

# Holocene slip rate and earthquake recurrence on the Honey Lake fault zone, northeastern California

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## ABSTRACT

The Honey Lake fault zone, a major right-lateral fault in the Basin and Range province of eastern California, is one of a broad system of faults that accommodate some of the relative motion between the Pacific and North American plates. These right-lateral faults may have significantly higher slip rates, and thus greater earthquake hazards, than the normal faults for which the Basin and Range is more commonly known. In the Honey Lake Valley, the fault forms a 50-km-long zone of landforms typical of active strike-slip faults. Right-lateral offset of an incised creek channel is used to estimate a Holocene slip rate of between 1.1 and 2.6 mm/yr. A fault exposure in Holocene alluvium shows evidence for at least four late Holocene surface-faulting earthquakes.

## INTRODUCTION

A significant amount of right-lateral shear related to the relative motions of the Pacific and North American plates occurs well to the east of the San Andreas fault. Right-lateral faults extend from near the San Andreas fault in southern California, through a broad area of eastern California and western Nevada, and may project into central Oregon (Pezzopane and Weldon, 1993). These faults may accommodate as much as 10 mm/yr of the right-lateral motion between the Pacific and North American plates (Argus and Gordon, 1990).

Although the Basin and Range province of the western United States is known for extensional tectonics, right-lateral faults are a major feature of the western Basin and Range (Gianella and Callaghan, 1934; Stewart, 1988). These right-lateral faults are up to 300 km long (e.g., the Death Valley fault system; Wills, 1989; Brogan et al., 1991) and have produced historic earthquakes as large as M 7.8 (e.g., the Owens Valley earthquake of 1872; Topozada et al., 1981). Reported slip-rate estimates (Clark et al., 1984; Bryant, 1993) suggest that major right-lateral faults within the western Basin and Range commonly have slip rates  $>2$  mm/yr, whereas few normal faults have slip rates  $>1$  mm/yr. Because earthquake frequency is directly related to fault area and slip rate (Molnar, 1979), the right-lateral faults may be considerably more hazardous than the normal faults.

This report presents the findings of a reconnaissance-level investigation of the faults of the Honey Lake basin for the fault evaluation and zoning project of the California Division of Mines and Geology. The purpose of this investigation was to identify faults showing evidence of Holocene surface offset that should be included in Alquist-Priolo special studies zones, where development is restricted (Hart, 1992).

Our investigation identified geomorphic evidence for Holocene faulting and a locality where the rate and frequency of faulting could be investigated in detail. The right-lateral strand of the Honey Lake fault, mapped only recently (Grose et al., 1991; Hart et al., 1991), clearly has been active in Holocene time. Normal strands, which have been recognized for some time (Russell, 1885; Diller, 1908), appear to be largely inactive. This paper reviews the geomorphic evidence for Holocene tectonism and presents paleoseismologic re-

sults derived from offset late Holocene deposits in a cutbank of Long Valley Creek.

## GEOMORPHIC EXPRESSION

The Honey Lake fault zone forms a line of scarps and tonal lineaments trending N45°W for  $>50$  km across the Honey Lake basin. It displaces latest Pleistocene lacustrine deposits and younger alluvium, all below the shorelines of Pleistocene Lake Lahontan. The geomorphic expression of the fault must have formed since 12.5 ka, when Lake Lahontan receded rapidly (Benson and Thompson, 1987).

The southeastern end of the Honey Lake fault offsets Holocene alluvial fans along the southwest margin of the Fort Sage Mountains (Fig. 1). These fans have youthful-appearing constructional surfaces and weak soil development in unconsolidated sandy alluvium.

North of Doyle, the Honey Lake fault crosses a broad, gently northward sloping surface (Fig. 2). This surface is the bed of Lake Lahontan, and has a veneer of alluvial sediments. The straight fault trace is marked by scarps that face either northeast or southwest and by small depressions at right steps in the trace.

The channel incised by Long Valley Creek in the late Pleistocene alluvial surface is offset right laterally where it crosses the Honey Lake fault zone (Fig. 1, locality 1). An inset terrace on the north bank of the creek (Fig. 3) is also offset. A cutbank in the inset terrace provided an ideal exposure for the paleoseismological work discussed below.

North of Long Valley Creek, scarps are as high as 6 m where the fault makes a small right step and bounds one side of a closed depression. Farther northwest, the fault makes another right step and forms a rhombic sag pond (Fig. 1, locality 2).

At Honey Lake, the fault is exposed in a wave-cut cliff (Fig. 1, locality 3). There, thinly bedded siltstone and sandstone lake deposits are intensely deformed and faulted, and a loose gray sand appears to have been injected into an irregular fissure along the fault zone, probably as a result of liquefaction.

Northwest of Honey Lake, a strand of the fault is exposed in the east bank of a small stream channel (Fig. 1, locality 4). Another strand can be traced across Lahontan shorelines (Fig. 1, locality 5).



