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Preliminary Geologic Map of the Sanchez Reservoir Quadrangle and Eastern Part of the Garcia Quadrangle, Costilla County, Colorado

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DESCRIPTION OF MAP UNITS

[Map-unit names and stratigraphic relations are based on mapping of the entire Alamosa ½° x 1° sheet, which contains many more units. Thin units (such as Qes) that cover widespread older units (such as Qai) are shown as Qes/Qai. See Birkeland (1999) and Machette (1985) for soil horizon nomenclature and carbonate morphology.]

Man-made deposits

Artificial fill (Historic)—Comprises earth-fill dam of Sanchez Reservoir, located in northeast part of map area

Lacustrine deposits

Lake sediment (Holocene)—Comprised of organic-rich fine sand, silt, and clay in Sanchez Reservoir and isolated deposits of reworked eolian sand and silt in closed depressions (playas) on San Pedro Mesa. Thickness 2–10 m

Eolian deposits

Eolian sand (Holocene)—Forms small, pronounced dunes as much as 3 m high and thicker (5–10 m) sand ramps against the western base of San Pedro Mesa. Some dunes and ramps are active; others are inactive, vegetated, and have weak buried soils (A horizons) indicating multiple episodes of landscape stability and deposition of sand

Alluvial deposits

Stream alluvium, undivided (Holocene)—Organic-rich clay and silt to sand and gravel that form active stream channels and floodplains along most drainage courses; some deposits are too small to map separately. Grain size and lithology vary depending on material being eroded in stream headwaters. Gravel clasts generally <10 cm in diameter, slightly coarser (10–15 cm) along streams draining the Culebra Range, northeast of map area. Thickness probably 2–10 m

Active stream alluvium (upper Holocene)—Fluvial sand and gravel in modern to prehistoric stream channels that retain fresh expression (such as oxbow loops and abrupt terrace escarpments). Gravel clasts generally <10 cm in diameter, slightly coarser (10–15 cm) along streams draining the Culebra Range, northeast of map area. Thickness probably 2–5 m

Younger stream alluvium (upper Pleistocene)—Fluvial sand and gravel in former floodplain that are now 1–2 m above modern stream level or form alluvial-fan and piedmont-slope deposits along the western foothills of the Culebra Range, northeast of map area. The surface of these deposits commonly has a weak soil with Bw and (or) Bk horizons. Thickness commonly 2–5 m

Intermediate stream alluvium (upper and middle Pleistocene). Fluvial sand and gravel that form intermediate-level elevation terrace surfaces (2–5 m above modern stream level) and moderately dissected alluvial fans and piedmont slopes along the western foothills of the Culebra Range, northeast of map area. The surface of these deposits has a moderately developed soil (Bt and stage II–III Bk horizons). Locally, thin deposits of unit Qay overlie unit Qai. Thickness commonly 2–5 m

Older stream alluvium (middle Pleistocene)-—Fluvial sand and gravel that form higher-level terrace surfaces (5–15 m above modern stream level in map area) and deeply dissected alluvial fans and piedmont slopes along the western foothills of the Cuelbra Range, northeast of map area. In addition, this unit forms a broad piedmont surface known as the Costilla Plain, west of San Pedro Mesa. Older stream alluvium forms surfaces at varying heights above modern stream level owing to downstream convergence and faulting. The surface of these deposits commonly has a strongly developed calcic soil with thick Btk and (or) stage III Bk horizons. Locally, thin deposits of unit Qay overlie unit Qao. Thickness commonly 2–5 m

Alluvial and colluvial deposits

Alluvium and colluvium, undivided (Holocene and upper Pleistocene)—Mantles gentle to moderately sloping surfaces adjacent to and on San Pedro Mesa. Material is typically pebbly to cobbly silty sand to pebbly sand. Most of the silt and sand was probably eolian, but has been reworked by alluvial (chiefly sheetwash) and colluvial (chiefly mass wasting) processes. Surface of deposits typically not dissected and has weakly to moderately developed soils with A, Bw, and (or) Bk horizons. Thickness probably 2–10 m

Colluvial deposits

Colluvium, undivided (Holocene and upper Pleistocene)—Poorly sorted, nonstratified, sandy to gravelly deposits; common on moderate to steep slopes adjacent to resistant bedrock. Typically includes minor eolian deposits and locally derived alluvium. Thickness probably 2–10 m

