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QUATERNARY FAULTS IN THE ALBUQUERQUE AREA—AN UPDATE

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Abstract—More than two dozen faults and fault zones offset Quaternary deposits in the northern Albuquerque basin of the Rio Grande rift near Albuquerque, New Mexico. At least five faults near Albuquerque (County Dump, East Paradise, Hubbell Spring, Rincon, and Tijeras-Cañoncito) have demonstrated movements in the late Quaternary, but little is known about the paleoearthquake history of most faults in the basin, so other young faults will undoubtedly be identified in future investigations. Most Quaternary faults in the northern Albuquerque basin have low rates of slip (<0.2 mm/yr) and long recurrence intervals (tens of thousands of years or longer) between surface-faulting earthquakes. However, limited paleoseismic data indicate typical individual coseismic displacements of 1–2 m and fault rupture lengths of 20–30 km; such data indicate maximum paleoearthquake moment magnitudes (**M**) of 7 or greater. Earthquakes of this size on any nearby faults would cause extensive damage to the rapidly growing Albuquerque-Rio Rancho metropolitan area.

INTRODUCTION

The primary purpose of this paper is to provide geologic information useful for seismic-hazard evaluations in the Albuquerque basin, a prominent structural element of the Rio Grande rift in central New Mexico. Seismic-hazards studies of regions of low to moderate seismicity commonly rely on geologic (paleoseismic) studies of Quaternary faults to provide long-term information on earthquake recurrence to complement historical earthquake catalogs. Paleoseismic studies are especially important in areas such as the Basin and Range province and Rio Grande rift, where recurrence intervals between large earthquakes on individual faults commonly exceed the length of the historical seismic record. The historical record of seismicity of northern New Mexico (1849–present; Northrop, 1976, 1982; House and Hartse, 1995) is typical of much of the Intermountain West in showing little association between patterns of diffuse seismicity and mapped Quaternary faults. Seismic-hazards studies based solely on seismic catalogs may underestimate the long-term seismic hazards in the Albuquerque basin and elsewhere in the Rio Grande rift.

Despite the general lack of damaging earthquakes in the 150-year recorded history of the Albuquerque basin (Northrop, 1976, 1982; House and Hartse, 1995), the presence of numerous Quaternary faults in the region attests to the past occurrence of large, surface-rupturing earthquakes. Faults in the Albuquerque basin portion of the Rio Grande rift can be grouped as: (1) a series of normal faults that form the steep western margin of the Sandia, Manzanita, and Manzano Mountains; (2) a larger group of intrabasin normal faults that offset the floor of the Albuquerque basin; and (3) poorly exposed transverse structures that allow accommodation between zones of differing fault polarity (Hawley and Whitworth, 1996; Machette, 1998). The most prominent transverse structure, the Tijeras-Cañoncito fault system, forms an accommodation zone that divides the Albuquerque basin into an east-tilted domain to the north and a west-tilted domain to the south (Russell and Snelson, 1994).

The Quaternary age of the faults shown in Figure 1 is based on the presence of fault scarps on and/or offset of deposits thought to Quaternary in age. (Herein we use the following Quaternary age designations, as described in Machette et. al. (1998): Holocene—<10 ka; latest Pleistocene 10–15 ka; late Pleistocene—10–130 ka; middle Pleistocene—130–750 ka; early Pleistocene—750–1600 ka; late Quaternary—<130 ka; late and middle Quaternary—<750 ka). Unfortunately, very few surficial deposits in the northern Albuquerque basin have been radiometrically dated, so most age determinations are based on geologic mapping and correlations to detailed soils studies in the region (e.g., Machette, 1985; Connell, 1995; GRAM Inc. and William Lettis & Associates, Inc., 1995). The Quaternary age of some faults included in this report is based on offset of ancient basin-floor surfaces such as the Llano de Albuquerque and Llano de Manzano, which represent the culmination of Santa Fe Group deposition and subsequent abandonment caused by integration of the modern Rio Grande drainage system. The ages of these ancient surfaces also are poorly known. Earlier studies (e.g., Machette, 1985) used soils data to calculate an age of ~500 ka for the Llano de Albuquerque, but ongoing mapping, tephrochronology, and radiometric dating of volcanic rocks suggests that these surfaces may be 1 Ma or older in the northern Albuquerque basin. However, detailed paleoseismic studies on one of these faults (County Dump fault) reveal evidence of recurrent coseismic movements throughout the Quaternary, so we have assumed that faults with similar geomorphic expression probably have similar histories and thus are included in this compilation.

This paper is an update of Machette's (1982) summary of Quaternary faults in the region and summarizes data from a recently completed statewide assessment of Quaternary faults in New Mexico (Machette et al., 1998). Herein we briefly describe what is presently known about the mapped extent, age, and rate of activity of several dozen faults with known or suspected Quaternary movement in the northern Albuquerque basin. Table 1 is a summary of pertinent data relating to each fault plotted on Figure 1. Figure 1 and the summaries below are intended only as a general guide to fault locations; please refer to Machette et al. (1998) and references cited therein for more precise fault locations and descriptive information. Readers are cautioned that the conspicuous lack of Quaternary faults in the central portion of Figure 1 may be an artifact of preservation—this area is heavily urbanized and is partly underlain by Holocene alluvium of the Rio Grande and Tijeras Arroyo, which probably hides additional structures. We fully expect that future surface and subsurface studies will reveal evidence of additional Quaternary faults in the Albuquerque area.

FAULT DESCRIPTIONS

(The following fault descriptions are keyed by number to Figure 1.)

Nacimiento fault (1)

The Nacimiento fault is an east-dipping reverse fault bordering the Laramide-aged Nacimiento uplift—an 80-km-long, 10- to 16-km-wide structural block that lies west of the Jemez Mountains and forms the eastern margin of the San Juan Basin. The Nacimiento fault forms the western margin of the uplift, and as used herein, includes the Nacimiento and Pajarito faults of Woodward (1987). The fault lies west of the western margin of the Rio Grande rift, and only the southern section of the fault extends into the Albuquerque basin (Fig. 1). Detailed mapping by Formento-Trigilio and Pazzaglia (1996, 1998) and Formento-Trigilio (1997) along the southern part of the fault near Arroyo Peñasco shows several short normal faults with both down-to-the-east and down-to-the-west displacements of Quaternary deposits. Down-to-the-east displacements may indicate normal-slip reactivation of the Nacimiento reverse fault in the late Quaternary.

Formento-Trigilio and Pazzaglia (1996, 1998) and Formento-Trigilio (1997) have conducted recent detailed studies of Quaternary faulting near Arroyo Peñasco, 10 km north of the northern margin of Figure 1. Most of the Quaternary faults mapped by Formento-Trigilio and Pazzaglia (1996, 1998) and Formento-Trigilio (1997) dip west, oppo-

