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CENOZOIC RIFT-RELATED SEDIMENTATION AND FAULTING, NORTHERN CULEBRA RANGE, SOUTHERN COLORADO

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Abstract—The development of the Rio Grande rift along the margin of the Culebra Range in southern Colorado involved the complex interaction between orogenic sedimentation and high-angle normal faulting. Prior to rifting, the study area was covered by a partially eroded, intermediate-composition, 28 Ma stratovolcano. Early rifting began at about 26 Ma with the creation of a broad basin into which orogenic sediments were shed from the east. The basal units were in part volcanic rich, and continued downcutting into the rising source highland produced increasingly Paleozoic- and Proterozoic-rich sediments. Basalt flows locally were erupted across the sediments during sedimentation. High-angle normal faulting commenced in the middle Miocene and produced mutually offsetting NNE-trending, down-to-the-west, and WNW-trending, generally down-to-the-south fault systems. The rift-bounding uplift changes northward from an east-tilted homocline to a completely fault-bounded horst, and the mosaic of high-angle faults are present in the general transition zone. This change in structural style may reflect the presence of two similar-facing half-grabens rather than a single graben.

INTRODUCTION

The Rio Grande rift extends from north-central Colorado south through central New Mexico and western Texas into northern Mexico (Baldridge et al., 1984). From central New Mexico northward, the rift consists of a series of opposite-dipping, asymmetric half-grabens that are separated by structurally complex accommodation zones (Chapin and Cather, 1994). The Oligocene and Miocene development of the rift in southern Colorado produced the broad, east-dipping asymmetric graben of the San Luis Valley and the towering Sangre de Cristo horst along its east side (Fig. 1). The southern part of the horst, the Culebra Range, forms a generally north-trending, east-dipping tilted fault block with high-angle normal faults along its western flank. At Blanca Peak, the range front makes a pronounced, 25-km westward jog before resuming its northerly trend (Fig. 1) along the main northern segment of the Sangre de Cristo Range. The range at this point becomes structurally bounded by high-angle normal faults on both its western and eastern flanks (Tweto, 1979). The eastward topographic embayment of the range front into the core of the Culebra Range from Fort Garland south to Amalia in northern New Mexico (Fig. 1) is referred to as the "Culebra reentrant".

Recent mapping in the northern Culebra Range and Blanca Peak area has identified a complex array of rift-related normal faults which are in part synchronous with, but largely post-date, orogenic sediments of the Santa Fe Group. This report, based upon work in progress, describes rift-related sedimentation and normal faulting in the region where the Sangre de Cristo Mountains change from their northerly trend in the Culebra Range to the westerly trend across the southern base of Blanca Peak. The data upon which this paper is based are derived from geologic mapping in the Ojito Peak (Wallace and Soulliere, in press), Trinchera Peak (Wallace and Lindsey, in press), Trinchera Ranch (Wallace, in press), and McCarty Park (Lindsey, in press, b) quadrangles, and work by the author in parts of the surrounding Taylor Ranch, El Valle Creek, Russell, Fort Garland, and Blanca Peak quadrangles.

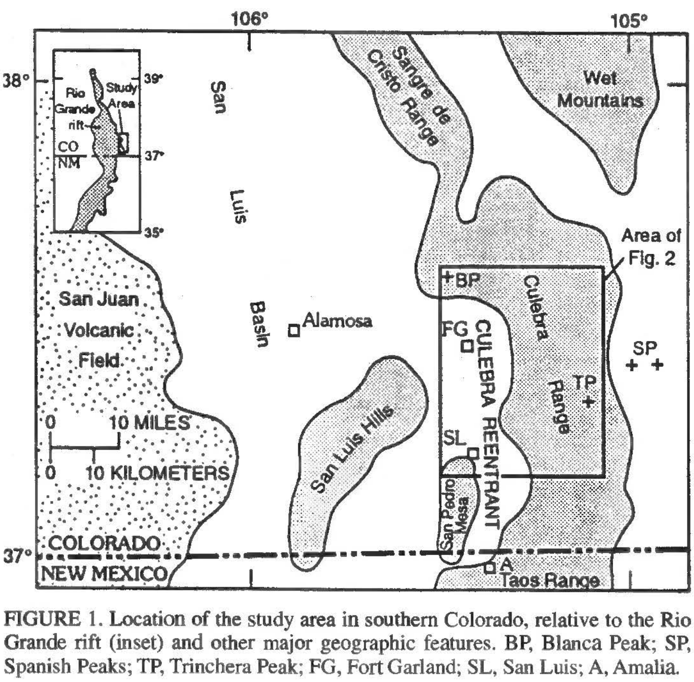

FIGURE 1. Location of the study area in southern Colorado, relative to the Rio Grande rift (inset) and other major geographic features. BP, Blanca Peak; SP, Spanish Peaks; TP, Trinchera Peak; FG, Fort Garland; SL, San Luis; A, Amalia.

GEOLOGIC UNITS

The rock units in the northwestern Culebra Range fall into pre- and synrift time-tectonic packages. The prerift rocks include Proterozoic igneous and metamorphic rocks, Paleozoic and Eocene sedimentary rocks, and Oligocene volcanic rocks. Synrift units include an Oligocene-Miocene volcanic conglomerate, sediments of the Miocene and Pliocene Santa Fe Group, and Miocene and Pliocene basalt flows.

