Timing of late Quaternary faulting in the 1954 Dixie Valley earthquake area, central Nevada

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ABSTRACT

The 1954 Dixie Valley earthquake (M 6.9) in central Nevada produced about 3 m of total vertical displacement distributed across two principal fault zones along the east flank of the Stillwater Range. Most of the 1954 displacement was along the range-front fault with minor amounts on the piedmont fault zone, in contrast to an earlier Holocene displacement that was restricted to the piedmont fault. Detailed chronostratigraphic, exploratory drilling, and trenching studies indicate that faulting events have migrated back and forth between the range-front and piedmont fault zones in the late Quaternary. Prior to the 1954 earthquake, the range-front fault last ruptured in the late Pleistocene, during a large-magnitude event here called the IXL event. The northern half of the piedmont fault zone last ruptured between 1.5 and 6.8 ka during a large-magnitude event here called the Bend event. On the basis of 6 m total slip since the deposition of shoreline gravels at ~12 ka, the estimated Holocene vertical-slip rate is 0.5 mm/yr for the Dixie Valley rupture zone. Overlapping and migratory patterns of late Quaternary faulting indicate that the Dixie Valley zone does not fit a simple segmentation model.

INTRODUCTION

On December 16, 1954, an earthquake (M 7.1) occurred near Fairview Peak in central Nevada, followed 4 min later by a second M 6.9 earthquake located on the west side of Dixie Valley about 50 km to the north. Spectacular surface faulting was associated with both events, totaling an end-to-end distance of 102 km and a composite width of 32 km (Slemmons, 1957). These earthquakes are within a north-trending zone of historical surface faulting informally called the central Nevada seismic belt (Wallace, 1984). Other earthquakes that produced surface faulting in this belt include the 1903 Wonder (M > 6), 1915 Pleasant Valley (M 7.6), 1932 Cedar Mountain (M 7.2), 1934 Excelsior Mountain (M 6.3), July 1954 Rainbow Mountain (M 6.6), and August 1954 Rainbow Mountain (M 7) earthquakes. Geologic field data and focal mechanisms indicate that these earthquakes have ranged from predominantly normal to predominantly right-slip events.

The Dixie Valley earthquake faulting is one of only two historical, large-magnitude events in the Basin and Range province rupturing single, range-bounding faults and having segmentation-like behavior (the 1983 Borah Peak event is the other). We present here a synopsis of the Quaternary chronostratigraphic mapping, exploratory drilling, and fault trenching that we have conducted in the Dixie Valley zone, interpret the late Quaternary slip history of the rupture zone, and assess the evidence for segmentation (repeated rupture of discrete fault segments).

Coseismic slip related to the four 1954 Rainbow Mountain–Dixie Valley–Fairview Peak earthquakes was distributed along several separate faults (Fig. 1A). Both of the Rainbow Mountain earthquakes produced surface rupturing with the displacement down toward the Stillwater Range. The faulting associated with the Dixie Valley earthquake occurred along a zone about 50 km long and was distributive, extending from the range front to 3–5 km east (Fig. 1B). Wallace and Whitney (1984) called the zone containing Holocene fault scarps along the Stillwater Range between the Dixie Valley and the 1915 Pleasant Valley rupture zones the Stillwater seismic gap (Fig. 1A). The Fairview Peak faulting occurred along a large graben bounded on the west by Fairview Peak and on the east by the Clan Alpine Mountains, offset about 10 km from the Dixie Valley zone.

STRUCTURAL SETTING

Dixie Valley is an asymmetrically faulted, graben-in-graben structural basin (Burke, 1967; Thompson and Burke, 1973; Anderson et al., 1983; Okaya and Thompson, 1985). The west side of the valley is bounded by several closely spaced, large-displacement normal faults, which have created the deepest part of the structural basin.

Seismic-refraction and surficial geologic data indicate that the Stillwater Range is uplifted along a normal fault at the base of the range front, here called the range-front fault, and along a series of synthetic, antithetic, and graben-in-graben faults a few kilometres eastward of the range front, here collectively called the piedmont fault zone (Bell and Katzer, 1987; Fig. 2). Granitic basement rocks are at depths of about 150 m near the range front but are downfaulted as much as 1.8 km beneath the piedmont (Herring, 1967; Meister, 1967).

