Bulletin of the Seismological Society of America, 89, 6, pp. 1458–1472, December 1999

Large-Magnitude, Late Holocene Earthquakes on the Genoa Fault, West-Central Nevada and Eastern California

by Alan R. Ramelli, John W. Bell, Craig M. dePolo, and James C. Yount

Abstract The Genoa fault, a principal normal fault of the transition zone between the Basin and Range Province and the northern Sierra Nevada, displays a large and conspicuous prehistoric scarp. Three trenches excavated across this scarp exposed two large-displacement, late Holocene events. Two of the trenches contained multiple layers of stratified charcoal, yielding radiocarbon ages suggesting the most recent and penultimate events on the main part of the fault occurred 500–600 cal B.P., and 2000–2200 cal B.P., respectively. Normal-slip offsets of 3–5.5 m per event along much of the rupture length are comparable to the largest historical Basin and Range Province earthquakes, suggesting these paleoearthquakes were on the order of magnitude 7.2–7.5. The apparent late Holocene slip rate (2–3 mm/yr) is one of the highest in the Basin and Range Province.

Based on structural and behavioral differences, the Genoa fault is here divided into four principal sections (the Sierra, Diamond Valley, Carson Valley, and Jacks Valley sections) and is distinguished from three northeast-striking faults in the Carson City area (the Kings Canyon, Carson City, and Indian Hill faults). The conspicuous scarp extends for nearly 25 km, the combined length of the Carson Valley and Jacks Valley sections. The Diamond Valley section lacks the conspicuous scarp, and older alluvial fans and bedrock outcrops on the downthrown side of the fault indicate a lower activity rate. Activity further decreases to the south along the Sierra section, which consists of numerous distributed faults. All three northeast-striking faults in the Carson City area ruptured within the past few thousand years, and one or more may have ruptured during recent events on the Genoa fault.

Introduction

The Genoa fault, a major normal fault in west-central Nevada and eastern California, displays a prominent several-meter-high scarp with a youthful geomorphic expression (Fig. 1). The appearance of the scarp led early workers in the area to speculate that a very recent strong earthquake had occurred on the fault (Russell, 1887; Lawson, 1912). Early settlers of the area, who arrived in the mid-1800s, described the scarp as being relatively unchanged since their arrival (Lawson, 1912), suggesting this event occurred at least several decades earlier. Pease (1980) mapped Holocene deposits offset by the fault, and based on soils and scarp morphology, he speculated (Pease 1979a,b) that the most recent event occurred within the past several hundred years.

The Genoa fault is the most prominent part of a range-front fault system, the Carson Range fault system (CRFS), that bounds the east slope of the Carson Range, a north-trending fault-bounded block that splays from the northern Sierra Nevada (Fig. 2). The two ranges are separated by the Lake Tahoe basin, which has structural relief of at least 2000 m. Although structurally part of the Basin and Range Province, the CRFS forms an abrupt boundary between the high average elevations and associated alpine climate of the Sierra Nevada and the moderate average elevations and arid climate of the Basin and Range and is thus considered the eastern boundary of a broad transition zone between the two provinces.

Geomorphic expression of the range front and large offsets of alluvial deposits indicate the CRFS has generated strong earthquakes ($M > 7$), and it appears to be the most active fault system within the Basin and Range/northern Sierra Nevada transition zone (Ramelli *et al.*, 1996). Due to its seismogenic potential, relatively high activity rate, and location, the CRFS poses the principal seismic hazard to the urban areas of west-central Nevada. Most of the region's population, including the Reno/Sparks area (the second largest population center in Nevada) and Carson City (the state capital), is located along the eastern front of the Carson Range. Resort communities around Lake Tahoe, on the west side of the range, would also be affected by strong earthquakes on the CRFS.

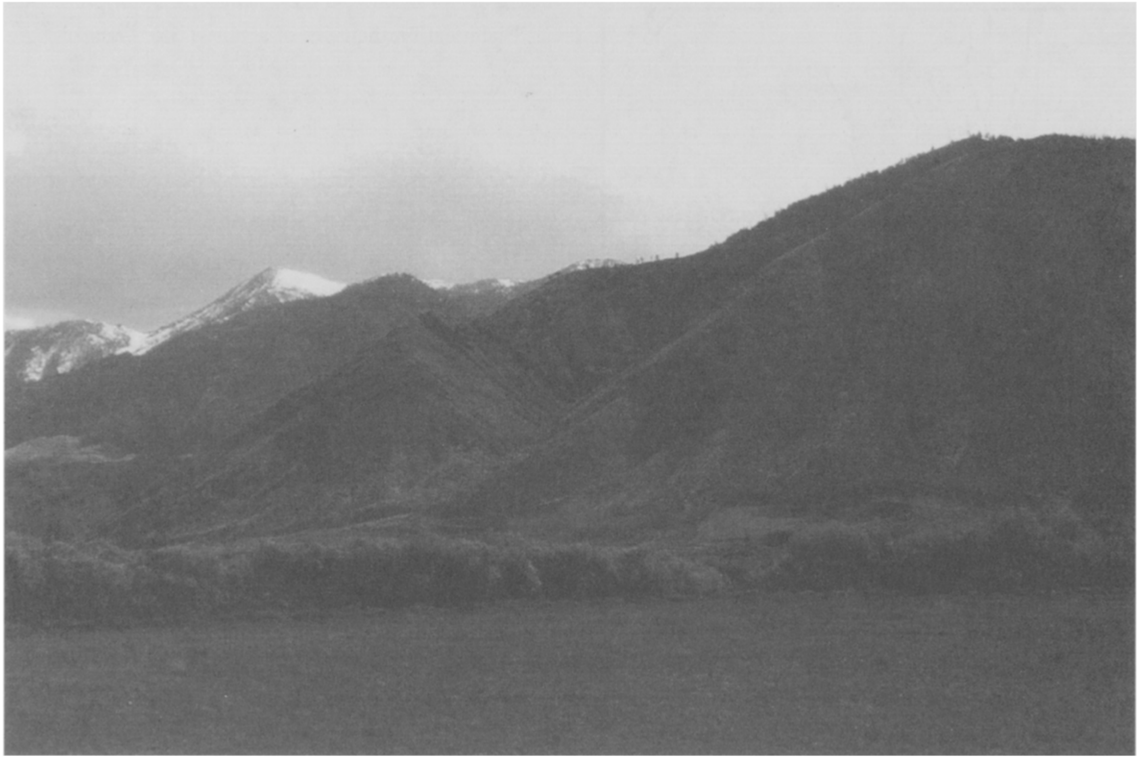

Figure 1. View of the prominent scarp along the Genoa fault (the dark, shadowed line near the base of the hillslope), just south of the town of Genoa. The gravel pit in the central part of the photo exposes the bedrock fault plane (photo by A. Ramelli).

The tectonic significance of the northern Sierra Nevada/Basin and Range transition zone is underscored by a diffuse belt of historical seismicity (Toppozada *et al.*, 1981; Martinelli, 1989) and geodetic deformation evident from recent GPS results (Thatcher *et al.*, 1999). Numerous historical earthquakes of about magnitude 5 or larger have occurred in the vicinity of the CRFS (Table 1).

Approach and Methods

In this study, we attempt to more fully characterize the seismogenic potential of the Genoa fault. Detailed mapping of the entire CRFS using both conventional and large-scale (1:12,000), low-sun-angle aerial photographs together with field studies in key locations provide a basis for evaluating changes in activity and behavior reflected in fault-scarp and range-front morphology and for defining principal discontinuities along the system. Based on these efforts, we make a first attempt at evaluating the possible extent and distribution of rupture during recent events. To define the size of recent events and frequency of earthquake occurrence, we estimate displacements and timing of events on the Genoa fault from three trenches excavated along the main part of the fault.

Late Cenozoic Structure of the Carson Range

Steep escarpments suggest both sides of the Carson Range are bounded by active normal faults, although the structure of the western front is poorly understood because most of it lies beneath Lake Tahoe. The eastern frontal fault, the CRFS, is one of several generally north-striking, left-stepping, down-to-the-east normal faults that are the principal structures of a broad transition zone between the northern Sierra Nevada and the Basin and Range Province.

Basin and Range Province extension has split the Carson Range from the main Sierra Nevada block during Plio-Quaternary time, possibly within the past 2.5–3 Ma (Birkeland, 1963). Because the two range blocks merge at the southern end of the Carson Range, structural basins located between the two ranges (principally Hope Valley, Lake Tahoe basin, and Martis Valley) indicate differential rotation of the two blocks. In general, from south to north with increased separation from the Sierra Nevada, the CRFS becomes a broader, more distributed zone and the Carson Range becomes increasingly broken by internal faults.

