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Refining fault slip rates using multiple displaced terrace risers—An example from the Honey Lake fault, NE California, USA

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ABSTRACT

Faulted terrace risers are semi-planar features commonly used to constrain Quaternary slip rates along strike-slip faults. These landforms are difficult to date directly and therefore their ages are commonly bracketed by age estimates of the adjacent upper and lower terrace surfaces. However, substantial differences in the ages of the upper and lower terrace surfaces (a factor of 2.4 difference observed globally) produce large uncertainties in the slip-rate estimate. In this investigation, we explore how the full range of displacements and bounding ages from multiple faulted terrace risers can be combined to yield a more accurate fault slip rate. We use 0.25-m cell size digital terrain models derived from airborne lidar data to analyze three sites where terrace risers are offset right-laterally by the Honey Lake fault in NE California, USA. We use ages for locally extensive subhorizontal surfaces to bracket the time of riser formation: an upper surface is the bed of abandoned Lake Lahontan having an age of 15.8 ± 0.6 ka and a lower surface is a fluvial terrace abandoned at 4.7 ± 0.1 ka. We estimate lateral offsets of the risers ranging between 6.6 and 28.3 m (median values), a greater than fourfold difference in values. The amount of offset corresponds to the riser's position relative to modern stream meanders: the smallest offset is in a meander cutbank position, whereas the larger offsets are in straight channel or meander point-bar positions. Taken in isolation, the individual terrace-riser offsets yield slip rates ranging from 0.3 to 7.1 mm/a. However, when the offset values are collectively assessed in a probabilistic framework, we find that a uniform (linear) slip rate of 1.6 mm/a (1.4–1.9 mm/a at 95% confidence) can satisfy the data, within their respective uncertainties. This investigation demonstrates that integrating observations of multiple offset elements (crest, midpoint, and base) from numerous faulted and dated terrace risers at closely spaced sites can refine slip-rate estimates on strike-slip faults.

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1. Introduction

Geologic estimates of fault slip rates require measurements of displacement determined from correlative piercing points or lines across a fault and age constraints derived from chronologic or stratigraphic data. For strike-slip faults, offset fluvial terrace risers are semi-planar landforms that are commonly used to constrain late Quaternary slip rates (Fig. 1a). These sloping escarpments between terrace surfaces record intervals of stream incision, and their age is bracketed by the age of the adjacent subhorizontal terrace treads. Early efforts to use terrace risers in Quaternary fault studies focused on the South Island of New Zealand (Lensen, 1964, 1968; Suggate, 1960). More recently, terrace risers have been utilized in slip-rate investigations in the Indo-Asia collision zone (Cowgill, 2007; Cowgill et al., 2009; Gold et al. 2009, 2011; Haibing et al., 2005; Harkins and Kirby, 2008; Lasserre et al., 1999; Mériaux et al., 2004; Van der Woerd et al., 1998), in New Zealand (Berryman, 1990; Gold and Cowgill, 2011; Knuepfer, 1992; Mason et al., 2006), in western North America (Hunter et al., 2011; Simpson et al., 1999; Turner et al., 2008; Weldon and Sieh, 1985; Wills and Borchardt, 1993), and elsewhere (Hubert-Ferrari et al., 2002; Prentice et al., 2003).

While fluvial terrace risers have geometries that are well-suited for measuring lateral displacement, constraining their ages is more challenging (Cowgill, 2007). Specifically, the age of the sloping escarpment is difficult to directly measure. Instead, terrace-riser ages are typically constrained by the abandonment ages of the bounding upper and/or lower terrace(s). Extensive theoretical and field-based observations have explored how terrace ages can best be correlated to the age of a faulted terrace riser (Cowgill, 2007; Gold et al. 2009, 2011; Harkins and Kirby, 2008; Lensen, 1964, 1968; Mériaux et al., 2004; Suggate, 1960; Van der Woerd et al., 2002). There are three approaches that have been used to pair terrace ages with riser offsets: (1) *Lower terrace*—In settings where streams

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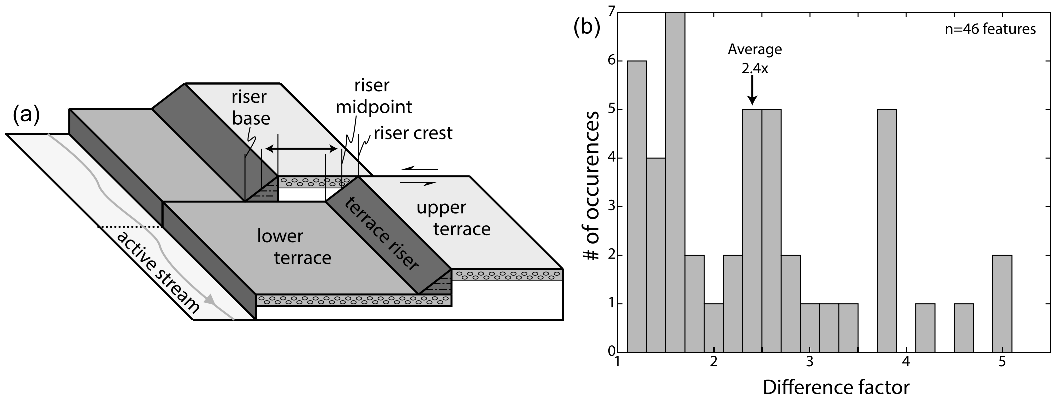

