OPEN-FILE REPORT 02-6

Geologic Map of the Fort Garland SW Quadrangle, Costilla County, Colorado

By Robert M. Kirkham and Christine M. Heimsoth

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DEPARTMENT OF NATURAL RESOURCES

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RECLAMATION•MINING SAFETY•SCIENCE

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FOREWORD

The Colorado Department of Natural Resources is pleased to present the Colorado Geological Survey Open File Report 02–6, *Geologic Map of the Ft. Garland Quadrangle, Costilla County, Colorado.* Its purpose is to describe the geologic setting of this 7.5–minute quadrangle located between the towns of Fort Garland and San Luis.

Robert M. Kirkham, geologist for the Colorado Geological Survey, and Christine M. Heimsoth, Adams State College, completed the field work on this project in the summer of 2001.

This mapping project was funded jointly by the U.S. Geological Survey (USGS) and the Colorado Geological Survey (CGS). USGS funds are competively awarded through the STATEMAP component of the National Cooperative Geologic Mapping Program (Agreement No. 01HQAG0094). The program is authorized by the National Mapping Act of 1997. The CGS matching funds come from the Severance Tax Operational Account that is funded by taxes paid on the production of natural gas, oil, coal, and metals.

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ACKNOWLEDGEMENTS

This geologic mapping project was funded jointly by the Colorado Geological Survey and U.S. Geological Survey through the STATEMAP component of the National Cooperative Geologic Mapping Program, Agreement no. 01HQAG0094. The State of Colorado provided funding through the Department of Natural Resources Severance Tax Operational Fund, which is derived from the production of gas, oil, and minerals.

Alan Steube shared soil maps and information collected as part of the Natural Resource Conservation Service's mapping program of Costilla County. He also arranged for the loan of aerial photography. Alan Wallace (USGS), who recently mapped several quadrangles north and east of our mapping area, answered our numerous questions about the geology of areas that he mapped and spent time in the field with us.

Rob Benson, Adams State College, led us on a field trip to the recently reclaimed Battle Mountain Gold Company's San Luis Mine, which is about 1.5 mi east of the southeast corner of the quadrangle.

Brian Brister, New Mexico Bureau of Mines and Mineral Resources, discussed the stratigraphy and structure of the Alamosa Basin with us on several occasions and supplied us with a copy of his in-press paper (Brister and McIntosh, in press).

$^{40}Ar/^{39}Ar$ dates of basalts within and adjacent to the quadrangle were generously provided by Dan Miggins (USGS). Questions about the volcanic stratigraphy of the region, in particular that of the Servilleta Basalt, were answered by Ren Thompson (USGS). Mitchell Drilling contributed subsurface information and allowed us to examine cuttings from water wells that were drilled while our field work was underway.

We appreciate the cooperation of the many landowners, especially Ty and Alicia Ryland of the Forbes Trinchera Ranch and Dick and Cindy Hartl.

We appreciate the thoughtful review comments of Alan Wallace and Jim McCalpin; the map and text benefited significantly from their attention. Jane Ciener served as the technical editor. We thank Matt Morgan and John Keller for training us to use the DVP photogrammetric system. Karen Morgan prepared the digital maps for peer review by modifying the files compiled on the DVP photogrammetric system. Cheryl Brchan prepared the final map and booklet for publication, and Larry Scott drafted the figures.

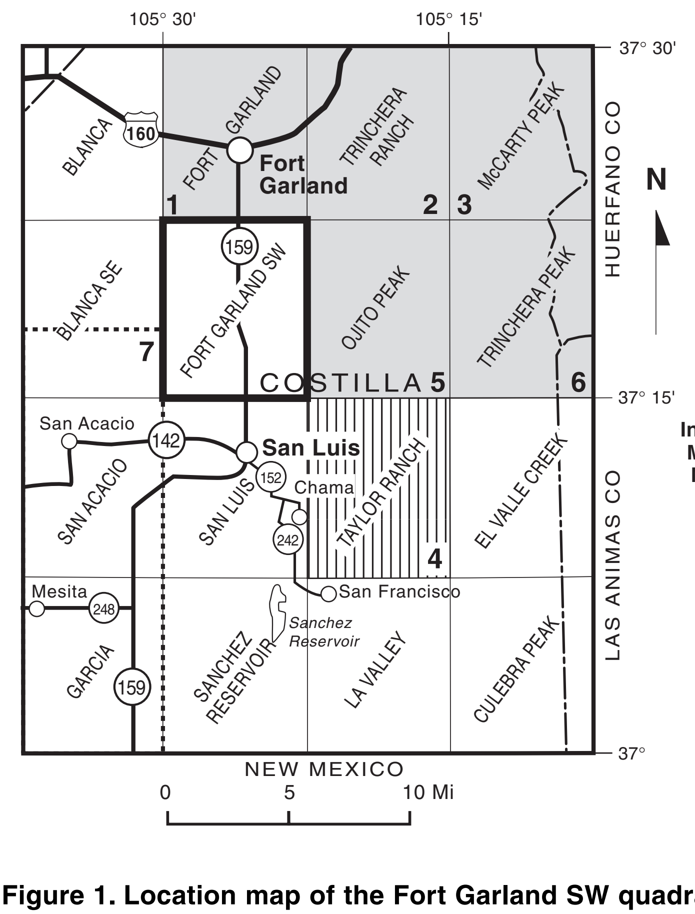
CONTENTS

INTRODUCTION

The Fort Garland SW 7.5-minute quadrangle covers about 59 sq mi of Costilla County in south-central Colorado between the towns of Fort Garland and San Luis (Fig. 1). Colorado Highway 159 runs north-south through the central part of the quadrangle, which lies in the eastern part of the large, high-elevation, intermontane San Luis Valley.

The collection of structural and stratigraphic data is an important element of the CGS mapping effort in Costilla County. This information will improve our understanding of earthquake hazards and ground-water resources in the San Luis Valley part of the Rio Grande Rift. Crosscutting relationships between faults and Quaternary deposits provide constraints on the timing and size of prehistoric earthquakes. The 1:24,000-scale geologic mapping lays the ground work needed for future detailed earthquake-hazard investigations. Sediments and volcanic rocks exposed in the quadrangle, and strata that are correlative to them, serve as the major aquifers of San Luis Valley. The structural features identified by mapping influence the geometry of the aquifers. The maps describe the geology of the quadrangle at a scale valuable to many map users, and they also serve as good starting points for both regional and site-specific studies.

San Luis Valley lies in the Southern Rocky Mountain physiographic province of Fenneman (1931). The Sangre de Cristo Mountains are on the eastern side of the valley, and the San Juan



EXPLANATION

- This report
- CGS 1:24,000-scale geologic map
- USGS 1:24,000-scale reconaissance geologic maps
- USGS 1:50,000-scale geologic map

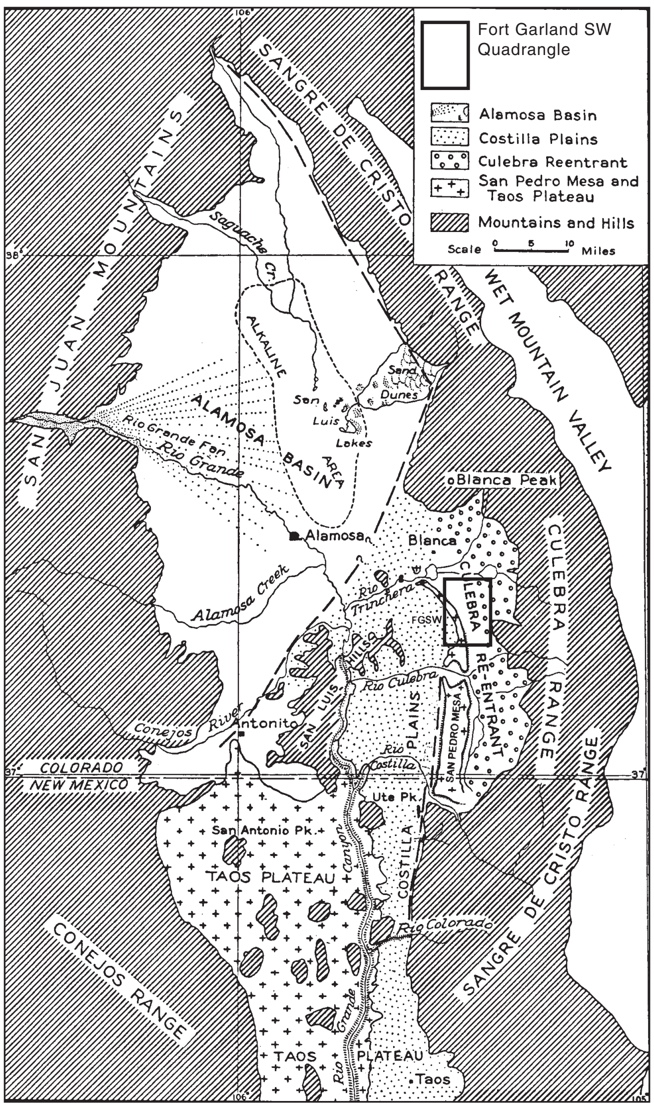
Completed 1:24,000-scale and larger geologic maps:

Index Map No.	Publication No.	Date	Scale
1	USGS MF-2312-E Wallace	1997	1:24,000
2	USGS MF-2312-C Wallace	1996	1:24,000
3	USGS MF-2282 Lindsey	1995	1:24,000
4	CGS OF 03-15 Kirkham and others	2003	1:24,000
5	USGS MF-2312-B Wallace and Soulliere	1996	1:24,000
6	USGS MF-2312-A Wallace and Lindsey	1996	1:24,000
7	USGS I-1906 Thompson and Machette	1989	1:50,000

Figure 1. Location map of the Fort Garland SW quadrangle, and status of geologic mapping in adjacent areas.

Mountains form the western side of the valley in Colorado. A prominent block of steep, rugged, mountainous terrain in the Sangre de Cristos north of the quadrangle, which includes the 14,345-ft-high Blanca Peak (Fig. 2), is referred to as the Blanca massif.

Upson (1939, 1971) subdivided the valley into five distinct physiographic subdivisions (Fig. 2). The northern part of San Luis Valley, an area that lies north of a roughly southwest-oriented line that runs from the southwest corner of the Blanca massif to near Antonito, is within Upson's Alamosa Basin. The San Luis Hills, which are in the central part of the valley and have almost 1,000 ft of local topographic relief, are relatively low and subdued compared to the Sangre de Cristo Mountains. The San Luis Hills separate most of the Alamosa Basin from the balance of the valley. The Taos Plateau to the south is a broad undulatory surface with local rounded hills and mountains and steep-walled, narrow valleys. The southeastern margin of San Luis Valley is recessed eastward from south of the Blanca massif to a short distance south of the Colorado-New Mexico state line. Upson (1939) named this recessed area the Culebra Reentrant. The part of the Sangre de Cristo Mountains east of the Reentrant is called the Culebra Range. All of the Fort Garland SW quadrangle is within Upson's Culebra Reentrant, except for the western edge of the quadrangle, which is within the Costilla Plains physiographic subdivision. The Costilla Plains form a nearly planar, very slightly west-sloping surface mantled with alluvial deposits.



