An Overview of the Sangre de Cristo Fault System and New Insights to Interactions Between Quaternary Faults in the Northern Rio Grande Rift

By Cal Ruleman and Michael Machette

CHAPTER J

Abstract

On the basis of differences in geomorphic expression, we propose to subdivide the Sangre de Cristo fault system into three distinct parts: the northern Sangre de Cristo fault zone, the central Sangre de Cristo fault zone, and the southern Sangre de Cristo fault zone. In this report, we summarize evidence of Pliocene and Quaternary tectonic activity on these three fault zones as determined by previous studies and by our recent investigations along the Latir Peaks section of the southern Sangre de Cristo fault zone, which further indicates the interaction between two of the three parts. The 50–55 km long Latir Peaks section (in northernmost New Mexico) of this fault zone is characterized by a linear, precipitous range front that has sharp, basal, faceted spurs and scarps that vertically offset alluvium as much as 7.8 m. This study and previous investigations have quantified long-term (about 4 m.y.) slip rates of 0.1–0.2 mm/yr along this section of the southern Sangre de Cristo fault zone. Contrary to these neotectonic assessments, our recent surficial geologic mapping indicates probable late-middle to late Pleistocene vertical tectonic activity rates that are only one-half (0.06 mm/yr) of the previously reported long-term slip rates, suggesting that short-term (<100 k.y.) slip rates change within the long-term tectonic history, as appears to be the case for the northern Sangre de Cristo fault. In comparison, the central Sangre de Cristo fault zone in southern Colorado has a more subdued geomorphic expression than the northern and the southern Sangre de Cristo faults but a higher late Pleistocene slip rate (0.17 mm/yr). Thus, we propose that the foci of tectonic activity on the Sangre de Cristo fault system has shifted from the southern and northern parts of the fault system to the central part during the late Quaternary; before this shift, the ends of the fault system were more active than at present, as shown by their impressive topographic expression.

Introduction

The Sangre de Cristo fault system, which is the structure that bounds the eastern margin of the northern Rio Grande rift in the San Luis Basin, consists of a complex array of range-bounding, piedmont, and intrabasin faults (fig. J–1). This 250-km-long fault system extends from Poncha Pass, Colo., south to near Taos, N. Mex., and is composed of three discrete parts, herein described from north to south. Currently, the U.S. Geological Survey National Seismic Hazard maps divide this fault (that is, fault system) into two faults (that is, two zones): the northern Sangre de Cristo fault and the southern Sangre de Cristo fault, having potential rupture lengths of 185 km and 104 km, respectively (Haller and others, 2002). However, recent paleoseismic investigations, morphometric analyses of scarps and range-fronts, and mapping of geologic structures in the fault zone's footwall that could create asperities in the fault and that could truncate lateral propagation of individual Quaternary faulting events provides criteria for subdividing the fault system into three parts: the northern Sangre de Cristo fault zone, central Sangre de Cristo fault zone, and southern Sangre de Cristo fault zone.

As herein defined, the northern Sangre de Cristo fault zone extends about 104 km from Poncha Pass along the northeastern margin of the San Luis Valley, east of the Great Sand Dunes, to the southern flank of the Blanca Peak massif, a young structure whose uplift may have begun 5 Ma ago (Wallace, 2004). The central Sangre de Cristo fault zone extends about 60 km from the south flank of the Blanca Peak massif through Fort Garland, along the western margin of Culebra Range, and along the east side of the Culebra graben as far south as the northern border of New Mexico. The southern Sangre de Cristo fault zone extends about 96 km from southwest of San Luis, Colo. (where it overlaps the central portion of the fault zone), along the western side of San Pedro Mesa (see chapter B, stop B9) and the Sangre de Cristo Mountains of New Mexico, to southeast of Taos, N. Mex., near the small community of Talpa (Personius and Machette, 1984). Here, it merges with the northeast-trending Embudo fault zone. The following summary of tectonic activity along each part of the Sangre de Cristo fault system is based primarily on

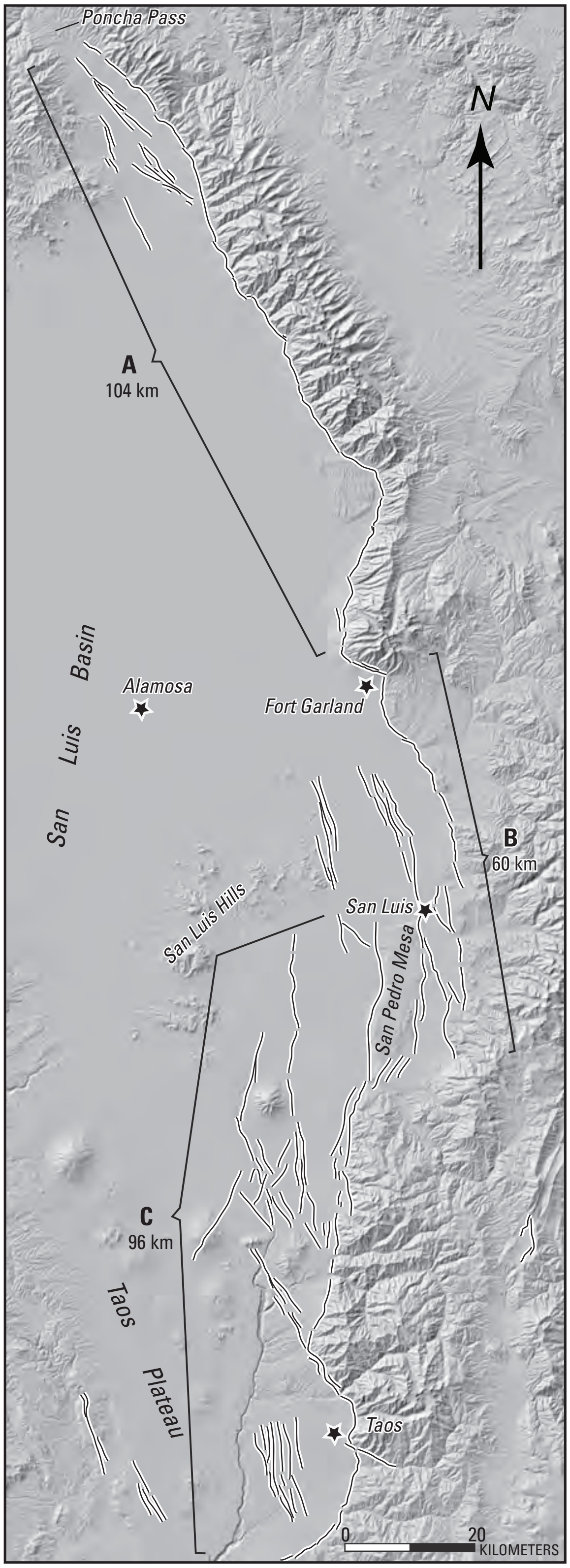

Figure J–1. Sangre de Cristo fault system and fault zone boundaries. Fault zone boundaries shown as follows: A, northern; B, central; C, southern. Fault traces modified from U.S. Geological Survey (2005) and Menges (1990).

modified information from the U.S. Geological Survey's Database of Quaternary faults and folds (U.S. Geological Survey, 2005; http://earthquake.usgs.gov/regional/qfaults/).

