GENERAL GEOLOGY OF THE NORTHERN SAN LUIS VALLEY, COLORADO

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INTRODUCTION

The San Luis Valley (SLV) of south-central Colorado is a major physiographic and structural element of the Rio Grande rift. The valley measures 75 km wide (east-west) and 160 km long (north-south) with an average floor elevation of ca. 2440 m. It is flanked by the San Juan Mountains (to the west) and the Sangre de Cristo and Culebra Ranges (to the east), both of which contain peaks higher than 4270 m (Fig. 1). This paper describes the general geology of the northern part of the valley from Poncha Pass at its north end to approximately the latitude of Alamosa, Colorado.

Fig. 1. Winter view of the eastern Alamosa Basin and Sangre de Cristo Range, looking southeast toward Crestone. Highest peaks are Crestone Peak (left, elevation 4319 m) and Kit Carson Peak (right, elevation 4317 m).

GEOMORPHOLOGY AND CLIMATE

Physiographically, the SLV can be divided into four subsections (Fig. 2; from Upson, 1939): 1) the Alamosa Basin, which includes all of the internally-drained basin north of the San Luis Lakes, as well as the giant alluvial fan of the Rio Grande River northwest of Alamosa, 2) the Culebra reentrant, a piedmont at the base of the Culebra Range in the southeastern part of the valley, 3) the Costilla Plains, an old valley floor east of the incised channel of the Rio Grande River, and 4) the Taos Plateau, a volcanic bench located almost entirely in New Mexico. In this paper I discuss only the Alamosa Basin, which is the largest subsection by area. The northernmost arm of the Alamosa Basin was named

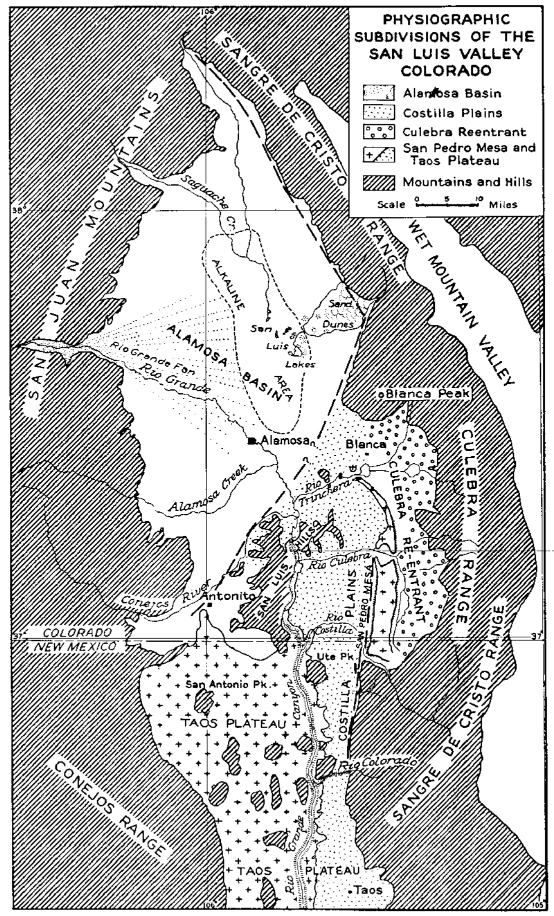

Fig. 2. Physiographic subdivisions of the San Luis Valley, from Upson (1939).

the Villa Grove reentrant by Knepper and Marrs (1971).

Although two large perennial streams (Saguache Creek and San Luis Creek) traverse the northern Alamosa Basin, dissection of the valley floor is negligible. A well-developed bajada exists along the base of the Sangre de Cristo Range and most streams from this range sink into alluvial fans rather than connecting to San Luis Creek (Figs. 3, 4).

Fig. 3. View down the glaciated valley of Willow Creek, immediately north of Kit Carson Peak, looking west toward the valley floor and the Baca Grande land grant. In center foreground is Willow Park, an infilled lake basin impounded behind latest Pleistocene glacial moraines. Streams such as Willow Creek and the Crestone Creeks traverse glaciofluvial fans, only to sink into the valley floor.