Proterozoic and Paleozoic rocks

The Proterozoic rocks (Fig. 2) include metamorphosed Early Proterozoic supracrustal and intrusive rocks. The supracrustal rocks are predominantly hornblende gneisses and amphibolites, with variable amounts of felsic microcline gneisses, lesser pyroxenite, and rare metaquartzite. The intrusive rocks form an extensive body of augen gneiss that tentatively is correlated with the 1644 Ma quartz monzonite of Costilla Creek in the Taos Range of northern New Mexico (Reed, 1984; Lipman and Reed, 1989).

Sedimentary rocks of the Pennsylvanian Sandia and Madera Formations and the Pennsylvanian and Permian Sangre de Cristo Formation overlie the Proterozoic rocks, and they consist of limestone, conglomerate, and arkose. As discussed later, the basal contact of Paleozoic rocks with Proterozoic rocks is in most places a Laramide thrust fault (Fig. 2), but the original depositional contact has been preserved locally (Lindsey, in press, b; Wallace and Lindsey, in press; Vine, 1974; A. Wallace, unpubl. mapping, 1994).

Prerift sedimentary and volcanic rocks

Vallejo Formation

Small remnants of the Eocene Vallejo Formation, a red conglomerate originally described by Upson (1941), unconformably overlie Proterozoic basement rocks near the range front and occur locally in fault slivers within the core of the range (Fig. 2). The formation likely is equivalent to the Eocene Blanco Basin Formation in San Juan Mountains (Brister, 1990) and the Eocene El Rito Formation of northern New Mexico

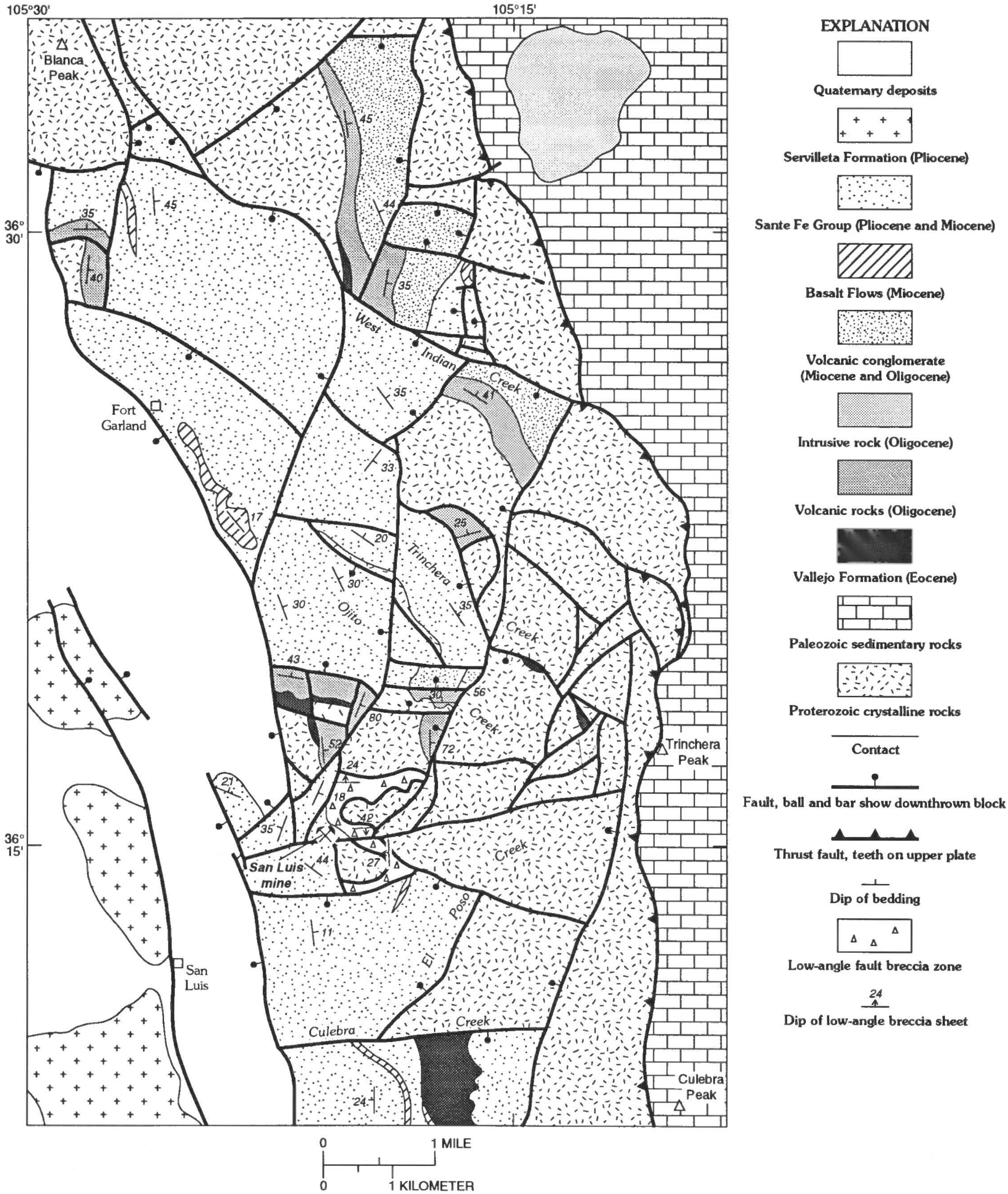

FIGURE 2. Geologic map of the northern Culebra Range and adjacent parts of the southern Sangre de Cristo Range and the San Luis Valley.

(Ingersoll et al., 1990), both of which filled Eocene basins late during Laramide tectonism.

