CONTRASTS BETWEEN SHORT- AND LONG-TERM RECORDS OF SEISMICITY IN THE RIO GRANDE RIFT—IMPORTANT IMPLICATIONS FOR SEISMIC-HAZARD ASSESSMENTS IN AREAS OF SLOW EXTENSION

Michael N. Machette
U.S. Geological Survey, MS 966
Geologic Hazards Team—Central Region
Denver, Colorado 80225
(machette@gldvxa.cr.usgs.gov)

ABSTRACT

The Rio Grande rift has a relatively short and unimpressive record of historical seismicity. However, there is abundant evidence of prehistoric (Quaternary) surface faulting associated with large (M>6) earthquakes. This paradox between historical and prehistoric seismicity (paleoseismicity) has important implications for seismic-hazards analyses based primarily on modern seismicity.

The paleoseismic record of faulting in the rift is poorly documented compared to most seismically active regions, mainly because there have been few detailed studies and partly because many of the faults have long recurrence intervals (e.g., 10,000-100,000 years), which makes dating them difficult by radiocarbon methods alone. Nevertheless, a new compilation of Quaternary fault data for the rift suggests Holocene (<10,000 years) movement on at least 20 faults. Several of these faults have evidence for multiple movements; thus, at least 22 large earthquakes of probable M >6.25 were associated with surface ruptures during the past 10,000 years, or one about every 450 years.

Because the level of seismicity of the Rio Grande rift is generally low, the populace (in general) believes that earthquakes do not pose a significant threat to them, whereas the presence of abundant young faults tells a different story. From a geologic viewpoint, it seems obvious that modern seismic-hazards assessments for regions like the Rio Grande rift must use not only catalogs of modern seismicity, but also integrate data from a comprehensive inventory of Quaternary faults, especially those structures showing evidence of movement in the past 100,000 years (a time interval which encompasses a complete earthquake cycle for most all active faults). A myopic view of earthquake hazards posed by individual faults (i.e., having recurrence intervals of 10,000 years or more) can lead to a complacent attitude that strengthens a perception of low seismic potential for the region. Without proper caution, this attitude can be manifested in inappropriate construction styles, building codes, land-use policies, and the siting (or relocation) of important or critical facilities.

INTRODUCTION

Virtually all modern earthquake-hazards assessments are based primarily on historical seismicity coupled with geologic evidence of faulting that is associated with strong ground motion (paleoseismology). The predictive nature of these assessments follows the widely accepted paradigm that "the past is the key to the future." This seismological basis for earthquake-hazards assessments is natural, quantitative, and justified through traditional practice. However, a paradox exists in many recently developed countries with short historical records, such as the United States where the recorded history of seismicity may be only 100-300 years long and the instrumental record may be considerably shorter. The problem lies in the potential disparity between short-term records of strong ground motion reflected by historical seismicity and long-term records of strong ground motion indicated from paleoseismic studies. This paper reflects on these disparities and the reasons they exist.

The U.S. and many other countries have geologically distinct regions that fall into markedly different seismogenic settings. Commonly, these regions are directly associated with tectonic provinces, their seismic activity being controlled by their proximity to tectonic plate margins, regional geologic setting, and their current state of stress. Although there is probably a continuum between these regions, let us consider that there are three general types of seismogenic settings in the United States. This simple characterization allows us to frame the present and Neogene seismotectonic setting of the Rio Grande rift.

In tectonically active regions, especially those bordering convergent or transpressive plate margins, large (M >6) earthquakes are associated with catastrophic movement on faults having slip rates that are typically tens of mm/year to several cm/year and recurrence intervals of several hundreds (e.g., San Andreas fault) to several thousand years long (e.g., blind thrust faults within the Los Angeles basin). Strike-slip and thrust faults in coastal California and the Cascadia subduction zone fall in this broad category of tectonically active regions. Here, the brief record of felt seismicity (100-150 years) may adequately portray many of the active faults. Nevertheless, even seismicity fails to image some seismogenic structures, such as blind thrusts (e.g., the 1994 Northridge earthquake).

In tectonically less-active regions such as the extensional domains of the Basin and Range Province and Rio Grande rift of the western U.S., fault slip rates are typically <1-2 mm/year; thus, recurrence intervals for surface rupturing fault are as little as several thousand years (e.g., the Wasatch fault zone) or as long as 10,000 years (e.g., a typical Basin and Range fault) to 100,000 years (e.g., some of the least active Quaternary faults in the Rio Grande rift). Obviously, the 150- to 300-year-long record of felt seismicity only portrays a small fraction of the potentially active faults in these regions.

Finally, in even less tectonically active regions, such as the passive margin of the eastern U.S. and compressional domain of the stable continental interior of the U.S., Canada, and Australia, fault slip rates are probably measured in hundredths of a mm/year, and intervals between surface rupturing events may be extremely long (>100,000 years) or immeasurable. However, these regions also seem prone to clustered earthquake activity—that is, one where seismic structures are recurrently active over relatively short geologic time frames (hundreds to thousands of years), then inactive for long intervals of time (thousands to tens of thousands of years). The New Madrid and Charleston seismic zones (mid-continent and eastern U.S., respectively) and the Cheraw fault (southeastern Colorado) are examples of faults that have evidence of short-term clustering but no geologic evidence of similar long-term tectonic activity.

In extensional domains such as the Rio Grande rift, a situation exists where the record of historical seismicity is relatively short and generally unimpressive. Instrumental data exist from the mid-1960s and felt reports go back to the 1600s in specific locations (e.g., Santa Fe). Although the paleoseismic record reveals evidence of abundant late Pleistocene (i.e., 10,000-130,000 years ago) and Holocene (<10,000 years ago) faulting in the rift, we only have evidence of a single historic surface rupture from an earthquake that occurred a little more than 110 years ago in northern Sonora, Mexico, south of Douglas, Arizona. Within the U.S. portion of the rift, the largest felt or recorded earthquake (Ms 6.3) occurred in 1931 near Valentine, Texas, and although this event did not form a demonstrable surface rupture, it may have had as much as 38 centimeters of slip in the subsurface (Doser, 1987). This earthquake, and similar-size ones in the Basin and Range Province (see Wells and Coppersmith, 1994), suggest that the threshold for surface ruptures is in the lower half of the M 6 range (i.e., M 6.25±0.25) for normal faults that have earthquakes nucleating at depths of 15 kilometers to perhaps 20 kilometers. Thus, there is an apparent paradox in the Rio Grande rift between the short-term record of seismicity (relatively aseismic, no surface rupture) and the long-term record (abundant evidence of late Quaternary faults and, hence, paleoseismicity). The manner in which this disparity is dealt with has important implications for seismic-hazards analyses.

QUATERNARY FAULTING IN THE RIO GRANDE RIFT

The Rio Grande rift lies within the eastern part of the Basin and Range and the southern part of the Rocky Mountain provinces as defined by Fenneman (1931); it forms a nearly continuous, deep, sediment-filled valley of

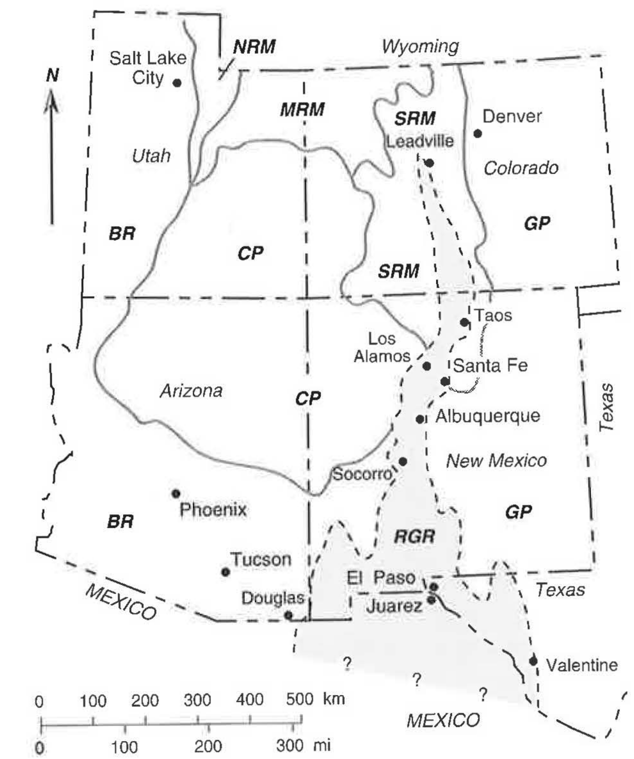

Figure 1. Index map of the Rio Grande rift showing cultural and geographic features mentioned in the text. Physiographic provinces (from Fenneman, 1931) are as follows: BR, Basin and Range; CP, Colorado Plateau; GP, Great Plains; MR, Middle Rocky Mountains (includes Wyoming Basin); RGR, Rio Grande rift subprovince (shaded pattern); and SR, Southern Rocky Mountains. Solid lines show province boundaries; dashed line shows limits of Rio Grande rift as used in this paper.