QUATERNARY STRATIGRAPHIC RELATIONS

In order to estimate fault slip rates, we differentiated and mapped Quaternary deposits on the basis of genesis, surface morphology, relative stratigraphic position, degree of soil development, tephrochronology, and radiometric data (Table 1). Lithologic characteristics were important, but not determining, criteria. This approach, commonly referred to as "alluvial geomorphology" (e.g., Ku et al., 1979), facilitates the mapping of synchronous (chronostratigraphic) units.

The oldest differentiated unit, old alluvial-fan deposits (Qfo), occurs as dissected remnants locally preserved across the range-front fault and as larger, moderately preserved remnants across the piedmont fault zone (Fig. 1B). The age of Qfo is estimated from the degree of soil development. Strongly developed paleoargid and durargid soils in this unit are morphologically equivalent to the Cocoon geosol of Morrison (1964), or possibly to an older soil-stratigraphic unit. The age of the unit is thus at least that of oxygen-isotope stage 7, about 200 ka, and it may be as old as 400–500 ka (Morrison and Davis, 1984).

On the basis of stratigraphic relations, intermediate-age alluvial-fan deposits (Qfi) are late Pleistocene in age. The morphology and thickness of the argillic B horizon in this unit indicate that the soil predates the last major highstand of pluvial Lake Lahontan (Nettleton et al., 1975) dated at 12.5–13.5 ka (Benson and Thompson, 1987). Morphologically, the haplargid soil in this unit is correlated with the youngest haplargid soil in the nearby Lake Lahontan area, the Churchill geosol of Morrison (1964), placing its age at about 30 or 100 ka depending upon whether it is correlated with oxygen-isotope stage 3 or 5 (Morrison and Davis, 1984).

Lacustrine deposits related to pluvial Lake Dixie include beach gravels (Qbg) and a finer-grained facies (Qbfy). Thompson and Burke (1973) obtained ^{14}C dates of 11,560 ±180 and 11,700 ±110 B.P. on calcareous tufa from the high shoreline of Lake Dixie about 14 km north of the study area. The Mazama ash (about 6.8 ka) is found in Qbfy deposits at several locations near trench 2 (Fig. 1B).

The bulk of the piedmont is composed of alluvial-fan deposits that postdate the highstand beach gravels. Moderately young (Qfm) and young (Qfy) alluvial-fan deposits form a broad, coalescing surface beveling and burying the highstand gravels and older deposits. The young alluvial-fan deposits contain the Turupah Flat tephra in several canyons along the range front. This Mono Crater ash is widespread throughout

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much of western Nevada (Davis, 1978) and has been bracketed by ^{14}C dates of 1550 ±140 and 1680 ±110 B.P. (Bell, 1981).

AGE AND DISTRIBUTION OF LATE QUATERNARY FAULTING

The timing and amount of late Quaternary faulting in Dixie Valley can be determined on the basis of the mapped structural and stratigraphic relations and data from seven drill holes and four exploratory trenches across several faults (Fig. 1B). Our results show that although most of the 1954 faulting occurred on the range-front fault, the piedmont fault zone has been the principal site of previous Holocene faulting. The range-front fault exhibits no stratigraphic or geomorphic evidence of Holocene offset prior to 1954. The piedmont fault zone, however, previously ruptured between 1.5 and 6.8 ka.

Most of the 1954 displacement was located along the range-front fault, where scarps as high as 3.6 m formed. True vertical offsets (throws) are 1.8–2.5 m. Additional smaller offsets were distributed across numerous synthetic and antithetic faults and grabens on the piedmont. Individual piedmont displacements based on scarp heights are about 30–60 cm; total offsets are difficult to determine because of the complex distributive nature of the faulting.

