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A. R. Wallace

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EVOLUTION OF THE SOUTHEASTERN SAN LUIS BASIN MARGIN AND THE CULEBRA EMBAYMENT, RIO GRANDE RIFT, SOUTHERN COLORADO

ALAN R. WALLACE
U.S. Geological Survey, MS 176, University of Nevada, Reno, Reno, Nevada 89557

Abstract.—The Culebra half-graben and horst in southern Colorado form the southern half of the asymmetric San Luis graben-horst system along the Rio Grande rift. The Blanca Peak horst forms the northern margin of the Culebra half-graben and is linked with the Sangre de Cristo horst to the north. These elements comprise the Culebra reentrant, an eastward recess in the rift margin south of Blanca Peak. Rifting in the Culebra horst-graben system began at about 25 Ma, and Santa Fe Group sediments were shed westward into alluvial fans and the developing depocenter. Clasts of progressively older source lithologies were carried to the depocenter, reflecting early uplift of the Culebra horst through at least 18.7 Ma, and sedimentation continued to at least 3.7 Ma. The drainage divide in the rising horst shifted westward, eventually limiting the alluvial sources to the western side of the modern range. Blanca Peak was not a topographic high during these stages of sedimentation. The structurally active part of the Culebra horst-graben system coincides with the thrust-faulted west side of a Laramide arch. Normal faulting along the western side of the Culebra horst began in the late Oligocene and was most active from the late Miocene to the present. The dominant faults strike northeast and are down-dropped into the basin, creating at least 4600 m of total offset. Rifting reactivated Laramide tear faults to form northwest-striking normal faults. The interaction between the rift-parallel faults and the oblique reactivated tear faults created a compartmentalized fault system and demonstrates a clear Laramide influence on rift-related faulting. Initial uplift of the Blanca Peak horst began in the early Miocene, but substantial uplift did not take place until the late Miocene and Pliocene. Since that time, uplift of the Culebra horst and Blanca Peak horsts overlapped in time and, in part, in space. The Culebra reentrant is a product of contrasting uplift styles along the margins of the two horsts and conjecturally some clockwise rotation of the Blanca Peak horst.

INTRODUCTION

The late Cenozoic Rio Grande rift extends from northern Colorado to southern New Mexico, and it consists of numerous half grabens of alternating polarity that are separated by structural accommodation zones. The north-northwest-elongate, east-dipping San Luis graben system defines the rift in southern Colorado and northernmost New Mexico (Fig. 1). It is composed of two half grabens: a younger one to the north (Alamosa graben), and an older one to the south (Culebra graben). This study focused on sedimentation and faulting during the formation of the Culebra graben and the adjacent Culebra horst, and on the role of Laramide thrust and tear faults in the development of rift-related, high-angle faults. This area has been called the Culebra reentrant, in reference to the marked eastern shift of the basin margin between the Blanca Peak area of the Sangre de Cristo Mountains and the western front of the Culebra Range (Fig. 1). This shift, as documented here, is a product of the paired, in part contemporaneous, formation of the two half grabens and related horsts. This paper substantially updates the preliminary results of and modifies the conclusions presented in Wallace (1995).

GEOLOGIC SETTING

The San Luis graben system extends south from the Villa Grove accommodation zone near Poncha Pass to the Embudo accommodation zone of northern New Mexico. A thick section of Oligocene volcanic rocks underlies the San Juan Mountains west of the San Luis graben system (Fig. 1; Lipman et al., 1970). Paleozoic sedimentary rocks, which are in thrust and depositional contact with the underlying Early Proterozoic basement, underlie the Sangre de Cristo and Culebra horsts east of the graben. The western margin of the graben system is a hinge zone with relatively minor faulting, whereas the eastern side is the site of high-angle, rift-related normal faulting. High-angle faults bound the west, south, and east sides of the Sangre de Cristo horst east of the Alamosa graben. In contrast, the Culebra horst east of the

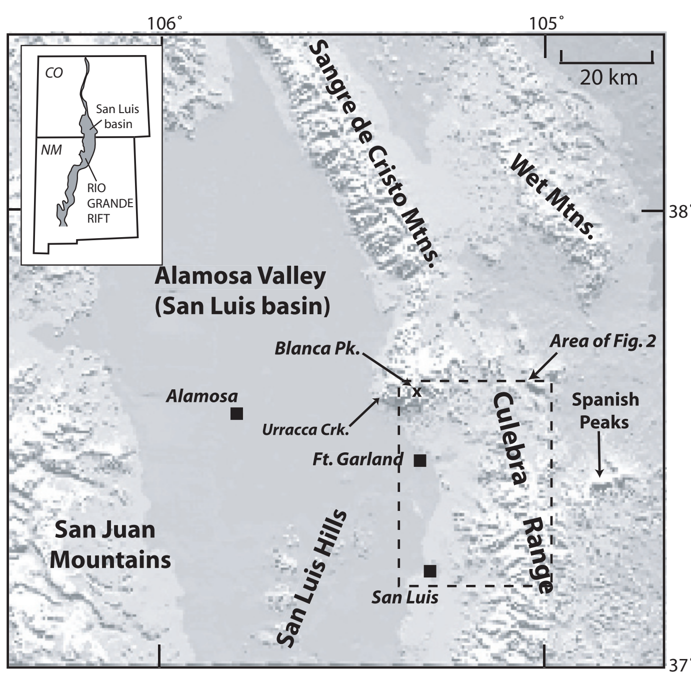

FIGURE 1. Location of major features in the San Luis basin area. The dashed line shows the location of Figure 2. The inset map shows the Rio Grande rift in Colorado and New Mexico (modified from Russell and Snelson (1994), with extension of the rift into northern Colorado from Tweto, 1979).

Culebra graben is an east-tilted basement block with high-angle faults only along the western margin.

Gravity and drilling data show that the Alamosa graben is filled with 6 to 7 km of sediments of the late Tertiary Santa Fe Group and the Plio-Pleistocene Alamosa Formation (Brister and Gries, 1994). These units overlie Oligocene volcanic rocks, Eocene conglomerate of the Blanco Basin Formation, and Proterozoic igneous and metamorphic rocks (Brister and Gries, 1994; Kluth and Schafenaar, 1994). Based upon seismic and drilling data, the Alamosa graben is composed of two east-dipping half grabens (Brister and Gries, 1994). Gravity data in the Culebra graben indicate that the Santa Fe sediments are up to 2500 m thick in the vicinity of Ft. Garland (Keller et al., 1984), but no drilling or seismic data are available to indicate what lithologies underlie the Tertiary sediments. Oligocene volcanic rocks underlie the San Luis Hills in the western and central parts of the graben (Fig. 1; Thompson and Machette, 1989), and the eastward continuation of these volcanic rocks beneath the sediments is likely but unknown.

Both the Alamosa and Culebra grabens contain north-trending intra-basin horsts, although the horsts are not connected. The Alamosa horst in the Alamosa graben is not exposed, but drilling, seismic, and gravity data show its presence (Brister and Gries, 1994). The horst in the Culebra graben is exposed in the San Luis Hills. It ends abruptly to the north against a northeast-striking subsurface fault that separates the Alamosa and Culebra grabens (Tweto, 1979; Brister and Gries, 1994).

