mehnert, 1975) and the feature may be causally related to the high heat flow measurements obtained along the western edge of the San Luis Basin (Reiter et al., 1975).

Profile B-B'

Profile B-B' (Fig. 12) extends across the midsection of the San Luis Basin, crossing just south of the Blanca Peak Precambrian massif. Again, the San Luis Basin is characterized by two grabens which flank a central horst. The western graben is located between 64 and 95 km and is filled with sediments of the Los Pinos Formation. A thin wedge of less dense sedimentary fill, thickening toward the center of the basin, is shown to rest on this graben fill and represents flood plain alluvium of the Rio Grande River. Two major faults, the first at 71 km and second at 82 km bound the deepest portion of this graben, which is shown to be 1100 meters deep. This feature is characterized by a broad, somewhat oval gravity low on Figure 8.

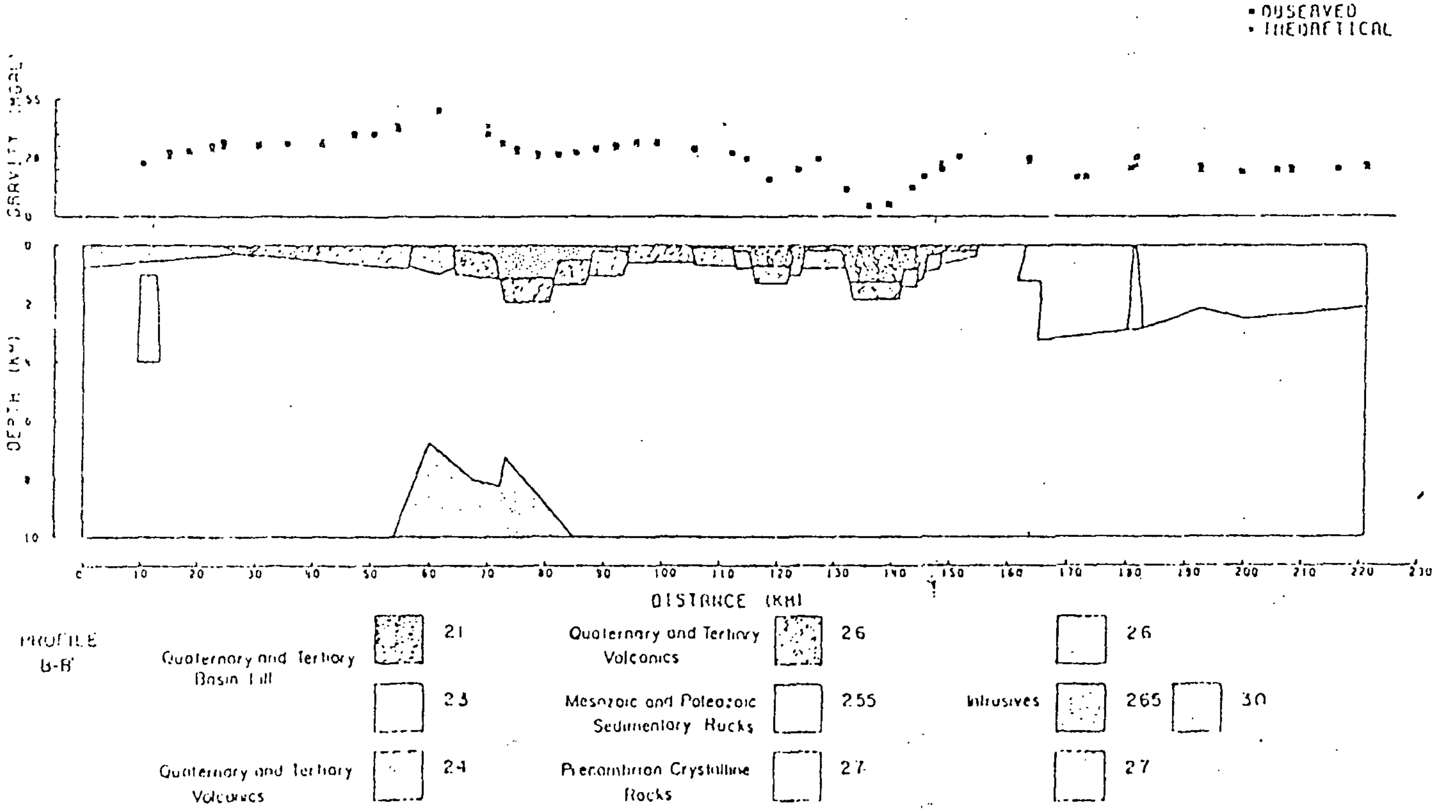


Figure 12. Gravity Profile B-B'

The central horst, capped by a 600 meter thick layer of Oligocene volcanics, lies between 95 and 106 km. Although this horst does not crop out on the valley floor at this location, this model suggests that it lies very near the surface.