Modified from Upson (1939, 1971)

Figure 2. Physiographic subdivisions of San Luis Valley. The mapped quadrangle is shown by the bold-outlined rectangle at right center.

The topography of Fort Garland SW quadrangle is relatively flat, sloping from its highest elevation of about 8,890 ft in the northeast corner to 7,730 ft in the northwest corner. Ojito Creek is the only named creek on the published topographic base map of the quadrangle. The creek heads on the west flank of Ojito Peak a few miles west of and about 2,000 ft lower than the main crest of the Culebra Range. It flows generally westward until reaching the Ojito Creek strand of the Northern Sangre de Cristo Fault, at which point it bends southwest. Ojito Creek seeps into surficial deposits and disappears about 1 mi southwest of where it crosses the Ojito Creek strand of the fault. The major drainages of Trinchera Creek and Culebra Creek lie just north and south, respectively, of the quadrangle.

The Basaltic Hills in the northwest quadrant of the map are one of the few landforms named on the U.S. Geological Survey's 7.5-minute topographic base map. We informally have identified several other landforms on the accompanying geologic map. Most, but not all, of the added landform names were used in previously published geological literature. Upson (1939) called the low, gently west-sloping surface west of

Highway 159 and north of Culebra Creek, most of which is south of the mapped quadrangle, the San Pedro Cuesta. The northern end of San Pedro Cuesta extends about a mile into Fort Garland SW quadrangle. Upson (1939) named the flat-topped mesas in Fort Garland and Fort Garland SW quadrangles that are east of Highway 159, south of Highway 160, and north of Ojito Creek the Garland Mesas. We apply the name South Garland Mesa to that part of Upson's Garland Mesas which is south of Trinchera Creek (see Fig. 2). The southern end of South Garland Mesa is in the northeast corner of the map area. A low piñon-covered hill in the southeast corner of the quadrangle is herein called Skull Hill because of the pre-Hispanic human skull found there by the authors during this mapping project.

A prominent, regionally extensive, north-south-trending topographically low area crosses the Fort Garland SW quadrangle (Fig. 3). Stevenson (1881) named this valley Culebra Park, a practice followed by Upson (1939, 1971). Culebra Park starts in New Mexico near where Rio Costilla flows out from the Sangre de Cristo Mountains (Fig. 2), runs generally northward about 25 mi to the center of the Fort Garland SW quadrangle, and then swings

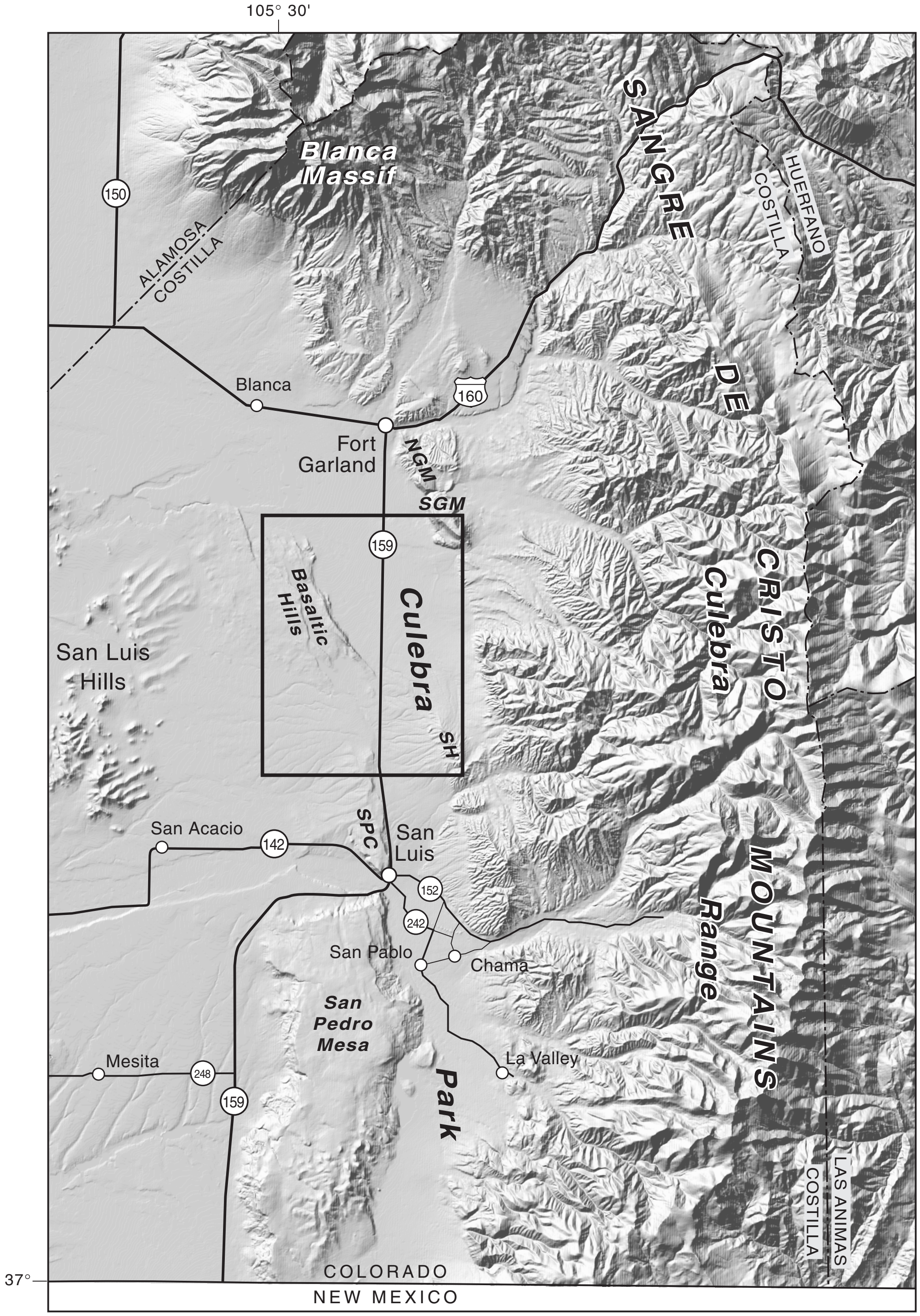


Figure 3. Selected physiographic landforms in and near the Culebra Reentrant. NGM—North Garland Mesa, SGM—South Garland Mesa, SH—Skull Hill, SPC—San Pedro Cuesta

northwestward for about 20 mi, past the town of Blanca to where it merges with the Alamosa Basin. Rio Costilla has incised about 500 ft through the floor of Culebra Park, but northward the park floor is generally now about at the level of modern stream grades except in the southern part of the quadrangle. Here, between Skull Hill and the northern end of San Pedro Cuesta and also northwest of Skull Hill, the land surface ranges from tens of ft to about 100 ft higher than the base level of modern streams.

An ancient alluvial fan that is now slightly dissected occupies much of the southwestern part of the quadrangle. The head of this fan is between the Basaltic Hills and San Pedro Cuesta. An ancestral creek, perhaps Rio Costilla or Rio Culebra, deposited the ancient alluvial fan. Historically, much of the quadrangle has been used for agricultural purposes, chiefly dry-land grazing. Irrigation supported farming in Culebra Park in the north-central part of the map area. Flood irrigation that utilized ditches was the preferred means of irrigation for many decades, but center-pivot irrigation systems fed by high-capacity irrigation wells are now the primary means of applying water to irrigated fields. Subtle landforms associated with the various Quaternary deposits were modified by farming practices associated with flood irrigation, but they were drastically altered by land leveling conducted prior to installation of the center-pivot irrigation systems. Older aerial photography was invaluable in areas disturbed by farming. The presence of very old, locally breached irrigation ditches and remnants of abandoned diversion structures in arroyos and stream drainages suggests that flood irrigation was at least attempted in other parts of the eastern half of the quadrangle at some time in the past.

Previously published geologic maps of the area that includes Fort Garland SW quadrangle are regional and small scale. No large-scale (1:24,000 or larger) geologic maps have been published for the quadrangle. Nonetheless, the geology portrayed on each small-scale map has aided the mapping of the quadrangle. Burbank and others (1935) and Tweto (1979b) compiled geologic maps of the entire state at a scale of 1:500,000. A regional tectonic map of the Rio Grande Rift by Tweto (1978); scale 1:1,000,000, also covers the Fort Garland SW quadrangle. Johnson (1969) mapped the geology of the Trinidad 1° x 2° quadrangle at a scale of 1:250,000. Upper Cenozoic strata and Quaternary faults were mapped by Colman and others (1985) at a scale of 1:125,000. The northwest corner of the quadrangle was mapped as part of a 1:250,000-scale map by Burroughs (1971).

More recent and more detailed geologic mapping of adjacent areas was very useful to this investigation. The 1:50,000-scale map of the San Luis Hills (Thompson and Machette, 1989) borders the southwestern part of Fort Garland SW quadrangle. Recent 1:24,000-scale mapping (Fig. 1) of the adjacent Trinchera Ranch, Fort Garland, and Ojito Peak quadrangles was conducted by Wallace (1996, 1997) and Wallace and Soulliere (1996), respectively.

Field work was conducted by the authors periodically from July to December, 2001. Traverses were made along all public roads in the quadrangle except for a few in the Basaltic Hills. Multiple foot traverses crossed South Garland Mesa, the cliffy parts of the Basaltic Hills, and San Pedro Cuesta. Traverses were made in all arroyos where the Santa Fe Group crops out in the northeast corner of the quadrangle and in most arroyos on Skull Hill and the hill immediately to the south. Aerial photography was used extensively during the project. Black-and-white photography at scales of 1:53,000 (flown in 1953), 1:20,000 (1963), and 1:40,000 (1999) and color infrared photography at a scale of 1:40,000 (1988) each provided complete coverage of the quadrangle. Geologic information collected in the field was plotted on the 1:40,000-scale black-and-white aerial photographs using a pocket stereoscope; areas of more complex geology (approximately one-half of the quadrangle) were plotted on the 1:20,000-scale photographs as well. Information drawn on the aerial photographs was compiled digitally using the DVP photogrammetric system recently acquired by the CGS. The geologic map utilizes the 1:24,000-scale topographic base map of the Fort Garland SW quadrangle that was first published in 1967 and updated in 1982 using aerial photographs taken in 1979.

Grain-size terminology used herein follows the modified Wentworth scale (Ingram, 1989). This classification system describes pebbles, cobbles, and boulders as differing sizes of gravel. The general term "gravel" also is commonly used for rounded clasts that show evidence of fluvial transport. To avoid confusion, non-fluvial angular and subangular clasts ranging in size from 2-256 mm are referred to as pebble-size or cobble-size clasts. Terms used for sorting are those of Folk and Ward (1957). Sedimentary clasts are defined in this study as rock fragments larger than 2 mm in diameter, whereas matrix refers to surrounding material that is 2 mm or less in diameter (sand, silt, and clay). In clast-supported deposits, the majority of the material consists of clasts that are in point-to-point contact. Material smaller than 2 mm is dominant in matrix-supported deposits, and most clasts are separated by or embedded in matrix.