Landslide deposits

Younger landslides (Holocene and upper Pleistocene)—Non-sorted, non-stratified, cobble- to boulder-size blocks and large coherent slabs of basalt (unit Tsb) in and on remobilized sediment of the lower Santa Fe Group (unit Tsf); typical on moderate to steep slopes beneath bedrock cliffs. The younger landslides commonly have a hummocky appearance with sediment-filled closed depressions. Some landslides have surface features that suggest flowage, perhaps having formed during former moist climatic episodes. Thickness unknown, probably 10–50 m

Older landslides (upper and middle Pleistocene)—Non-sorted, non-stratified, cobble- to boulder-size blocks and large coherent slabs of basalt (unit Tsb) in and on remobilized sediment of the lower Santa Fe Group (unit Tsf); typical on moderate to steep slopes beneath bedrock cliffs. The older landslides commonly have hilly, but smoothed appearance with thick accumulations of eolian sand, alluvium, and ponded deposits. Some landslides have abrupt, linear toes resulting from displacement by the Sangre de Cristo fault zone. However, young depositional units (such as Qa, Qay and Qes) are not commonly displaced, suggesting that the most recent faulting occurred before the Holocene in this area. Thickness unknown, probably 10–100 m

Talus deposits

Talus (Holocene and upper Pleistocene)—Non-sorted, nonstratified, gravel- to boulder-size blocks deposits of bedrock. Forms boulder fields mainly on moderate to steep slopes below resistant volcanic rocks such as the Servilleta basalt (unit Tsb). Thickness commonly 5–20 m

Sedimentary rocks

Upper Santa Fe Group (middle Pleistocene to Pliocene)—Slightly oxidized, weakly consolidated sandstone, siltstone, and pebble to cobble conglomerate stratigraphically above Servilleta Basalt (unit Tsb). Mostly preserved in subsurface beneath Costilla Plain, west of San Pedro Mesa, but locally exposed at the southern end of San Pedro Mesa on Servilleta basalt (unit Tsb) and in foothills west of the central section of the Sangre de Cristo fault zone. Thickness probably 100–200 m where exposed

Lower Santa Fe Group (Pliocene to upper Oligocene)—Moderately oxidized, moderately consolidated sandstone, siltstone, and pebble to cobble conglomerate stratigraphically below Servilleta Basalt (unit Tsb). Sediment in most exposures is remarkably fine grained considering proximity to source areas in Culebra Range, suggesting that coarse-grained component may have been deposited in Culebra graben (the valley occupied in part by Sanchez Reservoir). Locally exposed in landslide scars and deposits around San Pedro Mesa and well exposed in the western foothills of the Culebra Range. Thickness probably 100–200 m where exposed; almost 1,500 m of sediment and Miocene volcanic rock (units Tad and Tv?) were encountered in the Energy Operating Co. Williamson No. 1 well (R.M. Kirkham, written commun., 2005), south of Sanchez Reservoir (fig. 1)

Volcanic rocks

Servilleta Basalt (Pliocene)—Thin (2–5 m), dark-gray flows of tholeiitic basalt characterized by small olivine phenocrysts, diktytaxitic texture, and local vesicle pipes and segregation veins. As many as six flows are exposed along the western rim of San Pedro Mesa in southwestern part of map area. Likely erupted from vents to the south and west of the map area. $^{40}Ar/^{39}Ar$ ages of 4.37±0.17 Ma reported for sample collected near eastern boundary of map area and 4.85±0.11 Ma for sample from Energy Operating Co. Williamson No. 1 well (see map; R.M. Kirkham, written commun., 2005). Unit is dominant basalt type of the Taos Plateau volcanic field (Dungan and others, 1984). Maximum exposed thickness 40 m

