



## *Geology of the San Luis Hills, south-central Colorado*

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# GEOLOGY OF THE SAN LUIS HILLS, SOUTH-CENTRAL COLORADO

by

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## INTRODUCTION

The San Luis Hills occupy an area of 428 square miles in the center of the San Luis Basin. They consist of volcanic rocks of the Tertiary Conejos Formation intruded by Late Oligocene stocks dated at  $27.4 \pm 0.6$  and  $27.9 \pm 0.6$  m.y. Three local members of the Conejos Formation are recognized; the Wildhorse, La Sauses, and Manassa Members. The Conejos volcanics are rhyodacites of intermediate composition having a  $\text{SiO}_2$  content ranging from 53 to 65 percent. The rock suite has a Peacock alkali-lime index of 55.8, falling on the boundary between the alkalic and calc-alkalic classes.

Beginning with Wildhorse time the eruptions became more silicic through La Sauses time. With the beginning of eruptions in Manassa time the relationship was reversed as volcanism progressed, suggesting differentiation of the magma chamber during an interval of quiescence in which the La Sauses Member was subjected to considerable erosion. The center of this volcanic activity appears to be in the general vicinity of the King Turquoise Mine.

After volcanism a major north-south fault zone developed passing through the center of previous eruptions. This faulting resulted in uplift of the eastern San Luis Hills relative to those west of the fault zone. Large dikes intruded along planes of weakness produced by the faulting. The course of the Rio Grande presently follows the fault zone although it is not controlled by it.

As subsidence and tilting of the San Luis Basin took place, beginning in Miocene time, the hills were further uplifted resulting in those east of the Rio Grande being broken into a series of southeastward tilting fault blocks. The hills were subsequently eroded to a mature topography and surrounded by sediments of the Santa Fe Formation as the basin continued to subside. In Late Pliocene time tholeiitic olivine-tholeiitic basalts of the Servilleta Formation flooded around the south and east margins of the hills and became islands in a sea of lava. After deposition of additional sediments around the hills the area was rejuvenated resulting in the Rio Grande being superposed across the hills and forming the La Sauses Gorge. The hills are presently being exhumed.

Normative classification of rock types is based on a modified Johannsen (1939, p. 144) triangular diagram (fig. 2) in which normative quartz, potassium feldspar and plagioclase feldspar are plotted to determine rock name. The rhyodacite-trachyandesite boundary has been placed

at 5 percent normative quartz after recalculation of end members to 100 percent.

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## PREVIOUS WORK

Very little previous work has ever been done in the San Luis Hills although the hills have been noted by several authors: Hayden (1869), Stevenson (1875, 1881), Conkling (1876), Endlich (1877), Siebenthal (1910ab), Bryan (1927ab, 1928, 1938), Atwood and Mather (1932), Upson, J. E. (1938ab, 1939, 1941), Pearl (1941ab, 1942, 1957), Larsen and Cross (1956), Powell (1958). Of the above the most extensive notations were by Atwood and Mather (1932), Upson (1938) and by Larsen and Cross (1956) although only two or three paragraphs from each reference apply to the San Luis Hills. Larsen and Cross (1956, p. 87) published six chemical analyses from this area and Upson (1938, p. 48) mentioned seeing a field map of the area by E. S. Larson, Jr. This map, however, has never been published and its whereabouts is not known to the author.

## PHYSIOGRAPHIC SETTING

The San Luis Basin, an intermontane structural depression, is made up of the San Luis Valley in south-central Colorado and the Taos Plateau in north-central New Mexico. On the east it is bounded by the Sangre de Cristo Mountains and on the west by the San Juan Volcanic province and the Tusas uplift. The northern portion of the San Luis Basin from Villa Grove to Poncha Pass was referred to as Homan's Peak by Endlich (1877, p. 140). Siebenthal (1910a, p. 9 and 10) described the basin as a great lowland about 150 miles long and 50 miles wide, arbitrarily placing its southern limit about 15 miles south of the Colorado border. Bryan (1938, p. 199) marks the southern end of the basin at the San Luis Hills where a shallow canyon has been developed by the Rio Grande 15 miles north of the New Mexico line. Upson (1939, p. 722) subdivided the basin into five physiographic provinces (see Upson, this guidebook); the Alamosa Basin, the San Luis Hills, the Taos Plateau, the Costilla Plains and the Culebra reentrant, a subdivision generally accepted today.