The eastern graben has a complex gravity signature, consisting of two lows flanking a central high. From west to east, the first low is centered at 119 km and is modeled as a graben 700 meters in depth. A horst between 125 and 132 km separates the two lows and rises to within 200 meters of the surface. This horst is caused by the northeastward extension of the San Luis Hills (Fig. 7 and 8). A major fault bounds the eastern edge of this horst and offsets the volcanic density unit by 1000 meters, forming a graben 1200 meters in depth. As in profile A-A', the eastern flank of this graben is formed by a series of step faults, all up to the east, with the last fault marking the edge of the San Luis Basin at 155 km. The subsurface volcanic density unit in this profile is considered to be exclusively Conejos Formation, and is shown to thin from 800 to 200 meters eastward across the basin. The Precambrian basement crops out in the Sangre de Cristo Mountains between 155 and 136 km. A high angle reverse fault at 163 km juxtaposes Paleozoic-Mesozoic sedimentary rocks with these Precambrian exposures. This fault marks the edge of the Laramide age San Luis Highland (Fig. 6). A steep normal fault at 165 km marks the edge of the Raton Basin, which is shown to have a depth of 3200 meters, indicating a thinning of this basin to the north.

This structural boundary is admittedly more complex than is shown but its oversimplification is necessary due to a lack of subsurface data in this region.

A good fit between observed and theoretical gravity values was achieved along this profile. However, it was again necessary to add the intrabasement body of density 3.0 gm/cc described above, although its position was shifted towards the western edge of the San Luis Basin.

Profile C-C'

Profile C-C' (Fig. 13) traverses the two most pronounced negative gravity anomalies in the San Luis Basin (Fig. 8). These two gravity lows correspond to the deepest portions of the two grabens which trend north-northwestward through the basin, thereby suggesting a maximum depth for the San Luis Basin. The western graben extends from 57 to 87 km, attaining the same width as in profile B-B'. Its western flank is apparently characterized by stepfaulting which downdrops the volcanic density unit to a depth of 1800 meters below the surface. However, this depth is attained only over a narrow (3 km) region, and thus, the average depth of this graben is approximately 950 meters. The central horst is less prominent along this profile, rising to within 700 meters of the valley floor between 87 and 92 km. The volcanic density units, which again blankets the Precambrian basement beneath the entire San Luis