Fig. 4. View looking upstream (north) up the braided channel of Medano Creek, at the Great Sand Dunes National Monument. The active dune field is at left. Medano Creek is reknown for its surging flow during the spring runoff season (Schumm et al., 1982). During peak flow (ca. 50 cfs at the range front), the creek flows for about 8 km before it sinks into the valley floor.

At the low point in the basin, the San Luis Lakes comprise a hydrologic sump, separated by a low topographic divide from the Rio Grande drainage basin to the south. Sandy basin fill around the sump area has been mobilized as eolian sand, which has been transported northeast and piled up into the 185 m- high dunes (Fig. 5) of the Great Sand Dunes National Monument (Johnson, 1967).

Fig. 5. Dunes in the Great Sand Dunes National Monument (right center) rise 185 m above the valley floor, and are a result of southwesterly winds funneling through Medano and Mosca Passes (out of sight to right). High peaks of the Crestone group are visible above the dunes, and the Villa Grove reentrant is visible in the distance at left center. Photo was taken from the head of the North Zapata alluvial fan, looking north.

The steep, linear range front of the Sangre de Cristo Range exhibits well-developed faceted spurs, indicative at active uplift (Peterson, 1979; McCalpin, 1982). On the west (hinged) side of the valley, foothills of the San Juan Mountains descend more gradually to the valley floor.

Strong gradients of temperature and precipitation exist between the valley floor and flanking ranges. Precipitation falls largely as winter snow or late summer (monsoonal) thunderstorms. Annual precipitation ranges from 178 mm/yr on the valley floor to 1016 mm/yr on the higher peaks. Mean monthly temperatures at Alamosa, in the basin center, range from -8ºC in January to 18ºC in July, with extremes of -40ºC to +38ºC recorded. In general, potential evapotranspiration (ET) exceeds precipitation (P) in the valley, while the reverse is true in the mountains. The P=ET boundary lies approximately at the pinyon-juniper/pine forest boundary, which is often equivalent to the base of the range front. Due to strong meteorologic gradients, the valley and surrounding mountains contain ecozones ranging from Upper Sonoran (greasewood and rabbitbrush) on the valley floor to Alpine tundra above elevations of ca. 3810 m.

In this paper, I first describe the stratigraphy of Precambrian, Paleozoic, and Cenozoic rocks exposed in the flanking ranges, and then make some inferences on basin fill stratigraphy based on indirect data. Structural geology will then be likewise described.

PREVIOUS WORKS

Geologic mapping in the San Luis Valley area has occurred in sporadic episodes, often associated with specific research programs of universities and the U.S. Geological Survey. Early regional works include Siebenthal (1910), Burbank and Goddard (1937), Gableman (1952), and Litsey (1958). Thesis mapping in the Sangre de Cristo Range began at the University of Colorado (Boulder) in the 1950's (Toulmin, 1953; Litsey, 1954; Munger, 1959), at the Colorado School of Mines in the 1960's (Koch, 1963; Karig, 1964; Nolting, 1970; Wychgram, 1972; Knepper, 1974), and at other universities (e.g. Volckmann, 1965; Peterson, 1979; Reynolds, 1986). Subsurface thesis studies in the basin (geophysics, hydrogeology) include Gaca (1965), Gaca and Karig (1966), Stoughton (1977) and Huntley (1977, 1979a, 1979b). Thesis students also mapped volcanic rocks in the mountains west of the valley, particularly the Bonanza volcanic field on the western side of the Villa Grove reentrant (Bridwell, 1968; Kouther, 1968; Mayhew, 1969; and Perry, 1971), building on the early works of Pattern (1915) and Burbank (1932) in the Bonanza mining district. These thesis studies supplemented more regional volcanic studies (Lipman and Mehnert, 1970, 1975). For several decades some of the best geologic syntheses for the San Luis Valley existed only in field trip guidebooks (e.g. James, 1971; Huntley, 1976a, 1976b; Hawley, 1978) or in conference proceedings (Tweto, 1975, 1979).

A shorter hiatus in the 1970's was terminated by studies of the U.S. Geological Survey in support of wilderness designation of the bulk of the Sangre de Cristo Range (Johnson et al., 1974). These studies resulted in regional-scale (Johnson et al., 1987) and 1:24,000-scale mapping of the Sangre de Cristo Range (Lindsey et al., 1984, 1985a, 1985b, 1987; Lindsey and Soulliere, 1987; Bruce and Johnson, 1991; Johnson et al., 1989; Johnson and Bruce, 1991).

