FINAL TECHNICAL REPORT

Paleoseismic Studies in the Central Nevada Seismic Belt: 1954 Rainbow Mountain

External Grant Award Number 00HQGR0022

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ABSTRACT

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The central Nevada seismic belt (CNSB) is a semi-continuous zone of historical surface faulting Province produced by eight moderate- to large-magnitude earthquakes in the last century that extends for more than 300 km in the western Basin and Range. This study examines the paleoseismic history of the 1954 Rainbow Mountain fault by conducting detailed chronostratigraphic studies, exploratory trenching, and age dating in order to better understand contemporary and paleoseismic processes in the CNSB.

Two exploratory trenches were excavated across the main trace of the 1954 Rainbow Mountain fault. The trenches exposed a faulted sequence of subaerial and lacustrine sedimentary deposits ranging in age from mid- to late Sehoo (< 30 ka) in age. Two pre-1954 events are recognized based on fault-stratigraphic relations: the triultimate event occurred between 11.8-14.5 ka based on the ages of faulted subaerial deposits containing a buried paleoroot horizon and unfaulted organic mid-Sehoo lake clay deposits. The penultimate event is dated between 6.3-8.0 ka based on the ages of faulted late Sehoo subaerial deposits and unfaulted late Sehoo shoreline deposits. Based on measured offsets of displaced units in the trenches, the earlier events had event offsets of 1-1.5 m each; together with the 30 cm 1954 displacement a cumulative vertical displacement of 2.5-3.0 m has occurred during the last 14.5-17.8 ka. The three events had strong components of right-oblique slip with an estimated vertical-to-horizontal slip ratio of 1:1.6; accounting for the oblique slip component, the net slip rate from the three events is estimated at 0.3-0.4 mm/yr. An average interseismic interval is on the order of 7,000 years.
The results of the Rainbow Mountain paleoseismic study are consistent with the results obtained in earlier studies for the 1932 Cedar Mountain, and 1954 Fairview Peak and 1954 Dixie Valley

zones where it was found that collectively these historical fault zones are characterized by a wide range in slip histories. While most of the historical zones have at least one Holocene faulting event, it is evident that the historical rupture pattern has not been replicated in the last 10 ka if the timing of the penultimate events is compared among zones. The Rainbow Mountain, Dixie Valley, and Cedar Mountain zones have had at least one Holocene event, but the timing is different based on relatively well constrained ages in these areas; the age of the penultimate event on Fairview Peak fault is >35 ka. Paleoseismic slip rates determined for each of the zones are between 0.1-0.5 mm/yr and are considered to moderate to low rates. Such rates suggest that moment rate estimates used in the construction of probabilistic seismic hazards maps may not fully characterize the short-term hazard in the CNSB.

This section of the CNSB provides an opportunity for comparing contemporary strain measured by geodetic (GPS) methods with the longer term geologic strain measured from paleoseismic studies. The results of our study show that although the resolved geologic and GPS slip directions are nearly the same, there is a significant discrepancy in rates. We averaged the GPS velocity vectors of Thatcher et al. (1999) across the CNSB and found an average N30W vector with a 4 mm/yr velocity. The geologic slip vectors measured from the 1954 focal mechanisms and from the paleoseismic data indicate that the regional fault blocks are moving in a N30W direction nearly identical to the average GPS vector. We combined the Rainbow Mountain results with other new data and earlier studies at Fairview Peak to estimate collective slip rates through the Rainbow Mountain to Fairview Peak section of the CNSB. The total maximum vertical slip rate summed across this area is about 1.2 mm/yr. If the horizontal component of this geologic slip is resolved on the same N30W azimuth as the GPS vector, the net horizontal geologic slip is about1 mm/yr, about 25% of the rate measured by the GPS network across the same area.

NON-TECHNICAL ABSTRACT

This study investigated the nature of prehistorical faulting associated with moderate- to large-magnitude earthquakes based on the geological record in the central Nevada seismic belt. The study focused on detailed studies in the 1954 Rainbow Mountain fault zone, which produced three surface-rupturing earthquakes, for comparison with earlier similar studies conducted in the 1932 Cedar Mountain and 1954 Fairview Peak-Dixie Valley fault zones. Investigations included detailed geologic mapping, radiocarbon dating, and exploratory trenching of the fault traces.

The results of the study show that the Rainbow Mountain fault is similar to other historically active faults, having comparable rates of geologic movement during the last 10,000-20,000 years. These geologic rates can be compared to contemporary rates of crustal deformation determined by space-base geodetic (GPS) measurements, and it was found that while the directions of geologic and geodetic movement are nearly identical, there is a significant (factor of four) discrepancy between the rates of movement. The results also show that the Rainbow Mountain and other historically active faults have low to moderate slip rates, suggesting that probabilistic seismic hazard maps that use such slip rates for modeling hazard may not adequately reflect an appropriate level of hazard.

TECHNICAL REPORT

BACKGROUND

The contemporary seismotectonics of the western Basin and Range province are related to a broad zone of diffuse northwest-oriented, right-lateral shear between the Sierra Nevada microplate and the Basin Range (Thatcher et al., 1999; Wernicke et al., 2000; Oldow et al., 2001).The principal structural tectonic features of the region are dominated by the Walker Lane belt, a 700-km-long zone of right-lateral transcurrent late Cenozoic faulting in western Nevada, and the central Nevada seismic belt (CNSB), a historical zone of large-magnitude, strike-slip and normal-slip earthquakes and surface faulting which splays from the Walker Lane belt (Fig. 1).

The CNSB is a semi-continuous zone of surface faulting extending for more than 300 km from the Eastern California Shear Zone through central Nevada, and includes eight moderate- to large magnitude events (Fig. 1): 1903 Wonder (M6.5?), 1915 Pleasant Valley(M7.6), 1932 Cedar Mountain (M7.2), 1934 Excelsior Mountain (M6.3), 1954 Rainbow Mountain (M6.3, M6.4, M7.0), 1954 Fairview Peak (M7.2), and 1954 Dixie Valley (M6.8). The 1954 portion of the CNSB, consisting of the Rainbow Mountain, Fairview Peak, and Dixie Valley fault zones (Fig. 2), comprises a continuous north-trending, left-stepping zone more than 200 km in length.

Surface faulting was produced by all three Rainbow Mountain earthquakes. The July event included an initial (M6.3) event that produced surface rupture along the east side of Rainbow Mountain; a second (M6.4) event is believed to have produced surface ruptures south into Fourmile Flat (Caskey et al., 1999, 2000). The August event was the largest of the three (M7.0) producing surface faults from Rainbow Mountain north into the Cason Sink. The epicenters for all three earthquakes were located near Fourmile Flat and the focal mechanisms showed right-oblique first motions (Doser, 1988).

Previous NEHRP studies in the CNSB by the Principal Investigators investigated the paleoseismic history of the Fairview Peak fault (Bell and Ramelli, 1999) and the slip distribution patterns associated with the Rainbow Mountain faulting (Caskey et al., 1999). These studies were integrated with earlier studies in the Dixie Valley zone (Bell and Katzer, 1990) and in the Cedar Mountain zone (Bell et al., 1999) to develop a preliminary comparison of rates and timing of paleoseismic activity in the CNSB. This study examined the timing of late Quaternary faulting events on the Rainbow Mountain fault zone in order to further establish timing of events.

INVESTIGATIONS UNDERTAKEN

The principal topics addressed by this study included:

! The late Quaternary slip history of the 1954 Rainbow Mountain fault zone and its bearing on the nature of contemporary tectonic and paleoseismic processes in the CNSB.

! The nature of long-term geologic slip rates in the CNSB and a comparison with contemporary geodetic (GPS-derived) rates.

! The relevance of low slip rate faults to estimating probabilistic seismic hazard in the Basin and Range.

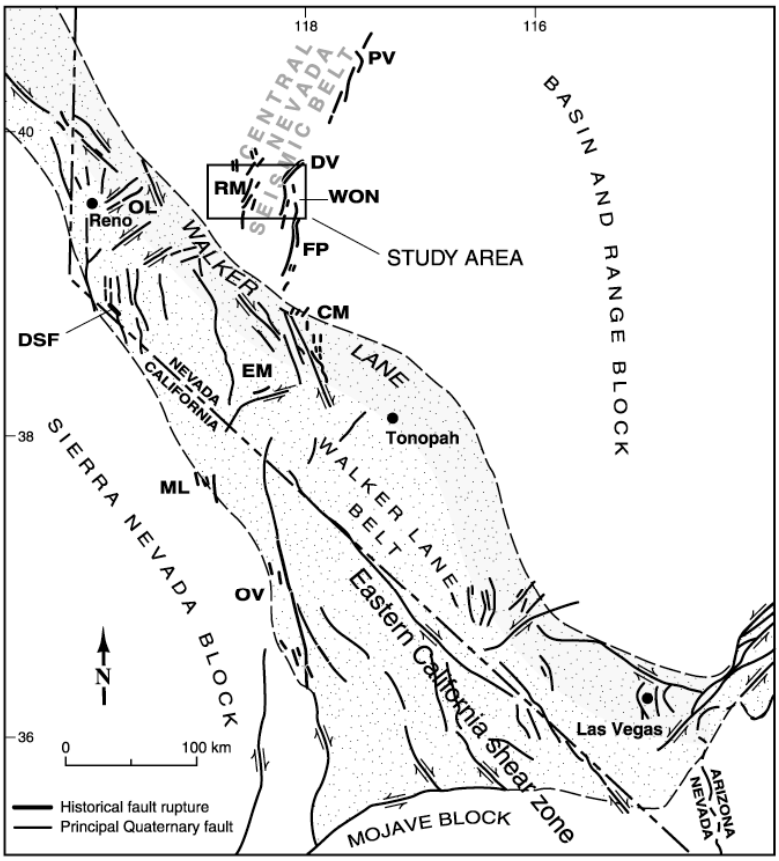


Figure 1. Principal seismotectonic features of the western Basin and Range province showing Walker Lane region and major Quaternary faults and historical surface ruptures (bold). Historical faulting events associated with the central Nevada seismic belt include 1872 Owens Valley (OV), 1903 Wonder (WON), 1915 Pleasant Valley (PV), 1932 Cedar Mt (CM), 1934 Excelsior Mt (EM), 1954 Fairview Peak (FP), 1954 Dixie Valley (DV), and 1954 Rainbow Mt (RM) events. Study area for this project is outlined.

