## U.S. Department of the Interior U.S. Geological Survey

**DESCRIPTION OF MAP UNITS** [Surficial units have been mapped and differentiated based on stratigraphic and crosscutting relationships, geomorphic characteristics such as degree of preservation of original depositional landform, pedogenic (soil) development, and correlated and inferred regional chronologies from multiple Quaternary chronologic proxies (table 1). Imagery and elevation data used for geologic mapping was generated from multiple 1.25-meter/ pixel lidar (light detection and ranging) surveys across the region (see figures 1 and 2

## SURFICIAL DEPOSITS

ANTHROPOGENIC DEPOSITS Mine waste deposits (latest Holocene)—Unconsolidated to loosely compacted rubble composed of silt, sand, rock, and waste rock commonly found adjacent to mine workings such as shafts, adits, and glory holes mainly at the Orient Mine location just north of Valley View Hot Springs, but found throughout the surrounding mountains, most being too small for display on this geologic map. Lithologies vary depending on available rock sources, but are predominantly Proterozoic metamorphic and Tertiary volcanic rocks. Abandoned mining equipment and other scrap metal is common around and within deposits. Estimated thickness several meters (m) to 10 m

/////af//// Artificial fill (latest Holocene)—Consists of silt, sand, and cobble- to boulder-size fragments of unconsolidated to loosely compacted gravel and/or broken and redistributed country rock and engineered material used primarily for stabilizing slopes around and within gravel borrow pits and local landfills. Clast and rubble lithologies are chiefly Proterozoic metamorphic rocks and Tertiary volcanic rocks. Unit also includes landfill and dump deposits of the San Luis Valley Landfill comprising waste products including but not limited to metal, plastic, glass, food waste, and grass clippings. Artificial fill is mainly used for rainwater catchment and diversion dams and dikes and roadway construction. Thickness generally 1–20 m

**EOLIAN DEPOSITS** .: Qgsd . Great Sand Dunes (latest Holocene to middle Pleistocene)—Well-sorted, ross-bedded, wind-deposited, coarse sand covered by a thin sheet of active sand and shifting dune forms as defined by Madole and others (2008). Unit forms the main landforms of Great Sand Dunes National Park. Cross beds are commonly greater than 1 m in height and are marked by dark (mafic) mica grains or hematite grains defining paleosurfaces on climbing dune fields. Optically-stimulated luminescence ages of the deposits are variable, but generally indicate that most of the dune field was deposited before 60 ka (Madole and others, 2013), and mainly between draining of Lake Alamosa (approximately 440 ka) and onset of late Pleistocene glacial conditions (130 ka)

Younger eolian sheet and dune sand (Holocene)—Light brown to light yellowish brown, light gray and yellowish white, thin-bedded to massive, moderately to well sorted, silt to coarse sands. These have wind-deposited landforms such as sand sheets and barchan, transverse, crescent, linear, and coppice dunes. Cross stratification in dunes and ripple bedforms are prevalent marking variable depositional intervals, marked by common buried, organic-rich, pedogenic A horizons (Machette and Puseman, 2007). Unit Qey includes Holocene eolian units Qes1, Qes2, and Qes3 of Madole and others (2016). Younger eolian deposits (Qey) are inset into older eolian deposits (Qeo) and are generally on the basin floor at active stream level and/or aggrading within bordering ponded wetlands. Unit may locally contain older dune sand (Qeo), late Pleistocene younger alluvium (Qay), Holocene channel and flood plain alluvium (Qa) and local playa and paludal deposits. Includes middle to late Holocene (approximately 5,600– 2,800 ka) dune sand of Thompson and others (2015) (unit Qed). Thickness 1-5 m

Qeo Older eolian sheet and dune sand (late and middle? Pleistocene) Wind-deposited sand with similar characteristics to unit Qey, but with surface morphology and pedogenic development indicating abandonment and stabilization. These deposits generally include vegetated dunes (namely, coppice dunes), smoothed surfaces indicating steam dissection, abandonment, and eolian aggradation, and the presence of Bt and Bk soil horizons of varying development (Thompson and others, 2015). Thickness variable and may exceed 5 m, but most

LACUSTRINE DEPOSITS Qlp Lake and pond deposits (Holocene and latest? Pleistocene)—Massive, to moderately stratified and laminated, silty clay to silty sand deposits locally within small closed basins, undrained depressions, ephemeral lakes and ponds, and engineered reservoirs. Commonly contains organic-rich marsh and wetland (bog) deposits. Unit locally includes eolian sand sheet and dune sand (Qey), where eolian deposition has impeded surface water flow and caused local ponding. Unit contains coarser pebble lenses (alluvium) and coarse sand proximal to water bodies (Thompson and others, 2015). Unit generally represents localized closed-basin deposition. Thickness varies, but may be as much as 5 m around the San Luis Lake