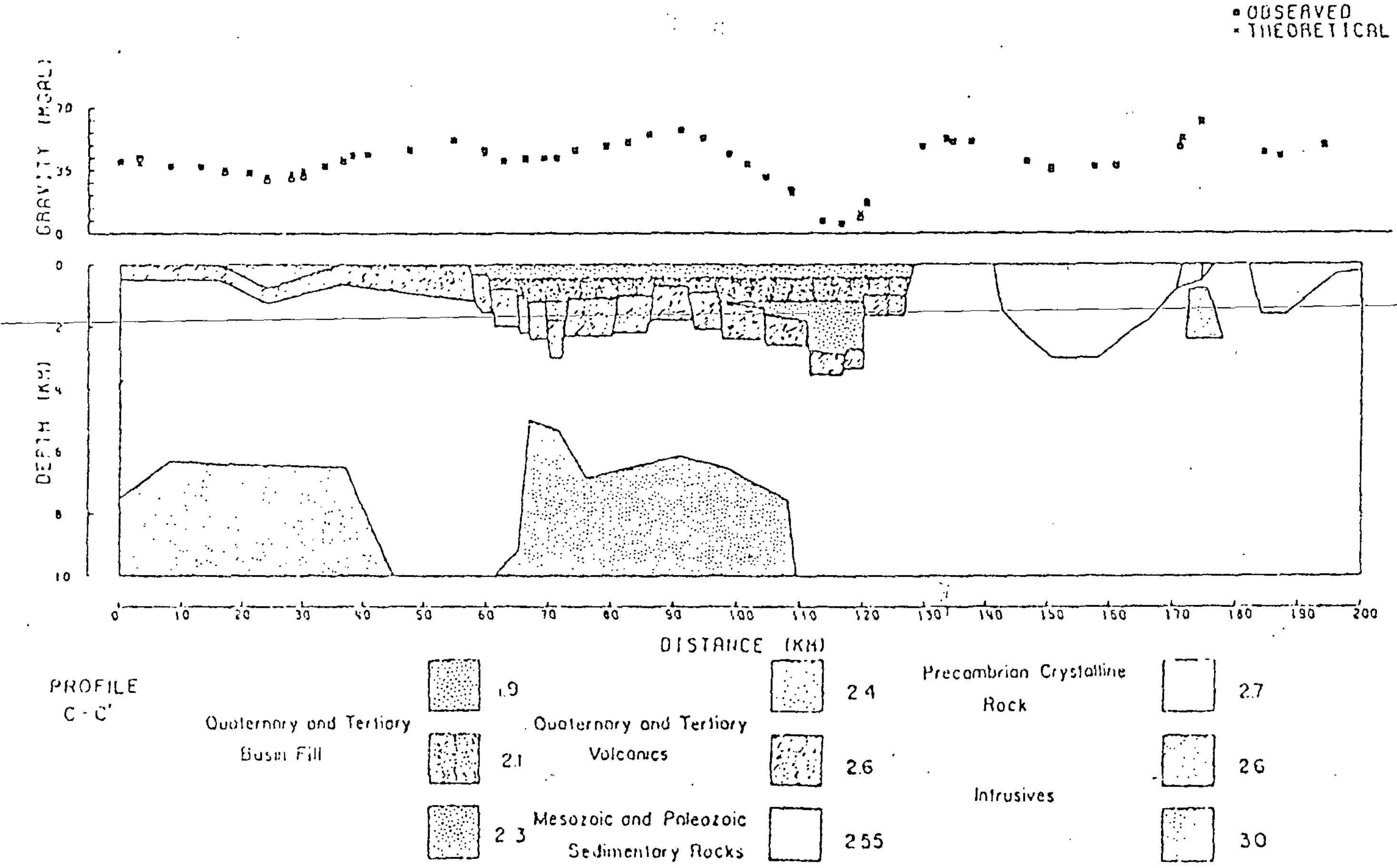


Figure 13. Gravity Profile C-C'

Basin, is shown to maintain a thickness of 1200 meters to about 92 km and then thin eastward to 600 meters along the eastern margin of the basin.

The eastern graben lies between 92 and 128 km along the profile and has a configuration considerably different than that indicated along the two profiles to the south. Along C-C' it is featured as a single, deep graben whose eastern boundary is formed by two, steeply dipping, normal faults of large throw. Step faulting forms the western flank of this graben, down-dropping the volcanic density unit to a depth of 2900 meters (~9500 ft) beneath the valley floor. This profile crosses the most negative Bouguer gravity anomaly in the basin and thus, should provide an indication of the maximum thickness of basin fill present. The deep central portion of this graben is shown to be approximately 9 km wide, extending from 111 to 120 km. At 120 km, a steeply dipping fault with a throw of 1700 meters is shown to exist in the subsurface. A similar fault occurs at 128 km marking the edge of the graben as well as the mountain front of the Sangre de Cristo Mountains. This fault has a combined surface and subsurface throw of nearly 3700 meters (~12,000 ft) and has been referred to as the Sangre de Cristo fault (Taylor, 1975).

The Sangre de Cristo Mountains are situated between 128 and 141 km and are represented by a gravity high (Fig. 8). This high is caused by the Precambrian basement rocks exposed in the range. A broad basin filled to a depth of 3000 meters with Paleozoic and Mesozoic sedimentary rocks lies to the east of this mountain range. This basin, located between 141 and 176 km, coincides with the Huerfano Park region which is the northernmost extension of the Raton Basin (Fig. 7). A second outcrop of basement rocks exists between 176 and 181 km and reflects the Precambrian exposures of the southern Wet Mountains. An intrabasement body of density 3.0 gm/cc is shown to exist in the subsurface beneath the eastern flank of the Raton Basin and the southern Wet Mountains. This body represents the possible existence of a near-surface mafic intrusive which may have acted as a source for mafic volcanic rocks exposed in the southern Wet Mountains.