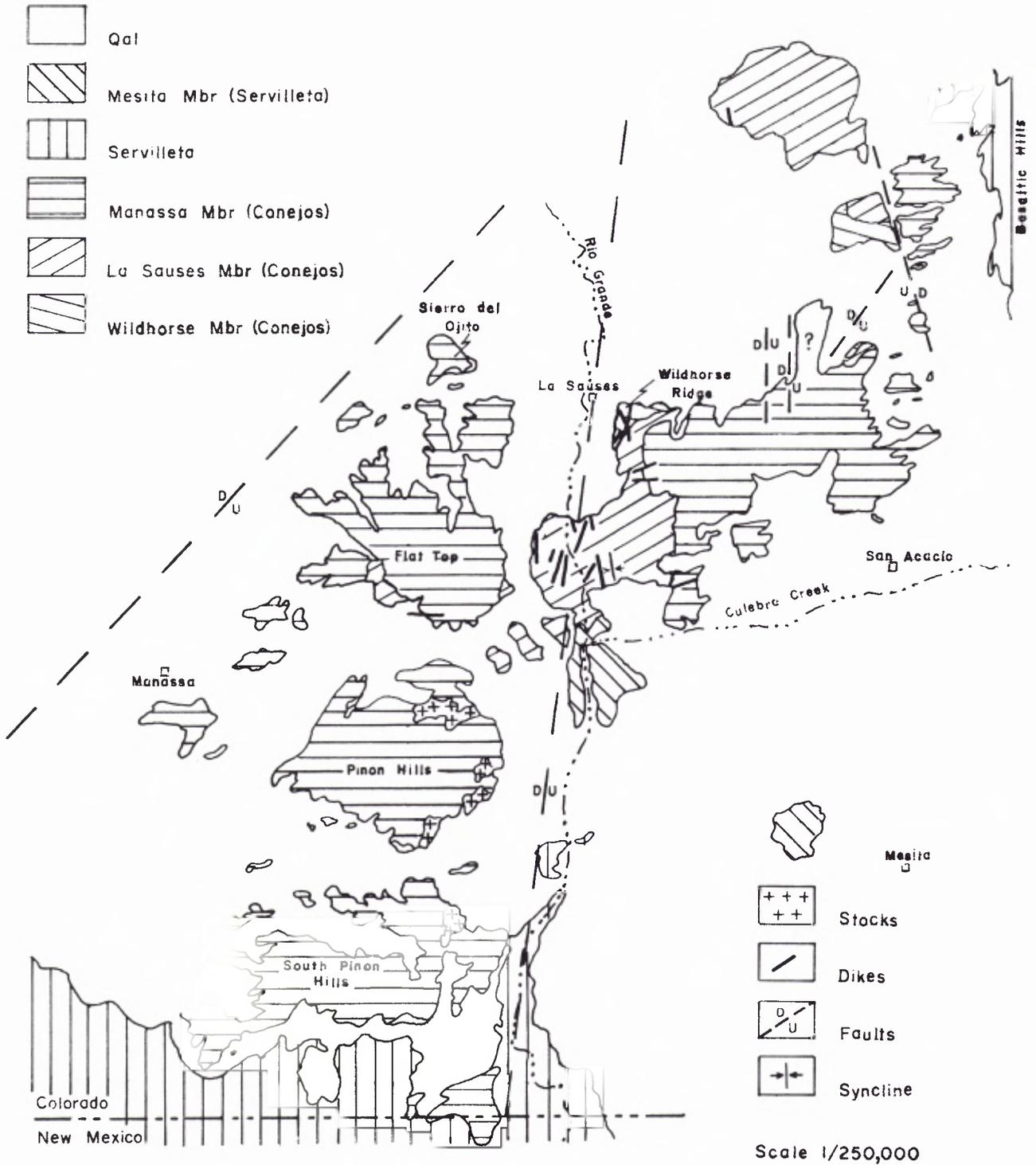


FIGURE 1.  
Generalized geologic map of the San Luis Hills, Colorado.

After perhaps a long, hard day in the field Stevenson (1875, p. 422) described the basin along the Colorado-New Mexico state line as he looked eastward from the foothills of the San Juan Mountains: "From these mountains eastward, across San Luis Valley to the Spanish Range,

one sees nothing but a dull repulsive plain of lava, from which rise the high basaltic domes known as Ute Peak and Cerro San Antonio." Although I can at times understand Stevenson's feelings, I would tend to agree more with the descriptions of Pearl (1942, 1957) as he pointed out the

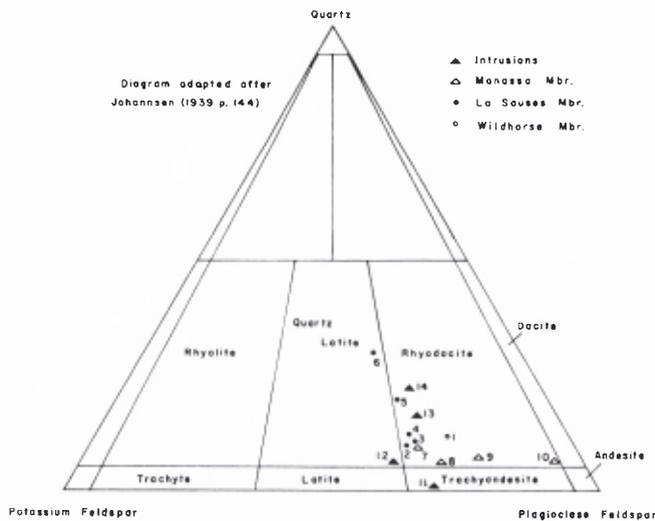


FIGURE 2.

Normative composition of rocks from the Conejos Formation plotted on a Johansen diagram. Numbers refer to analysis given in Table 1.

remarkable combination of scenic beauty and natural wealth which the valley possesses—a land of many contrasts, both geologically and historically: a land which is the driest and wettest part of Colorado—both at the same time; an area in which one finds shrubs characteristic of arid regions along with alkali flats next to saturated ground, lakes, sand dunes and disappearing streams.

### TECTONIC SETTING

The Rio Grande depression, as defined by Bryan (1938, p. 199) extends from Poncha Pass at the head of the San Luis Basin, southward for about 450 miles through New Mexico to about El Paso, Texas. It is not a single graben structure but consists of a series of en echelon grabens with a northerly trend; the grabens being arranged north-easterly along the course of the Rio Grande (Kelley, 1952, p. 93). Until recently it was believed that the San Luis Basin was the most northerly of this series of en echelon basins, with its northern end being bounded by a complex fault zone within Precambrian rocks in the vicinity of Poncha Pass. However, Van Alstine (1968, p. C158) has shown that a north-trending structural trough 3 to 4 miles wide in the vicinity of Poncha Pass connects the San Luis Basin and the upper Arkansas River Valley. Along the western flank of this trough Van Alstine has postulated that a fill of about 10,000 feet may be present. Kelley (1970, p. 157) has continued with this idea of extending the Rio Grande depression northward. He said, "the Rio Grande depression is an integral part of the Eastern Rockies tectonic belt which, from a regional point of view, extends from southern Wyoming through Colorado and most of New Mexico. In this belt the Rio Grande depression, Colorado 'Parks,' and possibly the Laramie Basin form a grand linked right-echeloned system of intermontane troughs."

The San Luis Basin includes all the physiographic provinces of Upson (1939, p. 722) with its northern boundary at Poncha Pass and its southern boundary being defined by Kelley (1956, p. 109) as that of the Embudo constriction. On the east the basin is bounded by the Sangre de Cristo uplift along the high-angle Sangre de Cristo fault zone. On the west the boundary is that of the San Juan volcanic province in Colorado and the Tusas uplift in New Mexico.