QTIa Alamosa Formation of Siebenthal (1910) (middle Pleistocene to **Pliocene?)**—Massive to finely laminated, moderately consolidated clay silty clay, clayey sand and silty sand closed-basin lacustrine deposits related to shallow- and deep-water phases of ancient Lake Alamosa (Rogers and others, 1985, 1992; Rogers and Larsen, 1992; Brister and Gries, 1994; Thompson and others, 2015; Davis and others, 2017). Unit thickens towards the axis of the valley with the massive clays being centrally located and coarsening mountainward to silty sand, coarse sand, and sandy pebble gravel with symmetrical and assymetrical ripple cross stratification at lake highstand margins approximately 2,340 m above sea level (Machette and others, 2013). Unit contains beds of Lava Creek B ash (approximate <sup>40</sup>Ar/<sup>39</sup>Ar age of 631 ka, Lanphere and others, 2002; Matthews and others, 2015) near the town of San Luis, Colorado (Kirkham and others, 2003, 2004; Machette and others, 2008), and both Bishop ash (759±2 ka, Sarna-Wojcicki and others, 2000) and Huckleberry Ridge ash (approximately 2.1 mega-annum [Ma]) at Hansen Bluff (Rogers and others, 1985, 1992), about 15 km south of the quadrangle boundary along the Rio Grande (Thompson and others, 2015). Strongly developed calcic soils and <sup>3</sup>He surface-exposure dating suggest that the lake overflowed through the San Luis Hills at about 430 ka (Machette and others, 2007, 2013), with highstand lake levels maintained until approximately 385 ka and complete draining by approximately 200 ka (Ruleman and others, 2016, 2019). Where exposed at the surface, formation is commonly marked by white to light gray playa evaporite deposits abandoned and incised by active stream networks. Thickness laterally variable; commonly about 400 m (Thompson and others, 2015), but may be as much as 550 m thick (Huntley, 1979; Brister and Gries, 1994)

ALLUVIAL DEPOSITS Qaa Active alluvium (latest Holocene)—Moderately to well sorted, thin- to thick-bedded, sandy pebble to cobble gravel, organic-rich silty clayey sand, and coarse sand along the modern Rio Grande and active tributary streams. Unit locally includes flood plain alluvium (Qfp) and young alluvium (Qay). Depositional morphology is generally well preserved and includes actively migrating meander belts, prograding bars, and oxbows. Areas underlain by this mapped unit are subject to frequent shallow groundwater and stream inundation. Soils are generally organic-

rich, A/C profiles. Unit thickness 1–5 m Qa Channel and flood plain alluvium, undivided (Holocene)—Moderately to well sorted, silty, sandy pebble to clast-supported, pebble-cobble gravel interbedded with minor amounts of massive clayey silt and well-sorted sand along broader stream channels and canyons. Unit is commonly capped by a loess mantle as much as 1 m in thickness and a weakly developed argillic (A/Bw) soil profile with bulk matrix stage I pedogenic carbonate (Bk) visible in stringers and thin carbonate films on the underside of pebbles and occasional cobbles. Includes overbank and flood plain deposits of organic-rich, fine-grained, silt and clay. Unit includes pebbly sand and gravel deposits along small tributary perennial streams. Also includes active spring and Holocene paleospring discharge deposits that have reworked older basin-fill deposits along drainages. Locally includes minor amounts of slopewash colluvium, recent landslides, debris flows, and reworked older fan gravels and glacial till derived from adjacent slopes. Estimated thickness generally 1–5 m

Qfp Flood plain alluvium (Holocene)—Moderately to well-sorted, silty clay, silt, silty sand, coarse sand and pebble gravel. Mapped along the Rio Grande and differentiated from active alluvium based on preservation of depositional morphology preservation. Landform preservation is generally lacking due to agricultural and eolian processes, and weak to moderately oxidized A/C soil profiles are common within a mantle of thin silty sand (loess) cap 10–20 cm in thickness. Flood plains subject to occasional flooding. Unit generally lies 1–3 m above active stream channels and active alluvium (Qaa). May locally include active alluvium (Qaa) and/or young alluvium (Qay). Thickness generally 1-3 m where exposed, but may be as much as 5 m

Qay Younger alluvium (late Pleistocene)—Moderately to well sorted, weakly to well-stratified, subangular to subrounded, pebble-boulder gravel commonly with a silty sand matrix. Typically lacks bedding within coarse gravels, but fining-upward sequences and clast imbrication are still prevalent. Stratification commonly defined by well-sorted, silty sand lenses interbedded with coarser gravels. Relict bar-and-swale surficial topography is well expressed with commonly ≥1 m of topographic relief. Surfaces are locally characterized by channels and levees formed from episodic debris-flow events. Where deposits have a strong eolian silt component, soils generally have weakly developed Bw horizons or discontinuous Bk horizons with stage I–II pedogenic carbonate development. See table 1 for unit pedogenic carbonate development and regional correlation with other early to middle Pleistocene gravel deposits. See figure 3 for regional stratigraphic correlation. Soils on coarse, well-sorted gravels typically have weak A/C development. Based on topographic position, pedogenic development, and correlation with deposits in adjacent regions, these gravels are inferred to have been deposited during the Last Glacial Maximum (Pinedale glaciation, approximately 22–21 kilo-annum [ka]) with deposition terminating by approximately 14–13 ka (Kellogg and others, 2017). Unit predominantly deposited by alluvial-fan complexes filling the basin, but locally includes glacial outwash, stream, sheetwash, and recent landslide deposits deposited during Pinedale glaciation (Thompson and Machette, 1989). Along the Rio Grande, unit forms