PRE-RIFT GEOLOGY

Stratigraphy

Prior to the onset of rifting at about 25 Ma, Early Proterozoic metamorphic rocks, Paleozoic sedimentary rocks, an Eocene conglomerate, and Oligocene volcanic rocks underlay the study area (Figs. 2, 3). Proterozoic metamorphic rocks with strong northeast-trending compositional layering form the cores of the ranges. The principal lithology in the Culebra Range is leucocratic augen gneiss, with lesser amounts of hornblende gneiss and amphibolite. In contrast, lithologies in the Blanca Peak area include gabbro, tonalite, and pyroxenite, and the augen gneiss is not present. Numerous northwest- to north-northwest-striking diabase dikes, likely of early Paleozoic age (Larson et al., 1985; Johnson and Bruce, 1991), cut Proterozoic rocks in both areas and indicate that the contrast in Proterozoic lithologies occurred prior to the early Paleozoic. Gray sandstone, limestone, and siltstone of the Pennsylvanian Madera and Minturn Formations are exposed in both ranges, and red sandstone and arkose of the Permo-Pennsylvanian Sangre de Cristo Formation is exposed in the Culebra Range. Mesozoic and early Tertiary sedimentary rocks, primarily sandstone and shale, are exposed on the eastern side of the Culebra Range.

Pre-rift Tertiary rocks include the late Eocene Vallejo Formation and overlying Oligocene intermediate-composition volcanic rocks. The Vallejo Formation, described originally by Upson (1941), is a dark maroon conglomerate that is irregularly present between the Proterozoic basement and overlying Tertiary units (Fig. 2; Wallace, 1995). Oligocene volcanic rocks overlie both the Vallejo Formation and the Proterozoic basement. The principal volcanic units were derived locally, and they include basal lahars and breccias, which contain both volcanic and lesser Proterozoic clasts, and overlying air-fall tuffs and andesite, dacite, and basaltic andesite flows and breccias (Fig. 3). A thick, 29.6±0.1 Ma latite welded ash-flow tuff separates the two sequences (Fig. 3; Table 1; Kearney, 1983; Wallace, 1996) and likely was erupted in the San Juan Mountains to the west. The flow and breccia sequences resemble the Oligocene Conejos Formation in the San Luis Hills to the west (Fig. 1; Thompson and Machette, 1989) and the Conejos and overlying andesite flows along the New Mexico border,

TABLE 1. Isotopic ages of rocks in the northern Culebra Range area

Unit	Age (Ma)	Method	Source
Servilleta basalt flow (Ft. Garland)	3.66±0.03	$^{40}Ar/^{39}Ar$	1
Servilleta basalt flow (San Luis)	4.49±0.02	$^{40}Ar/^{39}Ar$	7
Hinsdale basalt flow	18.86±0.01	$^{40}Ar/^{39}Ar$	2
San Luis gold deposit	21.24±0.24	$^{40}Ar/^{39}Ar$	3
	22.5±0.4	$^{40}Ar/^{39}Ar$	3
East Spanish Peak pluton	23.21±0.06	$^{40}Ar/^{39}Ar$	4
West Spanish Peak pluton	24.6±0.1	$^{40}Ar/^{39}Ar$	4
Mt. Mestas pluton	25.01±0.05	$^{40}Ar/^{39}Ar$	5
Pre-rift volcanic rocks (San Luis Hills)	>27.7±0.3	$^{40}Ar/^{39}Ar$, K/Ar	6
Pre-rift welded tuff	29.6±0.1	$^{40}Ar/^{39}Ar$	2
	29.2±7.0	Fission-track (apatite)	8

Sources of data: 1: Wallace (1997a); 2: Wallace (1996); 3: Benson (1997); 4: Penn et al. (1992); 5: Miggins et al. (2000); 6: Thompson and Machette (1989); R. Thompson, oral commun. (1995); 7: Miggins et al. (2002); 8: Kelley et al. (1992).

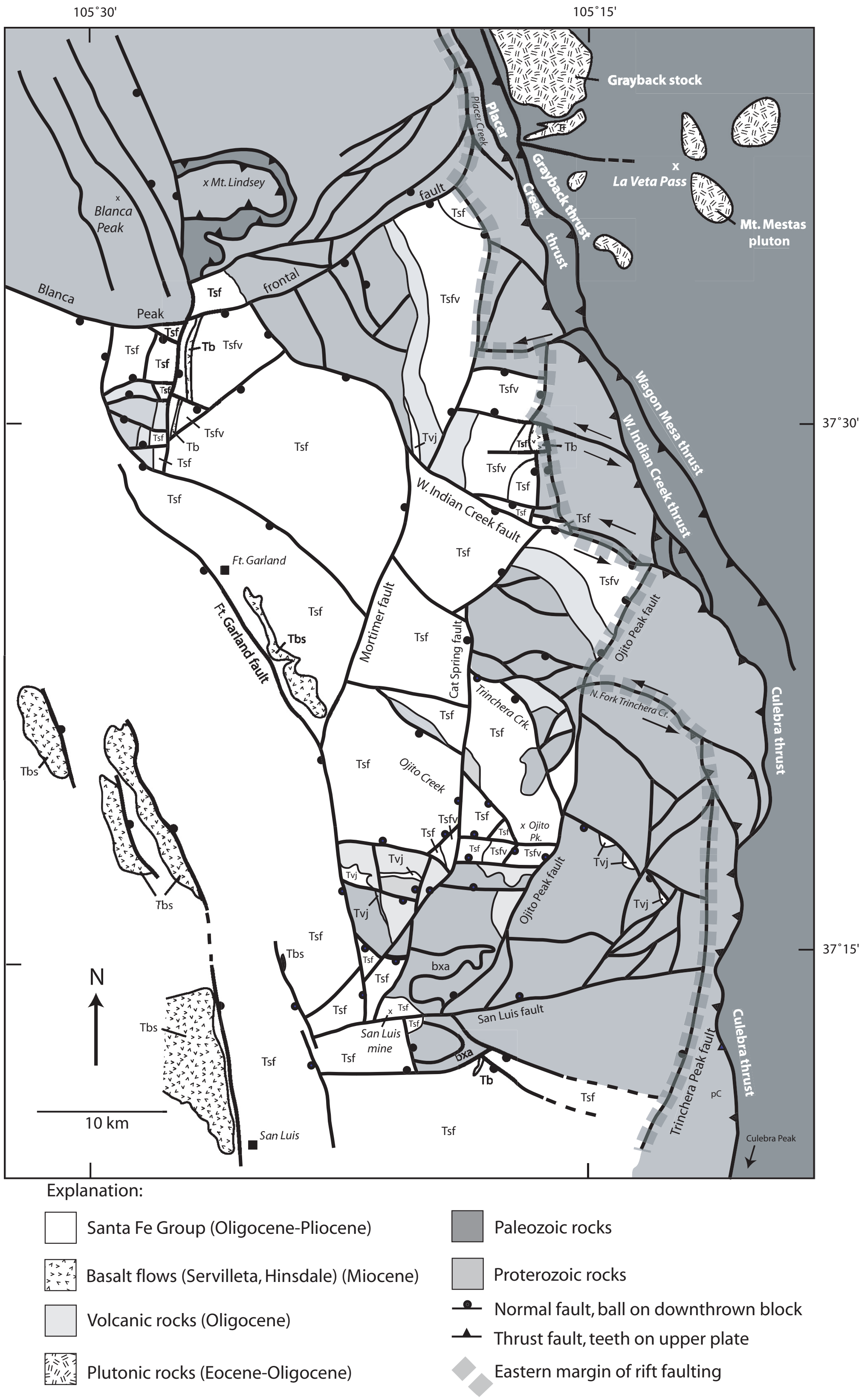

FIGURE 2. Geologic map of the Culebra Range and Blanca Peak horsts and adjoining grabens. Arrows show relative movement along tear faults. The stratigraphic section is shown in Figure 3. Tvj, Vallejo Formation (Eocene); Tsfv, volcanic clast-rich member of Santa Fe Group; Tb, Hinsdale Formation basalt (Miocene); Tbs, Servilleta Formation basalt (late Miocene-Pliocene); bxa, breccia unit; Quaternary units are not shown. Geology from Wallace (1996), Wallace and Lindsey (1996), Wallace and Soulliere (1996), Wallace (1997a, b), Lindsey (1995), Johnson and Bruce (1991), and A. Wallace, unpubl. mapping (1992-95).

