

GENERAL GEOLOGY OF THE NORTHERN SAN LUIS VALLEY, COLORADO

James P. McCalpin

GEO-HAZ Consulting
P.O. Box 1377
Estes Park, CO 80517

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

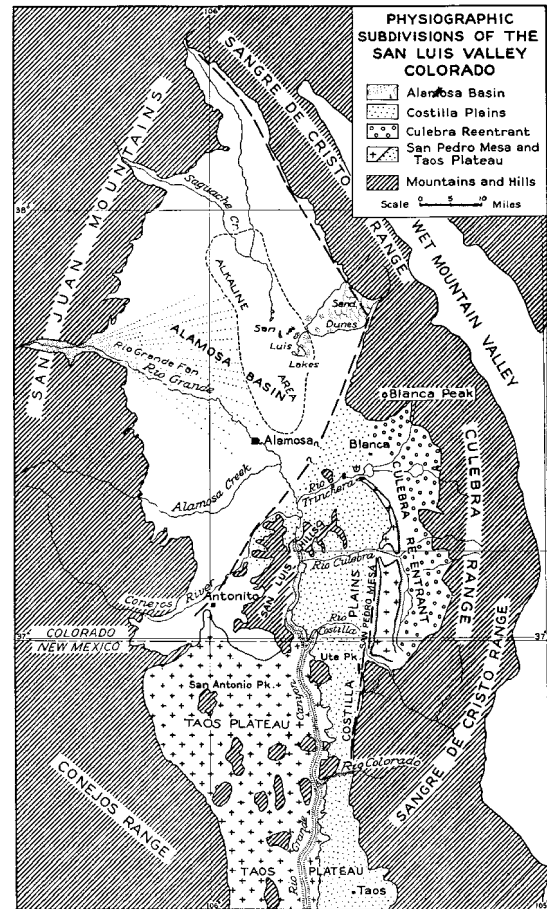


Fig. 2. Physiographic subdivisions of the San Luis Valley, from Upson (1939).

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

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 renowned 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 of 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 -8°C in January to 18°C in July, with extremes of -40°C to $+38^{\circ}\text{C}$ 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; Kouter, 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 monzonite), and a younger (middle Proterozoic, 1.4 Ga) quartz monzonite 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)

AGE	FORMATION	THICKNESS	DESCRIPTION
CENOZOIC			Glacial gravel and alluvium
PENNSYLVANIAN AND PERMIAN	SANGRE DE CRISTO FORMATION	6500'	Arkosic conglomerate interbedded with red micaceous sandstone and thin limestones
PENNSYLVANIAN AND PERMIAN (?)	MINTURN FORMATION	8000'	Dred sandstones and fine conglomerates interbedded. All are massive. Thin limestone at top.
PENNSYLVANIAN	KERBER FORMATION	0-150'	Sandstone and coaly shale
MISSISSIPPIAN	LEADVILLE LIMESTONE	238'-336'	Limestone, massive, medium gray. Contains black chert nodules.
DEVONIAN	CHAFFEE FORMATION	187'-125'	Dolerite, fine-grained, almost lithographic, weathers grayish yellow.
		10'-62'	Quartzite and sandy shale.
ORDOVICIAN	FREMONT LIMESTONE	196'-283'	Dolomite, thick bedded or massive, medium gray, somewhat fossiliferous
	HARDING SANDSTONE	65'-116'	Quartzite, thick to thin bedded, soft shaly zone at base. Fish plates at top.
	MANITOU FORMATION	121'-197'	Dolomite, crystalline, weathers medium light gray or yellowish gray. Layers of chert common.
PRE-CAMBRIAN	CRYSTALLINE ROCKS		Hornblende gneiss and quartz biotite gneiss intruded by granite

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 volcanoclastic rocks of the Oligocene Conejos Formation. The Conejos Formation (30-35 Ma) is a

series of intermediate-composition volcanoclastic rocks and lava flows derived from the San Juan 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 Sangre 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 Cristo 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, slaty

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-Brazos 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 (Bristler 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.



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.

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).