A third episode of applied studies began in the late 1980's, fueled by a controversial water development project (Harmon, 1991) and subsequent exploration for minerals and petroleum in the eastern part of the basin (Gries, 1985; Gries and Brister, 1989; Brister and Gries, 1994; Watkins, this volume).

STRATIGRAPHY

Precambrian Rocks

Precambrian igneous and metamorphic rocks form the basement of both the San Luis Valley and flanking uplifts. In the Bonanza-Kerber Creek area, fine-grained biotite granite occurs in the cores of the central and eastern anticlines (Burbank, 1932), whereas the upper plates of the Kerber and Noland faults are composed of foliated porphyritic granite. Farther north in the southern Sawatch Range, an older suite of Precambrian high-grade metamorphic rocks (quartz-mica schist, amphibolite gneiss, and quartz-feldspar gneiss) are locally intruded by granite and pegmatite dikes, probably correlative with the Bonanza granites. In the Sangre de Cristo Range Precambrian rocks are exposed in the upper plates of Laramide thrusts along the western side of the range. These rocks are divided into four groups by Lindsey et al. (1984, 1985a); three of lower Proterozoic age (1.7-1.8 Ga) (gneiss, leucogneiss, and quartz monzanite), and a younger (middle Proterozoic, 1.4 Ga) quartz monzanite that locally intrudes the metamorphic rocks.

Paleozoic Rocks

Paleozoic rocks in the northern SLV comprise a relatively thin sequence of lower Paleozoic shelf clastics and carbonates, overlain by a thick sequence of late Paleozoic coarse clastics deposited in a rapidly-subsiding basin (Fig. 6).

The Cambrian Sawatch Quartzite is the oldest sedimentary rock unit and locally overlies a low-relief erosion surface cut on Precambrian gneiss. However, in most of the region the Ordovician Manitou Formation (dolomite 27-68 m thick) forms the base of the sedimentary section and directly overlies Precambrian rocks. Disconformably overlying the Manitou Formation are the Harding Sandstone (fine-medium grained quartz sandstone, 18-35m thick) and the Fremont Formation (dolomite, 70-91 m thick), both of Ordovician age. No Silurian strata are preserved in the area; this stratigraphic break is the largest gap in the pre-Pennsylvanian sedimentary record (Litsey, 1958, p. 1154)

Devonian and Mississippian rocks of the Sangre de Cristo Range are comparable in thickness to the lower Paleozoic rocks, and include the Devonian Chaffee Formation (with a 3 to 19 m thick quartzite member and a 26 to 38 m thick dolomite member)

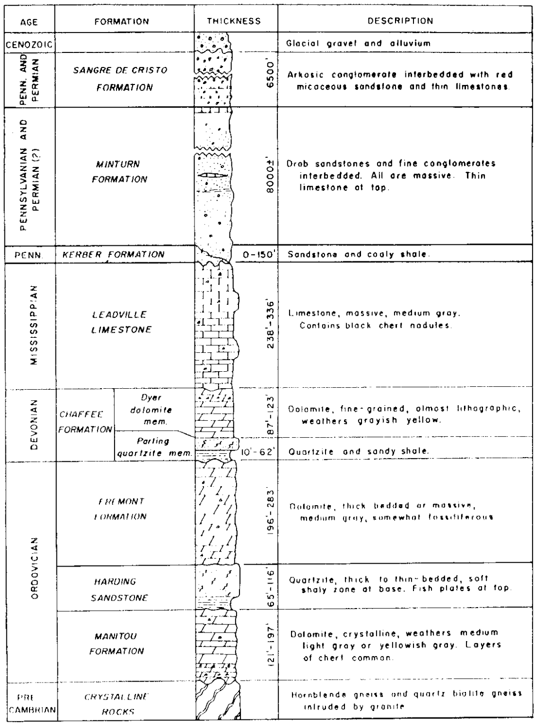

Fig. 6. Stratigraphic column of the northern Sangre de Cristo Range, from Litsey (1958).

and the Mississippian Leadville Limestone (a massively bedded blue to gray limestone, 64-102 m thick in this area).