Fig. 1. (a) Schematic diagram illustrating the geometric elements of a laterally faulted terrace riser. (b) Histogram plot showing the relative difference in age between upper and lower terrace surfaces from 46 dated terrace-risers in published slip-rate studies. This compilation shows that on average, upper and lower surfaces differ by a factor of 2.4. This difference translates into significant uncertainty in slip rate measurements. Data sources include 28 features from compilation by Cowgill (2007), with additional data from Gold et al. (2009, 2011), Harkins and Kirby (2008), Mason et al. (2006), Knuepfer (1992), and McCalpin (1996).

have sufficient erosive power to continually erode and refresh a terrace riser while occupying the lower terrace tread, the fault's lateral offset is only recorded following abandonment of the lower terrace (Knuepfer, 1992; Mason et al., 2006; Mériaux et al., 2004; Van der Woerd et al., 1998). (2) *Upper terrace*—In settings where streams have limited lateral erosive power, the terrace riser records the fault's offset immediately after abandonment of the upper terrace surface (e.g, Cowgill, 2007; Lensen, 1968). (3) *Bracketing*—To avoid errors with selecting the "correct" terrace age model (upper vs. lower), the most conservative and widely used approach is to bracket the age of a terrace riser, using the abandonment ages of both the upper- and lower-terrace surfaces (Cowgill, 2007; Cowgill et al., 2009; Gold and Cowgill, 2011; Gold et al., 2009; Harkins and Kirby, 2008; Mériaux et al., 2005). While the latter approach fully accounts for the epistemic uncertainty in terrace riser age—that is, uncertainty from imperfect knowledge about how riser formation, terrace abandonment, and faulting interacted—it can lead to large slip-rate uncertainties at sites where the difference in age between the bracketing upper and lower terraces is large. A global compilation of terrace-riser slip-rate studies shows that the average age between upper and lower surfaces differs by a factor of 2.4 (Fig. 1b, updated from Cowgill, 2007; raw data provided in Table S1 in the supplemental materials).

In this study, we demonstrate that combined treatment of the full range of offsets and age uncertainties across multiple sites can improve constraints on slip rates. We illustrate this approach with a paleoslip investigation focused on the right-lateral Honey Lake fault system in NE California. At three closely spaced sites (<1.5 km apart), we identify laterally faulted terrace risers formed by Long Valley Creek, all of which are bracketed by the same locally extensive upper and lower terrace surfaces. We derive three measures of offset for each terrace riser using three geomorphic elements—crest, midpoint, and base—from far-field projections into the fault zone. We examine how measurements of lateral offset vary as a function of the position in the stream system (e.g., outside vs. inside meander). Additionally, we use our results to refine the slip-rate bounds on the Honey Lake fault system and show the value of considering multiple offset markers in a probabilistic framework to reduce slip-rate uncertainties.

2. Honey Lake fault

The northwest-striking Honey Lake fault transects Long Valley near the town of Doyle in northeastern California, USA and is part of a network of active, dextral, strike-slip faults in the northern Walker Lane (Fig. 2). The Walker Lane is a zone of distributed shear that extends 700 km along the western margin of the Basin and Range province (Stewart, 1988) and accommodates 15–20% (5–7 mm/yr) of relative Pacific-North America plate motion at the latitude of the Honey Lake fault (Hammond et al., 2011; Thatcher, 2003). The 98-km-long Honey Lake fault zone is one of a series of strike-slip faults with a clear and consistent geomorphologic expression in the northern Walker Lane, and thus it is interpreted as one of the major seismogenic structures in the region (Adams et al., 1999a; Wills, 1990). Paleoseismic investigations document evidence for four, post-6.8 ka surface-rupturing earthquakes along the Honey Lake fault (Turner et al., 2008; Wills and Borchardt, 1993). The fault displays alternating components of east- and west-side up motion, which is typical of strike-slip faults and relates to small changes in the trend of the fault. This investigation focuses on the lateral component of slip.

2.1. *Prior slip-rate investigations*

Previous studies have established general bounds on the late Quaternary slip rate of the Honey Lake fault. Wills and Borchardt (1993) report a slip rate of 1.1–2.6 mm/a, on the basis of a faulted terrace riser that is laterally offset 16 $\pm$ 2 m and is bracketed by an upper terrace surface (T2) cut into the bed of Lake Lahonton (the authors report an age of 12.5 ka; subsequent work revises that age to 15.8 ka, as discussed below) and a lower Holocene terrace (T1) with an age of 5.7 ka (subsequent work revises that age to 4.7 ka, as discussed below). Turner et al. (2008) present new observations at the same site, including new displacement constraints based on ground-based topographic surveys and radiocarbon-age constraints on the faulted, lower terrace riser. They propose a revised right-lateral offset for the terrace riser of 5.3–10.6 m. Based on new radiocarbon ages from detrital charcoal, they revise the age of the lower T1 terrace to 4.7 ka. Additionally, on the basis of historically documented erosion of the terrace riser separating an abandoned terrace and the modern floodplain, they propose that the 4.7 ka lower terrace provides a close approximation of the age of the faulted terrace rise, yielding a revised slip rate of 1.7 $\pm$ 0.6 mm/a since 4.7 ka. Taken together, the Wills and Borchardt (1993) and Turner et al. (2008) studies use a single offset terrace riser to constrain an apparent late Quaternary slip rate of 1.1–2.6 mm/a.

2.2. *Fluvial terraces*

Our field area encompasses the original studies of Wills and Borchardt (1993) and Turner et al. (2008), where two key terrace surfaces are recognized (Fig. 3). The upper terrace (T2) is a regionally extensive surface cut into pluvial deposits associated with Lake