Volcanic rocks-continued

Hinsdale Formation (middle? Miocene)—Dark-gray, fine-grained, silicic alkali-olivine basalt and basaltic andesite lava flows, associated breccia, and near-vent reddish-brown pyroclastic deposits. Contains small olivine phenocrysts that are typically partly altered to iddingsite, and locally minor xenocrysts of quartz and feldspar. Typically forms flat-topped mesas in the central and eastern part of map area that are above stratigraphically younger Servilleta Basalt (unit Tsb), which caps San Pedro Mesa. Lava flows fill paleovalleys cut into underlying volcanic rock (unit Tad) and vary laterally and abruptly in thickness. Likely partly correlative with Miocene basaltic lava flows of the Latir volcanic field (Lipman and Reed, 1989) south of the map area; regionally correlative with rift-related basaltic volcanic rocks ranging in age from 6 Ma to 26 Ma (Lipman and Mehnert, 1975; Thompson and Machette, 1989). Maximum exposed thickness 220 m

Andesite and dacite of San Pedro Mesa (middle? Miocene)—Light-gray to light-brown porphyritic andesite to dacite lava flows and flow breccias preserved in highlands in the east-central part of San Pedro Mesa. Phenocrysts of pyroxene, hornblende, and plagioclase are common, with lesser amounts of biotite, Fe-Ti oxides, and minor quartz. Phenocrysts vary considerably in size and proportion within map unit. Although undated, this unit may be broadly correlative with volcanic deposits in the adjacent La Valley quadrangle to the east (unit Tbt of Kirkham and others, 2004), which have yielded $^{40}Ar/^{39}Ar$ ages as young as 10.74±0.10 Ma and as old as 15.16±0.03 Ma (Miggins, 2002; Miggins and others, 2002). Maximum exposed thickness 250 m

Older (lower) volcanic rocks, undivided (Oligocene)—Small exposures of dark-brown, lithic-rich, moderately welded ash-flow tuff with small phenocrysts of plagioclase and biotite and common elongate lithophysal cavities as much as 4 cm long. Welded tuff blocks typically are enclosed in a matrix of poorly welded, altered tuff or tuffaceous and volcaniclastic sediment. Poorly exposed along the western margin of San Pedro Mesa. Best exposed (and only mapped) on north wall of canyon about 1.8 km north of Proterozoic and Paleozoic rocks in northwest part of the map area, but more commonly seen in largely intact, but rotated landslide blocks (see detailed inset map). The unit is stratigraphically beneath Servilleta Basalt and Santa Fe Group sediment (units Tsb and Tsf, respectively) and above Eocene? boulder conglomerate (unit Tbc). Possibly correlative with basal tuffs (ca. 25 Ma) of the Latir volcanic field to the south in northern

New Mexico, or to far-traveled tuffs of the Treasure Mountain Group (ca. 29 Ma) in the southeastern San Juan volcanic field to the west. Thickness 6–10 m

Sedimentary rocks

Boulder conglomerate (Eocene?)—Boulder conglomerate comprised exclusively of Early Proterozic rocks (unit Xg). Clasts are commonly 0.5–3 m in long dimension, moderately rounded, and of mixed lithologies, suggesting long transport distances. Not exposed in place, but seen in largely intact, but rotated landslide blocks beneath Pliocene Servilleta Basalt (unit Tsb) and Oligocene(?) ash-flow tuff (unit Tvl) (see detailed inset map). Possibly correlative with the Eocene and Paleocene Vallejo Formation of Upson (1941). Maximum exposed thickness only 10 m

Sandstone and siltstone (Paleozoic?)—Fractured or brecciated, reddish-brown, slightly pebbly arkosic sandstone and siltstone, well consolidated. Possibly correlative with the Sangre de Cristo Formation (Permian to Middle Pennsylvanian) exposed about 25 km east of the map area in the Culebra Range. Thickness unknown, about 15 m exposed in low hill west of granitic basement rock (unit Xg)

Basement rocks

Granitic rock, undivided (Early Proterozoic)—Pinkish-white, medium-grained granodioritic orthogneiss; weakly foliated and uniformly brecciated. Only found adjacent to Paleozoic rocks (unit Pz) on small hills in west-central part of map area (Kirkham, 2006). Poorly exposed; may underlie Paleozoic rocks or be juxtaposed by faulting. Gravity and resistivity data suggests these basement rocks might be rooted and not part of an ancient landslide block. Thickness unknown

SYMBOLS

Fault—Bar and ball on downdropped side; shown in red where fault has Quaternary movement