Neogene age that extends almost 1,000 kilometers from Leadville, Colorado, south into western Texas, southeastern Arizona, and northern Chihuahua and Sonora (northernmost Mexico) (figure 1). The rift widens to the south; it is a singular 30- to 40-kilometer-wide, half-graben north of Taos, New Mexico. The down-to-the-west Sangre de Cristo fault zone (faults 3 and 4 , figure 2) is the predominate rift-bounding structure in this area. South from a line between roughly Taos and Los Alamos, New Mexico, the rift widens to 40-60 kilometers, with alternating-polarity half grabens in the Espanola, Santo Domingo, and Albuquerque basins. South of Socorro, the rift becomes even wider (60-150 kilometers) and is comprised of 2 or more half grabens or grabens. The southern part of the Rio Grande rift lies with a southeastern part (extension) of the Basin and Range, the rift's western margin is herein considered to be near the Arizona/New Mexico border; however, some have placed the boundary of the Neogene Rio Grande rift further east near Deming, New Mexico. Nevertheless, at the International Border with Mexico, the rift is on the order of about 400 kilometers wide. On the basis of the north-south orientation and youthfulness of faulting, the Quaternary Rio Grande rift probably extends from the Animas Valley in southwestern New Mexico and San Bernardino Valley in northern Sonora, Mexico (on the west) to the Lobo Valley near Valentine, Texas (on the east) (figure 2).

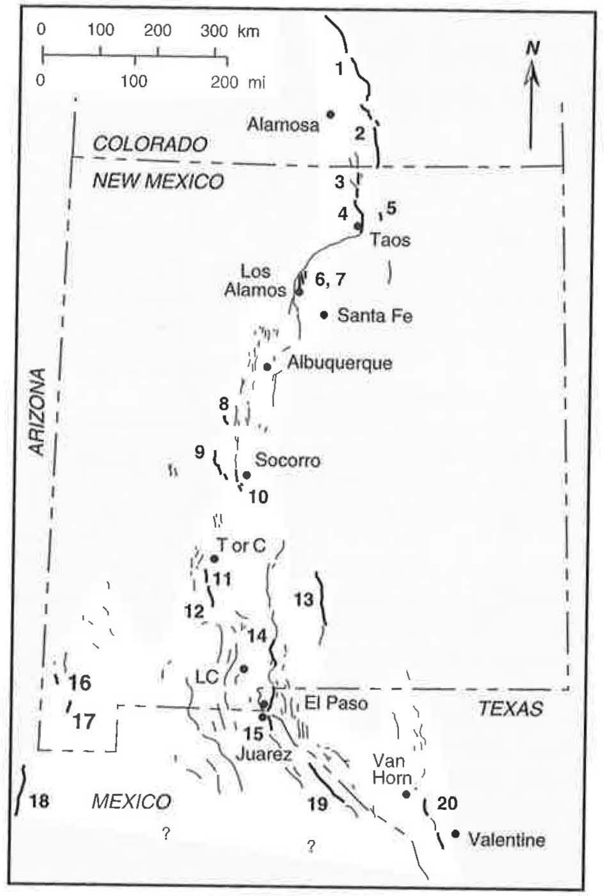

***Figure 2.** Generalized map of Quaternary faults of the Rio Grande rift in southern Colorado, New Mexico, western Texas, and northern Mexico. Faults of Holocene (and historic) age are numbered and described in table 1.*

Quaternary faults are both widespread and common in the Rio Grande rift (Nakata and others, 1982; Machette and others, 1996), but relatively young (<15,000 year old) surface ruptures are restricted primarily to major range-bounding faults (Machette and Hawley, 1996) such as those along the Sangre de Cristo, Jemez, Socorro, Magdalena, Caballo, San Andres, Organ, and Franklin Mountains (see figure 2). The paleoseismic record of faulting in the rift is poorly understood, mainly because there have been few detailed studies and partly because many of the faults have long recurrence intervals (i.e., 10,000-100,000 years), which makes dating times of movement on them difficult by radiocarbon methods. Thus, it is difficult to assess prehistoric levels of seismicity in the rift. However, based on preliminary studies of fault age and distribution, I previously suggested a composite recurrence interval (CRI) of about 750±250 years for a major surface-rupturing earthquake in the New Mexico part of the Rio Grande rift (Machette, 1987a). We now have a compilation of paleoseismic data for the rift in southern Colorado (Sangre de Cristo fault), New Mexico, west Texas and northern Mexico (Collins and others, 1996; Machette and others, 1996; respectively). These data indicate Holocene movement on 20 faults (table 1), including the one historical rupture in northern Mexico. In addition to these 20 earthquake events, the Sangre de Cristo and Organ Mountains faults have evidence for two separate movements in the Holocene; thus, one should consider that there have been at least 22 large (M >6.25) earthquakes associated with surface ruptures in the Rio Grande rift in the past 10,000 years. These data suggest a Holocene composite recurrence interval (CRI) of about 450 years for the above mentioned portion of the rift. Some portions of the rift, especially those settled by Spanish missionaries along the Rio Grande, have been continuously occupied since nearly A.D. 1600 , thus the CRI is approaching the time that the region has been occupied by Americans of European origin (i.e. the historical record). The new calculated CRI is considerably less than before (750 years) because I have included faults from a larger area (Texas, Mexico, and southern Colorado) and because there are several newly documented faults in the listing. The most recent movement on the prehistoric faults seems to have been along the Organ Mountains fault about 1,000 years ago (Gile, 1987), whereas the Pitaycachi fault is the only historic surface rupture in the rift (see table 1). Based on past experience, it seems likely that with further paleoseismic studies the number of faults with known Holocene movement will probably increase, and the CRI will decrease somewhat, as it has in many other parts of the Basin and Range. In contrast, the CRI for the rift is roughly equivalent to that of the Wasatch fault zone (5 active segments) in Utah (Machette and others, 1991, table 2), a fault zone which is considerably more active that those typical of the Basin and Range Province.

There are two major urban centers in the relatively sparsely populated Rio Grande rift. The northern center includes Los Alamos, Santa Fe, and Albuquerque, a region where an estimated 50 percent (i.e., 750,000) of New Mexico's population lives (ca. 1.5 million in 1990). This area is close to or includes several Quaternary faults (the Embudo, Parajito, Guaye Mountain, Rendija Canyon, and Hubbell Springs) that have clear evidence for either Holocene or latest Pleistocene movements associated with large earthquakes. New studies of the Parajito fault indicate latest Pleistocene (Kelson and others, 1993) or possibly younger movement (James McCalpin, oral communication 1997), whereas two of its subsidiary faults (the Rendija and Guaye Mountain) are known to be Holocene (Kelson and others, 1993). The Parajito fault has a long history of Quaternary movement—its scarp on 1.1-million-year-old Bandelier Tuff is commonly 120 meters high; more importantly, the fault bounds the west side of the Los Alamos National Laboratory, an important research and defense-related facility. In addition, there are several other critical facilities (Kirkland Air Force Base and Sandia National Laboratory), the State Capital, and Cochiti Reservoir within this region, all of which could be subject to damage from severe ground shaking during large earthquakes on nearby active faults.