The extreme southern end of the Carson Range, where it merges with the Sierra Nevada, is cut by many small- to moderate-displacement faults, some of which form intermontane basins. From the southern end of the range north to the vicinity of Spooner Summit, a distance of about 35 km, the Carson Range is generally an intact block bounded on the east by a singular range-front fault (the Genoa fault). From Spooner Summit north approximately to Galena Creek, a distance of about 25 km, the Carson Range is still bounded by a prominent frontal fault zone, but it is also cut

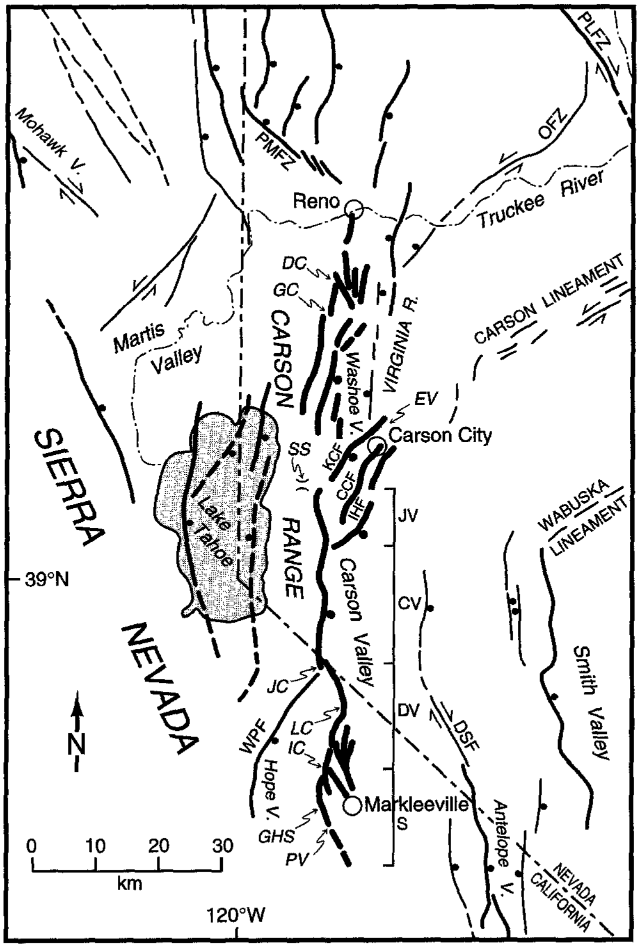

Figure 2. Generalized Quaternary fault map of west-central Nevada and eastern California (modified from Dohrenwend, 1982; Bell, 1984; Hawkins *et al.*, 1986). Bold lines, Carson Range fault system (CRFS); medium lines, other principal faults; light lines, other selected faults. Fault abbreviations: PMFZ, Peavine Mt. fault zone; OFZ, Olinghouse fault zone; PLFZ, Pyramid Lake fault zone; KCF, Kings Canyon fault zone; CCF, Carson City fault; IHF, Indian Hill fault; WPF, Waterhouse Peak fault; DSF, Double Spring Flat fault. Place names referred to in text: DC, Dry Creek; GC, Galena Creek; EV, Eagle Valley; SS, Spooner Summit; JC, Jobs Canyon; LC, Luther Creek; GHS, Grover Hot Springs; PV, Pleasant Valley. Brackets indicate sections of the Genoa fault referred to in text: JV, Jacks Valley; CV, Carson Valley; DV, Diamond Valley; S, Sierra.

by several internal faults, most of which strike northeast, although a few strike north or northwest. The northeast-striking faults parallel a regional structural grain and appear to be influenced by preexisting structures. In the Carson City area, the CRFS splays into three principal northeast-striking faults (the Kings Canyon, Carson City, and Indian Hill faults), and in the Washoe Valley area, it consists of two principal subparallel, north-striking faults (the Washoe Valley and Little Valley faults).

From Galena Creek north to the vicinity of the Truckee River, a distance of about 20 km, the northern Carson Range has been generally characterized as a broad antiform cut by numerous faults, many of which are antithetic to the range front (Thompson and White, 1964). Along this part of the range, the CRFS is a broad, distributed zone up to 7.5 km wide. Several subparallel, sygmoidal, nested graben are the principal structures of this part of the system, indicating deformation involved significant broad-scale flexure. The discernible frontal fault trace dies out in the vicinity of Dry Creek, about 5 km north of Nevada S.R. 431 (Mt. Rose Highway); north of Dry Creek the range front is a broad warp cut by several small-displacement faults. A characteristic feature of the northern CRFS is a 300- to 500-m-wide, nested graben centered about 1.5 km east of the range front. Where the frontal fault dies out, some of the range uplift steps away from the range front to this graben, which extends discontinuously into the Reno urban area.

Table 1
Historical Earthquakes of about *M* 5 or Greater in Proximity to the CRFS

Year	*M*	General Location
1857	6.2?	Lake Tahoe region
1869	6.1?	Steamboat Springs
1877	5?	Lake Tahoe?
1887	6.3?	Carson Valley
1892	?	Reno
1896	?	Carson City
1897	?	Carson City
1914	6	Verdi
1914	6.4	Reno
1930	5?	Lake Tahoe
1943	5.3	Lake Tahoe
1948	6.0	Verdi
1952	5.1	Steamboat Springs
1953	5.5	Reno
1978	5.2	Diamond Valley
1994	5.9	Double Spring Flat
1998	4.9	Lake Tahoe

Segmentation of the Southern CRFS

Distinct structural discontinuities and differences in fault orientation, style, and behavior can lend important clues as to a fault's rupture behavior or segmentation. In one of the earliest known discussions of segmentation, Lawson (1912) noted the appearance of fault scarps and geomorphic expression of the Carson Range front as possibly related to different rupture ages along the Genoa fault.

The Genoa fault is here divided into four principal sections with apparent differences in activity rate and behavior—from south to north, the Sierra, Diamond Valley, Carson Valley, and Jacks Valley sections (Fig. 2)—and is distinguished from three northeast-striking faults comprising the CRFS in the Carson City area. These sections are not defined as earthquake segments (i.e., extent of ground rupture during individual events or sequences), which requires detailed timing information along the entire rupture. Additional age constraints are needed along the entire system to better evaluate the extent of rupture during the two most recent events on the Genoa fault, but these events may have involved most or all of the sections discussed next.

Main Genoa Fault

The part of the Genoa fault characterized by a prominent paleoseismic scarp comprises the Carson Valley and Jacks Valley sections (Fig. 2). These sections are divided at a range-front salient at the south end of Jacks Valley, where the Genoa fault abruptly bends westward and the Indian Hill fault splays to the northeast. The scarp extends continuously around this salient, maintaining its position near the base of the range, but the two sections have several notable differences. They have different overall orientations, with the Carson Valley section striking north-northeast and the Jacks Valley section striking north-northwest; the Jacks Valley section has less total offset, with throw across the entire system split between the Jacks Valley section and the overlapping Indian Hill and Carson City faults; and a narrow, continuous graben along the northernmost 3 km of the Carson Valley section suggests a change either in fault dip or in sense of slip across the salient.

The Carson Valley section, the most prominent part of the CRFS, is a singular, range-bounding fault trace extending about 18 km from Jobs Canyon to the south end of Jacks Valley. The range front along the Carson Valley section is quite steep and marked by prominent fault facets, the lower parts of which are rilled due to steepening, a characteristic indicative of recent activity. The Carson River flows very near the mountain front along most of the Carson Valley section, suggesting recent westward tilting of the valley floor (Moore, 1969; Slemmons, 1975), and detailed mapping of meander belts indicates a recent, westward shift in the river's course (Leeder and Jackson, 1993; Yount *et al.,* in prep). Age analyses (^{14}C and thermoluminescence) indicate this westward shift occurred very close in time to the most recent event on the Genoa fault (Peakall, 1995) and suggest it occurred in response to coseismic basin subsidence.

The Jacks Valley section, extending about 7.5 km to near U.S. Highway 50, is likewise a singular, range-bounding trace. Offsets associated with the most recent event are largest at Jacks Valley, being consistently greater than 4 m and reaching a maximum of more than 5 m at the trench site discussed later. These displacements may be enhanced by downdropping of Jacks Valley, a large-scale graben.

Southern Genoa Fault

The southern part of the Genoa fault, which is distinguished from the main part of the fault based on a lower rate of activity and different geomorphic expression, is also divided into two sections: the Diamond Valley and Sierra sections. The Diamond Valley section is divided from the Carson Valley section at Jobs Canyon, where the fault system steps left about 1.5 km (Fig. 2). A northeast-striking bedrock extension of the Waterhouse Peak fault, which bounds the west side of Hope Valley, trends along the axis of Jobs Canyon (Stewart *et al.,* 1982), obliquely intersecting the Genoa fault and likely influencing formation of this left step. The geometric discontinuity presented by this step should behave conservatively, because slip is predominantly normal, but there are distinct differences in the fault's appearance and behavior across this general area. Basin subsidence along the Diamond Valley section is dramatically less than along the Carson Valley section, as evidenced by bedrock outcrops and relatively old alluvial fans with well-developed argillic soils on the downthrown side of the fault. Whereas the Carson Valley section is principally a singular, range-bounding fault trace, the Diamond Valley section has several distributed faults in the hanging wall, especially along its southern part.