The formation is named for Vallejo Creek east of San Luis, Colorado (Fig. 2; Upson, 1941), where the Vallejo is several hundred meters thick and is overlain by Santa Fe Group rocks and basalt flows of the Hinsdale Formation. Farther north, the red beds are present locally between the Proterozoic basement and Oligocene volcanic rocks; the thickness at those localities varies from several tens of meters to less than ten meters. Clasts are subrounded to rounded and are composed of Proterozoic gneiss and pegmatitic quartz, identical to lithologies exposed in the core of the range to the east, and sedimentary rocks of the Madera Formation; coarse sand-sized grains of chert may have been derived from Mesozoic sedimentary rocks. The rocks and clasts are stained bright red to maroon by hematite. Brister (1990) questioned whether the Vallejo at Vallejo Creek, which he felt was petrologically more similar to upper Tertiary sedimentary rocks, was actually Eocene. However, the sedimentary rocks along Vallejo Creek are significantly different from the younger sedimentary rocks (Santa Fe and volcanic conglomerate) and are identical to the red beds that underlie the Oligocene volcanic rocks several kilometers to the north.

Volcanic rocks

During middle Oligocene time, much of the area of the present southeastern San Luis Valley and western Culebra Range was blanketed by intermediate-composition lava flows and laharic breccias. These are exposed in the San Luis Hills west of San Luis, where they have been dated at about 28 Ma (Thompson et al., 1991), and in fault blocks along the west margin of the Culebra Range (Wallace and Soulliere, in press; Wallace, in press; Lindsey, in press, b; Wallace, unpubl. mapping, 1992-94). Similar andesitic flows and breccias have been identified northeast of Blanca Peak (Bruce and Johnson, 1991), but their relation to the volcanic rocks in the San Luis Valley is unknown. Where exposed along the western part of the Culebra Range (Fig. 2), the volcanic rocks rest unconformably on Proterozoic gneisses and, in places, the Vallejo Formation. In the San Luis Hills, the volcanic rocks are overlain unconformably by lava flows of the Hinsdale Formation, which there have been dated at 26 Ma (Thompson and Machette, 1989). In the western Culebra Range, an early rift-related volcanic conglomerate mantles the volcanic units. East of Fort Garland the volcanic rocks reach a maximum thickness of 900 m; an unknown thickness of volcanic rock was removed by erosion prior to rift-related sedimentation.

The volcanic section consists of a basal lahar sequence and an upper andesite and basalt flow sequence. The lahar sequence contains thick, poorly sorted, chaotic to well-bedded layers of subrounded to angular volcanic and minor Proterozoic clasts. Other layers contain more angular fragments and may have formed during explosive volcanic eruptions. The flow sequence is composed of pyroxene andesite flows, basalt flows, and interbedded flow breccias, and minor biotite dacite flows, lahar breccias, and thin poorly to strongly welded tuffs, including a 10-m-thick layer of welded tuff at the approximate contact between the lahar and flow sequences. Kearney (1983) tentatively correlated the tuff with the 29.8 Ma Ra Jadero Member of the Treasure Mountain Tuff, which was erupted from the Platoro caldera in the eastern San Juan Mountains (date recalculated from Lipman [1975] using new isotopic standards). This age for the base of the flow sequence is consistent with the 28 Ma date for equivalent flow units in the San Luis Hills.

Thompson and Machette (1989) considered the volcanic rocks in the San Luis Hills to be part of the Conejos Formation, which is thick and extensive in the San Juan Mountains to the west and predates caldera-related eruptions in that area (Lipman, 1975). More recent regional work indicates that the rocks are slightly younger than the Conejos (R. Thompson, oral commun., 1994). They and the units exposed along the flank of the Culebra Range more likely are part of a post-Conejos andesitic volcanic complex situated in the south-central and southeastern parts of the San Luis Valley. This sequence was not encountered in deep drill holes in the San Luis Valley west of Blanca Peak (Brister, 1990), suggesting that the volcanic rocks were relatively localized and did not extend that far north or that they were eroded prior to rift-related sedimentation.

Synrift sedimentary and volcanic rocks

During the development of the Rio Grande rift, clastic sediments were shed westward from the rising Culebra and Sangre de Cristo blocks to form two sedimentary units: an early volcanic-clast-dominated alluvial deposit, called here the volcanic conglomerate, and overlying Proterozoic-clast-dominated sandstones and conglomerates of the Santa Fe Group. Basalt flows of the Oligocene and Miocene Hinsdale Formation locally are interbedded with the Santa Fe Group. The volcanic conglomerate is not a regionally extensive unit, but lithologically and stratigraphically it is akin to the Los Pinos Formation, which forms the basal, volcanic-rich rift sequence in the Tusas Mountains of northern New Mexico; the source area there was the middle Tertiary San Juan volcanic field (Manley, 1981). The Santa Fe Group in the study area probably is correlative with the Tesuque Formation of the Santa Fe Group in the Española Basin, which is due south of the study area. The Tesuque Formation was deposited in a similar depositional environment and had a similar Proterozoic source terrain to the east (Ingersoll et al., 1990). However, until mapping in the intervening region can confirm or deny correlation, the broader name Santa Fe Group is used in this study area.