terraces at two levels, 1–2 to 5–10 m above modern streams and river (Thompson and others, 2015). Estimated thickness less 1–5 m Qai Intermediate alluvium (late and middle Pleistocene)—Moderately to well sorted, weakly to well-stratified, subangular to subrounded, pebbleboulder gravel commonly in a silty sand matrix. Deposits are similar to younger alluvial deposits (unit Qay) in characteristics and mode of deposition but are generally more broadly dissected with abandoned surfaces being smoothed by eolian silt and sand deposition. Soils are better developed than for unit Qay, with moderate to strong argillic textural Bt horizons and common stage I-III pedogenic carbonate Bk horizons. See table 1 for unit pedogenic carbonate development and regional correlation with other early to middle Pleistocene gravel deposits. Relative elevational difference between Qay and Qai deposits increases down drainages from source areas to local base levels, but generally Qai deposits are less than 5 m above Qay deposits within map area. Thompson and others (2015) document Qai deposition at two distinct elevations above modern streams, 2–5 m and 25–60 m dependent upon proximity to active faults and major streams. Main deposition was during Bull Lake glaciation (Thompson and Machette, 1989). Kellogg and others (2017) assigned an age of approximately 167–95 ka (marine oxygen isotope stage [MIS] 6) (Lisiecki and Raymo, 2005) for correlative Bull Lake-age geomorphic surfaces in the upper Arkansas River valley. Nicovich (2020) further supported this age assignment with pedogenic carbonate rind U-series and depositional luminescence ages of approximately 105 ka and approximately 100 ka, respectively. Estimated thickness less than 5 m

Older alluvium, undivided (middle to early? Pleistocene)—Massive to well-stratified, poorly to well sorted, subangular to subrounded silty, sandy pebble-cobble gravel with interbedded eolian silt and alluvial sand layers and lenses. Deposits locally contain large, subrounded boulders exceeding 1 m in diameter proximal to range fronts and glaciated drainages. Deposits generally have well developed argillic soils and

common stage II–IV pedogenic carbonate development, with stage IV pedogenic development not uncommon (carbonate content exceeding 40% in overlying loess cap and gravels). See table 1 for unit pedogenic carbonate development and regional correlation with other early to middle Pleistocene gravel deposits. Clast composition is predominantly locally derived Proterozoic metamorphic and intrusive and Tertiary volcanic rocks. Mostly deposited as alluvial fans and pediment slopewash gravel veneers, but also forms large alluvial aprons prograding sequentially into lower lake shoreline elevations associated with the draining of Lake Alamosa during the interval of approximately 400– 200 ka. Geomorphic upper surfaces of unit are commonly roughly planar and include thin eolian silt veneers. Many clasts are weathered with iron staining and desert varnish. Deposits are generally preserved on the maximum aggradation surfaces along stream drainages now represented by gently basinward sloping interfluves and inset benches capped by gravel veneer. Apparent neotectonic displacement of the older gravels makes it difficult to accurately correlate deposits across basin-margin fault zones; thus we attempt to provide a maximum and minimum age for these older gravels. Previous work by McCalpin (1981, 1982), Machette (1985), Kelson (1986), Pazzaglia and Wells (1990), Kelson others (2007, 2013, 2016, 2019) established a framework in which

and Bauer (2006), Machette and others (2007, 2013), and Ruleman and properties of soils and landforms were used to correlate surficial deposits in the San Luis Valley of north-central New Mexico and south-central Colorado and assign relative ages. In addition, this unit unconformably overlies upper Oligocene to middle Pleistocene Santa Fe Group (following the nomenclature of Brister and Gries, 1994) basin-fill sediments, unit R herein, containing the Lava Creek B ash (Kirkham and others, 2006; Machette and others, 2008) (approximately 631 ka, Matthews and others, 2015). For the Fort Garland region in the southeast quadrant of the map, Wallace and Machette (2008) inferred that unit Qao was deposited across the basin between the time interval of approximately 450–150 ka. Madole and others (2013) concluded that these older gravels postdate approximately 440 ka and predate approximately 130 ka, supporting the previous age estimate. Unit is divided into three subunits (oldest to youngest: Qao1, Qao2, and Qao3) after Ruleman and others (2007, 2013, 2016, 2019) based on

degree of geomorphic preservation, inset relations, and relative elevation of deposits; mainly correlative to units Qg2, Qg3, and Qg4 of Kellogg and others (2017) within the upper Arkansas River valley and units Qlg and Qgpb of Minor and others (2019). Deposits within the oldest subunit, Qao1, are correlated with terrace gravels "No. 7" of Behre (1933) and Powers (1935), who reported paleontologic and pedogenic evidence for a non-glacial paleoclimatic depositional environment; this correlation is also supported by studies of Rogers and others (1985, 1992, 2000), Rogers and Larsen (1992), and Rogers and Wang (2002). Hudson and others (2019) and Ruleman and others (2019) demonstrated that all three of these gravels have pedogenic carbonate U-series ages and accompanying <sup>3</sup>He surface exposure ages on basalts overlying the Rio Grande Gorge less than approximately 400 ka, with active alluviation terminating on both sides of the Rio Grande Gorge by approximately 200 ka. If unit Qao1 has a non-glacial origin, this unit could both the pre-glacial basin deposition and middle Pleistocene MIS 12 (approximately 478–424 ka) (Lisiecki and Raymo, 2005) glacial conditions. The initiation of middle Pleistocene glacial cycles with larger than previous extents as recorded by the global marine oxygen-isotope record (Lisiecki and Raymo, 2005) and regional chronostratigraphic/ geomorphic relationships (Ruleman and others, 2016, 2019), Lake Alamosa highstand, and drainage and formation of the Rio Grande Gorge to the south (approximately 400–200 ka) would be represented by these older gravels (Qao1, Qao2, and Qao3). Within this map area and the northern San Luis Basin, deposits vary from 5–120 m in height above modern stream levels (Thompson and others, 2015), whereas they are approximately 120–240 m above modern streams across the southern