The Diamond Valley section extends about 17 km from Jobs Canyon to Indian Creek, about 4 km south of Woodfords, where the range front splays and the Diamond Valley section is divided from the Sierra section (Fig. 2). The range front along the Diamond Valley section has rather similar expression to that along the main part of the fault but lacks the conspicuous scarp, suggesting that it did not rupture as recently or that it ruptured with smaller displacements. However, locally preserved scarps indicate late Quaternary rates of activity along the two parts of the fault are not greatly different, and at least one fairly recent event on the Diamond Valley section is suggested by hanging drainages at Woodfords and about 1 km north of Luther Creek. A latest Pleistocene outwash terrace at Woodfords (Qo1 in Fig. 3) is offset about 10 m, indicating a slip rate of about 1 mm/yr (Clark *et al.,* 1984; this study). A higher, older outwash terrace at that same location (Qo2 in Fig. 3) is displaced at least 50 m, and a very large scarp (several tens of meters high) is present at Luther Creek. These older terraces are likely of Tahoe age (70–150 ka) and suggest a long-term average slip rate of 0.3–0.8 mm/yr.

The Sierra section, which extends southward into the Sierra Nevada block, is highly distributed and includes two range-front traces, several hanging-wall splays, and down-to-the-west faults within the footwall. These various lesser faults may represent the distributed ends of ruptures along the Genoa fault, or smaller, local events. The main range front along the Sierra section, which has relief of up to 600 m, extends from Indian Creek south through Grover Hot Springs to Pleasant Valley, south of which the fault separates Tertiary andesite to the east from Mesozoic granite to the west with no appreciable vertical relief (Stewart *et al.,* 1982). A secondary range front, which has relief of about 180 m but no obvious late Quaternary scarps, trends away from the main range front at Indian Creek and extends southeast to near Markleeville. This secondary range front is bounded by one of several northwest-striking faults in the hanging wall of the southern Genoa fault and lies on-line with a linear stretch of the East Carson River that may be structurally controlled. These faults parallel other northwest-striking

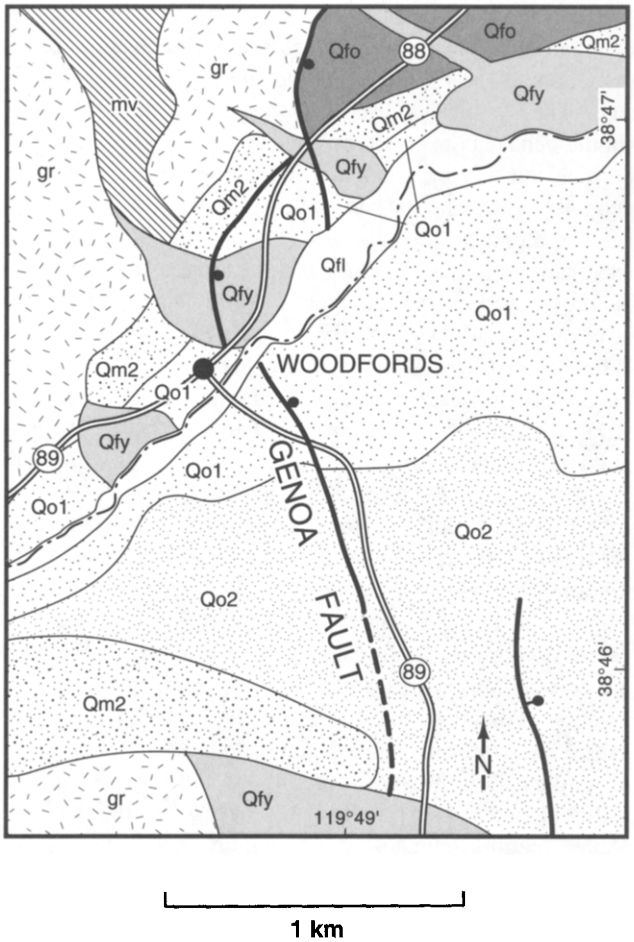

Figure 3. Generalized surficial geology of the Woodfords area (this study). Qfl, young floodplain deposits; Qfy, young alluvial fans; Qo1, Tioga(?) glacial outwash; Qo2, Tahoe(?) glacial outwash; Qm2, Tahoe(?) moraines; Qfo, older alluvial fans; gr, granodiorite; mv, metavolcanics. At this location, the Genoa fault offsets outwash terraces along the West Fork of the Carson River, indicating a slip rate of about 1 mm/yr; farther north, the main part of the fault is considerably more active and has a slip rate of 2–3 mm/yr.

structures in the region (e.g., Double Spring Flat fault) and likely have strong components of right slip.

Carson City Area

To the north of the singular, range-bounding Genoa fault, the CRFS splays into three northeast-striking, left-stepping, and overlapping faults in the Carson City area: from southeast to northwest, the Indian Hill, Carson City, and Kings Canyon faults (Fig. 2). These three faults generally parallel the Carson lineament, a regional structural and topographic feature that likely dates to the Mesozoic and has strongly influenced the development of the CRFS (Rogers, 1975; Bell, 1984). East of the Carson City area, evidence of activity along the Carson lineament is limited to scattered Quaternary fault scarps and diffuse seismicity, and it does not appear to be a major active structure. The faults at Carson City are much more active, so they are likely responding to range-front deformation rather than regional activity along the Carson lineament.

The Indian Hill fault, which is at least 7.5 km long, splays from the Genoa fault at the south end of Jacks Valley, and uplifts Jacks Valley and Indian Hill, relative to Carson Valley. Two previous trenches across the Indian Hill fault suggest two events have occurred in the last 3 kyr (Trexler and Bell, 1979a). The most recent and penultimate events had vertical offsets of 0.6 and 0.9 m, respectively, at the trench site. Trexler and Bell (1979a) interpreted that prior to these two late Holocene events, the Indian Hill fault had not ruptured since the late Pleistocene.

The Carson City fault, which is at least 14 km long, extends from the east side of Jacks Valley north through Carson City, thus posing a substantial surface rupture hazard. The south end of the Carson City fault is taken to include down-to-the-west faults bounding the west side of Indian Hill. Trenching along the south end of the Carson City fault suggested displacement of 1 to 2 m for the most recent event (Bell *et al.,* 1984). A nearby faulted fan yielded a ^{14}C age of 7140 ± 400 yr B.P., providing a maximum age for this event, which Pease (1979a) suggested is less than 3 ka, based on scarp morphology and offset soils.

The Kings Canyon fault zone, a distributed zone at least 12.5 km long and up to 2 km wide, bounds the west side of Kings Canyon and the southeast side of the Virginia Range. There is a gap and right step of 2 to 3 km between mapped active traces of the southern Kings Canyon fault zone and northern Genoa fault (Fig. 2), but the two faults may connect essentially continuously via bedrock faults. Over much of its length, the Kings Canyon fault zone is highly distributed, with scarps within the range, on the range-front slope, at the mountain–valley contact, and on the piedmont. West of Carson City, trenches across two prominent scarps bounding opposite sides of a 100-m-wide graben along the fault suggested a minimum of three events since late Wisconsin time (Trexler and Bell, 1979a). Trexler and Bell (1979a, 1979b) interpreted a very recent age for the most recent event, based on a distinct, 30-cm scarp in loose surficial deposits. This scarp coincided with a break extending to the ground surface in one of the trenches.

Exploratory Trench Results

The fresh appearance of the Genoa fault scarp has long led to speculation about the recency of faulting. This study provides the first direct evidence of ages of surface faulting and displacements associated with individual events. Three exploratory trenches excavated across the main part of the Genoa fault (Fig. 4) provided good constraints on the surface offsets associated with the most recent and penultimate events, and radiocarbon dating of numerous charcoal horizons tightly bracket the ages of these two events.

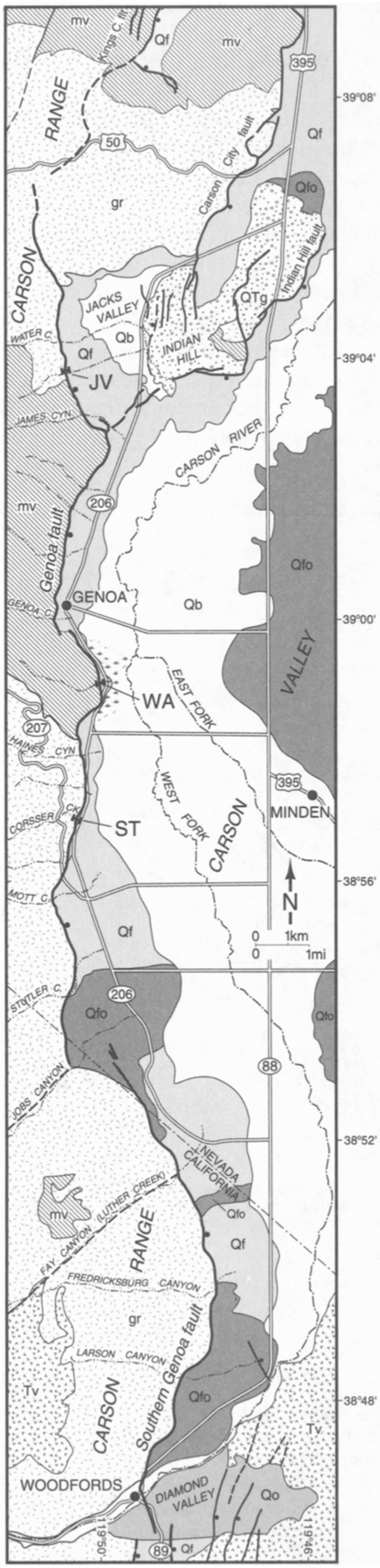

Figure 4. Generalized geologic strip map along the Genoa fault, showing exploratory trench sites: JV, Jacks Valley; WA, Walleys; ST, Sturgis (after Trexler, 1977; Pease, 1980; Armin and John, 1983; Armin et al., 1984).