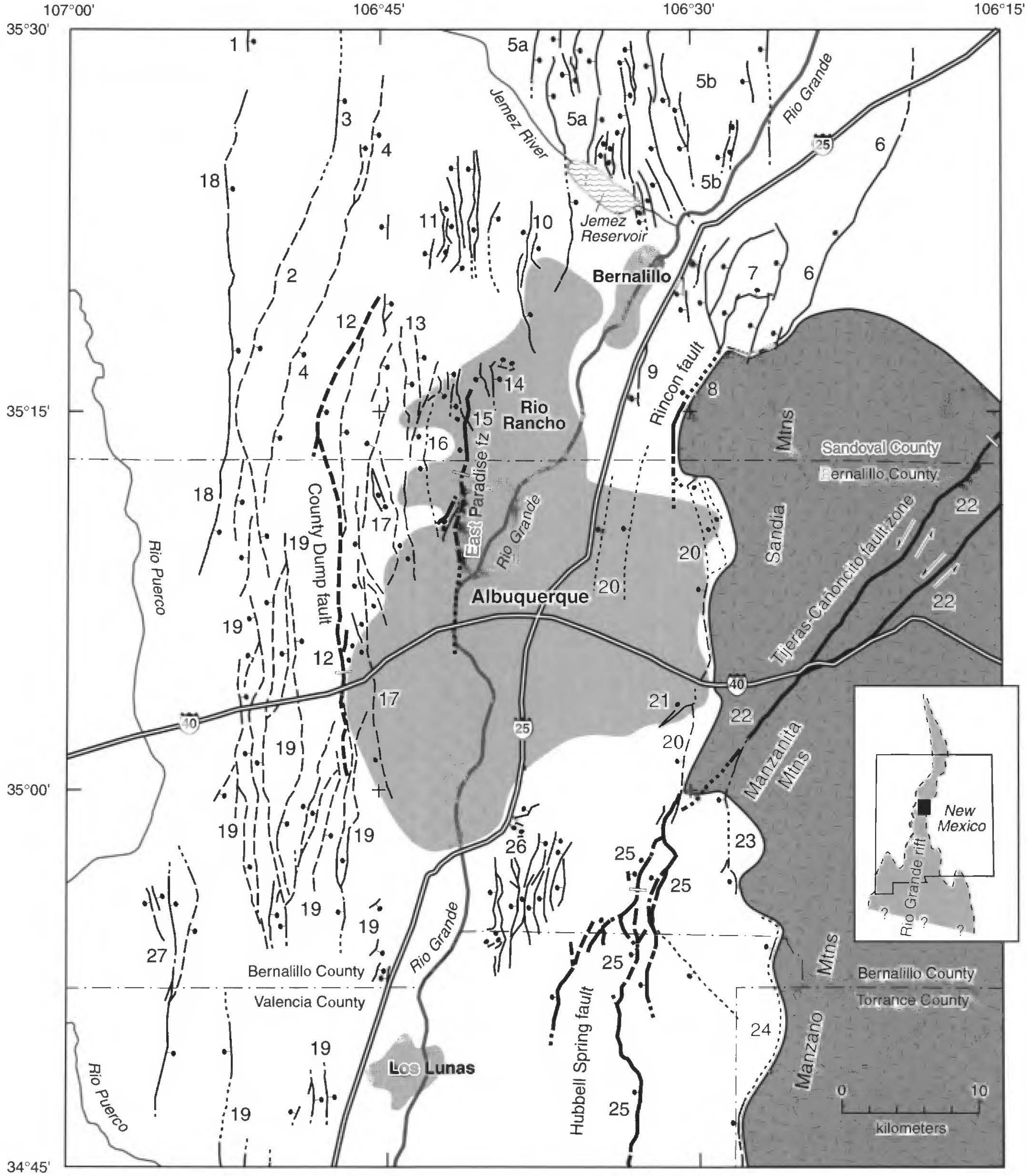

FIGURE 1. Map showing faults with known and suspected displacements in Quaternary deposits near Albuquerque, New Mexico; modified from Machette et al. (1998). Faults with known displacements in the late Pleistocene (10–130 ka) or Holocene (<10 ka) are shown with heavier line weight; hollow bars mark locations of detailed trench studies discussed in text. Shaded and stippled area depicts pre-Tertiary rocks in the Manzano, Manzanita, and Sandia Mountains; lighter shaded area depicts urbanized areas.

site to the dip of the fault mapped by Woodward (1987) in this area. These faults are short (no more than 2-km long) and are marked by scarps as much as 17-m high, although some of this apparent displacement may be related to landslides in underlying Triassic shale. Down-to-the-east Quaternary displacement of travertine-cemented alluvium on one fault strand on the north rim of Arroyo Peñasco may either represent normal reactivation on a trace of the Nacimiento reverse fault mapped by Woodward (1987), or is an antithetic splay to the down-to-

TABLE 1. Data on Quaternary faults near Albuquerque, New Mexico; modified from Machette et al. (1998). All faults have slip rates less than 0.2 mm/yr.

Fault no.	Number in database[1]	Name of fault	MRE[2]	Length[3] (km)	Fault type, dip direction
1	2002b	Nacimiento fault, southern section	<750 ka	45	Reverse, normal, E & W
2	2035	Calabacillas fault	<750 ka	40	Normal, E
3	2029b	Jemez-San Ysidro fault, San Ysidro section	<750 ka	34	Normal, E
4	2046	Zia fault	<750 ka	32	Normal, E
5a	2030a	San Felipe fault, Santa Ana section	<1.6 Ma	NA	Normal, E
5b	2030b	San Felipe fault, Algodones section	<1.6 Ma	NA	Normal, W
6	2031	San Francisco fault	<1.6 Ma	26	Normal, W
7	2043	Faults north of Placitas	<750 ka	NA	Normal, NW
8	2036	Rincon fault	<15 ka	12	Normal, W
9	2034	Bernalillo fault	<750 ka	6	Normal, W
10	2045	Unnamed faults near Loma Barbon	<1.6 MA	NA	Normal, W & E
11	2041	Unnamed faults near Picuda Peak	<1.6 MA	NA	Normal, E & W
12	2038	County Dump fault	<130 ka	35	Normal, E
13	2048	Unnamed faults near Star Heights	<750 ka	NA	Normal, E>W
14	2047	Unnamed faults near Loma Colorado de Abajo	<1.6 Ma	NA	Normal W, & Normal(?) N
15	2040	East Paradise fault zone	<130 ka	>13	Normal, W
16	2042	West Paradise fault zone	<750 ka	10	Normal, W
17	2049	Unnamed faults near Albuquerque Volcanoes	<750 ka	NA	Normal, E & W
18	2039	Sand Hill fault zone	<1.6 Ma	36	Normal, E
19	2121	Faults on the Llano de Albuquerque	<750 ka	NA	Normal, E & W
20	2037	Sandia fault	<750 ka	NA	Normal, W
21	2044	Four Hills Ranch fault	<750 ka	3	Normal(?), NW(?)
22	2033b	Tijeras-Cañoncito fault system, Canyon section	<130 ka	42	Sinistral, vertical
23	2128	Coyote fault	<750 ka	11	Normal, W
24	2119	Manzano fault	<750 ka	54	Normal, W
25	2120	Hubbell Spring fault	<130 ka	NA	Normal, W
26	2135	McCormick Ranch faults	<750 ka	NA	Normal, E & W
27	2122	Cat Mesa fault	<750 ka	20	Normal, E

[1]Fault number from Machette et al. (1998)
[2]Most recent surface-faulting event, age in ka (thousands of years) or Ma (millions of years); categories from Machette et al. (1998)
[3]Rounded length from Machette et al. (1998); NA—not applicable for groups of individual faults or complex fault zones

the-west faults mapped farther east by Formento-Trigilio and Pazzaglia (1996, 1998) and Formento-Trigilio (1997). Timing of the most recent event on this east-dipping strand, determined from uranium-series dating of faulted travertine-cemented alluvium by Formento-Trigilio (1997), constrain the age of the offset alluvium between about 270 ka and 60 ka. Formento-Trigilio and Pazzaglia (1996, 1998) and Formento-Trigilio (1997) measured 4.2-m offset of this alluvium; these data yield an average middle to late Pleistocene slip rate of 0.02–0.07 mm/yr. Formento-Trigilio and Pazzaglia (1998) calculated an average slip rate of 0.013 mm/yr for all Quaternary faults in the southern Sierra Nacimiento.

Calabacillas fault (2)

The Calabacillas fault is a prominent intrabasin down-to-the-east normal fault that offsets the Llano de Albuquerque along the western margin of the Rio Grande rift. Part of the Calabacillas fault was originally mapped by Bryan and McCann (1937, fig. 4), and later described in detail by Wright (1946). More recently, the fault was mapped and named by Cather et al. (1997). Wright (1946, p. 426–428), Kelley et al. (1976) and Kelley (1977) included the Calabacillas fault with the Sand Hill fault zone, which lies 1–2 km to the west. However, recent mapping (Cather et al., 1997) indicates that the Calabacillas fault does not intersect the Sand Hill fault zone, but rather trends northeastward and southeastward from the fault exposures described by Wright (1946). The fault location is also evident in recently acquired high-resolution aeromagnetic data (U.S. Geological Survey and SIAL Geosciences Inc., 1997; Grauch and Millegan, 1998). The Calabacillas fault probably is a southern continuation of the Jemez fault, but the name is retained herein until this connection is established in the Sky Village NE (now Cerro Conejo) quadrangle. The Calabacillas fault is expressed as discontinuous east-facing scarps along most of its length, and is intermittently exposed near its intersections with the Ceja del Rio Puerco. At these locations, the presence of sequences of downdropped colluvial deposits and interbedded calcic soils indicate repeated fault movements (Wright, 1946; Machette, 1978a; Machette et al., 1997). Minor offsets of pediment remnants on the northeast-trending section of the fault have been described north of the Ceja del Rio Puerco (Kelley, 1977).