Solid where well located

Dashed where approximately located or inferred

Dotted where concealed

Contact

Landslide escarpment—Topographic headwall or escarpment associated with landslides chiefly along margins of San Pedro Mesa where Servilleta Basalt (unit Tsb) is underlain by sediment of the lower Santa Fe Group (unit Tsf). Large slide blocks of basalt shown by Tsb[ls] symbol. Only prominent or continuous escarpments are shown

Location of drill hole—Location of Energy Operating Co. Williamson No. 1, a wildcat exploration hole for oil and gas drilled in the Culebra graben, south of Sanchez Reservoir (Kirkham, 2005). Logs, interpretations, and ages of volcanic rocks provided by Brian S. Brister, Robert M. Kirkham, and Lisa Peters (R.M. Kirkham, written commun., 2005). $^{40}Ar/^{39}Ar$ ages of volcanic units are shown on the map

Location and age of dated volcanic rock—^{40}Ar/^{39}Ar ages by D.P. Miggins (2002 and unpubl. data)

STRUCTURE AND GEOLOGIC HISTORY

The major geologic features in the map area and the adjacent San Luis quadrangle to the north (Machette and others, 2007) are a prominent mesa (San Pedro Mesa) that is a N-trending horst; a N-trending graben to the east of the mesa (Culebra graben); uplifted western foothills of the Culebra Range; and the eastern part of the Costilla Plain, a large composite alluvial fan deposited by Culebra Creek. Most faults that bound the San Pedro Mesa horst and Culebra graben (i.e., San Luis and Sangre de Cristo fault zones) offset surficial deposits as young as late Pleistocene. The trace of the central section of the Sangre de Cristo fault zone (which separates the Culebra graben from the Culebra Range) has a consistent pattern of right steps, from Sanchez Reservoir on the south to Fort Garland, 33 km north of the map area (see quadrangle index map; Kirkham and Heimsoth, 2002; Wallace and Machette, 2007; Machette and others, 2007). However, the individual strands in this zone are not simple linear structures; rather they are complex, curvilinear, intersecting, overlapping, and have abundant en-echelon stepovers. At Rito Seco Creek, about 5 km northeast of San Luis, Crone and others (2006) describe evidence of four surface-faulting earthquakes on the central section of the Sangre de Cristo fault zone in the past 48 ky, with the most recent event occurring about 9000±2000 yrs ago (Crone and Machette, 2005). No other paleoseismic data exist for the central or southern sections of the Sangre de Cristo fault zone or for the overlapping San Luis fault zone (see fig. 1). However, this map and the San Luis quadrangle to the north (Machette and others, 2007) suggests that late Quaternary movement has occurred on all of these faults. In addition to faulting hazards, many slopes below the mesa rims are covered with unstable landslide deposits, colluvium, and (or) rockfall debris. This instability is caused by hard, competent basalt lying on soft, incompetent sediment of the Santa Fe Group.

The oldest unit exposed in the map area is Early Proterozoic granitic rocks (unit Xg) restricted to small exposures near the western edge of San Pedro Mesa where they form low hills (Kirkham, 2006) above the surrounding mesa, which is underlain by Servilleta Basalt (unit Tsb). The granites are poorly exposed, brecciated, and texturally variable. Mineralogically they are orthogneisses similar to the gneissic granite of Jaroso Creek (unit Xggj of Kirkham and others, 2004) exposed in the Culebra Range to the east. On San Pedro Mesa, the granitic rocks are juxaposed against reddish sandstone and sandy pebble conglomerate (unit Pz) of uncertain, but likely Middle Pennsylvanian to Permian age. Although fractured and brecciated, these "red beds" may be a remnant of basin sediments of the Sangre de Cristo Formation in the Culebra Range as mapped by Lindsey (1996), Lindsey (1995), and C.J. Fridrich and others (unpublished mapping, Culebra Peak area, 2006). Locally, Eocene(?) boulder conglomerate (unit Tbc) and sparse outcrops of Oligocene ash-flow tuffs (unit Tvl) are exposed beneath basin-fill sediment of the lower Santa Fe Group (unit Tsf) along the western edge of San Pedro Mesa. These deposits lie topographically below but are stratigraphically above Early Proterozoic and Paleozoic rocks that underlie San Pedro Mesa about 1.6 km to the south.

Remnants of intermediate- to mafic-composition volcanic rocks (units Thb and Tad) form topographic and tectonic highlands in the east-central part of San Pedro Mesa.