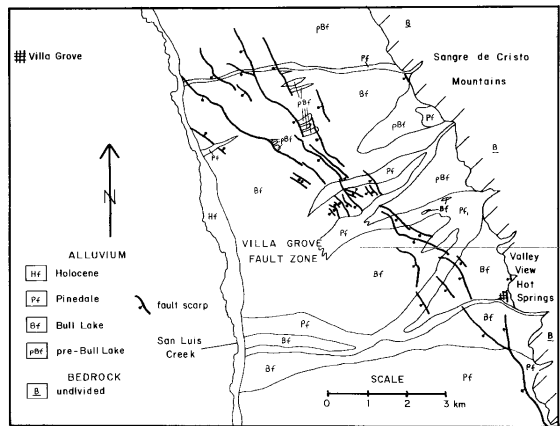


Fig. 9. Simplified geologic map of the Villa Grove fault zone, from McCalpin (1982).

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° - 9° 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, @ 37°N, 106°W; 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.

REFERENCES

- Bridwell, R. J., 1968, Geology of the Kerber Creek area, Saguache County, Colorado: M.S. Thesis 1367, Colorado School of Mines, Golden.
- Brister, B.S. and Gries, R.R., 1994, Tertiary stratigraphy and tectonic development of the Alamosa Basin (northern San Luis Valley), Rio Grande rift, south-central Colorado, in Keller, G.R. and Cather, S.M. (eds.), Basins of the Rio Grande Rift; Structure, Stratigraphy, and Tectonic Setting: Geol. Soc. Amer. Spec. Paper 291, p. 39-58.
- Bruce, R. M. and Johnson, B. R., 1991, Reconnaissance geologic map of parts of the Zapata Ranch and Mosca Pass quadrangles, Alamosa and Huerfano Counties, Colorado: U.S. Geological Survey Map MF-2168, scale 1:24,000.
- Burbank, W. S., 1932, Geology and ore deposits of the Bonanza Mining district, Colorado: U.S. Geological Survey Professional Paper 169, 166 p.
- Burroughs, R.L., 1981, A summary of the geology of the San Luis Basin, Colorado and New Mexico, with emphasis on the geothermal potential for the Monte Vista graben: Colo. Geol. Surv. Spec. Pub. 17, 30 p.
- Clark, R. F. and Walz, D. M., 1985, Stratigraphic section, depositional environments, and metal content of upper part of Mid-Pennsylvanian Minton Formation, Sangre de Cristo Range, Custer and Saguache Counties, Colorado: U.S. Geological Survey Map MF-1622-D.
- Colman, S.M., McCalpin, J.P. Ostenaar, D.A. and Kirkham, R.M., 1985, Map showing upper Cenozoic rocks and deposits and Quaternary faults, Rio Grande rift, south-central Colorado: U.S. Geol. Surv. Map I-1594, scale 1:125,000.
- DeVoto, R. H., Peel, F. and Pierce, W. H., 1971, Pennsylvanian and Permian stratigraphy, tectonism, and history, northern Sangre de Cristo Range, Colorado, in James, H. L. (ed.), Guidebook of the San Luis Basin, Colorado: New Mexico Geological Society Guidebook, 22nd Field Conference, p. 141-163.
- Eaton, G. P., 1987, Topography and origin of the southern Rocky Mountains and Alvarado Ridge, in Coward, M. P., Dewey, J. F., Hancock, P. L. (eds.), Continental extensional tectonics: Geological Society of London Special Publications, vol. 28, p. 355-369.
- Epis, R.C. and Chapin, C.E., 1975, Geomorphic and tectonic implications of the post-Laramide, late Eocene erosion surface in the southern Rocky Mountains, in Curtis, B.F. (ed.), Cenozoic history of the Southern Rocky Mountains: Geol. Soc. Amer. Memoir 144, p. 45-74.
- Gableman, J. W., 1952, Structure and origin of northern Sangre de Cristo Range, Colorado: American Association of Petroleum Geologists Bulletin 36, p. 1547-1612.
- Gaca, J. R., 1965, Gravity studies in the San Luis Valley area, Colorado: M.S. Thesis 1021, Colorado School of Mines, 73 p., Golden.
- Gaca, J. R. and Karig, D. E., 1966, Gravity survey of the San Luis Valley area, Colorado: U.S. Geological Survey Open-File Report, 21 p.
- Gries, R., 1985, Seismic lines in the San Luis Valley, south-central Colorado, in Gries, R.R. and Dyer, R.C. (eds.), Seismic exploration of the Rocky Mountain region: Rocky Mountain Assoc. of Geologists and Denver Geophysical Society, p. 267-274.
- Gries, R. and Brister, B.S., 1989, New interpretations of seismic lines in the San Luis Valley, south-central Colorado, in Harmon, E.J. (ed.), Water in the Valley: Colo. Ground-Water Assoc., 8th Annual Field Trip Guidebook, Denver, CO, p. 241-254.
- Hadsell, F. A., 1968, History of earthquake activity in Colorado: Colorado School of Mines Quarterly 63 (1), p. 57-72, Golden.
- Harmon, E.J. (ed.), 1989, Water in the Valley: Colo. Ground-Water Assoc., 8th Annual Field Trip, Guidebook, Denver, CO..