Volcanic conglomerate

The earliest sedimentary record of rifting is a volcanic conglomerate that unconformably overlies the Oligocene volcanic rocks. The predominant volcanic lithology is a light-gray, fine-grained volcanic to hypabyssal rock with sparse to abundant small blades of hornblende and rare plagioclase laths. These volcanic rocks are very similar to late Oligocene and early Miocene (Penn et al., 1994; L.W. Snee, personal commun., 1994) subvolcanic intrusions exposed along the crest of the Culebra Range to the east (Vine, 1974). In addition, some clasts at the base of the section were derived from the volcanic rocks which underlie the volcanic conglomerate, indicating local erosion and deposition of the volcanic rocks. The clasts at the base of the section are composed entirely of volcanic rocks. Higher in the section, subrounded clasts of limestone and sandstone from the Middle Pennsylvanian Madera Formation and gneisses from the Proterozoic basement comprise as much as fifty percent of the clasts. This trend in the composition of the clasts indicates erosion first of intermediate-composition volcanic and subvolcanic edifices, likely to the east and north, and then, with progressive downcutting, into the underlying Paleozoic and Proterozoic rocks. The absence of clasts of Mesozoic rocks, sources for which currently are exposed east of the modern range crest (Vine, 1974), indicates that the paleodrainages did not extend that far east.

The volcanic conglomerate weathers easily and outcrops are therefore sparse. Roadcuts into the formation along Highway 160 northeast of Fort Garland reveal generally planar bedding with some broad channeling and crossbedding (a Master's thesis on these exposures is in progress by Leon Deering, University of Akron). Strata vary widely from silt layers to beds composed of small boulders; beds composed of sand- to cobble-sized clasts are most common.

The volcanic conglomerate is thickest and most extensive northeast of Fort Garland, where it forms a 1500-m-thick section between the underlying Oligocene volcanic rocks and the overlying Santa Fe Group sediments (Fig. 2). The contact with the volcanic rocks is an erosional unconformity that locally represents at least several hundred meters of volcanic rocks that were removed prior to deposition of the volcanic conglomerate. The upper contact with the Santa Fe Group is poorly exposed but also is believed to be an erosional unconformity and to be marked by an abrupt change from volcanic clast-dominated to a Proterozoic clast-dominated composition typical of the Santa Fe. The volcanic conglomerate is absent to the south of Trinchera Creek (Fig. 2), where Santa Fe rests directly on older rocks. However, volcanic-rich zones within the Santa Fe in that area, described below, suggest that the basal Santa Fe locally might be temporally equivalent to the volcanic conglomerate.

Santa Fe Group

Clastic alluvial sediments of the Santa Fe Group are widespread in the San Luis basin, and they are exposed along the flanks of the Culebra

Range and Blanca Peak (Fig. 2). In contrast to the volcanic conglomerate, clasts in the Santa Fe are predominantly Proterozoic felsic gneisses (50-100%), with subordinate Pennsylvanian and Permian limestone and sandstone (10-50%), and variable amounts of Tertiary volcanic rocks (0-30%). The volcanic rocks include the hornblende-bearing lithology common in the volcanic conglomerate, but pebbles to boulders of andesite and basalt from the pre-rift Oligocene volcanic flow sequence predominate in some sections, especially in the southern part of the study area. The uppermost part of the Santa Fe section is devoid of volcanic clasts.

Clast sizes and bedforms vary considerably throughout the area of exposure. Bedding is generally sheetlike, with some channels, graded bedding, and cross-stratification. Beds of pure mudstone commonly are interlayered with beds containing boulder-sized clasts in a sand matrix, and some sections distal to the range front are composed almost entirely of mud and sand with only scattered pebbles. Exposures in the vicinities of West Indian Creek, Ojito Creek, Culebra Creek, and El Poso Creeks (Fig. 2) on average contain the beds with the coarsest clasts, whereas exposures in intervening areas are generally finer grained and composed largely of sandstone to mudstone. Along the range front near West Indian Creek, tilted beds of Santa Fe are cut by a steep-sided upper Santa Fe channel filled with clasts more than a meter in size. This channel is only a few hundred meters from what is interpreted to be a relatively young range-bounding fault, suggesting a very proximal, fault-controlled fan-head depositional environment. The overall, subjective impression is of fan heads at the latitudes of the modern West Indian Creek, Ojito Creek, and Culebra/El Poso Creeks drainages that provided the coarsest material, with finer-grained clasts being deposited distally and radially away from those source points. Unfortunately, normal faults have cut virtually all sections in the Santa Fe Group, and additional unexposed faults may have complicated identification of breaks in section even further. As a result of faulting, a sequence of sedimentation like that postulated by Cavazza (1989) in the Tesuque Formation of the Santa Fe Group in northern New Mexico may be present but very difficult to define.

The upward trend in clast composition indicates a continuation of the erosional unroofing established during deposition of the volcanic conglomerate. Proterozoic rocks and lesser Paleozoic rocks were eroded as contributions from volcanic sources decreased. Clast lithologies are identical to rocks exposed to the east in the core of the Culebra Range, and obscure clast imbrication suggests transport from the east and northeast. Alluvial fans in the central and southern parts of the area may have had predominantly Proterozoic and Paleozoic source rocks, whereas fans to the north initially included volcanic source rocks. Intervening areas of Proterozoic-rich sediments may have had episodic contributions of volcanic material as channels changed courses across the fans. For example, in the northeast part of the study area, the Santa Fe rests unconformably on the volcanic conglomerate; to the south, the volcanic conglomerate as a major discrete unit is absent and the Santa Fe was deposited on older rocks. However, locally thick volcanic-rich intervals are interbedded with the Santa Fe near Ojito Creek (Fig. 2), suggesting that the base of the Santa Fe there may be in part temporally equivalent to the volcanic conglomerate but with a different or varying source-rock lithology. Unfortunately, lateral correlation of units is impossible due to post-sedimentation faulting.

East of the town of San Luis (Fig. 2), some to most of the clasts in the basal part of the Santa Fe are identical to clasts in the nearby thick exposures of the Vallejo Formation, which may have been the source for some of the early Santa Fe sediments. As the Vallejo was stripped, Paleozoic and Proterozoic clasts, with some volcanic clasts, became dominant in the Santa Fe.