At the southern margin of the rift, population is mainly concentrated in the El Paso/Juarez metropolitan area (estimated population of more than 1.8 million), with a smaller urban area at Las Cruces (70 kilometers to the north-northwest). El Paso has nearly 600,000 people living in a relatively small area (El Paso County), whereas

***Table 1.** Faults with known or suspected Holocene movement in the Rio Grande rift.*

(Abbreviations: SM, scarp morphology; ST, stratigraphic relations; S, soils; C14, radiocarbon dating; T, trenching; Mtns., mountains; EQ, earthquake)

Name of fault	Number & general location (see figure 2)	Time of most recent event	Evidence for timing & main reference(s)
Sangre de Cristo (section A)	1. West front of Sangre de Cristo Mtns., NE of Alamosa, Colorado.	Early Holocene	SM, ST, S, C14, & T; McCalpin,1982.
Sangre de Cristo (section B)	2. West front of Sangre de Cristo Mtns., E of San Luis, Colorado.	2-3(?) events in Holocene	ST & C14; Kirkham & Rogers, 1981.
Sangre de Cristo (section C)	3. West front of Sangre de Cristo Mtns., near Cuesta, New Mexico.	Middle to early Holocene	SM & ST; Menges, 1990.
Sangre de Cristo (section D)	4. West front of Sangre de Cristo Mtns., near Taos, New Mexico.	Early (?) Holocene	SM & ST; Machette & Personius, 1984.
Valle de Vidal	5. East side of Valle Vidal, northern New Mexico.	Late to middle Holocene	SM; Menges & Walker, 1990.
Guaye Mountain	6. West side of Espanola basin, N of Los Alamos, New Mexico.	Middle Holocene	ST, T, & C14; Kelson & others, 1993. Gardner
Rendija Canyon	7. West side of Espanola basin, N of Los Alamos, New Mexico.	Early Holocene ? or latest Pleistocene	ST, T, & C14; Kelson & others, 1993. 6
Coyote Springs	8. North flank of Ladrone Mtns., central New Mexico.	Early (?) Holocene	SM; Machette & McGimsey, 1983.
La Jencia	9. West side of La Jencia basin, central New Mexico.	1-2(?) events in Holocene	SM, ST, S, & T; Machette, 1988.
Socorro Canyon	10. East side of Socorro Mtns., S of Socorro, New Mexico.	Early (?) Holocene	SM; Machette & McGimsey, 1983.
Caballo (Williamsburg scarp)	11. Northern segment of Caballo fault, S of Truth or Consequences, New Mexico.	Late(?) Holocene maybe 2 events	SM, ST, C14, & T; Machette, 1987c, Foley & others, 1988.
Caballo	12. Central segment of Caballo fault, S of Truth or Consequences, New Mexico.	Middle Holocene	SM, ST, & T; Machette, 1987c, Foley & others, 1988.
Alamogordo	13. West flank of Sacramento Mtns, Alamogordo, New Mexico.	Early (?) Holocene	SM & ST; Machette, 1987b.
Organ Mountains	14. East flank of Organ Mtns., southern New Mexico.	2 events in Holocene	SM, S, C14, & T; Gile, 1987; Machette, 1987b.
East Franklin Mountains	15. East flank of Franklin Mtns., north of El Paso, Texas.	Early (?) Holocene	SM & ST; Machette, 1987b.
Washburn (zone)	16. East flank of Pelloncillo Mtns., W. of Animas, New Mexico.	Holocene	SM; Machette & others, 1986.
Gillespie Mtn.	17. West flank of Animas Mtns., Animas Valley, SW New Mexico.	Holocene	SM; Machette & others, 1986.
Pitaycachi (Sonora EQ)	18. East side of San Bernardino Valley, NE Sonora, Mexico	Historic (May 3, 1887)	75 km rupture, scarp height 4 m max., Bull & Pearthree, 1988.
West Lobo Valley	19. West side of Lobo Valley, W of Valentine, Texas.	Holocene (?)	SM; Machette unpubl. data, 1982; Collins & Raney, 1991.
Amargosa	20. Northeast side of Amargosa Mtns., NW Chihuahua, Mexico.	Early (?) Holocene	SM, ST; Collins & Raney, 1991.
Rincon	W. side Sandia Mtns.	Late-mid Holocene	S, SH Cornell, 1995

Ciudad Juarez just across the Rio Grande has a burgeoning population roughly estimated at 1.2 million in 1990. The largest historical earthquake to affect the El Paso region was a MM VI (cited in Collins and Raney, 1991). However, both El Paso and Juarez would be threatened by movement of the East Franklin Mountains fault, which extends through the heart of both urban areas. The East Franklin Mountains fault is just the southern one-quarter of a 182-kilometer-long fault zone that extends from south of the International Border with Mexico (in the city of Juarez) north through El Paso and Fort Bliss and into New Mexico along the west side of White Sands Missile Range and the Tularosa Basin. This fault zone is one of the longer active normal faults in the Rio Grande rift, exceeded only by the Sangre de Cristo fault zone in northern New Mexico and southern Colorado. The most recent movement on the East Franklin Mountains fault probably was in the latest Pleistocene or early(?) Holocene (J. Keaton and J. Barnes, written communication, 1995), but the fault has a history of recurrent movement as documented by Quaternary scarps as much as 60 meters high. In earlier studies, Machette (1987b) estimated that this entire fault zone is comprised of five discrete parts (fault segments), each having recurrence intervals of 10,000-20,000 years. If this is true, then a major surface-rupturing earthquake may occur, on average, about once every 2,000-4,000 years (CRI) somewhere on the 182-kilometer-long fault zone. This fault system and many others are invisible (not imaged) on seismicity maps of the Rio Grande rift.

SEISMICITY

Seismicity in the rift is relatively diffuse with few meaningful concentrations or associations with active faults (figure 3). About half of the earthquakes shown in figure 3 are within the rift, and the other half are in the Colorado Plateaus Province and, to a lesser extent, the Great Plains Province adjacent to the rift. Much of the felt (but not recorded) seismicity for the period 1849-1961 (Northrup, 1976) was concentrated along the Rio Grande Valley between Albuquerque and Socorro. The historical documentation of these earthquakes probably reflects the concentration of early settlers in towns along the Rio Grande and local sources of low to moderate seismicity. For example, the swarm of earthquakes that occurred at Soccoro in 1906 (MM VIII; Sanford and others, 1991) appears likely a result of magma movement at depth. The Socorro area continues to be a focus of small, but numerous earthquakes (figure 3). Conversely, the distribution of M≥2.5 earthquakes in New Mexico for the period of 1962-86 (figure 5 in Sanford and others, 1991), shows only a weak association with the rift and some of the transverse structures such as the Jemez lineament, which partly control the geometry of the rift (i.e., accommodation zones).

Within New Mexico between 1962 and 1986, there were only six earthquakes larger than M 3.5, and the largest (1966 Ms 4.6-4.9; Sanford and others, 1991) occurred in the Colorado Plateaus province near the border with Colorado (figure 3). The largest instrumentally recorded earthquakes in the rift have been a M 5 in 1989 near Bernardo (between Socorro and Belen, New Mexico; Sanford and others (1991) and a significantly larger Ms 6.3 earthquake in 1931 near Valentine, Texas (Doser, 1987). Although the Valentine earthquake was not quite large enough to cause surface faulting, the epicentral area has several Quaternary faults that have been active in the Holocene(?) or latest Pleistocene (table 1; Collins and Raney, 1991; Collins and others, 1996). Also, it is interesting to note that on the basis of instrumental data (through 1977), the Great Plains and Colorado Plateaus - two provinces considered to be tectonically stable—had equivalent or greater seismicity than the Rio Grande rift (Sanford and others, 1991). The most recent moderate size earthquake was an M 5.7 shock that struck Alpine, Texas (east of the rift) in April 1995. Thus, modern seismicity within the rift is remarkable only for its subdued level and lack of association with known Quaternary faults.