GEOLOGIC SETTING

The Fort Garland SW quadrangle lies along the eastern margin of the Rio Grande Rift in south-central Colorado. It is within the southeastern part of San Luis Basin, which is a structural feature that approximately coincides with the physiographic area called San Luis Valley. Regional aspects of the rift and basin were described in numerous prior reports, books, and guidebooks, including those by Siebenthal (1910), James (1971), Tweto (1978, 1979a), Baldridge and others (1984), Chapin and Cather (1994), Brister and Gries, (1994), Kluth and Schaftenaar (1994), and Brister and McIntosh (in press).

STRATIGRAPHY

Holocene and upper and middle Pleistocene deposits blanket much of the quadrangle. The only pre-Quaternary bedrock units that crop out are the Santa Fe Group, a thick and regionally extensive sequence of syn-rift sedimentary strata, and the Servilleta Basalt, which is intercalated with the upper part of the Santa Fe Group.

Hayden (1869) originally named the sediments exposed in the hills near Fort Garland and San Luis the Santa Fe Marls. Siebenthal (1910) called them the Santa Fe Formation. Kottlowski (1953) raised the rank to a group status on the basis of work in southern New Mexico. This practice was followed by many later workers, including Spiegel and Baldwin (1963), who favored a group ranking "that includes all the synrift basin fill, both volcanic and sedimentary, ranging in age from late Oligocene to Quaternary, but excluding deposits that postdate entrenchment of the Rio Grande in middle Pleistocene time." Following this approach, Brister and Gries (1994) included all pre-middle Pleistocene sediments in the Alamosa Basin that overlie the upper Oligocene tuffs in the Santa Fe Group. They placed sediments that most prior workers called the Santa Fe Formation (e.g. Siebenthal, 1910; Powell, 1958) in the lower Santa Fe. The fluviolacustrine Alamosa Formation of Siebenthal (1910), which occurs only in the Alamosa Basin, constituted their upper Santa Fe. Most Santa Fe sediments exposed in the quadrangle are Miocene and Pliocene fan alluvium, but it is possible that some are upper Oligocene and/or Quaternary.

Butler (1946) originally named the late Tertiary basalts in the Taos Plateau in the southern part of the San Luis Basin the Servilleta Formation. Initially the formation included intercalated sediments (Butler, 1946; Montgomery, 1953). Lipman and Mehnert (1979) excluded the sediments from the formation and renamed it the Servilleta Basalt. Here, we also exclude the sediments from the unit, although in areas with poor exposure and stacked flows, some undetected Santa Fe sediments may be intercalated with the flows and included within the mapped boundaries of Servilleta.

STRUCTURE

The San Luis Basin is a large east-tilted half graben that began to form in the late Oligocene (Lipman and Mehnert, 1975). Brister and Gries

(1994) and Wallace (1995) demonstrated that part of San Luis Basin (Alamosa Basin) contains a pair of half grabens (Fig. 4). Late Cenozoic sediments conceal a buried, north-trending, mid-valley structural high between the two half grabens in the Alamosa Basin (Tweto, 1978, 1979a; Brister and Gries, 1994). Oligocene and younger volcanic rocks and minor intrusive rocks crop out in the San Luis Hills in the southern part of the San Luis Basin. A complex and major north-northwest-striking, west-dipping, normal-displacement structure called the Sangre de Cristo Fault forms the eastern margin of San Luis Basin. This fault, which extends southward from near Poncha Pass at the north end of San Luis Valley to beyond Taos, New Mexico, is subdivided into the Northern Sangre de Cristo Fault and the Southern Sangre de Cristo Fault by Widmann and others (1998) and Machette and others (1998). This two-part subdivision of the fault system is used in this report, even though we recognize that the Northern Sangre de Cristo Fault must cross the structural boundary at the southern margin of the Alamosa Basin. The Fort Garland SW quadrangle lies along the southeastern side of the San Luis Basin. Three strands of the Northern Sangre de Cristo Fault, herein named the Fort Garland, Ojito Creek, and Rito Seco strands, cross the eastern side of Fort Garland SW quadrangle (Fig. 4).

Prominent scarps in Quaternary deposits northwest of the town of Fort Garland document late Quaternary activity on the Fort Garland strand of the Northern Sangre de Cristo Fault (Kirkham and Rogers, 1981; Colman and others, 1985; Wallace, 1997). The scarp diminishes in height southward near where it crosses Highway 160 within Fort Garland and appears to transition into several low scarps, at least one of which extends to the base of North Garland Mesa. No scarps were reported farther south along the western base of North Garland Mesa by Wallace (1997), and none were detected by our reconnaissance work in this area. Nonetheless, we conclude that the Fort Garland strand does continue south-southeastward along the base of the mesa into the Fort Garland SW quadrangle, the same conclusion reached in prior investigations (Kirkham and Rogers, 1981; Colman and others, 1985).

Structural relationships between the Fort Garland strand and Ojito Creek strand are not well understood. A very subtle north-striking scarp along the Highline Canal west of where Ojito Creek exits the foothills is interpreted as the southern end of the Fort Garland strand. Unfortunately, anthropogenic activities have disturbed this general area, so it is possible that this scarp may not have a tectonic origin. However, there is an apparent left-stepping offset between the topographic base of South Garland Mesa and the low gravel-capped mesas on the footwall side of the Ojito Creek strand south of Ojito Creek. This landform relationship, along with the mapped traces of the scarps, lead us to conclude that the most recent surface ruptures on the Fort Garland and Ojito strands are en echelon.

A northeast-trending scarp cuts late Quaternary sediments along Ojito Creek where the creek exits the foothills and enters Culebra Park. The scarp has been armored with basaltic riprap and likely is anthropogenically altered. It starts at the northern end of the well-constrained location of the Ojito Creek strand, but it strikes about N45°E across the valley axis, which is sharply discordant with the N5°W strike of the Ojito Creek strand. Despite the abrupt strike change in the scarp, we tentatively conclude that the scarps are tectonic and that the most recent ruptures on the Ojito Creek strand may have connected with the N20°E-striking Mortimer Fault on Trinchera Ranch quadrangle (Wallace, 1996; A.R. Wallace, 2002, written commun.). It is also possible that prior fault ruptures along the Ojito Creek and Fort Garland stands, but not the most recent rupture, may have been connected. If the scarp mapped at the southern end of the Fort Garland strand is not tectonic, then the Ojito Creek strand may cut across the valley of Ojito Creek at about N30°W. It would continue northwest beneath the landslide complex on the southwest side of South Garland Mesa and merge with the Fort Garland strand. In this model, both strands are part of the same master fault. The queried, concealed, N40°W-striking fault that we include on our map would be the connecting fault between the Ojito Creek and Fort Garland strands.

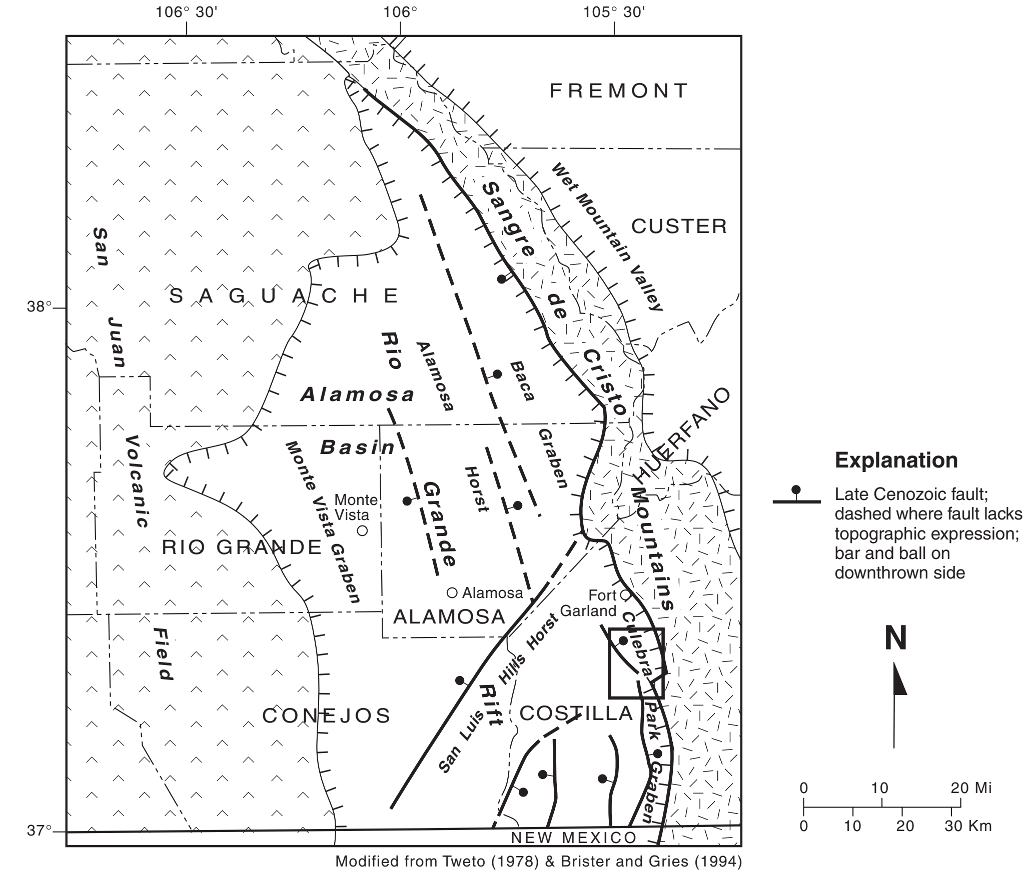
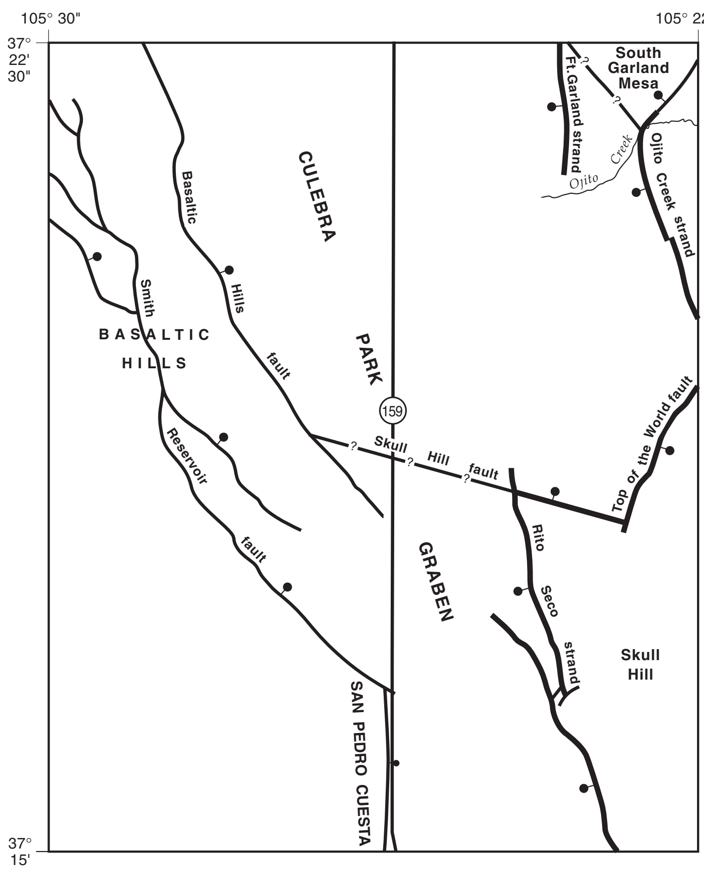
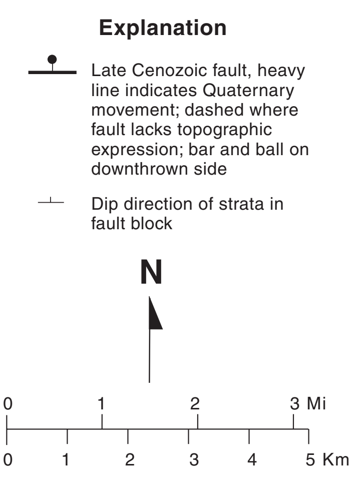