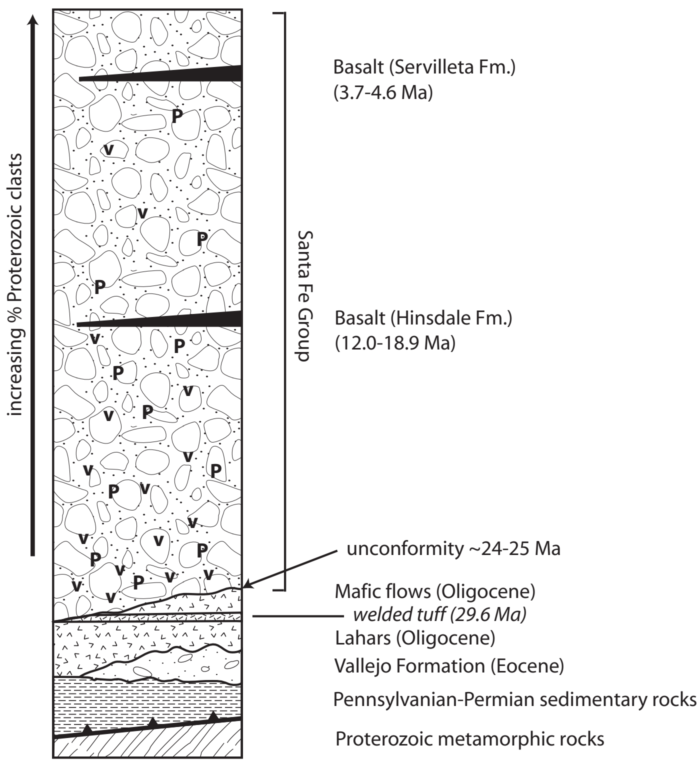

FIGURE 3. Generalized stratigraphy of the western Culebra Range. "P" and "v" show distributions of Paleozoic and volcanic clasts, respectively, in Santa Fe Group section. The unconformity between pre-rift and rift-related units formed between 27 and 25 Ma.

which were emplaced between 29.3 and 31.1 Ma (Miggins et al., 2002).

Late Oligocene and early Miocene intrusive rocks are exposed near the crest of and east of the Culebra Range. These include subvolcanic plutons in the vicinity of La Veta Pass and multiphase volcanic necks and related dikes of the Spanish Peaks intrusive complex (Figs. 2, 4). The Mt. Mestas plutonic complex east of La Veta Pass was emplaced at 25.01±0.05 Ma (Miggins et al., 2000), and the East and West Spanish Peaks intrusions were emplaced at 23.21±0.06 and 24.6±0.1 Ma, respectively (Penn et al., 1992). Small plutons related to the Mt. Mestas complex are exposed west of La Veta Pass and cut the late Eocene Grayback stock (Fig. 2; Wallace, 1997b; D. Miggins, unpubl. data, 2003).

Pre-rift Structures

Early Proterozoic rocks have a predominantly northeast-striking foliation that is common to both the Culebra Range and Blanca Peak area, despite the pronounced lithologic differences between the two areas. Isoclinal, bedding-parallel folds are common at the outcrop scale, and a few large-amplitude, open folds trend north-northwest.

As exposed in the core of the Culebra Range, five east- to northeast-directed thrust sheets were emplaced during the Late Cretaceous-Paleocene Laramide orogeny (Lindsey, 1998; Wallace, 1997b). These include the Placer Creek, Grayback, West Indian Creek, Wagon Mesa, and Culebra thrust faults (Fig. 2). In addition, remnants of two thrust sheets are exposed east of the crest of Blanca Peak (Johnson and Bruce, 1991; A. Wallace, unpubl. mapping, 1995), and multiple thrust sheets are exposed extensively in the Sangre de Cristo Mountains north of Blanca Peak (Lindsey et al., 1986). Thrusting typically carried Proterozoic or Paleozoic rocks over Paleozoic and Mesozoic rocks, with less-common Paleozoic over Proterozoic thrust relations. Almost all exposed Paleozoic-Proterozoic contacts in the study area are thrust faults (Fig. 2; Lindsey, 1995; Wallace and Lindsey, 1996; Wallace, 1997b). Thrusting produced complex fold, thrust, back-thrust, and tear fault patterns that are very evident in the Paleozoic rocks, and many of the exposed thrust faults and related structures extended into and involved the Proterozoic basement.

The thrust sheets were emplaced sequentially, and west-north-west-striking tear faults formed between adjacent thrust sheets. The Sangre de Cristo Creek fault is related to the West Indian Creek and possibly Wagon Mesa thrusts, and the West Indian Creek fault is related to the Culebra thrust (Fig. 2). Two other possible tear faults, such the Trinchera Creek fault, are within the Culebra thrust plate and may indicate thrust subdomains within the plate. The geometries of these tear faults at depth is unknown. As described below, segments of these faults were reactivated during late Tertiary rifting.

PRE-SANTA FE UNCONFORMITY

The variable preservation of pre-Santa Fe units, coupled with several exposed unconformities at the base of the Santa Fe, indicate variable relief and pre-Santa Fe erosion. Santa Fe sediments were deposited on Proterozoic basement, the Vallejo Formation, and Oligocene volcanic rocks (Fig. 2). The absence of the Vallejo in many places may be due to erosion at one or more times, local non-deposition, or both. The coarse interbedded lahars of the volcanic sequence indicate significant primary relief shortly before Santa Fe sedimentation. Non-deposition or deposition only in topographic lows may explain the erratic absence of the Oligocene volcanic flow rocks, but the absence in many places of the multiple, presumably widespread air-fall and ash-flow tuffs in the upper half of the sequence argues for some post-volcanic erosion. In the West Indian Creek area (Fig. 2), an erosional unconformity with more than a hundred meters of relief separates the basal Santa Fe sediments from the underlying volcanic rocks. In the Ojito Peak area, basal Santa Fe sediments deposited on Proterozoic rocks contain abundant volcanic clasts derived from volcanic exposures just to the south (Figs. 2, 6), suggesting an early volcanic upland that was shedding debris to a site of early Santa Fe sedimentation. Although Santa Fe Group sediments have admittedly poor exposures, beds near the base of the Santa Fe appear to have the same dip as the immediately underlying volcanic rocks, indicating that older units were not tilted prior to Santa Fe sedimentation.

SANTA FE GROUP

The Santa Fe Group, as presently exposed, consists of coarse- to fine-grained clastic sediments that were deposited in the middle and distal alluvial fan and alluvial slope environments. Coarse proximal fan deposits are preserved locally. The sediments were derived from the Culebra Range to the east and carried onto coalescing alluvial fans and the flats of the broad San Luis basin to the west (Fig. 1). Most sediments of the proximal fan facies, which likely extended farther east, were stripped away during rift-related faulting and uplift of the Culebra Range.

General Characteristics

Sedimentary rocks of the Santa Fe Group exhibit a wide range of bedding features and clast size and composition. The majority of the beds are tan, massive, poorly sorted pebble to cobble conglomerate with interbedded sandstone and siltstone. Clasts are subrounded to subangular and typically range in size from silt and clay to cobbles; boulders are present locally. The overall clast size decreases to the west, with some variations as described below. Although faulting disrupted the stratigraphic section, no systematic vertical change in clast size is readily apparent in any particular fault-block section.