Even though the rift seems to be a relatively quite seismogenic region, past history shows its potential for large and devastating earthquakes. For example, the great 1887 Sonoran earthquake (Mw 7.4) of northern Mexico

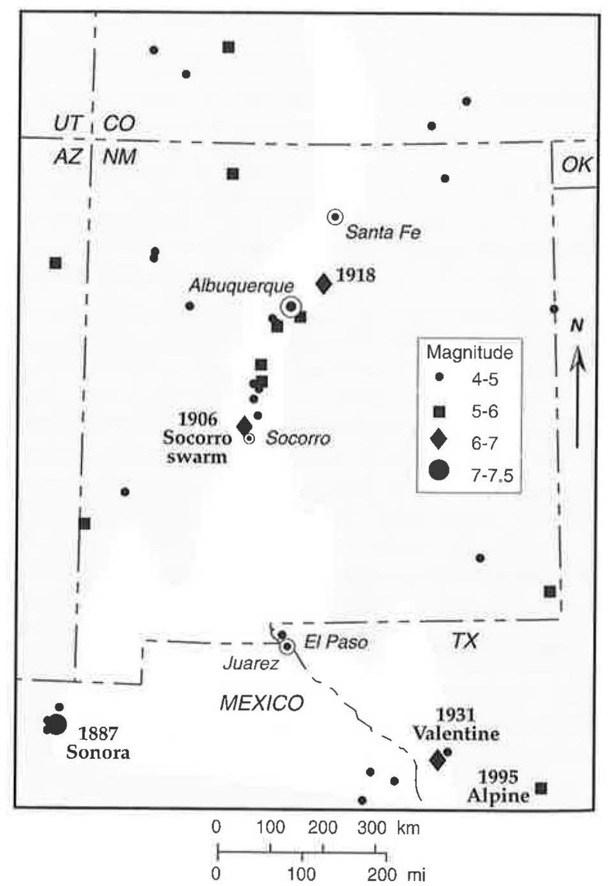

Figure 3. Map showing earthquakes with magnitudes 4.0 and greater in New Mexico and adjacent regions. Earthquakes, keyed to magnitude by symbols, are from the combined catalog used by Frankel and others (1996). The 1887 Sonora, Mexico earthquake (table 1, no. 18) is the largest historic surface-rupturing earthquake to have occurred in the region. Other large earthquakes, such as the 1931 Valentine, Texas earthquake and the 1906 Sonora, New Mexico earthquake (swarm), are discussed in the text.

has not been traditionally associated with the Rio Grande rift because the earthquake occurred in Mexico and the rift has been considered to be a largely U.S. feature. However, many of the rift structures in New Mexico and west Texas continue south into Chihuahua and Sonora. The 1887 Sonoran earthquake occurred along the Pitachychi fault (Bull and Pearthree, 1988)—a range-bounding, north-south-trending, high-angle normal fault that is a southward continuation of Quaternary faulting in the San Bernardino Valley of southwestern New Mexico (see Machette and others, 1986). As such, this fault should be considered as a modern rift structure. It has the characteristics of a major surface-rupturing rift fault (see for example Pearthree and Calvo, 1987; Machette, 1988) in that it has an extremely low slip rate and long-recurrence interval (Bull and Pearthree, 1988). Although almost forgotten because it occurred about 110 years ago, movement on the Pitachychi fault formed the longest (75 kilometers) historic surface rupture of a normal fault in North America. Tucson, then a dusty frontier town and now a major urban area of Arizona, was subject to strong ground motion and portions of the intervening countryside experienced both liquefaction and artesian water spouts.

SEISMIC HAZARDS IN THE RIO GRANDE RIFT

The scarcity of historical surface faulting (figure 2) and the general low level of seismicity of the Rio Grande rift (figure 3) has led the populace in that area to believe that earthquakes do not pose a significant threat to the region. In fact, the most recent series of USGS seismic-hazard maps (Frankel and others, 1996) indicate 1) low levels of ground acceleration (≤0.1 g) with 10 percent probability of excedance in 50 years and 2) low to moderate (≤0.3 g) levels of ground acceleration with 2 percent probability of excedance in 50 years (see figure 4a and 4b, respectively). For example, 0.10 g may be an appropriate threshold for damage to older structures (pre-1965 dwellings) or dwellings not made resistant to earthquakes (see Frankel and others, 1996). The seismic-hazard maps shown in figure 4a illustrates the domination of moderate seismicity in areas of slow extension, such as the Rio Grande rift, whereas figure 4b starts to show the affect of faults on the hazard. Thus, the populace's perceptions are well based on what has happened in New Mexico over the past several centuries. The areas of highest map-

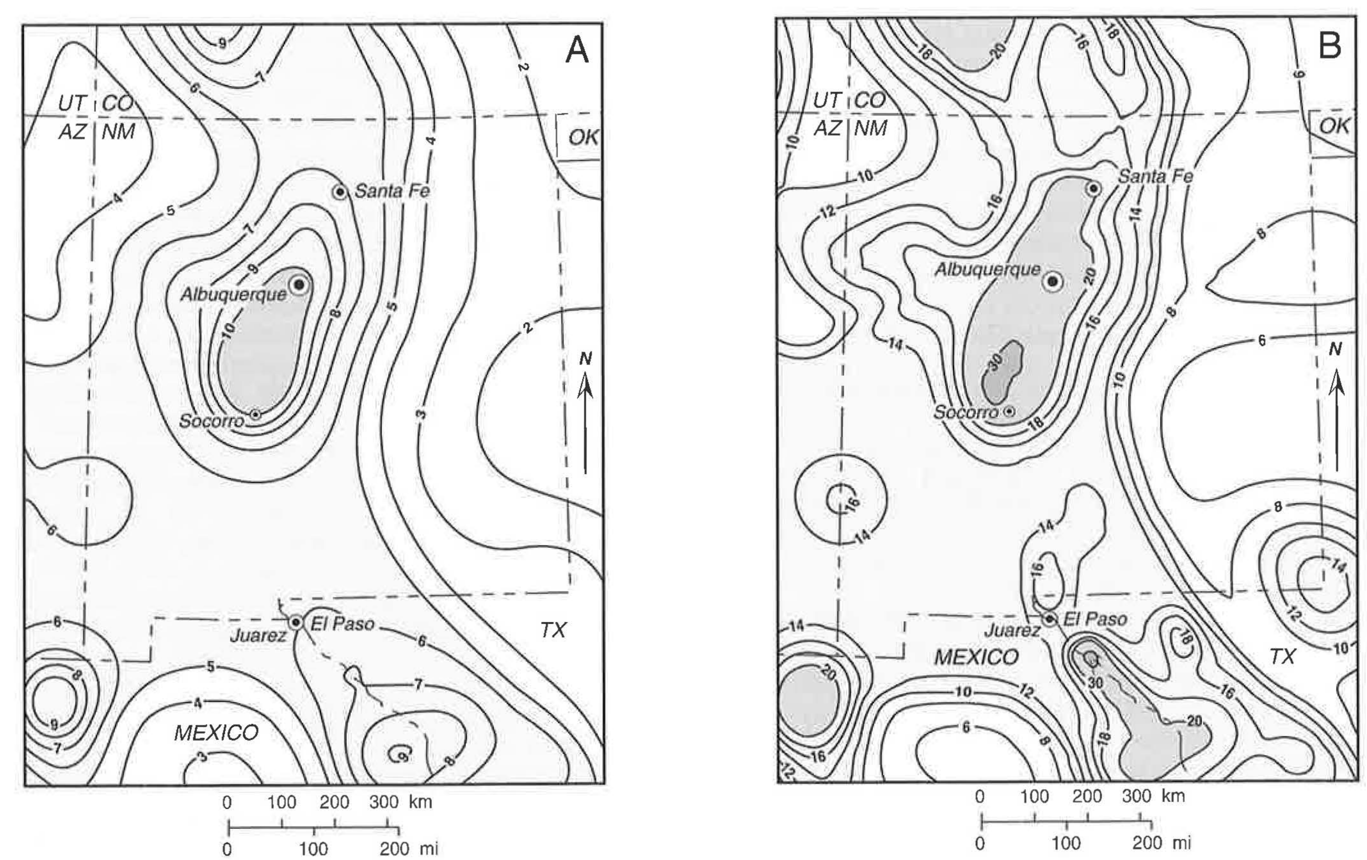

Figure 4. Recent seismic-hazard maps of the New Mexico portion of the Rio Grande rift. Maps show ground-motion hazard (contoured in percent g) at a given level of probability. A) 10 percent probability of exceedance in 50 years. B) 2 percent probability of exceedance in 50 years. Maps based on Frankel and others, 1996. Data downloaded from U.S. Geological Survey web site at http://gldage.cr.usgs.gov/eq/html/custom.shtml, which allows you to create custom ground-motin-hazard maps using varying parameters.