Pennsylvanian and Permian rocks in the region reflect a major change in sedimentation style associated with the Ancestral Rockies orogeny. The northern San Luis Valley was located in the central Colorado trough between two northwest trending uplifts (the Uncompahgre highland to the west and the Front Range highland to the east). The oldest Pennsylvanian rocks deposited in this trough are fine-grained clastic rocks and limestones, but younger rocks contain vast volumes of very coarse clastics of granitic provenance. The Permo-Pennsylvanian section begins with the Kerber Formation (stratigraphically equivalent to the Belden Formation of central Colorado), about 60 m of coarse sandstone and carbonaceous shale that overlies the Leadville Limestone. The Kerber Formation is overlain by the 2440 m thick Minturn Formation (Pennsylvanian and Permian?). Litsey (1958) informally subdivides this formation into a basal gray quartzose to micaceous sandstone (122 m thick), interbedded red to gray sandstones and conglomerates (365 m thick), olive to brown sandstone with thin shales, siltstones, and conglomerates (1737 m thick), and an upper 213 m of gray limestone and brown sandstone (Lindsey et al., 1985; Clark and Walz, 1985).

The most distinctive Paleozoic formation, which crops out over most of the Sangre de Cristo Range, is the Sangre de Cristo Formation (Pennsylvanian-Permian; equivalent to the Maroon Formation of central Colorado). The formation ranges from 1676 to 2930 m thick, and is dominantly composed of cyclotherms in piedmont-facies alluvium, with a basal arkosic conglomerate grading upward to finer sandstones and local nodular limestones. A very coarse-grained lens, the Crestone Conglomerate (Fig. 7), contains boulders up to 10 m in diameter and represents proximal alluvial fan material derived from the Uncompahgre highland to the west (Lindsey et al, 1986).

Fig. 8. The U-shaped valley of Willow Creek (center) was carved by glaciers through the resistant strata of the Crestone Conglomerate. The aspen-fringed meadow at lower right is Willow Park, a moraine-dammed lake basin (also seen in Fig. 3).

The reference section for this formation is described by Lindsey and Schaefer (1984). Subeconomic deposits of copper and uranium occur in the Permo-Pennsylvanian section (Lindsey and Clark, 1995).

Mesozoic Rocks

Previous mappers failed to find any preserved Mesozoic rocks in the Sangre de Cristo Range (e.g. Burbank and Goddard, 1937; Litsey, 1958), and their absence was also inferred beneath the SLV. Based on the presence of Mesozoic rocks in adjacent basins, Litsey concluded that "During the Mesozoic sediments were undoubtedly deposited in the northern Sangre de Cristo Mountains, but they were removed by erosion during and following Laramide uplifts" (Litsey, 1958, p. 1172-1173). Subsequent workers (e.g. Tweto, 1975) accepted this conclusion, but recent discoveries of Mesozoic strata on the piedmont near Crestone (Watkins, this volume) may force reappraisal of this conclusion, and its implications for a Laramide highland at the present site of the San Luis Valley (see Structure section).

Cenozoic Rocks

Cenozoic rocks include volcanic flows and tuffs exposed in the mountains west of the valley, mid-Tertiary intrusives in high flanking ranges, and thick basin fill sediments beneath the valley floor. In the Bonanza volcanic field Oligocene andesites, rhyolites, latites, tuffs, and breccias cover most of the mountain range, and have an aggregate thickness of 1341-2470 m. Similar volcanic rocks farther south, along the western margin of the valley and in the San Luis Hills south of Alamosa, belong to the Conejos Formation. Basal flows have been dated by Lipman et al. (1970) at 33.4-34.2 Ma.

Contemporaneous with volcanism was the intrusion of dikes, sills, and stocks in the Bonanza caldera and in the northern Sangre de Cristo Range (Rio Alto and Slide-Rock Mountain stocks). These intrusives yield ages of 25.8 to 32.8 Ma according to fission tracks (Lindsey et al., 1986).