Bedding typically is planar, with broad, shallow channels that grade laterally into planar beds. These channels contain alternating beds of pebble-rich coarse sand and poorly sorted conglomerates, and graded bedding and cross-stratification locally are common. Other conglomerate-filled channels are narrower and deeper, and they were cut into finer-grained sediments. The fine-grained distal-fan deposits are so poorly exposed that no sedimentary structures are apparent. Extremely coarse debris flow deposits, with boulders up to 3 m in diameter, overlie tilted finer-grained Santa Fe sediments north of West Indian Creek (Fig. 2). The huge boulders suggest both a high-energy depositional environment and closer proximity to the source, and the incision into tilted Santa Fe beds indicates that these debris flows represent very young parts of the Santa Fe.

The Santa Fe within individual fault blocks is as thick as 1500 m, and gravity data indicate that the depth to basement in the distal-fan depocenter south of Fort Garland exceeds 2500 m (Keller et al., 1984). The total thickness of the Santa Fe is unknown due to fault-related repetition and disruption of all sections. Marker beds are not apparent, and contacts with underlying units that would allow structural reconstruction are not exposed in many fault blocks. Similarly, faulting and uplift-related erosion dismembered the original alluvial fans and obscured evidence of thickening towards the basin.

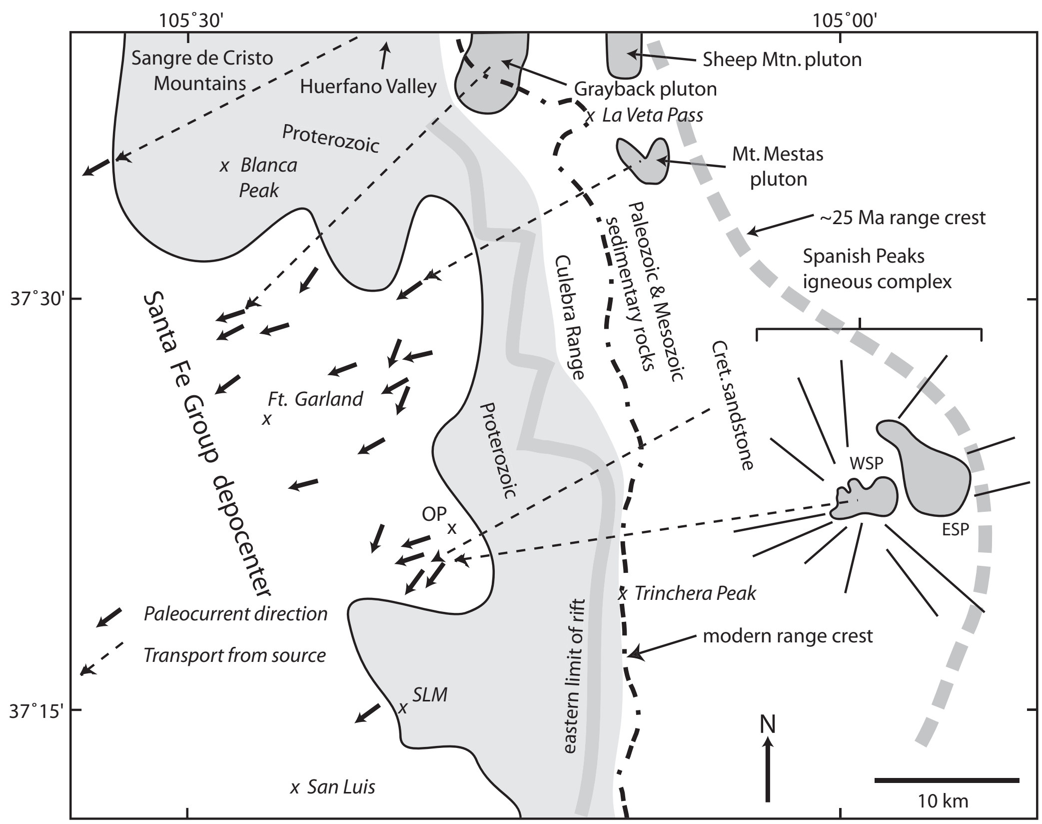

FIGURE 4. Paleotopographic features and paleocurrent directions from clast imbrications in Santa Fe Group sediments. Dashed arrows connect lithologically unique, site-specific sources and sites of deposition. Cretaceous source rocks are exposed only along the east flank of the Culebra Range, but sources are not otherwise site specific. The solid, wide shaded line is the eastern limit of rift-related normal faulting in Culebra Range; the shaded area shows Proterozoic rocks; the unshaded area to the east is Paleozoic and Mesozoic sedimentary rocks (see Fig. 2). The modern range crest of the Culebra Range is shown with a dot-dash line; the range crest at ~25 Ma is shown as a dashed, wide shaded line. ESP, East Spanish Peak; WSP, West Spanish Peak; OP, Ojito Peak; SLM, San Luis mine.

Source Areas and Paleocurrent Directions

Clasts in the Santa Fe Group were derived from Proterozoic and Paleozoic rocks exposed in the Culebra Range, and from Mesozoic sedimentary rocks and Tertiary igneous rocks east of the modern range crest (Figs. 2, 4). Imbricate clasts indicate transport principally to the southwest. Some source-area lithologies are very distinctive and site specific, and clasts in the Santa Fe that were derived from these sources provide unique connections between sources and the site of deposition (Fig. 4). Clasts derived from the distinctive basement units in the Blanca Peak area are notably absent, even in sediments that overlie a 3.66±0.03 Ma intra-Santa Fe basalt flow near Ft. Garland.

Northeast of Fort Garland, clast composition and percentages systematically change upward in the section (Fig. 3). Clasts near the base of the Santa Fe section are composed principally of Tertiary volcanic clasts and Paleozoic rocks, and Proterozoic clasts are absent. Volcanic and Paleozoic clasts decrease in abundance upward as Proterozoic clasts, which eventually comprise the only clast lithology, become more abundant. Wallace (1995) described a "volcanic conglomerate" at the base of the Santa Fe section, but further studies show that it is part of the overall Santa Fe sequence and is not restricted to the base of the section in all locations. The volcanic clasts in this area were derived largely from the large 25.01±0.05 Ma Mt. Mestas and Sheep Mountain igneous centers east of La Veta Pass (Fig. 4; Miggins et al., 2000). The Paleozoic clasts largely are from arkose and siltstone beds in the Madera Formation, with sparse clasts of Madera limestones and Sangre de Cristo Formation redbeds. The Proterozoic clasts are composed primarily of gneisses that are exposed only on the western side of the modern Culebra Range. Therefore, clasts deposited early came from sources far to the east, and later clasts were derived from more proximal sources (Fig. 4). This clast stratigraphy is the inverse of the volcanic and sedimentary stratigraphy exposed in the Culebra Range.

The clasts compositions are more variable in the Ojito Peak and San Luis mine areas (Fig. 2). Proterozoic clasts are common throughout the section, including the base. Locally derived volcanic clasts are present locally at the base of the Santa Fe near exposed volcanic rocks (see previous section). Volcanic clasts derived from the Spanish Peaks area (Fig. 4) form thick beds, several meters to several hundred meters thick, within Proterozoic-rich Santa Fe sediments, and channels filled with volcanic clasts were cut into the Proterozoic-rich facies. The volcanic-rich facies is notably coarser grained than the enclosing Proterozoic-rich beds, indicating both a change in source area and an increase in stream energy. Clasts of Paleozoic rocks and some Cretaceous sandstones, the latter derived from sources east of the modern Culebra Range, are most abundant in these volcanic-rich beds but are present throughout the section.