ped ground acceleration are centered over areas where M >4 earthquakes have occurred historically (compare figure 3 with figures 4a and 4b). Interestingly, one of the areas of large predicted ground acceleration (≤ 0.2 g, figure 4b) is centered over the 1887 Sonoran Mw 7.4 earthquake partly as a result of continued M 4 earthquakes in the area (which might be aftershocks from 1887 earthquake). Interestingly, the Pitachychi fault, on which this earthquake occurred, has an estimated recurrence interval of 100,000 years or more (see Bull and Pearthree, 1987) for large surface ruptures. Thus, although the maps indicate potential for moderate ground acceleration associated with a M <6 earthquake in Sonora, Mexico area, paleoseismologic studies predict an extremely long return time for another 1887-like M >7 earthquake.

The paleoseismic record clearly demonstrates that potentially large and devastating earthquakes may occur somewhere in New Mexico as frequently as every 750 years (or less) to as frequently as every 450 years for the rift. On this basis alone, one cannot argue that large earthquakes will not occur on low-slip (long-recurrence) faults. More likely, one might argue that these faults are typically aseismic for long intervals between movements, and that most of the seismicity that is occurring in the rift occurs as minor adjustments on a myriad of non-surface rupturing faults. In a sense, the elephant is snoring. From a geologic perspective, it seems that most major surface-rupturing, normal faults tend to be aseismic (the normal mode), but can move during M >6.25 earthquakes without significant precursory activity (foreshocks). Similarly, the Wasatch fault zone in Utah (a world-class normal fault with a Holocene slip rate of 1-2 mm/year) is currently less seismic that the surrounding basin-and-range blocks, yet it has a proven history of recurrent movement on roughly 400-year intervals during the Holocene (see Machette and others, 1991, 1992a, 1992b).

Variations in Slip Rate Through Time

When geologic data are used in probabilistic hazard assessments, one of the most important parameters is the slip rate (and the associated recurrence interval) of a fault. In regions such as the Rio Grande rift and Basin and Range Province (as a whole), reliable slip-rate data are difficult to obtain. In many cases, one must use long-term slip rates because data for recent deformation (i.e., Holocene or late Pleistocene) do not exist.

The main problem with long-term slip rates (those averaged over several to hundreds of earthquake cycles) is that there can be major variations in slip rate through time. These variations are difficult to document and many times are based on first-order observations such as geomorphology or sedimentation rates. One moderately well documented example exists for the Wasatch fault zone. On this fault, most of the slip-rate data are from faulted deposits of Holocene or latest Pleistocene age (post high stand of Lake Bonneville; 15,000 years ago). These slip rates are typically 1-2 mm/yr, but some data from the interval between 12,000 and 15,000 years ago suggest much higher slip rates, perhaps related to the catastrophic draining and crustal rebound of Lake Bonneville (see Machette and others, 1992b for a more complete discussion). Conversely, sparse data from older datums (70,000- to 140,000-year-old lake deposits) indicate much slower slip rates (i.e., 0.1-0.2 mm/yr) on the Wasatch and associated faults. Thus, in the span of one complete climatic cycle (e.g., 120,000 years), the Wasatch fault zone may have had a 10-fold variation in slip rate. This example may be somewhat extreme owing to possible lake/rebound affects, but an analysis of slip rates at Socorro, New Mexico suggests a similar potential change through time.

The Socorro Canyon fault zone (fault 10 on table 1 and figure 2) bounds the eastern margin of the Socorro Mountains, a rotated fault block which is composed of Precambrian and Paleozoic rocks and intruded by a mid-Tertiary volcanic caldera. The northern margin of the caldera is spectacularly exposed in cross section within the mountain front escarpment. The range was uplifted during early rift formation (early Miocene time), but by late Miocene time (ca. 9-10 million years ago) the range was covered by playa deposits of the Popotosa Formation. Subsequent rejuvenation of the mountain range by uplift along the Socorro Canyon fault zone has resulted in about 500 meters of local relief and about 750 meters of vertical offset of the 9-million-year-old playa deposits (C, figure 5). Although these ages and offset amounts are relatively crude estimates, they yield a long-term vertical slip rate of 0.08 mm/yr (750 m in 9 million years).

Two additional datums are present across the fault zone for temporal comparison of slip rate: 4.1- to 4.5-million year-old basalts and a early Quaternary (ca. 750,000 years) piedmont surface. These datums have about 200 meters and 25 meters of vertical offset, respectively (see A and B, figure 4). Using the three datums, the slip rate on the Socorro Canyon fault zone appears to have slowed from about 0.18-0.20 mm/yr in the latest Miocene, to about 0.05 mm/yr in the Pliocene, and 0.02-0.04 mm/yr in the past 750,000 years of the Quaternary. As with the Wasatch fault zone, there appears to be a 5- to 10-fold change (decrease in this case) in slip rate and, by inference, seismic activity along the Socorro Canyon fault zone. The youngest slip rate is extremely slow (0.02-0.04 mm/yr) and the recurrence interval is probably on the order of 50,000-100,000 years, but the fault is characteristic of many other major faults within the rift. The most recent surface-rupturing event on the Socorro Canyon fault zone appears to have occurred in latest Pleistocene time (Machette and McGimsey, 1983), and thus would be considered to be an active fault in the seismic-hazards sense.

Hazard versus Recurrence Time

In regions of high seismicity such as the West Coast, many Holocene faults have a record of movement that suggests relatively high rates of slip (>5 mm/year), short recurrence intervals (hundreds to a thousand years), and are often associated with ongoing seismicity. Thus, these faults pose an obvious hazard and are recognized as such. However, as we know, much of the Rio Grande rift is characterized by faults with low slip rates and long recurrence intervals; they are most often not associated with