generally 1 to 5 m; may locally exceed 10 m Qao3 Older alluvium, youngest (middle Pleistocene)—Youngest and lowest in elevation gravel deposits associated with the draining of Lake Alamosa. Thickness is generally 1–5 m

San Luis Basin (Ruleman and others, 2016, 2019). Thickness is

Older alluvium, intermediate (middle Pleistocene)—Intermediate-age gravels associated with the draining of Lake Alamosa. Geomorphic position generally below and inset into Qao1 and above Qao3 in the mapped region. Thickness is generally 1–5 m Older alluvium, oldest (middle to early? Pleistocene)—Oldest gravel associated with Lake Alamosa highstand and maximum basin aggradation elevations. Locally, Qao1 gravels may include pre-glacial

deposits overlain by coarse boulder gravel deposits associated with

middle Pleistocene glacial intervals (Rogers and others, 1985, 1992;

## Lisiecki and Raymo, 2005). Thickness is generally 1–5 m ALLUVIAL AND COLLUVIAL DEPOSITS

Alluvium and colluvium, undivided (Holocene to middle? **Pleistocene**)—Poorly to moderately sorted, non-stratified to wellstratified, granule-pebble-boulder gravel with a sandy silt and silty clay matrix. Deposited primarily by ephemeral and discontinuous streams, colluviation sheetwash, and slow, creeping mass wasting processes on moderate to gentle slopes and in ravines. Unit displays weak to strong Bk soil development, with stage III–IV pedogenic carbonate (Ck horizons) locally developed where unit grades to abandoned middle Pleistocene gravel deposits and geomorphic surfaces. Locally includes organic-rich, silty, sandy pebble stream-deposited gravel and clayey silt overbank deposits. Includes piedmont-slope deposits and local sheetwash derived from underlying units. Clast lithology varies with local bedrock units from which it is derived. Average thickness ranges from 1 to 3 m, but may locally exceed 5 m

MASS MOVEMENT DEPOSITS

Qls Landslide deposits, undivided (Holocene to middle Pleistocene)— Massive, poorly sorted to non-sorted, angular to subangular, granule to boulder gravel in with a clayey silt and silty sand matrix. Landslide deposits have not been differentiated on map by process or age. Includes deposits formed by rock-fall, rock-slide, block-slide, debris-flow, and earth-flow processes. More recent landslide deposits are generally characterized by well-expressed hummocky topography and bulging toe slopes, with many exhibiting steep crown escarpments, and various extensional features across active surfaces. Includes recent debris-flow deposits with well-expressed, channel-and-levee networks on active surfaces. Older, inactive landslides have subdued and eroded surficial morphology and pedogenic development, indicative of slope stability and antiquity. Some large landslide complexes along the range front are of probable seismogenic origin (for example, Urraca and South Zapata Creeks), possibly providing proxy for paleoearthquake frequency and magnitude. In some places, substantial eolian silt and clay mantle older landslide deposits, promoting strong pedogenic carbonate formation (Bk horizons). Older, inactive landslides generally exist at higher elevations, with more recent, active landslide deposits grading to younger, lower geomorphic surfaces along steep canyons and active fluvial systems. Estimated thickness varies from 3 m to locally more than 10 m

GLACIAL DEPOSITS Org Rock glacier deposits (Holocene and latest? Pleistocene)—Deposits are generally unsorted, massive accumulations of clast-supported, angular cobbles and boulders that grade down into a matrix of finer rock fragments; younger deposits may have interstitial ice and an ice core or an ice core. Rock fragments on and within rock glacier deposits are primarily derived from steep slopes and upslope cliffs chiefly by rockfall and locally by rock slide and avalanche. Orientations of curvilinear ridges and gullies on rock glacier deposits indicate downslope motion. Deposits form hummocky and lobate topography within the headwater cirque basins of Rito Alto and Cedar Creeks north of Crestone, Colo. Most of the rock glacier deposits in Colorado are of latest Pleistocene or early Holocene age (Meierding and Birkeland, 1980), but may cover and

estimated rates of movement of 1–10 cm/yr (White, 1971, 1976). Thickness 20–50 m Till of Pinedale glaciation (late Pleistocene)—Massive, unsorted to moderately sorted, subangular to subrounded, pebble-boulder gravel with silty sand and clayey silt matrix. Unit locally includes small, mass-wasting deposits along steeper slopes of the moraines where streams have undercut the unstable deposits. Boulders are mostly fresh and unweathered, but locally contain deeply weathered cobbles of metamorphic rock reworked from older glacial deposits. Deposits of Pinedale glaciation are predominantly within the Sangre de Cristo and San Juan Mountains, but reach the mountain-piedmont junction between Crestone, Colo. and Great Sand Dunes National Park, as well as along steep drainages flowing off the Blanca Peak massif. Soils are generally nonexistent on bouldery moraine crests, but weak argillic textural B horizons with spotty pedogenic carbonate stage I development are preserved in morainal depressions and swales of moraines. Deposits correlative with the early part of MIS 2 glacial episode (specifically, the Pinedale glaciation, approximately 31–13 ka) (Lisiecki and Raymo, 2005) based on similarities with morainal deposits elsewhere in region

(Kellogg and others, 2017). Estimated thickness increases from 5 m to

as much as 70 m along the lateral moraines westward towards the

conceal rock glacier landforms formed during former glacial episodes.