Northern Sangre de Cristo Fault Zone

The northern Sangre de Cristo fault zone is characterized by a precipitous, linear range front with well-developed basal faceted spurs, deeply incised canyons in the footwall, and geomorphically fresh fault scarps on late Pleistocene and Holocene deposits (McCalpin, 1982, 1986; Colman and others, 1985). In the San Luis Valley, the deepest part of the San Luis Basin coincides with the northern Sangre de Cristo fault zone (Gaca and Karig, 1965). The northern fault zone has been previously divided into four sections (fig. J–2) listed from north to south: the 19-km-long Villa Grove fault, the 8-km-long Mineral Hot Springs fault, the 80-km-long Crestone section, and the 26-km-long Zapata section (Widmann and others, 2002; USGS, 2005). Average single-event vertical displacements along the northern Sangre de Cristo fault zone range between 1.5 and 2.5 m, which suggest earthquakes having probable moment magnitudes (M_w) of 6.8–7.1 (U.S. Geological Survey, 2005).

The northern end of the northern Sangre de Cristo fault zone is marked by a dramatic narrowing of the San Luis Basin and a potentially active graben that has Quaternary displacement on both east- and west-dipping, basin-bounding faults, the Mineral Hot Springs fault on the west and Crestone section on the east of the fault zone, respectively. The northwest-trending, down-to-the-west Villa Grove fault consists of multiple fault strands that cut obliquely across the basin and connect the Mineral Hot Springs fault with the Crestone section of the northern Sangre de Cristo fault zone. This Villa Grove fault has predominantly southwest-facing scarps (synthetic to the Crestone section) on Pinedale (about 15 ka), Bull Lake (about 130 ka), and pre-Bull Lake equivalent deposits, the latter of which is offset by as much as 14 m (McCalpin, 1981). The Mineral Hot Springs fault has scarps on Bull Lake and Pinedale equivalent deposits (Colman and others, 1985; Kirkham and Rogers, 1981); however, the tectonic origin of these escarpments is uncertain (J.P. McCalpin, 1997, oral commun. cited on http://earthquake.usgs.gov/regional/qfaults/). On the basis of its apparent association with the northern Sangre de Cristo fault zone and the Mineral Hot Springs fault, we include the Villa Grove fault as part of the northern Sangre de Cristo fault zone. It seems probable that the 8-km-long Mineral Hot Springs fault and the 26-km-long Villa Grove fault could rupture coincidently with large events on the Crestone section.

For the northern Sangre de Cristo fault zone and general basin structure, Kellogg (1999) described a "perched basement wedge" of Precambrian metamorphic rocks in the footwall (fig. J–3), resulting from preexisting (Laramide) thrust faulting and Neogene normal faulting. Neogene extensional faulting utilizes preexisting thrust fault planes as reactivated normal

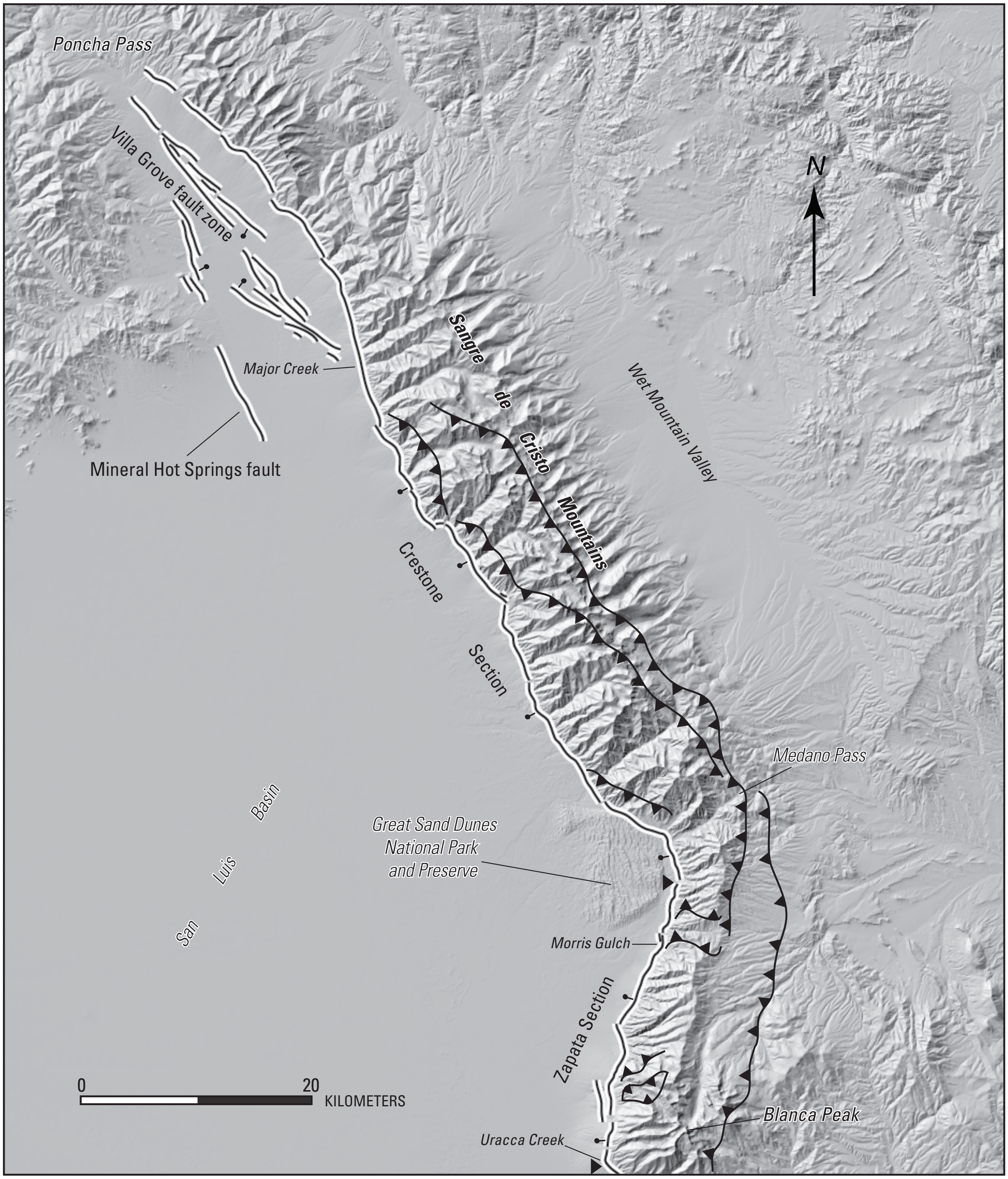

Figure J–2. Shaded relief map of the northern Sangre de Cristo fault zone, showing sections discussed in text. Highlighted black piedmont and intrabasin lines are Quaternary normal faults from the U.S. Geological Survey Quaternary fault and fold database; bar and ball symbol is on downthrown side. Lines with teeth are thrust faults from Tweto (1979). Changes in range-bounding normal fault trends coincide with Laramide thrust faults possibly reactivating thrust ramps as normal faults, creating a "perched basement wedge" (Kellog, 1998). The section boundaries between the Crestone and Zapata sections and the northern and southern fault zones near Great Sand Dunes National Park and Preserve and Urraca Creek are illustrated by a black triangle. Shaded relief map processed and created by Ted Brandt (USGS).

faults. The general geometry of faults developed in the hinge of a fault-propagated fold allows for subsidiary faults to sole into the main basin-bounding fault plane. With large events on the main fault, these subsidiary faults can be activated coseismically (for example, the 1959 Hebgen Lake event, where both the Red Canyon and Hebgen Lake faults were activated during one earthquake).