Miocene and Pliocene(?) basalt units

Basalt flows locally are interbedded within or at the base of the Santa Fe Group from the base of Blanca Peak southward into northern New Mexico. Flows near Fort Garland are entirely within the Santa Fe Group, and, near the San Luis gold mine northeast of San Luis (Fig. 2), a small flow overlies brecciated Proterozoic gneiss and in turn is overlain by the Santa Fe. One flow east of San Luis is present along the Vallejo-Santa Fe contact, and a second flow is entirely within the Santa Fe some 200 m higher in the section (Fig. 2); similar basalt flows within the Santa Fe near Amalia in extreme northern New Mexico were dated at about 16 Ma (Lipman and Reed, 1989). In the study area, only the flat-lying flows which cap San Pedro Mesa south of San Luis (Fig. 2) have been dated (4.3±0.8 Ma; Lipman et al., 1986). The various other flows permissively may belong to the upper Oligocene to Miocene Hinsdale Formation and/or the Pliocene Servilleta Basalt, although all but the flows at San Pedro Mesa lack the diktytaxitic texture typical of the Servilleta flows (Dungan et al., 1984). Geochronologic studies of several intra-Santa Fe flows near Fort Garland are in progress.

Erosional unconformities

The complete Tertiary stratigraphic section is not preserved anywhere in the study area. In those few places where at least parts of all the units are represented, major inter- and intraformational erosion has cut out significant parts of the section. Commonly, one or more of the Tertiary units is missing completely. In places, such as at the San Luis mine, the Santa Fe rests directly on Proterozoic basement, although the entire volcanic sequence and the Vallejo overlie the Proterozoic less than three kilometers to the north (Fig. 2). Both nondeposition and erosion may explain the local absence or relative thinning of some units, but angular unconformities within and between units clearly are evidence of episodic erosion.

A major period of erosion can be identified after middle Tertiary volcanic activity and early rift-related sedimentation. Along West Indian Creek (Fig. 2), several hundred meters of pre-rift volcanic rocks were removed prior to deposition of the volcanic conglomerate. In the San Luis Hills to the west (Fig. 1), Thompson and Machette (1989) demonstrated a similar period of major erosion between the 28 Ma "Conejos" volcanic rocks, which are equivalent to those along West Indian Creek, and the overlying flows of the 26 Ma, rift-related Hinsdale Formation. Along the southeast margin of the San Juan volcanic field (Fig. 1), Hinsdale Formation basalt flows are interbedded with the Los Pinos Formation, which likely is equivalent to the volcanic conglomerate, and both unconformably overlie 27-35 Ma, east-tilted volcanic rocks (Lipman and Mehnert, 1975). Therefore, early rifting may have been accompanied by a period of erosion in an area including much of the modern southern San Luis Valley.

STRUCTURE

The development of the Rio Grande rift involved three sets of faults: (1) Laramide thrust and tear faults, (2) a possible late Oligocene low-angle fault, and (3) Neogene and younger high-angle normal faults. Folds and compositional layering in the Proterozoic rocks did not have any obvious effect on the development of the younger structures.

Laramide thrust faults

Multiple east-directed thrust plates were formed during the Laramide orogeny, and the contact between the Paleozoic sedimentary rocks and the Proterozoic basement is, in most places, a thrust fault (Fig. 2; Lindsey, in press; Wallace and Lindsey, in press). Thrusting produced complex fold and thrust patterns in the Paleozoic rocks. Faults formed between adjacent thrust sheets, most notable of which are exposed along West Indian and North Fork Trinchera Creeks (Fig. 2), and some were reactivated during late Tertiary rifting. Most of the structures are within the Paleozoic rocks, but several tear faults and thrusts can be traced into the Proterozoic rocks. Some of the many other faults mapped in the basement, especially those with demonstrable middle Tertiary and younger movement, permissively may have formed during the Laramide, but Laramide offset is virtually impossible to determine.

Middle Tertiary low-angle fault

Jones (1991) described remnants of a generally west-dipping, low-angle normal fault along the west flank of the Sangre de Cristo Mountains from near Poncha Pass south to the Questa area of northernmost New Mexico, and concluded that the structure as a whole represented a detachment fault related to early rifting along this segment the Rio Grande rift. Within the present study area, the only low-angle faults are exposed in the vicinity of the San Luis mine (Fig. 2), where hydrothermal fluids ponded beneath or against one of the breccia zones to form the 24 Ma ore deposit (Benson and Jones, 1990). In the vicinity of the mine, a major zone of gouge and breccia within Proterozoic rocks forms a gently west-plunging antiform that is truncated on its south, east, and west sides by high-angle, rift-related normal faults. The limbs of the antiform dip moderately to steeply, and the crest is flat in places. The central part of the breccia zone is a variably thick gouge zone. The footwall beneath gouge is unbrecciated to extremely brecciated; the hangingwall contains crushed to crackled gneisses that extend more than a hundred meters above the gouge zone. Less than a kilometer southeast of the mine, a similar breccia sheet dips 25-30° to the west and is truncated on all sides by high-angle normal faults. The few Proterozoic rocks that are exposed elsewhere in the study area show no effects of brecciation related to a low-angle fault. If indeed a west-dipping low-angle detachment fault was once continuous through the area, it is possible that the Proterozoic rocks exposed in the core of the range are in the footwall of the now-eroded low-angle fault.