Wright (1946) described 19 and Machette (1978a) and Machette et al. (1997) described 9 post-Llano de Albuquerque fault-scarp-derived colluvial and soil deposits adjacent to the Calabacillas fault where it intersects the Ceja del Rio Puerco. The soils developed between these fault-related deposits have strong carbonate development (Machette et al., 1997), suggesting significant periods of landscape stability between faulting events. The ages of these offset deposits are unknown, but most are probably Pliocene to middle(?) Pleistocene in age. Such a sedimentary record is clear evidence of a recurrent fault history that may extend into the late Pleistocene. A precise slip rate has not been determined, but Wright (1946) described about 45 m of accumulated fault-derived colluvial deposits on the downthrown block. Such offsets in Plio–Pleistocene deposits indicate low rates of Quaternary slip.

San Ysidro section of Jemez-San Ysidro fault (3)

The Jemez-San Ysidro fault is an east-dipping normal fault that, in part, forms the western margin of the Rio Grande rift south of the Valles caldera in the northern Albuquerque basin. The Jemez-San Ysidro fault extends from near Arroyo Piedra Parada, north to the southern rim of the Valles caldera. The fault is divided into two sections on the basis of a 45° change in fault strike at the latitude of Cañones (Wong et al., 1995): the northern Jemez section consists of northeast-striking faults (the Jemez fault of Goff and Kron, 1980), and the southern San Ysidro section consists of north-striking faults along the northwestern margin of the Albuquerque basin (the Jemez and San Ysidro faults of Woodward, 1987). Only the southern end of the fault is shown in Figure 1.

No detailed studies of Quaternary offset have been conducted along the San Ysidro section, but detailed geologic maps at a scale of 1:24,000 are available along most of the fault trace (Woodward and Ruetschilling, 1976; Woodward et al., 1977; Pazzaglia et al., 1998, unpubl., 1998). Formento-Trigilio and Pazzaglia (1996, 1998) and Formento-Trigilio (1997) recently completed mapping of Quaternary deposits and faults near Jemez Pueblo and San Ysidro, 6–11 km north of the northern margin of Figure 1. Formento-Trigilio and Pazzaglia (1996, 1998) and Formento-Trigilio (1997) measured offsets of 2–11 m in alluvial deposits along several strands of the San Ysidro section. The clearest evidence of faulting is found in deposits that contain the middle Pleistocene Lava Creek B ash, deposited about 620 ka (Izett and Wilcox, 1982; Sarna-Wojcicki et al., 1987). Formento-Trigilio and Pazzaglia (1996, 1998) and Formento-Trigilio (1997) also describe probable offset of a 100–200-ka strath terrace along the Jemez River. The timing of the most-recent event is unknown, but if a 100–200-ka fluvial terrace is offset, then the San Ysidro section has been active in the middle and probably the late Pleistocene. A precise slip rate has not been determined, but Formento-Trigilio and Pazzaglia (1996, 1998) and Formento-Trigilio (1997) measured offsets of as much as 6–11 m on several strands of the San Ysidro section in alluvial deposits containing the 620-ka Lava Creek B ash, and used these data to calculate an average slip rate of 0.013 mm/yr for all Quaternary faults in the southern Sierra Nacimiento.

Zia fault (4)

The Zia fault is one of several north-trending normal faults named by Kelley (1977) in the Rincones de Zia, in the northern part of the Albuquerque basin. Galusha (1966), Manley (1978) and F. J. Pazzaglia and colleagues (1998, unpubl., 1998) mapped the northern end of the Zia fault in the Sky Village NE (now Cerro Conejo) and Bernalillo NW quadrangles, south of the Jemez River. Recent mapping by Hawley and Whitworth (1996), Cather et al. (1997), and S. F. Personius (unpubl., 1998) extends the Zia fault farther south than originally mapped by Kelley (1977). The fault location is also expressed in high resolution aeromagnetic data (U.S. Geological Survey and SIAL Geosciences Inc., 1997; Grauch and Millegan, 1998). The down-to-the-east Zia fault is well exposed in Santa Fe Group sediment in the Rincones de Zia badlands; farther south, the fault forms broad, dissected fault scarps across the Llano de Albuquerque. The timing of the latest event is unknown, but it probably occurred in the middle or late Quaternary, based on a 0.5-m offset of middle or upper(?) Pleistocene alluvium on the Zia fault in the Bernalillo NW quadrangle as described by Manley (1978). No detailed studies of fault offset are available, but the 60 m of offset of Santa Fe Group rocks described by Kelley (1977) indicate low rates of Quaternary slip.

Santa Ana section of San Felipe fault zone (5a)

The San Felipe fault zone is a broad zone of normal faults that offset basalts of the San Felipe volcanic field (Santa Ana Mesa) and underlying Santa Fe Group sedimentary rocks in the northern part of the Albuquerque basin. Faults in this zone are well preserved as escarpments covered by basalt talus on Santa Ana Mesa; faults are poorly expressed below the Mesa rim in poorly indurated Santa Fe Group rocks, except where locally marked by clastic dikes (Soister, 1952) or strongly cemented zones. Some of the faults in this zone may be related to volcano-tectonic processes; some studies (e.g., Smith et al., 1996) suggest that displacements on such faults are accompanied by smaller earthquakes than those associated with coseismic displacements on tectonic faults. The Santa Ana section of this fault zone primarily consists of down-to-the-east normal faults that form the western flank of the San Felipe graben (Soister, 1952; Kelley, 1954, 1977; Smith et al., 1970; Kelley and Kudo, 1978; Wong et al., 1995). The Santa Ana section includes the Santa Ana, Luce, and Cocida faults of Kelley (1977) and numerous smaller displacement faults. Average displacements on most faults in the San Felipe fault zone are 15–30 m, although some larger structures, such as the Luce fault, have as much as 90–120 m of vertical displacement (Soister, 1952; Kelley, 1977) in 2.5 ± 0.3-Ma (Bachman and Mehnert, 1978) basalts of the San Felipe volcanic field. No detailed studies of the time of most recent movement have been conducted, but 90–120 m of post-San Felipe basalt displacement on some structures in this fault zone indicate a history of recurrent faulting that probably continued at least into the early Pleistocene. No precise estimates of slip rate are available, but 90–120 m of displacement of 2.5 ± 0.3-Ma San Felipe basalts yield long-term slip rates of 0.03–0.05 mm/yr.

Algodones section of San Felipe fault zone (5b)

The Algodones section of the San Felipe fault zone consists of primarily down-to-the-west normal faults that form the eastern flank of the San Felipe graben (Soister, 1952; Kelley, 1954, 1977; Smith et al., 1970; Kelley and Kudo, 1978; Wong et al., 1995). The Algodones section includes the Algodones fault of Kelley (1977) and numerous smaller displacement faults; the Algodones fault has 50–60 m of vertical displacement in 2.5 ± 0.3-Ma (Bachman and Mehnert, 1978) basalts of the San Felipe volcanic field. No detailed studies of the time of most recent movement have been conducted, but 50–60 m of post-San Felipe basalt displacement on the Algodones fault indicates a history of recurrent fault movement that probably continued at least into the early Pleistocene. No precise estimates of slip rate are available, but 50–60 m of displacement of 2.5 ± 0.3-Ma basalts of the San Felipe volcanic field yields long-term slip rates of 0.02–0.03 mm/yr.

San Francisco fault (6)

The San Francisco fault, in conjunction with the La Bajada fault (located northeast of Figure 1), forms the eastern margin of the Santo Domingo basin of the Rio Grande rift. The fault was named by Stearns (1953) after springs near the village of San Francisco, and extends from near Cochiti Pueblo south to Placitas. The fault trace shown on Figure 1 is from Machette et al. (1998) and includes the Placitas fault of Kelley and Northrop (1975), Menne (1989), Woodward and Menne (1995), and Connell et al. (1995). The northern end of the San Francisco fault is poorly expressed near Cochiti Pueblo, but its southern end occurs in a complex transition zone that marks the right-stepping margin of the Rio Grande rift at the north end of the Sandia uplift (Kelley, 1982; Woodward and Menne, 1995; Connell et. al, 1995). Topographic escarpments are associated with the northern part of the fault (Wong et al., 1995), but there are no published reports of scarps on Quaternary deposits. Hoge (1970) and Kelley (1977) map splays of the San Francisco fault that displace Quaternary deposits, but the timing of the most-recent activity is poorly constrained. Hoge (1970) considered the last movement on the fault to be early Quaternary based on displacement of older Quaternary gravel north of Placitas, although Kelley (1977) noted a lack of evidence of displacement of the early(?) Pleistocene Ortiz pediment surface. Connell et al. (1995) described movement on the Placitas (San Francisco) fault that is bracketed between offset of lower Pleistocene to upper Pliocene(?) deposits and burial by middle to lower(?) Pleistocene deposits. Near its northern end, a possible correlative splay of the fault (the Domingo fault of Smith and Kuhle, 1998) offsets lower Pleistocene Bandelier Tuff about 200 m (Smith and Kuhle, 1998). A precise slip rate has not been determined, but Wong et al. (1995) estimated a wide range in slip rate (0.01–0.58 mm/yr) and used a preferred value of 0.07 mm/yr; Kelson and Olig (1995) used a preferred value of 0.06 mm/yr for the San Francisco fault.