The approach undertaken in this study was to investigate the paleoseismic history of the Rainbow Mountain fault zone by exploratory trenching, age dating, and construction of slip-rate distribution patterns that could be used for comparison with previously established paleoseismic

histories of adjacent fault zones and with the contemporary geodetic strain measurements. Chronostratigraphic studies were conducted along the principal zone of surface faulting produced

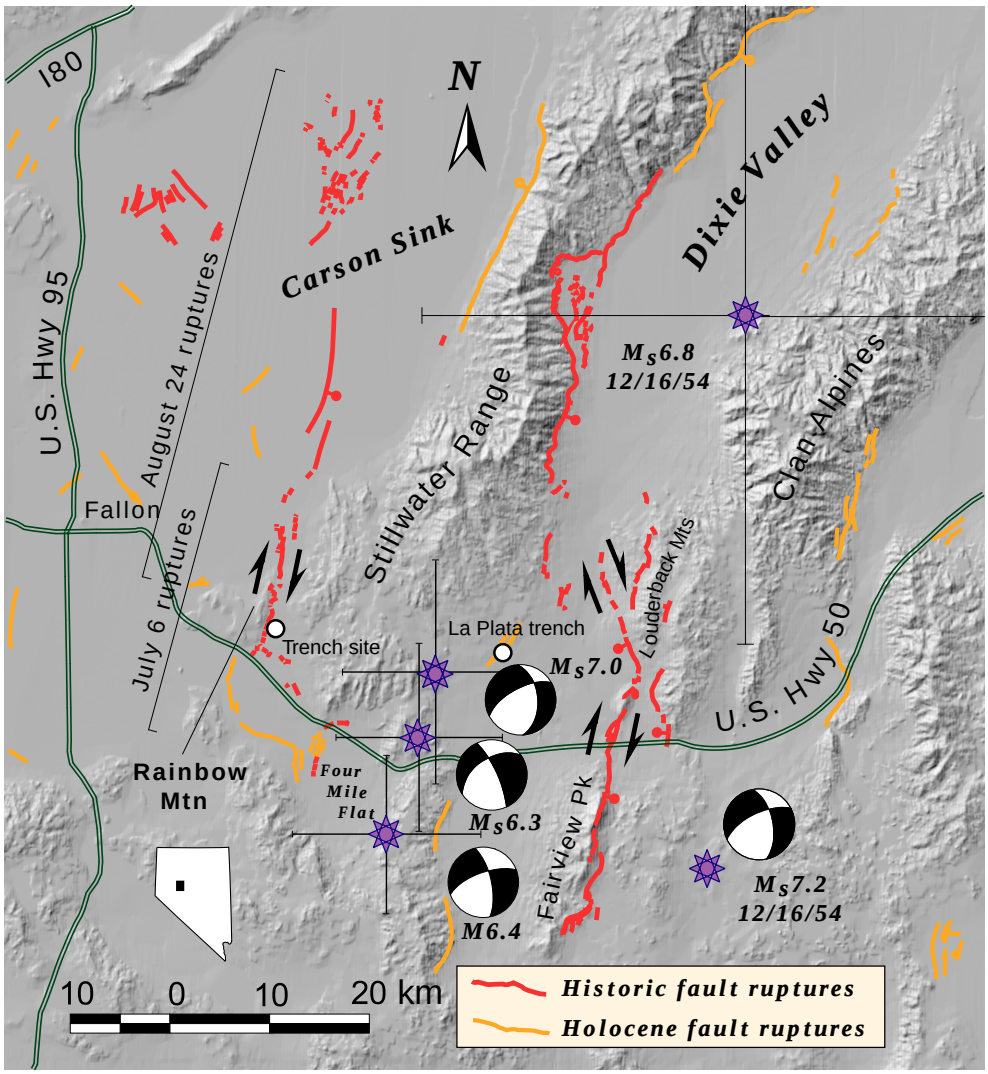


Figure 2. Physiographic location map showing distribution of 1954 fault ruptures (red) and Holocene faults (orange) in the Rainbow Mountain to Fairview Peak area of the CNSB. The Rainbow Mountain ruptures were associated with three events occurring in July (two events) and August (one event), with all three epicenters located near Fourmile Flat. The Fairview Peak and Rainbow Mountain events had similar right-oblique focal mechanisms; the Dixie Valley epicenter is poorly constrained and the focal mechanism is unknown because the seismic coda was obscured by the Fairview Peak record. Focal mechanism data are from Doser (1988).

by the Rainbow Mountain events utilizing existing in-house 1:12,000-scale low-sun-angle aerial photography and combined with the detailed fault trace mapping of Caskey et al. (1999). Chronostratigraphy used in this study was primarily based on the detailed chronology of pluvial

Lake Lahontan developed by Morrison (1964, 1991) and Benson et al. (1990); additional age constraints were provided by ^{14}C dating and tephrochronology during the course of the study. In the La Plata Canyon area of southern Dixie Valley, the chronostratigraphic relations of Bell and Katzer (1990) were used (Fig. 3).

Two exploratory trenches were excavated across the main trace of the 1954 fault on the east flank of Rainbow Mountain (Fig. 2). The trench sites were located within archeologically sensitive areas and required detailed archeological mapping and clearance to permit excavation. Radiocarbon dating of organic samples collected from trench units allowed age constraints to be placed on structural-tectonic relations exposed across the fault.

During earlier NEHRP studies conducted in FY 98-99, exploratory trenches were excavated in Fourmile Flat and La Plata Canyon to investigate, respectively, the southern extent of 1954 Rainbow Mountain faulting and the timing of Holocene faulting at the left step-over between 1954 Fairview Peak and Dixie Valley faulting (Fig. 2; Bell and Ramelli, 1999; Caskey et al., 1999). During this study additional age data were developed from these earlier sites through radiocarbon dating and tephrochronology.

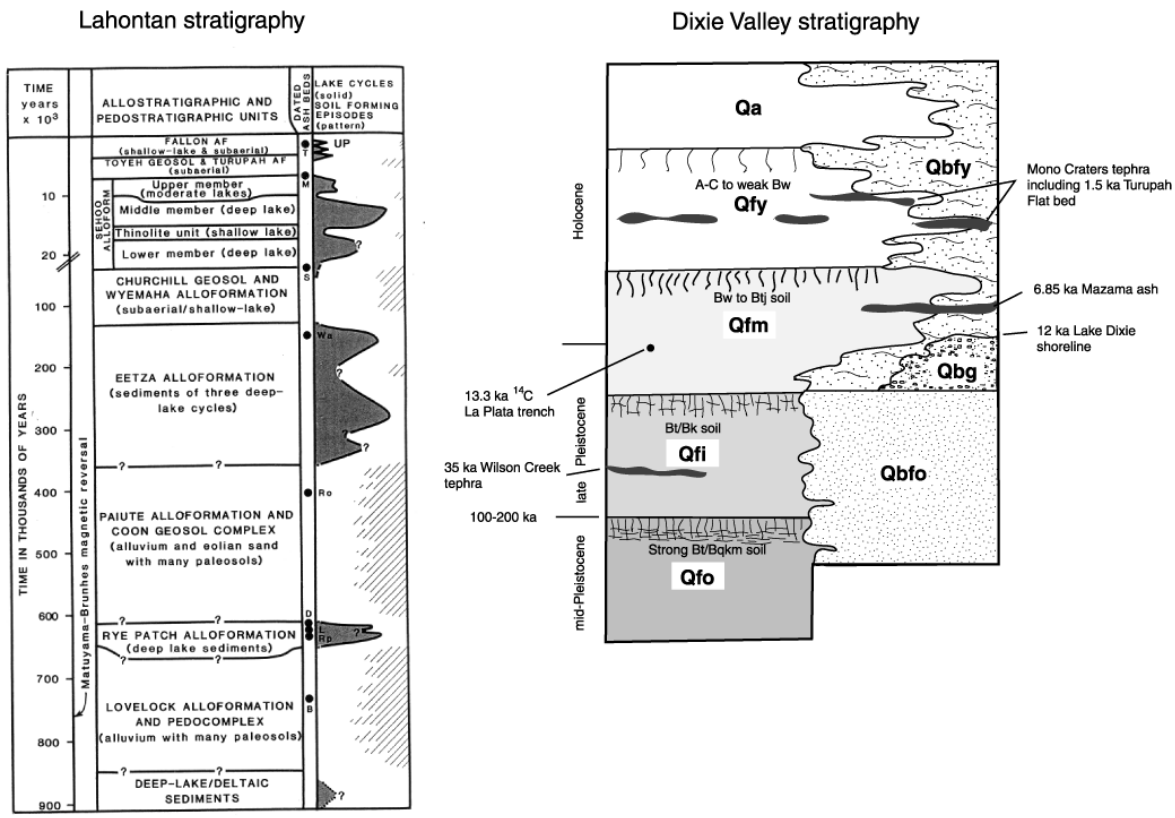


Figure 3. Left: Quaternary chronostratigraphy for the Lake Lahontan region (Morrison, 1991) and Right: the Dixie Valley-Fairview Peak region (Bell and Katzer, 1990).