These rocks are truncated to the east along southern strands of the San Luis fault zone. Locally about 225 meters of lava flows, lava domes, and associated near-vent pyroclastic and volcaniclastic colluvial deposits are exposed in dissected remnants on the mesa. Deeply dissected dacite to low-silica rhyolite lava flows and domes (unit Tad) are overlain by basaltic and basaltic andesite lava flows of the Hinsdale Formation (unit Thb). Locally, deposits of the Hinsdale Formation appear correlative with Miocene (14.8–10.8 Ma) basalt and trachyandesite lava flows (Kirkham and others, 2004) exposed east of the Sangre de Cristo fault zone (central section) between the Jaroso Creek and Willow Creek drainages that head in the Culebra Range. However, the thick sequence of older, predominantly dacitic lavas (unit Tad) that underlie lava flows of the Hinsdale Formation apparently have no counterpart in the Culebra Range, but may be correlative with volcanic rocks of the San Luis Hills, 25 km to the west of the map area. There, 26 Ma Hinsdale Formation lava flows fill deeply incised paleovalleys cut into dacite flows and domes and andesite flows of the 29–30 Ma Conejos Formation (Thompson and Machette, 1989). The absence of Santa Fe Group sediment between the two older volcanic units (Tad and Thb) suggest that the central part of the San Pedro Mesa horst was tectonically and topographically elevated during the Miocene and perhaps the Oligocene.

Sedimentary rocks of the upper Oligocene to middle Pleistocene Santa Fe Group (units QTsf and Tsf) underlie San Pedro Mesa north of the middle Tertiary volcanic deposits, underlie the Costilla Plain and Culebra graben, and are exposed in the foothills east of the Sangre de Cristo fault zone and on the southern part of San Pedro Mesa. As mapped, the Oligocene to Pliocene part of the group (unit Tsf) generally underlies the Servilleta Basalt (unit Tsb) or is exposed in the uplifted foothills of the Culebra Range (see Kirkham and others, 2004). The thickness of this unit is poorly known, but almost 1500 m of sediment and Miocene volcanic rock (units Tad and Tv?) were encountered in the Energy Operating Co. Williamson No. 1 well (R.M. Kirkham, written commun., 2005), south of Sanchez Reservoir. In Pliocene time, Servilleta Basalt was erupted from numerous vents on the Taos Plateau, tens of kilometers to the southwest, and perhaps locally from unmapped or buried vents closer to the map area. In southern Colorado, the Servilleta Basalt is typically 4.8 Ma to 3.7 Ma. These basalt flows lapped against the sedimentary foothills of the Culebra Range and, thus, are only preserved east of the Sangre de Cristo fault zone in a few localities. South of Sanchez Reservoir, multiple flows of the Servilleta Basalt are reported to be about 143 m thick in the Williamson No. 1 drill hole (R.M. Kirkham, written commun., 2005). On San Pedro Mesa, the Servilleta Basalt is typically 30–40 m thick, but thins to the northwest to a minimum of several meters. Thus, it appears that the Servilleta Basalt filled at least 100 m of the Culebra graben before covering San Pedro Mesa.

The Pliocene to middle Pleistocene upper part of the Santa Fe Group (unit QTsf) is exposed mainly west of the Sangre de Cristo fault zone; either these rocks were eroded or sparsely deposited on the uplifted, eastern side of the central section of the fault zone. Aeromagnetic data, which is sensitive to the depth of strongly magnetic rocks such as basalt (fig. 1), suggests that the top of Servilleta Basalt (unit Tsb) is buried to depths of 200 m or more in parts of the Culebra graben. The Servilleta Basalt appears to be shallow at several locations in the graben owing to structural complications from cross faults.

Northeast of San Luis, the uppermost part of the Santa Fe Group contains tephra (Lava Creek B ash) from the 639±2 ka eruption of the Yellowstone caldera in northwestern Wyoming. This tephra is interbedded with fine-grained sediment (unit QTsf; Machette and others, 2007) that dips about 3° to the north and is unconformably overlain by 3–5 m of coarse gravel (unit Qao). Thus, within the Culebra graben the uppermost part of the Santa Fe Group (unit QTsf) is younger than 0.64 Ma (early middle Pleistocene). The older stream alluvium, which forms a complex alluvial fan on the Costilla Plain, is everywhere coarser than and lies unconformably on sediment of the Santa Fe Group. We suspect that the older alluvium may be as old as 0.6–0.5 Ma on the basis of the thickness and morphology (advanced stage III) of calcic soils developed on the fan surface.