Cenozoic basin fill deposits are poorly exposed because there has been minimal dissection into the valley floor. However, an increasing number of oil test wells and geophysical transects made in the past two decades permit a relatively detailed characterization of the basin fill in some areas. The basal valley fill is pre-volcanic redbeds encountered in the bottom of drill holes in the western part of the valley (Monte Vista graben), where they directly overlie Precambrian basement. The redbeds range from nearly 700 m thick in the center of the Monte Vista graben to 115 m thick on the Alamosa horst, and form an eastward-thinning wedge that may extend as far as the eastern basin margin. The taper of this wedge does not appear to be affected by the presence of the Alamosa horst, and thus this formation is presumed to predate the formation of major rift normal faults. Brister and Gries (1994) correlate these redbeds to the Blanco Basin Formation (Eocene), which outcrops on the southwestern flank of the San Juan Mountains. In contrast, Huntley (1979a) and Burroughs (1981) correlated these redbeds to the Vallejo Formation of Upson (1941), which outcrops in small fault-bounded slivers in the Culebra reentrant.

These Paleocene (?) to Eocene (?) redbeds are overlain by an eastward-thinning wedge of volcanic and volcaniclastic rocks of the Oligocene Conejos Formation. The Conejos Formation (30-35 Ma) is a series of intermediate-composition volcanisclastic rocks and lava flows derived from the San Juam volcanic field west of the SLV. Like the underlying redbeds, the eastward-tapering wedge of Conejos volcanics does not appear to be controlled by rift normal faults, and thus predates rift formation.

Overlying the Conejos Formation is a series of 26-30 Ma ash-flow tuffs derived from volcanic centers west of the SLV. These distinctive welded tuffs form a recognizable subsurface stratigraphic marker between the pre-rift redbeds and Conejos Formation, and the overlying, post-rift Santa Fe Formation (Brister and Gries, 1994, this volume).

Overlying the ash flow tuffs is the bulk of the basin fill, which previous workers have assigned to the Miocene-Pliocene Santa Fe Formation (equivalent to the Dry Union Formation of the upper Arkansas Valley and the Los Pinos Gravel of the San Juan Mountains). Most of the Santa Fe Formation logged in boreholes is sandy, similar to the sandy sediments accumulating on the basin floor today. Only near the steep Sangre de Cristo Range front are coarser fanglomerates encountered. The Santa Fe Formation varies in thickness according to its position within the present graben, being as thin as 250 m over the Alamosa horst and up to 3100 m thick in the axis of the Baca graben (Brister and Gries, 1994, this volume).

Quaternary deposits have been mapped within the Sangre de Cristo Range and piedmont (McCalpin, 1982) and studied in the valley floor exposures (Rogers et al., 1992). The uppermost valley floor fill was defined as the Alamosa Formation by Siebenthal (1910) and its upper 20 m is exposed in Hansen's Bluff, an old fluvial (?) scarp about 8 km east of Alamosa. According to Rogers et al (1992), this section of alternating sands and silts is of mixed fluvial, lacustrine, and eolian origin, and reflects closed-basin deposition on the valley floor before ca. 600 ka, when the Rio Grande River was integrated to drainage farther downstream and became entrenched into the valley floor.

Subsequent to 600 ka, deposition has been limited to eolian reworking of valley floor deposits, and to alluvial fan deposition along the Rio Grande River and the bajada at the base of the Sangre de Cristo Range. Many of the Sangre de Cristo alluvial fans can be traced to terminal moraines at, or slightly upstream of, the range front, suggesting that they are mainly glacial outwash features (see Fig. 3). In contrast, Holocene deposition has been restricted to narrow stream channels and low-terraces that comprise <5% of the surface area of the northern basin. In general, alluvial fan surfaces become older and more dissected going north in the Villa Grove reentrant, which suggests that the basin is not subsiding as rapidly at its northern end.

STRUCTURE

The San Luis Valley has been the site of repeated orogenesis since Pennsylvanian, and perhaps Precambrian, time. The elevated basin floor and lofty rift-margin uplifts of today are merely the latest manifestation of vertical tectonics that includes the Ancestral Rockies orogen (Pennsylvanian) and Laramide orogeny (Late Cretaceous-Eocene). Even older orogenies may be represented by the isoclinal folding of foliations in Precambrian metamorphic rocks. Several previous workers (Tweto, 1975, 1979; Knepper, 1974) have speculated that movement in each orogeny takes advantage of high angle faults and shears created in earlier orogenies, perhaps dating back to the Precambrian.