Jacks Valley Site

The Jacks Valley trench was excavated into a 6-m-high scarp cutting a Holocene alluvial fan on the west side of Jacks Valley (Fig. 4). The trench exposed sandy fan deposits containing at least 15 layers of disseminated charcoal (Fig. 5). Aside from variations in clast content and abundance of charcoal, individual sand deposits are generally indistinguishable, but two relatively clean sand layers (S1, S2), a gravel lens (g), and the thickest, most prominent charcoal layer (C) served as marker horizons.

The trench is located at a bend in the fault, which to the south strikes about N25°W, and to the north about N5°E. About 0.35 km north of the trench site, the fault swings back to a north-northwest strike. The average orientation of the principal fault traces in the trench (N10°E, 65°E) is likely similar to, albeit somewhat steeper than, the unexposed bedrock fault at that site. No slip indicators were exposed in the trench.

The trench exposed a distributed fault zone about 12 m wide, with individual fault traces generally striking north-northeast, dipping steeply east, and having displacements of up to 0.8 m. When summed, down-to-the-east dip slip across these fault traces totals 3.2 ± 0.5 m (2.9 ± 0.5 m vertical offset). About 80% of the discrete displacement occurs on five principal faults within the westernmost 3 m of the fault zone.

All deposits except scarp colluvium overlying the upper sand layer (S2; Fig. 5) are faulted, with individual faults showing generally consistent offsets. Some small offsets die upward, likely due to absorption by the soft, unconsolidated materials rather than progressive fault offsets. The consistent offsets, combined with uniform deposit thicknesses and

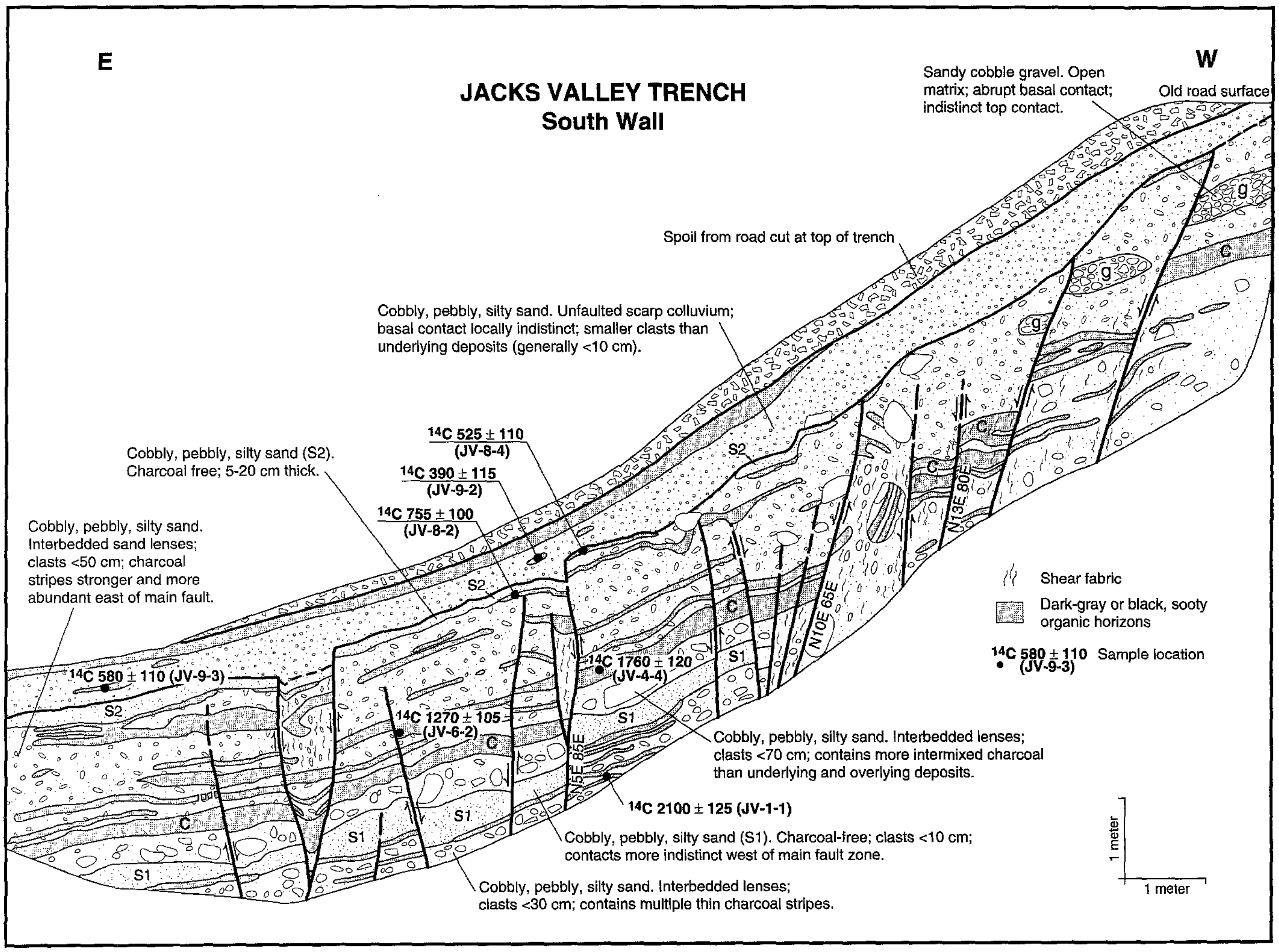

Figure 5. Log of the Jacks Valley trench, located at the mouth of an unnamed drainage on the west side of Jacks Valley. Deposits are generally indistinguishable, but a gravel lens (g), two sand lenses (S1 and S2), and the strongest of several charcoal layers (C) serve as marker horizons. Deposits ranging in age from about 600 to 2000 cal B.P. are offset by consistent amounts, indicating the most recent event (estimated to have occurred between 500 and 600 cal B.P.) caused displacement of more than 5 m at this site.

stratigraphic positions, indicate the scarp was formed during a single event. Relatively steep dips within the fault zone apparently resulted from warping that accompanied faulting, rather than reflecting an original depositional dip (i.e., scarp colluvium from a prior event).

The scarp's size and steepness at this site precluded excavation of its uppermost part, but superposing the trench log and an adjacent surveyed topographic profile suggests the trench exposed the entire fault zone and a representative sample of footwall deposits (Fig. 6) and indicates 4.6 ± 0.4 m of vertical separation (5.7 ± 0.6 m dip slip) across the scarp. Subtracting the discrete displacement measured across fault traces suggests this includes about 2.5 m of warping. A topographic profile of a fault scarp at the head of another late Holocene alluvial fan about 0.4 km south of the Jacks Valley trench site indicates vertical separation of about 4 m (4.5- to 5-m dip slip), indicating the persistence of large offsets associated with the most recent event in this area.

The charcoal layers are distinctive enough to be confidently correlated across the fault zone. We interpret these layers to indicate that organic material was repeatedly accumulated on the ground surface, burned during wildfires, and periodically buried and preserved by stream or slope wash deposits. During extended periods without depositional events, relatively thick layers of charcoal accumulated and became progressively intermixed with the surficial fan deposits. Several characteristics of the charcoal layers suggest they were buried *in situ:* some thin layers are nearly entirely composed of charcoal; nearly all layers are essentially continuous throughout the trench exposure; and most layers are somewhat thicker and more conspicuous downslope from the fault zone, suggesting the fault localized moisture and vegetation density. The charcoal layers provided abundant opportunities for ^{14}C dating, and eight samples were analyzed (Fig. 5; Table 2). Faulted deposits yielded ^{14}C ages ranging from 2100 ± 125 yr B.P. to 755

Table 2
Summary of ^{14}C Analyses: Genoa Fault Trenches

Sample ID	^{14}C Age (yr B.P.)	Cal. Age* (max., min.)** (cal B.P.)
JV-9-2	390 ± 115	479 (597, 0)
ST-5	580 ± 115	550 (702, 460)
JV-9-3	580 ± 110	550 (698, 465)
ST-3	1025 ± 315†	942 (1536, 481)
Most Recent Event		
JV-8-4‡	525 ± 120	528 (687, 314)
JV-8-2§	755 ± 100	684 (906, 539)
JV-8-3	870 ± 95	752 (959, 660)
JV-6-2	1270 ± 105	1199 (1352, 959)
ST-20	1370 ± 120	1288 (1505, 1020)
JV-4-4	1760 ± 120	1665 (1930, 1377)
ST-16	1815 ± 90	1738 (1923, 1522)
ST-18	1965 ± 105	1893 (2140, 1658)
JV-1-1	2100 ± 125	2049 (2351, 1771)
Penultimate Event		
W-1‖	225 ± 90	292 (521, 0)
W-3‖	295 ± 175	317 (751, 0)
ST-14#	2290 ± 110	2323 (2702, 2015)
ST-7	3095 ± 155	3319 (3648, 2861)

*Stuiver and Reimer (1993); a sample age span of 100 yr was used in calibration of ^{14}C ages to calendar years, because the charcoal layers are mixtures of material spanning an unknown age range, and there is an average of about one charcoal horizon per 100 yr in the Jacks Valley trench.
**Two sigma.
†Out of stratigraphic order, but large uncertainty and possibly reworked.
‡Relationship to faulting uncertain.
§Stratigraphically about 20 cm below event horizon.
‖Anomalous (modern) ages; possibly burned roots.
#Stratigraphically about 50 cm below event horizon.