Based upon the general absence of coarser, proximal-fan sediments in the Santa Fe Group, the original alluvial fans likely extended somewhat farther east. During the uplift of the range discussed later, fan heads likely were stripped from the rising horst and the sediments redeposited to the west. The effect of sediment reworking and redeposition on the litho-stratigraphy of the basin sediments is unknown. Near Ojito Peak, coarse volcanic-rich beds and channels may represent reworked proximal fan materials. In the northern part of the basin, however, the consistent upward increase in Proterozoic clasts and decrease in volcanic clasts argues against major contributions from reworked fan heads that would have had significant amounts of volcanic clasts.

Santa Fe sediments exposed at Urracca Creek at the western base of Blanca Peak (Fig. 1) contain abundant clasts that are similar to volcanic rocks exposed in the upper Huerfano River Valley east of Blanca Peak (Fig. 4). Clast imbrications indicate a southwestward transport direction, consistent with the locations of the source and depositional sites. Alternatively, Brister and Gries (1994) concluded that the volcanic clasts were derived from the San Juan Mountains to the west, and that they were carried to the Urracca Creek area by a south-flowing stream. None of the Proterozoic or Cambrian units exposed in the Blanca Peak area to the east, and only a trivial amount (<1% total clasts) of Paleozoic rocks, are represented in the Santa Fe sediments at Urracca Creek. If the volcanic clasts were derived from the Huerfano River Valley, then this absence indicates that, at least during this undated phase of Santa Fe sedimentation, Blanca Peak was not a highland, it did not contribute sediments to this depositional site, and streams were able to traverse that area unimpeded.

INTRA-SANTA FE VOLCANIC ROCKS

Two suites of mafic volcanic rocks are interbedded with sediments of the Santa Fe Group, and their ages constrain the timing of sedimentation and tectonic activity. The oldest volcanic rocks are basaltic andesite flows. In the north part of the Culebra reentrant, a single flow fed by a northwest-striking, 18.86±0.01 Ma dike is conformable within the Santa Fe near the middle of the Santa Fe section (Table 1; Wallace, 1996). Another flow at approximately the same stratigraphic interval is exposed north of Ft. Garland (Wallace, 1997a), and several small, undated flows within or at the base of the Santa Fe are exposed south of the San Luis mine (Wallace and Soulliere, 1996; A. Wallace, unpubl. mapping, 1995). Other middle Miocene, intra-Santa Fe mafic flows are exposed elsewhere in the eastern San Luis basin, where they have been included in the Hinsdale Formation (Lipman and Mehnert, 1975; Thompson and Machette, 1989; Miggins et al., 2002; R. Kirkham, personal commun., 2003).

The younger volcanic rocks within the Santa Fe Group are tholeiitic basalt flows southeast of Fort Garland and on San Pedro Mesa near San Luis. The Fort Garland flows were erupted at 3.66±0.03 Ma, and the San Pedro Mesa flows formed at 4.59±0.02 Ma (Table 1; Wallace, 1997a; Miggins et al., 2002). Thompson and Machette (1989) included the latter flows in the Servilleta Formation, which includes late Miocene and Pliocene basalt flows that are interbedded with rift-related sedimentary rocks.

RIFT-RELATED FAULTS

Miocene and younger high-angle normal faults cut the western side of the Culebra horst and the southern margin of Blanca Peak horst. In addition, some evidence suggests late Oligocene low-angle normal faulting along both ranges. The faults along the west flank of the Culebra horst were responsible for the uplift of that area; those on the west, south, and east sides of the Blanca Peak horst caused uplift of that massif (Fig. 2). Possible northwestward continuations of Culebra-related faults traverse the Blanca Peak area and both cut and are cut by Blanca Peak-related faults.

Early Low-angle Faults

Generally west-dipping, low-angle normal faults are exposed along the west flanks of the Sangre de Cristo Mountains and Culebra Range (Jones, 1991; Benson, 1997). At the San Luis gold mine northeast of San Luis (Fig. 2), hydrothermal fluids ponded beneath one of the fault zones to form the ~22 Ma gold deposit (Benson, 1997; Benson and Jones, 1990). Kinematic indicators suggests that the latest movement was normal and to the south-southeast (Benson, 1997). In the mine area, Santa Fe sediments and Hinsdale mafic flows were deposited with angular unconformity on the breccia zone. High-angle, rift-related normal faults truncated the breccia zone and tilted Oligocene volcanic and Miocene sedimentary units in the same fault block (Wallace and Soulliere, 1996).

Based upon the age and origin of the San Luis gold deposit (Benson, 1997), the low-angle breccia zone at the mine was present by 22 Ma, but there is no upper age limit for the structure. Benson (1997) and Jones (1991) concluded that the structure represented a detachment fault related to early rifting along this segment of the Rio Grande rift. Alternatively, the structure may have had a Laramide origin with or without subsequent reactivation, and later high-angle faults may have tilted the fault block by an unknown amount to its present orientation (Wallace and Soulliere, 1996), similar to many other tilted fault blocks in the area as described below. Due to the very limited exposures of this structure in the study area, this feature is not discussed further.

Culebra Range Faults

Northeast- and west- to northwest-striking, high-angle faults dominate the structural fabric along the Culebra Range. These faults cut rocks ranging in age from Proterozoic to less than 3.7 Ma, and the absence of fanning of dips in the Santa Fe Group indicates that faults that cut those sedimentary rocks were active after sedimentation, which continued to at least 3.7 Ma near Ft. Garland.

A west-stepping set of north- to northeast-striking faults defines the eastern limit of late Cenozoic faulting in the Culebra Range (Fig. 5). This fault set traverses the entire study area, roughly following the crest of the Culebra Range (Fig. 4), and it continues farther south towards the Colorado-New Mexico border. Post-Laramide faults are absent east of and rift-related faults are abundant west of that fault set (Lindsey, 1995; Wallace and Lindsey, 1996; Wallace, 1996, 1997b; Vine, 1974). Faults in this system closely parallel the nearby traces of Laramide thrust faults and, in places, reactivated Laramide tear faults.

Northeast-striking faults define continuous northeast-trending fault-block domains east of the Mortimer fault (Figs. 2, 5).