RESULTS

Chronostratigraphic relationsB Rainbow Mountain

The Rainbow Mountain trenches were excavated in faulted lacustrine and subaerial deposits of mid- to late Sehoo age (Fig. 4). The site is located in a sequence of shorelines that post-date the last highstand of Lake Lahontan extensively radiocarbon dated at about 13 ka (Broecker and Kaufman, 1965; Benson and Thompson, 1987; Benson et al., 1990; Morrison, 1991). These previous studies showed that this last major lacustral phase of Lake Lahontan began 25-30 ka ago with the rise of the early Sehoo lake phase; the early Sehoo lake receded nearly completely at

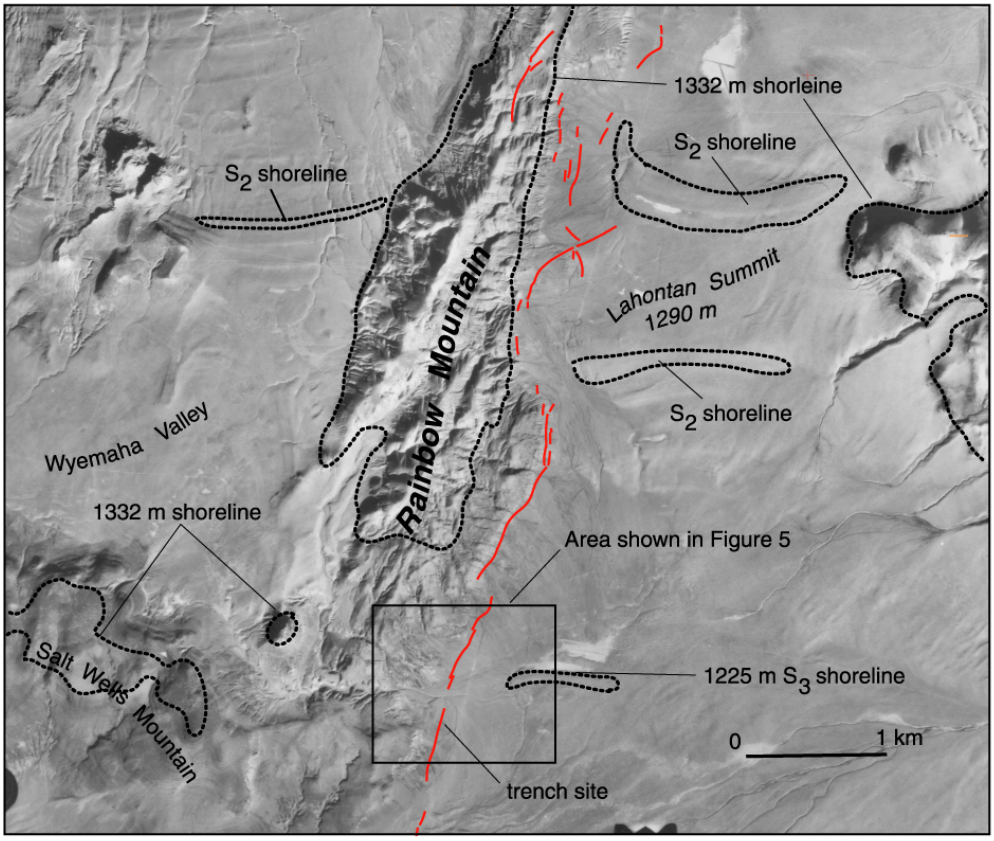


Figure 4. Low-sun-angle aerial photograph of the southern portion of Rainbow Mountain showing the 1954 rupture traces (red) and the key Lake Lahontan shoreline features: the 1332 m highstand (12-13 ka), the recessional dendritic terrace (Lahontan summit) formed by the S_2 shorelines (10-11 ka) at 1290 m, and the last lacustral shoreline S_3 produced by the last rise of Lake Lahontan to 1225 m elevation at about 6 ka.

about 15 ka and then rose sharply to the maximum middle Sehoo highstand at 12-13 ka. Following the mid-Sehoo highstand, the lake receded sharply to near dessication level, to be later followed by smaller lacustral phases in late Sehoo and Fallon lake time (Morrison, 1991). Rainbow Mountain exhibits a suite of late Sehoo highstand and post-highstand shorelines and constructional beach bars (Fig. 4). The 13 ka highstand occurs at 1332 m around the upper margins of the Rainbow Mountain block, with the post-highstand shorelines forming a recessional sequence at lower elevations. The principal post-highstand shorelines defined by Morrison (1991) include the recessional dendritic (S_2) shoreline at 1290 m elevation and a late Sehoo lacustral (S_3) shoreline at about 1225 m; the dendritic shoreline is previously radiocarbon dated at about 11 ka (Broecker and Kaufman, 1965) and the S_3 shoreline was estimated to be 8-9 ka by Morrison (1991).

The Rainbow Mountain fault trace is nested within post-highstand shorelines along most of the Rainbow Mountain block, including the trench site, and low-sun-angle aerial photography and field investigations show that it follows a subtle paleoscarp (Fig. 5). Of particular importance are the cross-cutting relations of two sets of shorelines present at the trench site; an older set of recessional shorelines containing the 1954 rupture and paleoscarp are truncated by a younger shoreline displaying only the 1954 rupture.

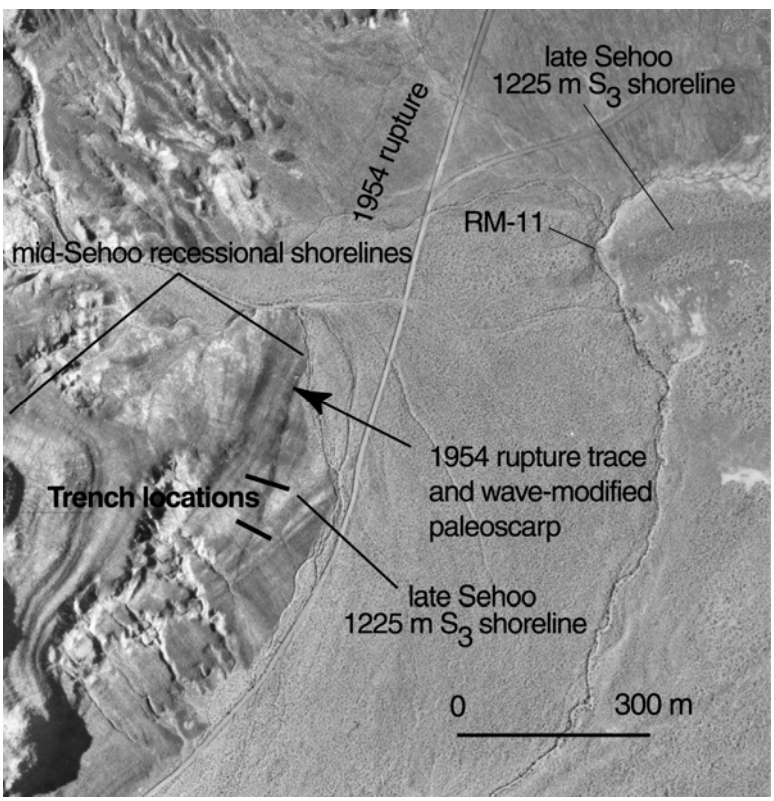


Figure 5. Low-sun-angle aerial photograph showing trench locations across the 1954 rupture trace, the multiple post-mid-Sehoo recessional shorelines and the late Sehoo lacustral S_3 shoreline at 1225 m. The S_3 shoreline is dated at <6.3 ka based on a radiocarbon date on sample RM-11 taken from a natural wash exposure several hundred meters northeast of the trenches.

Trenching results

North trench

The north trench was excavated across the 1954 trace and paleoscarp, and it exposed a sequence of subaerial and lacustrine deposits exhibiting structural-stratigraphic evidence for two older faulting events (Fig. 6). The footwall of the fault is composed of tuffaceous sandstones and mudstones of the Tertiary Truckee Formation, which at this location has been extensively pedimented and occurs at shallow depths beneath a veneer of Lake Lahontan sediments (Morrison, 1964).

The lower unit in the hanging wall of the trench (Qf_1) is a small pebble sand containing angular, locally derived alluvial fan clasts; the clast composition and the occurrence of a paleoroot zone in the top of the deposit demonstrate that this unit was deposited under subaerial conditions. A radiocarbon date on the paleoroot horizon yielded an age of 17.8 ka (Table 1; sample RM-8); the age indicates that this deposit was formed during the mid-Sehoo subaerial phase.

The subaerial unit Qf_1 is overlain by a sequence of lacustrine sand and beach gravel deposits; each of the deposits is distinguished by different bedding characteristics and discontinuities suggesting rising and descending shoreline levels during middle Sehoo time. Upper and lower beach gravels (Qsg_1 and Qsg_2) are separated by a thin lacustrine clay (Qsc). The lowest unit of the sequence Qsg_1 (a) is interbedded lacustrine beach sand and gravel; the sand deposit lies disconformably on the paleoroot horizon of Qf_1, and grades laterally into sandy pebble gravel beach bar deposits. Units Qsg_1 (b) and Qsg_1 (c) consist of sandy pebble to cobble beach gravels similar to Qsg_1 (a) but containing beach bar clast imbrication. The upper Qsg_1 (c) unit contains prominent west-dipping imbrications representing a pro-grading beach bar. A distinctive red-brown 15 cm thick clay (Qsc) occurs as a secondary deposit impregnating the Qsg_1 (b) and Qsg_1 (c) gravels, representing the deep water deposition occurring after the lake rose above the beach deposits. The clay occurs in the same stratigraphic position in the fault zone and on the footwall block. A radiocarbon date on organic sediment from the clay yielded an age of 11.8 ka (Table 1; sample RM-2). The lacustrine clay is overlain by imbricated foreset beach bar gravels of unit Qsg_2 representing another shoreline phase of the lake. A radiocarbon date on calcareous tufa collected from Qsg_1 (c) gravel yielded an age of 30.1 ka (sample RM-1), an age that is anomalously old based on the age of the underlying lake clay and the buried paleoroot horizon.

A 1 m thick colluvial wedge (Qc) overlies unit Qsg_1 (c) and is associated with a 1 m high paleoscarp at the north trench. The clasts contained in the wedge are locally coated with calcareous tufa suggesting the wedge may have formed in shallow water.