The basin, a complex hinged graben having an eastward tilt, began subsiding in Miocene time and has continued to subside to the present. Siebenthal (1910a, p. 51), and Bryan (1938, p. 204) noted that wide-scale volcanic activity and uplift of the adjacent mountains along with corresponding sedimentation began in Miocene time. This was also suggested by Kelley (1956, p. 113) who attributed the initial development of the Rio Grande depression to the Late Miocene. From studies of the upper Arkansas River Valley, Chapin and others (1970, p. 159) found a series of palcoveys trending at right angles to the present day major structural and topographic features. Studies of these valleys along with studies of the Thirtynine Mile volcanic field to the east show that Ash-Flow 1 of that area, dated at 36 m.y. (Early Oligocene), erupted west of the Salida-Buena Vista region prior to the development of the upper Arkansas River Valley. On the basis of vertebrate fossils the graben-filled sediments of that area have been dated as Late Miocene and Early Pliocene. Lipman and Mehnert (1969) suggested that subsidence of the San Juan Basin began in Early Miocene time. They point out that ash-flows from the San Juans dated at 27 m.y. thin toward the basin indicating that no depression existed in that area during Late Oligocene time and that an angular unconformity exists between flows dated at 21 m.y. indicating an eastward tilting of the basin beginning with the Early Miocene. The continual development of the basin into the Holocene has long been recognized: Bryan (1938, p. 204); Upson, J. E. (1938b, p. 316-317); Upson, R. H. (1940, p. 72); Knepper (1970, p. 158); Scott (1970, p. C16-C17).

Baltz (1965, p. 2068) suggested that the deepest part of the basin was adjacent to the Sangre de Cristo Mountains and within the physiographic Alamosa Basin. Kleinkopf and others (1970, p. B79) show a large gravity minimum of about 30 mgal centering 10 miles northwest of the Great Sand Dunes National Monument. On the basis of gravity data Gaca and Karig (1966) concluded that within this area the graben contained a maximum of 30,000 feet of sediment. At the north end of the basin the structural trough linking the upper Arkansas River Valley with the San Luis Valley can be traced only a few miles south of Poncha Pass (Van Alstine, 1968, p. C158). According to Knepper (1970, p. 158), the area between Poncha Pass and Mineral Hot Springs has 0 to 300 feet of Tertiary volcanics, pediment gravels and alluvial fan material overlying Precambrian rocks. South of the Mineral Hot Springs fault the basement is 1,800 to 2,200 feet below the surface becoming progressively deeper to the area of the 30 mgal minimum. South of here the trough becomes structurally

shallower. About 10 miles northwest of Alamosa the sedimentary material is about 8,000 feet thick and along the Colorado-New Mexico border, just east of the Rio Grande, about 6,000 feet of buried sedimentary and volcanic material is present (Kleinkopf and others, 1970, p. B79). Between these later two areas is located the up-faulted blocks of the San Luis Hills volcanics.

## ROCK UNITS

### GENERAL

The volcanic and plutonic rocks of the San Luis Hills are of Oligocene age, representing a local accumulation equivalent to that of the Conejos Formation of the San Juan Mountains. On the State Geologic Map of Colorado (1935) the hills are mapped as Conejos and other Potosi rocks undifferentiated. Upson (1938, p. 40) states that the hills belong to the Potosi volcanics of the San Juans. He gained this information from a field map of the area and by personal communication with E. S. Larsen, Jr. Sometime between 1938 and 1956 Larsen apparently changed his mind as to the age of these volcanics as Larsen and Cross (1956, p. 81, 86) indicated that these rocks along with those of the Beidell, Tracy Creek and Bonanza centers are of pre-Potosi age. On the basis of more recent field work and isotopic data Lipman and others (1970, p. 2332) stated that the Beidell, Tracy Creek and Bonanza centers represent local accumulations within the Conejos Formation. Potassium-Argon dates of  $27.4 \pm 0.6$  and  $27.9 \pm 0.6$  m.y. (uppermost Oligocene) have been obtained from the South Piñon Hills stock, which intrudes flows of the Manassa Member (later) of the Conejos Formation. The author believes that the times of the intrusions in the San Luis Hills are closely related to the volcanic events.

Within the San Luis Hills five volcanic units have been recognized. The three lowermost units are hereby named the Wildhorse, La Sauses and Manassa Members of the Conejos Formation. This subdivision is proposed as local usage and should probably be confined to the San Luis Hills. The contact of each member is marked by an unconformity in which alluvial deposits are locally present. Overlying these units is the Servilleta Formation of Butler (1946) and a younger member of that formation hereby named the Mesita. The Mesita Member is probably equivalent to the Upper Series of Aoki (1967, p. 191) of the Taos Plateau.

### WILDHORSE MEMBER

The Wildhorse Member of the Conejos Formation is named for exposures at the north end of Wildhorse Ridge, a cuesta, 1 7/10 miles east of La Sauses, Colorado. Exposures are limited and found only along the lower portion of the scarp (fig. 1). The maximum thickness noted for the unit is about 650 feet. The lower boundary is covered by alluvium, however, the lower part of the section is composed of mudflows and basaltic-appearing flow breccia grading upward into an autobreccia and overlying lava flows, which are dominant in the upper half of the unit.

Within the section moderately sorted to well-sorted, cross-bedded, tuffaceous sediments of fluvial origin are present, the material being derived from adjacent volcanic rocks. Breccia fragments making up the lower half of the section are homogeneous in composition, subangular to angular, dense to somewhat vesicular and are generally poorly sorted. Fragments up to 1½ feet in size are common. Petrographically the rock is porphyritic andesite with a felty groundmass. Phenocryst (augite and andesine) content ranges from 10 to 40 percent, averaging about 0.3 mm in long dimension in the breccias and about 1 mm in the overlying flows. The upper flows are generally glomeroporphyritic, contain minor hypersthene and biotite and are characterized by an intense alteration of some augite to fibrous actinolite (?). Chemically the rocks are mafic rhyodacites (fig. 2).