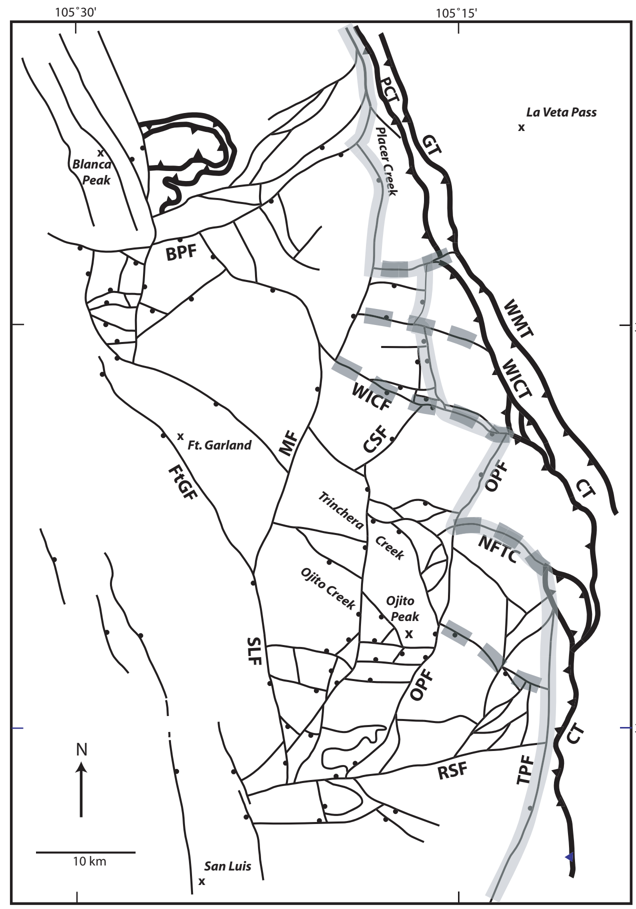

FIGURE 5. Thrust, tear, and rift-related faults in the Culebra Range and Blanca Peak areas. Same area and fault locations as shown in figure 2. Thrust faults are shown as hachured dark lines; tear faults with heavy dashed gray lines; and rift-related faults with thinner dark lines, with ball on downthrown side. The eastern limit of rift-related faulting is shown by the solid gray line. Thrust faults: CT, Culebra thrust; GT, Grayback thrust; PCT, Placer Creek thrust; WICT, West Indian Creek thrust; WMT, Wagon Mesa thrust. Major domain-bounding rift-related faults: BPF, Blanca Peak border fault; CSF, Cat Spring fault; FtGF, Ft. Garland fault; MF, Mortimer fault; NFTC, N. Fork Trinchera Creek fault; OPF, Ojito Peak fault; RSF, Rito Seco fault; SLF, San Luis fault.

Movement along these faults consistently was down to the west, forming a west-descending staircase of elongate fault blocks. The amount of dip-slip movement along some faults was as much as 1500 m, and the elevation difference from Mt. Mestas, an early Santa Fe source area, to the base of the Santa Fe basin near Ft. Garland (Keller et al., 1984) is about 4600 m. West- to west-northwest-striking faults internally cut each northeast-trending domain but largely do not extend into adjacent domains. In the northern part of the study area, movement along these internal faults was predominantly down to the south, whereas movement along faults farther south was more commonly down to the north, creating a structural low in the general area of Ojito Creek (Fig. 5). Faulting tilted the strata in each domain, involving rocks as old as Proterozoic. The predominant dip is to the east and northeast and ranges from less than 10° to more than 70°. However, opposing dips in adjacent internal fault blocks is common, such as in the Ojito Peak-San Luis mine area and near West Indian Creek (Fig. 2).

The West Indian Creek fault is the most extensive of the west- and northwest-striking faults. It extends from the upper reaches of West Indian Creek in the Culebra Range to the base of Blanca Peak, where normal faults related to uplift of the Blanca Peak area apparently terminate or offset the fault (Fig. 5). No northeast-striking faults cross or cut the West Indian Creek fault, which effectively created northern and southern fault domains within the Culebra reentrant (Figs. 2, 5). In the Culebra Range, the fault originally formed as a Laramide tear fault between the Culebra and West Indian Creek thrust plates (Fig. 2; Lindsey, 1995, 1998; Wallace, 1996). West of its intersection with the Ojito Peak fault (Fig. 5), the tear fault was reactivated with as much as 2000 m of down-to-the-south, post-Santa Fe normal apparent movement, based upon offset of Tertiary units (Fig. 2; Wallace, 1996). How much, if any, late Cenozoic strike-slip faulting took place along this fault is unknown.

Other west-northwest-striking Laramide tear faults were reactivated during rifting. These include the tear fault between the West Indian Creek and Placer Creek thrust plates, an internal tear fault within the West Indian Creek plate, and a tear fault within the Culebra plate along N. Fork Trinchera Creek (Fig. 5). Like the West Indian Creek fault, these faults have normal apparent movement where they offset the Oligocene and Miocene rocks. In addition, remnants of the Vallejo Formation are preserved along a northwest-striking fault in Proterozoic rocks east of Ojito Peak (Fig. 2), indicating post-Eocene movement within the crystalline core of the range. The many normal faults that are internal to the northeast-trending fault domains have strikes and apparent normal offset similar to those along the reactivated tear faults, and the faults cut the Santa Fe. These relations suggest that northwest-striking Laramide faults may extend beneath basin-filling sediments and were reactivated during rift-related faulting.

The general truncation of the west- to northwest-striking faults by the northeast-striking faults suggests that the latter faults are the younger of the two sets, with a possible westward and northward migration of fault development. This assumes purely dip-slip movement on the faults based on bedding strikes and tilt axes parallel to the strikes of the faults. However, marker beds or piercing points that could indicate true offset are absent, so a strike-slip component of movement is possible. Such movement, even if small compared to the much larger dip-slip component, could have produced the apparent fault truncations. Given that some northeast-striking faults bend and merge into northwest-striking faults, the two sets could have had contemporaneous movement or overlapped in time to some degree.

Blanca Peak Area Faults

Laterally continuous and broadly arcuate normal faults form the southern and southeastern boundaries of the Blanca Peak horst (Figs. 2, 5). These faults have a general down-to-the-south or -southeast apparent displacement, based on offset of units and Quaternary dip-slip movement along some of the faults. Total displacement along this fault set was at least 4600 m, based upon the elevation difference between the Proterozoic rocks at the crests of Blanca Peak and Mt. Lindsey and the base of the Santa Fe depocenter near Fort Garland (Keller et al., 1984). This assumes that the Blanca Peak horst largely formed after Santa Fe sedimentation, on the basis of the clast lithologies at Urracca Creek described earlier and the absence of Blanca Peak lithologies in Santa Fe sediments overlying the 3.7 Ma Servilleta flow units near Ft. Garland.

The arcuate faults along the southern and southeastern flanks of the Blanca Peak horst parallel the compositional layering in the Proterozoic basement. The dramatic change in Proterozoic lithologies across this fault zone suggests that these late Tertiary faults may have reactivated a Proterozoic fault or suture zone that originally juxtaposed two contrasting basement terranes. East of Blanca Peak, the faults bend sharply north at Placer Creek and are parallel to but do not cut the nearby north-northwest-striking Placer Creek thrust fault (Fig. 2). Although the north-striking normal faults along Placer Creek are within 500 m of the thrust fault, they are entirely within Proterozoic rocks, so a direct Laramide influence on this sharp bend cannot be confirmed. The easternmost of these normal faults forms the eastern limit of rift-related faulting in that area, merging with the Culebra fault set extending from the south (Fig. 5)

North-northwest-striking, high-angle normal faults are internal to and traverse the Blanca Peak horst (Figs. 2, 5; Johnson and Bruce, 1991; A. Wallace, unpubl. mapping, 1995). Early Paleozoic mafic dikes fill a few of these faults, indicating at least an early Paleozoic ancestry (Johnson and Bruce, 1991). However, at least two major faults offset Laramide thrust faults near the range crest and a small area of Santa Fe sedimentary rocks on the southern base of the mountain (Fig. 2), indicating latest movement after Santa Fe sedimentation. These two faults merge southward, truncate an inner Blanca Peak-related fault, very slightly offset the “outermost” Blanca Peak-related fault, and then continue south through the Santa Fe (Fig. 5).

In the area bounded by the Mortimer, West Indian Creek, Blanca Peak, and Ft. Garland faults (Fig. 5), northwest and north-striking faults, including the post-Santa Fe fault extending south from Blanca Peak, cut east-striking faults. For the most part, however, tilts on both volcanic and Santa Fe units in the area are to the east, similar to relations along the Culebra Range, and the east-striking faults cut and segment these tilted blocks. The combined relations suggest that initial movement along and tilting related to the northwest- and north-striking faults preceded movement along the east-striking faults, and that continued or renewed offset of the northwest to north faults produced the final cross-cutting relations. One or more faults in this area tilted 3.7 Ma Servilleta basalt flows, and several faults between Ft. Garland and the base of Blanca Peak have Quaternary offset (Colman et al., 1985). Thus, this area has experienced significant fault movement since the Pliocene, although how much faulting took place before then is unknown.