Subaerial deposits (Qf_2) occur on the footwall block where they overlie thin Qsg_1 sand and gravel deposits. They were deposited following the Qsg_2 recessional phase, and they exhibit a moderately developed soil containing a 10 cm Av, 20 cm Bw, and 35 Cm stage II Bk horizon. The hanging wall section is capped by a thin alluvial deposit (Qf_3) that thickens to about 1 m thick near the scarp and may in part be associated with the Qc wedge deposits. A charcoal sample

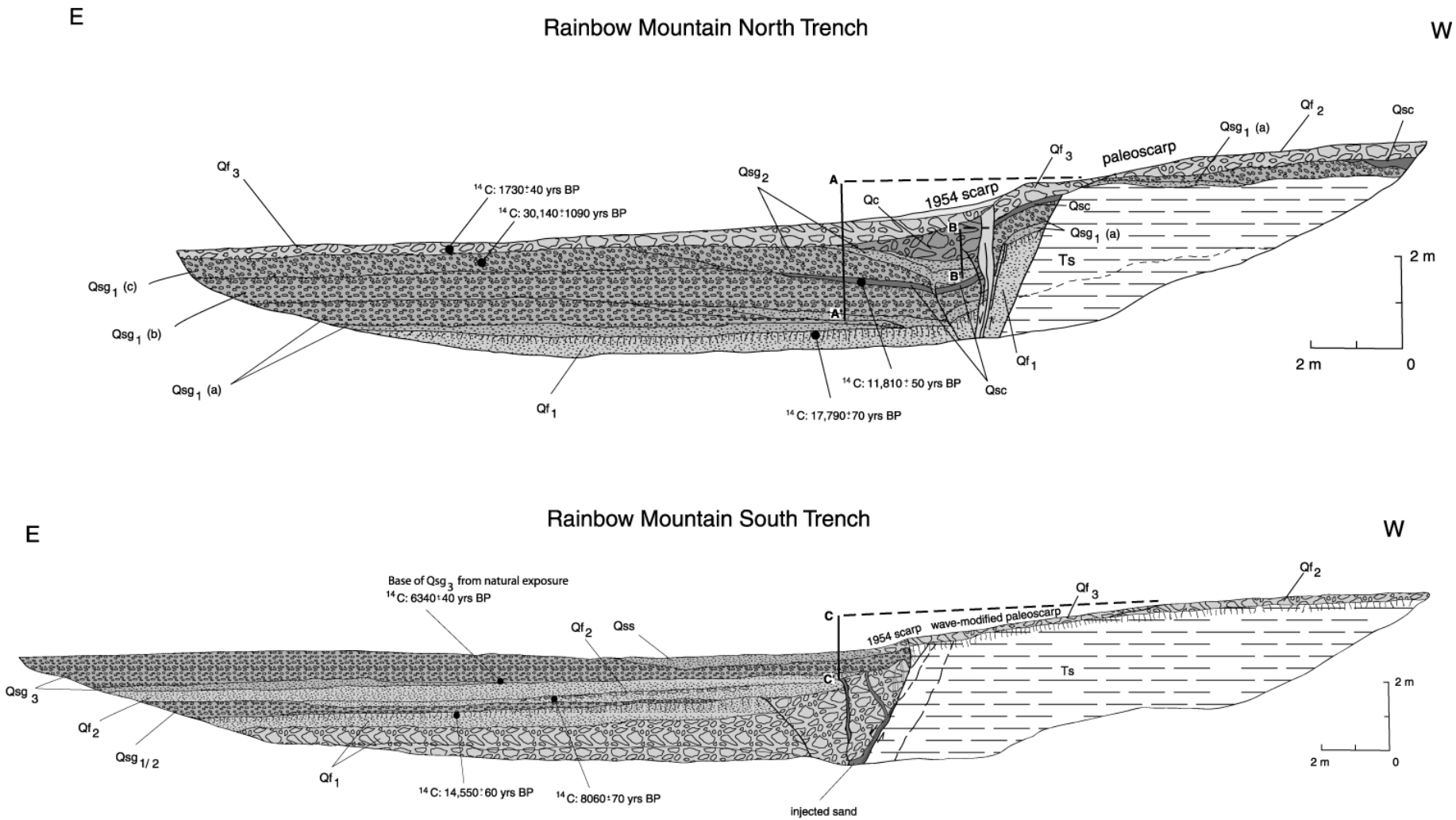


Figure 6. Logs of Rainbow Mountain trenches showing fault-straigraphic relations, and location of radiocarbon samples (see Table 1)

from the deposit yielded a radiocarbon age of 1.7 ka (sample RM-4).

South trench

The south trench was excavated across the fault where the paleoscarp visible at the north trench has largely been removed by erosion related to the last lacustral phase of the lake. A sequence of subaerial and lacustrine deposits similar to those in the north trench is present, with an additional beach gravel deposit associated with the last lacustral phase. The footwall of the south trench contains similar tuffaceous sedimentary rocks of the Truckee Formation.

The lowermost unit in the hanging wall is the mid-Sehoo subaerial deposit Qf_1 , which here consists of gravelly alluvial fan deposits and the sandy alluvial fan containing the paleoroot horizon; a radiocarbon date from the root horizon yielded a slightly younger age of 14.5 ka (sample RM-7). The Qf_1 deposits are disconformably overlain by $Qsg_{1/2}$ gravels that here consist of a thin deposit containing undifferentiated mid-Sehoo beach gravels. The Qf_1 and $Qsg_{1/2}$ deposits show prominent reverse fault relations associated with the oldest event in the trench, indicative of a lateral component of fault motion.

The faulted Qf_1 and $Qsg_{1/2}$ deposits are unconformably overlain by Qf_2 subaerial alluvial fan gravels that consist predominantly of reworked beach deposits and subaerial sand containing a weak Bk carbonate soil. Charcoal collected from the sand facies yielded a radiocarbon age of 8.1 ka (sample RM-6). The Qf_2 deposits are the uppermost deposit on the footwall and contain a reddened Bw soil. The unit is vertically offset by the penultimate event about 1.5 m; a well-sorted fine sand along the fault plane was injected by liquefaction during the faulting event.

The uppermost deposits in the south trench are Qsg_3 beach gravel and back-bar silt deposits associated with the last major lacustral phase of Lake Lahontan. The gravels form a distinctive bar visible on aerial photographs (Fig. 5) and comprise the S_3 shoreline of Morrison (1964). The S_3 shoreline rose to the elevation of the fault, and the beach eroded the paleoscarp of the penultimate event at the south trench, accounting for the lack of pre-1954 surficial fault evidence at this site. The deposits are younger than the charcoal date of 8.1 ka obtained from the trench and slightly younger than the radiocarbon age of 6.3 ka (sample RM-11) on an organic clay in Qf_2 deposits buried beneath the S_3 beach bar in a nearby natural exposure (Fig. 5).

Sequence of lacustral and subaerial deposition at the study site

The sequence of interbedded lacustrine sand and gravel deposits, lake clay, and subaerial alluvial fan deposits exposed at the trench site (elevation 1228 m) is interpreted as follows: The oldest lowest Quaternary unit is an alluvial fan deposited during the early to mid-Sehoo age recessional phase of the lake occurring at about 15 ka (Morrison, 1991). The lower Qsg_1 (a) deposit represents the transgressive phase of the middle Sehoo lake as it rose following the mid-Sehoo subaerial period. The Qsg_1 lake shoreline may have fluctuated over time producing a succession of beach sand and gravel deposits represented by units Qsg_1 (b) and Qsg_1 (c). Following the deposition of Qsg_1 (c) gravel bar deposits, the lake is inferred to have risen to the maximum mid-

Sehoo highstand (12-13 ka) at 1332 m during which time the deep-water lake clay (Qsc) was deposited at the trench site. During the post-highstand mid-Sehoo recessional phase, the lake level dropped rapidly below trench site elevation to near dessication level, and subaerial alluvial fan gravel was deposited by 8 ka. During late Sehoo time, the lake rose to the elevation of the south trench during the last major lacustral phase dated in this study at #6.3 ka, and then again receded to near dessication level, and the late Holocene Qf_3 alluvial fan gravels were deposited at the site.

Table 1. Rainbow Mountain ^{14}C results			
^{14}C sample number	Sample material	Sample location	^{14}C Age (yrs BP)
RM-1	calcareous tufa	Qsg in north trench	30,140 ± 1090
RM-2	organic clay	Qsc in north trench	11,810 ± 50
RM-4	charcoal	Qf_3 in north trench	1730 ± 40
RM-6	charcoal	Qf_2 in south trench	8060 ± 70
RM-7	carbonized roots	Qf_1 in south trench	14,550 ± 60
RM-8	carbonized roots	Qf_1 in north trench	17,790 ± 70
RM-11	organic soil	Qf_2 in wash cut	6340 ± 40

Table 2. La Plata trench ^{14}C results			
^{14}C sample number	Sample material	Sample location	^{14}C Age (yrs BP)
DV-8	organic soil	colluvial wedge	7330 ± 50
DV-9	organic soil	colluvial wedge	3440 ± 250
DV-10	organic soil	buried Bt soil	7280 ± 280
DV-11	organic soil	buried fan deposit	23,020 ± 100
DV-12	organic soil	buried Av soil	13,300 ± 50

Event timing and slip rate estimates

Two pre-1954 faulting events are recognized based on fault-stratigraphic relations exposed in both trenches. The older of the two events (triultimate) offsets Qf_1 and lower Qsg_1 deposits, but does not offset Qsc (Fig. 7A); the age of the event is therefore bracketed by the ^{14}C ages of samples RM-2, -7, and -8: 11.8-14.5 ka. The penultimate event displaces Qsc lake clay, upper Qsg_1, and Qf_2 deposits, but does not displace Qsg_2 beach gravel at the south trench (Fig. 7B). The age of Qf_2 alluvial fan deposits is 8 ka based on a date on detrital charcoal (RM-6), and the age of the unfaulted Qsg_2 beach gravel is #6.3 ka based on a ^{14}C date on organic soil immediately beneath the gravel in natural outcrop (Fig. 5). The age of the penultimate event is therefore placed at 6.3-8.0 ka.