Figure 4. Simplified structure maps for San Luis Valley (upper diagram) and Fort Garland SW quadrangle. (lower diagram).





Servilleta Basalt flows that cap South Garland Mesa dip gently northeastward, while Santa Fe sediments exposed in the drainages on the southeast side of the mesa dip between 7 and 49° to the northwest. Small-displacement faults cut these sediments. One fault trends N5–10°E and dips about 50° east in the upper part of the exposure; the fault plane flattens to a dip of about 35° in the lower part of the outcrop. Another fault strikes about N45°W and dips about 40° northeast; calcite veining is locally present, and the slickenlines support dip-slip movement.

There are at least two possible explanations for the apparent unconformity between the Santa Fe sediments and Servilleta flows. The underlying Santa Fe sediments may have been tilted and an erosion surface cut across them prior to eruption of the Servilleta flows. In this scenario the faults exposed on the side of the mesa might be interpreted as part of the northeast-striking Mortimer Fault (Wallace, 1996; A.R. Wallace, 2002, written commun.). Presence of a volcanic ash in the Santa Fe Group about 250 ft stratigraphically below the base of the Servilleta flows that cap South Garland Mesa supports this interpretation. Glass shards in the ash are geochemically similar to glass contained in the Ibex Hollow ash (A.M. Sarna-Wojcicki, 2002, written commun.), which is dated at 11.93 ± 0.03 Ma (Perkins and others, 1998). The Servilleta flows that cap South Garland Mesa are geochemically correlated with a flow exposed along Trinchera Creek north of the quadrangle and dated at 3.66 ± 0.01 Ma (Wallace, 1997). Therefore, the 250 ft of Santa Fe sediment between the ash bed and the Servilleta flows represents over 8 m.y. of time. Either the sediment deposition rate was very low between about 12 and 3.7 m.y. ago, or there is an unconformity between the base of the flows and the top of the ash bed that represents a significant period of geologic time. The latter scenario supports the interpretation that the Santa Fe sediments were tilted prior to eruption of the Servilleta flows.

An alternate explanation of the observed dip changes on the southeast side of South Garland Mesa involves landsliding after the mesa became a prominent landform during the Quaternary. In this case, slumping along the mesa margin, a process common in many areas where the Servilleta flows cap poorly lithified, fine-grained underlying Santa Fe sediments, would have disrupted the Santa Fe sediments and the "faults" would be landslide slip planes. To the north, Wallace (1997) mapped extensive landslides on the north end of South Garland Mesa, and he also reported northeast dips in the sediments, evidence that favors a landslide origin for the faults exposed on the southeast side of South Garland Mesa. If the "faults" exist vertically beneath the intact Servilleta cap on the mesa, then they would be of tectonic origin.

The Ojito Creek strand of the Northern Sangre de Cristo Fault strikes S20°E between Ojito Creek and the eastern margin of the quadrangle. Low, dissected mesas capped by uplifted middle(?) Quaternary alluvium are present on the footwall (east) side of the fault. Holocene and late Pleistocene(?) sediments in Culebra Park are on the hanging wall side. Absolute age dating of these deposits is required to understand the Pleistocene behavior of the Ojito Creek strand. Another left-stepping en echelon structural relationship occurs along the Ojito Creek strand about 1.2 mi southwest of where Ojito Creek exits the foothills. The fault strand generally lies at the base of the low mesas and is concealed by Holocene alluvium along all but one of the modern valleys. A subtle, low scarp cuts a narrow remnant of unit Qa_{1-2} (Holocene and late? Pleistocene) that extends up the valley about 0.5 mi north of where the strand crosses the edge of the map area.

In Ojito Creek quadrangle, the Ojito Creek strand forms the western margin of a north-tilted block of rock that includes Oligocene volcanic flows, breccias, and lahars, underlying Eocene Vallejo Formation, and Proterozoic crystalline rocks (Wallace and Soulliere, 1996). Scarps in Quaternary deposits are present in some of the valleys that extend across the Ojito Creek strand. Colman and others (1985) measured profiles along a scarp that cuts deposits of at least two different ages in the small Basin east of the now-abandoned Willow Creek Reservoir. At the south end of the basin, in the Ojito Peak quadrangle, the scarp bends to a nearly north-south orientation and then aligns with a prominent southwesttrending escarpment cut into Santa Fe sediments. The Ojito Creek strand probably follows this escarpment southwestward and re-enters the Fort Garland SW quadrangle south of Willow Creek Reservoir. The Ojito Creek strand probably underlies an anomalous wind or water gap present at the south end of Skull Hill, and it apparently intersects the north-northwest-striking Rito Seco strand of the Northern Sangre de Cristo Fault at the southwest end of Skull Hill.

A prominent normal fault is exposed in the western end of the reclaimed open pits at Battle Mountain Gold Company's San Luis mine in Ojito Peak quadrangle about 1.7 mi east of the map area. This fault may be the southward continuation of the Ojito Creek strand. In the reclaimed pit, this N15–20°W-striking, 55–65° west-dipping fault drops Santa Fe sediments against Proterozoic rocks that are shattered and rich in clay gouge in a 25- to 30-ft-wide zone that is adjacent and parallel to the fault. The Santa Fe sediments in the footwall adjacent to the fault dip east 30 to 35°, suggesting they are part of an east-tilted fault block. An exploration drill hole for the gold mine (R.G. Benson, 2001, oral commun.) penetrated about 1,000 ft of Santa Fe sediments on the west side of the structure, which truncates the ore body at the San Luis mine. The drill hole did not reach the base of the Santa Fe sediments, but it demonstrates that the vertical displacement on the fault exposed in the pit at San Luis mine probably exceed 1,000 ft.

The N25°W-trending Rito Seco strand includes a series of right-stepping en echelon scarps formed mostly in middle(?) Pleistocene alluvium along the west side of Skull Hill. The fault is exposed near the southern edge of the quadrangle in an old irrigation ditch on the north side of the valley that cuts through Skull Hill. It has an apparent dip of about 75° to the west. Sediments on the upthrown or east side of the fault. are probably middle Pleistocene alluvium. Sediments on the downthrown western side of the fault are mapped as unit Qa_3 on the basis of the weakly to moderately developed argillic B horizon exposed in the ditch bank, but these sediments probably are at least in part scarp-derived colluvium.

Two northeast-tilted blocks of rock that include flows of the Servilleta Basalt lie along the Rito Seco strand near the northern end of Skull Hill. Structural relationships between the faults that deform these blocks of rock and the Rito Seco strand are uncertain. The northeast-tilted blocks may be a result of an earlier phase of tectonism, or they could be very eroded remnants of older landslides that are analogous to the Quaternary landslides on the flanks of South Garland Mesa.

Scarps associated with the Rito Seco strand continue northward nearly 2 mi beyond the northern end of Skull Hill. Here they interact with a N80°W-striking, down-to-the-north scarp that we name the Skull Hill Fault. It is interesting to note that scarps along both the Rito Seco strand and Skull Hill Fault appear to continue at least a short distance beyond the intersection of the two faults. The Skull Hill Fault forms the northern structural margin of the block that includes Skull Hill, and it provides a structural connection between the Rito Seco strand and the Top of the World Fault. The Skull Hill Fault offsets middle Pleistocene alluvium, but no obvious evidence of Holocene or late Pleistocene movement was observed. Two small arroyos bend sharply where they cross the Skull Hill Fault. If the bends have a tectonic origin, then the Skull Hill Fault may have a small component of right-lateral slip.

The eastern end of the Skull Hill Fault appears to terminate against the N20–30°E-striking Top of the World Fault. This structure splays off the Ojito Creek strand near a structural junction where the N70–80°W-striking fault that borders the north-tilted block on Ojito Peak quadrangle (Wallace and Soulliere, 1996) intersects the Ojito Creek strand. The Top of the World Fault cuts deposits as young as unit Qa_2 (early Holocene and late Pleistocene), is downthrown to the east forming an antithetic relationship with the Ojito Creek strand, and has an uphill-facing scarp along it. The scarp appears to have temporarily dammed north to northeast-flowing drainages, because clayey organic-rich sediments are locally found along the eastern side of the fault.

Culebra Park is the north-trending topographic low that forms the broad valley between the Basaltic Hills and South Garland Mesa and the narrower and less distinct topographic low between Skull Hill and San Pedro Cuesta. Upson (1939) stated that San Pedro Mesa is a horst. If a down-to-east fault borders the east side of the Basaltic Hills, then that part of Culebra Park also would be a graben. Some prior studies (e.g. Johnson, 1969; Tweto, 1978, 1979a, b) did not map faults along the east side of the Basaltic Hills, whereas others did depict all or parts of Culebra Park as a graben (e.g. Colton, 1976; Kirkham and Rogers, 1981; Colman and others, 1985; Wallace, 1995).

On the basis of (1) regional structural relations, (2) faults that cut the Pliocene basalt flows in the Basaltic Hills, (3) geochemical correlation of basalt flows that crop out in the Basaltic Hills with those on South Garland Mesa, (4) inferred fault scarps north of the Basaltic Hills, and (5) basalt flows encountered in drill holes in Culebra Park, we conclude that down-to-the-east faults control the eastern margins of the Basaltic Hills and San Pedro Cuesta. We have named the two faults with greatest displacement and length the Basaltic Hills and Smith Reservoir Faults.