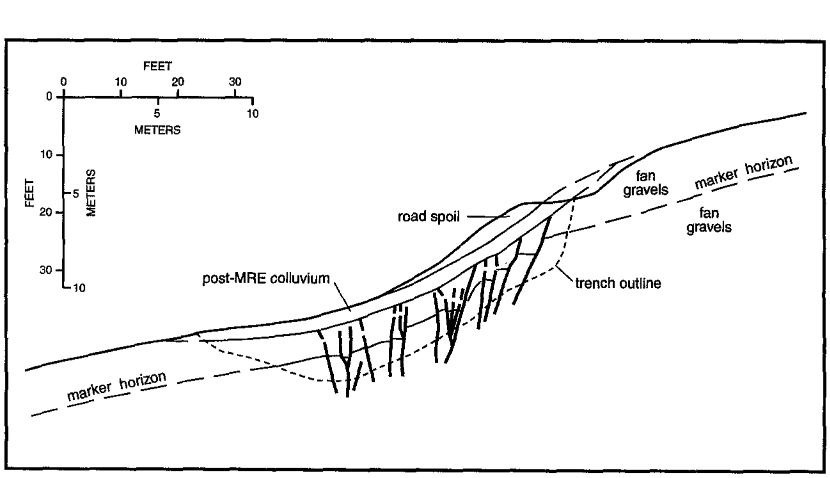

Figure 6. Simplified cross section at the Jacks Valley trench site based on trench relations and an adjacent surveyed topographic profile. Consistent stratigraphic position of a marker horizon (strongest charcoal layer) indicates that the trench exposed alluvial fan deposits displaced by more than 5 m during the most recent event.

± 100 yr B.P. The oldest ^{14}C age from a clearly unfaulted deposit is 580 ± 110 yr B.P. As shown in Figure 5 and Table 2, a charcoal sample interpreted as part of the uppermost faulted layer yielded a ^{14}C age of 525 ± 120 yr B.P., suggesting the most recent event is constrained within the overlap in uncertainty in these two ages, but offset of this layer was nondefinitive owing to similarity of deposits.

Walleys Site

The Walleys trench was excavated into a 10-m-high scarp in the lower of two uplifted stream terraces at the head of an alluvial fan near Walleys Hot Springs (Figs. 4 and 7). The trench exposed alluvial fan deposits overlying and faulted against granitic bedrock (Fig. 8). A 30- to 50-cm-thick, weakly developed A/B soil indicates the fan deposits are of late Holocene age. On the footwall, fan deposits rest directly on bedrock. On the hanging wall, the fan deposits are overlain by scarp colluvium that consists of rhythmically bedded layers of gravel and sand deposited at the angle of repose and grading downslope into open-matrix jumbled boulders at the toe of the scarp.

The trench exposed a bedrock fault plane oriented N15°E, 58° E. The fault plane steepens upward through the alluvial fan deposits and juxtaposes scarp colluvium derived from the penultimate event against the footwall fan gravels. Unfaulted scarp colluvium derived from the most recent event overlies the faulted scarp colluvium and truncates the fault. A minor antithetic fault is suggested by apparent downdropping of the soil horizon and clast alignment.

Similar to the Jacks Valley trench, the size and steepness of the scarp at this site precluded excavation of its uppermost part, but a surveyed topographic profile indicated cumulative vertical separation of 6.1 ± 0.4 m (8.2 ± 0.6 m dip slip) for the two late Holocene events. From the trench log, a reconstruction of the offsets during these two events suggests the most recent event was somewhat larger than the penultimate event (estimated dip slip of 4.5 and 3.7 m, respectively), but uncertainties in these estimates overlap. A second topographic profile across a scarp in undated colluvium at the base of the hillslope just south of the trench site suggests a similar amount of displacement (7.6 ± 1.0 m dip slip) and thus appears to reflect the same two events.

Fault-plane striations in the Walleys trench, striations and fault-plane mullions in an adjacent gravel quarry, and a sinuous surface trace along this part of the fault indicate nearly pure normal displacement. Vadurro (1993) interpreted various slip indicators on bedrock faults in the footwall near the Walleys trench to indicate a period of predominantly dextral shear on northwest planes preceded the period of normal slip on north–south planes that continues to the present.

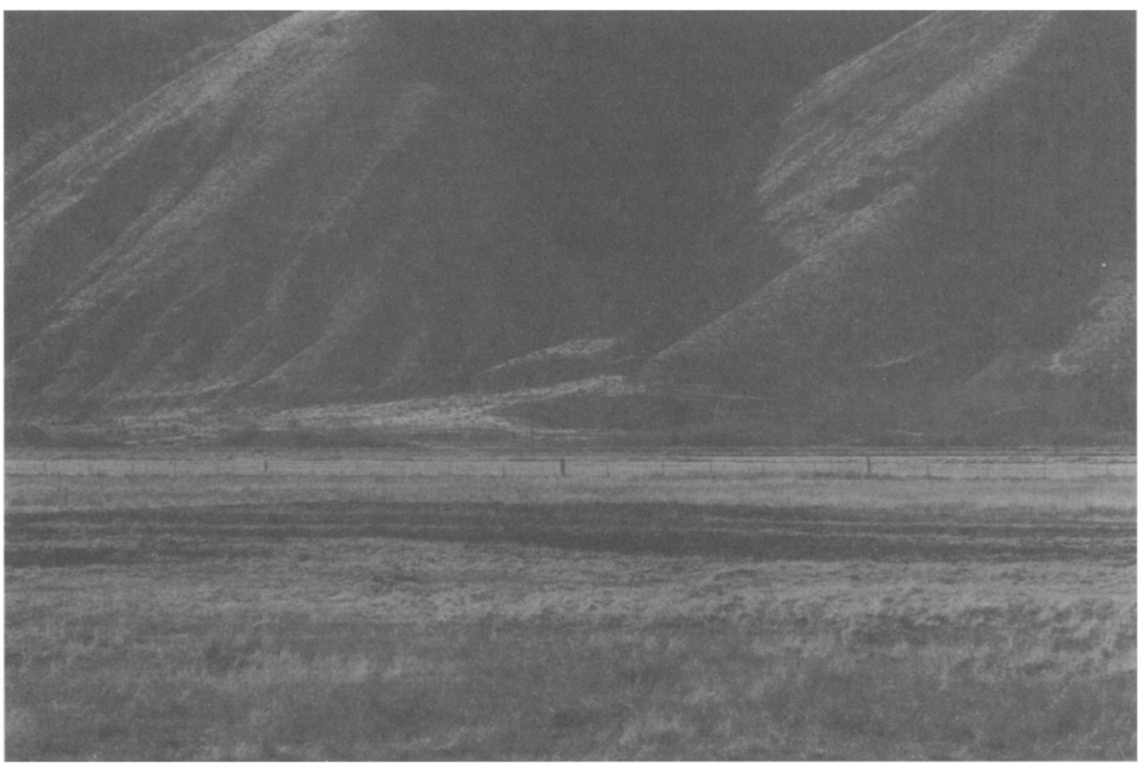

Figure 7. View of the Walleys trench site. The trench was excavated into the 10-m-high scarp on the smaller and lower of two alluvial terraces in the center of the photo. The larger, higher terrace has a fault scarp about 25 m high and contains a well-developed argillic soil, indicating an age of at least several tens of thousands of years (photo by J. Yount).