A good fit between observed and theoretical gravity values was obtained along this profile, particularly in the San Luis Basin itself. The density stratification for the unconsolidated basin fill sediments suggested by the bulk density log from the Amoco Mapco #1-32 well discussed above was used in the construction of this profile with satisfactory results. As in profiles A-A' and B-B', an intrabasement intrusive body of density 3.0 gm/cc was necessarily added to the model beneath a portion of the San Luis Basin. Its effect on the observed gravity values was most widespread along this profile and resulted in an increased overall size for the feature. A pronounced peak on this intracrustal feature occurs beneath the western graben causing its gravity signature to be less negative than expected. An intrabasement intrusive body with a density of 2.6 gm/cc was added along the profile between 0 and 45 km, a location beneath the San Juan Mountains. This body represents a late Tertiary batholith which Plouff and Pakiser (1972) associated with the San Juan volcanic field. The density value assigned to this body agrees with their initial modeling of the body which indicated a density contrast of 0.1 gm/cc between the batholith and the surrounding basement rocks.

Profile D-D'

Profile D-D' (Fig. 14) is the northernmost of the four profiles shown in Figure 7 and crosses the San Luis Basin in a straight line between Saguache and Crestone. The physiographic edge of the basin at 66 km is not marked by a distinct subsurface fault as in the profiles to the south but instead consists of volcanics which dip gently beneath the overlying basin fill. The western graben (66 and 81 km) is least pronounced along this profile attaining a maximum depth of only 400 meters. Analysis of Figure 8 suggests that this graben pinches out immediately north of the line of this profile.

The central horst, which is situated between 81 and 88 km is similar in nature to its configuration along profile A-A'. Along this profile, its gravity signature is more pronounced than at any other point in the basin (Fig. 6). In this model, this structural feature is shown to be composed of uplifted Precambrian rocks. However, in actuality this feature is capped by a thin layer of the volcanic density unit which thins