The older alluvial-fan deposits (Qfo and Qfi) that straddle the range-front fault exhibit small cumulative late Quaternary offsets both in the study area and along the rupture zone to the south. There is no evidence for pre-1954 Holocene activity; Qfm and Qfy alluvial-fan deposits are cut only by the 1954 faulting. At IXL Canyon, remnants of Qfo are offset by about 12 m of pre-1954 displacement, and at Brush Canyon the Qfo deposits are displaced about 15 m. Comparable displacements are present at the south end of the rupture zone near Coyote Canyon and Eleven Mile Canyon (Fig. 1A). At Rock Creek Canyon, intermediate-age alluvial-fan (Qfi) deposits are vertically offset 2.5–3 m by a late Pleistocene event that is recognized the length of the 1954 rupture zone. This range-front event, comparable in displacement to the 1954 faulting, is here called the IXL event.

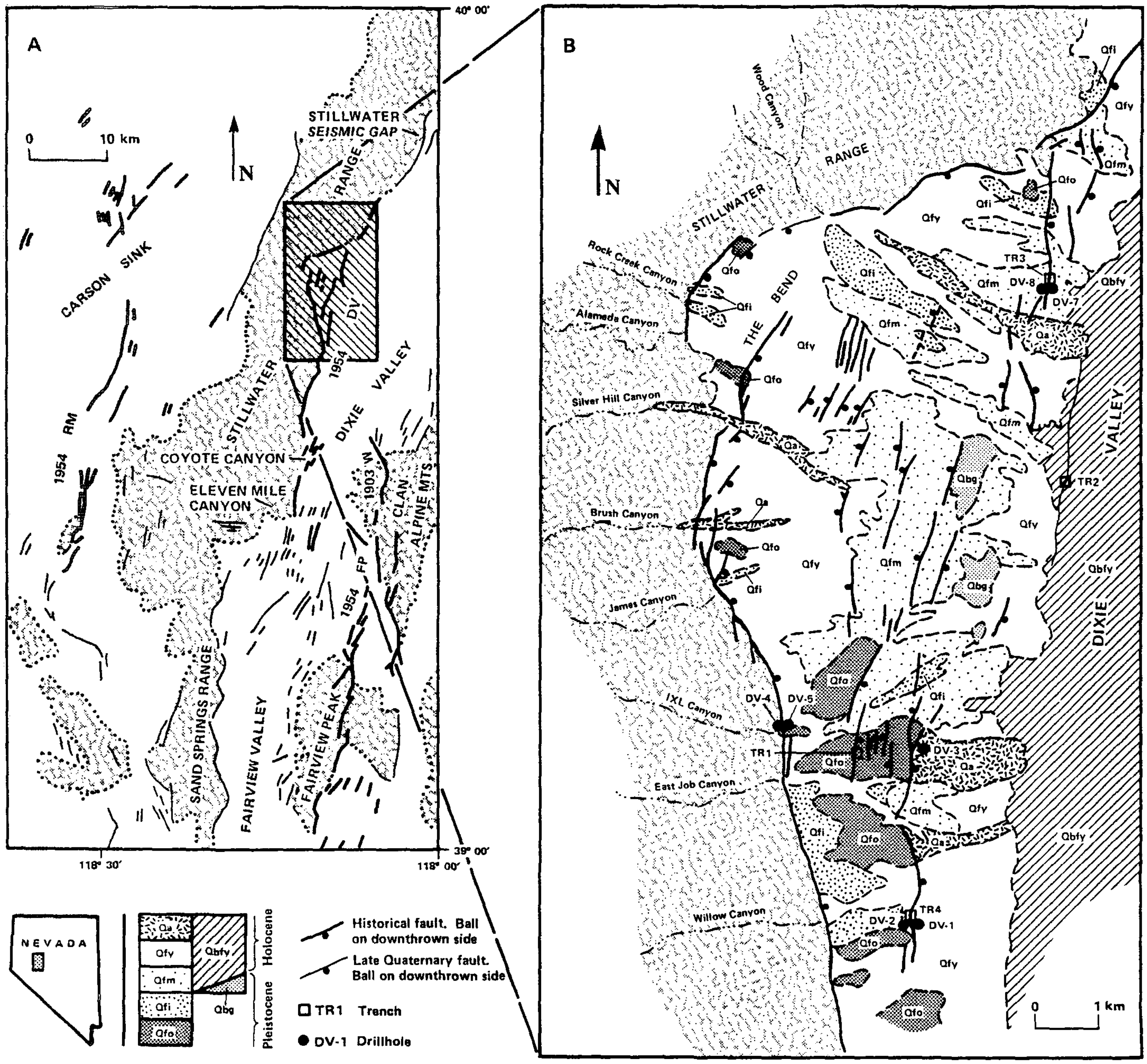

Figure 1. A: Map of 1954 Rainbow Mountain (RM), Dixie Valley (DV), Fairview Peak (FP), and 1903 Wonder (W) faults and other late Quaternary faults (Bell, 1984). B: Quaternary geology and surface faults in area of 1954 Dixie Valley earthquake. See Table 1 for explanation of units.