EVOLUTION OF THE RIFT MARGIN

The Culebra and Blanca Peak horsts and adjacent Culebra graben developed in two somewhat overlapping stages. During the first stage, alluvial fans formed along the west side of a slowly rising Culebra horst, with probable sedimentation across the future site of the Blanca Peak horst. During the second stage, numerous faults dissected the alluvial fans and formed the Culebra horst. Late in this stage, but overlapping in time with uplift of the Culebra horst, the Blanca Peak horst was uplifted at the south end of the Sangre de Cristo Mountains.

Stage I: Sedimentation and Early Uplift

Rifting in the Culebra reentrant area began after the eruption of the middle Oligocene volcanics. The youngest dated pre-rift units in the area include the 29.6±0.1 Ma welded tuff in the middle of the volcanic sequence on the west side of the Culebra Range (Wallace, 1996) and 27.7±0.3 Ma and older flows and dikes in the San Luis Hills (Table 1; Thompson and Machette, 1989; R. Thompson, oral commun., 1995). The 25.01±0.05 Ma Mt. Mestas and Sheep Mountain igneous centers (Fig. 2; Miggins et al., 2000) contributed clasts to the basal Santa Fe sediments just east of Ft. Garland, and the East and West Spanish Peaks igneous centers, which formed at 23.21±0.06 and 24.6±0.1 Ma, respectively (Table 1; Penn et al., 1992), provided clasts to the Ojito Peak area; these sources give a maximum age for sedimentation in those areas. Therefore, rift activity and the formation of early Santa Fe depocenters began at about 24-25 Ma. Near the New Mexico border, and in part including the Culebra reentrant, sedimentation began shortly before (in places shortly after) the eruption of the 24.96±0.11 Ma Amalia Tuff (Miggins et al., 2002). These ages are consistent with rift inception elsewhere along the Rio Grande rift (Chapin, 1988; Ingersoll et al., 1990; Chapin and Cather, 1994).

Early sediments derived from Tertiary volcanic and Paleozoic sedimentary sources east of the modern range crest were shed southwestward into alluvial fans, which now comprise the Santa Fe Group. The early sediments in the northern fans were derived from volcanic edifices and Paleozoic rocks exposed some 20 km east of the depocenter (Fig. 4). Although only medial- and distal-fan environments were preserved, the alluvial fans likely extended somewhat farther east, although not necessarily all the way to the source rocks. The westward transport required a 25 Ma highland of unknown height to the east and a decrease in elevation to the west towards the base of the alluvial fans. Based upon the locations of specific source rocks for clasts in the alluvial fans, the crest of this early highland may have been as much as 25 km east of the modern range crest.

Between the start of rifting at about 25 Ma and the 18.9 Ma eruption of intra-Santa Fe Hinsdale flows, the original source rocks far to the east contributed progressively fewer clasts to the alluvial system. At the same time, Paleozoic and underlying Proterozoic rocks, which were exposed west of the volcanic sources, contributed progressively more clasts. Thus, the range crest apparently migrated westward and the highland gained elevation during sedimentation, thereby limiting and eventually blocking clast transport from the more easterly sources and inducing downcutting into deeper rocks west of the drainage divide. By 18.9 Ma, most of the clasts deposited in the alluvial fans were derived from Proterozoic source rocks, all of which are west of the modern range crest and thus relatively closer to the fans. The clast lithologies and the locations of their sources indicates that the drainage divide at and after 18.9 Ma was approximately along or near the Proterozoic-Paleozoic contact on the west side of the Culebra Range, and structural evidence shows that the eastern limit of rift-related faulting is just west of and parallel to this contact (Fig. 2).

In the Ojito Peak area (Fig. 2), Proterozoic, Paleozoic, and volcanic clasts are common throughout the exposed section, both in the same beds and in beds rich in one or two lithologies. Unlike to the north, streams that fed early sediments to this area had incised into the Proterozoic basement while carrying clasts derived from Paleozoic, Mesozoic, and Tertiary sources farther to the east. Overall, though, clasts of Proterozoic rocks become dominant in the upper parts of the section, indicating that more easterly sources eventually were isolated from the drainage system. Volcanic clasts are absent and Paleozoic clasts are much less abundant in the vicinity of the San Luis mine (Fig. 2). Their absence or scarcity may indicate that streams that fed that area did not extend very far to the east, or that sedimentation in that area began after the more easterly sources were eliminated, possibly suggesting that it was a low-relief topographic high that did not receive early sediments.

Alluvial-fan sedimentation continued, but at an unknown rate, into the Pliocene, based upon the 3.7 and 4.3 Ma ages of intra-Santa Fe Servilleta basalt flows near Fort Garland and San Luis, respectively.

Stage II: Major faulting and Horst Development

Most of the Santa Fe sediments are exposed west of the Culebra Range, but changes in clast lithologies in sediments, especially in the northern part of the depocenter, indicate that uplift in the Culebra Range began between 25 and 18.9 Ma. The easternmost rift-related faults (Fig. 5) must have been responsible for this uplift, given that faults to west did not become active until after sedimentation, as described below. Both the elimination of eastern clast sources from west-draining streams and the progressive downcutting on the west side of the developing horst indicate that movement along the fault zone may have created an east-dipping monocline that cut off west-flowing streams and accelerated downcutting on the steeper west side. On the basis of this geomorphic evidence, the west side of the Culebra horst rose in an absolute sense, as downdropping of the Santa Fe depocenter to the west may have caused the streams to cut headward and the drainage divide to migrate even farther to the east.

The apparent absence of fanning (decrease in dip higher in the section) in the Santa Fe, even in sections as thick as 1500 m, indicates that much of the observed fault-related tilting took place after deposition of the sediments. Near West Indian Creek, an 18.9 Ma intra-Santa Fe basalt flow and conformable sediments well above and below the flow were tilted 26º towards the range after deposition, indicating that faulting and rotation at that location did not commence until at least the middle Miocene. Farther west near Ft. Garland, conformable sediments and basalt flows were tilted 20º eastward after the 3.7 Ma eruption of the basalts. Coupled with the evidence of 25 to 18.9 Ma faulting to the east described above, these limited time-constrained relations suggest that faulting related to uplift of the Culebra horst may have migrated westward and was spread over multiple faults. However, major faulting throughout much of the Santa Fe depocenter apparently took place until after 3.7 Ma, indicating an early period of faulting to the east and a much later period along the faults to the west.

Laramide tear faults exerted a strong influence on the formation of the northwest-striking faults and likely the development of the fault patterns as a whole. In many places, the tear faults and rift-related faults appear to have been linked structurally. Elsewhere, the northeast-striking faults were the dominant structures. Those faults parallel the thrust faults, but no genetic relation can be inferred or established. The dominance of the West Indian Creek tear fault on rift-related faulting, especially how it both compartmentalized and merged with the northeast-striking fault domains, is notable and suggests contemporaneous movement.