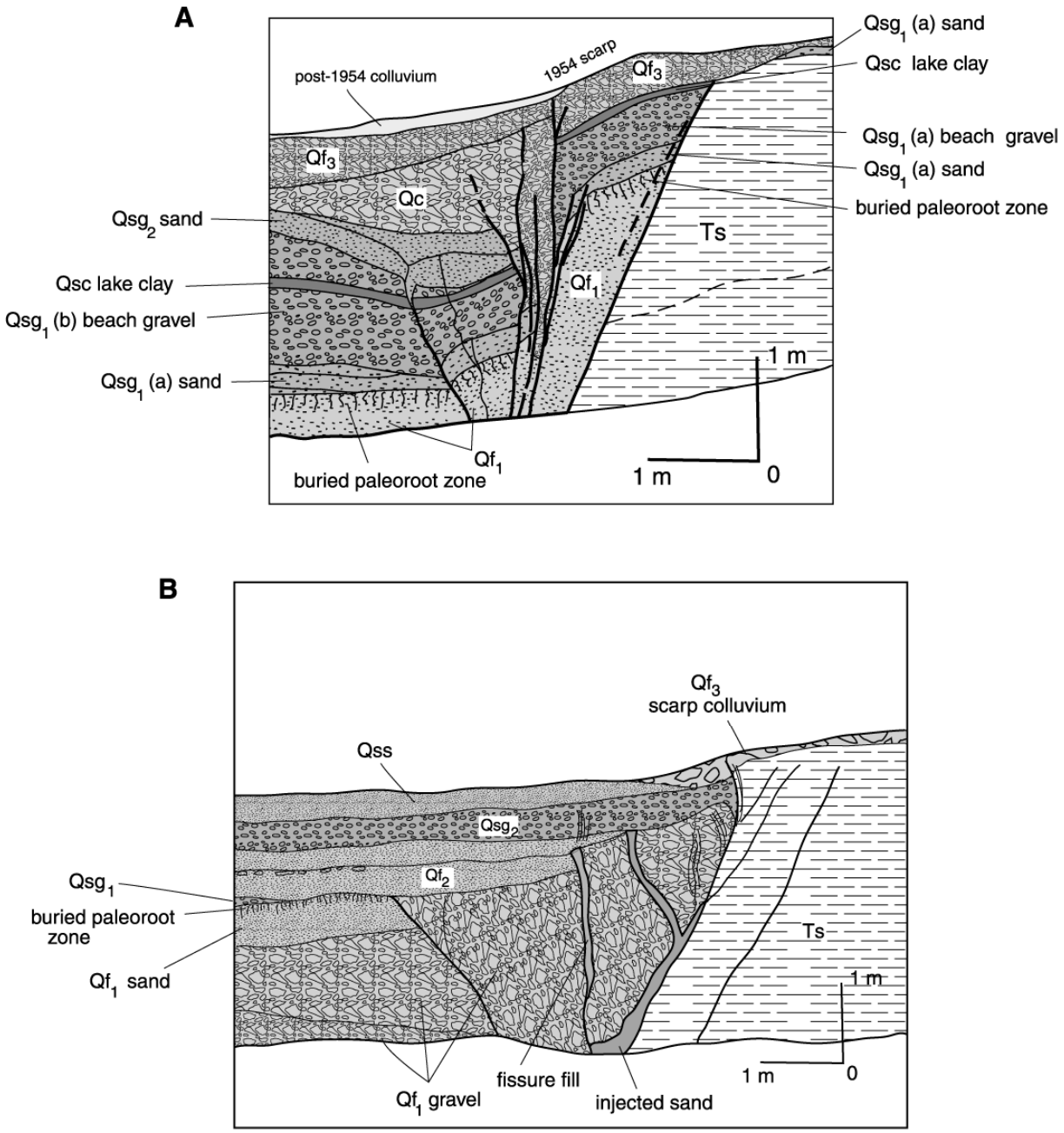


Figure 7. Enlarged trench logs for Rainbow Mountain trenches showing fault gemetry and stratigraphic relations in the shear zone. A. North trench log showing Qsc clay truncating triultimate rupture trace and colluvial wedge derived from penultimate event. B. South trench log showing prominent reverse fault relations, faulted Qf_2 deposits from the penultimate event, and Qsg_2 deposits truncating the penultimate event

Based on measured offsets of trench stratigraphy, each of the earlier events appears to have been associated with 1-1.5 m of vertical displacement (Table 3). The cumulative vertical displacement from all events is measured by the 2.5-3.0 m offset of the base of the lower Qsg_1 (a) deposits (line A-A= on Fig. 6) with 30 cm of this offset accounted for by the 1954 rupture. A 1-1.2 m vertical displacement associated with the penultimate event is measured by subtracting 1954 displacement from offset Qsc and Qf_2 deposits (lines B-B= and C-C= on Fig. 6), and a 1.5 m vertical displacement for the triultimate event is measured by subtracting 1954 and penultimate event displacement from the cumulative total. A significant component of lateral or oblique slip during the triultimate event is evident from the reverse fault relations in Qf_1 and Qsg_1 (a) deposits.

Table 3. Event offsets

Event	Unit	Cumulative vertical offset (m)	Event offset (m)
1954	Qsg_2	0.3	0.3
penultimate	Qf_2 Qsc	~1.5 1.2-1.3	~1.2 ~1.0
triultimate	Qsg_1 Qf_1	2.5-3.0 3.0±	~1.5

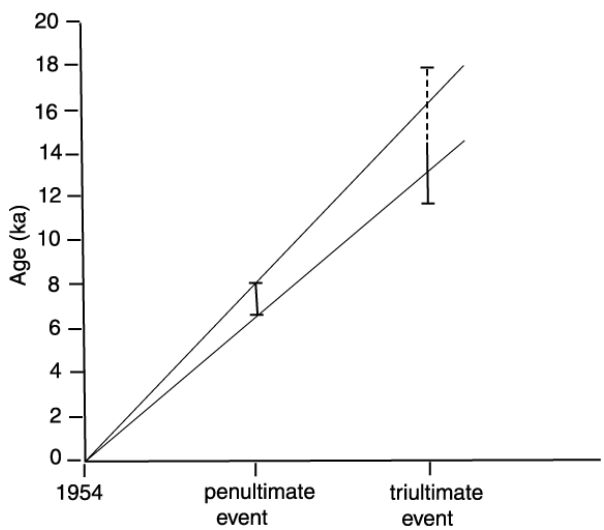


Figure 8. Time-dependent plot of the three Rainbow Mountain events based on constraining ages derived from trench relations. The projected time line brackets the age of the penultimate event and may correspond to a periodic recurrence line based on the range in age of the triultimate event. If the recurrence is periodic, it would correspond to an interseismic interval of about 7,000 yrs.

We believe that the triultimate event occurred either during the mid-Sehoo subaerial period or during the early stages of the mid-Sehoo lacustral phase because the event predates the deep-water phase of the lake. The deep-water clay deposit Qsc was deposited as a thin layer impregnating the older lacustrine gravels and draping the 1.5 m high fault scarp formed by the triultimate event; it was subsequently vertically displaced 1-1.2 m by the penultimate event. We infer that the penultimate event occurred below or very close to lake level because of the presence of injected (liquified) sand along the fault trace. The age of the event is bracketed by the offset Qf_1 subaerial deposits and the unfaulted Qsc lake clay and placed at between 11.8 and 14.5-17.8 ka.

Based on the ages of the penultimate and triultimate events, an average interseismic interval of about 7,000 yrs is estimated (Fig. 8). Although the radiocarbon age range for the triultimate event is 6 ky, an event line representing periodic timing between events of 7 ky can fit all three rupture points. Although this suggests periodic behavior, the range in radiocarbon ages also allows aperiodic timing, especially if the age of the triultimate event is closer to 11.8 ka.. The event timing is not considered characteristic; although the older events had the same relative vertical displacement (1-1.5 m), the 1954 displacement was one-third or less (0.3 m) the size of the earlier events.

The cumulative 3 m vertical offset of 14.5-17.8 ka Qf1 deposits yields a vertical slip ratio of 0.2 mm/yr. Fault geometry exposed in the trenches and mapping along the Rainbow Mountain rupture zone, however, show that the 1954 and earlier faulting events had significant oblique-slip components. Slickenlines measured by Caskey et al. (1999) on exposed fault surfaces north of the trench site had rakes of 30E, indicating a vertical to horizontal slip ratio of about 1:1.6. Using this slip ratio and the cumulative vertical displacement of 3 m measured in 14.5-17.8 ka Qf_1 deposits, a net slip rate of 0.3-0.4 mm/yr is calculated for the Rainbow Mountain fault.

New data on Lake Lahontan fluctuations

The chronology of lake fluctuations in the Carson Desert portion of the Lake Lahontan basin has been described by Morrison (1991) based on a synthesis of his earlier mapping (Morrison, 1964) and the age dating studies of Broecker and Kaufman (1965), Thompson et al. (1986), and Benson and Thompson (1987). Based on radiocarbon dating of lacustrine and subaerial deposits exposed at our Rainbow Mountain trench site and recent tephrochronology data from the Carson basin, we are able to further refine Morrison=s (1991) lake fluctuation curve (Fig. 9).