The Crestone section spans most of the northern Sangre de Cristo fault zone and is the main range-bounding fault from Poncha Pass to Great Sand Dunes National Park and Preserve (GSDNPP). In a trenching study at Major Creek, McCalpin (1986) indicates a surface-rupturing earthquake about 8 ka, a preceding event between 8 and 13 ka, and a still earlier event between 13 and 35 ka. Largely on the basis of surface offsets of Bull Lake and pre–Bull Lake–equivalent deposits, McCalpin also inferred three prior events between 35 ka and 140 ka and possibly 6 to 12 events between 140 ka and approximately 400 ka. From these data, he calculated slip rates that vary markedly during 100 k.y. intervals; three events took place in the last 35 ka and three other events during the preceding 100 ka (35–140 ka). His long-term (>100 k.y.) slip rates are roughly 0.1–0.2 mm/yr; short-term intervals (<100 k.y.) decrease or increase by approximately 50 percent. Such fluctuations in slip rate are well documented on other major Basin and Range faults, particularly the Wasatch fault zone in Utah (Machette and others, 1992).

The Zapata section extends south-southwestward from the Crestone section at the Great Sand Dunes National Park and Preserve, and it creates almost a 90° bend in the fault zone and a deep embayment in the range front. Older structures in the footwall of the fault apparently control the geometry of this embayment as mapped by Tweto (1979) and Bruce and Johnson (1991); preexisting thrust faults may have created asperities in the fault system that could arrest the propagation of fault ruptures. However, precise structural relations and controls on Quaternary normal faulting have not been determined.

Along the Zapata section, McCalpin (1982, 1986) mapped scarps on Pinedale-age deposits that are 4–7 m high, and trenching studies suggest two post-Pinedale surface-rupturing events (McCalpin, 1986, 2006). At Urraca Creek, McCalpin (1986) trenched a piedmont scarp approximately 1.2 km (0.75 mi) northwest of the range front and determined that the most recent event occurred between 5640±100 ^{14}C yr B.P. and 8 ka and produced approximately 2.0 m of vertical displacement. In a more recent study, McCalpin (2006) identified two post-Pinedale events at Morris Gulch of which the most recent event occurred between 5300 and 5500 ^{14}C yr B.P. He notes that the broad time constraints on the most recent event at these two locations allow these scarps to be contemporaneous; however, the potential 2–3 k.y. interval between the most recent events on the Crestone section (at Major Creek) and the Zapata section (at Urraca Creek and Morris Gulch) likely suggest a behavior of fault contagion and interaction, rather than contemporaneous coseismic displacement.

Central Sangre de Cristo Fault Zone

The northern end of the central Sangre de Cristo fault zone is marked by a major eastward step in the range at Blanca Peak. From here, the fault zone extends southward 59 km along the eastern side of the Culebra graben (fig. J–4) (Wallace, 2004; Kirkham and others, 2005) in an area named the Culebra reentrant by Upson (1939). Blanca Peak (14,345 ft), which is the highest peak of the Blanca massif, creates a major salient in the range and is bounded on the south by the 7-km-long Blanca section of the central Sangre de Cristo fault zone. Although it was originally included as a section of the northern Sangre de Cristo fault (Widmann, 2002; U.S. Geological Survey, 2005), we include the Blanca section with the central Sangre de Cristo fault zone on the basis of geomorphic, geometric, and structural data. McCalpin (1982, 1986) reported

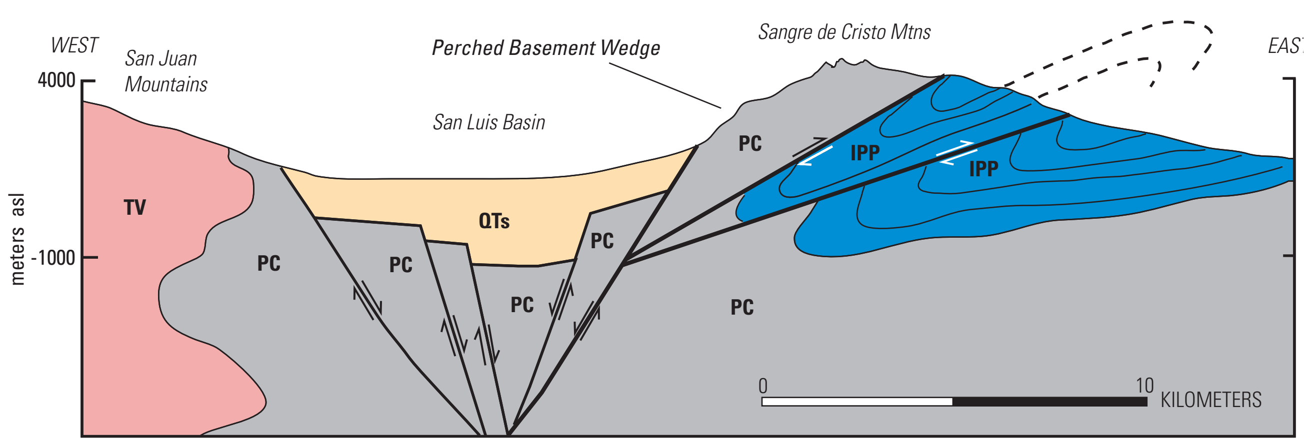

Figure J–3. Schematic cross section showing a perched basement wedge and relations between preexisting thrust faults and Cenozoic normal faults. Arrows indicate sense of motion on faults. Units as follows: PC, Precambrian crystalline rocks; PP, Pennsylvanian and Permian sedimentary rocks; Tv, Tertiary volcanic rocks; QTs, Tertiary and Quaternary basin fill.

that only one post-35 ka event has occurred on the Blanca section and, thus, only one-half of the events recognized along the adjacent northern Sangre de Cristo fault have occurred along this section. In addition, complex bedrock fault structures mapped in the footwall (A.R. Wallace, written commun., 2005) suggest that preexisting structures control the east-west-oriented Quaternary faulting on this section. It has yet to be determined if events on the Blanca section are associated with faulting on the San Luis section of the central Sangre de Cristo fault zone or on the northern Sangre de Cristo fault zone.

From the eastern end of the Blanca section, the San Luis section of the central Sangre de Cristo fault zone turns abruptly south and extends south-southeast through Fort Garland, where scarps of differing heights are formed on middle to latest Pleistocene alluvium. The range front along the San Luis section is much more subdued than along either the northern or southern Sangre de Cristo fault zones. Neogene and Quaternary faulting can be described as a complex right-stepping pattern of range-bounding and intrabasin faults within the Culebra graben (Kirkham and Rogers, 1981; Kirkham and others, 2005; Machette and others, 2007; Thompson and others, 2007). Low-lying foothills underlain by Pliocene to Miocene Santa Fe Group rocks and sediment bound the eastern side of the fault, and the crest of the Sangre de Cristo Mountains is as much as 20 km east of the range-bounding fault. This subdued range-front morphology contrasts with the steep, precipitous front to the range along the northern and southern Sangre de Cristo fault zones. Most of the central Sangre de Cristo fault zone has discontinuous scarps that are best preserved on middle Pleistocene and older deposits (Colman and others, 1985), although more recent mapping by Thompson and others (2007) shows that almost the entire section presents evidence for latest Pleistocene or early Holocene surface rupturing. The overall geomorphic expression of the central Sangre de Cristo fault zone indicates a considerable difference in its long-term Cenozoic tectonic activity rate compared with activity rates in the adjoining northern and southern Sangre de Cristo fault zones.