Active rock glaciers north of the Sangre de Cristo Mountains have

Sangre de Cristo Range front Till of Bull Lake glaciation (late and middle Pleistocene)—Massive to weakly stratified, subangular to subrounded, pebble-boulder gravel in a silty sand and clayey silt matrix. Unit has very little stratification and sorting. Large boulders at surface are generally well weathered, oxidized and iron stained, and partly to mostly buried. Primary moraine morphology is subtle to nonexistent due to erosion of original geomorphic features and colluvium and eolian silt infilling of depressions. Exposed granitic boulders are generally rounded and weathered with grussification of their outer surfaces. Till forms relatively dissected and subdued lateral moraines adjacent to, and outboard of, the Pinedale lateral moraines around the Blanca Peak massif. An age of 167–95 ka is assigned to these deposits (generally, MIS 6 of Lisiecki and Raymo, 2005) on the basis of cosmogenic-nuclide-exposure ages on correlative Bull Lake age geomorphic surfaces in the northern upper Arkansas River basin (Kellogg and others, 2017). Estimated thickness 10–70 m

Till of Pre-Bull Lake glaciation (middle and early? Pleistocene)—Massive to weakly stratified, pebble to boulder gravel mantling ridge crests and older geomorphic surfaces. Locally contains lenses of pebbly sand and silty sand with boulders in a silty clay matrix, such as along Burnt Gulch and Rock Creeks on the north side of Greenie Mountain and the Alamosa River at Terrace Reservoir, in the southwest corner of mapped area. Clasts are mostly poorly sorted to unsorted, subangular to subrounded pebbles, cobbles, and boulders of locally derived Proterozoic metamorphic and Tertiary volcanics. Boulders are commonly greater than 1 m in diameter, and locally exceed 3 m (Minor and others, 2019). Clasts are commonly deeply weathered and oxidized thus forming an overlying grussified residium with an A/C soil profile. Deposits are typically poorly exposed, mantled by thick soil and bouldery colluvium, creating a smooth abandoned geomorphic surface with large boulders (tors, knockers, and erratics?) of local country rock protruding as much as 1 m above the soil surface. Unit correlative with units Qtpb of Kellogg and others (2017) and Lindsey and others (1984, 1985), Qtpb/QTd of Minor and others (2019), and QTd of Kirkham and others (2006) and Fridrich and Kirkham (2007). Deposits likely represent a combination of proximal syntectonic alluvial, rock avalanche, and other mass movement deposition derived from the uplifting of the Sangre de Cristo and San Juan Mountains (Minor and others, 2019), and from the onset of extensive middle Pleistocene glaciation. Deposits unconformably overlie finer-grained, closed-basin fill deposits associated with the upper

to greater than 10 m BEDROCK AND OLDER BASIN-FILL SEDIMENTARY DEPOSITS

Oligocene to middle Pleistocene (greater than 631 ka) Santa Fe Group

likely temporally correlative with the old alluvial deposits (units Qao1,

Qao2, and Qao3). Estimated thickness varies greatly from a thin mantle

(Thompson and others, 2015; Ruleman and others, 2019). Unit most

R Undifferentiated bedrock (middle Pleistocene to early Proterozoic)— Underlying bedrock on the margins of the San Luis Valley and (or) weakly cemented or lithified sediments of the Santa Fe Group within the valley, following the nomenclature of Brister and Gries (1994) and Machette and others (2008). This unit consists generally of Oligocene to Pliocene volcanic rocks on the western half of the map and Proterozoic metamorphic and Paleozoic sedimentary rocks on the eastern half. The latter represents a complex assemblage of sedimentary fill that accumulated in response to basin subsidence within the Rio Grande rift. These deposits span a large part of the Neogene, and were deposited prior to, during, and after eruptions from the Taos Plateau volcanic field (Pliocene) and creation of Lake Alamosa and Lake Sunshine, in the northern and southern parts of the San Luis Valley, respectively (Machette and others, 2013; Ruleman and others, 2013). Within the mapped area, the Santa Fe Group (see figures 3 and 4 and stratigraphic relationships of units Tsf and QTsf) consists chiefly of fine-grained silty sand with minor lenses of pebble gravels. In northern New Mexico within the southern San Luis Valley in an area south of the Red River, the upper part of the Santa Fe Group (informal Lama formation of Pazzaglia and Wells, 1990) contains the Tsankawi Pumice Bed, which has a sanidine <sup>40</sup>Ar/<sup>39</sup>Ar age of 1.25–1.21 Ma (Izett, 1981; Slate and others, 2013). North of the mapped area near the town of San Luis, Colo., the Santa Fe Group contains the 631 ka Lava Creek B ash (Matthews and others, 2015) less than 2 m below the eroded top of the Santa Fe Group (Lanphere and others, 2002; Machette and others, 2008; Thompson and others, 2015), providing a near minimum age for the fine-grained, basin-fill deposits. Thickness of Santa Fe Group within map area is highly variable and generally thins to the west across the basin, but may exceed 3,000 m (Brister and Gries, 1994)