Miocene and younger normal faults

By far the most common types of Cenozoic structures in the study area are Neogene to Holocene high-angle normal faults. These faults form a polygonal, mutually offsetting pattern with two dominant fault orientations: west-northwest-trending (WNW) faults, and north-north-east-trending (NNE) faults (Fig. 2). The WNW faults generally have a down-to-the-south sense of movement, with some down to the north; with a few exceptions, the NNE faults have down-to-the-west senses of offset.

Within the study area, the eastern limit of late Cenozoic faulting is marked by a slightly west-stepping set of WNW and NNE faults that extends north from near Culebra Peak to beyond the area shown in Figure 2; detailed mapping east of that fault set demonstrates the absence of post-Laramide faults (Lindsey, in press a, b, c; Vine, 1974). The NNE fault set extends west to the floor of the San Luis Valley, where the faults cut and slightly rotated Miocene basalt flows. The WNW faults are less common north of the major WNW fault along West Indian Creek than to the south; the western extension of the West Indian Creek fault bifurcates and in part controls the southern flank of Blanca Peak (Fig. 2). The region south of the West Indian Creek fault contains abundant faults of both sets and, as a result, has a complex pattern of faults and rotated blocks.

The fault pattern is a product of late Cenozoic extension, but reactivation of older faults can be demonstrated in a few locations. The Laramide fault between thrust plates along West Indian Creek was reactivated, with at least 2 km of down-to-the-south, post-Santa Fe offset. Similarly, Laramide thrust-related faults truncate several late Tertiary faults in the Proterozoic basement northwest of Trinchera Peak (Fig. 2), suggesting probable reactivation of Laramide structures. Some of the Oligocene volcanic rocks were rotated prior to rift sedimentation; faults responsible for rotation have been obscured by later sedimentation and faulting. For the most part, the faults that cut post-Laramide units do not show evidence of pre-Miocene ancestry.

Horizontal-axis rotation during movement along both sets of normal faults produced a complex array of tilted fault blocks. Santa Fe sediments within a majority of the blocks dip moderately (20-45°) to the northeast, in keeping with a general down-to-the-north rotation on the WNW faults and a down-to-the-east rotation on the ENE faults. Dip reversals to the west or southwest are present but less common, and throughout the area fault blocks may dip at right angles to, or even in, the opposite direction of adjacent blocks. Cross-cutting relationships locally indicate that faulting generally migrated south and west with time, which may explain why Holocene offset along faults is located on the west side of the study area (Colman et al., 1985; Kirkham and Rogers, 1981). However, major faults in both the NNE and WNW sets cut faults to the west and south, respectively, indicating that movement continued along those structures during the evolution of the fault system as a whole.

Much of the observed horizontal-axis rotation of the rift sediments took place after deposition of the Santa Fe Group. Dips of the volcanic conglomerate and the Santa Fe within individual fault blocks do not vary markedly or consistently through more than a kilometer of section, which argues strongly against synrotation sedimentation (Luchitta and Suneson, 1993). However, some rotation did take place during deposition of upper Santa Fe sediments, as shown north of West Indian Creek (Fig. 2) where feeder dikes and intra-Santa Fe basalt flows have been rotated clockwise an equivalent amount (26°), suggesting that the dikes were originally vertical and the flows horizontal when emplaced. The dips of the volcanic conglomerate and Santa Fe down section from the flow are steeper and indicate about 18° of pre-basalt clockwise rotation. In an adjacent fault block, Santa Fe conglomerates were rotated 37° clockwise and then cut by a now-east-dipping channel filled with a boulder conglomerate near the top of the section. Therefore, rotation commenced relatively late in the sedimentary cycle and continued after Santa Fe sedimentation ceased. Rotation may have begun earlier on blocks to the east, but that cannot be documented due to the erosion of the Tertiary rocks.

DISCUSSION

The Culebra reentrant south of Blanca Peak and north of about the New Mexico-Colorado border is characterized by a complex mosaic of WNW and NNE normal faults with a net down-to-the-southwest displacement; to the north and south, the NNE faults predominate. Also, the range north of the reentrant changes from an east-tilted block (Culebra Range) bounded only on the west side by high-angle faults to a horst (Sangre de Cristo Range) bounded on the east, west, and south sides by high-angle faults. The fault mosaic is atypical of the margins of other structural basins along the rift, which predominantly are controlled by rift-parallel normal faults (Chapin and Cather, 1994).

The sequence of early basin-filling sedimentation followed by major high-angle faulting is similar to other parts of the Rio Grande rift. Other basins related to the rift formed during two phases: an early period (mid-Oligocene to mid-Miocene) during which broad shallow basins developed, and a later phase (mid-Miocene to present) during which the narrower, fault-bounded grabens were produced (Morgan et al., 1986). Considering that the structural margin of the younger, fault-controlled basin in the Culebra Range area was near the modern range crest, the eastern extent of the earlier basin into which the volcanic conglomerate and Santa Fe sediments were shed may have been even greater, perhaps extending as far east as the volcanic edifices that overlay the intrusions along the range crest. As such, the volcanic conglomerate in part may be a distal volcaniclastic apron related to the volcanic edifices (Smith, 1991). Subsequent uplift of the core of the horst caused erosion of the overlying volcanic conglomerate and exposed the underlying pre-Tertiary rocks, which were themselves sources for the increasingly Proterozoic-rich sediments in the basin to the west. As a result, the Santa Fe Group undoubtedly includes a significant amount of reworked early basin-fill sediments. The transition from early basin to late basin sedimentation may be recorded at the erosional unconformity between the volcanic conglomerate and the Santa Fe, where the clast composition changes dramatically from volcanic rich to Proterozoic rich.