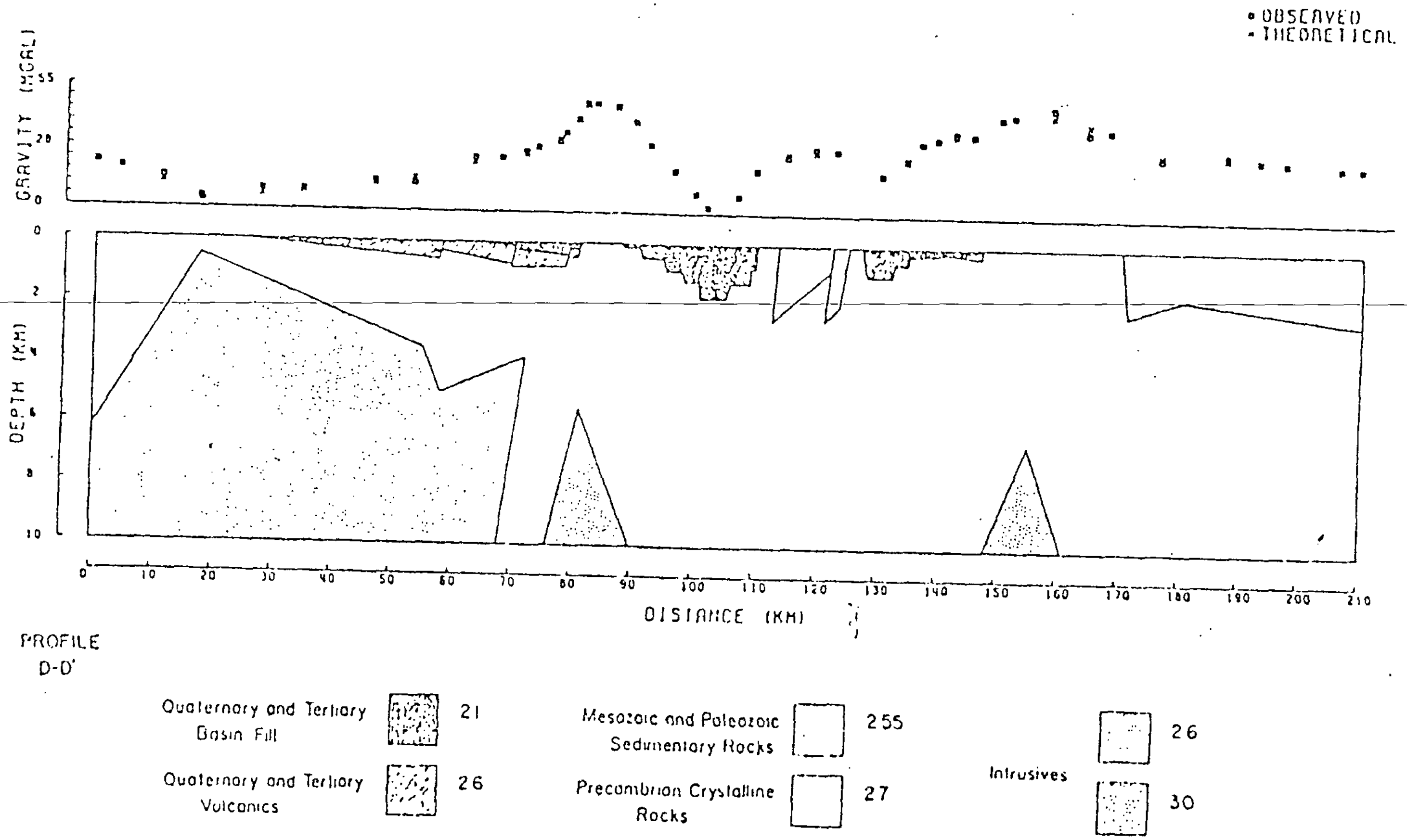


Figure 14. Gravity Profile D-D'

from 300 to 0 meters west to east over this feature. This unit is not shown on the model as it lies above the 2135 meters (7000 ft) datum of the profile.

The eastern graben narrows to a width of 23 km along this profile. Beginning at 88 km, its western flank is characterized by stepfaulting. At 100 and 105 km there are two basement faults of equal throw that are downthrown to the east and west respectively, bounding the deepest portion of this trough which is 1800 meters in depth. Immediately east of this deep trough lie two faults which mark the edge of the graben and the San Luis Basin. These faults are so close spatially that they probably act as one, and their surface expression, the steep front of the Sangre de Cristo Mountains, has been termed the Sangre de Cristo fault (Taylor, 1975). Total displacement along this fault is approximately 3500 meters (~12,000 ft), similar to its expression in profile C-C'. An examination of the gravity signature of this fault on Figure 6 allows one to mark the trace of this fault from Blanca Peak northward to Poncha Pass.

The Sangre de Cristo Mountains are shown to be most complex along this profile. Precambrian basement rocks are exposed along either flank of the range and Paleozoic sedimentary rocks rest unconformably in between, bounded by steep Laramide thrust faults. A fault at 126.5 km, which corresponds to the Alvarado fault of Taylor (1975), marks the eastern side of the range and also marks the western edge of another graben.

This graben is shallower than those in the San Luis Basin and is associated with the Wet Mountain Valley. This trough is asymmetrical, with its deepest portion being located to the west between 126.5 and 133 km. Maximum depth of the trough is shown to be 1000 meters. The eastern boundary fault of this graben occurs at 146.5 km and has been termed the Westcliffe fault (Taylor, 1975). The geology along this portion of the profile is somewhat simplified due to a lack of subsurface geologic information in this area. The Wet Mountains lie east of this graben and are characterized by a wide outcrop of Precambrian basement rocks. A fault marking the boundary of the front range of the southern Rocky Mountains and the Great Plains occurs at 170 km.

As in the three profiles to the south, it was necessary to add an intrabasement intrusive body of density 3.0 gm/cc to the model beneath a portion of the San Luis Basin in order to achieve a suitable fit between observed and theoretical gravity values. As in profiles A-A' and B-B', the position of this feature is limited to the central and western portions of the profile and does not affect the gravity signature of the eastern graben. Another intrabasement intrusive body with a density of 2.6 gm/cc was included in this model between 0 and 70 km. This feature represents the Tertiary batholith associated with the San Juan volcanic field and is defined by a large gravity low on Figure 6.

SUMMARY AND CONCLUSIONS

This study had the following major objectives: 1) determine the depth of basin fill within the San Luis Basin; 2) determine the basic subsurface structure of the San Luis Basin; and 3) enhance the general knowledge of the regional structural relations of the San Luis Basin and surrounding tectonic elements, most notably the Rio Grande rift.