If a graben does not exist beneath Culebra Park, then the Basaltic Hills and Culebra Park would be part of an east-tilted half-graben that is bounded on the east by the Northern Sangre de Cristo Fault. Strata within the graben would dip eastward into the deepest part of the half-graben. However, the Pliocene basalt flows that cap the Basaltic Hills dip about 1.5° to 4.0° southwest and west. Some of the flows that crop out in the Basaltic Hills are geochemically correlative to the 3.66-Ma Servilleta flows on South Garland Mesa (J.R. Budahn, 2002, written commun.). If the flows in the Basaltic Hills are projected eastward to South Garland Mesa using these 1.5° to 4.0° southwest and west dips, then their projected elevations would be either equal to or as much as 2,000 ft above equivalent flows on South Garland Mesa, depending on which dip angle is used for the calculation. This relationship is feasible only if the Fort Garland strand has not experienced any movement since middle Pliocene time, or if the direction of movement was down to the east. Available data conflict with both of these hypotheses; however, the data do support the presence of a graben beneath Culebra Park. The Smith Reservoir Fault and Basaltic Hills Fault may form or be part of the structural system on the western margin of the Santa Fe depocenter reported by Keller and others (1984) and Wallace (1995).

Several minor, northwest-striking faults that are downthrown to the northeast cut the basalt flows that cap the Basaltic Hills. These structures are probably related to the Basaltic Hills and Smith Reservoir faults. A potential alternative explanation of these structures involves landsliding, in which case these minor faults would be similar to the landslide scarps and incipient landslide scarps on South Garland Mesa. However, if slope failure caused these minor faults, then Culebra Park must have once been eroded to a much greater depth, because gravity sliding would be required to account for the observed structures. The linear character of the structures does not favor a landslide origin. There is no evidence for and it is unlikely that significantly greater topographic relief once existed between the floor of Culebra Park and the Basaltic Hills.

The flows that cap the Basaltic Hills appear to continue northward beyond the northern end of the Basaltic Hills, but they descend in elevation and extend into the subsurface. Lineaments in Quaternary deposits occur along the probable trace of a splay of the Basaltic Hills Fault north of where the basalt flows disappear into the subsurface. Farther north, beyond Trinchera Creek and Smith Reservoir, lineaments and subtle east- and northeast-facing scarps in Quaternary alluvium align with projections of the Basaltic Hills and Smith Reservoir Faults. These features need additional detailed study before they are conclusively identified as faults, but the fact that they locally act as barriers to ground-water flow suggests that they are faults.

Basalt flows were penetrated by several water wells drilled in Culebra Park between the Basaltic Hills and Northern Sangre de Cristo Fault (Colorado Division of Water Resources files, driller's logs, permit numbers 2889F, 2890F, 23263F, 47540FR). Other wells in this area (e.g. permit numbers 10295F and 14097) reported “rock” in a sequence of otherwise poorly lithified Santa Fe sediments; these hard strata also may basalt. The basalts encountered in the wells may be correlative with the Servilleta flows exposed in the Basaltic Hills and on South Garland Mesa, which, if correct, substantiates the presence of a graben beneath Culebra Park.

Existence of a graben beneath Culebra Park neither supports nor discounts the proposal put forward by Upson (1939) that an ancestral northward-flowing Rio Costilla eroded Culebra Park. If a unique bedrock lithology cropped out in the upper part of the Rio Costilla drainage basin, then the presence of clasts composed of that unique lithology in or beneath units Qa_4 or Qa_5 east of Skull Hill would demonstrate that Rio Costilla did flow northward through Culebra Park. The authors are not presently aware of any unique bedrock lithologies exposed in the drainage basin of Rio Costilla that could be used for this purpose. Evidence of north- or northwest-oriented paleocurrent directions in the sediments beneath Culebra Park also would support Upson's suggestion that Rio Costilla flowed through the park. Unfortunately, these sediments are very poorly exposed, and no paleocurrent indicators were noted in this area.

Correlation of Servilleta flows on the basis of geochemical composition (J.R.Budahn, 2002, written commun.) requires that a small displacement, probably northeast-striking, down-to-northwest fault be present near the northeast end of San Pedro Cuesta. The Servilleta flow that crops out along the south boundary of the quadrangle (sample FS96) correlates geochemically with a flow exposed at the northeast end of San Pedro Cuesta (sample FS98). Field relations suggest the vertical displacement on this inferred fault is at least 40 to 50 ft.

GEOLOGIC HAZARDS

Geologic hazards and engineering constraints present in Fort Garland SW quadrangle include sediment-laden flooding, debris flows, earthquakes and surface rupture of faults, rockfall, landslides, and problematic soils. Areas mapped as alluvium one (unit Qa_1) and younger fan deposits (unit Qfy) are prone to future flooding, including sediment-laden flood waters, debris flows, and mud flows. Sheet flooding may be expected to occur in areas mapped as sheetwash (unit Qsw).

Potentially catastrophic damage may result from future activity of faults within or adjacent to the quadrangle. Faults that displace Quaternary deposits have experienced movement during the recent geologic past and are probably capable of future movement. Future earthquakes as large as about magnitude 6¾ to 7¼ may occur on these faults, and differential movement of the ground surface along these faults will be likely during large earthquakes. Structures built on and near the faults can be damaged by rupture of the ground surface, but the ground shaking generated by the earthquakes poses a more far-reaching threat. Earthquakes can also trigger secondary effects, such as liquefaction, rockfall, and landsliding, which potentially can cause greater damage than ground shaking or surface rupture.

Rockfall is a hazard on and beneath cliffs where ledges of Servilleta Basalt (unit Ts) crop out. These cliffs are present along the margins of South Garland Mesa and locally within the Basaltic Hills. The only mapped landslide (unit Qls) in the quadrangle is on the southern side of South Garland Mesa. Although no evidence of recent movement was noted in this landslide during our mapping project, any disturbance of this deposit involving cut or fill activities should be carefully engineered. Areas where hard Servilleta basalt flows overlie weakly indurated, fine-grained sediments in the Santa Fe Group are prone to future landslide activity.

Fine-grained sediments deposited in fan environments and on colluvial slopes may create conditions favorable for hydrocompaction and piping. Such sediments may be found in units Qfy, Qa_1, Qa_2, Qa_3, Qa_4, Qa_5, Qsw, Qc, Qcs and Qcf.

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Surficial deposits blanket much of Fort Garland SW quadrangle and conceal the underlying bedrock. Most of the surficial deposits in the quadrangle are not well exposed. Therefore, the attributes of these units, such as thickness, texture, stratification, and composition, are based on observations made at only a few locations and on geomorphic characteristics. Since many of the intended users of this map will be interested in unconsolidated surficial materials and active surficial processes, the surficial deposits are subdivided into a relatively large number of map units compared to traditional bedrock-oriented geologic maps.

Most of the surficial map units are classified by genesis and relative age. Surficial units shown on the map generally are more than about 3 ft thick. Deposits associated with distinct landforms may locally be thinner than 3 ft. Fractional map units (such as Qcs/Qa_3) indicate that a thin mantle material, in this case colluvium and sheetwash undivided, overlies another deposit, alluvium three. Surficial deposits with a width of about 75 to100 ft or less are not shown on the map because they cannot be depicted on a 1:24,000-scale map. Artificial fill of limited areal extent and residuum were not mapped. Contacts between many surficial units may be gradational and therefore should be considered as approximate boundaries.

Divisions of the Quaternary and Pleistocene used herein correspond to those summarized by Madole and Thorson (2003). Characteristics such as the position in the landscape, degree of erosional modification of original surface morphology, and relative degree of weathering and soil development were used to estimate the relative ages for the surficial deposits. Since the streams responsible for deposition of Pleistocene alluvial sequences in the quadrangle were not fed by glacial meltwaters, correlation of these alluvial sediments to episodes of Pleistocene glaciation was not attempted. Differences in the soil-profile development were only sometimes useful, because (1) good exposures of well-preserved soil profiles are relatively rare in the quadrangle, (2) limited field time prevented the excavation of numerous soil pits, and (3) the available soil exposures were difficult to interpret because deposits that were suspected of being late and middle Pleistocene commonly had only weakly developed soil profiles. The latter factor may result from a number of causes, including the complicating effects of wind erosion and deposition and the fact that many surficial deposits are composed of very granular sediments with few fine-grained particles.

Soil-horizon names used here are those of the Soil Survey Staff (1975) and Guthrie and Witty (1982), and the stages of secondary carbonate morphology are from Gile and others (1966), with the modifications of Machette (1985). Concurrent soil mapping by the U.S. Department of Agriculture's Natural Resource Conservation Service (Alan Steube, 2001, written commun.) aided our attempt to utilize pedogenic soils as a tool to determine relative ages of the surficial map units.

In much of Colorado, fluvial deposits underlie sequences of terraces and their relative ages are readily apparent, but most fluvial deposits in the mapped area do not underlie inset terrace sequences, which complicates relative age assignments. The presence of faults that have moved during the deposition of the surficial map units further hampers efforts to determine relative ages of surficial map units. On the upthrown or footwall side of young faults, preserved remnants of fluvial deposits found higher in the landscape are usually older than those that are lower. On the downthrown side of young faults, however, older deposits may occur at higher, lower, or the same elevation as younger deposits, depending on factors such as the slip-rate of the fault, the rate of sediment deposition, and the effects of changing base levels.

HUMAN-MADE DEPOSITS—Materials placed by humans

af **Artificial fill (latest Holocene)**—Consists of fill and waste rock placed during construction of roads and dams. This unit is composed mostly of unsorted silt, sand, and rock fragments but may include construction materials. Maximum thickness is about 30 ft. Artificial fill may settle when loaded, if not adequately compacted.

ALLUVIAL DEPOSITS—Gravel, sand, silt, and clay deposited by flowing water in channels and on flood plains and fans, or as sheet flow. Deposits resulting from sheet flow are referred to as sheetwash. Sheetwash alluvium locally grades to small, unmapped areas of playa deposits in closed depressions in the Basaltic Hills. Units Qa_1 (youngest) through Qa_5 (oldest) are divided on the basis of their position in the landscape and, to a lesser extent, on the pedogenic soil formed on the surface of the deposits.

Qa_1 **Alluvium one (Holocene)**—Chiefly poorly sorted, clast-supported, unconsolidated, sandy pebble and cobble gravel, gravelly sand, silty sand, and sandy silt along modern drainages, including a broad area in the northeast part of the quadrangle. Locally includes small boulder-sized material. Deposits are commonly well bedded and have cut-and-fill channels. Locally includes very poorly sorted, matrix-supported gravelly silt and sand that probably was deposited by debris flows.

Unit Qa_1 also underlies low terraces adjacent to Ojito Creek on the east (footwall) side of the Fort Garland strand of the Northern Sangre de Cristo Fault zone and adjacent terraces. Most sediment included in unit Qa_1 is reworked from the weakly lithified sediments of the Santa Fe Group or from other surficial deposits. The clasts in these reworked deposits are subangular to round and consist mostly of gneiss, potassium feldspar, quartz, and basalt, with minor sandstone, limestone, and shale. In the east-central part of the quadrangle many of the clasts are first-cycle material eroded directly from Oligocene volcanic rocks, Proterozoic felsic gneiss and hornblende gneiss, and reddish conglomerate and sandstone from the Eocene Vallejo Formation, all of which are exposed in the hills east of the quadrangle (Wallace and Soulliere, 1996). These clasts are generally angular to subangular. Where deposits of unit Qa_1 are near exposures of Servilleta Basalt, they may include angular clasts of basalt derived from the Servilleta.