Morrison (1991) suggested that the early Sehoo lacustral phase reached a maximum elevation around 17-18 ka and that it was followed by a sharp recessional phase at about 15 ka. The radiocarbon dating of subaerial deposits in the trenches suggests, however, that the lacustral phase ended slightly earlier, before 17.8 ka, and that the recessional phase may have extended for several thousand years to <14.5 ka. Numerous radiocarbon ages derived from previous studies elsewhere within the Lahontan basin closely constrain the age of the middle Sehoo highstand at

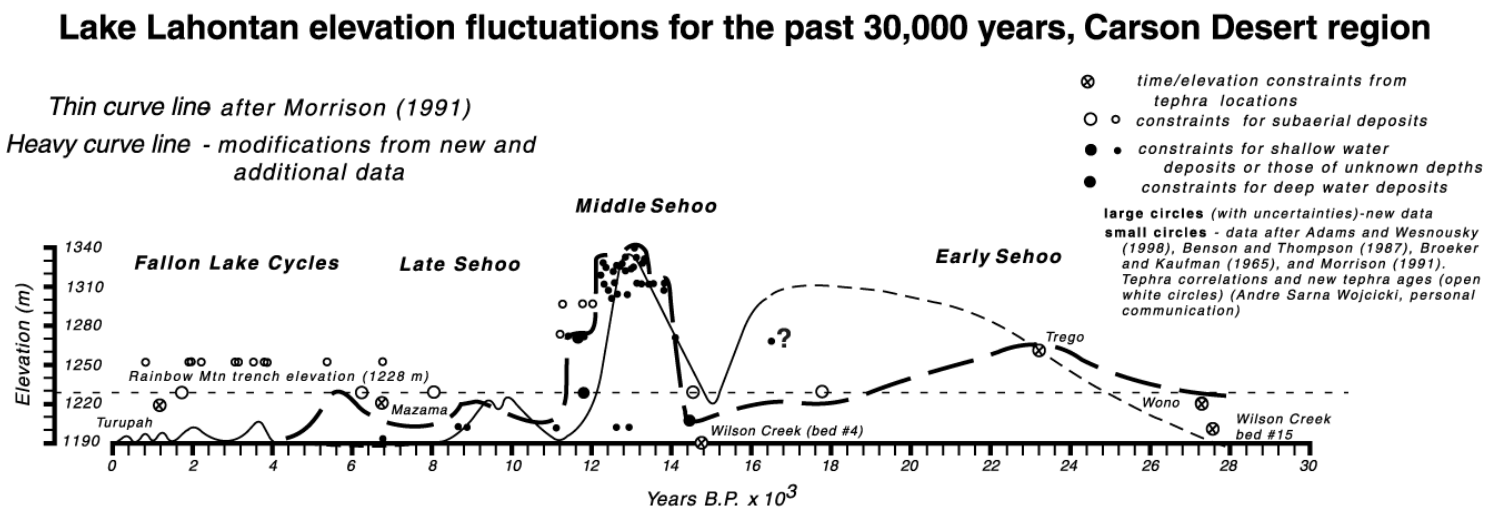


Figure 9. Elevation fluctuation curve for Lake Lahontan lacustral phases of early Sehoo age and younger. The thin black line is the curve of Morrison (1991), and the heavy black line is our revised curve based on stratigraphic and radiocarbon age relations developed during this study. The dashed line is the elevation of the trench sites.

12-13 ka. The trench site is located at 1225 m elevation, well below the highstand shoreline (1332 m), but the occurrence of a deep water lake clay dated at 11.8 ka in the north trench confirms the high lake position at this time.

Morrison=s (1991) compilation suggests that the mid-Sehoo maximum lacustral ended with a sharp recessional phase at 10-11 ka, at which time the lake receded to near-dessication levels, and that this recessional was followed by the last late Sehoo lacustral phase at 9-10 ka. Few radiocarbon dates constrain the time at which the lake reached the lowest elevation in this recessional phase or the timing of the last lacustral in the Carson basin, with most age constraints derived from the Pyramid Lake basin (Broecker and Kaufman, 1965; Benson and Thompson, 1987).

New data from our study shows, however, that following the mid-Sehoo maximum highstand at 12-13 ka, the lake level did not rise again to the 1225 m elevation level of the trench site until around 6 ka. The shoreline associated with the late Sehoo lacustral phase, the S_3 shoreline of Morrison (1964), reached the level of the south trench but did rise to the level of the north trench which is situated a few meters higher (Fig. 5). Subaerial deposits underlying the S_3 beach gravels in the south trench yielded an of 8.1 ka; a buried clay soil underlying S_3 beach gravel in natural exposure several hundred meters northeast of the trench site (Fig. 5) yielded an age of 6.3 ka. The ages suggest indicate that the late Sehoo recessional lasted between 6.3-10-11 ka, and although we do not know with certainty the exact age of the S_3 shoreline, it is slightly younger than 6.3 ka. This age appears consistent with the distribution of Mazama ash (6.85 ka) which occurs in subaerial deposits below elevations of 1200 m in the Carson basin (Morrison, 1991).

Fourmile Flat exposure

Surface ruptures associated with Rainbow Mountain events extended as far south as Fourmile Flat where they are believed to have been produced by a second sub-event in the July 6 sequence (Fig. 2; Caskey et al., 2000). Natural wash exposures near the 1954 Fourmile Flat ruptures expose a sequence of faulted mid- Sehoo lake clay (Fig. 10) that provides paleoseismic information useful in defining the slip history of the Rainbow Mountain fault zone. During this study we have revised slightly the original interpretation of faulting history presented in previous reports.

The Fourmile Flat faults exhibit a very subdued 60 cm high paleoscarp, which farther south increases to as much as 2 m. The channel cut exposes a 15 m wide zone of mid-Sehoo clay containing three tephra layers. The lowermost tephra (T1) correlates with the Wilson Creek ash #4 dated at 14.7 ka (A. Sarna-Wojcicki, personal commun.). The two upper tephra (T2, T3) form a couplet that correlates with a number of mid- to late Holocene ashes that may be as young as 1.5 ka.

The fault slip history is interpreted as follows. The lower T1 tephra was displaced by a faulting event with about 1 m vertical offset. The faulted playa surface was eroded and the T2, T3 tephra couplet was deposited over the truncated fault zone; this couplet was subsequently faulted by a second event producing the presently visible 60 cm scarp. The total net vertical separation of the

T1 tephra is 1.6 m, and the vertical slip rate during the last 14.7 ka is 0.1 mm/yr. Although there is no direct surficial evidence for lateral- or oblique-slip movement on the faults, if we assume based on the focal mechanisms that motion included a right-lateral component and we use a vertical-to-horizontal slip ratio of 1:1.6 similar to that on the main fault trace, a net slip of 3.2 m during the last 14.7 ka yields a slip ratio of 0.2 mm/yr.

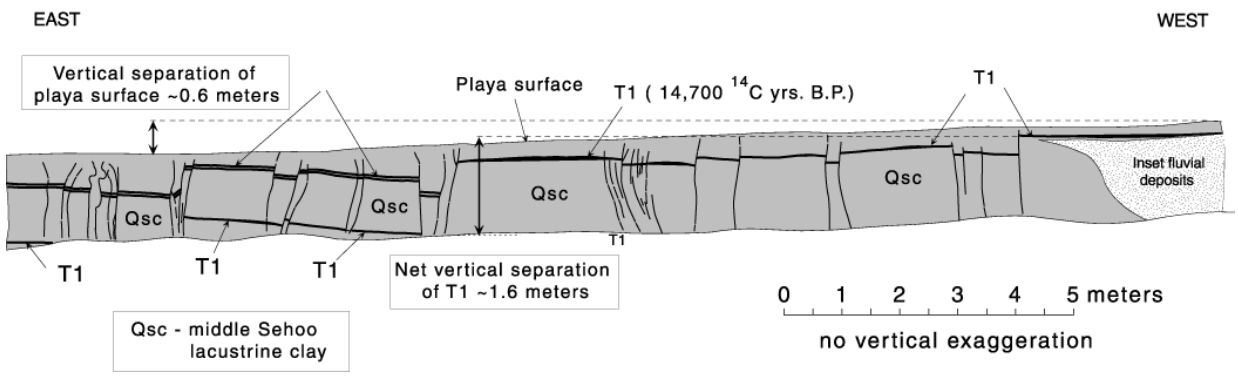


Figure 10. Log of Fourmile Flat wash exposure showing faulted mid-Sehoo age lake clay deposits containing three volcanic tephra. The paleoscarp associated with the most recent event has very subdued relief of about 0.6 m.

La Plata Canyon trench

The La Plata fault is located at the left-step-over between the 1954 Fairview Peak and Dixie Valley ruptures zones (Fig. 2) and although it did not rupture during the 1954 events, it displays one of the largest (7 m) Holocene scarps in the area. An exploratory trench was excavated across the fault during FY 98-99 studies which exposed a stack of four colluvial wedges overlying displaced alluvial fan deposits. Based on stratigraphic correlation with alluvial fan deposits in central Dixie Valley, the faulted La Plata deposits were inferred to be equivalent to Qfm deposits which are younger than the 12-13 ka Lake Dixie shoreline (Bell and Katzer, 1990). Bell and Ramelli (1999) therefore interpreted the colluvial wedges as representing four faulting events in the last 12-13 ka.