Uplift of the San Pedro Mesa horst and subsidence of the Culebra graben was largely accommodated by vertical to sub-vertical displacement on the bounding faults. Culebra Creek, which bisects San Pedro Mesa in the San Luis quadrangle to the north, has probably been superposed across the horst since deposition of the Servilleta Basalt, but downcutting has managed to keep pace with up-to-the-west-uplift across the San Luis fault zone. Deposition of alluvium from the Culebra Range has kept pace with ongoing graben formation, such that Ventero Creek flows north into Culebra Creek, which in turn flows across the sedimentary sill formed by San Pedro Mesa horst. As a result, most of the topographically lower parts of the graben, which are covered by upper Pleistocene and Holocene alluvium, have a high water table, typically within 5 m of the surface. Along the margins and outside of the graben, the ground-water table is many tens to hundreds of meters deep, especially beneath San Pedro Mesa and in the foothills of the Culebra Range.

SELECTED REFERENCES

Bankey, Viki, Grauch, V.J.S., Drenth, B.J., and Geophex Ltd., 2006, Digital data from the Questa-San Luis and Santa Fe East helicopter magnetic surveys in Santa Fe and Taos Counties, New Mex., and Costilla County, Colo.: U.S. Geological Survey Open-File Report 2006-1170, available at http://pubs.usgs.gov/of/2006/1170/.

Birkeland, P.W., 1999, Soils and Geomorphology, 3rd edition: New York, Oxford University Press, 430 p.

Crone, A.J., and Machette, M.N., 2005, Paleoseismic activity on the Sangre de Cristo fault near San Luis, Colorado: Geological Society of America Abstracts with Program, v. 37, no. 7, p. 558, Abstract 256-2.

Crone, A.J., Machette, M.N., Bradley, L.-A., and Mahan, S.A., 2006, Data related to late Quaternary surface faulting on the Sangre de Cristo fault, Rito Seco site, Costilla County, Colorado: U.S. Geological Survey Scientific Investigations Map SI-2955, 1 oversize plate.

Dungan, M.A., Muehlberger, W.R., Leininger, L., Peterson, C., McMillan, N.J., Gunn, G., Lindstrum, M., and Haskin, L., 1984, Volcanic and sedimentary stratigraphy of the Rio Grande Gorge and the late Cenozoic geologic evolution of the southern San Luis Valley, in Baldridge, W.S., Dickerson, P.A., Riecker, R.E., and Zidek, J., eds., Rio Grande rift—Northern New Mexico: New Mexico Geological Society Guidebook, 35th Annual Field Conference, p. 157–170.

Kirkham, R.M., Brister, B.S., Grauch, V.J.S., and Budahn, J.R., 2005, Culebra graben—A major intrarift structure in the San Luis basin, Rio Grande rift: Geological Society of America Abstracts with Programs, v. 37, no. 6, p. 14.

Kirkham, R.M., 2006, Surprises in the Culebra graben, a major sub-basin within the San Luis basin of the Rio Grande rift: Geological Society of America Abstracts with Programs, v. 38, no. 6, p. 36.

Kirkham, R. M., and Heimsoth, C.M., 2002, Geologic map of the Fort Garland Southwest quadrangle, Costilla County, Colorado: Colorado Geological Survey Open-File Map 02-6, scale 1:24,000, pamphlet.

Kirkham, R.M., Lufkin, J.L., Linday, N.R., and Dickens, K.E., 2004, Geologic map of La Valley quadrangle, Costilla County, Colorado: Colorado Geologic Survey Open-File Report 04-8, scale 1:24,000, pamphlet.

Lanphere, M.A., Champion, D.E., Christiansen, R.L., Izett, G.A., and Obradovich, J.D., 2002, Revised ages for tuffs of the Yellowstone Plateau volcanic field—Assignment of the Huckleberry Ridge Tuff to a new geomagnetic polarity event: Geological Society of America Bulletin, v. 114, no. 5, p. 559–568.

Lindsey, D.A., 1995, Geologic map of the Cuchara quadrangle, Huerfano County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2283, scale 1:24,000.