Deposits of unit Qa_1 usually lack any appreciable soil development or have only weakly developed, sometimes stacked, A/C horizons. Unit includes sediment deposited historically in some areas. Charcoal was collected from a deposit of unit Qa_1 exposed in an arroyo cut into a low terrace on the south side of Ojito Creek in Ojito Peak quadrangle about 1 mi east of Fort Garland SW quadrangle boundary. This location is on the northwest side of Sween and Bateman Roads (approximate UTM coordinates: x = 468,322 meters, y = 4,134,381 meters). The charcoal yielded a conventional radiocarbon age of 1,390 ± 70 years BP (1 sigma calibrated age range 1,270-1,330 years BP) (analysis by Beta Analytic, Inc., sample no. 163525). The charcoal appeared to be fragments of a burned branch or tree limb and consisted of disseminated fragments as much as 0.8 in. in diameter and 2.5 in. long. The fragments were found about 4.5 to 5.0 ft below the ground surface near the base of a 3 to 3.5 ft thick deposit of medium-grayish-brown slightly gravelly silt and clayey silt. The bed containing the charcoal was overlain by 1 to 1.5 ft of thinly bedded sandy silt and silty sand, and about 1.0 to 1.5 ft of sandy pebble gravel was exposed between the base of the charcoal-bearing bed and the floor of the arroyo.

Since the base of unit Qa_1 is not exposed in the quadrangle, the unit thickness is unknown. It probably is commonly 5 to 15 ft thick. Topographically low areas are prone to flooding. Unit Qa_1 is a good source of sand and gravel.

Qa_2 **Alluvium two (early Holocene and late Pleistocene)**—Sediment is similar to unit Qa_1. Alluvium two underlies a large gently northwest-sloping piedmont surface along the eastern side of the Basaltic Hills. Elsewhere, it chiefly occurs as small remnants of fan and terrace deposits adjacent to unit Qa_1. Clasts contained within unit are typically unweathered or very slightly weathered. Soil on unit Qa_2 locally has a thin to moderately thick A horizon, a weak clayey argillic B horizon and a Cca horizon with stage I to weak stage II carbonate morphology. Elsewhere the soil is less well developed. Thickness is unknown. Unit is a good source of sand and gravel.

Qa_{1-2} **Alluvium one and two, undivided (Holocene and late Pleistocene)—**Mapped where limited exposures and poorly preserved landforms preclude distinction of the units Qa_1 amdQa_2.

Qa_3 **Alluvium three (late middle Pleistocene)—**Sediment is similar to unit Qa_1. Remnants of fans, terraces, and piedmont slopes underlain by alluvium three are preserved in the eastern half of the quadrangle, east of the Basaltic Hills, and along the northern boundary of the map area. Test hole TH-1, located between the northeast end of the Basaltic Hills and Smith Road, was drilled in 1998 (Kirkham, 1998). Drive samples from this 41.5 ft deep test hole recovered mostly sandy sediments ranging from slightly gravelly, medium- to coarse-grained sand to very fine-grained sand. The hole penetrated slightly clayey, silty, very fine- to fine-grained sand from 11 to 11.5 ft and clayey sand silt from a depth of 30.5 to 31 ft. Gravel clasts in unit Qa_3 are slightly to moderately weathered. The strongest soils present on unit Qa_3 usually have moderate to strong organic-rich A horizons, and moderate to well-developed argillic B horizons that sometimes have stage I carbonate morphology and blocky or weak prismatic structure. The Cca horizon, which is not present everywhere, includes stage II to weak stage III morphology. Thickness is unknown. Unit is a potential source of sand and gravel.

Qa_{2-3} **Alluvium two and three, undivided (early Holocene to late middle Pleistocene)—**Mapped where limited exposures and poorly preserved landforms preclude distinction of units Qa_2 and Qa_3.

Qa_4 **Alluvium four (middle Pleistocene)—**Chiefly poorly to moderately well-sorted, clast-supported, unconsolidated, sandy pebble and cobble gravel with rare boulder-sized clasts, gravelly or silty sand, and sandy silt. Locally includes very poorly sorted, matrix-supported gravelly silt and sand interpreted as debris-flow deposits. Unit underlies broad areas that are moderately dissected on the north and west sides of Skull Hill and an extensive, slightly dissected fan in the southwest part of the quadrangle. Clasts are chiefly subround to subangular fragments of Proterozoic gneiss (mostly felsic and hornblende gneiss), andesite, basalt, quartz, and potassium feldspar.

Unit Qa_4 forms a large fan in the southwest part of the quadrangle. The modern drainage basin of the large fan is underfit, so an ancestral stream with much larger drainage basin must have deposited the fan. Upson (1939) suggested that Rio Costilla formerly flowed northward through Culebra Park. If so, then ancestral Rio Costilla, or perhaps an ancestral Culebra Creek or Rito Seco, may have deposited part of unit Qa_4 within Culebra Park, as well as those deposits that underlie the large fan. No paleocurrent indicators were found in unit Qa_4 within Culebra Park that would support this supposition. Furthermore, the authors are presently not aware of any unique bedrock lithologies within the drainage basins of ancestral Rio Costilla, Culebra Creek, or Rito Seco that could be used to demonstrate which of these streams once flowed through Culebra Park and was responsible for deposition of the large fan.

Gravel clasts contained in unit Qa_4 are slightly to strongly weathered. A and B soil horizons are commonly absent or thin on deposits of unit Qa_4, perhaps because they were removed by erosion. Preserved soils are calcic and have strong Cca horizons and weak K horizons that are about 2 to 6 ft thick. They are characterized by stage III and sometimes weak IV morphology. Unit Qa_4 is estimated to be as much as 40 ft thick, which is the maximum height of the unit above adjacent drainages. Unit is a potential source of sand and gravel.

Qa_{3-4} **Alluvium 3 and 4, undivided (middle Pleistocene)—**Mapped where limited exposures and poorly preserved landforms preclude distinction of units Qa_3 and Qa_4.

Qa_5	Qa_{5y}
	Qa_{5o}

Alluvium five (middle Pleistocene)—Sediment is similar to unit Qa_4. Dissected remnants of alluvium five are found between Skull Hill and the Basaltic Hills, and southwest of Skull Hill. They are differentiated from unit Qa_4 chiefly on the basis of being slightly higher in the landscape (about 10 to 20 ft). Unit Qa_5 is subdivided locally into younger (Qa_{5y}) and older (Qa_{5o}) deposits. Unit Qa_5 underlies a narrow northwest-trending ridge that is about 10 ft higher than adjacent deposits of unit Qa_{5y}. It is also possible that the elevation difference is the result of erosion, in which case the age of the sediments beneath the higher ridge is the same as that of the sediments underlying the lower surface, but the ages of the surfaces cut into the deposits would be different. Clast weathering and soil development is similar to unit Qa_4. Thickness may exceed 35 ft, which is the approximate height of the deposits above adjacent streams.

Qsw **Sheetwash deposits (Holocene and late Pleistocene)**—Sheetwash alluvium fills numerous topographic depressions and low-gradient ephemeral tributary valleys in the Basaltic Hills. These deposits are derived locally from weathered bedrock and, to a much lesser extent, surficial materials. Sheetwash typically consists of pebbly silty sand, sandy or clayey silt, and sandy silty clay. Locally it grades to and interfingers with unmapped playa and slackwater deposits in the lowest parts of the topographic depressions, many of which are shown as ephemeral ponds on the photorevised base map of 1982. The playa and slackwater deposits appear to range from clayey silt to silty sand, on the basis of a few shallow hand-dug pits.

The sheetwash alluvium appears to rest on flows of Servilleta Basalt. However, remnants of Santa Fe sediments or other deposits may be buried beneath some sheetwash deposits. The Servilleta flows are interbedded with sediments of the Santa Fe Group east of the Garland Mesas (Wallace, 1997). Before mining activities disturbed much of the Mesita cinder cone, the senior author in 1976 and Epis (1977) observed remnants of fluvial deposits locally overlying the central part of the cone, which is located about 11 mi southwest of the quadrangle. The remnants of alluvium on top of the 1.03 ± 0.01 Ma volcano (Appelt, 1998) suggest that alluvial strata was stripped from the Costilla Plains during the past 1 million years. On the basis of this evidence, it is likely that the Servilleta flows in the Basaltic Hills also were formerly overlain by other deposits, and that remnants of those deposits may be locally preserved beneath the younger sheetwash deposits.

Maximum thickness of sheetwash alluvium is estimated to be about 10 ft. Areas mapped as sheetwash are subject to future sheet-flow deposition and locally to ephemeral ponding of surface runoff. Unit may be prone to hydrocompaction, settling, and piping where fine grained and low in density.

MASS-WASTING DEPOSITS—Sand, gravel, silt, and clay on hillslopes and adjacent valley floors that were transported downslope primarily by gravity. In contrast to other forms of material transport, the debris carried by mass wasting is not transported within, on, or under another medium such as flowing water or wind (Jackson, 1997). Water is an important element in mass wasting and commonly triggers the movement; it is a part of the moving mass, not the transporting agent. Landslide deposits and colluvium are the principal types of mass-wasting deposits in Fort Garland SW quadrangle. As used here, colluvium generally follows the definition of Hilgard (1892) in that it (1) is derived locally and transported only a short distance, (2) is not distributed by channelized water flow, (3) contains clasts of varying size, (4) has no sedimentary structures or stratification caused by channelized flow of water, and (5) may include minor amounts of sheetwash and debris-flow deposits.

Qc **Colluvium (Holocene and late Pleistocene)**—Deposits on or at the foot of hillslopes that consist of poorly sorted, sandy or silty, fine to coarse gravel and gravelly sand and silt. Clast lithology depends on the source area: where the Servilleta Basalt provides clasts, they are mostly pebble- to boulder-size angular fragments of basalt; elsewhere most clasts are reworked from the Santa Fe Group and are typically subangular to subround Proterozoic gneiss and Tertiary volcanic rock. On the eastern side of escarpments within and east of the Basaltic Hills, deposits mapped as colluvium may locally include local thin beds of eolian deposits. Maximum thickness of colluvium is estimated at 15 ft. Areas mapped as colluvium may be prone to rockfall hazards.