Along the 5-km-long section of the piedmont between IXL and Willow canyons, the older alluvial-fan deposits are well preserved; however, on the basis of drilling data, the deposits are relatively thin near the range front. About 200 m east of IXL Canyon, drill hole DV-5 encountered a gray claystone at 61 m, beneath older alluvial-fan deposits. The claystone is inferred to be part of the Tertiary (Miocene-Pliocene) nonmarine sedimentary sequence (Page, 1965), although a younger age cannot be precluded. The presence of Tertiary sedimentary rocks at this relatively shallow depth agrees with the seismic-refraction interpretations of Meister (1967), who identified Pliocene(?) nonmarine sedimentary rocks at depths of 61–91 m about 0.7 km east of IXL Canyon. We believe that such a thin Quaternary alluvial cover is suggestive of relatively small cumulative Quaternary displacement along the range-front fault.

The total displacement of Qfo deposits on the piedmont zone equals and probably exceeds that at the range front. On the principal trace of the piedmont fault zone, lithologic and geophysical data from drill holes DV-1, DV-2, and DV-3 (Fig. 1B) indicate that a clayey bed in the old alluvial-fan deposits is displaced 21 to 23 m, 20 to 30 cm of which occurred in 1954.

In contrast to the range-front fault, the piedmont fault zone contains Holocene scarps that extend across The Bend to just south of trench 4 and offset Qfm, Qfy, Qbg, and Qbfy deposits (Fig. 1B). Total vertical throw in the Holocene deposits is 2.5–3 m; movement on these faults in 1954 ranged from 0 to 60 cm. Surficial mapping and exploratory trenching show that the Holocene scarps result from a single pre-1954 rupture, here referred to as the Bend event. Both trenches 3 and 4 revealed a single colluvial wedge abutting the fault (Fig. 3). In trench 3, Qfm deposits are vertically offset about 3 m and are buried by about 1.5 m of scarp colluvium on the downthrown side. Both the alluvial-fan deposits and the colluvium contain a typic camborthid soil that is offset about 30 cm by the 1954 event. Similar relations are seen in trench 4, where Qfy deposits are vertically offset 2.5 m and overlain by 1.5 m of scarp colluvium. The lack of greater displacements in the ~12 ka beach gravel is evidence of no other large Holocene events. Drill holes DV-7 and DV-8 straddle the fault near trench 3, and the top of the beach gravel is offset about 3 m between the two holes, the same throw that is observed in trench 3.

The age of the Bend event is bracketed by the Mazama and Turupah Flat tephras, thus placing the age of the event between 1.5 and 6.8 ka. In the vicinity of trench 3, Mazama ash stratigraphically underlies faulted Qfm deposits, and at trench 2, the unfaulted Turupah Flat tephra is draped across the scarp.

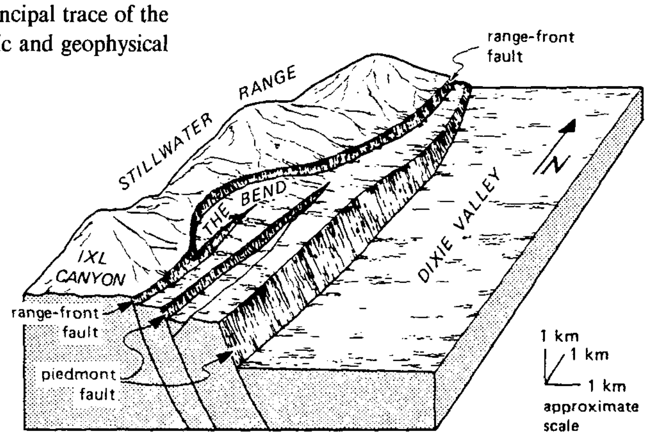

Figure 2. Schematic block diagram of basement and fault relations in IXL Canyon area. Late Cenozoic volcanic and sedimentary cover is not shown. (Modified from concept of Burke, 1967.)