Crone and Machette (2005) and Crone and others (2006) conducted the only paleoseismic investigation along the central Sangre de Cristo fault zone. They excavated two trenches across the San Luis section at Rito Seco (5 km northeast of San Luis, Colo.) that revealed evidence for four events in the past 50 ka. The most recent event (paoleoevent (PE)1) had a preferred age of 9.0±2.0 ka (optically stimulated luminescence (OSL) and C^{14} dating); earlier events were about 23.4±2 ka (PE2; OSL dating), about 30.3 (PE3; OSL dating), and about 45.0±4.3 ka (PE4; OSL dating). The oldest deposits in the trenches (about 48 ka) have a minimum surface offset of 6.8 m, which suggests a minimum late Pleistocene slip rate of 0.17 mm/yr and recurrence intervals that average about 12 k.y. These late Pleistocene slip rates contrast with the overall (long-term) geomorphic expression of the central Sangre de Cristo fault zone, further suggesting variations in the slip rate of the Sangre de Cristo fault system during the past 5 m.y. (Pliocene to Pleistocene time).

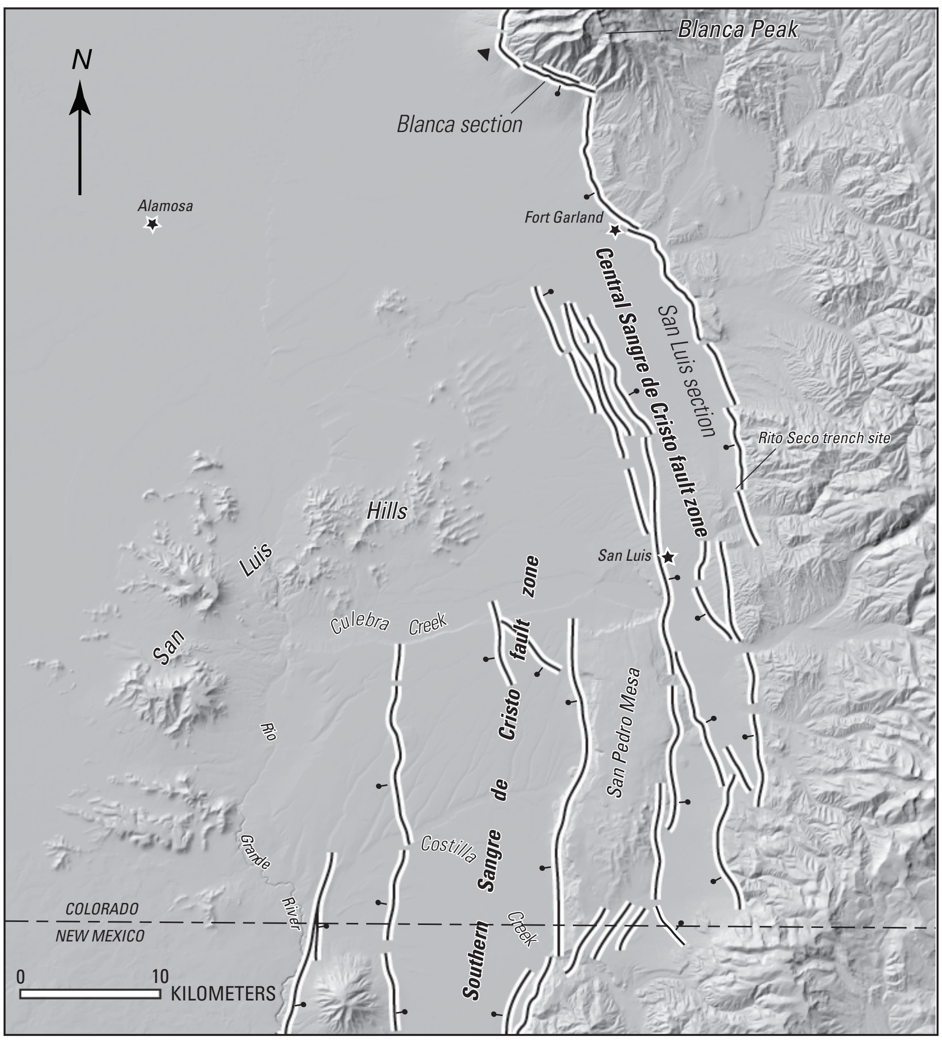

Figure J–4. Central Sangre de Cristo fault zone. Highlighted black lines are Quaternary faults, bar and ball on downthrown side. Section boundary between northern and central fault zones is marked by the black triangle. Heavy white lines along east side of San Luis Hills are older pre-Quaternary faults. Shaded-relief map created by Ted Brandt (USGS).

Southern Sangre de Cristo Fault Zone

The southern Sangre de Cristo fault zone is the only part of the larger fault system that we see in New Mexico on the third day of the Friends of the Pleistocene field trip (see chapter C, this volume). The southern Sangre de Cristo fault zone extends about 96 km from southwest of San Luis, Colo., to near the small community of Talpa, N. Mex. (Personius and Machette, 1984), where it merges with the northeast-trending Embudo fault zone (fig. J–5). Previous work on this part of the fault system has been mainly based on surficial geologic mapping and morphometric analysis of fault scarp profiles (Machette and Personius, 1984; Kelson, 1986; Menges, 1988; Thompson and Machette, 1989), although Kelson and others (2004) trenched the fault near Taos. On the basis of a compilation by Machette and others (1998), the southern Sangre de Cristo fault zone is subdivided into five geometric sections, listed north to south (fig. J–5): San Pedro Mesa (24 km), Urraca (22 km), Questa (18 km), Hondo (22 km), and Cañon (15 km) (U.S. Geological Survey, 2005). There is a major eastward step between the central Sangre de Cristo fault zone and Urraca section, which coincides with the latitude of the southern extent of the Culebra graben. A northeast-trending set of subsidiary Quaternary faults provide a structural link between the southern and the central Sangre de Cristo fault zones across the southern end of San Pedro Mesa (Thompson and others, 2007), but scarps on these faults are largely concealed by late Quaternary landslides that could be of seismogenic origin. On the basis of the geomorphic expression of these fault scarps, morphometric analyses of scarps, and surficial mapping (C.A. Ruleman, unpub. mapping, 2007), we consolidate the Urraca and Questa sections into the new Latir Peaks section of the southern Sangre de Cristo fault zone.

Our studies of the southern Sangre de Cristo fault zone are focused on the northern 64 km of the fault zone (San Pedro and Latir Peaks sections), which contains our map areas in the Alamosa and Wheeler Peak 1:100,000-scale geologic maps, respectively. We make field trip stops at both of these sections. We discuss the San Pedro section at field trip stop B9 (chapter B, this volume), and the Latir Peaks section at field trip stops C6 and C7 (chapter C, this volume).

The San Pedro section has a 24-km-long fault trace that forms the curvilinear western side of San Pedro Mesa, which is capped by Pliocene Servilleta Basalt (4.0±0.3 Ma). Massive landslides largely conceal the fault, but we recognize a few discontinuous scarps on alluvium and colluvium. Thompson and others (2007) mapped offsets of middle and late Pleistocene alluvium; however, the inferred age (latest Pleistocene) for the most recent event is based on the fault being buried by late Pleistocene to Holocene landslides of probable seismogenic origin. Long-term slip rates for this section are based on vertical displacements of the Servilleta Basalt (4.0±0.3 Ma) and range from 0.075 to 0.1 mm/yr (see chapter B, this volume). These long-term rates increase southward towards New Mexico.