No faults in the study area can be shown to have experienced significant vertical displacement in the Ancestral Rockies orogeny. However, on the eastern flank of the Sangre de Cristo Range near Howard, Colorado, the bounding reverse fault of the Front Range-Apishapa highland (the Pleasant Valley fault) displaced Precambrian basement as much as 300 m and folded the lower Paleozoic strata into a series of NW-trending anticlines and synclines. Kluth (1986) discusses the plate tectonic of this orogeny.

Most of the prominent faults and folds exposed in the Sangre de Cristo Range date from the Laramide orogeny (Late Cretaceous-middle Eocene or ca. 65-55 Ma) (Tweto, 1975). The SLV occupies the site of the former San Luis-Brazos uplift, a broad area of crustal upwarping and high-angle reverse faulting. Major west-dipping reverse faults exposed in the Sange de Cristo Range are (from west to east) the Crestone, Sand Creek, Deadman, and Spread Eagle thrusts. The eastern margin of the range is marked by the east-dipping Alvarado fault system, about which little is known. South of Valley View Hot Springs the Crestone thrust turns west and is truncated by the range-front Sangre de Cristo normal fault. A similar south-dipping thrust on the west side of the Villa Grove reentrant, the Kerber Creek fault, has been postulated as the continuation of the Crestone thrust.

The Crestone and Sand Creek thrusts have shoved Precambrian basement up and eastward over late Paleozoic rocks, typically the Sangre de Ccristo Formation. According to Litsey (1958) the Crestone Thrust is a complex fault zone at least 800 m wide that contains numerous fault slivers of pre-Pennsylvanian sedimentary rocks. Mylonite, slatey cleavage, and chloritoid phyllite mark the thrust footwall (Lindsey et al., 1986). Thrusts farther east are within the upper Paleozoic section and are separated by the NW- to NNW-trending anticlines and synclines that typify the range.

Following the Laramide orogeny the San Luis-Broazos uplift was eroded to low relief and the widespread Eocene erosion surface (Epis and Chapin, 1975) evidently formed across the SLV. This erosion surface is preserved in the subsurface as an unconformity between the Eocene (?) redbeds and the overlying Oligocene Conejos Formation (Brister and Gries, 1994, this volume).

Rift-Related Structures

The present topography of the San Luis Valley and margins is a direct expression of post-Oligocene displacements on normal faults of the Rio Grande Rift. The valley displays classical rift structure, with a valley flanked by raised rift shoulders (Eaton, 1987). In a gross sense, the valley is an east-tilted half graben, with major boundary fault(s) at the base of the Sangre de Cristo Range, and a broad hinge on the western valley margin. Drilling and geophysics have documented a buried intrarift horst (the Alamosa horst) with no surface expression in the Alamosa Basin, but which surfaces farther south as the San Luis Hills. This horst divides the basin into two subbasins, an east-tilted western one with up to 3027 m of post-Eocene sediments (the Monte Vista graben), and a deeper narrow eastern one (the Baca graben) with up to 5000 m of sediments. On the Alamosa horst, basin fill thins to 1650 m.

The eastern margin normal fault, named the Sangre de Cristo fault by Litsey (1958), lies at the base of the steep linear range front of the Sangre de Cristo Range. Steep gravity gradients indicate that the fault is either a single steeply-west-dipping fault (Tweto, 1979) or a narrow belt of step faults (Kluth and Schaftenaar, 1994). Fission tracks suggest that the Sangre de Cristo Range was rapidly uplifted about 19 Ma, although total uplift to date has not exceeded ca. 4 km (Lindsey et al., 1986). These dates are compatible with the observation of Scott and Taylor (1975) that volcanic flows dated at 19.5 Ma crossed unimpeded from west to east across the present site of the northern Sangre de Cristo Range. Late Miocene to recent uplift is responsible for the ca. 2 km of present relief on the range (Lindsey et al., 1986), and continuing uplift is evidenced by multiple-event fault scarps (Fig. 8) that offset Quaternary deposits and landforms of diverse ages (McCalpin, 1982). Fault scarp profiling and trenching suggest: 1) average vertical displacement