TABLE 1. QUATERNARY STRATIGRAPHY, DIXIE VALLEY, NEVADA

Unit	Distinguishing characteristics	Estimated age (ka)
Qa Active-channel and debris-flow deposits	Recently active water-flood, debris- and mud-flow deposits; sandy mud to boulder gravel; soils are torriorthents.	<1.5
Qfy Young alluvial-fan deposits	Coalescing alluvial-fan deposits consisting of many discrete water-flood and debris-flow events; sandy pebble to cobble gravel and gravelly sand; contains the Turupah Flat tephra bed; soils are torriorthents and xerollic camborthids.	1.5-6.8
Qfm Moderately young alluvial-fan deposits	Coalescing, slightly dissected alluvial-fan remnants; sandy pebble to cobble gravel and gravelly sand; interfingers with Qbfy and Qbg deposits; contains the Mazama ash; soils are typic camborthids, locally natrargids.	6.8-12
Qbfy Young basin-fill deposits	Lacustrine, paludal, and fine-grained fluvial deposits; sandy silt, silty sand, and clayey silt; locally eolian sand; contains Turupah Flat and Mazama tephras; soils are natrargids.	<12
Qbg Beach gravel	Shoreline remnants of pluvial Lake Dixie; sandy subrounded pebble gravel and gravelly coarse sand; highstand shoreline elevation is at 1086 m; soils are typic camborthids.	~12
Qfi Intermediate-age alluvial-fan deposits	Moderately dissected alluvial-fan remnants; sandy pebble to cobble gravel and gravelly sand; soils are typic haplargids with 30-cm-thick Bt and Btk horizons.	30-100
Qfo Old alluvial-fan deposits	Deeply dissected alluvial-fan remnants; muddy to sandy pebble to boulder gravel and gravelly sand; soils are paleargids and durargids having 50- to 100-cm-thick Bt and Btk horizons and locally 20- to 30-cm-thick Bkm horizons.	200-500

DISCUSSION

The late Quaternary faulting history in the 1954 Dixie Valley earthquake area is complex, split in space and time between major faults lying at the range front and beneath the alluvial piedmont. At the range front, late Quaternary deposits record multiple Pleistocene events, but there is no evidence for pre-1954 Holocene slip. Cumulative displacements of old alluvial-fan deposits, estimated to be a minimum of 200 ka old, are about 15–18 m, including 2.5 m of 1954 displacement. Late Pleistocene intermediate-age alluvial-fan deposits are consistently offset about 2.5 m by the IXL event, an event comparable in length and vertical displacement to the 1954 rupture, extending at least from The Bend to Coyote Canyon (Fig. 1A). Compound scarps to the north and south may also contain evidence of this event. The comparable nature of these events would be indicative of characteristic earthquake behavior—in which faults repeatedly generate earthquakes of the same magnitude and displacement (Schwartz, 1988)—if not for the significant amount of late Quaternary activity on the piedmont fault zone.

The northern half of the piedmont fault zone was offset by the Bend event between 1.5 and 6.8 ka. Drilling data show that this zone has late Quaternary displacements equal to or greater than those on the range-front fault. The location of most of the 1954 displacement and the IXL event on the range-front fault is thus difficult to explain, given the level of late Quaternary activity on the piedmont fault zone. Prior to 1954, the piedmont fault zone would have been identified as the more active structure.