The Latir Peaks section of the southern Sangre de Cristo fault zone is about 40 km long. It extends southward from Costilla to San Cristobal, N. Mex. (fig. J–5), as the main range-bounding fault along the Latir Peaks of the Taos Mountains (a local part of the longer Sangre de Cristo Mountains). This section has been previously divided into the Urraca

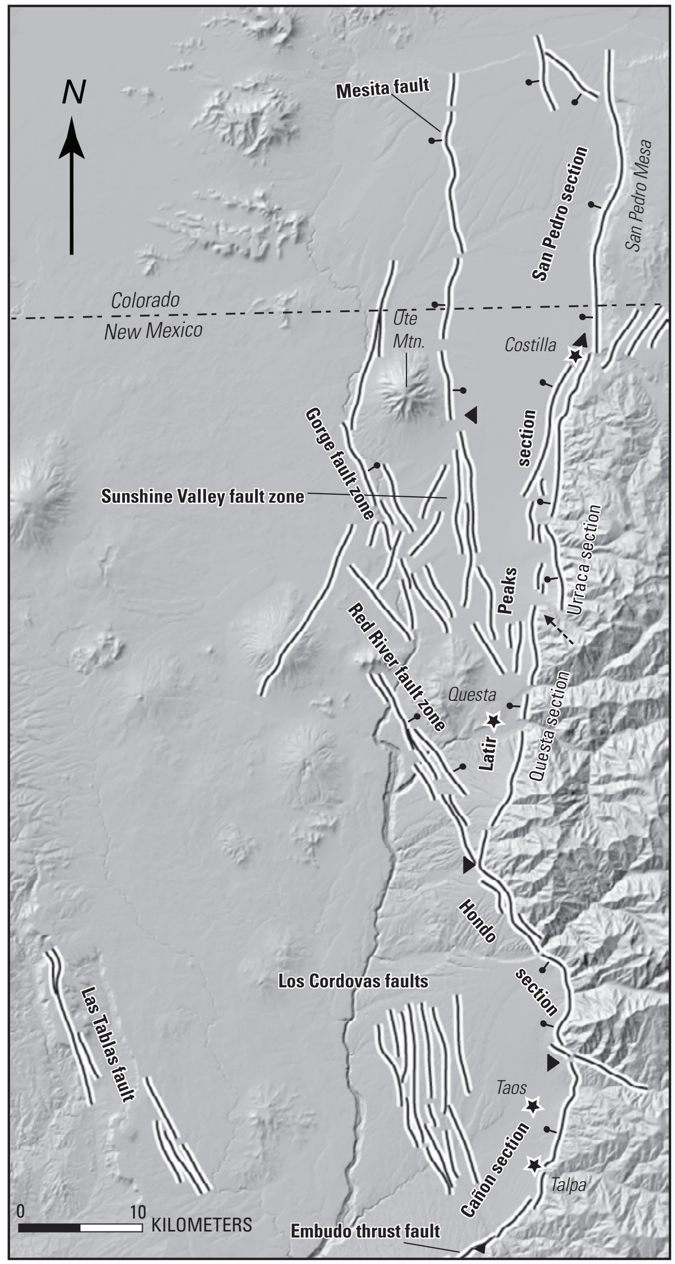

Figure J–5. Quaternary faults along the southern Sangre de Cristo fault zone. Highlighted black lines are Quaternary normal faults with bar and ball on downthrown side. Embudo thrust fault has teeth on the hanging wall. Black triangles mark section boundaries discussed in text. Arrow shows location of previously subdivided Urraca and Questa sections to be consolidated into the Latir Peaks section. Shaded-relief map created by Ted Brandt (USGS).

section (on the north) and Questa section (on the south) (U.S. Geological Survey, 2005), and it includes the Cedro Canyon and Urraca Ranch piedmont faults of Machette and Personius (1984). The Latir Peaks section has a steep, precipitous, linear range front with well-developed faceted spurs, deeply incised canyons on the footwall, and discontinuous range-front and piedmont scarps on late middle Pleistocene to Holocene alluvium and colluvium (Menges, 1987, 1988, 1990). Pazzaglia (1989) mapped range-front deposits along this section of the fault zone and showed offsets in late Pleistocene fan gravels. More-detailed unpublished maps by C.A. Ruleman (2007) show differing ages of faulted deposits and amounts of offset on these deposits, but a detailed paleoseismic study for this section (including trenching and dating) has not been completed.

Range-front scarps are primarily preserved on late-middle Pleistocene alluvium and Holocene colluvium (C.A. Ruleman, unpub. mapping, 2007). Piedmont scarps are mapped on late-middle and late Pleistocene fan deposits (about >130 ka). The lack of well-preserved fault scarps on late Pleistocene alluvium along the range front suggests that late Pleistocene fan-head incision occurred at the canyon mouths and that late Pleistocene deposits prograde into the basin. South of Questa, the fault is expressed as a linear range front with discontinuous, subtle scarps at the bedrock-colluvium junction, which suggests but doesn't require late Quaternary faulting. The adjacent piedmont is deeply dissected with little to no late Pleistocene to Holocene deposition, leaving sparse evidence of latest Quaternary faulting events.

Menges (1990) discusses variations in Pliocene to Quaternary slip rates along this section and notes that long-term (>1 Ma) slip rates are several times greater than those indicated by the late Pleistocene to Holocene record, suggesting temporal changes in slip rates in 100-k.y.-long time spans. In support of his observations, fault scarps on late middle Pleistocene deposits (about >130 ka) have surface offsets between 5.3 and 7.8 m, yielding minimum slip rates of 0.04–0.06 mm/yr for the last 130 k.y. (see stops C6 and C7, chapter C, this volume). However, vertical offset on the Servilleta Basalt (4.6–3.5 Ma; ages of faulted basalt are uncertain because subsurface basalts have not been dated) just south of Costilla, N. Mex. (see stop C7, chapter C, this volume), indicates a long-term slip rate of 0.14–0.16 mm/yr, indicating slip rates that change by a factor of 2–3 during 100-k.y.-long seismic cycles (fig. J–6). A plot of scarp height versus maximum slope angle for fault scarp profiles along the Latir section suggests that only one Holocene event has displaced latest Pleistocene to Holocene deposits, but larger (older) scarps have a steepened bevel caused by this event (fig. J–7). Rough calculations suggest that late Quaternary recurrence intervals are at least 20–40 k.y.

In addition to these observations along the Latir Peaks section, some bedrock escarpments in the footwall block of the range are suspected to be of seismic origin from Quaternary earthquakes on the main range-bounding fault. The continuity of these scarps in rapidly eroding, steep terrain indicates that they were reactivated throughout Bull Lake and Pinedale glacial cycles in order to preserve them. Lipman and Reed (1989) mapped numerous preexisting faults in the Questa caldera complex, which formed during a major 25-Ma caldera eruption. If properly oriented to the modern stress regime, then these preexisting volcanogenic faults might be reactivated and slip during large earthquakes on the Sangre de Cristo fault zone, such as occurred with the interaction of the Red Canyon and Hebgen Lake faults during the 1959 M_s7.5 Hebgen, Mont., earthquake (Myers and Hamilton, 1964). These previously formed volcanogenic faults crosscut and possibly sole into preexisting Laramide thrust faults creating a complex array of faults to be reactivated during large events on the main range-bounding fault as previously described along the northern Sangre de Cristo fault zone.