Computer modeling has shown the thickness of the fill in the San Luis Basin to be approximately 3 km (9600 ft) at its deepest point. This point is located northwest of Alamosa within the confines of the eastern graben. Since the fill is underlain by between 500 and 1000 meters of Oligocene volcanics and there is a negligible thickness of pre-Oligocene sediments present, the maximum depth to the Precambrian basement in the San Luis Basin is between 3.5 and 4 km (11,500 ft and 13,000 ft respectively). This value is significantly less than the 9 km (30,000 ft) maximum depth arrived at by a similar gravity study by Gaca and Karig (1965). This discrepancy is probably due to the lack of horizontal and vertical control present in their study and the simplistic subsurface geologic model of the basin used in their two-dimensional modeling process which did not allow for a separate and unique Oligocene volcanic unit beneath the Miocene to Recent sedimentary fill. General agreement was attained with the results of Stoughton (1977), who postulated the maximum depth of the basin to be approximately

5 km (16,000 ft) on the basis of seismic reflection data. These results suggest that the San Luis Basin is not atypical, but instead typical in depth for basins associated with the Rio Grande rift.

Figure 15 depicts the generalized subsurface configuration of the San Luis Basin. This figure indicates that the basin is a complex structural feature composed of two grabens which parallel and flank a central horst. All of these features trend north-northwesterly through the study area. The western graben, composed of two linear troughs, extends from the Colorado-New Mexico state line to a point 10 km southeast of Saguache, where the graben pinches out against the upthrown Precambrian basement. Along its strike, the graben averages 1000 to 2000 meters in depth and attains a maximum depth of ~1800 meters just east of Del Norte.

The eastern graben is somewhat more complex and is composed of two, en-echelon, elongate troughs which extend from Poncha Pass southward into New Mexico. The northern segment, extending from Poncha Pass to just west of Blanca Peak, is characterized by a deep, narrow, fault-bounded trough. The deepest portion of the eastern graben and the entire basin occurs in this segment and is approximately 3000 meters (Fig. 13). The southern portion of the graben is distinguished by widening and the presence of a horst which interferes with its linearity (Fig. 15). This horst is genetically related to the San Luis Hills and therefore to the more prominent horst which