Away from the fault, these beds form three sequences, designated buried soil 7 (b7), buried soil 5 (b5), and the modern soil (Fig. 4). Each sequence has at its base a bed of medium- to coarse-grained sand, which becomes finer upward, and a soil layer at the top, generally formed in clayey silt. The horizontal layering and consistent thicknesses of these beds, except at the fault zone, suggest that the sequence represents a relatively passive filling of the channel, rather than repeated scour and fill. This deposition may be due to a middle Holocene partial refilling of Honey Lake, which would have changed the base level of Long Valley Creek.

The b5 unit may have been deposited at about 5.7 ka, on the basis of a sample of detrital charcoal dated by accelerator mass spectrometry. The age of this charcoal (sample AA-5787) is reported to be  $5715 \pm 65$  radiocarbon years.

### SLIP RATE

The horizontal slip rate of the Honey Lake fault is estimated by dividing the amount of right-lateral offset of the incised channel of Long Valley Creek by the age of the channel. The channel margin forms a broad, relatively smooth curve on both sides of the fault. Thus, it is relatively simple, both on aerial photographs and from the ground, to project the top of the channel margin into the fault zone and measure its offset. Assuming that the channel margin originally projected across the fault on a relatively straight line, it has been offset by  $16 \pm 2$  m.

The channel margin is younger than Lake Lahontan and older than Mazama ash. It was probably an erosional surface from the time that Lake Lahontan receded until sedimentation began in the channel. Deposition of the inset terrace effectively isolated the stream from the former channel margin and prevented further erosion. The fault has since offset the former channel margin.

If the history of this stream consisted of simple incision-deposition-incision, as outlined above, then the offset channel margin would be closer to the age of the oldest material in the inset terrace than to the age of the upper terrace surface. Alternatively, deposition of the inset terrace could have been interrupted by periods of erosion, including lateral erosion of the older channel margin. If any lateral erosion occurred during the deposition of the inset terrace, it

could have effectively "reset the clock," erasing evidence for previous lateral offset.

A right-lateral offset of  $16 \pm 2$  m in 7 to 12.5 ka yields a minimum horizontal slip rate of 1.1 mm/yr and a maximum of 2.6 mm/yr. If erosion of the channel margin during deposition of the inset terrace erased previous offsets, which we feel is unlikely, 2.6 mm/yr would represent a minimum slip rate.

Because the channel margin probably dates more closely to the oldest deposits in the inset terrace than the surface into which it cuts, we prefer a preliminary slip rate estimate of 2.0 mm/yr, which is in the higher part of the range of possible rates.

### PALEOSEISMOLOGY

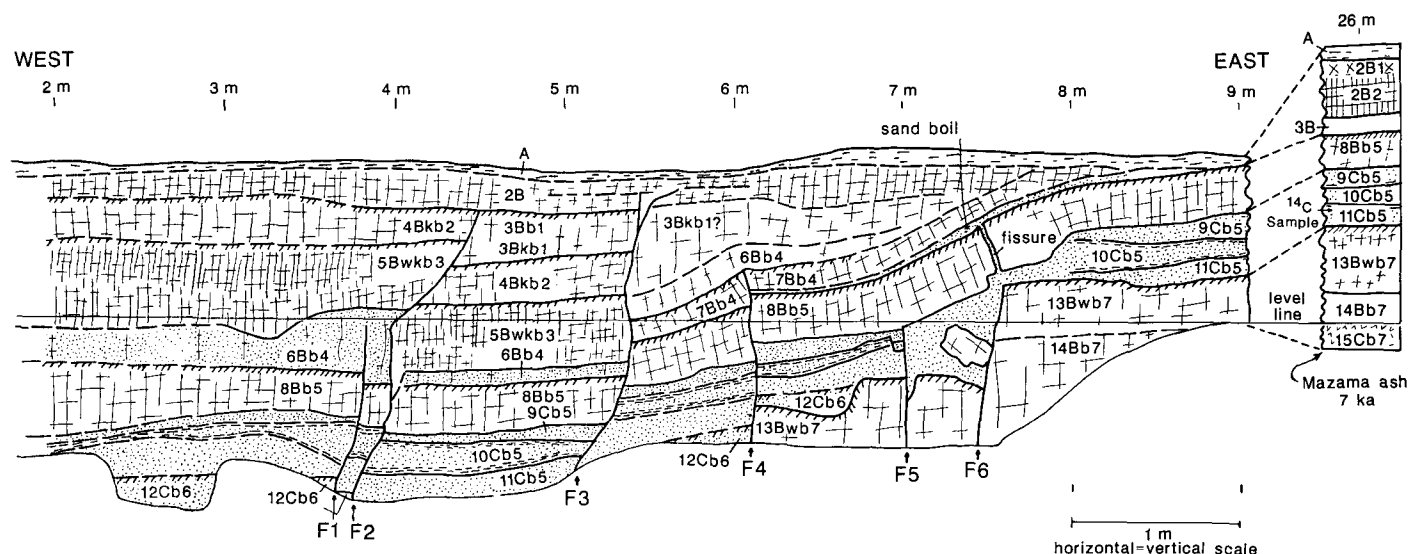
A detailed log of the cutbank of Long Valley Creek shows six strands of the fault in a zone 4 m wide (Fig. 4). These fault strands, which cut to different levels in the sequence, enable us to estimate the number and relative timing of events, described here from youngest to oldest and designated in reverse alphabetical order.