Lindsey, D.A., 1996, Reconnaissance geologic map of the Cucharas Pass quadrangle, Huerfano and Las Animas Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2294, scale 1:24,000.

Lipman, P.W., and Mehnert, H.H., 1975, Late Cenozoic basaltic volcanism and developement of the Rio Grande depression in the southern Rocky Mountains, in Curtis, B.F., ed., Cenozoic history of the Southern Rocky Mountains: Geological Society of America Memoir 144, p. 119–154.

Lipman, P.W., and Reed, J.C., Jr., 1989, Geologic map of the Latir volcanic field and adjacent areas, northern New Mexico: U.S. Geological Survey Miscellaneous Investigation Series Map I-1907, scale 1:48,000.

Machette, M.N., 1985, Calcic soils of the southwestern United States, in Weide, D.L., ed., Soils and Quaternary geology of the southwestern United States: Geological Society of America Special Paper 203, p. 1–21.

Machette, M.N., Thompson, R.A. and Drenth, B.J., 2007, Geologic map of the San Luis quadrangle, Costilla County, Colorado: U.S. Geological Survey Scientific Investigations Map SI-2963, scale 1:24,000, 1 sheet.

Miggins, D.P., 2002, Chronologic, geochemical, and isotopic framework of igneous rocks within the Raton basin and adjacent Rio Grande rift and northern New Mexico: Boulder, University of Colorado, M.S. thesis, 417 p.

Miggins, D.P., Thompson, R.A., Pillmore, C.L., Snee, L.W., and Stern, C.R., 2002, Extension and uplift of the northern Rio Grande rift—Evidence from $^{40}Ar/^{39}Ar$ geochronology from the Sangre de Cristo Mountains, south-central Colorado and northern New Mexico, in Menzies, M.A., Klemperer, S.L., Ebinger, C.J., and Baker, J., eds., Volcanic Rifted Margins: Geological Society of America Special Paper 362, p. 47-64.

Thompson, R.A., and Machette, M.N., 1989, Geologic map of the San Luis Hills area, Conejos and Costilla Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1906, scale 1:50,000.
Upson, J.E., 1941, The Vallejo Formation—New early Teritary red-beds in southern Colorado: American Journal of Science, v. 239, no. 8, p. 577–589.
Wallace, A.R., and Machette, M.N., 2007, Revised geologic map of the Fort Garland quadrangle, Costilla County, Colorado: U.S. Geological Survey Scientific Investigations Map SI-2965, scale 1:24,000, 1 sheet.

Figure 1. Simplified map showing relative depth to magnetic rocks east of San Pedro Mesa as determined from high-resolution aeromagnetic data of Bankey and others (2006). Area east of San Pedro Mesa has relatively deep magnetic rocks owing to downdropping of the Servilleta Basalt (unit Tsb) in the Culebra graben, which is compartmentalized by NNW-SSE-trending splays of the San Luis and Sangre de Cristo fault zones. On San Pedro Mesa, Early Proterozoic and Paleozoic rocks that are possibly rooted and pre-Servilleta volcanic rocks (units Thb and Tad) suggest the area was a Neogene structural high in addition to being a Pliocene-Pleistocene horst.

SCALE 1: 24 000
CONTOUR INTERVAL 20 FEET, EAST OF LONGITUDE 105°30’ W
CONTOUR INTERVAL 10 FEET, WEST OF LONGITUDE 105°30’ W

Index to 7.5-minute topographic quadrangles in map area

This map was printed on an electronic plotter directly from digital files. Dimensional calibration may vary between electronic plotters and between X and Y directions on the same plotter, and paper may change size due to atmospheric conditions; therefore, scale and proportions may not be true on plots of this map.

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Base from Garcia 1:24,000-scale topographic map, 1967 edition, and from Sanchez Reservoir topographic map, 1967 edition, photorevised 1982. Polyconic projection, North American Datum of 1927 (NAD27)

Geology mapped in 2006 using 1983 NHAP aerial photographs (1:80,000 scale), aeromagnetic and gravity data, and field reconnaissance. Geology compiled on 1:24,000-scale topographic base maps (see index map) using a photogrammetric plotter (Kern PG-2) and USGS 1:24,000 scale-digital orthophotographic maps