INTRODUCTION The San Luis Valley is the largest intermountain basin within western North America and lies at the northern reaches of the Rio Grande hydrologic basin and intra-continental neotectonic rift systems. Active faulting along the Sangre de Cristo fault system defines the eastern side of the valley, which has formed the linear, precipitous mountain front of the Sangre de Cristo Mountains. Displacement of multiple generations of Pleistocene alluvial deposits is documented along the eastern side of the geologic map by fault scarps of various sizes and lineaments of probable tectonic origin. The dissected and embayed west side of the valley gradually grades westward to the glaciated plateau country of the San Juan Mountains, but has discontinuous, eroded fault scarps and lineaments, indicative of lesser tectonic activity and longer time intervals between faulting events and their associated large magnitude (M7) earthquakes. Both basin-

bounding mountain ranges exceed 4,000 m elevation and have abundant evidence of

multiple Pleistocene glacial episodes and resulting landscape change. This geologic map records the type and spatial distribution of surficial deposits within the map area associated with these Pleistocene climatic episodes and neotectonic displacement of the deposits. The overall goal of this large-sized map (1:75,000) is to compile preexisting work and new geologic mapping into a lidar-based georeferenced framework (see figures 1 and 2 on sheet 1), which can be used for broader regional geologic map compilations, syntheses of neotectonics and paleoclimatic cycles, and appraisals of mineral resources and geohazards. Active stream networks and associated spring-discharge flooded regions are mapped to assist hydrologic and geomorphic studies requiring precise definition of present basin surficial-flow base level. Most mapped fault scarps and associated lineaments need further geomorphic and paleoseismic investigation to confirm landform interpretation and for recency and cyclicity of fault movement. All surficial geologic units have been placed into a relative-age framework derived from the pedologic and chronologic studies and geologic mapping of Steven and others (1974), McCalpin (1981, 1982), Knepper (1974), Colman and others (1985), Thompson and Machette (1989), Pazzaglia and Wells (1992), Machette and Puseman (2007), Machette and others (2007, 2013), Ruleman and Machette (2007), Ruleman and others (2007,

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Table 1. Soil-carbonate stages of calcic soils formed in Holocene-to-middle Pleistocene deposits in south-central Colorado and north-central New Mexico\*

Geologic age	Age of deposits	North Crestone, Colo., fan deposits McCalpin (1981, 1982) MAP=34 cm		Alamosa/Basin Center, Colo., alluvial deposits Thompson and others (2015) MAP=18 cm		San Luis Hills area, Colo., fan deposits Thompson and Machette (1989) MAP=18 cm		Sunshine Valley–Costilla Plain, N. Mex., alluvial deposits Ruleman and others (2013, 2016, 2019) MAP=32 cm		Red River area, N. Mex., alluvial deposits Pazzaglia and Wells (1990) MAP=32 cm		South Santa Fe area, N. Mex., alluvial deposits Shroba and others (2005) MAP=35 cm	
		Map unit	Calcic hor. CaCO <sub>3</sub> stage	Map unit	Calcic hor. CaCO <sub>3</sub> stage	Map unit	Calcic hor. CaCO <sub>3</sub> stage	Map unit	Calcic hor. CaCO <sub>3</sub> stage	Map unit	Calcic hor. CaCO <sub>3</sub> stage	Map unit	Calcic hor. CaCO <sub>3</sub> stage
Holocene	<11.5 ka — — —	Hf  	I  	Qaa Qfp Qa —		Qfpo Qfp Qa —	I 	Qal — —	_ _ _ _	Qt10 Qt9 Qt8 Qt7	_ _ _ _	Qfp	
late Pleistocene	11.5–130 ka	Pf	I to II	Qay	I to II	Qay	I to II-	Qay	I	Qt6	I+	Qty	I
late middle Pleistocene	130–200 ka —	Bf —	II to III-	Qai —	II to III	Qam —	II to III-	Qai —	II —	Qt5 Qt4	II+ to III II+ to III+	Qti —	II to III
middle Pleistocene	200–300 ka 300–400 ka >400 ka	pBf  	III to III+ — —	Qao — —	III to IV	Qao — —	III to IV-	Qao3 Qao2 Qao1	III to III+ III to III+ III to III+	Qt3 Qt2 Qp1	III to III+ III+ to IV	Qgo3 Qgo2 Qgo1	_ _ _

\*Carbonate stages are those of Machette (1985). Where there are no data, "—;" hor.—horizon; cm—centimeter; ka—kilo-annum. Values for mean annual precipitation (MAP) are for stations near the communities and towns of Crestone, Colo., for the Crestone area; Alamosa, Colo., for the San Luis Hills area; Cerro, N. Mex., for the Sunshine Valley and Red River areas; and Santa Fe, N. Mex., for the Santa Fe area