Faults north of Placitas (7)

A system of short, northeast-trending, down-to-the-northwest normal faults near Placitas forms part of a structural transition zone between normal faults that form the right-stepping eastern margin of the Rio Grande rift at the northern end of the Sandia uplift. At least five individual faults are included in this system, from west to east: the Valley View fault, which was first mapped by Kelley and Northrop (1975) and later named by Kelley (1977); the Ranchos fault of Kelley and Northrop (1975) and Kelley (1977); the Lomas fault of Connell (1995); the Caballo fault of Kelley and Northrop (1975) and Menne (1989); and the Escala fault of Kelley (1977). Connell (1995) and Connell et al. (1995) have recently remapped these faults in greater detail; they generally are poorly expressed as eroded slope breaks on upper Santa Fe Group rocks.

No detailed paleoseismic studies have been conducted, but detailed mapping shows that individual faults in the fault system north of Placitas offset early and middle(?) Pleistocene alluvial deposits and upper Santa Fe Group sedimentary rocks less than 100 m. The timing of the most recent events is unknown, but if the youngest deposits are middle(?) Pleistocene in age, then the youngest event probably occurred in the middle or late Quaternary. No detailed studies of fault offset or age of offset deposits are available, but data from Connell (1995) indicate that individual faults in the Placitas area have maximum vertical displacements of 20–90 m in middle(?) and early Pleistocene deposits. These data indicate low rates of Quaternary slip.

Rincon fault (8)

The Rincon fault forms the western flank of Rincon Ridge, which forms the northwestern end of the Sandia Mountains. The fault is part of the eastern, active margin of the Rio Grande rift and the Albuquerque basin, north of Albuquerque. The western side of Rincon Ridge exhibits classic faceted spur and ridge topography (Connell, 1995) that commonly is associated with active, normal-fault-controlled mountain fronts. Although the Rincon fault trace is shown on early maps (Bernalillo fault of Stearns, 1953), little detailed work was done on this structure until the geologic investigations of the Sandia Mountains by Kelley and Northrop (1975). More recently, the fault has been mapped in detail by Connell (1995), Connell et al. (1995), and Connell (1997a).

Although no definitive fault studies have been conducted, analyses of fault scarp morphology and soil development (Connell, 1995) indicate that the Rincon fault may have undergone Holocene displacement. The central 4 km of the Rincon fault are well expressed as a series of discontinuous fault scarps on alluvial-fan deposits (Connell, 1995). Connell (1995) measured single-event fault scarps with 2–3 m of offset in latest Pleistocene to middle Holocene(?) alluvial-fan deposits, and compound scarps with 6–8 m of offset in middle to late Pleistocene deposits. Connell (1995) used detailed soil stratigraphic and fault scarp morphologic studies to estimate the timing of the latest (≤5 ka) and penultimate (~100 ka) events on the Rincon fault. These time estimates yield a recurrence interval of ~105 ky. No precise estimates of slip rates are available, but 6–8 m of offset in late Pleistocene deposits and the relatively long recurrence interval suggest low long-term slip rates. Based on its geomorphic expression and timing of most recent faulting event, the Rincon fault is one of the more active faults in this part of the Rio Grande rift.

Bernalillo fault (9)

The Bernalillo fault deforms the piedmont about 1 km southeast of Bernalillo; it is one of several down-to-the-west faults that are sympathetic to the Rincon fault, which forms the eastern boundary of the Albuquerque basin and Rio Grande rift at this latitude. The fault was originally described by Lambert (1978, p. 158–159), and later named the Bernalillo fault and mapped in detail by Connell (1995). The exposed length of the Bernalillo fault is about 2 km, and is readily recognized by offset of a white diatomite bed in middle Pleistocene Rio Grande alluvium. At its northern end, the Bernalillo fault projects beneath the modern floodplain of the Rio Grande. Its southern extent is poorly constrained, but high-resolution aeromagnetic data indicate that the Bernalillo fault may step to the southeast and probably extends to the vicinity of Sandia Wash (Connell, 1995, personal commun., 1997; U.S. Geological Survey and SIAL Geosciences Inc., 1997; Grauch and Millegan, 1998).

No detailed paleoseismic studies have been conducted, but Connell (1995) measured 6–7 m of displacement in the middle Pleistocene alluvium of Edith Boulevard and possibly ≥2 m of displacement in the alluvium of middle or late Pleistocene alluvium of Menaul Boulevard. The displacement data measured by Connell (1995) indicate a history of recurrent faulting that probably extended into the late Pleistocene. No precise slip rate data are available, but offsets of 6–7 m in middle Pleistocene deposits indicate low rates of Quaternary slip.

Unnamed faults near Loma Barbon (10)

Several north-trending, down-to-the-east and down-to-the-west intrabasin faults offset upper Santa Fe Group rocks near Loma Barbon in the northern Albuquerque basin. Kelley (1977) mapped one of these structures as the southern end of the Santa Ana fault, but more recent mapping in the area (Manley, 1978; S. F. Personius, unpubl., 1998) indicates that the Santa Ana fault does not extend this far south. These faults are exposed in upper Santa Fe Group sedimentary rocks, but do not appear to offset extensive alluvial surfaces, and thus have little geomorphic expression.

No detailed paleoseismic studies have been conducted on any of the faults near Loma Barbon. These faults offset Pliocene to early Pleistocene(?) Upper Santa Fe Group sedimentary rocks, but do not appear to offset middle Pleistocene alluvial deposits. Thus, the latest events on these structures probably occurred in the early Pleistocene. No detailed studies of fault offset or age of offset deposits are available, so slip rates cannot be determined. Their lack of geomorphic expression indicate that slip rates in the Quaternary have been very low.

Unnamed faults near Picuda Peak (11)

Faults near Picuda Peak form a swarm of down-to-the-east and down-to-the-west, north-trending, intrabasin normal faults near the northern margin of the Albuquerque basin. Most of these faults trend northeastward at their southern ends near Picuda Peak; farther north, they trend generally north. Some faults near Picuda Peak were previously described by Black and Hiss (1974) and Kelley (1977). Detailed mapping in the nearly complete exposures of Santa Fe Group rocks in the Rincones de Zia (Manley, 1978; S. F. Personius, unpubl., 1998) show very closely spaced normal faults, most of which have displacements of only a few meters. Only the faults with larger displacements or those that can be mapped continuously for several kilometers are shown on Figure 1. Most faults form narrow topographic ridges and valleys that are consistent with sense of fault displacement.

No detailed paleoseismic studies have been conducted on the faults near Picuda Peak. However, detailed mapping indicates that these faults offset Pliocene to early Pleistocene(?) sedimentary rocks of the upper Santa Fe Group a few tens of meters, and do not appear to offset younger surficial deposits (S. F. Personius, unpubl., 1998). No precise slip-rate estimates are available, but offsets of Pliocene to early Pleistocene(?) conglomerates across individual faults are probably no more than 20–30 m, indicating low rates of Quaternary slip.

County Dump fault (12)

The County Dump fault is a north-trending intrabasin normal fault located along the eastern rim of the Llano de Albuquerque. The fault was originally mapped and named by Lambert (1968) for a down-to-the-east normal fault exposed at the now abandoned Bernalillo County landfill about 1.5 km north of Interstate 40. Kelley (1977) renamed this structure the Nine Mile fault and combined it with a down-to-the-west fault south of I-40 that was originally mapped by Lambert (1968). Machette (1982) used the name "Bernalillo County Dump fault" for this structure, but most workers since Kelley (1977) have used either "County Dump fault" (Machette, 1978a; Hawley and Haase, 1992) or "Nine Mile fault zone" (Hawley and Whitworth, 1996) when describing this structure. Cather et al. (1997) called the northern end of the County Dump fault the "Centipede fault" in the Sky Village SE quadrangle. Herein, we follow Machette et al. (1998) in using the name "County Dump fault" for all the down-to-the-east parts of the fault zone. Some of the fault zone is apparent in high-resolution aeromagnetic data (U.S. Geological Survey and SIAL Geosciences Inc., 1997; Grauch and Millegan, 1998).