### LA SAUSES MEMBER

The La Sauses Member of the Conejos Formation is named for the major cliff-forming exposures along the entire length of Wildhorse cuesta east of the town of La Sauses. Exposures continue southward and are present on both sides of the La Sauses Gorge 3 miles south of La Sauses. It makes up the hills east of the gorge and is locally found in buried hills beneath the Manassa Member west of the river (fig. 1). The highly variable thickness of the unit, about 50 to 800 feet, is due principally to pronounced erosion of the upper surface that took place before deposition of pyroclastic breccias, flow breccias, mudflows and lava flows of the Manassa Member. Relief of this surface may amount to several hundred feet. Unconformities within the unit, normal thinning of volcanic rocks and their often small lateral extent account for further thickness variability. With detailed mapping the member can be locally subdivided into two or more units.

East of the Rio Grande the section is composed of fresh to highly-oxidized, grayish-pink, dark-reddish-brown and light- to dark-gray interbedded tuff-breccias, mudflows, lava flows and dense crystal tuffs, along with thick local epiclastic deposits. The crystal tuffs are generally massive, while lava flows often show well-developed flow structure (fig. 3). Vitrophyres up to 5 feet thick at the base of some flows have served as local marker horizons; unfortunately they do not have great lateral extent. Exposures east of Wildhorse cuesta often consist of pumiceous tuffs interbedded with cross-bedded sediments of fluvial origin. West of the river exposures are locally present beneath the Manassa volcanic rocks. Near Pikes Stockade soft, light-colored, crystal tuffs are present along the south side of Sierrito del Ojito. On the southwest side of Mesa de La Sauses (Flatop) are tuff-breccias, lava flows and dense crystal tuffs. South of here on the northwest side of the Piñon Hills are soft crystal tuffs. Crudely stratified, light gray ash and tuff-breccias of pyroclastic origin are present along the south side of the hills. Along the southern edge of the South Piñon Hills adjacent to Punche Valley about 200 feet of soft, homogeneous, light tan ash is present. In each case these isolated deposits in the western San Luis Hills are beneath basaltic-appearing volcanic rocks of the



FIGURE 3.

Typical flow structure of lava flows of La Sauses Member. "Most geologists use picks as scale indicators."—Ed.

Manassa Member and are thus believed to be roughly stratigraphically equivalent representing isolated buried erosional remnants of this unit.

Petrographically, rocks of the La Sauses member are typically glomeroporphyritic, augite-biotite-sanidine latites with a felty groundmass. The sanidine is generally resorbed and is characteristic of the formation although it is not always present. Magnetite and biotite, partly to completely altered to hematite are also typical, with fresh magnetite being very scarce. Some pigeonite is present in the upper two-thirds of the section. Plagioclase crystals have commonly been subject to resorption; some being deeply embayed. The crystals are commonly zoned and broken, with broken ones serving as centers for precipitation of additional zoned plagioclase suggesting a complex history in the magma chamber. Apatite and sphene have also been noted and secondary calcite is abundant adjacent to fault zones. Chemically the rocks are rhyodacites (fig. 2).

#### MANASSA MEMBER

The Manassa Member of the Conejos Formation is named for exposures throughout the western San Luis Hills east of Manassa, Colorado. Maximum thickness of the unit is about 1,500 feet. Explosive breccias, flow breccia and lava flows, all of basaltic appearance, make up the section. About 800 feet of highly oxidized dark-red scoria with fine tuffaceous binding material is present along the southeast side of Mesa de La Sauses. It grades both laterally and vertically into flow breccias and lava flows along the north side of the mesa. This is the most extensive pile of scoriaceous material in the San Luis Hills. Basaltic-appearing lava flows cap the mesas throughout the western San Luis Hills. At Sierrito del Ojito the lava flows lie unconformably on crystal tuffs of the La Sauses Member. In the

Piñon Hills and South Piñon Hills flows are dominant throughout the section, with scoria similar to that at Mesa de La Sauses being generally absent. In the eastern San Luis Hills basaltic-appearing flows of the Manassa Member cap the Wildhorse cuesta and represent the dominant unit throughout the hills east of the cuesta. Locally minor ash deposits are found between flows and volcanoclastic sediments are often present at the base of the unit filling in topographic lows before eruption of the lava flows.

Petrographically the upper and lower parts of the Manassa section are basaltic-appearing andesites. The upper flows capping the mesas west of the Rio Grande are characterized by the presence of olivine altering to iddingsite and by the notable absence of abundant plagioclase phenocrysts. These are the only rocks within the San Luis Hills in which plagioclase phenocrysts are not abundant. The matrix texture of the upper flows is generally pilotaxitic. Beneath the upper flows the pyroclastic breccias, flow breccias and lava flows are characterized by plagioclase phenocrysts of 1-5 mm long; a general absence of olivine and a presence of biotite. Texturally the rocks are commonly glomeroporphyritic with a felty groundmass. All parts of the section are characterized by fresh magnetite in contrast to highly oxidized magnetite of the underlying units. Augite and orthopyroxene are present throughout the section. Apatite and quartz have been locally recognized. Chemically the rocks are mafic rhyodacites (fig. 2). They are slightly more basic than the basaltic-appearing rocks of the Wildhorse Member.

#### SERVILLETA FORMATION

The Servilleta Formation was named by Butler (1946, p. 133) for Late Tertiary basalts flooding the Taos Plateau in the southern half of the San Luis Basin. This usage was continued by Montgomery (1956, p. 53) and by Lipman (1969, p. 1347). The rocks are informally termed "Taos basalts" of Aoki (1967, p. 195). The Servilleta basalts of the Rio Grande gorge were dated by Ozima and others (1967, p. 2618) as 3.6 to 4.5 m.y. (Upper Pliocene).

After the San Luis Hills were eroded to a mature topography, the Servilleta basalts flooded the southern and eastern margins of the hills; the hills thus becoming islands in a sea of lava. Within the San Luis Hills the Servilleta basalts are present throughout Punche Valley lapping upon the southern margin of the South Piñon Hills and completely isolating Cerrito del Poncho, which straddles the Colorado-New Mexico state line. Good exposures make up the cliffs along the Rio Grande at the Old State Bridge 5½ miles north of the border. Exposures are also present on the northeast side of the San Luis Hills along Trinchera Creek 4 miles south of Blanca, Colorado. The Servilleta basalts are those found throughout the Basaltic Hills south of Smith Reservoir. They continue south of San Luis, Colorado, forming the caprock of San Pedro Mesa. They are also present as the caprock of Garland cuesta southeast of Fort Garland.