(http://www.wrcc.dri.edu). Unit pBf in the Crestone area and unit Qao in the San Luis Hills area are undivided units

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Research, v. 57, no. 2, p. 200–207, accessed January 13, 2021, at Ruleman, C.A., Hudson, A.M., Thompson, R.A., Miggins, D.P., Paces, J.B., and Qa/Qfp/Qaa R (QTsf)6 د'(R (Tb'د ~5-2.5 Ma Servilleta Basalt/ Taos Plateau Volcanic Field6'

R (Tsf)

+ + + + + **N** (Tv) √

MIS 5,4,3 (126-30 ka) MIS 6 (191–126 ka) MIS 7 (243-191 ka) MIS 8 (300-243 ka) MIS 9 (337-300 ka) MIS 10 (374–337 ka) \_\_\_\_\_\_ MIS 11 (424–374 ka) MIS 12 (478–424 ka) 444-385 ka Lake Alamosa highstand 631 ka Lava Creek B ash 750 ka Bishop ash

2.1 Ma Huckleberry Ridge Tuff 5,7 Qao3 Older alluvium, youngest (middle Pleistocene) Undifferentiated and older basin-fill sedimentary deposits (Pliocene)—Servilleta **Contacts**—Dotted where inferred

**EXPLANATION** Qaa/Qa/ Qfp Channel alluvium and flood-plain alluvium (latest Holocene and Holocene) Qay Younger alluvium (late Pleistocene) Qai Intermediate alluvium (late and middle Pleistocene)

Qao2 Older alluvium, intermediate (middle Pleistocene) Older alluvium, oldest (middle Pleistocene) Undifferentiated and older basin-fill sedimentary deposits (early Pliocene)—Santa Fe Group of Rogers and others (1985, 1992, 2000); and Machette and others (2008) Undifferentiated and older basin-fill sedimentary deposits (Miocene)—Santa Fe Group of Brister and Gries (1994)

Basalt of Lipman and Mehnert (1979) and Thompson and others (2015) Undifferentiated and older basin-fill sedimentary deposits (late Miocene– Pliocene)—Intermediate volcanic rocks forming large, eroded volcanic edifices in R (Ti) central-southern San Luis Valles (for example, Ute Mountain, Guadalupe Mountain ☐ San Antonio, and Cerro de la Olla) of Thompson and Machette (1989), Thompson and others (1991), Ruleman and others (2013), and Thompson and others (2015)

Undifferentiated and older basin-fill sedimentary deposits (Oligocene-R (Ty) | **Miocene**)—Santa Fe Group of Lipman (2007), Lipman and others (1970), Lipman and Mehnert (1975), and Thompson and others (1991) Undifferentiated and older basin-fill sedimentary deposits (Proterozoic to

Normal fault—Arrows show relative motion; dashed where inferred Stratigraphic markers—Named units, calculated ages, and references Marine oxygen isotope stages (MIS) and ages from Lisiecki and Raymo (2005)

Age from Machette and others (2013) and Ruleman and others (2016, 2019) Age of Lava Creek B ash from the Yellowstone caldera complex from Matthews and others (2015) Age of Bishop ash from the eastern Sierra Nevada region from Zeeden and 5 Age of Huckleberry Ridge Tuff from the Yellowstone caldera complex from

Lanphere and others (2002) 6 Age of Servilleta Basalt and Taos Plateau Volcanic field from Thompson and Age and stratigraphy from Rogers and others (1985)

Figure 4. Conceptual stratigraphic and structural relationships of unit R on the geologic map. Generalized unit chronologic and structural relationships from the previous work listed above in the Explanation. Middle Pleistocene to Holocene alluvial deposits are described in this report. MIS—marine oxygen sotope stage; Ma—mega- annum; ka—kilo-annum.