The 22-km-long Hondo section to the south was previously described and mapped by Kelson (1986) and Menges (1988). The range-front morphology of this section is very similar to that of the Latir Peaks section—it is steep and linear, and it has well-defined basal faceted spurs. Menges (1990) reported early to middle Holocene displacement and documented two slip rates along this section of the southern Sangre de Cristo fault zone: (1) a slow, late-middle Pleistocene to Holocene (about 130 ka to present) rate of 0.03–0.06 mm/yr, and (2) a faster post-Pliocene (<4 Ma) rate of 0.12–0.23 mm/yr (Menges, 1988). The contrast in long-term (>1 Ma) and short-term (<200 ka) slip rates are consistent with rates quantified by Ruleman and others (chapter C, this volume) for the Latir Peaks section and by McCalpin (1982) for the northern Sangre de Cristo fault zone.

To the south, the 15-km-long Cañon section is composed of the Taos Pueblo and Cañon faults of Machette and Personius (1984); as such it extends southward from the Rio Pueblo de Taos to the Rio Grande del Rancho, which is about 1 km south of the small community of Talpa. The boundary between the Hondo and Cañon sections is marked by a salient in the range front that extends about 1.5 km to the northwest. Discontinuous, northwest-facing scarps are present along the range front. This part of the range front has less precipitous basal faceted spurs and canyons are not incised as deeply compared with the area to the north. Previous mapping by Machette and Personius (1984), Kelson (1986), and Menges (1988) indicates that late Pleistocene and possibly Holocene deposits are offset along this section. Machette and Personius (1984) measured scarp heights of 2–5 m on early(?) to late Pleistocene deposits.

Along the Cañon section, Kelson and others (2004) excavated one trench across a scarp on late Pleistocene alluvium near the Taos Pueblo and concluded that one surface-rupturing event occurred between 10 ka and 30 ka, producing 1.5 m of vertical offset. Inconclusive timing of previous events did not allow a recurrence interval to be estimated. However, on the basis of our cursory analyses of their trench maps (Kelson and others, 2004, figs. 4 and 5), it seems unlikely that deposits with Bk stage III+ morphology soil development are offset more than 5–10 m. This development of a calcic horizon suggests that these deposits correlate with

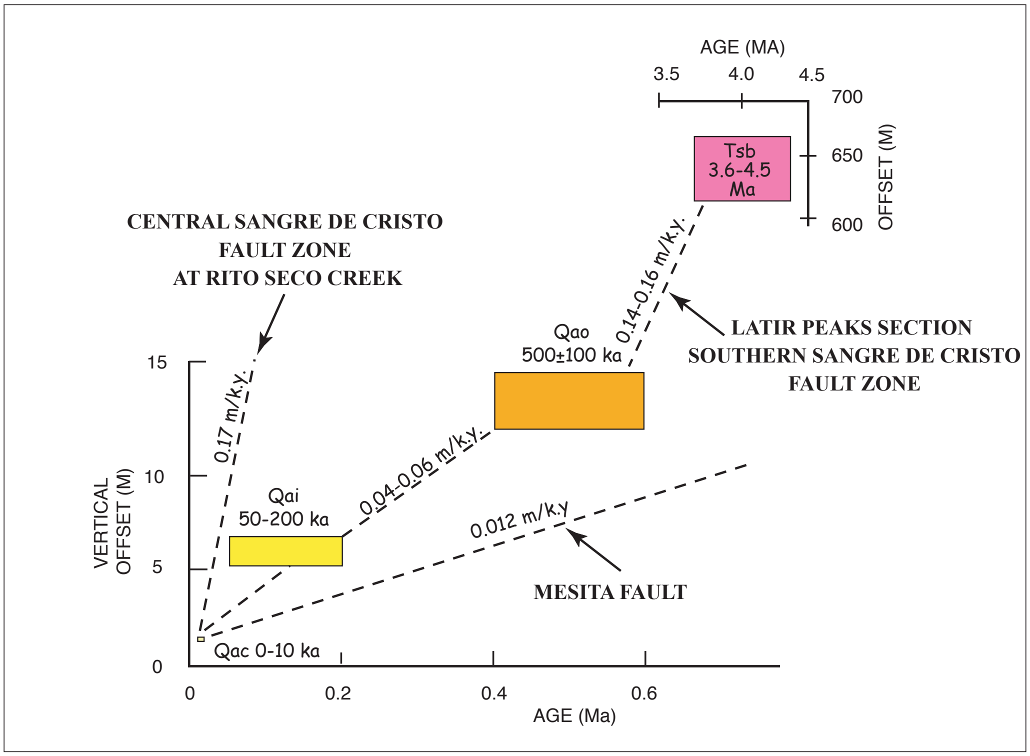

Figure J–6. Surface offset versus age of geologic units along the Latir Peaks section of the southern Sangre de Cristo fault zone, compared with the central Sange de Cristo fault zone and the Mesita fault (see stop B8, chapter B, this volume). Dashed lines indicate average slip rate for past 1.0–4.0 m.y. versus Sangre de Cristo fault zone (past 50 k.y.) near San Luis, Colo. (see Crone and Machette, 2006). The Servilleta Basalt (unit Tsb) is offset 610–670 m (2,000–2,200 ft) as measured from cross section A-A' on fig. C–7 (chapter C, this volume).

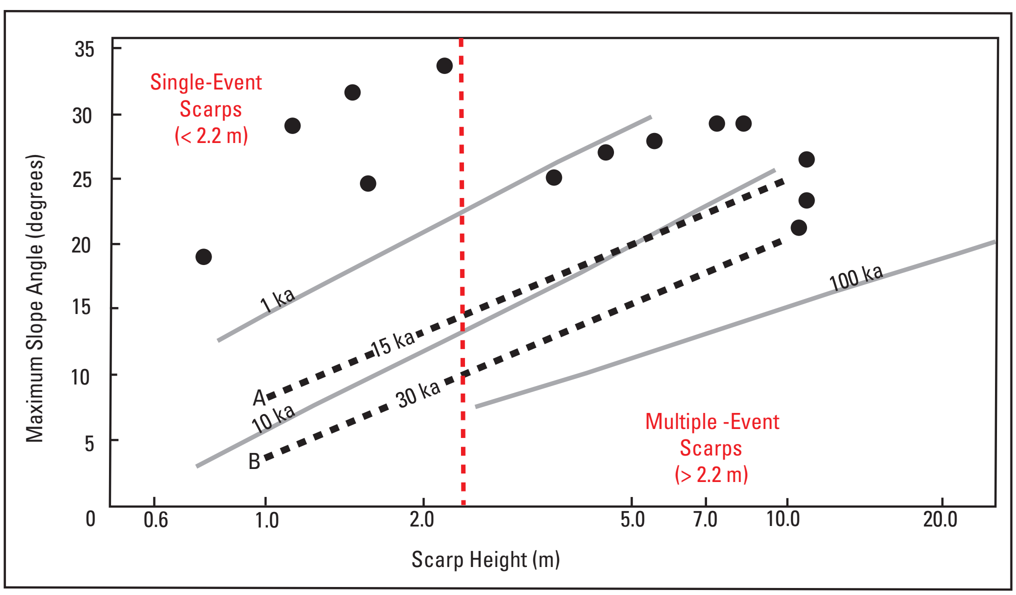

Figure J–7. Scarp height versus maximum slope angle for fault scarps profiled along the Latir Peaks section of the southern Sangre de Cristo fault zone. Solid gray lines are time-regression data from Bucknam and Anderson (1979). Dashed black lines labeled A and B are from Pierce and Colman (1986) and Pierce (1985), respectively.

deposits mapped as late middle Pleistocene and older in the region. With an inferred maximum offset of more than 10 m in >130 k.y., the maximum slip rate since late middle Pleistocene time would be 0.08 mm/yr for the trenched strand of the Cañon section.