The lava flows of the Servilleta Formation are predominantly olivine-tholeiite basalts in which the olivine is altered to iddingsite. The olivine, along with plagioclase

and clinopyroxene, is relatively coarse-grained and closely spaced, but with angular cavities present between feldspar laths of random orientation; a typical diktytaxitic texture is produced. Rock texture and presence of olivine generally make the Servilleta basalts easy to recognize in the field.

Rocks of the youngest volcanic unit in the San Luis Hills are locally referred to as the Mesita Member of the Servilleta Formation; named for exposures in Mesita Crater near Mesita, Colorado. These rocks represent local eruptions forming small hills above the plateau basalts. In the San Luis Hills area two such volcanic centers are recognized: the Mesita Crater and Volcano de La Culebra at the mouth of Culebra Creek. The Mesita Crater is a small volcanic center composed predominantly of loose, highly oxidized scoria. Mr. George M. Oringdolph of the Colorado Aggregate Co., Inc. has graciously furnished a chemical analysis of the scoria. The analysis indicates that the rock is a trachyandesite. No quartz is present in the norm. No analysis is presently available for rocks from Volcano de La Culebra; however, rocks from the upper part of that structure appear andesitic. Those from cliffs adjacent to the Rio Grande appear more like typical Servilleta basalts. The two small volcanic centers of Mesita age are probably equivalent to the Upper Series andesites of Aoki (1967, p. 192).

### INTRUSIVE ROCKS

Several stocks and dikes intrude the Conejos volcanics of the San Luis Hills. The stocks are located west of the Rio Grande being concentrated in the Piñon Hills and South Piñon Hills. Within the Piñon Hills four major intrusions have been mapped; one is present in the South Piñon Hills (fig. 1). The possible edge of a small intrusion has been noted at the northeast corner of Cerrito del Poncho along the Colorado-New Mexico state line. In the field rock exposed in the intrusions is very similar and it is presently believed that all the stocks were intruded at about the same time and that they have a common source. The rock making up the stocks is generally medium-crystalline, white to light tan, weathering to a light rust color. Detailed studies of the stocks would probably reveal significant variation in rock type with granodiorites and quartz monzonites being most abundant. Some rocks contain abundant quartz, while in others it is completely lacking. Three different analyses indicate that the stocks are chemically granodiorites, quartz monzonites and syenodiorites (table 1).

Dikes are concentrated in a zone adjacent to the La Sauses Gorge and have a general northerly trend (fig. 4). A small number of dikes have a general easterly orientation, the largest being the Manassa dike (fig. 5) along the south slope of Mesa de La Sauses. Some of the dikes are quite large, as much as 80 ft. thick and a mile long. Dike rocks are generally light gray, coarsely porphyritic, biotite-rich granodiorites. Large, green hornblende phenocrysts up to 5 mm in length have been recognized, but they do not occur in all the dikes. A few very small basic dikes are present but no chemical data are presently available for these dikes. Future petrographic and chemical studies of



FIGURE 4.

Looking south into La Sauses Gorge. North trending dikes intruding volcanics of La Sauses Member of Conejos Formation. Volcano de La Culebra of Mesita age (upper trachyandesite of Servilleta Formation) upper left. Rio Grande superposed across San Luis Hills at this point.



FIGURE 5.

East-west striking Manassa dike intruding Manassa Member of Conejos Formation. South side of Mesa de La Sauses (Flattop).

the dikes may show a relationship between rock type and dike orientation as well as a relationship to stocks mentioned above and to enclosing volcanic rocks.

### STRUCTURE

The San Luis Hills are a series of upthrown rocks in the central part of the San Luis Valley. A major north-south fault zone structurally divides the hills into eastern and western components. Although not controlled by it, the Rio Grande follows this fault zone through the hills and separates them physiographically.

Strata of the western hills are essentially horizontal while those of the eastern hills have a general southeasterly dip of 10 to 15 degrees. Local variations from the norm are

TABLE 1.

Chemical analyses and normative compositions of rocks of Conejos age, San Luis Hills.

Field Spl. No.	CONEJOS FORMATION														SERVILLETA FORMATION		
	Wild-horse Mbr.	La Sauses Member					Manassa Member				Intrusions				Mesita Mbr.		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
LS-80	SLH 3	SLH 36	LS 170	PS 2	M 144	LS 175	SLH 26	SLH 68	M 150	SLH 61	SLH 134	KH 6	M 18	KH 4	---	---	

CHEMICAL ANALYSES

SiO <sub>2</sub>	57.53	59.91	60.68	60.69	65.51	64.65	58.38	56.34	55.48	53.83	59.68	58.45	60.75	64.79	49.71	50.60	54.34
TiO <sub>2</sub>	1.01	1.54	0.93	0.80	0.44	0.72	0.99	1.08	1.58	1.29	1.28	1.38	0.65	0.51	1.04	1.30	1.56
Al <sub>2</sub> O <sub>3</sub>	18.50	16.92	17.14	17.75	16.36	19.32	16.86	16.34	15.04	15.08	18.40	16.61	16.37	15.42	16.73	16.30	17.42
Fe <sub>2</sub> O <sub>3</sub>	4.85	4.06	4.63	5.15	3.62	2.02	5.13	3.76	3.68	3.60	2.54	2.74	4.05	3.79	2.83	2.80	5.04
FeO	1.87	0.98	0.58	0.51	0.54	0.14	1.96	3.68	4.77	6.28	1.05	3.44	2.31	1.30	8.75	8.30	4.43
MnO	0.05	0.07	0.04	0.05	0.07	tr	0.14	0.06	0.07	0.15	tr	0.08	0.11	0.08	0.17	0.20	0.10
MgO	1.10	1.83	1.82	1.18	1.33	0.14	1.67	3.81	5.92	6.17	1.14	2.58	2.65	1.58	7.09	7.00	3.70
CaO	5.73	4.02	4.00	3.72	3.23	0.52	4.70	5.96	6.72	8.57	4.24	4.66	4.02	3.24	9.52	8.60	6.33
Na <sub>2</sub> O	3.72	4.26	4.27	3.98	3.81	3.93	4.07	3.70	3.62	2.87	6.40	4.16	3.65	3.74	2.88	3.00	5.21
K <sub>2</sub> O	3.49	4.66	4.37	4.48	4.31	3.83	4.28	3.56	2.14	1.04	4.42	4.66	3.75	3.69	0.20	0.80	2.28
P <sub>2</sub> O <sub>5</sub>	0.50	0.33	0.41	0.45	0.25	0.20	0.48	0.51	0.52	0.44	0.45	0.51	0.40	0.45	0.35	0.20	---
H <sub>2</sub> O <sup>+</sup>	1.26	0.73	0.85	0.80	0.22	2.68	0.79	0.75	0.65	0.74	0.36	0.46	0.90	0.87	0.58	0.80	---
H <sub>2</sub> O <sup>-</sup>	0.76	---	---	0.36	0.14	1.58	0.37	---	---	0.06	tr	0.14	0.12	0.22	0.18	0.20	---
Total	100.37	99.31	99.72	100.18	99.83	99.73	99.82	99.55	100.19	100.12	99.96	99.87	99.73	99.68	100.03	100.10	100.41