The County Dump fault is intermittently exposed in upper Santa Fe Group rocks along the eastern rim of the Llano de Albuquerque just north and south of I-40. A broad, sand-covered, 15- to 20-m-high fault scarp marks the trace of the fault where it crosses the Llano de Albuquerque north of the Bernalillo County Dump. Farther north, the County Dump fault skirts the western margin of the Albuquerque Volcanoes, and extends northward as a broad escarpment on upper Santa Fe Group rocks and eroded remnants of the Llano de Albuquerque. The fault forms the western margin of a broad graben that confines the Albuquerque Volcanoes volcanic field. South of the Bernalillo County Dump, the fault is poorly expressed as a sand-covered escarpment before dying out about 6 km south of I-40.

Two detailed studies have been conducted along the County Dump fault. One of the first applications of quantitative soil studies to normal faulting was conducted by Machette (1978a) at the Bernalillo County Dump site. He delineated four buried soils in a sequence of colluvial and eolian deposits, and used the amounts of pedogenic calcium carbonate to estimate times of four episodes of surface faulting. In a more recent study, McCalpin (1997, unpubl., 1998) excavated six exposures along the northern face of the Bernalillo County Dump exposure, and used detailed trench logging, soils data, and thermoluminescence (TL) dating to determine a long-term slip history. McCalpin (1997, unpubl., 1998) used 6 TL ages to determine rates of pedogenic carbonate accumulation for the past ~300 ka, and then calculated ages of displaced colluvial deposits based on these soil-accumulation rates. Preliminary results include evidence for 4–13 individual events, average recurrence intervals of 40.5 ± 47.3 ka, average vertical displacements of 1.4 ± 0.7 m, and an estimated long-term slip rate of 0.02–0.05 mm/yr. The timing of the youngest event is somewhat uncertain; TL ages suggest that the most-recent surface-faulting event occurred shortly after 41 ± 6 ka and before 38 ± 3.9 ka. However, McCalpin (1997, unpubl., 1998) also found evidence of a possible younger warping event that occurred shortly before deposition of sands that have a TL age of 28 ± 3 ka. Soils analysis suggest this possible event occurred about 24 ka. Machette (1978a) used soil-accumulation rates to estimate that the youngest event occurred about 20 ka.

Unnamed faults near Star Heights (13)

Several north-trending, mostly down-to-the-east normal faults offset upper Santa Fe Group rocks, the Llano de Albuquerque, and younger alluvial deposits near the neighborhood of Star Heights. This group of north-trending normal faults includes parts of the Star Heights fault of Kelley (1977) and Hawley and Whitworth (1996). Recent detailed mapping (S. F. Personius, unpubl., 1998) indicates that the Star Heights fault mapped by Kelley (1977) and Hawley and Whitworth (1996) includes parts of at least two separate faults, so this name has been abandoned (Machette et al., 1998). Some parts of these faults are imaged in aeromagnetic data (U.S. Geological Survey and SIAL Geosciences Inc., 1997; Grauch and Millegan, 1998).

No detailed paleoseismic studies have been conducted on faults near Star Heights. However, detailed mapping (S. F. Personius, unpubl., 1998) indicates that individual faults have displacements of a few tens of meters in upper Santa Fe Group rocks, 15–20 m of the early Pleistocene(?) Llano de Albuquerque, and 5–10 m in probable middle Pleistocene alluvial deposits. The age of the most recent event is unknown, but if the youngest offset deposits are middle Pleistocene in age, then the youngest event probably occurred in the middle or late Quaternary. No precise slip-rate estimates are available, but the small amounts of slip listed above and the poor geomorphic expression of these faults indicate low rates of Quaternary slip.

Unnamed faults near Loma Colorado de Abajo (14)

The unnamed faults near Loma Colorado de Abajo can be grouped into two categories based on their strike: a set of north- to northwest-trending normal faults and a set of generally east-trending faults. Both sets of faults offset upper Santa Fe Group rocks, although poor exposures prevent determination of age relationships between the two fault sets. Some of these unnamed structures have been previously mapped (Wyant and Olson, 1978; Hawley and Whitworth, 1996), but recent mapping (S. F. Personius, unpubl., 1998) shows these faults in detail. The northwest-trending faults are typical of intrabasin normal faults in this part of the Albuquerque basin, but the sense of displacement on the east-trending faults near Loma Colorado de Abajo is open to question. Hawley and Whitworth (1996) include these structures in their Loma Colorado transfer zone, and show both left-lateral and right-lateral displacement across this zone. However, an exposure of the easternmost fault shows a north dip of 50–70°, which may be more consistent with down-to-the-north normal faulting.

No detailed paleoseismic studies have been conducted on faults near Loma Colorado de Abajo. However, these faults are only preserved in upper Santa Fe Group rocks, with the exception of the two faults on Loma Colorado de Abajo, which offset strongly developed (stage III to IV) calcic soils that may be correlative with the early Pleistocene(?) Llano de Albuquerque. No fault scarps are apparent on post Santa Fe Group surficial deposits. Offsets of 5–15 m of the upper Santa Fe Group gravels and overlying calcic soils are apparent across the two faults on Loma Colorado de Abajo (S. F. Personius, unpubl., 1998). The timing of the most recent event is unknown, but offsets of 5–15 m in early Pleistocene(?) deposits indicate a recurrent faulting history that may have extended into the middle(?) Pleistocene. However, middle and late Pleistocene deposits are not offset by these structures (S. F. Personius, unpubl., 1998). No precise slip-rate estimates are available, but the small amounts of slip listed above and the poor geomorphic expression of these faults indicate low rates of Quaternary slip.

East Paradise fault zone (15)

The East Paradise fault zone is one of several north-trending intrabasin normal faults that form a wide graben that confines the Albuquerque Volcanoes volcanic field. The East Paradise fault zone was originally recognized and mapped by Bjorklund and Maxwell (1961, pl. 1a) in Arroyo de las Calabacillas; the fault was included on some subsequent maps (Baltz, 1976; Hawley and Whitworth, 1996), but not on others (Kelley, 1977; Hawley and Haase, 1992; Hawley et al., 1995). The fault zone is not well expressed in the landscape, probably because of burial by eolian sand. North of Arroyo de las Calabacillas, the fault is poorly expressed as isolated offsets and west-facing escarpments on pre-late Pleistocene alluvium. A single west-facing, ~5-m-high scarp on alluvium is visible on 1967 airphotos just north of the Rio Rancho Golf Course, but this scarp has been destroyed by subsequent development. The fault forms aligned drainages and eroded scarps northward from the golf course to the southern edge of Arroyo de las Montoyas. No evidence of the fault has been found north of the arroyo. South of Arroyo de las Calabacillas, most of the fault trace has been destroyed by development of Paradise Hills Golf Course and housing in the surrounding communities. In this area, two short, subparallel faults (only the western fault can be shown at the scale of Figure 1) form a small graben that lies a few hundred meters west of the East Paradise fault zone. The westernmost of these faults has offsets of 1–2 m at two places in the ~155-ka basalts (Geissman et al., 1990; Peate et al., 1996) of the Albuquerque Volcanoes volcanic field. These faults may be splays of the East Paradise fault zone.

S.F. Personius (1996, unpubl., 1998) conducted an investigation of several exposures of the East Paradise fault zone in a housing excavation on the north side of Arroyo de las Calabacillas in 1996 (Fig. 1). Mapping of two exposures of the fault zone indicated a total offset of 2.75 m across middle Pleistocene fluvial and eolian deposits and showed evidence of three surface-faulting events with offsets of about 0.5, 1.0, and 1.25 m. Several thermoluminescence (TL) ages on offset deposits were used to determine ages of 208 ± 25 ka and 75 ± 7 ka for the two older events. The timing of the youngest event is uncertain, but probably occurred in the late Pleistocene, sometime after 75 ± 7 ka. These data yield a single recurrence interval of 133 ± 26 ka and average recurrence intervals of 92 ± 10 ka. However, recurrence intervals must be highly variable, because the two youngest events occurred in less than 75 ka. The age and slip data from the Arroyo de las Calabacillas exposures yield a long-term average slip rate of 0.01 ±

0.001 mm/yr.