- Hawley, J. W. (comp.), 1978, Guidebook to the Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, 241 p.
- Huntley, D., 1976a, Field trip, northern San Luis Valley, Colorado, *in* Epis, R. C. and Weimer, R. J. (eds.), Studies in Colorado field geology: Colorado School of Mines Professional Contributions 8, p. 523-538, Golden.
- Huntley, D., 1976b, Hydrogeology of northern San Luis Valley, *in* Epis, R. C. and Weimer, R. J. (eds.), Studies in Colorado field geology: Colorado School of Mines Professional Contributions 8, p. 523-538, Golden.
- Huntley, D., 1979a, Cenozoic faulting and sedimentation in northern San Luis Valley, Colorado: Summary: Geol. Soc. Amer. Bull. 90, pt. 1, p. 8-10.
- Huntley, D., 1979b, Cenozoic faulting and sedimentation in northern San Luis Valley, Colorado: Geol. Soc. Amer. Bull. 90, pt. 2, p. 135-153.
- James, H. L. (ed.), 1971, Guidebook of the San Luis Basin, Colorado: New Mexico Geological Society Guidebook, 22nd Field Conference, 325 p.
- Johnson, B. R., Lindsey, D. A., Ellis, C. E., Hannigan, B. J. and Thompson, J. R., 1984, Mineral resource potential map of the Sangre de Cristo Wilderness study area, south-central Colorado: U.S. Geological Survey Map MF-1635-A, scale 1:62,500, 13 p. text.
- Johnson, B. R., Lindsey, D. A., Bruce, R. M. and Soulliere, S. J., 1987, Reconnaissance geologic map of the Sangre de Cristo Wilderness study area, south-central Colorado: U.S. Geological Survey Map MF-1635B, scale 1:62,500.
- Johnson, B. R., Bruce, R. M., and Lindsey, D. A., 1989, Reconnaissance geologic map of the Medano Pass quadrangle and part of the Liberty quadrangle, Alamosa, Huerfano, and Saguache Counties, Colorado: U.S. Geological Survey Map MF-2089, scale 1:24,000.
- Johnson, B. R. and Bruce, R. M., 1991, Reconnaissance geologic map of parts of the Twin Peaks and Blanca Peak quadrangle, Alamosa, Costilla, and Huerfano Counties, Colorado: U.S. Geological Survey Map MF-2169, scale 1:24,000.
- Johnson, R. B., 1967, The Great Sand Dunes of southern Colorado: U.S. Geological Survey Professional Paper 575-C, p. C177-C183.
- Karig, D. E., 1964, Structural analysis of the Sangre de Cristo Range, Venable Peak to Crestone Peak, Custer and Saguache County, Colorado: M.S. Thesis, Colorado School of Mines, Golden.
- Keller, G. R. and Adams, H. E., 1976, A reconnaissance micro-earthquake survey of the San Luis Valley, southern Colorado: B Seismologic Society of America 66, p. 345-347.
- Kirkham, R. M. and Rogers, W. P., 1981, Earthquake potential in Colorado: Colorado Geological Survey Bulletin 43, 171 p.
- Kluth, C. F., 1986, Plate tectonics of the Ancestral Rocky Mountains, *in* Peterson, J. A. (ed.), Paleotectonics and sediments: American Association of Petroleum Geologists Memoir 41, pp. 353-369.
- Knepper, D. H., Jr. and Marrs, R. W., 1971, Geologic development of the Bonanza-San Luis Valley-Sangre de Cristo Range area, south-central Colorado, *in* James, H. L. (ed.), Guidebook of the San Luis Basin, Colorado: New Mexico Geological Society Guidebook, 22nd Field Conference, 325 p.
- Knepper, D. H. J., 1974, Tectonic analysis of the Rio Grande rift zone, central Colorado: Ph.D. Dissertation, Colorado School of Mines, Golden.
- Koch, R. W., 1963, Geology of the Venable Peak area, Sangre de Cristo Mountains, Colorado: M.S. Thesis, Colorado School of Mines, Golden.
- Koucher, M. J. M., 1968, Geology and minerals of northwest part of Bonanza quadrangle, Chaffee and Saguache Counties, Colorado: M.S. Thesis 1237, Colorado School of Mines, 93 p., Golden.
- Lindsey, D. A. and Schaefer, R. A., 1984, Principal reference section for Sangre de Cristo Formation (Pennsylvanian and Permian), northern Sangre de Cristo Range, Saguache County, Colorado: U.S. Geological Survey Map MF-1622A.
- Lindsey, D. A., Scott, G. R., Soulliere, S. J., and De Angelis, B. L., 1984, Geologic map of the Horn Peak quadrangle, Custer and Saguache Counties, Colorado: U.S. Geological Survey, Map MF-1623, scale 1:24,000.