NORMATIVE COMPOSITIONS

Quartz	9.89	8.21	9.17	11.04	17.37	25.61	7.83	4.94	4.91	6.63	---	4.45	13.00	19.72	---	---	---
Orthoclase	21.15	27.95	26.10	26.85	25.60	23.70	25.80	21.30	12.65	6.25	25.75	27.70	22.60	22.30	1.20	4.80	13.35
Albite	34.30	38.80	38.75	36.25	34.50	36.95	37.25	33.65	32.55	26.20	53.30	37.60	33.35	34.35	26.20	27.30	46.35
Anorthite	24.10	13.48	14.88	16.95	14.55	1.37	15.43	17.73	19.50	25.60	7.25	12.97	17.53	13.45	32.55	29.05	17.30
Nepheline	---	---	---	---	---	---	---	---	---	---	2.04	---	---	---	---	---	---
Corundum	---	---	---	0.27	0.18	9.43	---	---	---	---	---	---	---	---	---	---	---
Diopside	1.40	0.40	1.12	---	---	---	4.08	7.08	8.40	11.80	6.20	5.36	0.08	---	10.36	10.28	11.08
Wollastonite	---	---	---	---	---	---	---	---	---	---	0.98	---	---	---	---	---	---
Hypersthene	2.42	4.92	4.52	3.30	3.98	0.40	2.66	8.72	14.90	16.92	---	5.98	7.42	4.46	23.16	22.34	0.86
Olivine	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1.32	0.99	3.69
Magnetite	2.31	---	---	---	0.33	---	2.55	3.98	3.80	3.83	---	2.88	4.17	2.10	3.00	2.97	5.19
Hematite	1.93	2.87	3.26	3.62	2.33	1.47	1.95	---	---	---	1.75	---	0.10	1.30	---	---	---
Ilmenite	1.44	1.54	0.90	0.80	0.62	0.22	1.40	1.52	2.20	1.82	1.60	1.94	0.86	0.72	1.46	1.82	2.16
Titanite	---	0.64	0.40	---	---	---	---	---	---	---	0.16	---	---	---	---	---	---
Rutile	---	---	---	0.16	---	0.42	---	---	---	---	---	---	---	---	---	---	---
Apatite	1.07	0.69	0.88	0.96	0.53	0.43	1.01	1.07	1.09	0.93	0.93	1.07	0.85	0.96	0.75	0.43	---
Total	100.01	99.50	99.98	100.02	99.99	99.98	99.96	99.99	100.00	99.98	99.96	99.95	99.96	99.36	100.00	99.98	99.98

No. 1, 4, 5, 6, 7, 10, 13, 14, 15 --- New analyses.

No. 6 --- Kaolinized and sericitized rock of King Turquoise Mine.

No. 11, 12 --- Stock north side of Pinon Hills.

No. 13 --- South Pinon Hills stock.

No. 14 --- La Sauses Dike.

No. 2, 3, 8, 9, 11, 12 --- After Larsen and Cross (1956, p. 87).

No. 16 --- Average of 17 analyses from Taos Plateau. After Aoki (1967, p. 197).

No. 17 --- Furnished by Mr. George M. Oringdulph, Colorado Aggregate Co., Inc., Mesita, Colorado.



FIGURE 6.

Looking east toward eastern San Luis Hills from Mesa de La Sauses. Note irregular nature of topography in contrast to flat surfaces of western San Luis Hills (fig. 9). North trending La Sauses dike (arrows) west of La Sauses Gorge (fig. 4). Cerrito de La Culebra is first large hill east of most extensive dike exposure.

present in both areas; being most common east of the Rio Grande (fig. 6). Along their western margin the western hills have been upthrown in respect to the San Luis Valley. The eastern hills are upthrown in respect to the western hills forming a southeasterly tilted fault block. Within the eastern hills this relationship is repeated forming a series of west-facing scarps. Scarps throughout the area are not always controlled by faulting but it is evident that major topographic features of the eastern San Luis Hills have been greatly influenced by structure.

East of La Sauses Gorge and Cerrito de La Culebra a small north striking syncline is present. Its eastern limb is also the western limb of an adjacent monoclinial flexure. Within this same general area several deviations of attitude from the norm are present; accounted for by minor folds, faults and by the movement of flows within the La Sauses Member over irregular topography.

Dikes of the La Sauses Gorge formed after the faulting, having intruded along planes of weakness produced by a north striking fault zone dividing the eastern and western hills. East of here one dike is offset about 20 feet and to the north two adjacent dikes have been offset by faulting along Wildhorse Ridge. The faulting that offset these dikes probably occurred very late in the tectonic history, not developing during the initial uplift of the hills. Two small northeast trending faults are present near the southern end of Wildhorse Ridge. These faults offset the upper part of the La Sauses Member and flows of the overlying lower Manassa Member. About four miles east of Wildhorse Ridge two north striking faults are present. The block between these two faults has dropped down and tilted eastward into the scarp formed by the eastern fault. This relationship is rather typical of the eastern San Luis Hills.