West Paradise fault zone (16)

The West Paradise fault zone is one of several north-trending, west-dipping intrabasin normal faults in a wide graben that confines the Albuquerque Volcanoes volcanic field. An exposure of this fault zone was originally recognized and mapped by Bjorklund and Maxwell (1961, pl. 1a) in Arroyo de las Calabacillas; they mapped a down-to-the-west normal fault from Arroyo de las Calabacillas northward about 2.5 km. This fault was not included on some subsequent maps, such as Kelley (1977) and Hawley and Haase (1992), but is included in more recent compilations (Hawley et al., 1995; Hawley and Whitworth, 1996). An excellent exposure of the West Paradise fault zone is present on the north rim of Arroyo de las Calabacillas, at a sharp bend in the arroyo channel. At this site, one or more fault strands offset upper Santa Fe Group rocks an unknown amount. The fault can be traced about 4 km north of Arroyo de las Calabacillas, where it forms aligned drainages and several west-facing escarpments on upper Santa Fe Group rocks. Remnants of the Llano de Albuquerque apparently extend undisturbed across the projected trace of the fault about 300 m south of Southern Boulevard in the City of Rio Rancho, but a prominent aeromagnetic anomaly (U.S. Geological Survey and SIAL Geosciences Inc., 1997; Grauch and Millegan, 1998) extends 2–3 km north of this location. Movement on the northern part of the West Paradise fault zone may have extended north of Southern Boulevard before development of the Llano de Albuquerque. To the south, the fault projects under but does not offset basalt flows on the south rim of Arroyo de las Calabacillas. However, the fault zone can be mapped several kilometers south of Arroyo de las Calabacillas, under the basalts, with aeromagnetic data and geomorphic indicators such as rubble zones and intermittent linear breaks in slope. These geomorphic features were caused by disruption and diversion of the basalt flows across preexisting fault scarps along the trace of the fault zone.

No detailed paleoseismic studies have been conducted on the West Paradise fault zone. However, the fault zone clearly offsets early Pleistocene upper Santa Fe Group rocks and strongly developed calcic soil remnants of the early Pleistocene(?) Llano de Albuquerque. Late Pleistocene eolian sand and alluvial deposits are not offset across the fault north of Arroyo de las Calabacillas. South of Arroyo de las Calabacillas, faulting along the West Paradise fault zone predates the ~155 ka (Geissman et al., 1990; Peate et al., 1996) basalts of the Albuquerque Volcanoes volcanic field. The timing of the most recent event is unknown, but must predate the age of the Albuquerque Volcanoes basalts, and thus is middle Pleistocene or earlier. No precise slip-rate estimates are available, but the small amounts of slip listed above and the poor geomorphic expression of these faults indicate low rates of Quaternary slip.

Unnamed faults near Albuquerque Volcanoes (17)

Several unnamed north-trending normal faults are located near the Albuquerque Volcanoes. The basaltic volcanic field associated with the volcanoes is apparently confined in a broad graben, defined on the west by the down-to-the-east County Dump fault and on the east by the down-to-the-west East Paradise fault zone. A series of smaller fault blocks and grabens are present between these two flanking faults. Some of these faults are included in the West Mesa fault zone of Wong et al. (1995) and Hawley and Whitworth (1996), but we follow Machette et al. (1998) in recommending that this name be abandoned. Most faults near the Albuquerque Volcanoes appear to be buried by the ~155 ka (Geissman et al., 1990; Peate et al., 1996) basalt flows. However, some of these faults can be mapped beneath the flows because they are marked by discontinuous linear breaks in slope, indicating that preexisting fault scarps disrupted lava-flow emplacement. Some buried faults are also evident in high resolution aeromagnetic data (U.S. Geological Survey and SIAL Geosciences Inc., 1997; Grauch and Millegan, 1998). Only one fault, a short down-to-the-east fault that lies between the East and West Paradise fault zones, clearly offsets basalt in two places along the eastern edge of the volcanic field. Recent seismicity may be associated with one or more faults near the Albuquerque Volcanoes. An earthquake swarm in 1978–1979 near the southwestern margin of the volcanic field yielded a composite fault-plane solution with a preferred nodal plane striking N5°E and dipping 74°W (Jaksha et. al., 1981). This fault plane projects to the surface very near the surface trace of an unnamed, ~30-km-long, down-to-the-west fault zone that bisects the volcanic field west of the West Paradise fault zone. The east-dipping County Dump fault is located between the surface trace of this fault zone and the surface projection of the 1978–1979 earthquake swarm, suggesting that the County Dump fault may sole into the fault zone at depth. North of the volcanic field, these faults are well expressed as eroded fault scarps on upper Santa Fe Group rocks and overlying surficial deposits. Most of the fault traces near the volcanic field have been partly to completely covered by eolian sand.

No detailed paleoseismic studies have been conducted on faults near the Albuquerque Volcanoes. However, at least one of these structures offsets the ~155 ka (Geissman et al., 1990; Peate et al., 1996) basalts of the Albuquerque Volcanoes volcanic field. Most of the faults cut upper Santa Fe Group rocks and surficial deposits that predate emplacement of the basalts. The timing of the most recent events on these fault are unknown, but the fault that offsets the 155-ka basalts probably has been active in the late Pleistocene. Most of the other faults have most recent movements that predate 155 ka, but probably occurred in the middle Pleistocene. No precise slip-rate estimates are available, but one fault offsets the 155-ka basalts of the Albuquerque Volcanoes volcanic field 1-2 m; these data yield late Quaternary slip rates of 0.006–0.01 mm/yr on at least one fault near the Albuquerque Volcanoes.

Sand Hill fault zone (18)

As used in this compilation, the Sand Hill fault zone is a down-to-the-east normal fault zone that extends from about 9 km south of the Sandoval-Bernalillo County line, northward along the Ceja del Rio Puerco to the vicinity of Cañada de las Milpas. The Sand Hill fault zone was first named, mapped, and described by Bryan and McCann (1937), and has subsequently been mapped in various degrees of detail by Wright (1946), Kelley et al. (1976, fig. 19), Kelley (1954, 1977), and Cather et al. (1997). Very little is known about the Quaternary history of the Sand Hill fault zone, other than that it cuts sedimentary rocks of the upper Santa Fe Group and is buried by younger surficial deposits. This fault zone is one of several north-trending faults that form the western boundary of the Rio Grande rift in the northern part of the Albuquerque basin. The fault is well expressed as linear breaks in slope in the eroded Santa Fe Group badlands below the western edge of the Llano de Albuquerque. No fault scarps on surficial deposits have been described along the Sand Hill fault zone.

No detailed paleoseismic studies have been conducted on the Sand Hill fault zone. The trace of the Sand Hill fault zone as originally mapped by Bryan and McCann (1937) lies entirely within the upper buff member of the Santa Fe Formation, which is roughly correlative with the Sierra Ladrones Formation (Machette, 1978b) of the upper Santa Fe Group (Hawley et al., 1991). In places the upper part of these deposits may be of early Pleistocene age. The timing of the most recent event is unknown, and no precise slip-rate estimates are available. The poor geomorphic expression of this fault indicates low rates of Quaternary slip.

Faults on the Llano de Albuquerque (19)

This widespread group of north-trending normal faults forms a series of horsts and grabens on the Llano de Albuquerque. The thick cover of eolian sand that covers most of the Llano de Albuquerque explains why faults of varying orientations have been mapped in this area (Kelley et al., 1976; Kelley, 1977; Machette, 1982; Machette and McGimsey, 1983; Hawley and Haase, 1992; Wong et al., 1995; Hawley and Whitworth, 1996). Named faults include several strands of the West Mesa fault zone area (Wong et al., 1995; Hawley and Whitworth, 1996) and the Atrisco fault (Hawley and Haase, 1992). However, we follow

Machette et al. (1998) in recommending that these names be abandoned. Some of the southern and eastern fault traces in this zone are from Machette and McGimsey (1983), Maldonado and Atencio (1998b), and Love (1997); the remainder are from air photo and field reconnaissance (S. F. Personius, unpubl., 1998), supplemented with aeromagnetic data (U.S. Geological Survey and SIAL Geosciences Inc., 1997; Grauch and Millegan, 1998). Most of these intrabasin faults are partly to completely covered by eolian sand, but they are intermittently marked by linear scarps, aligned drainages, and in some cases aligned ephemeral ponds caused by damming of the prevailing east-southeast-flowing drainages.