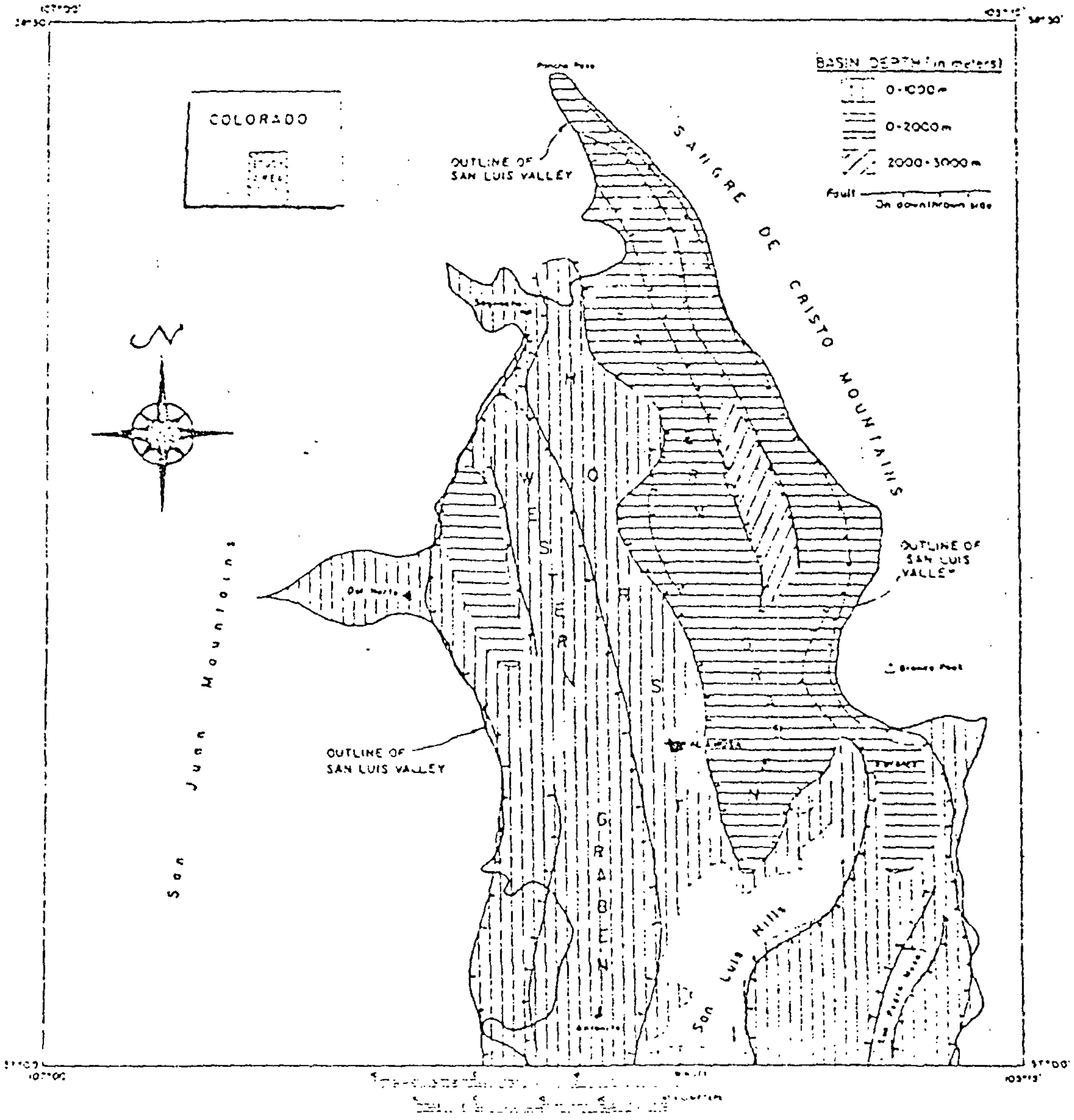


Figure 15. Map depicting generalized subsurface configuration of San Luis Basin, Colorádo, based on computer modeling results

dominates the central portion of the basin's subsurface. Average depth of the graben in this portion of the basin is between 500 and 1000 meters (Fig.11 and 12). The central horst shown on Figure 13 is well defined on the computer models and the gravity map shown in Figure 6. Bounded on either side by a series of step faults, this feature stretches the entire length of the basin and appears to extend southward into northern New Mexico. It is postulated that this feature is not really a horst, but instead, a structure remnant that remained near or in its original spatial position while the surrounding terrain was downdropped into grabens in mid-Miocene time. Moreover, a positive correlation seems to exist between the eastern boundary fault(s) of this apparent horst and the Pennsylvanian-Permian age Pecos-Picuris fault (Fig. 5) as mapped by Sutherland (1963, 1972) and Mallory (1960, 1972). This correlation implies that the Pecos-Picuris fault has again been reactivated due to tectonic stress. This reactivation coupled with recurrent tectonic activity in this area throughout geologic time may indicate that this region of the North American plate is underlain by a zone of crustal weakness which in turn may have influenced the development of this portion of the Rio Grande rift and the San Luis Basin.

Furthermore, the presence of an intracrustal intrusive mass, similar in character to one proposed by Bridwell (1976) for the Rio Grande rift in northern New Mexico, is suggested to underlie the central and western portions of the San Luis

Basin. Its exact size, density, and depth are speculative, but its existence is not because it was required to obtain a suitable fit between observed and theoretical gravity values during the computer modeling. The short wavelength character of the anomaly related to this proposed intrusive mass indicated an intracrustal source rather than a deep crustal or upper mantle one such as is proposed for an analogous anomaly in the southern portion of the Rio Grande rift (Ramberg et al., 1978). This intracrustal mass may be due to partial melting of the mantle or crust in a rifting environment or may be an upper crustal intrusive body similar to that proposed by Sanford et al. (1977) and may be causally related to the Miocene to Recent mafic volcanics present along the south and west boundaries of the San Luis Basin.

Finally, the gravity study has shown that the San Luis Basin is a distinct, major element of the Rio Grande rift. Its complex graben-horst-graben subsurface structure confirms its relationships with the better known and exposed portions of the rift and support the conclusions of Chapin (1971), Tweto (1975), and others that the Rio Grande rift extends well into central Colorado.

APPENDIX A

Observed Gravity Values for Base Stations used in Gravity Survey

APPENDIX A

BASE STATION LOCATION	LATITUDE	LONGITUDE	ELEVATION (IN FEET)	OBSERVED GRAVITY (MGALS)
Alamosa, Colorado	37° 28.21'N	105° 52.16'W	7549	979234.98
LaVeta, Colorado	37° 30.06'N	105° 00.32'W	7013	979325.82
Westcliffe, Colorado	38° 8.05'N	105° 27.78'W	7888	979307.02

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