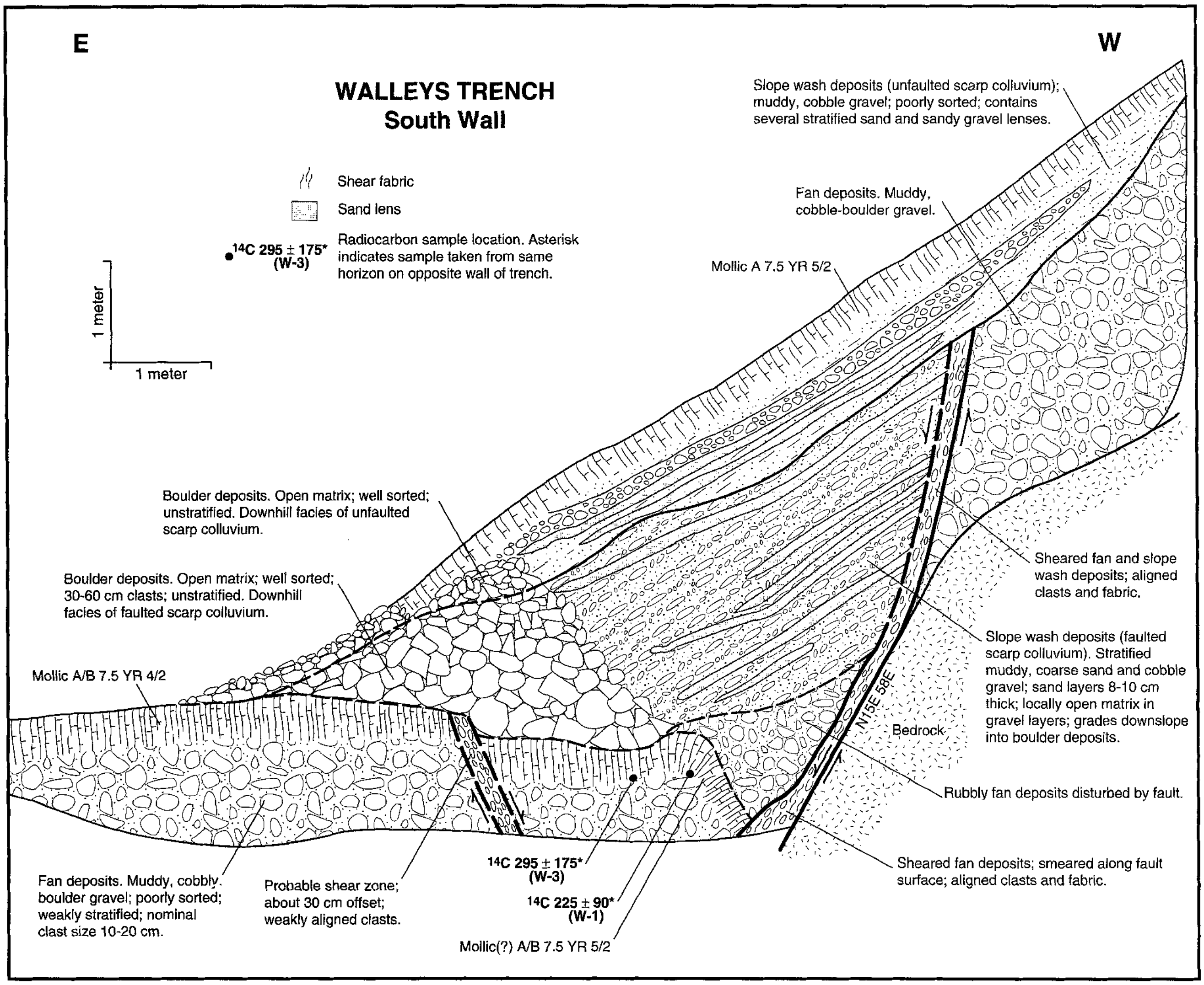

Figure 8. Log of the Walleys trench, located on the lower and smaller of two uplifted terraces near Walleys Hot Springs (Fig. 7). The trench exposed fan deposits displaced by more than 8 m during two events. Two charcoal samples yielded anomalous modern ages and are thus disregarded.

Sturgis Site

The southernmost trench (Fig. 4) was located about 4 km south of the Walleys trench on the Sturgis Ranch. The Sturgis trench was excavated into a 6-m-high fault scarp at the head of an alluvial fan from Corsser Creek, about 2.5 km north of the intersection of S.R. 207 (Kingsbury Grade) and S.R. 206 (Foothill Road). The trench (Fig. 9) exposed faulted fan deposits that we divided into two units: a lower unit of mostly coarse sand (grus) and an upper unit dominated by fine sand deposits that, similar to the Jacks Valley trench, contain several dark layers of disseminated charcoal. The downthrown section of fine sand is thicker and at least in part older than that on the footwall, suggesting these deposits draped and buried a pre-existing fault scarp.

The fine sand deposits are unconformably overlain by scarp colluvium (reworked fan deposits and thin gravel deposits that spilled over the scarp). Subsequent to faulting, erosion caused by both scarp degradation and stream flow over and along the scarp produced irregular disconformities. The north trench wall exposed two disconformities overlain by scarp-mantling gravel deposits. The lower gravel deposit is buried by the penultimate-event colluvial wedge, whereas the upper, more extensive gravel deposit drapes the scarp and is unfaulted. The upper gravel deposit extends farther up the scarp in the south trench wall than in the north wall and appears to have a source at a notched part of the scarp just south of the trench.

The trench exposed two principal fault traces near the base of the scarp (Fig. 9). The two traces are subparallel, strike approximately N30°E, and gradually converge southward. Fault dips are variable, ranging from about 55° E to 70° E, and averaging about 65° E. The fault likely steepens

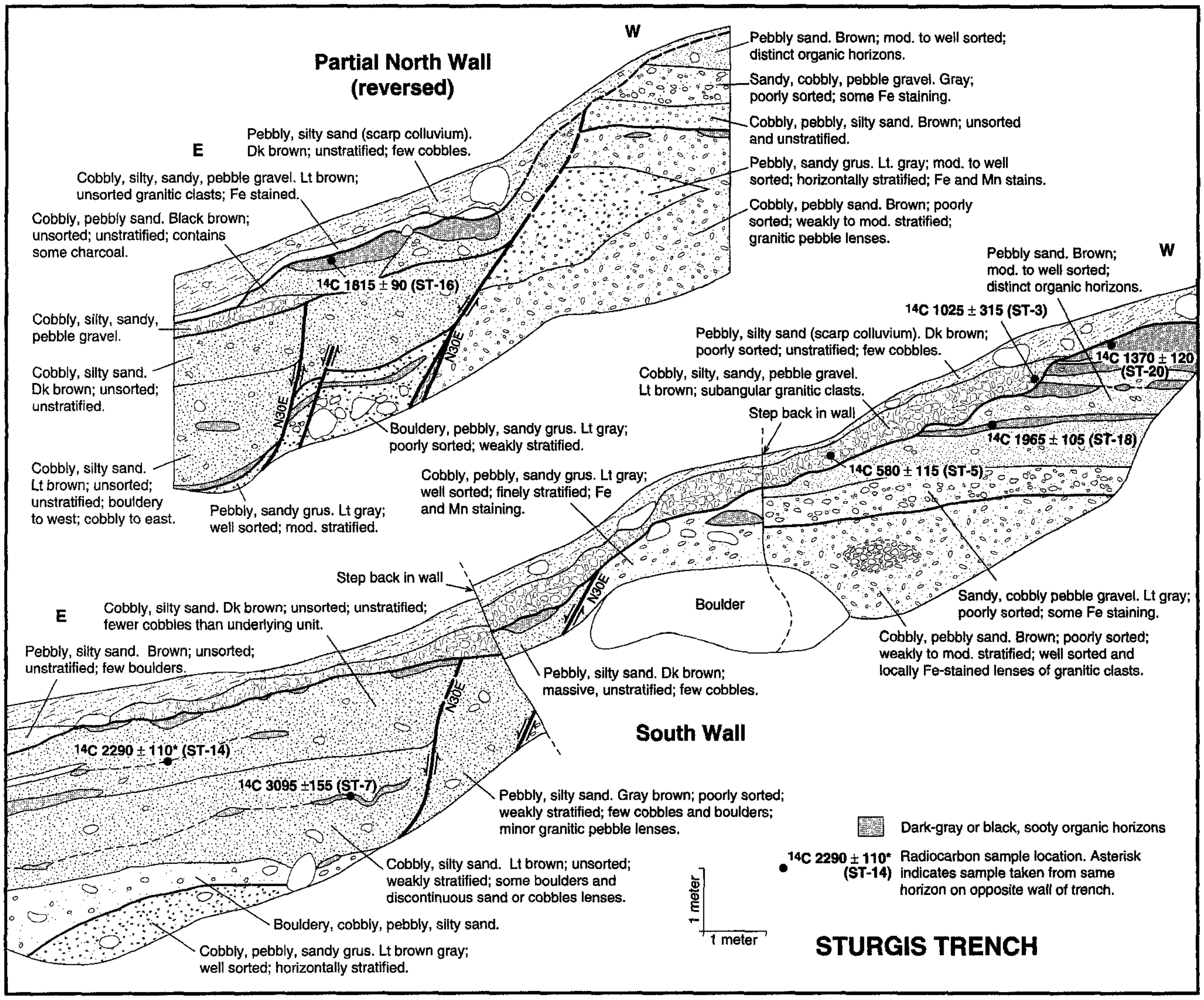

Figure 9. Log of the Sturgis trench, located at the mouth of Corsser Creek. The trench exposed fan deposits displaced by about 6 m during two events. The fan deposits are separated into two units (an upper group of dominantly fine sand deposits and a lower group of dominantly coarse sand or grus deposits); the boundary between the two units is denoted by the lowermost bold contact. The upper bold contacts denote disconformities buried by scarp colluvium and gravel deposits that flowed over and draped the scarp.

near the surface as it cuts alluvium, and the unexposed bedrock fault presumably has a dip closer to 60° E.

Trench relations, particularly in the north wall, indicate two events formed the scarp at this site. The eastern fault trace is truncated by deposits that are in turn cut by the western trace and thus slipped during the penultimate event but not during the most recent event. The penultimate-event colluvial wedge and a substantially larger offset indicate the western trace slipped during both events. Vertical separation of the upper part of the fine sand unit and two adjacent surveyed scarp profiles suggest cumulative dip slip of about 6 m, with an average of 3 m per event, but the apparent mismatch of fine sand deposits on either side of the fault adds some uncertainty to these estimates.