No detailed paleoseismic studies have been conducted on these intrabasin faults. However, faults in this zone clearly offset the early Pleistocene(?) Llano de Albuquerque 3–12 m (Machette and McGimsey, 1983). These relationships indicate a recurrent history of faulting that in some cases probably extended at least into the middle Pleistocene. Many of these faults are geomorphically indistinguishable from the better studied County Dump fault, so at least some faults included in this group probably have similar post-middle Quaternary paleoearthquake histories. No precise slip-rate estimates are available, but the small offsets listed above indicate low rates of Quaternary slip.

Sandia fault (20)

The Sandia fault forms the steep western flank of the Sandia Mountains, and the eastern margin of the Albuquerque basin in the vicinity of Albuquerque. Various traces of this fault zone have been mapped by Ellis (1922), Kelley (1954, 1977), Kelley and Northrop (1975), Connell (1995, 1997a), and GRAM Inc. and William Lettis & Associates, Inc. (1995). Several north-trending intrabasin fault strands that lie to the west of the main Sandia range front are included in this discussion of the Sandia fault. Little geomorphic evidence of Quaternary faulting is found along the trace of the Sandia fault, but the presence of a steep mountain front and a few fault scarps on unconsolidated deposits indicate that the Sandia fault has probably been active in the Quaternary. The intrabasin faults west of the main range front offset upper Santa Fe Group rocks, are mapped on the basis of subsurface well and geophysical data, and have little or no geomorphic expression (Connell, 1995, personal commun., 1997).

No detailed paleoseismic studies have been conducted on the Sandia fault. However, the Sandia fault offsets early Pleistocene(?) upper Santa Fe Group rocks north of Tijeras Arroyo (Kelley and Northrop, 1975; Lambert et al., 1982), and a few small discontinuous fault scarps have been mapped on middle Pleistocene alluvial-fan deposits at the northern and southern ends of the Sandia fault (Connell, 1995; GRAM Inc. and William Lettis & Associates, Inc., 1995; Gustafson, 1996). No precise slip-rate estimates are available, but the lack of significant geomorphic expression suggests low rates of Quaternary slip.

Four Hills Ranch fault (21)

The trace of the northeast-trending Four Hills Ranch fault is marked by topographic saddles, linear drainages, and vegetation lineaments on middle Pleistocene alluvial-fan deposits along the southern margin of Tijeras Canyon (GRAM Inc. and William Lettis & Associates, Inc., 1995). The fault lies in a structurally complex area near the eastern margin of the Rio Grande rift. This area is complicated by the intersections of the north-trending Sandia and Hubbell Springs faults and the northeast-trending Tijeras-Cañoncito fault system. The primary traces of the Four Hills Ranch fault were first mapped, named, and described by GRAM Inc. and William Lettis & Associates, Inc. (1995). The sense of displacement on the Four Hills Ranch fault is open to question. The fault is subparallel to the nearby left-lateral Tijeras-Cañoncito fault system, and lateral displacement could explain the apparent right-lateral offset of the Sandia fault at the mouth of Tijeras Canyon as mapped by Kelley and Northrop (1975) and Kelley (1977). However, GRAM Inc. and William Lettis & Associates, Inc. (1995) speculate that apparent lateral offset of the Sandia fault could be caused by a northwest-dipping strand of the Four Hills Ranch fault buried beneath Holocene alluvium in Tijeras Arroyo.

No detailed paleoseismic studies have been conducted on the Four Hills Ranch fault. However, GRAM Inc. and William Lettis & Associates, Inc. (1995) map the Four Hills Ranch fault trace primarily in middle Pleistocene alluvial fan deposits (their unit Pf3.ta). No precise slip-rate estimates are available, but the lack of significant geomorphic expression suggests low rates of Quaternary slip.

Tijeras-Cañoncito fault system (22)

The regionally extensive, left-lateral Tijeras-Cañoncito fault system consists of several northeast-striking, subvertical faults, including the Tijeras, Guiterrez, Zuzax, San Lazarus, Los Angeles, and Lamy faults (Lisenbee et al., 1979; Woodward, 1984; Maynard et al., 1991; Abbott and Goodwin, 1995). Parts of the fault system have been mapped by Bachman (1975), Kelley and Northrop (1975), Booth (1977), Kelley (1977), Lisenbee et al. (1979), Connolly (1982), Woodward (1984), Maynard et al. (1991), Maynard (1995), Abbott and Goodwin (1995), Abbott et al. (1995), GRAM, Inc. and William Lettis & Associates, Inc. (1995), and Connell (1997b). The fault system extends from its intersection with the Picuris-Pecos fault near Lamy, about 22 km southeast of Santa Fe, to the Sandia and Hubbell Spring faults in the Four Hills area, about 16 km southeast of Albuquerque. The Tijeras-Cañoncito fault system has been subdivided into as many as five sections based on structural style, fault trace complexity, and sense and amount of separation (Lisenbee et al., 1979; Wong et al., 1995, 1996), but Machette et al. (1998) determined that there were insufficient data to address the Quaternary activity of the entire fault system, and thus subdivided the fault system into the Galisteo and Canyon sections. The Galisteo section has little or no geomorphic expression related to late Quaternary fault movement, but the Canyon section exhibits evidence of Quaternary deformation near Golden (Abbott and Goodwin, 1995; Kelson et al., 1998, this volume), in Tijeras Canyon (Lisenbee et al., 1979; Connell, 1997b), and on Kirtland Airforce Base (GRAM Inc. and William Lettis & Associates, Inc., 1995). Only the southwestern part of the Canyon section is shown in Figure 1, so we restrict the rest of this discussion to this section.

Two sites with evidence of Quaternary displacement near Golden have been examined in detail. Abbott and Goodwin (1995) documented the presence of faulted alluvium along the Tijeras fault about 5 km southwest of Golden, and interpreted the alluvium as Quaternary(?). Four exploratory trenches excavated across two main strands of the Tijeras fault at a nearby site (Kelson et al., 1998, this volume) show offset of middle to late Pleistocene deposits. The timing of the most recent event is poorly constrained, but movement on the Canyon section may be as young as latest Pleistocene. No precise slip-rate estimates are available, but Wong et al. (1995, 1996) estimated a range in slip rates of 0.02–0.72 mm/yr and preferred a rate of 0.09 mm/yr, based on regional analysis of slip rates within the Rio Grande rift.

Coyote fault (23)

The Coyote fault forms part of the western range front of the Manzanita Mountains. The fault is truncated on the north by the Tijeras-Cañoncito fault system and appears to die out to the south, where younger faulting appears to step eastward to the Manzano fault. The Coyote fault was first mapped and named by Reiche (1949), and later appeared on compilations by Kelley (1954, 1977). Parts of the Coyote fault also appear on more detailed mapping of Myers and McKay (1970), GRAM, Inc. and William Lettis & Associates, Inc. (1995), and Karlstrom et al. (1997).

Evidence of Quaternary movement along the Coyote fault is equivocal. Myers and McKay (1970) map a Quaternary terrace deposit faulted against Pennsylvanian sedimentary rocks southwest of Coyote Springs. In contrast, GRAM Inc. and William Lettis & Associates, Inc. (1995, p. 2–25) found no conclusive evidence that this Quaternary deposit was faulted, but they mapped tonal and vegetation lineaments on middle to late Pleistocene alluvial-fan deposits and show the fault buried by late Pleistocene fan deposits. Karlstrom et al. (1997) show the

Coyote fault trace as buried by middle and late Pleistocene alluvial-fan deposits. No precise slip-rate estimates are available, but the lack of significant geomorphic expression and association with a deeply embayed mountain front suggest low rates of Quaternary slip.

Manzano fault (24)

The Manzano fault forms the eastern margin of the Rio Grande rift in the central part of the Albuquerque basin. Most maps show the Manzano fault as a northern continuation of the Los Piños fault; the Manzano fault extends from near US-60 northward along the steep eastern flank of the Manzano Mountains, to near the mouth of Hell Canyon at the Bernalillo/Valencia County line (Read et al., 1944; Reiche, 1949; Kelley, 1954; Myers and McKay, 1970; Baltz, 1976; Machette, 1982; Machette and McGimsey, 1983; Karlstrom et al., 1997). Karlstrom et al. (1997) named the northernmost section the "Manzanita fault", but to reduce confusion, we follow Machette et al. (1998) in retaining the name "Manzano fault" for the entire structure.