- Lindsey, D. A., Clark, R. F., and Soulliere, S. J., 1985, Reference section for the Minturn Formation (Middle Pennsylvanian), northern Sangre de Cristo Range, Custer County, Colorado: U.S. Geological Survey Map M-1622-C.
- Lindsey, D. A., Soulliere, S. J. and Hafner, K., 1985, Geologic map of Electric Peak and southwestern part of Beckwith Mountain quadrangles, Custer and Saguache Counties, Colorado: U.S. Geological Survey Map MF-1786, scale 1:24:000.
- Lindsey, D. A., Soulliere, S. J., Hafner, K. and Flores, R. J., 1985, Geologic map of Rito Alto Peak and northeast part of Mirage quadrangle, Custer and Saguache Counties, Colorado: U.S. Geological Survey Map MF-1787.
- Lindsey, D. A., Clark, R. F., and Soulliere, S. J., 1986, Minturn and Sangre de Cristo Formations of southern Colorado - A prograding fan delta and alluvial fan sequence shed from the Ancestral Rocky Mountains, *in* Peterson, J. A. (ed.), Paleotectonics and sedimentation: American Association of Petroleum Geologists Memoir 41, p. 541-561.
- Lindsey, D. A., Andriessen, P. A. M., and Wardlaw, B. R., 1986, Heating, cooling and uplift during Tertiary time, northern Sangre de Cristo Range, Colorado: Geological Society of America Bulletin 97, p. 1133-1143.
- Lindsey, D. A., Johnson, B. R., Soulliere, S. J., Bruce, R. M. and Hafner, K., 1986, Geologic map of the Beck Mountain, Crestone Peak, and Crestone quadrangles, Custer, Huerfano and Saguache Counties, Colorado: U.S. Geological Survey Map MF-1878, scale 1:24,000
- Lindsey, D. A. and Soulliere, S. J., 1987, Geologic map and sections of the Valley View Hot Springs quadrangle, Custer and Saguache Counties, Colorado: U.S. Geological Survey, Map MF-1942, scale 1:24,000.
- Lipman, P.W., 1976, Geologic map of the Del Norte area, eastern San Juan Mountains, Colorado: U.S. Geol. Surv. Map I-952, scale 1:48,000.
- Lipman, P. W., Steven, T. A. and Mehnert, H. H., 1970, Volcanic history of the San Juan Mountains, Colorado, as indicated by Potassium-argon dating: Geological Society of America Bulletin 81, p. 2329-2352.
- Lipman, P. W. and Mehnert, H. H., 1975, Late cenozoic basaltic volcanism and development 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.
- Litsey, L. R., 1958, Stratigraphy and structure of the northern Sangre de Cristo Mountains, Colorado: Geological Society of America Bulletin 69, p. 1143-1178.
- Mayhew, J. D., 1969, Geology of eastern part of Bonanza volcanic field, Saguache County, Colorado: M.S. Thesis 1226, Colorado School of Mines, 94 p., Golden.
- McCalpin, J. P., unpub., Assessment of faulting at the proposed new landfill site for Rio Grande County, Colorado: report prepared by GEO-HAZ Consulting for the Rio Grande County Commissioners, Nov. 28, 1992, 13 p.
- McCalpin, J. P., 1983, Quaternary geology and of the northern Sangre de Cristo Mountains, south-central Colorado: Colorado School of Mines Quarterly 77(3), 97 p, Golden.
- Munger, R. D., 1959, Geology of the Spread Eagle Peak area, Sangre de Cristo Mountains, Saguache and Custer Counties, Colorado: M.S. Thesis, University of Colorado.
- Nolting, R. M, III, 1970, Pennsylvanian-Permian stratigraphy and structure geology of the Orient-Cotton Creek area, Sangre de Cristo Mountains, Colorado: M.S. Thesis 1311, Colorado School of Mines, 102 p., Golden.
- Patton, H. B., 1915, Geology and ore deposits of the Bonanza District, Saguache County, Colorado: U.S. Geological Survey Bulletin 9, 136 p.
- Perry, H., 1971, Geology of the northern part of the Bonanza volcanic field, Saguache County, Colorado: M.S. Thesis, Colorado School of Mines, 362 p., Golden.
- Peterson, R. E., 1979, Tectonic geomorphology of the northern Sangre de Cristo Mountains near Villa Grove, Colorado: M.S. Thesis, University of Arizona, Tucson.
- Reynolds, T. B., 1986, Geology and regional significance of Blanca Peak area, Huerfano County, Colorado: M.S. Thesis, Wichita State University, Wichita, Kansas, 165 p.
- Schumm, S.A., Bean, D.W. and Harvey, M.D., 1982, Bed-form-dependent pulsating flow in Medano Creek, southern Colorado: Earth Surface Processes and Landforms 7: 17-28.