The eastern margin of the San Luis Hills is represented by flows of the Manassa Member dipping under Servilleta

basalts. In the Basaltic Hills the contact relationship is depositional; however, as one goes southward displacement of the basalts is noted along San Pedro Mesa. According to Upson (1938, p. 149) displacement along this fault is minimal at Rio Culebra and gradually increases southward to the Colorado-New Mexico state line. Upson suggests a stratigraphic throw of 2,100 feet from the top of the mesa to the basalt underlying the Costilla Plains west of the fault.

On the basis of gravity and magnetic data, Kleinkopf and others (1970, p. B82-84) indicate the presence of possible northeasterly trending faults or shear zones in the crystalline basement. One of these flanks the northern side of the San Luis Hills and another, parallel to this, the south side of the eastern San Luis Hills. The latter extends in a southwesterly direction beneath the Piñon Hills to Lobatos, Colorado. Renewed movement along these deep-seated fractures may have played a role in the general uplift of the San Luis Hills.

## PETROLOGY

Petrologic studies of the San Luis Hills are still in progress, and therefore will be considered only briefly at this time. The available chemical data (table 1) for the rock units and related intrusions are incomplete. Of the dikes only one, the La Sauses dike, has been chemically analyzed. More chemical data of the La Sauses Member, the lower half of the Manassa Member and of the dikes are desirable.

In spite of the above limitations it is evident that, when considered together, a close genetic relationship is present between the Conejos volcanics and associated intrusive rocks. This is evident in the field, but the chemical relationships are probably best illustrated by a series of Larsen (1938) type variation diagrams (fig. 7).

The chemical class of the rock suite, according to the Peacock alkali-lime index (Peacock, 1931) is 55.8. This is only 0.2 from the dividing line of the alkali-calcic and calc-alkalic classes at 56.

A triangular variation diagram plot of the  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$  and  $\text{CaO}$  shows the chemical variations within the rock suite (fig. 8). In this case it also shows the unconformable relationship between the La Sauses Member and the overlying Manassa Member. Beginning with Wildhorse time the nature of the eruptions became more silicic through La Sauses time. With the beginning of Manassa eruptions the relationship was reversed as volcanism progressed, suggesting differentiation of the magma chamber during erosion of the La Sauses Member.

## GEOMORPHOLOGY

After uplift and erosion to a mature topography, the hills were surrounded by Servilleta basalts along their southern and eastern margins. This was followed by continuous burial of the hills with sedimentary debris from the adjacent mountains. It is doubtful that the hills were ever completely buried but they have been buried to a greater extent than presently observed and are now being exhumed.

The topography of the San Luis Hills has been greatly influenced by underlying rock type and structure. The

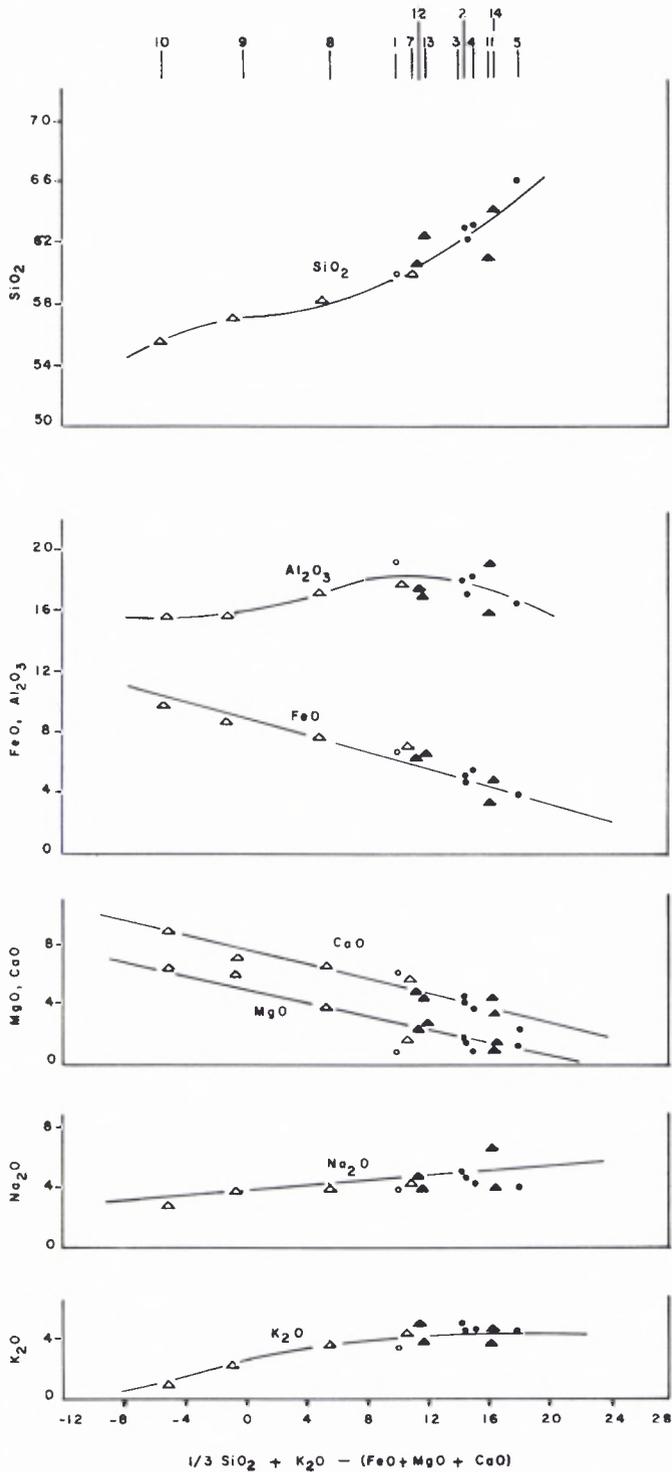


FIGURE 7.