Evidence of Quaternary movement along the Manzano fault is equivocal. The Manzano fault is usually mapped as a buried trace; no published geologic maps show offsets of late or middle Pleistocene deposits along the fault trace. However, discontinuous fault scarps on alluvial-fan deposits may be present along a 12-km-long, north-trending section of the fault between Ojito Canyon and Cañon del Trigo in the Bosque Peak quadrangle (J. W. Hawley, personal commun., 1997; S. D. Connell, personal commun., 1997). The timing of the most recent event is unknown; estimates based on the geomorphology of the western flank of the Manzano Mountains suggest an early Pleistocene time for the most recent event (Machette and McGimsey, 1983), but the recent discovery of fault scarps between Ojito Canyon and Cañon del Trigo suggest the youngest event occurred in the middle or late Pleistocene (Machette et al., 1998). No precise slip-rate estimates are available, but the poor geomorphic expression along most of the fault trace indicates low rates of Quaternary slip.

Hubbell Spring fault (25)

The Hubbell Spring fault forms the western edge of a prominent intrabasin topographic bench, the Hubbell bench, which lies 5–11 km west of the steep escarpment at the foot of the Manzano Mountains. The Hubbell Spring fault marks the active margin of the Rio Grande rift in this part of the Albuquerque basin. The fault trace merges with and offsets the Tijeras-Cañoncito fault system at the Travertine Hills on Sandia National Laboratory at its northern end, and extends southward to about the latitude of Belen. The Hubbell Spring fault was originally mapped and named the Ojuelos fault by Read et al. (1944). Numerous other investigators have used the names "Ojuelos fault", "Ojuelos-Hubbell Springs fault", and "Hubbell Spring (or Springs) fault" interchangeably for this structure (Reiche, 1949; Kelley, 1954, 1977; Stark, 1956; Titus, 1963; Baltz, 1976). The namesake for the fault is Hubbell Spring, a prominent spring that flows from the fault zone near its northern end, so the name "Hubbell Spring fault", as used in more recent publications (Machette, 1982; Machette and McGimsey, 1983; GRAM Inc. and William Lettis & Associates, Inc., 1995; Love et al., 1996) is retained herein. A northwest-trending splay fault (Sanchez fault of Karlstrom et al., 1997) south of Hubbell Spring may connect the Hubbell Spring fault to the Manzano fault. The Sanchez fault may offset early Pleistocene deposits south of the Hubbell bench (Love et al., 1996; Karlstrom et al., 1997; S. D. Connell, personal commun., 1997).

The Hubbell Spring fault is marked by aligned springs and 4- to 30-m-high scarps on deposits ranging in age from early to late Pleistocene (Machette and McGimsey, 1983; GRAM Inc. and William Lettis & Associates, Inc., 1995; Love et al., 1996). The fault has been recurrently active throughout the Quaternary, and shows evidence of movement in the late Pleistocene. Preliminary results of a trench investigation across a 7-m-high scarp near the northern end of the Hubbell Spring fault (Fig. 1; Personius, 1998) suggest three late Quaternary surface-faulting events with average vertical offsets of about 1.6 m. Several pending thermoluminescence (TL) and uranium-series ages should aid in the determination of the timing of the last three surface ruptures on the Hubbell Spring fault at this site. The timing of the most recent event is unknown, but preliminary data from the Hubbell Spring trench indicate that the most recent movement on the Hubbell Spring fault occurred in the late Quaternary. No precise slip-rate estimates are available, but fault scarp data from Machette and McGimsey (1983) indicate offsets of 2–11 m on late Pleistocene deposits; these data yield estimated long-term slip rates of 0.01–1.0 mm/yr. Preliminary data from the Hubbell Spring trench (S. F. Personius, unpubl., 1998) suggest slip rate values near the lower part of this range. The probable occurrence of three late Quaternary events reinforces the interpretation that the Hubbell Spring fault is one of the most active faults in this part of the Rio Grande rift.

McCormick Ranch faults (26)

The McCormick Ranch faults consist of numerous north- to northeast-trending normal faults that lie directly west of Sandia National Laboratories. Some of the more prominent faults in this zone were mapped by Kelley (1977) and Machette and McGimsey (1983). GRAM Inc. and William Lettis & Associates, Inc. (1995) named two of these faults after the nearby McCormick Ranch (East and West McCormick Ranch faults), and mapped several other faults that form smaller horst and graben blocks in the zone. Numerous fault-related ridges and swales mapped by D. W. Love and colleagues (1996, 1997) in the area are included in the McCormick Ranch faults.

No detailed paleoseismic studies have been conducted on the McCormick Ranch faults. The faults offset upper Santa Fe Group rocks that contain clasts of upper Bandelier Tuff (Love et al., 1996; Love, 1997), so the faulted deposits are younger than 1.2 Ma. The stable geomorphic surface formed on these deposits, locally known as the Llano de Manzano, is capped by a stage IV calcic soil (Love et al., 1996; Love, 1997), suggesting that this surface is also early Pleistocene in age. Machette and McGimsey (1983) estimated offsets of 5–20 m across the West McCormick Ranch fault, and GRAM Inc. and William Lettis & Associates, Inc. (1995) measured scarp heights of 10 m across several McCormick Ranch faults. The timing of the most recent event is unknown, but the offsets discussed above suggest recurrent movements that probably extended into at least the middle Pleistocene. No precise slip-rate estimates are available, but if the upper Santa Fe Group rocks offset by the McCormick Ranch faults were deposited after about 1 Ma and have offsets of 5–20 m (Machette and McGimsey, 1983; GRAM Inc. and William Lettis & Associates Inc., 1995), then long term Quaternary slip rates are 0.005–0.02 mm/yr on individual McCormick Ranch faults.

Cat Mesa fault (27)

The Cat Mesa fault is an intrabasin fault near the western margin of the central Albuquerque basin. The trace of the Cat Mesa fault extends from NM-6, west of Los Lunas, northward along the eastern edge of Cat Mesa. At about its midpoint, the Cat Mesa fault splits into two north-trending splays that offset upper Santa Fe Group rocks and die out near the western edge of the Llano de Albuquerque. The fault was originally mapped by Kelley (1954, 1977) and in more detail by Kelley and Kudo (1978). Minor modifications were made by Machette (1978c), Machette and McGimsey (1983), and Maldonado and Atencio (1998a). The Cat Mesa fault is well expressed where the resistant Cat Mesa basalt flow is exposed in the fault zone. Elsewhere, the fault strands are marked by broad swales on the Llano de Albuquerque.

No detailed paleoseismic studies have been conducted on the Cat Mesa fault. The fault offsets the Cat Mesa basalt flow about 30 m (Machette and McGimsey, 1983), which has been recently dated at 3.0 ± 0.1 Ma (Maldonado and Atencio, 1998a). The Cat Mesa basalt flow is interbedded with the upper part of the upper Santa Fe Group Sierra Ladrones Formation (Machette, 1978b), 6–10 m below the Llano de Albuquerque (Kelley and Kudo, 1978). The two fault strands near the northern end of the fault zone have total offsets of about 17 m (Machette and McGimsey, 1983). The age of the most recent event is unknown, but Machette and McGimsey (1983) measured offsets in early and middle Pleistocene deposits; these offsets suggest recurrent movements that probably extended into at least the middle Pleistocene. No precise slip-rate estimates are available, but if the 3 Ma (Maldonado and Atencio, 1998a) Cat Mesa basalt is offset about 30 m (Machette and McGimsey, 1983), then the long-term slip rate is 0.01 mm/yr.

CONCLUSION

Despite the existence of numerous Quaternary faults in the Albuquerque area, relatively little is known about their individual histories of offset and potential for future earthquakes. At least five of these faults (County Dump, East Paradise, Hubbell Spring, Rincon, and Tijeras-Cañoncito) have demonstrated movements in the late Quaternary (<130 ka). However, only four (County Dump, East Paradise, Hubbell Spring, and Tijeras-Cañoncito) of the dozens of Quaternary faults in the area have been the subject of detailed paleoseismic investigations, so the true number of faults with histories of late Quaternary displacement is probably larger. Fortunately, the few detailed studies available indicate that most faults in the Albuquerque area have low rates of slip and long recurrence times between surface-rupturing earthquakes. Thus the hazard associated with individual faults is probably low, but the large number of Quaternary faults increases the composite hazard to the Albuquerque metropolitan area. Empirical estimates of paleoearthquake magnitude based on displacements of 1–2-m and 20–30-km rupture lengths (Wells and Coppersmith, 1994) indicate that many of the faults shown in Figure 1 could generate surface-faulting earthquakes of **M** 7 or greater. Such earthquakes would cause extensive damage in the Albuquerque metropolitan area. Quantitative estimates of earthquake hazards in this part of the Rio Grande rift should be periodically revised as additional data are obtained in future detailed fault investigations.

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