Fig. 8. A typical fault scarp across an alluvial fan surface along the Sangre de Cristo fault zone. The scarp is located at Uracca Creek on the western edge of the Blanca Peak massif, is 9.3 m high, and has a maximum scarp slope angle of 23 degrees.

per faulting event is 1.2-2.9 m, 2) long-term return times for M>7 earthquakes are 10-47 kyr, and 3) the latest two M>7 paleoearthquakes occurred about 10-13 ka and 7.6 ka. Based on these data, the Sangre de Cristo fault has experienced Holocene displacement and is thus one of Colorado's few active faults by common definition (Kirkham and Rogers, 1981). Colman et al. (1983) show young faults and Quaternary deposits in this area.

A 10 km-long splay of the Sangre de Cristo fault, termed the Villa Grove fault zone by Knepper (1974), trends northwest across the valley floor between Valley View Hot Springs and Villa Grove Figs. 9, 10).

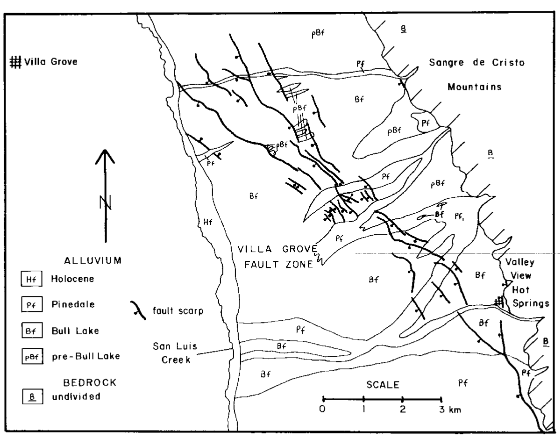

Fig. 9. Simplified geologic map of the Villa Grove fault zone, from McCalpin (1982).

Fig. 10. The largest fault scarp in the Villa Grove fault system trends across the photo at center, after splaying off the range front Sangre de Cristo fault zone (off the photo to right). At this location the scarp is 8.2 m high and has a maximum scarp slope angle of 27 degrees.

The trace is thus close to the subbasin projection of the Crestone thrust to the Kerber Creek thrust and may represent an extensional reactivation of that buried Laramide structure. Scarps of the Villa Grove fault zone range from 0.3 - 14 m high, and were created by discrete displacements of 0.8 - 1.4 m with return times of 30-100 kyr. The latest surface-rupturing earthquake occurred after ca. 13 ka, but its exact age is unknown.

The two flanking faults of the Alamosa horst have not created fault scarps on the valley floor. At several locations in the northern valley vague vegetation lineaments follow the inferred fault trace, possibly the result of groundwater anomalies. Mineral Hot Springs is located astride the eastern horst-bounding fault, and extensive mounds have travertine mark the fault trace. However, there is no evidence for late Quaternary movement on those faults.

The western basin margin is generally described as a broadly warped hinge zone, but several short (10 km long) east- and west-facing fault scarps disrupt mid-Pleistocene pediment surfaces west of Monte Vista (Lipman, 1976). These scarps, although striking on aerial photographs, are very broad and gentle, with scarp heights of 2-7 m, maximum scarp slope angles of 3^o-9^o and estimated ages of ca. 13-500 ka based on the diffusion dating technique for scarp profiles (McCalpin, unpub).

The Holocene and late Quaternary faults in the San Luis Valley are not associated with any recorded historic seismicity (Hadsell, 1968). In fact, in 120 years of recorded history only one felt earthquake has originated in the valley (on 10-07-1952, MMI V, @ 37ºN, 106ºW; Stover et al., 1988). Keller and Adams (1976) were unable to detect any earthquakes > M 1.5 during a brief microearthquake survey. However, a lack of historic seismicity in areas of late Quaternary (and even Holocene) faulting is typical in much of the Basin and Range Province. For example, the 1983 Ms 7.3 Borah Peak earthquake occurred in the Lost River Valley of central Idaho, an area with no recorded historic seismicity. Based on scarp heights and trench data, the Sangre de Cristo fault has generated earthquakes of Ms 6.8-7.4 in the past.

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