Qls **Landslide deposits (Holocene and Pleistocene)**—Heterogeneous deposits on the south side of South Garland Mesa that are dominantly composed of jumbled blocks of bedrock and unconsolidated matrix-supported rubble that have slumped off the mesa flanks, primarily as rotational landslides and minor earthflows. The deposits include blocks of bedrock derived from both the Servilleta Basalt and sediments of the Santa Fe Group. Ledges of intact but rotated and slumped basalt flows are prominent in the otherwise hummocky topography that typifies the landslides in the quadrangle. Landslides commonly form where the hard basalt flows of the Servilleta Basalt overlie weakly lithified sediments of the Santa Fe Group (Colton, 1976; Thompson and Machette, 1989; Wallace, 1997), especially where the Santa Fe sediments are fine grained. Prominent linear swales and scarps in the basalt that caps South Garland Mesa are interpreted as incipient landslide head-scarps; some of the scarps that cut the basalt flows in the Basaltic Hills may be related to slope instability, not tectonism. Landslide deposits may be as much as 50 ft thick. Although no evidence of recent movement was noted, landslide deposits may be prone to future movement, particularly if disturbed by human activities.

ALLUVIAL AND MASS-WASTING DEPOSITS

Qfy **Younger fan deposits (Holocene and late Pleistocene?)**—Includes sediments in small, geomorphically distinct fans on the flanks of South Garland Mesa and the west side of Skull Hill. Includes poorly sorted, clast-supported gravelly alluvium and matrix-supported debris-flow deposits that range from sandy pebble and cobble gravel to slightly gravelly silt and sand. Unit locally contains boulder-size clasts. Clasts are mostly angular to subangular fragments of basalt and subround to round gneiss, quartz, potassium feldspar, basalt, and andesite, with local minor amounts of sandstone, limestone, and shale. Maximum thickness is estimated at 25 ft. Areas mapped as younger fan deposits are subject to future flooding and sediment deposition. Unit may be a source of sand and gravel.

Qcs **Colluvium and sheetwash, undivided (Holocene and late Pleistocene)**—Mapped where these deposits are gradational and have boundaries that are difficult to discern or where they occur side by side but are too small to depict individually at the map scale. Unit is mapped in and north of the Basaltic Hills and on the southwest side of South Garland Mesa.

Qcf **Colluvium and fan deposits, undivided (Holocene and late Pleistocene)**—Mapped where these deposits are gradational and have boundaries that are difficult to discern or where they occur side by side but are too small to depict as individual polygons at the map scale. Unit occurs along the west side of Skull Hill.

Qfo **Older fan deposits (late? Pleistocene)**—Includes a single deposit on the southwest side of South Garland Mesa. Sediment is similar to that of unit Qfy. The original fan surface on deposits of Qfo is 5 to 30 ft higher than the surface on adjacent younger fan deposits. Estimated maximum thickness of the older fan deposits is 30 ft.

EOLIAN DEPOSITS—Sediments deposited chiefly by wind

Qe **Eolian sand (Holocene)**—Light-yellowish-brown to tan, medium to fine sand deposited on the east-facing (leeward) topographic escarpment on the east side of the Basaltic Hills. The unit includes sparce, angular, cobble- and pebble-size clasts of basalt eroded from adjacent cliffs of Servilleta Basalt. Where colluvium comprises a significant part of an eolian deposit, the unit is mapped as eolian sand and colluvium, undivided (Qec). Eolian sand deposits are unconsolidated and have no, or very little, soil development. Outcrops of basalt on the windward (west) side of deposits of eolian sand commonly are polished and fluted by the abrasive effects of wind-borne sediments. Maximum thickness of unit Qe is estimated at 20 ft.

EOLIAN AND MASS-WASTING DEPOSITS

Qec **Eolian sand and colluvium, undivided (Holocene and late Pleistocene?)**—Mapped in the Basaltic Hills where contacts between the two types of deposits are gradational and difficult to discern, or where they occur side by side but are too small to depict as individual polygons at the map scale.

BEDROCK

Tsf **Santa Fe Group (late Oligocene?, Miocene, Pliocene, and Quaternary?)**—Chiefly tan, light-brown, light- to medium-yellow-brown, and light- to medium red-brown, fine- to medium-grained sandstone, pebbly sandstone, sandy pebble conglomerate, minor cobble conglomerate, and sandy siltstone, and light- to medium-reddish-brown, grayish-red, tan, and rarely greenish-gray mudstone and shale that are typically only weakly lithified. Locally includes beds of volcanic ash. Santa Fe sediments exposed in the Skull Hill area are coarser grained than those that crop out in other parts of the quadrangle; their textures are as coarse as sandy cobble gravel. Bedding varies from thin (0.04–0.2 in.) to thick (>10 ft). Gravelly channel deposits, cut-and-fill structures, and graded bedding are present locally.

A tan to light-grayish-brown bed of volcanic ash about 2 ft thick is exposed in the northeast corner of the quadrangle on the east side of South Garland Mesa. The ash is an air-fall deposit that subsequently was reworked and mixed with fine-grained clastic deposits. The ash bed crops out about 250 ft below the base of the lowest Servilleta Basalt flow on South Garland Mesa, but the exact stratigraphic relationship between the Servilleta flows and the ash bed is uncertain. Faulting or landsliding may have disrupted the strata that include the ash bed. On the basis of the geochemistry of glass shards contained in the ash, A.M. Sarna-Wojcicki (2002, written commun.) correlated the ash with the tuff of Ibex Hollow, which is dated at 11.93 ± 0.03 Ma (Perkins and others, 1998). If the 250 ft elevation difference between the 3.66-Ma Servilleta flows and 11.93-Ma ash bed represents the approximate thickness of the Santa Fe sediments that stratigraphically separate the flows from the ash, then either the rate of sedimentation was low between 3.66 and 11.93 m.y., or there is an erosional unconformity in the Santa Fe strata between the flows and the ash bed.

Most clasts in Santa Fe sediments are subround to subangular and consist of gneiss, quartz, and feldspar, with much lesser but variable amounts of Tertiary volcanic and intrusive(?) rocks and sedimentary lithologies such as sandstone, shale, and limestone. In the low hills east of where the Ojito Creek strand leaves the eastern boundary of the quadrangle, the clasts have a significant component of angular to subangular Tertiary andesitic and basaltic rocks. These clasts may have been eroded from the steeply north-dipping Oligocene volcanic rocks that crop out in the Ojito Peak quadrangle (Wallace and Soulliere, 1996). There are a higher percentage of conglomeratic beds in this area, but there also are thick mudstones here, which are well exposed east of the quadrangle boundary in a few small pits. Clast imbrication suggests that streams flowed generally westward within the map area during Santa Fe time, except in the small area east of where the Ojito Creek strand crosses the quadrangle boundary. Here the streams may have flowed to the north and northwest until joining westward-flowing streams.

The age of the Santa Fe Group is not well constrained within the quadrangle. The onset of rifting, which triggered deposition of the syn-rift Santa Fe Group, is generally considered to be late Oligocene (summarized by Chapin and Cather, 1994). The Santa Fe overlies Oligocene volcanic rocks to the east and north of the quadrangle (Wallace, 1996, 1997; Wallace and Soulliere, 1997). Middle Pleistocene deposits such as units Qa_4 and Qa_5 overlie the Santa Fe and herein are excluded from the Santa Fe even though they are syn-rifting.

Most of the Santa Fe sediments exposed in the quadrangle probably are from the upper part of the formation, since intercalated Servilleta flows are 4.59 ± 0.02 Ma to 3.66 ± 0.01 Ma (Miggins, 2002; Wallace, 1997). Santa Fe sediments on the east side of the Ojito Creek strand of the Northern Sangre de Cristo Fault probably are from lower parts of the formation.

Total thickness of the Santa Fe Group in the quadrangle is unknown, because the base of the group is not exposed and no drill holes penetrate the entire formation. Wallace (1995) includes the mapped area within a major Santa Fe depocenter defined by gravity data that may contain over 8,000 ft of Santa Fe sediments (Keller and others, 1984). Water wells drilled between the Ojito Creek strand and Basaltic Hills Faults extend to depths as great as 1,551 ft (Colorado Division of Water Resources files, well permit number 12254F). This depth provides a minimum thickness for the Santa Fe, since the well did not reach the base of this formation.

Parts of the Santa Fe Group are potential sources of sand and gravel. Several pits were dug at some time in the past into the Santa Fe east of where the Ojito Creek strand of the Northern Sangre de Cristo Fault crossed the quadrangle boundary. The origin and purpose of these pits are unknown. Perhaps the thick beds of mudstone exposed in the pits were used for adobe bricks many decades ago.

Ts

Servilleta Basalt (Pliocene)—Includes thin flows of medium- to dark-gray tholeiitic basalt that are intercalated with sediments in the upper part of the Santa Fe Group. Distinguishing characteristics of Servilleta flows include small olivine phenocrysts, diktytaxitic texture, and locally common vesicle pipes and segregation veins (Lipman and Mehnert, 1979; Thompson and Machette, 1989; Burroughs, 1971). The olivine phenocrysts commonly are slightly altered to iddingsite. Phenocrysts of plagioclase and clinopyroxene also are present. Generally only one or two stacked flows were observed in outcrop, although three stacked flows are present on the west side of South Garland Mesa near the quadrangle boundary (samples FS8A, B, and C). In a few locations in the Basaltic Hills, subtle ledges were noted on hillslopes below two stacked flows, suggesting the presence of a third flow.

Fifteen samples from 11 Servilleta flows within the quadrangle and another five flows from adjacent quadrangles were collected and analyzed for major elements during this investigation (Table 1). On the basis of total alkali and silica contents (Le Bas and others, 1986), all eighteen samples are basalts (Fig. 5), although there are minor differences in silica contents and, to a lesser extent, in total-alkali content. The samples plot in the tholeiitic field of Miyashiro's (1974) FeO/MgO versus SiO_2 graph and are subalkaline on a plot of alkalies versus SiO_2.

A stacked sequence of two Servilleta flows is exposed in the San Luis quadrangle about 2 mi south of the Fort Garland SW quadrangle. Directly west of the Costilla County hospital, about 1 mi north of San Luis, the flows split and are separated by sediments of the Santa Fe Group. The upper flow pinches out about 1,200 ft north of where the flows split, and the lower flow continues northward for another 6,500 ft before it too pinches out. The lower flow in the San Luis quadrangle appears to be at about the same stratigraphic position within the Santa Fe Group as the flow in Fort Garland SW quadrangle from which sample FS98 was collected. The upper flow in San Luis quadrangle may correlate with the flow in Fort Garland SW quadrangle that was sampled as FS96.

In contrast to most Servilleta flows in the quadrangle, the flows that crop out along the western margin of Skull Hill are strongly tilted and broken by faults. It is unclear whether this deformation is associated with rifting or with slope failures. Landslides are common where Servilleta flows overlie fine-grained Santa Fe sediments on steep hillslopes; at Skull Hill these steeply tilted rocks may be erosional remnants of an older landslide.