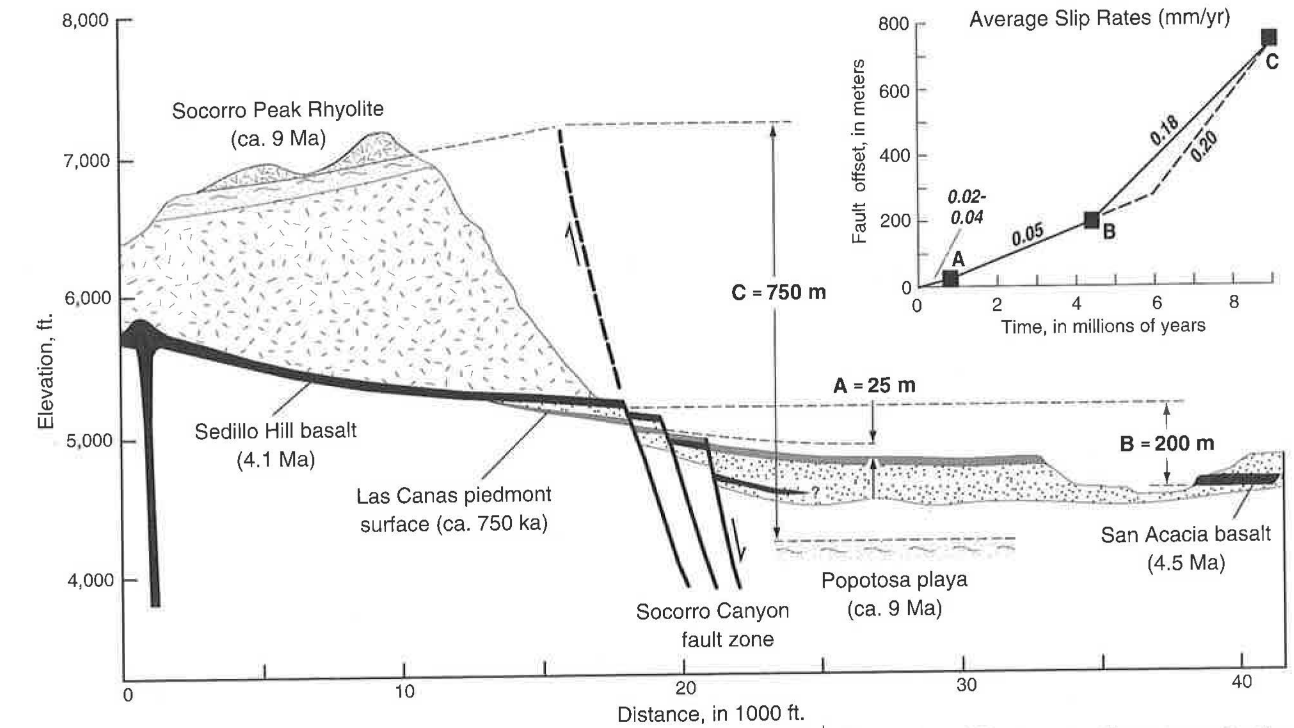

Figure 5. Schematic cross section near Socorro, New Mexico, showing evidence for late Cenozoic and Quaternary slip rates on the Socorro Canyon fault zone. Three age datums exist in the area: playa deposits of the Popotosa Formation (overlain by ca. 9-million-year-old rhyolite of Socorro Peak), early Pliocene basalts (4.1 - 4.5 million years old) that flowed on Rio Grande sediment (Sierra Ladrones Formation), and the uppermost piedmont-slope surface (Las Canas; ca. 750,000 years old) related to an ancient basin floor of the Rio Grande valley. The amounts of offset are estimates based on geologic mapping and stratigraphic relations in the area.

obvious patterns of seismicity and thus appear to be inactive (aseismic). This relation suggests the question of which faults pose more of a seismic hazard in terms of earthquake occurrence: a late Holocene (e.g., 1,000- to 2,000-year-old) fault with a 40,000-year recurrence interval or a 35,000-year-old fault with a 40,000-year recurrence interval? The answer may seem obvious from a geologic (i.e., deterministic) viewpoint, but most probabilistic seismic-hazard assessments, which are driven by patterns and rates of modern seismicity, see the younger fault as the potential hazard and minimize (or ignore) the older fault. Rarely is there adequate fault-timing information to make a meaningful deterministic assessment.

Preservation of Paleoseismic Evidence

Another problem that must be considered in regional analyses of fault activity is the preservation of the geologic record. Detailed analysis of subsurface well-logs, geologic mapping, and geophysical data from the Albuquerque basin by Hawley (1996) reveals a complex pattern of late Cenozoic deformation (figure 6), far more complex then previously determined from reconnaissance mapping of the basin. Although most of the faults in the subsurface strike north-south, there are a large number of subordinate faults that strike northeast-southwest. Previous mapping did not reveal surficial evidence for these cross-basin faults, perhaps because the prevailing paradigm was one of Quaternary north-south faulting related to east-west extension. However, recent surficial geologic mapping and the excellent subsurface work by Hawley (1996) is starting to reveal relations between the fault patterns shown in figure 6 and the location and lateral extent of young volcanic centers, deep basins, and the Quaternary geology of the basin.

The preservation of surficial evidence of this complex structural pattern is another complication in seismic-hazards analysis for this particular area, and likely for other basins of the rift. For example, large parts of the landscape in the Rio Grande rift are formed by either high-level surfaces related to tne early Pleistocene filling of the basins (prior to Rio Grande entrenchment) or are formed by latest Pleistocene (10,000-30,000 year old) sediment in alluvial-fan complexes or in entrenched stream valleys (figure 7). If faults in such basins have average recurrence intervals of 50,000-100,000 years, then virtually all faults would be recorded on the high-level surfaces whereas only some of the faults would be expected to have disturbed surfaces of late Pleistocene or Holocene age. Thus, in regions where faults are characterized by long recurrence intervals (10,000-100,000 years), one must look at a geologic record that is at least one recurrence interval long (or longer) in order to capture spatial and temporal patterns of faulting. Additional research using subsurface methods (high-resolution seismic reflection, geophysical surveys, analysis of water-well data, etc.) are needed to detect potentially active faults in areas of young landscape. One should note that most of the older buildings in the business districts of Albuquerque and El Paso are located close to the Rio Grande on young, low, flood-plain surfaces.