The exact timing of events is vague, but some general estimates can be made from available data. The volcanic rocks are prerift and are correlative with 28 Ma volcanic rocks in the San Luis Hills. Some tilting and erosion of these rocks took place prior to deposition of rift-related sediments, and clasts within the early-rift volcanic conglomerate were derived from 21-26 Ma igneous systems to the east. Tilted intra-Santa Fe basalt flows likely are equivalent to those in the 16 Ma intra-Santa Fe Hinsdale Formation near Amalia where they overlie early volcanic-rich Santa Fe conglomerates derived from the 26 Ma Questa caldera complex (Lipman and Reed, 1989). Fission-track studies at Blanca Peak (Kelley et al., 1992) indicate very rapid cooling, likely due to uplift, in the middle Miocene. In the Española basin to the south, basin filling ceased at about 10 Ma, roughly coincident with the inception of high-angle normal faulting and major uplift (Golombek et al., 1983; Baldridge et al., 1994). If the intra-Santa Fe basalt flows indeed are of Hinsdale age, the timing of sedimentation and faulting along the Culebra Range would approximate that in the adjacent Española basin. The relatively flat-lying orientation of 4 Ma Servilleta basalt flows near San Luis, which overlie east-tilted Santa Fe sediments, may indicate that much of the faulting and rotation had ceased by that time, consistent with paleomagnetic data in northern New Mexico (Hagstrum and Lipman, 1986). Whatever subsequent uplift has taken place apparently has produced only small amounts of tilting.

Although the original presence of a low-angle detachment in the region is not called into question here, the evidence for a such a structure within the study area is ambiguous. Based upon the age and inferred genesis of the San Luis gold deposit (Benson and Jones, 1990), the low-angle breccia zone at the mine was present by 24 Ma, but there is no upper age limit for the structure. The breccia zones at and near the mine are in fault blocks that are bounded entirely by younger high-angle faults, and throughout the study area Santa Fe Group rocks in similar structural blocks were rotated by as much as 45° and usually by more than 25° (Fig. 2). As a result, the breccia zone at the mine very possibly had an orientation significantly different than its present position and could have ranged from flat to nearly vertical; non-rotation of the block is possible but would have been extremely anomalous. In the Taos Range of northern New Mexico, early-rift (24-25 Ma) block rotation took place along

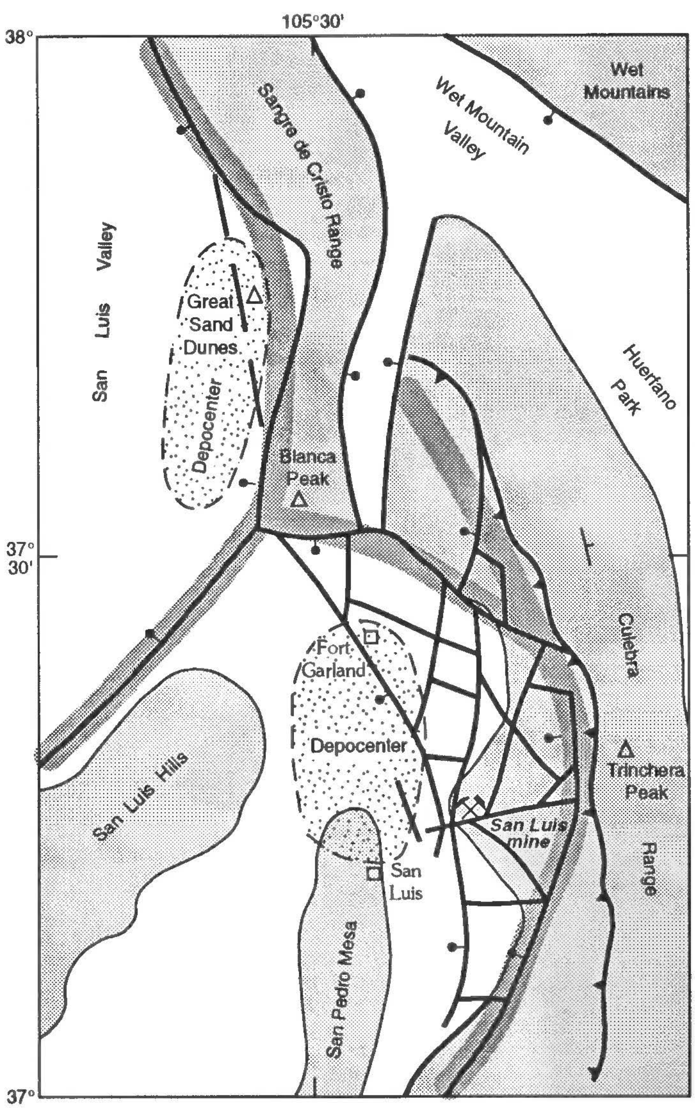

FIGURE 3. Schematic map showing major fault systems (dark lines), uplifts (shaded areas), and depocenters in the San Luis Valley graben (stippled). Laramide thrust faults in the Culebra Range shown with hachures on upper plate. The Culebra Range is an east-dipping monocline with faults on west flank; the Sangre de Cristo Range is bounded on both sides by high-angle faults. Broad shaded bands show possible structural margins of paired half-grabens, with down-to-the-west displacement.

listric-normal faults (Lipman and Reed, 1989; Hagstrum and Lipman, 1986), but breccia zones similar to those near San Luis were not identified (P.W. Lipman, oral commun., 1995). Similarly, somewhat steeper dips in the Oligocene volcanic rocks relative to Santa Fe sediments in the study area indicate that the volcanics were rotated prior to rift sedimentation, but rotation cannot be attributed to specific high- or low-angle faults.