	Marine Oxygen Isotope Stages and age <sup>3</sup>	San Juan Basin Durango, Colo. (Scott and Moore, 2007)	Northern San Luis Valley (Machette and others, 2013; Thompson and others, 2015; this report)		Southern San Luis Valley, Taos Plateau, Rio Grande Gorge (Ruleman and others, 2013, 2016, 2019)	Upper Arkansas Valley correlative units (Kellogg and others, 2017)	Wet Mountain Valley (Scott and Taylor, 1975; Lindsey and others, 1985, 1986)	Front Range correlative units (Kellogg and others, 2008)	Rocky Mountain Region-Wind River Range Glacial Chronologies (Richmond, 1960, 1964, 1965, 1986; Richmond and Fullerton, 1986; Dahms, 2004a, 2004b; Hall and Jaworowski, 1999)
COLD/ 818O(%) WET3 4.5 WARM/ DRY3 DRY3	11,700 to 0	Naha Alluvium Tsegi Alluvium Eolian sand	Qa			Qa		Post-Piney Creek Piney Creek	
ormal and a second seco	2 ~29 ka	Upper Animas City Middle Animas City till Lower Animas City till Lower Animas City outwash	Qay		Qay	Qtp/Qgp	Pinedale	Broadway Alluvium	Pinedale
SRUNHES CHRON (n	5–3 ~126 ka 6 ~191 ka	Loess Upper Spring Creek Outwash Upper Spring Creek Till Lower Spring Creek Outwash Lower Spring Creek Till	Qai	DEEP-CANYON INCISION RIO GRANDE GORGE FORMATION	Qai	Qtb/Qgb	Bull Lake	Louviers Alluvium	Bull Lake
~243 <u>ka</u>	7 ~243 ka 8	MAJOR INCISION	Qao3		- Qao3	Qtpb/Qg4	pre-Bull Lake	Slocum Alluvium (2) Scott (1960, 1963)	pre-Bull Lake
~300 ka	~300 ka 9 ~337 ka	Loess Upper Durango Outwash	Qao2	PROTRACTED DRAINAGE INTEGRATION	0000			Slocum Alluvium (1) Scott (1960, 1963)	pre-Bull Lake
~374 ka	10 ~374 ka 11	Upper Durango Till			Qao2 Highstand of Lake Alamosa <sup>3</sup>	MAJOR INCISION	MAJOR INCISION ?	MAJOR INCISION CAPTURE OF STREAMS INTO	pre Dun Lant
~424 ka	~424 ka 12 ~478 ka	Lower Durango Outwash  Lower Durango Till	Qao1/Qtpb/Qtd/Tg (around perimeter of basin)		Aiamosa	Qtpb/Qg3	Qtpb/Qa	DEPOSITION OF QTg/Qtpb/Tg ON INTERFLUVIAL FOOTHILLS	Sacajawea Ridge?
~533 ka	15–13	MINOR DOWN CUTTING AND DISSECTION	Qao1		Qao1	Qg2 (contains Lava Creek B)	QTsf	Verdos Alluvium (Scott, 1960)	
~563 ka 14 TO NARWW	~621 ka	Pediment alluvium				MINOR DOWN CUTTING AND DISSECTION		MINOR DOWN CUTTING, DISSECTION, PROTRACTED DRAINAGE INTEGRATION	
~621 ka	~631 ka⁴ 16	Lava Creek B ash (LCB) <sup>4</sup>	LCB (Kirkham and others, 2003; Machette and others, 2008)		LCB (Thompson and others 2014a, 2014b)	LCB	LCB	LCB	LCB
RATE <sup>1,2</sup>	~676 ka 17	Florida Gravel (outwash?)	QTIa/QTsf (Alamosa formation/ Santa Fe Group)		QTsf (Santa Fe Group/ Lama formation)	Qg1	QTsf		
COLD/ TEMPEJ	~761 ka⁵ 18	Bishop ash <sup>5</sup>	Bishop ash ?		Bishop ash ?	Bishop ash	Bishop ash ?	Bishop ash ?	
~780ka	~780 ka								
MATUYAMA CHRON (reversed)  WARM/ TEMPERATE <sup>1,2</sup> TEMPERATE <sup>1,2</sup> Temperative Pleistocene		Outwash or alluvium High gravels of the Animas River	QTIa/QTsf (Alamosa formation/ Santa Fe Group)		QTsf/QTg (Lama formation/ Blueberry Hill deposit, contains ~1.6 Ma ash) (Kelson and Bauer, 2006; Kelson and others, 2008)	Malta Gravel (Tweto, 1961; Richmond, 1986)		Rocky Flats Alluvium	Cedar Mesa (pre-glacial)
MATU WARM/ DRY12	2.1 Ma <sup>6</sup>	Huckleberry Ridge Tuff⁵	Huckleberry Ridge Tuff		Huckleberry Ridge Tuff	Huckleberry Ridge Tuff		Huckleberry Ridge Tuff	Huckleberry Ridge Tuff
WARM WAI TEN	3–2.5 <b>M</b> a	Gravel on Mesa Mountains Bridgetimber Gravel of the La Plata River	Tsf (Santa Fe Group)			Dry Union Formation (Tweto, 1961; Van Alstine, 1969; Minor and others, 2019)		Nussbaum Gravel Ogallala/Six Mile/ Flaxville Gravel	

Global benthic δ<sup>18</sup>O record from Lisiecki and Raymo (2005) <sup>2</sup>Climate relationships from Rogers and others (1985, 1992, 2000), and Rogers and Wang (2002) <sup>3</sup>Age from <sup>3</sup>He (helium) cosmogenic exposure ages for Lake Alamosa highstand and San Luis Valley maximum aggradation level (Machette and others, 2008; Ruleman and others, 2016, 2019) <sup>4</sup>Radiometric age from Matthews and others (2015) <sup>5</sup>Radiometric age of Bishop Tuff from Zeedan and others (2014)

<sup>6</sup>Radiometric age of Huckleberry Ridge Tuff from Lanphere and others (2002) Figure 3. Generalized stratigraphic sections and correlation of Pleistocene units in the Southern Rocky Mountains from the San Juan Basin to the Denver Basin. Blue text in the headings refers to cited map compilations; orange shading indicates correlated and dated volcanic ash units; green shading indicates unconformities from noted erosion processes. On the lefthand side, the  $\delta^{18}$  oxygen excursion is centered at 4.5 for marine oxygen isotope composition expressed relative to Vienna Pee Dee Belemnite (VPDB) for the Pleistocene (modified from Lisiecki and Raymo, 2005).

Surficial Geology of the Northern San Luis Valley, Saguache, Fremont, Custer, Alamosa, Rio Grande, Conejos, and Costilla Counties, Colorado

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