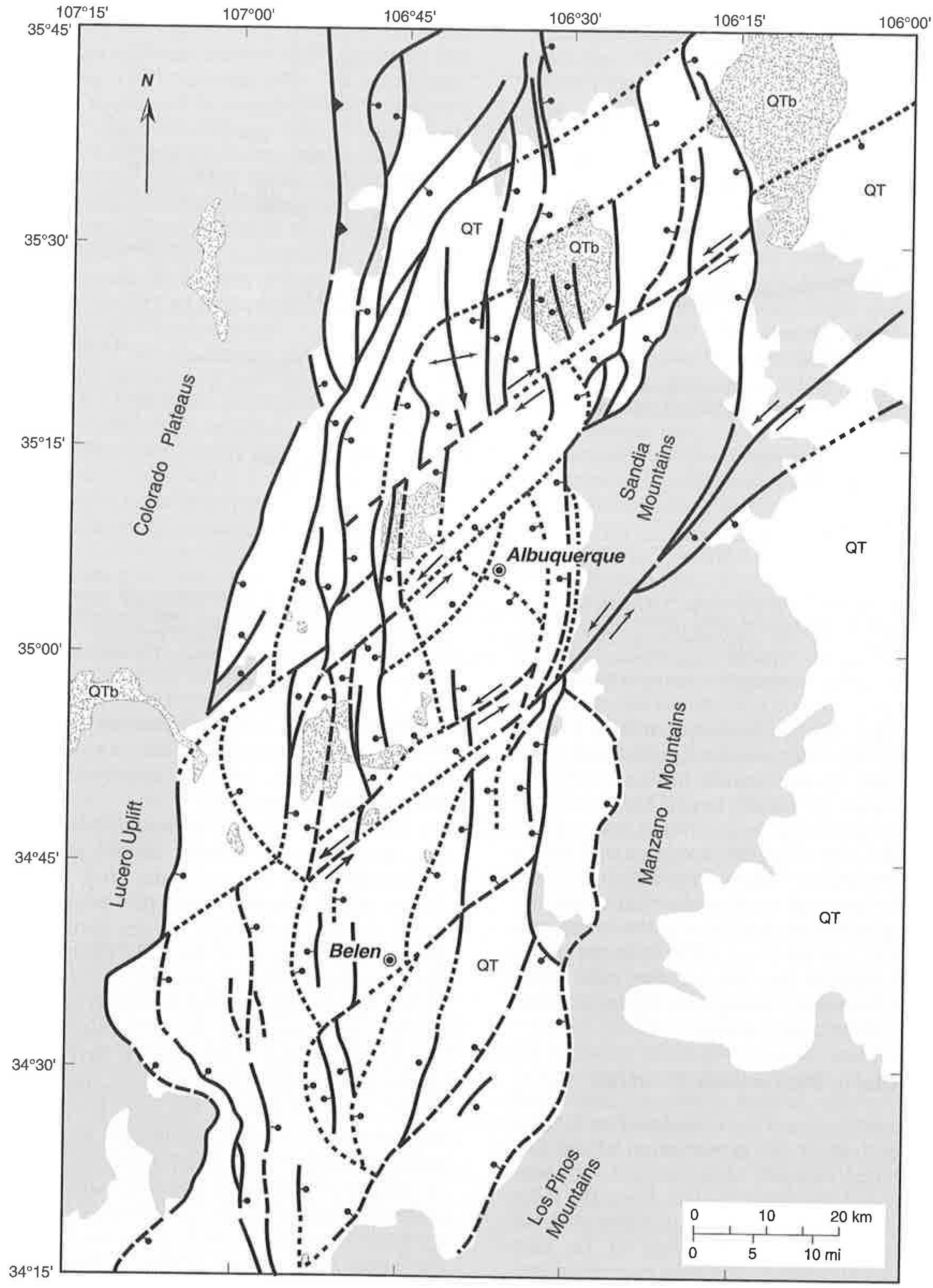

Figure 6. Late Cenozoic (Pliocene and Quaternary) faulting in the Albuquerque basin, middle Rio Grande rift. Fault pattern (simplified here) was determined by Hawley (1996) on the basis of detailed analysis of subsurface wells, geophysical data, and geologic mapping. Note the bimodel distribution of faults: predominately north-south with northeast-trending faults that accommodate disparate basin geometries and/or transfer slip. The basin deposits are shown as QT (undifferentiated Quaternary and upper Cenozoic sediment, light stipple pattern); Pliocene and Pleistocene basalts as QTb (v-pattern), and Tertiary and older bedrock (dark stippled pattern).

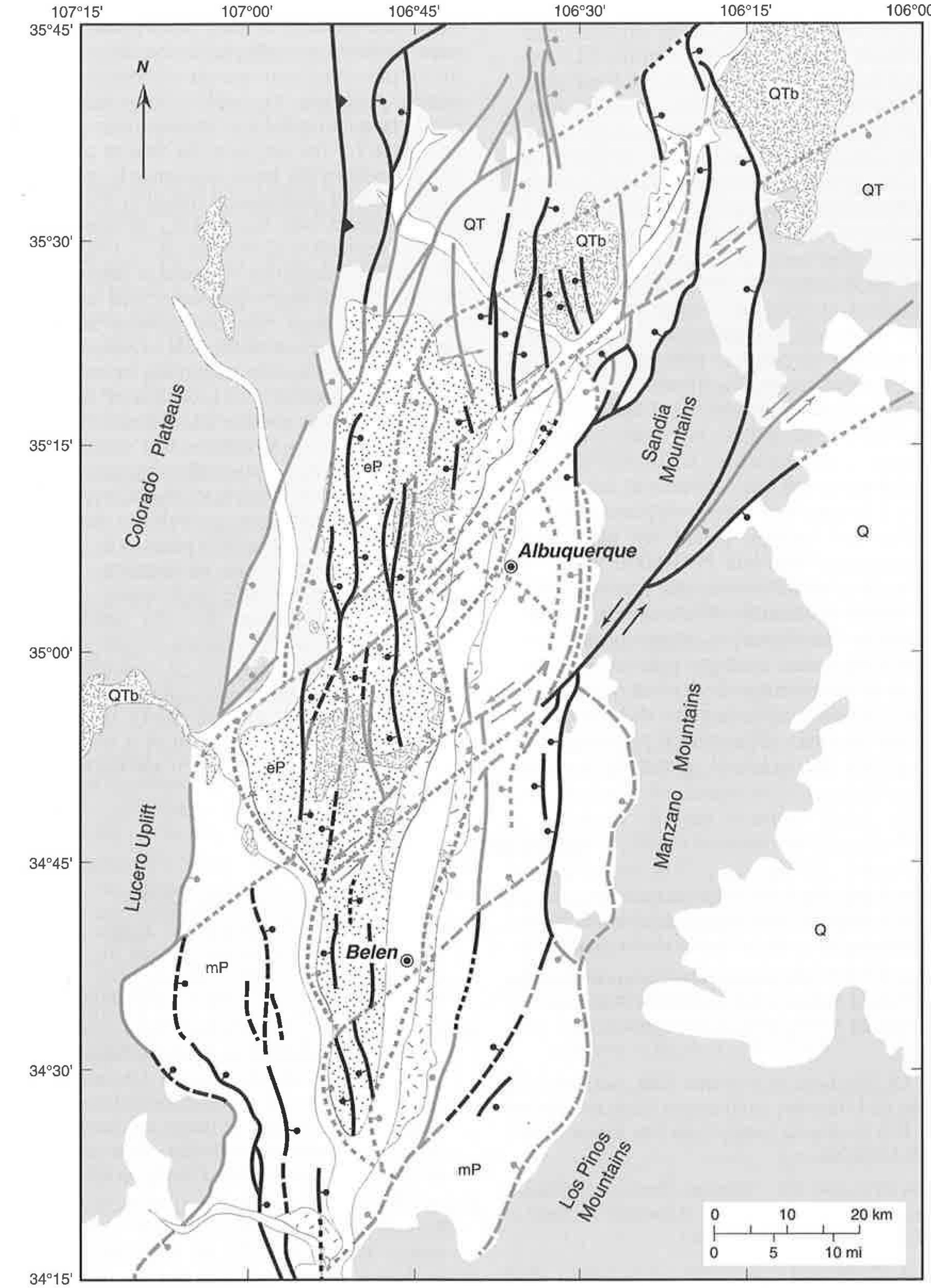

Figure 7. Quaternary faults and generalized geology of the Albuquerque basin, middle Rio Grande rift. Faults with surficial evidence of Quaternary movement are shown in black; those without such evidence are shown in gray (data from unpublished compilation; see Machette and others, 1996). Symbols: QTb, Quaternary and late Cenozoic basalts; QT, undivided basin deposits; eP, early Pleistocene sediment; mP, middle Pleistocene sediment; lP, late Pleistocene sediment; and H, Holocene sediment. Bedrock is shown by the darkest stippled pattern.

A GEOLOGIC PERSPECTIVE

From a geologic viewpoint, it seems obvious that modern seismic-hazard assessments for regions like the Rio Grande rift must use not only catalogs of modern seismicity, but also must integrate data from a comprehensive inventory of Quaternary faults, especially those structures showing evidence of movement in the past 100,000 years. By doing so, the geologic data will portray the true potential for surface-rupturing earthquakes on a time frame equivalent to the average earthquake cycle (10,000- to 100,000- year recurrence intervals). Once accomplished, the probability of occurrence of large earthquakes on individual structures may prove to be extremely low, but the location of these potential, strong-ground-motion-generating structures will be known in relation to urban areas and critical facilities. In addition, the hazard posed by numerous low-slip-rate faults within a given radius (e.g., 50-100 kilometers) of a town, city, or critical facility results in a composite recurrence interval (CRI) that can be just a fraction (i.e., 1/10th) of each individual fault. A myopic approach of not appreciating the potential for earthquake hazards posed by individual structures (i.e., recurrence intervals of 10,000 years or more) can lead to a complacent attitude that strengthens a perception of low seismic potential. Without proper caution, this attitude can be manifested in inappropriate construction styles, building codes, land-use policies, and the siting (or relocation) of important or critical facilities.

Various mitigation strategies require different portrayals of earthquake hazard. Emergency planning and disaster response plans, for example, generally require information regarding the potential effects of a large earthquake that are possible, but perhaps unlikely to occur. Their intention is to base such plans on a worst-case or near-worst-case earthquake scenario. If response plans are in place and can operate effectively for such an earthquake, response to smaller-magnitude earthquakes can easily be accomplished. Probabilistic ground-motion hazard maps for the engineering design of buildings of standard construction have customarily used a 1/500 annual probability of exceedance (roughly 10 percent in 50 years) as a standard (see figure 4a). In some circumstances, a lower probability (2 percent in 50 years, figure 4b) might be used for facilities of special interest. These ground-motion hazard maps generally will not reflect the influence of the large rare earthquakes in the rift that have recurrence times of thousands of years since the probability of that earthquake occurring in any 50-year period is low. On the other hand, design of important or critical facilities such as nuclear and defense facilities, reservoirs, hospitals, and any structures that should remain in service following a large earthquake are generally engineered to stricter standards and may make use of ground-motion estimates at very low probability levels (i.e., 1/10,000 annual or 5 percent in 500 years). In this case, the occurrence of rare, but large earthquakes on long-recurrence faults is of considerable importance. Thus, as paleoseismological information for the western United States becomes more widely known to user communities and to the public, there likely will be concerns and controversies over what is considered acceptable levels of risk. Clearly, resolution of such seismic-safety issues will require the cooperation and participation of a wide range of users of earthquake-hazard information and the research community.