Sedimentological evidence indicates that uplift of the Blanca Peak horst began substantially later than that of the Culebra horst. Fission track data from the summit of Blanca Peak indicate rapid uplift-related cooling between about 20 and 12 Ma (Kelley et al., 1992), and similar uplift dates (~19 Ma) were obtained in the Sangre de Cristo Range to the north (Lindsey et al., 1986). However, the Huerfano Valley-derived clasts and the absence of Blanca Peak-derived Proterozoic clasts in the Santa Fe at Urracca Creek argue against an intervening horst during southwestward clast transport. In addition, clasts derived from Blanca Peak are absent in all Santa Fe sediments south of the horst, including sediments as young as 3.7 Ma, although that could be a function of drainage directions. Enough uplift and cooling of the Blanca Peak horst may have taken place to produce the early Miocene fission track ages, but it did not affect surface processes and was not recorded in the sedimentary record until at least the Pliocene. It is clear, however, that Pliocene and younger faulting related to both the Culebra and Blanca Peak horsts overlapped both in space and time in the northern part of the Culebra embayment.

DISCUSSION

Regionally, many basins of the Rio Grande rift coincide with Laramide uplifts and Eocene grabens. Laramide arches formed during east- to east-northeast-directed thrusting (Erslev, 2001), and several rift basins, including the San Luis basin, formed parallel to and astride the Laramide arches (Kellogg, 1999). The faulted sides of the asymmetric rift basins generally coincide with the thrusted side of each Laramide uplift, and Kellogg (1999) postulated that the normal faults become listric and merge with the thrust faults at depth, as demonstrated in the Albuquerque basin (Russell and Snelson, 1994). North-striking, right-lateral faulting produced Eocene and early Oligocene sediment-filled basins in the southern Rocky Mountains, including the sites of future rift basins (Chapin and Cather, 1981; Erslev, 2001). The presence of the Eocene Vallejo Formation in the Culebra graben area may suggest related early Tertiary faulting in the area, although the limited exposures of the sediments preclude any definitive conclusions. Nevertheless, the San Luis basin, including the Culebra Range and graben, contains evidence of both Laramide and Eocene events that elsewhere influenced the formation of rift-related basins.

This study shows the strong influence of Laramide thrust-related faults on late Cenozoic rift-related faulting along the edge of the Culebra horst. In the Albuquerque basin in northern New Mexico, where the normal faults generally parallel the rift margin, Russell and Snelson (1994) used seismic data to show that rift-related listric faults merged with Laramide thrust faults at a depth of about 10 km. In the Alamosa graben, Kluth and Schaftenaar (1994) suggested that the listric faults there merged with a detachment fault at a depth of 16 km, but they did not call upon a Laramide precursor to that detachment. In the Culebra graben, the abundant normal faults are either parallel or oblique to the rift margin, and the subsurface intersections and geometries of this rift-related fault array and Laramide and older structures must be extremely complex. Absent any seismic data, it is impossible to determine if the rift-related normal faults sole into west-dipping Laramide thrust faults or possible rift-related detachment faults.

As described by Brister and Gries (1994) and Wallace (1995), the San Luis graben is composed of two east-facing half grabens, including the Alamosa graben to the north and the Culebra graben to the south (Fig. 6). Although rare, similar-facing paired half grabens have been reported from other rifts (Rosendahl, 1987), but this is the only known example along the Rio Grande rift. The two horst-graben systems had somewhat different sedimentological histories and structural geometries. In the eastern Alamosa graben, the presence of Proterozoic detritus throughout the section indicates that these source rocks were exposed throughout the basin history. In contrast, Proterozoic clasts in the Culebra graben did not become abundant until well after sedimentation began. The western side of the Sangre de Cristo horst has a relatively simple geometry, with a single or several closely spaced, down-to-the-west range-front faults that separate the east-dipping graben from the horst to the east (Kluth and Schaftenaar, 1994). This fault system continues southwestward from the southwest base of Blanca Peak across the San Luis basin, down-dropping the Alamosa graben relative to the Culebra graben (Fig. 6; Tweto, 1979; Brister and Gries, 1994). In contrast, multiple, widely spaced normal faults formed along the western margin of the Culebra horst. The reasons for the different styles of uplift are not obvious from relations seen in the study area, although the change from close-spaced to widely spaced faults appears to coincide with the Proterozoic lithologic boundary on the south side of the Blanca Peak horst. Minimum total offset along the Alamosa horst-graben fault system (approximately 8-9 km; Kluth and Schaftenaar, 1994) is significantly greater than that along the Culebra horst-graben system (approximately 5 km).

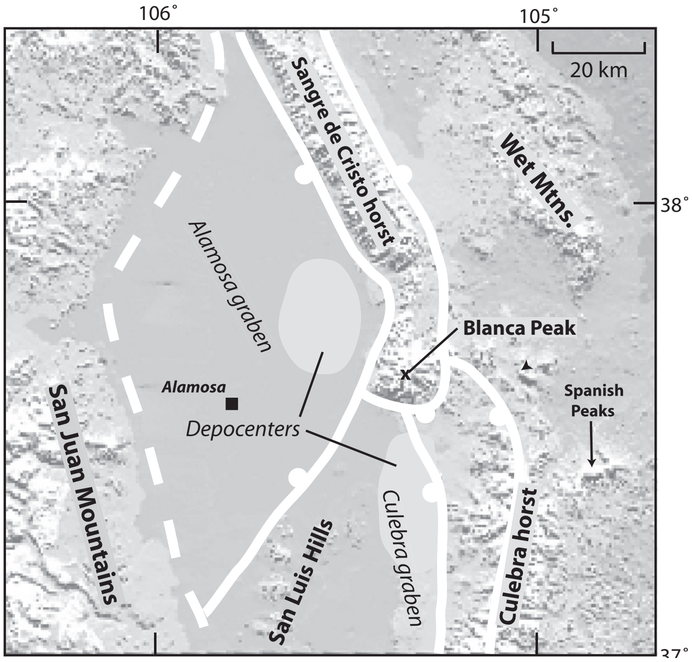

FIGURE 6. Shaded relief image of the San Luis basin, showing the structural relation between the Culebra and Alamosa half-grabens and the related Culebra Range and Sangre de Cristo Mountains horsts. Wide white lines are high-angle fault systems, with the ball on the downthrown side of the fault. The eastern white line in the Culebra Range represents the easternmost limit of rift-related faulting, and the western white line is the approximate western limit of significant faulting; numerous faults between these lines are shown in Figure 5. The wide dashed line on the west side of the San Luis basin is the passive hinge line for the two half-grabens. A, Alamosa; FG, Fort Garland; SL, San Luis. Santa Fe Group depocenters are from Keller et al. (1984). Modified from Wallace (1995).

Two lines of evidence hint that the Blanca Peak horst has been rotated clockwise about a vertical axis. First, as shown in Figure 6, the Blanca Peak horst trends markedly southwestward from the southeast-trending front of the Sangre de Cristo horst, deviating roughly at Mosca Pass. The main Sangre de Cristo front north of this deviation is in line with and parallels the Culebra fault system area. Second, the early Paleozoic diabase dikes in the Blanca Peak area strike north-northwest, compared to the northwest strike of the dikes in the Culebra Range. If these dikes are related to the early Paleozoic, northwest-trending rift system proposed by Larson et al. (1985) and reflected by northwest-striking dikes in the Gunnison region to the northwest (Hansen, 1971) and in the Culebra Range area, then the dikes in the Blanca Peak horst appear to have been rotated clockwise relative to other dikes in the system. The southern margin of the Blanca Peak horst, which contains the north-northwest-striking dikes, coincides with the Proterozoic lithologic boundary, which conjecturally may have had a stronger control on late Tertiary faulting events than is otherwise apparent. Therefore, the answer to the origin of the Culebra embayment in part may lie in the uplift history and controls of the Blanca Peak horst and its westward bulge into the San Luis basin, a topic that deserves further study.

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