Both the piedmont and range-front fault systems contribute to the cumulative uplift of the Stillwater Range, and late Quaternary vertical-slip rates can be approximated on the basis of stratigraphic constraints. Although the total amount of true slip is uncertain because of the distributive nature of the faulting, about 6 m of Holocene dip slip has occurred (3 m from the Bend event and 3 m of 1954 slip) since the deposition of the beach gravels (~12 ka), yielding an average slip rate of 0.5 mm/yr. A longer

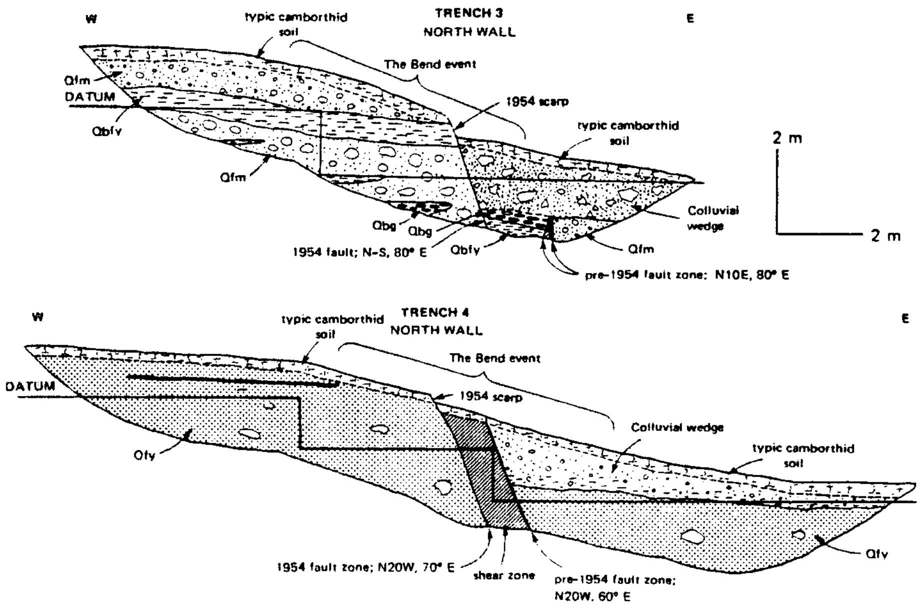

Figure 3. Logs of trenches 3 (top) and 4 (bottom).

term, but less well defined, rate of 0.2 mm/yr is based on an estimated 41 m of total displacement in the Qfo deposits (18 m on the range-front fault and 23 m on the piedmont fault zone) if Qfo deposits are assumed to be a minimum 200 ka. This rate would be less if Qfo deposits are older. Wallace and Whitney (1984) estimated vertical-slip rates for the Stillwater Range to be 0.26–0.35 mm/yr on the basis of uplifted Tertiary volcanic rocks. Similarly, Okaya and Thompson (1985) estimated a 2.9 km vertical offset for 8 Ma basalts in the Stillwater Range, which yields a vertical-slip rate of about 0.4 mm/yr. The 0.5 mm/yr Holocene slip rate we estimate here for the Dixie Valley fault zone is a reasonable value that agrees with the longer-term uplift rates given the uncertainties in the age and displacement of the older deposits and given the additional weight of the 1954 event in determining total slip.

The Dixie Valley rupture zone does not fit a simple segmentation model, such as the one Crone et al. (1987) proposed for the 1983 Borah Peak rupture zone, in which discrete segments repeatedly rupture independently. The paleoseismic and historical data presented here suggest a more complex, and perhaps unpredictable, interaction of separate fault zones. No known paleoseismic discontinuities bound the 1954 rupture zone. The Bend event may have been part of a single prehistoric rupture that propagated through both the Stillwater seismic gap and The Bend (Pearthree et al., 1986). If faulting was connected to an event in the gap, which seems likely based on continuity of fault traces, the faulting would have overlapped into the 1954 segment by nearly 25 km, almost half the length of the 1954 rupture zone. A similar 8 to 10 km overlap occurs at the south end of the rupture zone near Eleven Mile Canyon, where 1954 faults are adjacent to Holocene scarps that extend north from the Sand Springs Range.

The sequence of late Quaternary faulting in the 1954 rupture zone is as follows. The late Pleistocene IXL event ruptured the range-front fault for at least 25 km from The Bend to Coyote Canyon. The middle to late Holocene Bend event ruptured the piedmont fault without any significant slip on the range-front fault, displacing the northern half of the 1954 zone. The 1954 faulting reruptured both fault zones; most of the displacement was on the range-front fault, and it possibly duplicated the IXL event. The overlapping relations and the migratory nature of range-front and piedmont faulting suggest that neither the patterns nor the timing of faulting events are easily predicted here on the basis of simple segmentation analyses.

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