Additional radiocarbon dating conducted in the La Plata trench during the present study suggests that the oldest Qc_1 deposit is not a colluvial wedge. We sampled weakly organic sediments from the Qfm and colluvial wedge deposits and obtained five ^{14}C ages that allow us to interpret the slip history of the fault (Fig. 11; Table 2). A sample taken from a buried Av soil horizon in the

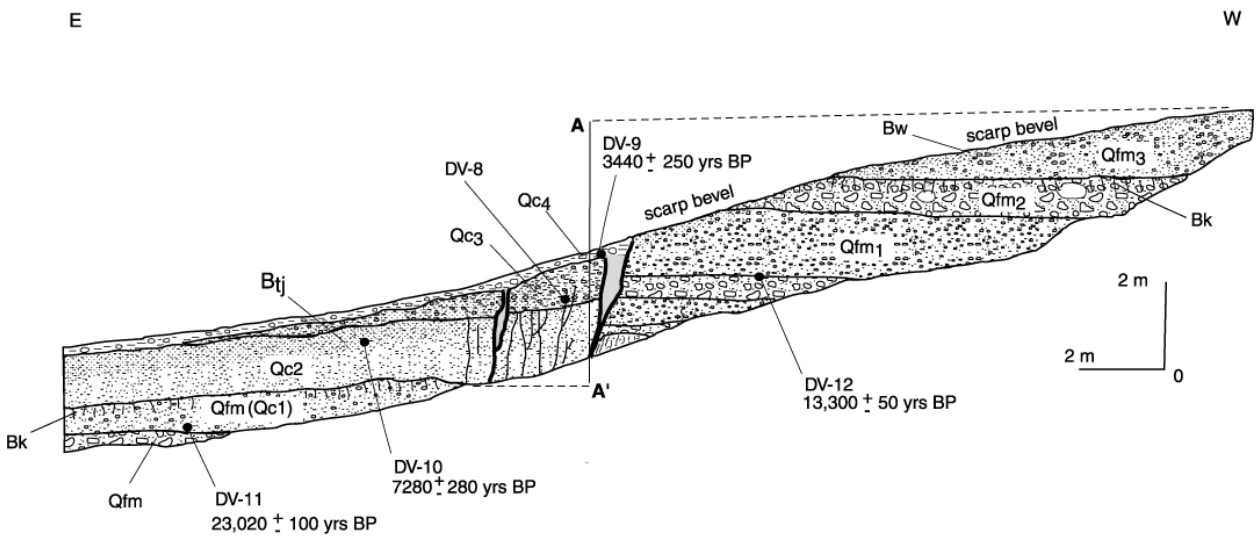


Figure 11. Log of La Plata trench showing location of recent radiocarbon samples (see Table 2). Earlier studies identified four colluvial wedges. The new radiocarbon dates indicate that the oldest wedge Qc_1 is probably not a wedge but a partial section of the faulted Qfm alluvial fan deposits.

footwall of the fault (sample DV-12) yielded an age of 13.3 ka, confirming our earlier age interpretation. Samples DV-10 and DV-8 were taken from the top of colluvial wedge Qc_2 and the base of Qc_3 and yielded essentially identical ages of 7.3 ka. The ages could be interpreted as either dating the age of third event (buried surface/base of fault-produced wedge) or as dating the Btj soil which formed in both wedges some time after the third faulting event. A sample from the base of the fourth wedge Qc_4 yielded an age of 3.4 ka. Although this date may reflect the age of the event, the Qc_4 wedge is small, and older scarp-derived soil may have been intercalated into the deposit.

All of the radiocarbon ages are consistent with the stratigraphic relations except for the age of 23.0 ka obtained on sample DV-11 in lowermost Qc_1 deposits. The sample was taken from an organic mud at the base of Qc_1; if the age is accurate it would indicate that these are not colluvial deposits, because the age is greater than that of the footwall deposits, and that it is more likely that these are actually faulted older Qfm deposits. Supporting this interpretation is the occurrence of a laminar Bk horizon in Qc_1 that suggest the unit is somewhat older than originally inferred. Additional age dating of the units and/or deepening of the trench are necessary to more fully explain these differences.

The results of radiocarbon dating together with previous surface mapping of multiple-event scarps at the trench indicate that two large (2-3 m) and one smaller (0.5-1 m) events have occurred in the last 13.3 ka. The two larger and older events, represented by the Qc_2 and Qc_3 wedge deposits, appear to have occurred close in time based on the common Btj soil formed in both deposits. The ^{14}C ages from the soil suggest that the events occurred before 7.3 ka. The younger, small displacement event may be dated by the ^{14}C age of 3.4 ka; however, it may be

younger based on fresh scarp morphology and the possibility of incorporation of older organic material from the scarp into the wedge. Based on a total vertical separation of 6 m in Qfm deposits (line A-A= on Fig. 11), a slip rate of 0.4-0.5 mm/yr is calculated. There is no trench or surficial evidence of lateral or oblique slip along the La Plata fault, and both the Dixie Valley faults to the north and the Sand Springs Range faults to the south appear to be normal-slip faults.

Comparison of event timing and evidence for paleoseismic belts

A comparison of paleoseismic event timing for the 1932 Cedar Mountain, and 1954 Fairview Peak and Dixie Valley earthquakes was presented in Bell et al. (1999b) where we showed that each of these zones has a varied and different slip history. In Figure 12, the Rainbow Mountain events have been added to this comparison.

If the timing of penultimate events is compared for the three 1954 rupture zones and with the 1932 Cedar Mountain zone, it is evident that this historical rupture pattern has not been replicated in the last 10 ka. The penultimate event at Rainbow Mountain does not correspond to any events in either the Fairview Peak or Dixie Valley zone, although it may correspond to one of the last two events at La Plata Canyon or to the penultimate event at Cedar Mountain dated at about 4 ka (Bell et al., 1999a). The Fairview Peak and Dixie Valley zones have been comparatively less active during the Holocene than the Cedar Mountain, Rainbow Mountain, or La Plata faults. The Fairview Peak zone has no earlier events in at least the last 35 ka, and it has an anomalously low slip rate fault compared to the other historical rupture zones. Faulting overlapped the 1932 Cedar Mountain zone by about 15 km, but yet it has a strikingly different slip history. The age of the Holocene event in Dixie Valley (called the Bend event by Bell and Katzer, 1990) is now well constrained between 2.0-3.7 ka, and the rupture is associated with an event that nucleated from the north in the Stillwater seismic gap (Caskey, unpub. data).

Slip rates and seismic hazard

Paleoseismic slip rates are used for estimating moment rates in the construction of probabilistic seismic hazard maps (Frankel et al., 1996). The slip rates estimated for historically active faults within the CNSB (Figure 12) are considered moderate to low rates in comparison to other higher slip rate faults in the western Basin and Range province (Bell et al., 1999a). Despite these relatively low rates of long-term geologic slip, these faults have a measureable seismogenic potential that may not be adequately characterized by probabilistic methodologies which rely on moment rate to model potential hazard. The Rainbow Mountain fault has a relatively low slip rate of 0.2-0.3 mm/yr but produced three surface-rupturing events in 1954. The Fairview fault is perhaps the best example of a low slip rate fault that has produced a large-magnitude event despite not having ruptured during at least the prior 35 ka.

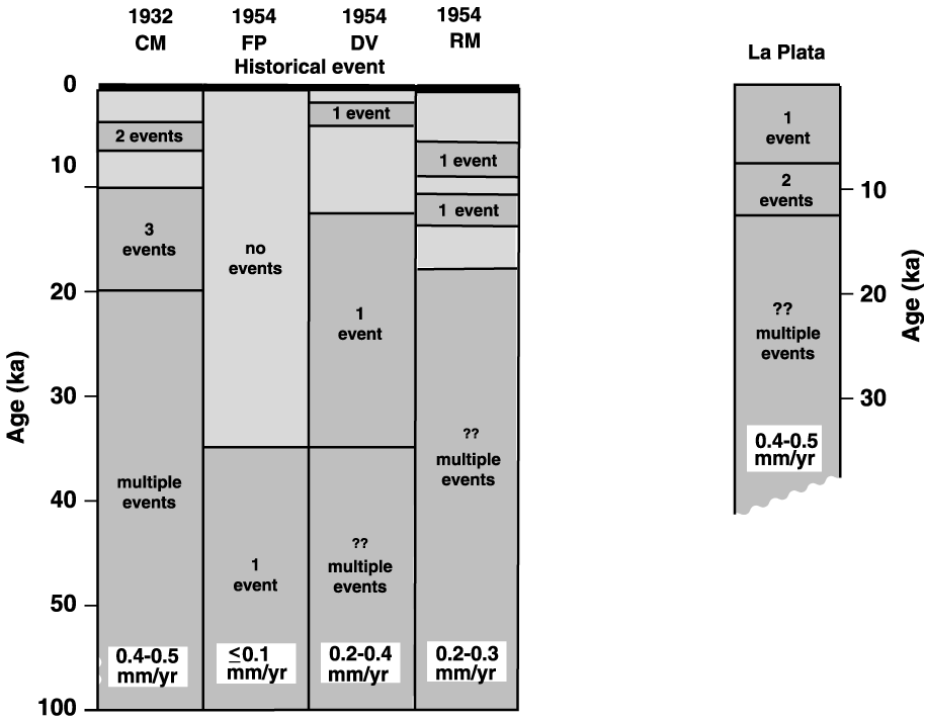


Figure 12. Correlation of event timing in the historical 1932 Cedar Mountain, the1954 Fairview Peak, Dixie Valley, and Rainbow Mountain rupture zones and the La Plata fault zone located at the left-stepover between the Fairview Peak and Dixie Valley faults.

Contemporary strain in the 1954 zone between Rainbow Mountain and Fairview Peak

The CNSB provides a unique site for comparing contemporary strain rates measured by geodetic (GPS) techniques with long-term geologic strain rates measured on historically active faults. The area of 1954 faulting between Rainbow Mountain and Fairview provides a compact 40 km transect through the CNSB where the paleoseismic slip rate data that we have developed can be used for a first-approximation comparison with the geodetic rates.