Larsen (1938) type variation diagram of rocks of Conejos age, San Luis Hills. Numbers refer to analysis given in Table 1. For symbols see Figure 2.

western hills are characterized by flat-topped buttes: Sierra del Ojito, Mesa de La Sauces (fig. 9), the eastern Piñon Hills and the southern half of the South Piñon Hills. In

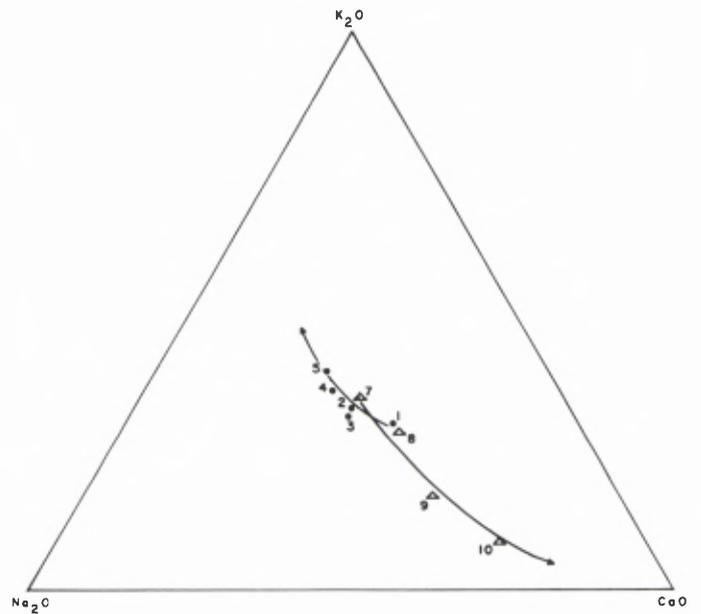


FIGURE 8.

Variation diagram of  $K_2O$ ,  $Na_2O$  and  $CaO$  for rocks of Conejos age, San Luis Hills. Numbers refer to analysis given in Table 1. For symbols see Figure 2.



FIGURE 9.

Looking west across top of Mesa de La Sauces (Flattop). Surface is made up of lava flows of Manassa Member of Conejos Formation.

each case the caprock is composed of horizontal cliff-forming lava flows of the Manassa Member. The eastern hills with their steep west-facing scarps and low eastward sloping gradients are a reflection of the tilted fault blocks. As seen from a distance these hills have a more irregular topography in contrast to the sharp angular topography of the western hills (fig. 5, 6). This is produced as the crests of the west-facing scarps are subjected to erosion and where flows of the Manassa Member are stripped away exposing crystal tuffs and tuff-breccias of the underlying La Sauces Mem-

ber. In the vicinity of Cerrito de La Culebra the effect is also produced by minor folding and faulting and by flows within the La Sauces Member moving over an irregular surface.

Only a few dikes, namely the Manassa and La Sauces dikes, are more resistant to erosion than the surrounding volcanic rock which they intrude (figs. 5, 6). Most dikes are very difficult to recognize from a distance and often show no major change in topographic relief because of the enclosing rocks. Some dikes have proven very difficult to follow on the ground, although they have been recognized from the air and from aerial photographs.

The San Luis Hills have been buried to a greater extent than is presently observed and are now being exhumed. That this relationship is true is best illustrated in the area extending from the north end of Wildhorse Ridge southward to Culebra Creek. In the Wildhorse Ridge area small superposed intermittent creeks have cut across ridges of volcanic rock forming shallow canyons (fig. 10). A study



FIGURE 10.

Small superposed creek across breccias of Wildhorse Member of Conejos Formation. Just north of Wildhorse Ridge.

by Fling (1970, this guidebook) of recent sediments in this area shows present-day river deposits along the Rio Grande at an elevation of 7,470 feet and in the adjacent higher reaches along Wildhorse Ridge sand dunes developed at elevations as high as 8,100 feet. When one considers the Rio Grande terrace levels north of La Sauces Gorge it is apparent that a correlation of surfaces can be made with levels near the mouth of Culebra Creek. Upson (1938, p. 195) believed that his 55- and 100-foot benches near the mouth of the Culebra were cut by the Rio Grande.

The Rio Grande has been superposed across the San Luis Hills and with rejuvenation has cut the La Sauces Gorge (fig. 4). Evidence of stream piracy is present throughout the area as west and south-flowing creeks erode headward into the eastern San Luis Hills. Eastward-flowing creeks, controlled by the dip slope of tilted fault blocks, are being captured by west and south-flowing creeks, diverting the drainage toward the Rio Grande and Culebra. Canyons

200 feet deep have been produced in this manner, although these creeks are dry most of the time and contain water only when it rains.

## SUMMARY AND CONCLUSIONS

The San Luis Hills are composed predominantly of Oligocene volcanic rocks of the Conejos Formation. Beginning in Wildhorse time and continuing through La Sauces time the eruptions became progressively more silicic. Following a period of erosion in which a surface of considerable relief was developed (locally several hundred feet) eruption of volcanic material of the Manassa Member took place. During these eruptions the volcanic material became progressively more basic, the reverse of the earlier eruptions. From field data all evidence seems to point to the general area of the King Turquoise Mine as the center of this volcanic activity. In close association with the volcanic activity Late Oligocene stocks intruded the Piñon Hills and South Piñon Hills. Some dikes of the area may be related to these intrusions, but the main dike swarm of La Sauces Gorge was intruded along planes of weakness produced by north-south faulting parallel to the present-day Rio Grande. The displacement along this fault resulted in uplift of the eastern San Luis Hills relative to the western hills. The fault passes through the probable center of the previous volcanic activity. With subsidence and eastward tilting of the San Luis Basin, beginning in Early Miocene time, the San Luis Hills were uplifted. This may have been the time of formation of the tilted fault blocks east of the Rio Grande. In conjunction with this uplift the area was eroded to a mature topography as it was being surrounded by sediments of the Santa Fe Formation accumulating in the subsiding basin. With eruption of the Late Pliocene Servilleta basalts from deep-seated fractures in the Rio Grande rift zone the hills were flooded around their southern and eastern margins. During the eruption of these plateau basalts the San Luis Hills acted as islands in a sea of lava. Following these eruptions the hills were further buried by sedimentary debris. With rejuvenation of the area the Rio Grande was superposed across the San Luis Hills gradually cutting down to form the La Sauces Gorge. The hills are presently being exhumed.

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