Seven charcoal samples from the Sturgis trench were ^{14}C dated (Table 2). The most recent event is bracketed at this site by ^{14}C ages of 580 ± 115 yr B.P. and 1370 ± 120 yr B.P. The penultimate event is bracketed by ^{14}C ages of 2290 ± 110 yr B.P., obtained from deposits displaced by this event, and 1815 ± 90 yr B.P., obtained from the colluvial wedge associated with this event. The event prior to the penultimate event is constrained only as occurring sometime before 3095 ± 155 yr B.P.

Discussion

Estimated Ages of Faulting

The three trenches across the main part of the Genoa fault revealed fairly consistent evidence for two late Holocene events. Due to the large offsets and young age of the deposits, the trenches did not expose evidence of any other prior events. Stratified charcoal layers provide very good ^{14}C-age control on the two late Holocene events (Table 2). The dating results are mostly consistent, and nearly all ages fall in stratigraphic order. In the following discussion, calendar-calibrated ages are used and rounded off to the nearest decade. For interpreting ages of faulting, we allow for stratigraphic position, and for estimating minimum ages, we consider a mean-residence-time factor of 50–100 years because the charcoal layers are assumed to be a mixture of material spanning a few to several decades. The Jacks Valley trench, for example, averaged about one charcoal layer per 100 years.

Two samples (JV-9-3 and ST-5) suggest the most recent event occurred just prior to 500 cal B.P., and one (JV-8-4) suggests this event occurred very close to this time. Sample JV-8-2 indicates a maximum age of about 680 cal B.P. for the most recent event, but this event is more tightly bracketed by the younger ages, so we prefer an age range of 500–600 cal B.P. Considering two sigma ranges in calibrated ages, the most recent event is constrained between 460 and 900 cal B.P.

At the Sturgis trench, the penultimate event is bracketed between 1740 cal B.P. (ST-16) and 2320 cal B.P. (ST-14). The latter age was derived from a deposit about 50 cm below the uppermost horizon cut by this event. Whereas the most recent event clearly ruptured the Jacks Valley section, we currently cannot preclude that some events, including the penultimate event, ruptured northward along the Indian Hill fault and bypassed the Jacks Valley section. If the penultimate event ruptured the Jacks Valley section, then it occurred prior to 2050 cal B.P. (JV-1-1). Alternatively, if this event bypassed the Jacks Valley section, then it may have occurred somewhat more recently than this. Assuming the former, we prefer an age for the penultimate event within the range of 2000–2200 cal B.P., and considering two sigma ranges in calibrated ages, the event is constrained between 1770 and 2700 cal B.P.

Two charcoal samples from the buried soil in the Walleys trench, which predates the penultimate event, yielded anomalous modern ages. These age estimates are discounted, because they would require the occurrence of two large events within the past few hundred years, which is inconsistent with the results from the other trench sites.

Displacements and Slip Rates

The two late Holocene earthquakes produced large displacements (3- to 5.5-m dip slip per event) along more than 15 km of the Genoa fault. Offsets at the three trench sites suggest a general southward decrease in displacement during the most recent event, with about 5.5-m dip slip at the Jacks Valley site, about 4.5 m at the Walleys site, and about 3 m at the Sturgis site. Displacements decrease rapidly north of the Jacks Valley trench, and within a few kilometers of the trench site, the scarp becomes difficult to follow through a forested area. The fault's most prominent expression occurs in the area between the Jacks Valley and Walleys trenches, so the offsets at these two sites seem reasonably representative of that part of the fault. Additional offset measurements would help to better characterize rupture distribution, but the rupture generally lies at the base of a steep hillslope, and alluvial scarps are present in only a few locations.

Averaging the displacements associated with the two late Holocene events observed in the trenches over the elapsed time since the penultimate event (about 10 m in the past 2 kyr) suggests a slip rate of about 5 mm/yr, but this probably significantly overestimates the actual slip rate due to the short elapsed time since the most recent event. A slip rate of 2–3 mm/yr, derived from the average per-event displacement determined from trenching (4–5 m) and the interseismic interval between the two events (1.5–2 kyr), is considered a better estimate of late Holocene activity. At Woodfords, where displacements appear to be smaller and events possibly less frequent, the slip rate is about 1 mm/yr (Clark *et al.,* 1984; this study).

We do not know how representative the Holocene slip rate, based on only a few events, is of the longer-term Quaternary slip rate. The few available constraints on longer-term activity suggest rates similar to or less than the Holocene rate. The outwash terrace of probable Tahoe age at Woodfords suggests an average slip rate of between 0.3 and 0.8 mm/yr, somewhat less than the Holocene rate at the same location. An upper faulted terrace adjacent to the Walleys trench (Fig. 7) is displaced by a minimum of 25 m and contains a thick (>1 m) argillic soil, suggesting an age of more than 100 ka and a significantly lower long-term slip rate, but actual offset of this surface is unknown due to burial of the hanging wall.

A period of increased activity over the late Quaternary, relative to longer time periods, is suggested by oversteepening of the range front and rilled fault facets at several locations (Fig. 10). These facets reflect throw of 150–200 m, but the time period over which this occurred is unknown. A Plio-Quaternary slip rate can be inferred from the uplift of a subhorizontal erosion surface within the Carson Range, which lies at an elevation of about 2700 m near Genoa. The vertical relief between this erosion surface and the floor of Carson Valley (about 1200 m), combined with the estimated depth of fill in Carson Valley (500–1000 m; Maurer, 1985), suggests 1700–2200 m of cumulative throw. Averaged over the past 3–5 Ma, the approximate period of the current seismotectonic regime (cf. Huber, 1981; Unruh, 1991), and assuming a fault dip of 60°, suggests a late Cenozoic slip rate of 0.6 ± 0.2 mm/yr.

Extent of Surface Rupture

The conspicuous scarp can be easily traced along nearly the entire lengths of the Carson Valley and Jacks Valley sections. The combined 25-km length of these two sections, from Jobs Canyon to Spooner Summit, is thus considered the minimum rupture length during recent events. The lim-

Figure 10. View of the southern Genoa fault showing rilled fault facets. Basal fault facets are consistently 150 to 200 m high along the fault and are believed to reflect a period of increased late Quaternary activity (photo by J. Yount).

ited available data suggest that recent events along the main part of the Genoa fault may have also ruptured the southern part but involved smaller displacements. The significantly different geomorphic appearance of the two parts of the fault appears at least in part due to differences in bedrock weathering, rather than significant differences in activity. The southern part of the Carson Range is predominantly granitic, and hillslopes are mantled by decomposed granite (grus), whereas that part of the range bounded by a conspicuous scarp is mostly metamorphosed Mesozoic pendant rocks, which yield more typical gravelly colluvium. If recent events also ruptured the full extent of the Diamond Valley section, then rupture length would exceed 40 km.

Individual events or sequences along the Genoa fault may involve one or more of the three northeast-striking faults in the Carson City area, in particular, the Kings Canyon fault, which nearly connects with the northern end of the Genoa fault. It seems unlikely that the large displacements along the Jacks Valley section would completely die out over a distance of only a few kilometers. Continuation of rupture northward along the Kings Canyon fault is possible based on available age constraints, but it is difficult to definitively prove. If the recent Genoa fault ruptures extended from the poorly defined southern end of the Sierra section to the northern end of the Kings Canyon fault, the total rupture length could be as long as 75 km, a length similar to the 1887 Sonora, Mexico, earthquake, the longest historical normal-slip Basin and Range Province event.

The bedrock high separating Eagle and Washoe Valleys, where the southwest end of the Virginia Range merges with the Carson Range, coincides with a significant left step between the Kings Canyon and Washoe Valley faults. This discontinuity, which appears controlled by structures associated with the Carson lineament, is the most distinct discontinuity in the CRFS and is likely the northernmost limit of Genoa fault ruptures. Subsequent trenching of the Washoe Valley fault indicated two events within a similar time range (Ramelli and dePolo, 1997). These could be northward extensions of Genoa fault surface ruptures, triggered events, or an example of beltlike behavior.

Conclusions

The first trenches excavated across a conspicuous, several-meter-high fault scarp along the Genoa fault provide evidence of two late Holocene events. Calendar-calibrated ages from stratified charcoal layers in two of the trenches provide very good age control and constrain the most recent and penultimate events to preferred ranges of 500–600 cal B.P. and 2000–2200 cal B.P., respectively.

Displacements associated with the late Holocene events on the Genoa fault are rather large for normal-faulting earth-

Table 3
Comparison of the Genoa Fault to Major Historical Basin and Range Province Earthquakes
(Parameters from Wells and Coppersmith, 1994)

Earthquake	*D* (m)*	*L* (km)†	*Ms*	*Mw*‡
ca. 1400 Genoa fault	5.7?	25–75	7.4–7.5?	7.2–7.3?
1872 Owens Valley, CA	11	108	8	7.9
1887 Sonora, Mexico	4.5	75	7.4	7.3
1915 Pleasant Valley, NV	5.8	62	7.6	7.2
1932 Cedar Mt., NV	2	61	7.2	6.8
1954 Fairview Peak, NV	4.1	57	7.2	7.2
1954 Dixie Valley, NV	3.8	45	6.8	6.9
1959 Hebgen Lake, MT	6.1	26.5	7.6	7.3
1983 Borah Peak, ID	2.7	34	7.3	6.9

*Maximum surface displacement.
†Surface rupture length.
‡Estimates of Wells and Coppersmith (1994) rounded to nearest tenth of a magnitude.

quakes (3–5.5 m along much of the fault), but they are comparable to the largest historical normal-faulting Basin and Range Province earthquakes (e.g., 1887 Sonora, Mexico, 1915 Pleasant Valley, and 1959 Hebgen Lake earthquakes), allowing a comparative magnitude estimate of M 7.2–7.5 (Table 3). Due to poor scarp preservation, forested terrain, and lack of age control along the ends of the ruptures, overall rupture lengths during these events are difficult to constrain, but available information indicates rupture lengths of between 25 and 75 km. The large displacements suggest the longer end of this range is more likely, but the 1959 Hebgen Lake earthquake, which had a rupture length of less than 30 km, indicates that such large displacements are not necessarily associated with long ruptures.