The Thatcher et al. (1999) GPS study showed a northwest-oriented horizontal velocity gradient of about 4 mm/yr across a series of stations through this portion of the CNSB (Fig. 13), and they modeled a master fault beneath the CNSB having a 8 mm/yr vertical slip rate to account for the

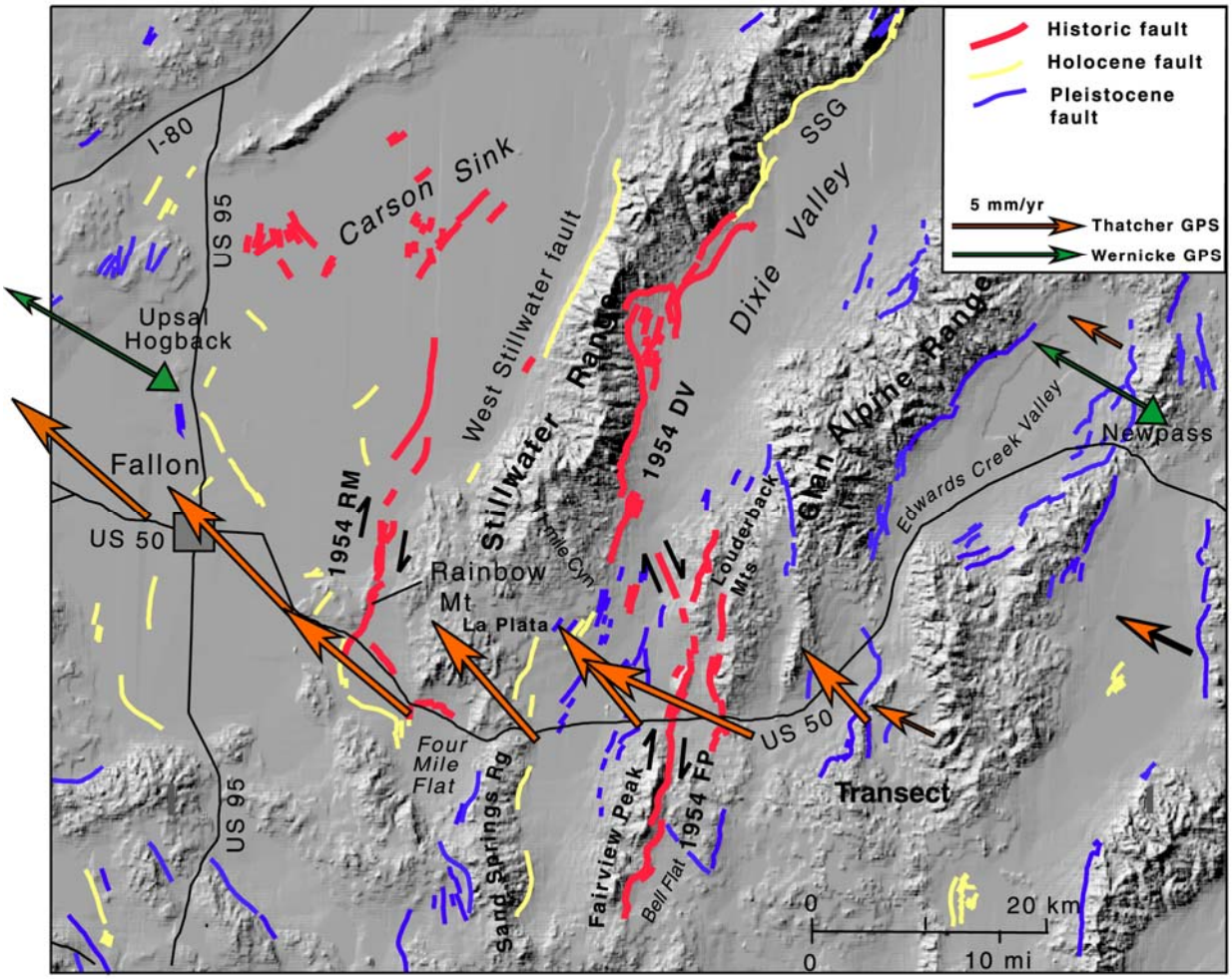
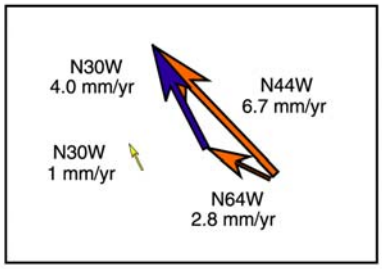


Figure 13. Physiographic location map of the central Nevada seismic belt showing the location of 1954 surface ruptures, Holocene and Pleistocene faults, and GPS observations stations and velocity vectors, Red arrows are the campaign GPS velocity vectors from Thatcher et al. (1999); green arrows are the continuous-station GPS velocity velocity vectors at Upsal Hogback and Newpass stations from Wernicke et al. (2000).

Box at right shows results of averaging GPS vectors of Thatcher et al. (1999) across the Rainbow Mountian-Fairview Peak zone. The N44W and N66W azimuth vectors yield an average N30W vector (blue) with an average strain rate of 4 mm/yr. Paleoseimic data from historical faults yield a cumulative slip rate of 1 mm/yr when resolved on a N30W azimuth (yellow arrow).



observed gradient (Fig. 14). Figure 13 shows the location of the Thatcher et al. (1999) GPS stations along highway US 50 between Fallon on the west side of the study area and Edwards Creek Valley on the east side. The Thatcher et al. stations are overlapped by two continuous GPS stations at Upsal Hogback and Newpass which show similar azimuths but different horizontal velocities (Wernicke et al., 2000). We do not know the reasons for the velocity differences, but assume that the denser network of Thatcher et al. (1999) is more representative of detailed fault block motion. The velocity vectors of Thatcher et al. increase and rotate across the 1954 rupture zone from N64W at 2.8 mm/yr (east side) to N44W at 6.7 mm/yr (west side); these produce an average GPS vector through the 1954 zone of 4.0 mm/yr at N30W.

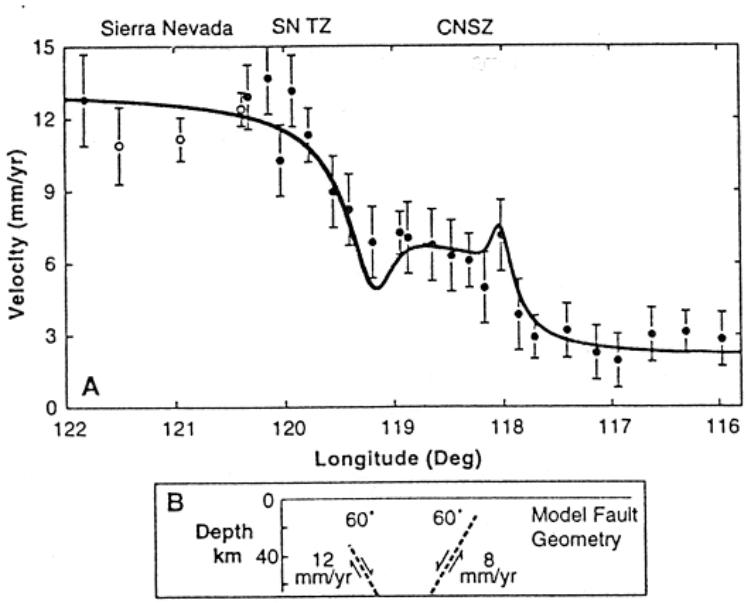


Figure 14. Observed and modeled GPS velocities across the western Nevada region (A). The horizontal velocities show a 4 mm/yr increase through the central Nevada seismic belt (CNSZ) which is attributed to a fault beneath the zone (B) having a vertical slip rate of 8 mm/yr (Thatcher et al., 1999).

Slip azimuths determined from the focal mechanisms and from field mapping of fault displacements produced by the Fairview Peak and three Rainbow Mountain events are essentially parallel to the average GPS vector, a significant confirmation of the contemporary strain orientation. First-motion studies by Doser (1988) showed that the four 1954 events had preferred nodal plane orientations of about N10W; the rupture strikes were northeast-oriented (N15E), however, and the actual slip azimuths are between N20-30W. These relations suggest that the fault ruptures rotated azimuth (fanned) as they moved upward from focal depths, a process indicative of Reidel shear mechanics. Similarly, previous mapping of the 1954 fault rupture orientation and net slip (Caskey et al., 1996; Caskey et al., 1999) can be used together

with the focal mechanisms to determine the regional geologic slip azimuth. Resolving the 1954 slip measured in the field along the northeast-trending faults onto the northwest-trending focal mechanism nodal planes indicates that the fault blocks appear to be moving in a N30W direction nearly identical to the GPS azimuth.

Comparison of paleoseismic and geodetic strain rates

In order to provide a conservative comparison of geologic and geodetic slip rates, we estimated the maximum amount of vertical slip that based on paleoseismic data could be realistically assigned to the historically active rupture zones to be 1.2 mm/yr (Table 3). We included the Fourmile Flat and Louderback Mountain data in order to fully account for possible distributive slip from the Rainbow Mountain and Fairview Peak events, and we included the La Plata fault data to conservatively maximize the counting even though the fault did not rupture in 1954.

Table 3. Preliminary estimates of maximum paleoseismic slip between Rainbow Mountain and Fairview Peak.

Fault	Vertical slip rate (mm/yr)
Rainbow Mountain	0.3
Fourmile Flat	0.2
Dixie Valley-La Plata	0.5
Louderback Mountains	0.1
Fairview Peak	0.1
Total geologic slip	1.2 mm/yr
Net horizontal slip resolved on N30W azimuth	–1 mm/yr

Determining paleoseismic right-lateral slip is problematic because of a general lack of surficial slip indicators, but horizontal slip (heave plus lateral offset) resolved as a slip vector along an azimuth consistent with the GPS vector (N30W) results in a cumulative slip of about 1 mm/yr (Fig. 13).

The results of this initial comparison indicate that a significant discrepancy may exist between the contemporary and longer term geologic strain rates through the CNSB. The difference of 3 mm/yr between the geologic rate (1 mm/yr) and the geodetic rate (4 mm/yr) is a discrepancy that cannot be accounted for in the paleoseismic record. While some additional geologic slip may be derived from the unstudied Holocene faults on the west side of the Stillwater Range and from several unstudied pre-Holocene faults in the Fairview Peak-Dixie Valley area (Fig. 13), it seems unlikely that these faults will have slip rates greater than the historically active zones or that an additional 3 mm/yr of geologic slip will be found. Based on the number of detailed mapping

studies conducted in the 1954 portion of the CNSB, it is also highly unlikely that any additional, unmapped active faults will be found.

If this initial comparison of strain rates is accurate, it suggests that the level of contemporary strain is elevated relative to the long-term rate. Further studies designed to better resolve this discrepancy would involve reducing the uncertainties in both the paleoseismic and GPS data. In order to better account for distributive geologic shear, extending the width of the study area would provide a more comprehensive data set that could be compared to the GPS measurements. Extending the transect and incorporating all unstudied faults lying along the GPS lines of Thatcher et al. (1999) and Wernicke et al. (2000) would provide a unique opportunity to closely compare and assess the contemporary and long-term geologic strain rates in a historically active fault zone.

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