- Scott, G. R. and Taylor, R. B., 1975, Post-Paleocene tertiary rocks and Quaternary volcanic ash of the Wet Mountain Valley, Colorado: U.S. Geological Society Professional Paper 868, 15 p.
- Stover, C.W., Reagor, B.G. and Algermissen, S.T., 1988, Seismicity map of the State of Colorado: U.S. Geol. Surv. Map MF-2036, scale 1:1,000,000.
- Taylor, R. B., 1975, Neogene tectonism in south-central Colorado, *in* Curtis, B. F. (ed.), Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, pp. 211-226.
- Toulmin, P., III, 1953, Petrography and petrology of Rito Alto Stock, Custer and Saguache County, Colorado: M.S. Thesis, University of Colorado.
- Tweto, O., 1975, Laramide (Late Cretaceous-early Tertiary) orogeny in the southern Rocky Mountains, *in* Curtis, B. F. (ed.), Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 1-44.
- Tweto, O., 1979, The Rio Grande rift system in Colorado, *in* Rieder, R. E. (ed.), Rio Grande rift: tectonics and magmatism: American Geophysical Union, Washington, D.C., p. 33-56.
- Upton, J. E., 1939, Physiographic subdivision of San Luis Valley, southern Colorado: *Journal of Geology* 47, p. 721-736.
- Upton, J. E., 1941, The Vallejo Formation: new early Tertiary red-beds in southern Colorado: *American Journal of Science* 239, p. 577-589.
- Volckmann, R. R., 1965, Geology of the Crestone Peak area, Sangre de Cristo range, Colorado: Ph.D. Dissertation, University of Michigan, Ann Arbor.
- Williams, M. D., 1992, Characteristics of unconfined alluvial aquifer system of northern San Luis Valley, Colorado, using GIS data management and visualization techniques: M.S. Thesis, Colorado School of Mines, 121 p., Golden.
- Wychgram, D. C., 1972, Geology of the Hayden Pass-Orient Mine area, northern Sangre de Cristo Mountains, Colorado: a geologic remote sensing investigation: M.S. Thesis, Colorado School of Mines, Golden.