Discussion

On the basis of our current understanding of the Sangre de Cristo fault system, we emphasize three main points:

1. We propose to subdivide the fault system into three main parts—the northern Sangre de Cristo, the central Sangre de Cristo, and the southern Sangre de Cristo fault zones;
2. Slip rates on individual sections of these three fault zones have varied throughout the Quaternary and Pliocene; and
3. The overall tectonic geomorphology of the three fault zones suggests marked differences in late Cenozoic fault behavior and leads to inferences about the interaction of these fault zones through time.

Our subdivision of the Sangre de Cristo fault system into three parts is based on geomorphic expression of the range fronts' evidence of Quaternary faulting, the presence of preexisting structures that could subdivide the fault zone, and fault-length parameters constrained by worldwide studies of active normal faulting. As discussed in each fault part's overview, individual sections show differing amounts of offset on deposits of differing ages, thus indicating that these three parts are internally segmented and that apparent interactions occur between sections as stress is relieved from one section and transferred to another following each event. However, we have only a rudimentary understanding of the timing of the most recent event, slip rates, and recurrence intervals for each section; we need more robust data to more clearly define which sections define potential segment rupture boundaries and how adjacent fault sections interact.

Preexisting bedrock structures interpreted from geophysical data and mapped in the footwall of the range-front faults can create asperities that might arrest lateral propagation of individual surface-rupturing earthquakes. On the basis of mapping of these structures, we note changes in Quaternary fault trend and geometry that might reflect control by preexisting faults developed during prior tectonic events and stress regimes.

Subdividing the Sangre de Cristo fault system into these three parts may give us some idea of potential fault rupture lengths that can be compared with observations of rupture characteristics from worldwide studies of active faults. Wells and Coppersmith (1994) show that historic normal-faulting earthquakes have rarely caused surface ruptures that exceed 70 km in length, so it is unlikely that the entire 104-km-long northern Sangre de Cristo fault or the 96-km-long southern Sangre de Cristo fault would rupture during a single earthquake, given the structural complexity of the three parts as previously mentioned. However, Suter and Contreras (2002) reported an historical rupture length of 104 km, but this length is very rare and has not been observed elsewhere. Thus, we conclude that these long structures can be subdivided into rupture sections as we have proposed. For comparison, studies of large (M>7) historic earthquakes in the Basin and Range Province (Doser and Smith, 1989) suggest that they all nucleated below 12 km depth and are composed of multiple subevents with individual rupture lengths <21 km, although the total rupture lengths approached 70 km. A classic example is the Dixie Valley and Fairview Peak earthquakes of December 16, 1954, in north-central Nevada. These two earthquakes occurred only 4 minutes apart, whereas the 1959 M_s7.5, Hebgen Lake, Mont. earthquake was composed of nearly indiscernible subevents (Doser, 1985). Thus, one needs to think of large (M>7) earthquakes as being composed of multiple subevents on individual rupture building blocks.

It is clear that the three individual parts in the large Sangre de Cristo fault system have sections of differing faulting behavior during 100 k.y. cycles, as their geomorphic expression exemplifies. Both the northern and southern Sangre de Cristo fault zones have geomorphic expressions indicative of tectonic activity rates that are as much as twice the calculated late middle Pleistocene to Holocene (<130 ka) slip rates of 0.01–0.09 mm/yr (Bull, 1984). Conversely, the central Sangre de Cristo fault zone has a geomorphic expression indicative of faults with only one-half of its calculated late Pleistocene slip rate (0.17 mm/yr). Lithology must be a major factor in geomorphic expression of the footwall block of Sangre de Cristo fault system. The geomorphic expression of relatively recent rapid uplift along central Sangre de Cristo fault zone is subdued by footwall rocks and sediment composed of easily eroded Santa Fe Group sediment, whereas the slower uplift along the northern and southern Sangre de Cristo faults contrasts with their precipitous footwalls composed predominantly of resistant Precambrian crystalline rock. Thus, we propose that the neotectonic signatures of the northern and southern Sangre de Cristo fault zones represent higher pre-late Quaternary slip rates with a decrease in tectonic activity during the past 130 k.y. As tectonic activity on the northern and southern fault zones decreased during the late Pleistocene, tectonic activity may have shifted to the central fault zone, thereby allowing the accumulated stress to be released on the central Sangre de Cristo fault between the two previously more active fault zones to the north and south, the northern and the southern Sangre de Cristo fault zones, respectively.

Acknowledgments

We appreciate the constructive and helpful comments of Anthony Crone (USGS) and Matthew Morgan (Colorado Geological Survey) who reviewed a preliminary version of this manuscript. However, any errors that may remain are the responsibility of the authors.

References Cited

Bruce, R.M., and Johnson, B.R., 1991, Reconnaissance geologic map of parts of the Zapata Ranch and Mosca Pass quadrangles, Alamosa and Huerfano Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF–2168, 1 sheet, scale 1:24,000.

Bucknam, R.C., and Anderson, R.E., 1979, Estimation of fault-scarp ages from a scarp height–slope-angle relationship, Geology, v. 7, p. 11–14.

Bull, W.B., 1984, Tectonic geomorphology: Journal of Geological Education, v. 32, p. 310–324.

Colman, S.M., McCalpin, J.P., Ostenaa, D.A., and Kirkham, R.M., 1985, Map showing upper Cenozoic rocks and deposits and Quaternary faults, Rio Grande rift, south-central Colorado: U.S. Geological Survey Miscellaneous Investigations Map, I–1594, 2 sheets, scale 1:125,000.

Crone, A.J., and Machette, M.N., 2005, Paleoseismic activity on the Sangre de Cristo fault near San Luis, Colorado [abs.]: Geological Society of America Abstracts with Programs, v. 37, no. 7, p. 558.

Crone, A.J., Machette, M.N., and Mahan, S.A., 2006, Paleoseismic investigation of Rito Seco site, central section of the Sangre de Cristo fault zone, Colorado—Data related to late Quaternary surface faulting on the Sangre de Cristo fault, Rito Seco site, Costilla County, Colorado: U.S. Geological Survey Scientific Investigations Map SI–2955, 1 oversize plate (available at: http://pubs.usgs.gov/sim/2006/2955).

Doser, D.I., 1985, Source parameters and faulting processes of the 1959 Hebgen Lake, Montana, earthquake sequence: Journal of Geophysical Research, v. 90, p. 4537–4555.

Doser, D.I., and Smith, R.B., 1989, An assessment of source parameters of earthquakes in the cordillera of the western United States: Bulletin of the Seismological Society of America, v. 79, no. 5, p. 1383–1409.

Gaca, J.R., and Karig, D.E., 1965, Gravity survey in the San Luis Valley area, Colorado: U.S. Geological Survey Open-File Report, unnumbered.

Haller, K.M., Wheeler, R.L., and Rukstales, K., 2002, Documentation of changes in fault parameters for the 2002 National Seismic Hazard maps–Conterminous United States except California: U.S. Geological Survey Open-File Report 02–467, 32 p. (available at: http://pubs.usgs.gov/of/2002/ofr-02-467/).

Kellogg, K.S., 1999, Neogene basins of the northern Rio Grande Rift—Partitioning and asymmetry inherited from Laramide and older uplifts: Tectonophysics, v. 305, p. 141–152.

Kelson, K.I., 1986, Long-term tributary adjustments to base-level lowering northern Rio Grande rift, New Mexico: Albuquerque, University of New Mexico, M.S. thesis, 210 p.