REFERENCES

Bull, W.A., and Pearthree, P.A., 1988, Frequency and size of Quaternary surface ruptures of the Pitaycachi fault, northeastern Sonora, Mexico: Bulletin of the Seismological Society of America, v. 78, p. 956-978.

Collins, E.W., and Raney, J.A., 1991, Tertiary and Quaternary structure and paleotectonics of the Hueco basin, trans-Pecos Texas and Chihuahua, Mexico: [Texas] Bureau of Economic Geology Geological Circular 91-2, 44 p.

Collins, E.W., Raney, J.A., Machette, M.N., Haller, K.M., and Dart, R.L., 1996, Map and data for Quaternary faults in west Texas and adjacent parts of Mexico: U.S. Geological Survey Open-File Report 96-002, 74 p., 1 plate, scale 1:500,000.

Doser, D.I., 1987, The 16 August 1931 Valentine, Texas, earthquake—Evidence for normal faulting in west Texas: Bulletin of the Seismological Society of America, v. 77, p. 2005-2017.

Fenneman, N.M., 1931, Physiography of western United States: New York, McGraw-Hill Book Co., 534 p.

Gile, L.H., 1987, Late Holocene displacement along the Organ Mountains fault: New Mexico Bureau of Mines and Mineral Resources Bulletin 116, 43 p.

Foley, L.L., LaForge, R.C., and Piety, L.A., 1988, Seismotectonic study for Elephant Butte and Caballo Dams, Rio Grande project, New Mexico: U.S. Bureau of Reclamation Seismotectonic Report 88-9, 60 p., 3 appendices, 1 pl., scale 1:24,000.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E.V., Dickman, N., Hanson, S., and Hopper, M., 1996, National Seismic Hazards Maps—Documentation June 1996: U.S. Geological Survey Open-File Report 96-532, 110 p. (see also http://gldage.cr.usgs.gov/eq/).

Hawley, J.W., 1996, Hydrogeologic framework of potential recharge areas in the Albuquerque basin, central Valencia County (Chapter 1), in Whitworth, T.M., and Hawley, J.W, editors, Hydrogeology of potential recharge and hydrogeochemical modeling of proposed artificial-recharge methods in basin- and valley-fill aquifer systems, Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 402-D, various pagination.

Kelson, K.I, Hemphill-Haley, M.A, Wong, I.G., Gardner, J.N., and Reneau, S.L., 1993, Paleoseismologic studies of the Parajito fault system, western margin of the Rio Grande rift near Los Alamos: Geological Society of America Abstracts with Program, v. 25, no. 5, p. 61-62.

Kirkham, R.M., and Rogers, W.P., 1981, Earthquake potential in Colorado - A preliminary evaluation: Colorado Geological Survey Bulletin 43, 171 p., 3 pls., scale 1:500,000.

Machette, M.N., 1987a, Neotectonics of the Rio Grande rift, New Mexico: Geological Society of America Abstracts with Program, v. 19, no. 7, p. 754.

—1987b, Preliminary assessment of paleoseismicity at White Sands Missile Range, southern New Mexico - Evidence for recency of faulting, fault segmentation, and repeat intervals for major earthquakes in the region: U.S. Geological Survey Open-File Report 87-444, 46 p.

—1987c, Preliminary assessment of Quaternary faulting near Truth or Consequences, New Mexico: U.S. Geological Survey Open-File Report 87-652, 40 p.

—1988, Quaternary tectonic history of the La Jencia fault, central New Mexico: U.S. Geological Survey Professional Paper 1440, 82 p., 25 figs., 23 tables, 2 pls., scale 1:48,000.

Machette, M.N., and Hawley, J.W., 1996, Neotectonics of the Rio Grande rift, New Mexico: Geological Society of America Abstracts with Program, v. 28, no. 7, p. A-271.

Machette, M.N., and McGimsey, R.G., 1983, Quaternary and Pliocene faults in the Socorro and western part of the Fort Sumner 1 x 2 quadrangles, central New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF-1465-A, 12 p., 1 pl., scale 1:250,000.

Machette, M.N., and Personius, S.F., 1984, Map showing Quaternary and Pliocene faults in the east part of the Aztec 1 x 2 quadrangle and west part of the Raton 1 x 2 quadrangle, northern New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF-1465-B, 14 p., 1 pl., scale 1:250,000.

Machette, M.N., Personius, S.F., Menges, C.M., and Pearthree, P.A., 1986, Map showing Quaternary and Pliocene faults in the Silver City 1 x 2 quadrangle and the Douglas 1 x 2 quadrangle, southeastern Arizona and southwestern New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF-1465-C, 20 p., 1 pl., scale 1:250,000.

Machette, M.N., Personius, S.F., Kelson, K.I., and Seager, W.R., 1996, New digital map and computer database of Quaternary faults and folds in New Mexico: Geological Society of America Abstracts with Program, v. 28, no. 7, p. A-377.

Machette, M.N., Personius, S.F., Nelson, A.R., Schwartz, D.P., and Lund, W.R., 1991, The Wasatch fault zone, Utah—Segmentation and history of Holocene earthquakes, in Hancock, P.L, Yeats, R.S., and Sanderson, D.J., editors, Characteristics of active faults (Special Issue): Journal of Structural Geology, v. 13, p. 137-149.

Machette, M.N., Personius, S.F., Nelson, A.R., 1992a, The Wasatch fault zone, U.S.A.: Annales Tectonicae, v. 6, Supplement, p. 5-39.

—1992b, Paleoseismology of the Wasatch fault zone—A summary of recent investigations, conclusions, and interpretations, in Gori, P. L., and Hays, W.W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500-A, p. A1-A71.

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 77, no. 3, 97 p., 1 pl., scale 1:250,000.

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, Chapter 7, in Krinitzsky, E.L., and Slemmons, D.B., editors, Neotectonics in earthquake evaluation: Geological Society of America Reviews in Engineering Geology, v. 8. p. 131-156.

Menges, C.M., and Walker, J., 1990, Geomorphic analyses of scarps along the eastern border of the Valle Vidal, north-central New Mexico, in Bauer, P.W., Lucas, S.G., Mawer, C.W., and McIntosh, W.C., editors, Tectonic development of the southern Sangre de Cristo Mountains: New Mexico Geological Society Guidebook, 41st Field Conference, p. 431-438.

Nakata, J.K., Wentworth, C.M., and Machette, M.N., 1982, Quaternary fault map of the Basin and Range and Rio Grande rift provinces, western United States: U.S. Geological Survey Open-File Report 82-579, 2 pls., scale 1:2,500,000.

Northrup, S.A., 1976, New Mexico's earthquake history, 1849-1975: New Mexico Geological Society Special Publication 6, p. 77-87.

Pearthree, P.A., and Calvo, S.S., 1987, The Santa Rita fault zone—Evidence for large-magnitude earthquakes with very long recurrence intervals, Basin and Range Province of southeastern Arizona: Bulletin of the Seismological Society of America, v. 77, p. 90-116.

Sanford, A.R., Jaksha, L.H., and Cash, D.J., 1991, Seismicity of the Rio Grande rift in New Mexico" (Chapter 12), in Slemmons, D.B, Engdahl, E.R., Zoback, M.D., and Blackwell, D.D., editors., Neotectonics of North America: Geological Society of America Decade of North American Geology Map Volume 1, p. 185-228.

Schwartz, D.P., and Coppersmith, K.J., 1984, Fault behavior and characteristic earthquakes—Examples from the Wasatch and San Andreas fault zones: Journal of Geophysical Research, v. 89, no. B7, p. 5681-5698.

Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, no. 4, p. 974-1002.