#### Event Z

The most recent event recorded in the sediments at Long Valley Creek occurred along fault F3 (Fig. 4). Two splays cut the modern soil. The fissure between the two fault splays at the top of fault F3 contains light-colored, relatively unweathered sandy silt. Because this fault extends to near the ground surface and overlying soils are poorly developed, the fault movement must have occurred relatively recently. No historical earthquakes can be correlated with this faulting. Earthquakes of M 5.8 to 5.9 occurred in the Honey Lake Valley in 1875 and 1889 (Topozada et al., 1981), but these magnitudes are not typically associated with large surface ruptures. Event Z probably occurred before the beginning of the historical record, but within the past few hundred years.

#### Event Y

This event occurred along fault F2 and displaced all units except the modern soil. Considerable mismatch in the thicknesses of units across fault F2 suggests either strike-slip displacement of laterally variable units or an earlier event on fault F2.



**Figure 4.** Log of exposure at Long Valley Creek showing displacement of soils across Honey Lake fault. Nomenclature for soil units is based on Soil Survey Staff (1951, 1975) modified by Birkeland (1984). Each soil unit is designated by sequence of letters and numbers, e.g., 3Bkb1, where first number refers to depositional unit, numbered in stratigraphic order from top to bottom. Capital letter refers to master soil horizon A, B, or C. Lower case letters signify characteristics of soil; k for carbonate, w for color or structure in B horizon. Buried soils (paleosols) are designated by lower case b. Buried soil horizons are numbered from top to bottom as suggested by Birkeland (1984).

## Event X

This event produced movement along fault F4 of units up through 7Bb4. Between faults F3 and F6, paleosols b4 and b5 are warped, in contrast with the relatively horizontal overlying layers, suggesting that warping and possibly minor movement on fault F6 also occurred during event X.

## Event W

The first event recorded in the sedimentary strata of Long Valley Creek caused displacement on faults F6 and F5. Liquefaction of units 9Cb5 through 11Cb5 between faults F5 and F6 and east of F6 changed these units from a well-bedded sequence to a homogeneous mass of medium to coarse sand. Sand apparently was forced through a fissure in the 8Bb5 horizon and formed a sand boil above fault F6 (Fig. 4). The sand boil appears to be relatively symmetrical about the fissure below it, indicating that it formed on a level surface. Warping of the b5 soil probably occurred later, along with additional minor movement on fault F6.

We found no clear evidence for further events in the exposure at Long Valley Creek. The lowest continuous beds across the fault zone, b5, appear to be undisturbed except at the faults described above. No earthquakes occurred between the time the parent material of soil b5 was deposited (~5.7 ka) and event W. However, there are differences in thickness of units across both faults F2 and F6. This mismatch may be due to strike-slip displacement of laterally variable units but could also be due to additional earthquake ruptures on those faults.

## CONCLUSIONS

The Honey Lake basin is similar to other "grabens" of the western Basin and Range (e.g., Death Valley, Owens Valley) in that the principal active fault is a right-lateral fault. This fault has produced abundant geomorphic evidence for Holocene faulting. Measurements of the displacement of a post-Lahontan channel margin enable calculation of a Holocene slip rate for the fault zone. The horizontal slip has been between 1.1 and 2.6 mm/yr through the Holocene; 2 mm/yr is the preferred estimate.

Interpretation of stratigraphic and structural relations exposed in a cutbank of Long Valley Creek yielded several findings. (1) Six fault traces, all of which offset late Holocene deposits, span a zone 4 m wide. (2) All of the soils in the exposure, including the modern soil, are displaced by one or more strands of the fault. (3) At least four major, ground-rupturing earthquakes have occurred in the past 6 ka. (4) Recurrence of major events averages 1.5 ka. (5) The latest event may have occurred in the past few hundred years.

Activity of the Honey Lake fault zone is similar to other right-lateral faults of the Basin and Range, particularly the Pyramid Lake fault (Anderson and Hawkins, 1984; Bell, 1984). The similarity between these two faults is not unexpected, because they are en echelon strands of the same fault system, the northern Walker Lane of Bonham and Slemmons (1968).

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