Kelson, K.I., Bauer, P.W., Connell, S.D., Love, D.W., Rawling, G.C., and Mansell, M., 2004, Initial paleoseismic and hydrogeologic assessment of the southern Sangre de Cristo fault at Taos Pueblo, *in* Brister, B.S., Bauer, P.W., Read, A.S., and Lueth, V.W., eds., Geology of the Taos region, New Mexico Geological Society 55th Annual Field Conference, Guidebook, p. 289–299.

Kirkham, R.M., Brister, B.S., Grauch, V.J.S., and Budhan, J.S., 2005, Culebra graben–A major intrarift structure in the San Luis Basin, Rio Grande rift [abs.]: Geological Society of America Abstracts with Programs, v. 36, no. 6, p. 14.

Kirkham, R.M., and Rogers, W.P., 1981, Earthquake potential in Colorado: Colorado Geological Survey Bulletin 43, 171 p.

Lipman, P.W., and Reed, J.C., 1989, Geologic map of the Latir volcanic field and adjacent areas, northern New Mexico, U.S. Geological Survey Miscellaneous Investigations Series Map I–1907, 1:48,000 scale.

Machette, M.N., and Personius, S.F., 1984, Map of Quaternary and Pliocene faults in the eastern part of the Aztec 1° by 2° quadrangle and the western part of the Raton 1° by 2° quadrangle, northern New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF–1465–B, 1 sheet, scale 1:250,000.

Machette, M.N., Personius, S.F., Kelson, K.I., Haller, K.M., and Dart, R.L., 1998, Map and database of Quaternary faults and folds in New Mexico: U.S. Geological Survey Open-File Report 98–521, 443 p., 1 plate (1:750,000 scale).

Machette, M.N., Personius, S.F., and Nelson, A.R., 1992, Paleoseismology of the Wasatch fault zone—A summary of recent investigations, conclusions, and interpretations, *in* Gori, P.A., and Hays, W.W., eds., Assessing regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500, chap. A, p. A1–A72.

Machette, M.N., Thompson, R.A., and Drenth, B.J., in press, Geologic map of the San Luis quadrangle, Costilla County, Colorado: U.S. Geological Survey Scientific Investigations Map 2963, 1 sheet, 1:24,000 scale (http://pubs.usgs.gov/sim/2007/2963).

McCalpin, J.P., 1981, Quaternary geology and neotectonics of the west flank of the northern Sangre de Cristo Mountains, south-central Colorado: Golden, Colorado School of Mines, Ph.D. dissertation, 287 p.

McCalpin, J.P., 1982, Quaternary geology and neotectonics of the west flank of the northern Sangre de Cristo Mountains, south-central Colorado: Colorado School of Mines Quarterly, no. 77, 97 p.

McCalpin, J.P., 1986, Quaternary tectonics of the Sangre de Cristo and Villa Grove fault zones, *in* Rogers, W.P. and Kirkham, R.M., eds., Contributions to Colorado seismicity and tectonics—A 1986 update: Colorado Geological Survey Special Publication 28, p. 59–64.

McCalpin, J.P., 2006, Active faults and seismic hazards to infrastructure at Great Sand Dunes National Monument and Preserve: Crestone, Colorado: unpublished report by GEO-HAZ Consulting, Inc., 49 p., 1 oversize plate.

Menges, C.M., 1987, Temporal and spatial segmentation of Plio-Quaternary fault rupture along the base of the western Sangre de Cristo mountain front, northern New Mexico, *in* Menges, C.M., Enzel, Y., and Harrison, B., eds., Quaternary tectonics, landform evolution, soil chronologies and glacial deposits—Northern Rio Grande rift of New Mexico: Friends of the Pleistocene Rocky Mountain Cell Fieldtrip, Guidebook, p. 71–94.

Menges, C.M., 1988, The tectonic geomorphology of mountain-front landforms in the northern Rio Grande rift near Taos, New Mexico: Albuquerque, University of New Mexico, Ph.D. dissertation, 339 p.

Menges, C.M., 1990, Late Quaternary fault scarps, mountain-front landforms, and Pliocene-Quaternary segmentation on the range-bounding fault zone, Sangre de Cristo Mountains, New Mexico, *in* Krinitzsky, E.L., and Slemmons, D.B., eds., Neotectonics in earthquake evaluation: Geological Society of America Reviews in Engineering Geology, v. 8, p. 131–156.

Myers, W.F., and Hamilton, Warren, 1964, Deformation accompanying the Hebgen Lake earthquake of August 17, 1959, U.S. Geological Survey Professional paper 435, p. 37–98.

Pazzaglia, F.J., 1989, Tectonic and climatic influences on the evolution of Quaternary depositional landforms along a segmented range-front fault, Sangre de Cristo Mountains, north-central New Mexico: Albuquerque, University of New Mexico, M.S. thesis, 246 p., scale 1:24,000.

Personius, S.F., and Machette, M.N., 1984, Quaternary and Pliocene faulting in the Taos Plateau region, northern New Mexico, *in* Baldridge, W.S., Dickerson, P.W., Riecker, R.E., and Zidek, J., eds., Rio Grande rift—Northern New Mexico: New Mexico Geological Society 35th Annual Field Conference, Guidebook, p. 83–90.

Pierce, K.L., 1985, Quaternary history of faulting along the Arco segment of the Lost River fault, central Idaho, *in* Stein, R.S., and Bucknam, R.C., eds., Proceedings of Workshop XXVIII on the Borah Peak, Idaho, Earthquake: U.S. Geological Survey Open-File Report 85–290, v. A, p. 195–206.

Pierce, K.L., and Colman, S.M., 1986, Effect of height and orientation (microclimate) on geomorphic degradation rates and processes, late-glacial terrace scarps in central Idaho: Geological Society of America Bulletin, v. 97, p. 869–885.

Suter, Max, and Contreras, Juan, 2002, Active tectonics of northeastern Sonora, Mexico (southern Basin and Range Province) and the 3 May 1887 M_w 7.4 earthquake: Bulletin of the Seismological Society, v. 92, no. 2, p. 581–589.

Thompson, R.A., and Machette, M.N., 1989, Geologic map of the San Luis Hills area, Conejos and Costilla Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I–1906, 1 sheet, scale 1:50,000.

Thompson, R.A., Machette, M.N., and Drenth, B.J., 2007, Geologic map of San Pedro Mesa and surrounding area, Costilla County, Colorado: U.S. Geological Survey Open-File Report 2007–1074, 1 sheet, 1:24,000 scale (*http://pubs.usgs.gov/ofr/2007/1074*).

Tweto, Ogden, 1979, Geologic map of Colorado, U.S. Geological Survey, 1:500,000 scale.

Upson, J.E., 1939, Physiographic subdivisions of the San Luis Valley, southern Colorado: Journal of Geology, v. 47, no. 7, p. 721–736.

U.S. Geological Survey, 2005, Quaternary faults and fold database of the United States: U.S. Geological Survey website, available at *http://earthquake.usgs.gov/qfaults/*.

Wallace, A.R., 2004, Evolution of the southeastern San Luis Basin margin and the Culebra embayment, Rio Grande rift, southern Colorado, *in* Brister, B.S., Bauer, P.W., Read, A.S., and Lueth, V.W., eds., Geology of the Taos region, New Mexico Geological Society 55th Annual Field Conference, Guidebook, p. 121–132.

Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture area, and surface displacement: Seismological Society of America Bulletin, v. 84, p. 974–1002.

Widmann, B.L., Kirkham, R.M., Morgan, M.L., and Rogers, W.P., 2002, Colorado late Cenozoic fault and fold database and Internet map server: Colorado Geological Survey Information Series 60a, available at *http://geosurvey.state.co.us/pubs/ceno/*.