The trench results indicate a late Holocene slip rate on the main part of the Genoa fault of 2–3 mm/yr, one of the highest slip rates in the Basin and Range Province. Considering its high rate of activity and large magnitude potential, the fault poses a significant seismic hazard to the Reno/Carson City urban corridor and the Lake Tahoe area, in particular Carson City and communities in Carson Valley that are located on the hanging wall of the fault.

Acknowledgments

This work was supported by the USGS National Earthquake Hazards Reduction Program (NEHRP Award Number 1434-92-G-2217). We are especially grateful to the U.S. Forest Service, Walleys Hot Springs Resort, and Sturgis Ranch for allowing access to the trench sites, and we thank Burt Slemmons and Gary Christenson for helpful reviews.

References

Armin, R. A., and D. A. John (1983). Preliminary geologic map of the Freel Peak 15-minute quadrangle, California and Nevada, with Quaternary geology by John C. Dohrenwend, U.S. Geol. Surv., Misc. Invest. Map I-1424, scale 1:62,500.

Armin, R. A., D. A. John, and W. J. Moore (1984). Geologic map of the Markleeville 15-minute quadrangle, Alpine County, California, with Quaternary geology by John C. Dohrenwend, U.S. Geol. Surv., Misc. Invest. Map I-1474, scale 1:62,500.

Bell, J. W. (1984). Quaternary fault map of Nevada—Reno sheet, Nevada Bur. Mines Geol. Map 79.

Bell, J. W., D. B. Slemmons, and R. E. Wallace (1984). Roadlog for Neotectonics of Western Nevada (Field Trip 18), in J. Lintz Jr. (Editor), *Geological Society of America, 1984 Annual Meeting Guidebook, Western Geological Excursions,* Vol. 4, Geological Society of America, Boulder, Colorado, 425–472.

Birkeland, P. W. (1963). Pleistocene volcanism and deformation of the Truckee area, north of Lake Tahoe, California, *Geol. Soc. Am. Bull.* **74,** 1453–1464.

Clark, M. M., K. H. Harms, J. J. Lienkaemper, D. S. Harwood, K. R. Lajoie, J. C. Matti, J. A. Perkins, M. J. Rymer, A. M. Sarna-Wojcicki, R. V. Sharp, J. D. Sims, J. C. Tinsley III, and J. I. Ziony (1984). Preliminary slip-rate table and map of late Quaternary faults of California, *U.S. Geol. Surv. Open-File Rept. 84-106.*

Dohrenwend, J. C. (1982). Map showing late Cenozoic faults in the Walker Lake 1X2 degree quadrangle, Nevada–California, U.S. Geol. Surv. Misc. Field Studies Map MF-1382-D, scale 1:250,000.

Hawkins, F. F., R. LaForge, and R. A. Hansen (1986). Seismotectonic study of the Truckee/Lake Tahoe area, northeastern Sierra Nevada, California for Stampede, Prosser Creek, Boca, and Lake Tahoe dams, *U.S. Bur. Reclam., Seismotectonic Rept. 85-4,* 210 pp.

Huber, N. K. (1981). Amount and timing of late Cenozoic uplift and tilt of the central Sierra Nevada, California—evidence from the upper San Joaquin River basin, *U.S. Geol. Surv. Profess. Pap. 1197,* 28 pp.

Lawson, A. C. (1912). The recent fault scarps at Genoa, Nevada, *Bull. Seism. Soc. Am.* **2,** 193–200.

Leeder, M. R., and J. A. Jackson (1993). The interaction between normal faulting and drainage in active extensional basins, with examples from the western United States and central Greece, *Basin Res.* **5,** 79–102.

Martinelli, D. M. (1989). Geophysical investigations of the northern Sierra Nevada–Basin and Range boundary, west-central Nevada and east-central California, Master's Thesis, University of Nevada, Reno, 172 pp.

Maurer, D. K. (1985). Gravity survey and depth to bedrock in Carson Valley, Nevada–California, *U.S. Geol. Surv., Water-Resources Invest. Rept. 84-4202.*

Moore, J. G. (1969). Geology and mineral deposits of Lyon, Douglas and Ormsby Counties, Nevada, *Nevada Bur. Mines Geol. Bull.* **75,** 18.

Peakall, J. (1995). The influences of lateral ground-tilting on channel morphology and alluvial architecture, Ph.D. Thesis, University of Leeds, 333 pp.

Pease, R. C. (1979a). Earthquake hazards map—Genoa 7½-minute quadrangle, Nevada Bur. Mines Geol. Map 1Ci.

Pease, R. C. (1979b). Scarp degradation and fault history south of Carson City, Nevada, Master's Thesis, University of Nevada, Reno, 90 pp.

Pease, R. C. (1980). Geologic map of the Genoa 7½-minute quadrangle, Nevada Bur. Mines Geol. Map 1Cg.

Ramelli, A. R., and C. M. dePolo (1997). Trenching and related studies of the northern Sierra Nevada range-front fault system: final technical report to U.S. Geological Survey, National Earthquake Hazards Reduction Program (NEHRP), Award Number 1434-95-G-2606.

Ramelli, A. R., J. W. Bell, and C. M. dePolo (1996). Late Holocene activity of the Genoa fault, western Nevada (abstracts with programs), *Geol. Soc. Am.* **28,** 103.

Rogers, D. K. (1975). The Carson lineament—its influence on recent left-lateral faulting near Carson City, Nevada (abstracts with programs), *Geol. Soc. Am.* **7,** 1250.

Russell, I. C. (1887). Notes on the faults of the Great Basin and of the eastern base of the Sierra Nevada, *Bull. Philos. Soc. Washington* **9,** 5–7.

Slemmons, D. B. (1975). Cenozoic deformation along the Sierra Nevada province and Basin and Range Province boundary, *Calif. Div. Mines Geol. Calif. Geol.* **28,** 99–119.

Stewart, J. H., J. E. Carlson, and D. C. Johannesen (1982). Geologic map of the Walker Lake 1 × 2 degree quadrangle, California and Nevada, U.S. Geol. Surv. Misc. Field Studies Map MF-1382-A, scale 1:250,000.

Stuiver, M. and P. J. Reimer (1993). Extended ^{14}C database and revised CALIB 3.0 ^{14}C age calibration program, *Radiocarbon* **35,** 215–230.

Thatcher, Wayne, G. R. Foulger, B. R. Julian, J. Svarc, E. Quilty, and G. W. Bawden (1999). Present-day deformation across the Basin and Range Province, Western United States, *Science* **283,** 1714–1718.

Thompson, G. A., and D. E. White (1964). Regional geology of the Steamboat Springs area, Washoe County, Nevada, *U.S. Geol. Surv. Profess. Pap. 458-A,* 52 pp.

Toppozada, T. R., C. R. Real, and D. L. Parke (1981). Preparation of isoseismal maps and summaries of reported effects for pre-1900 California earthquakes, *Calif. Div. Mines Geol. Open-File Rept. 81-11SAC,* 182 pp.

Trexler, D. T. (1977). Geologic map of the Carson City 7½-minute quadrangle, Nevada Bur. Mines Geol. Map 1Ag.

Trexler, D. T., and J. W. Bell (1979a). Earthquake hazard maps of Carson City, New Empire and South Lake Tahoe quadrangles, text to accompany earthquake hazard maps, Final Technical Report, USGS Grant Number 14-08-0001-G-494.

Trexler, D. T., and J. W. Bell (1979b). Earthquake hazards map—Carson City 7½-minute quadrangle, Nev. Bur. Mines Geol. Map 1Ai.

Unruh, J. R. (1991). The uplift of the Sierra Nevada and implications for late Cenozoic epeirogeny in the western Cordillera, *Geol. Soc. Am. Bull.* **103,** 1395–1404.

Vadurro, G. A. (1993). Strain analysis of the Genoa fault, Sierra Nevadan frontal fault system, NW Nevada and NE California, Bachelor of Science Thesis, Humboldt State University.

Wells, D. L., and K. J. Coppersmith (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bull. Seism. Soc. Am.* **84,** 974–1002.

Yount, J. C., A. R. Ramelli, L. G. Garside, and H. Bonham (in prep). Geologic map of the Minden 7½-minute quadrangle, Nevada Bur. Mines Geol. map series.

Nevada Bureau of Mines and Geology
University of Nevada, MS 178
Reno, Nevada 89557
(A.R., J.B., C.D.)

U.S. Geological Survey, MS 980
Box 25046 Denver Federal Center Denver, Colorado 80225
(J.Y.)

Manuscript received 8 January 1999