Miggins (2002) dated two flows in Fort Garland SW quadrangle using $^{40}Ar/^{39}Ar$ methods. The lower flow in the northeastern part of San Pedro Cuesta (same outcrop as sample FS98) is 4.59 ± 0.02 Ma, and the southwestern flow in Skull Hill (sample outcrop as sample FS44) is 4.55 ± 0.15 Ma. Wallace (1997) reported a $^{40}Ar/^{39}Ar$ age of 3.66 ± 0.01 Ma for a Servilleta flow (same flow as sample FG1B) that crops out along Trinchera Creek between North and South Garland Mesas in the Fort Garland quadrangle. The 3.66 Ma flow is geochemically correlative with all the flows which we sampled on South Garland Mesa (samples FS6, FS7A, FS7B, FS8A, and FS8B) and two flows sampled in the Basaltic Hills (FS70A and BS3). These recent $^{40}Ar/^{39}Ar$ ages are similar to other Servilleta flows in nearby areas dated using K/Ar (Aoki, 1967; Lipman and Mehnert, 1979; Thompson and Machette, 1989).

Individual Servilleta flows in the quadrangle range up to about 25 ft thick; the thickest stacked sequence of flows is about 100 ft, although part of this section may include poorly exposed intercalated sediments. Servilleta flows are difficult to excavate and can pose rockfall hazards where exposed in cliffs. They probably are suitable for use as riprap.

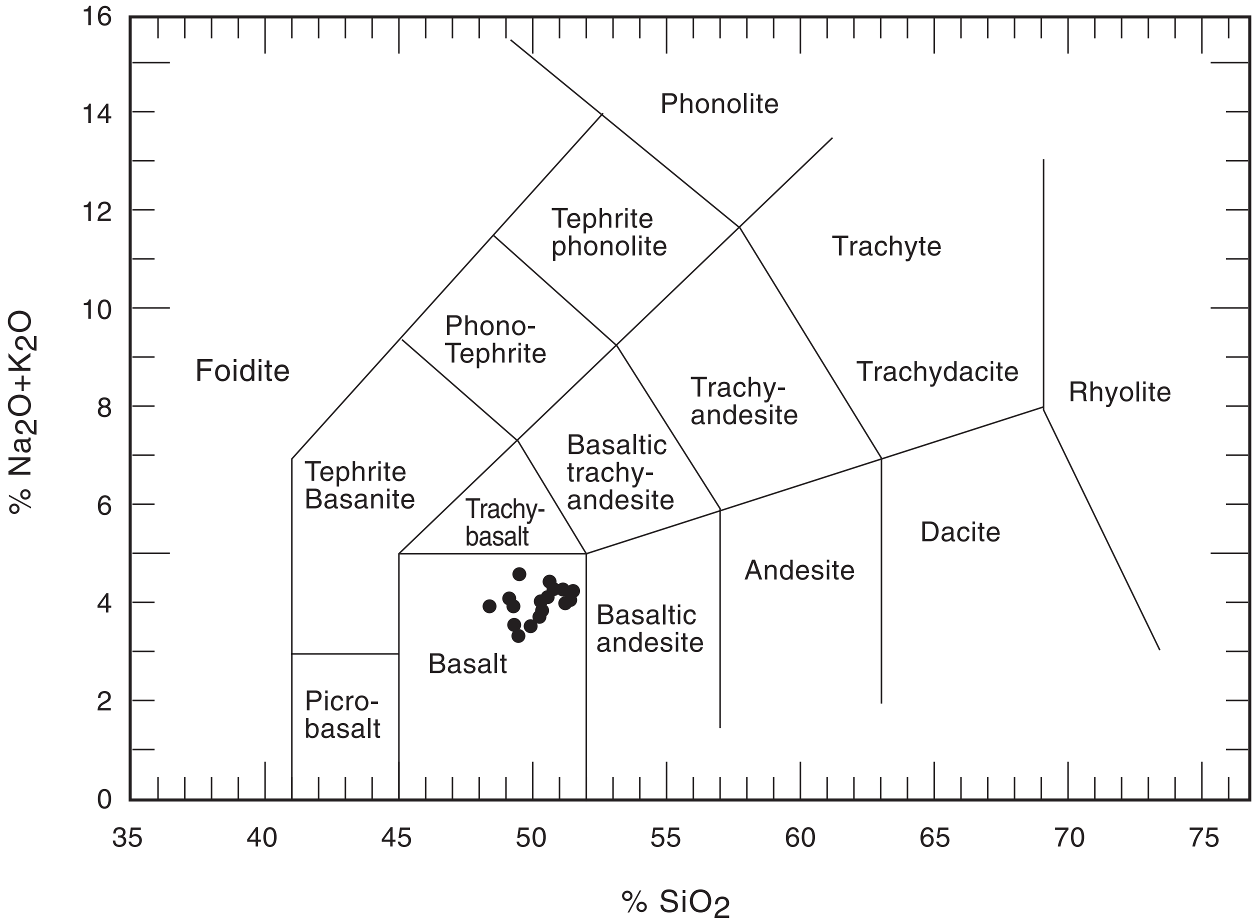


Figure 5. Total alkali-silica plot of samples of Servilleta Basalt (unit Ts) collected from the Servilleta Basalt in and near Fort Garland SW quadrangle. Plot uses the nomenclature of Le Bas and others (1986). Values are in percent and are not recalculated to 100% volatile free because of the low (<1%) loss in ignition. See Table 1 for geochemical analyses.

Table 1. Whole-rock major-element geochemistry, $^{40}Ar/^{39}Ar$ ages, and approximate UTM coordinates for basalt samples from Fort Garland SW quadrangle and adjacent quadrangles. Geochemical analyses by als Chemex using x-ray fluorescence methods.

Sample									Percent							$^{40}Ar/^{39}Ar$	~X	~Y
No.[1]	Al_2O_3	BaO	CaO	Cr_2O_3	Fe_2O_3	K_2O	MgO	MnO	Na_2O	P_2O_5	SiO_2	SrO	TiO_2	LOI	TOTAL	Age(Ma)	UTM	UTM
FS6	16.65	0.04	9.26	<0.01	10.73	0.97	6.59	0.15	3.06	0.33	50.25	0.06	1.33	0.32	99.74		466,121	4,136,117
FS7A	16.05	0.04	9.05	<0.01	10.79	1.02	6.35	0.16	3.05	0.33	51.25	0.06	1.32	0.16	99.63		465,837	4,135,957
FS7B	16.32	0.05	9.13	0.01	10.47	1.09	6.15	0.16	3.16	0.33	51.42	0.06	1.32	0.02	99.69		465,843	4,135,964
FS8A	15.28	0.04	9.18	0.01	10.80	1.17	7.63	0.16	3.40	0.29	49.46	0.07	1.30	<0.01	98.79		465,498	4,136,209
FS8B	15.80	0.04	8.76	<0.01	10.46	1.20	6.37	0.15	3.13	0.31	50.67	0.05	1.29	0.17	98.40		465,492	4,136,242
FS8C	16.38	0.04	9.27	<0.01	10.48	1.13	6.04	0.15	3.28	0.32	50.60	0.06	1.34	0.12	99.21		465,489	4,136,270
FS44	15.83	0.04	9.49	0.01	11.89	0.67	6.95	0.17	2.82	0.32	49.81	0.05	1.39	0.13	99.59	4.55±0.15[2]	464,352	4,125,015
FS46	15.92	0.02	9.20	<0.01	12.00	0.71	6.41	0.17	3.02	0.28	50.21	0.05	1.44	0.03	99.46		464,433	4,125,237
FS70A	16.08	0.04	9.12	<0.01	10.58	1.09	6.19	0.15	3.18	0.30	51.07	0.05	1.30	<0.01	99.15		460,007	4,129,626
FS70B	15.54	<0.01	9.17	<0.01	12.07	0.57	7.35	0.16	2.96	0.19	49.21	0.03	1.16	0.33	98.74		460,060	4,129,631
FS75	16.44	0.04	9.22	0.01	10.66	1.01	6.64	0.15	3.12	0.30	50.48	0.06	1.26	0.23	99.62		461,133	4,127,441
FS88	15,85	0.03	9.01	0.01	11.65	0.80	7.28	0.16	3.04	0.24	50.29	0.04	1.21	0.01	99.62		457,639	4,130,253
FS93	15.84	0.04	9.24	<0.01	10.54	1.15	6.78	0.16	3.16	0.29	50.64	0.05	1.24	<0.01	99.13		456,833	4,132,968
FS96	15.43	0.02	8.83	0.01	11.88	0.91	7.62	0.16	3.16	0.29	49.11	0.05	1.37	<0.01	98.84		460,974	4,122,513
FS98	15.70	0.02	9.07	<0.01	12.24	0.80	7.52	0.17	3.21	0.24	49.20	0.04	1.46	<0.01	99.67	4.59±0.02[2]	461,218	4,123,874
BS-2	15.52	<0.01	9.10	0.01	11.98	0.57	7.37	0.16	2.80	0.19	49.41	0.03	1.17	<0.01	98.31		454,567	4,134,696
BS-3	16.07	0.04	8.95	<0.01	10.79	0.94	7.01	0.15	3.06	0.30	51.14	0.05	1.25	0.12	99.87		455,199	4,134,077
FG1A	16.00	0.05	8.90	<0.01	10.81	1.06	7.02	0.15	3.01	0.29	51.12	0.05	1.25	0.23	99.94		464,631	4,138,486
FG1B	16.19	0.03	9.01	<0.01	10.80	1.08	6.96	0.15	3.24	0.28	50.66	0.05	1.29	<0.01	99.74	3.66±0.01[3]	464,660	4,138,495
SL-1	15.29	0.07	9.7	0.01	11.64	0.82	6.84	0.16	3.11	0.31	48.32	0.06	1.37	0.54	98.24		461,407	4,121,707

[1] Letters indicate quadrangle in which sample was collected: FS = Fort Garland SW, BS = Blanca SE, FG = Fort Garland and SL = San Luis
[2] Miggins (2002); dated sample is different than the sample used for chemical analysis, but both are from same outcrop
[3] Wallace (1997); dated sample is different than the sample used for chemical analysis, but both are from same outcrop

MINERAL RESOURCES

Potential sand and gravel resources occur in most Quaternary alluvial deposits and in the Santa Fe Group throughout the map area. There are no permitted sand and gravel operations in the quadrangle (Colorado Division of Minerals and Geology, http://mining.state.co.us/operatordb/report.asp), but evidence of past sand and gravel mining was noted in several areas. Hard, non-scoriaceous flows in the Servilleta Basalt may be suitable for moderate to high-quality riprap.

The gold deposit at the San Luis mine, which was operated by Battle Mountain Resources, Inc., is located in Ojito Peak quadrangle 1.7 to 2.5 mi east of the southeast corner of the quadrangle. Most mineralization in the San Luis deposit took place in brecciated Proterozoic biotite gneiss along a low-angle fault zone; minor mineralization was hosted in an underlying biotite gneiss cataclasite (Benson, 1997). It is very unlikely that an economically viable gold deposit similar to the San Luis mine exists in Fort Garland SW quadrangle, if for no other reason than the great depth of equivalent host rocks in the map area.

No petroleum exploration wells have been drilled in the quadrangle (Colorado Oil and Gas Conservation Commission (http://cogccweb.state.co.us). Only four wells have been drilled in all of Costilla County; all four were drilled and abandoned.

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