The minimum amount of down-to-the basin displacement can be approximated from the elevation difference between the crest of the range and the depth to Proterozoic basement in the basin. Gravity data (Keller et al., 1984) indicate as much as 4000 m of basin fill above the basement just south of Fort Garland. Trinchera Peak (Fig. 2) rises 1700 m above the valley floor, giving a minimum total vertical displacement of 5700 m. Similarly, the minimum total offset from the crest of Blanca Peak (1900 m above the valley floor) to the basement beneath the valley fill is 5900 m. This presumes that all of the observed elevation difference was due to vertical uplift, a supposition supported by middle to late Miocene cooling ages for the crest of Blanca Peak (Kelley et al., 1992). To the north, in the vicinity of Great Sand Dunes National Monument (Fig. 3), the minimum total offset from the crest of the Sangre de Cristo Mountains to the top of the basement in the deep basin to the west is 6400 m (Kluth and Schaftenaar, 1994; Keller et al., 1984).

The mosaic of WNW and NNE Miocene faults is enigmatic. The WNW faults largely are confined to a rectangular area, represented by the Culebra reentrant, between Blanca Peak, the easternmost NNE fault set, Amalia (New Mexico), and the flat-lying, generally unfaulted upper Oligocene volcanic rocks in the San Luis Hills (Fig. 1). Only the NNE faults are present to the north and south along the margin of the rift. Early rift-related faults in northern New Mexico trend northwest, indicating a south-westerly extension direction (Lipman, 1982; Lipman and Reed, 1989). Scattered dikes that cut the volcanic conglomerate and the Santa Fe Group in the study area also trend northwest, indicating a similar southwesterly extension direction during much of the rift-related sedimentation. Miocene and Pliocene faults in south-central Colorado have a polygonal pattern, but the dominant orientation is north-northwest to northerly (Taylor, 1975). Regardless, the jumble of variably oriented fault blocks in the study area (Fig. 2) indicates that response to extension was complicated.

A clue may lie in the change in structural style in the Sangre de Cristo-Culebra uplift from an east-dipping homocline to a fault-bounded horst, with a north-northeast-trending graben in the upper Huerfano River valley (Tweto, 1979) at the transition zone (Fig. 3). The uplift histories of the two blocks vary considerably as well. Based upon apatite fission track dates, the Sangre de Cristo horst cooled rapidly in early to middle Miocene time due to rift-related uplift, whereas the Culebra Range cooled more slowly as a result of Eocene uplift followed by relatively moderate uplift in the Miocene (Kelley et al., 1992). The variably tilted fault blocks of the study area lie southwest of the graben and generally within the zone of structural transition. As a result, the fault pattern and variable tilts on fault blocks reflect a somewhat chaotic adjustment to the transition from one structural regime to the other.

Throughout the length of the rift, adjacent, opposite-dipping half-grabens are separated by accommodation zones across which the structural transition takes place (Chapin and Cather, 1994). In the case of the San Luis basin and the Sangre de Cristo-Culebra horst, however, the structurally distinct domains are on the same side of the basin, which has a consistent easterly dip. Although not common, such a morphology has been described for parts of the East African rift, in which two similar-facing half-grabens are slightly offset from each another, with a complex accommodation zone in between (Rosendahl, 1987). As noted by Rosendahl (1987), these can be difficult to distinguish from a single half-graben. To complicate an already confusing setting, significant high-angle normal faulting was extensive outside of the rift proper (San Luis and related axial basins), and it was responsible for the fault-bounded Wet Mountain Valley and the Ilse fault to the northeast (Taylor, 1975). The effect or magnitude of that style of faulting on the San Luis basin and flanking horsts is unknown.

Evidence in the San Luis basin for a pair of half-grabens is sketchy, largely for lack of data in the southern half of the basin, but the available data do provide some support for the hypothesis. The basin contains two major depocenters, one west of the Sangre de Cristo horst and one west of the Culebra uplift (Fig. 3). Between the two is a fault, down-dropped to the northwest, that extends southwest from Blanca Peak (Fig. 3; Tweto, 1979; Brister, 1990). The fault truncates the northern end of the intrabasin San Luis Hills horst, and basin sediments are thicker on the down-dropped side. As such, this fault may be part of the accommodation zone between the two half-grabens, each of which has its own depocenter. The margin of the northern half-graben is defined by the high-angle fault along the west side of the Sangre de Cristo Mountains, arcing southwestward from Blanca Peak. The margin of the southern half-graben is defined by the eastern edge of the Culebra reentrant; it may splay at its north end into two segments, one across the base of Blanca Peak and the other along the graben to the north. However, additional data clearly are needed from the southern half of the San Luis basin to corroborate or disprove this concept.

SUMMARY

The formation of the Rio Grande rift along the Culebra Range began with a possible early low-angle detachment fault and the development of a broad basin into which orogenic sediments of the volcanic conglomerate and the Santa Fe Group were deposited, commencing in the latest Oligocene or earliest Miocene. The basin extended east past the crest of the modern range, and underlying rocks included Proterozoic, Mesozoic, and Tertiary units. High-angle normal faulting began in early to middle Miocene time and continued to perhaps the Pliocene. Many of the faults trend NNE, parallel to the rift axis, and have a down-to-the-west displacement. A second set of normal faults trend WNW and have a general down-to-the-south displacement. The rift-bounding uplift changes northward from an east-dipping homocline to a completely fault-bounded horst, and the high-angle faults are present in this transition zone. The change in structural style may reflect two similar-dipping half grabens rather than one single half-graben.

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