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Vertical deformation of lacustrine shorelines along breached relay ramps, Catlow Valley fault, southeastern Oregon, USA

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ABSTRACT

Vertical deformation of pluvial lacustrine shorelines is attributed to slip along the Catlow Valley fault, a segmented Basin and Range style normal fault in southeastern Oregon, USA. The inner edges of shorelines are mapped along three breached relay ramps along the fault to examine the effect of fault linkage on the distribution of slip. Shoreline inner edges act as paleohorizontal datums so deviations in elevation from horizontal, outside of a 2 m error window, are taken to be indications of fault slip. The sites chosen represent a spectrum of linkage scenarios in that the throw on the linking fault compared to that on the main fault adjacent to the linking fault varies from site to site. Results show that the maturity of the linkage between segments (i.e. larger throw on the linking fault with respect to the main fault) does not control the spatial distribution of shoreline deformation. Patterns of shoreline deformation indicate that the outboard, linking, and/or smaller ramp faults have slipped since the shorelines formed. Observations indicate that displacement has not fully localized on the linking faults following complete linkage between segments.

1. Introduction

Extensional faulting plays a role in driving large scale landscape morphology change over the life time of a fault system (Cowie et al. 2006; Gawthorpe and Hurst 1993; Gawthorpe and Leeder 2000; Kirby and Whipple 2012). In the last decade, work has focused on particular landscape elements, such as fluvial channels, and how they can be used to better understand processes such as changes in fault slip rate (e.g. Whittaker et al., 2007a, b, 2008) and normal fault interaction and linkage (Commins et al. 2005; Hopkins and Dawers 2015; Whittaker and Walker 2015). Geomorphic features are useful in this respect because they can survive within the landscape for significant amounts of time (~10^5 years) and can record changes in tectonic activity over these timescales. Deformation over these intermediate, or geomorphic, timescales gives us an important perspective because they are more representative of long-term tectonics than single events (Burbank & Anderson, 2011). This is especially true because tectonic processes that control landscape evolution may not manifest on timescales of an earthquake cycle.

Here we use the deformation of pluvial lacustrine shorelines along the footwall escarpment of a segmented normal fault as a proxy for fault slip, in order to test whether *en echelon* fault tips remain active after segment linkage. Shorelines have previously been used to study fault related deformation and rock uplift because they are useful paleohorizontal datums (e.g. Anderson and Menking 1994; Choi et al. 2008; Merritts and Bull 1989; Oldow and Singleton 2008; Scott and Pinter 2003; Yildirim et al. 2013). The utility is that these datums serve a dual purpose, i.e., the ability to measure both the vertical deformation along the fault and the spatial distribution of that deformation along strike. We expect that if the overlapping portions of a linked pair of faults remained active post-linkage, then the shorelines would not be horizontal over length scales of 100s of meters to kilometers. We expect that individual shorelines will vary in elevation along strike and that the pattern of warping, among a series of shorelines, will provide clues about the evolution of the structures since shoreline formation.

The fate of the overlapping portions of *en echelon* fault tips after a linking fault connects the two segments remains poorly understood (Fig. 1). In the case of normal faults, which typically grow by segment linkage (e.g., Cartwright et al. 1995; Dawers and Anders 1995), previous work implies that this process is geologically rapid (e.g., Childs et al. 1995; Cowie 1998; Imber et al. 2004; Peacock & Sanderson, 1991, 1994). Although numerous studies examine the development of normal-fault overlaps, also known as relay ramps (e.g. Childs et al. 1995, Imber et al. 2004; Peacock & Sanderson, 1991, 1994; Trudgill and Cartwright 1994), these studies assume that the ramp passively subsides into the basin after linkage and that the adjacent portion of the outboard fault becomes inactive. Analog models, however, show that the overlapping portions of fault segments remain active for some time after the relay ramp is fully breached (Hus et al. 2005). Continued

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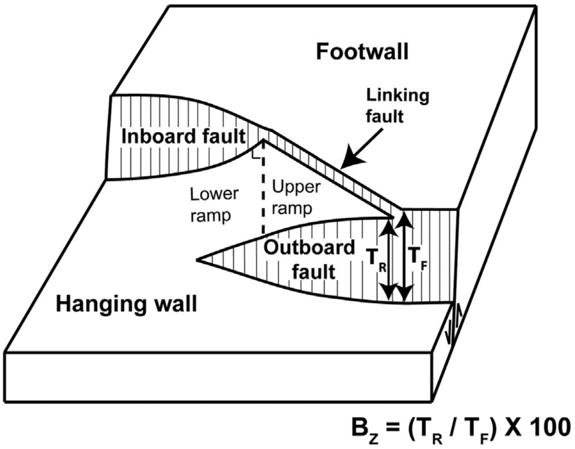

Fig. 1. Schematic block diagram of a linked pair of normal faults. Cartwright et al.'s (1995) breaching index (BZ) is shown as an indication of relative linkage maturity between fault segments. TR = throw at the crest of the relay ramp. TF = throw on the main fault directly adjacent to the crest of the relay ramp. Dashed line demarcates the boundary between upper and lower ramp.

activity on these portions of the faults is an important controller of landscape evolution because it will directly affect sediment transport pathways and dispersion patterns across a ramp surface.

The sites we examined are three fully breached relay ramps along the Catlow Valley fault in southeastern Oregon, USA (Fig. 2). The ramps are footwall breached, meaning the linking fault extends from the inboard fault tip to the outboard fault and breaks the upper portion of the ramp. This orientation is the expected way a linking fault breaches a ramp based on numerical models (Crider and Pollard 1998). The sites we chose cover a range of linkage scenarios from a relatively immature linkage to relatively mature one. Our purpose is to examine shoreline elevation changes relative to segment linkage to investigate how the ramp deforms post-linkage and where that deformation occurs within the relay ramps over geomorphic timescales.

2. Geological setting

The study area is in the Catlow Valley located within the Basin and Range in southeastern Oregon, USA (Fig. 2). The Catlow Valley fault is a ca. 65 km long, north-south striking normal fault system (Fig. 3) that displaces lava flows associated with the 16.6 ± 0.02 Ma old Steens basalt (Hooper et al. 2002). The topographic expression of the fault system is a steep escarpment, up to several hundred meters high. It is made up of at least six linked segments; unfortunately there is no direct slip rate information on any of these segments. Fault chronology is not directly known but we bracket fault initiation to between 16.6 and approximately 10 Ma, using the age of the Steens basalt (Hooper et al. 2002) and the onset of Basin and Range extension in southeastern Oregon (Scarberry et al. 2010). A population of northwest striking faults, smaller in scale than the Catlow Valley segments, is present but do not appear to have any structural control over the Catlow segments. We interpret these faults as being related to the Brothers fault zone, which is a zone of distributed normal faults that are generally more pronounced northwest of Catlow Valley (Scarberry et al. 2010; Weldon et al. 2002).

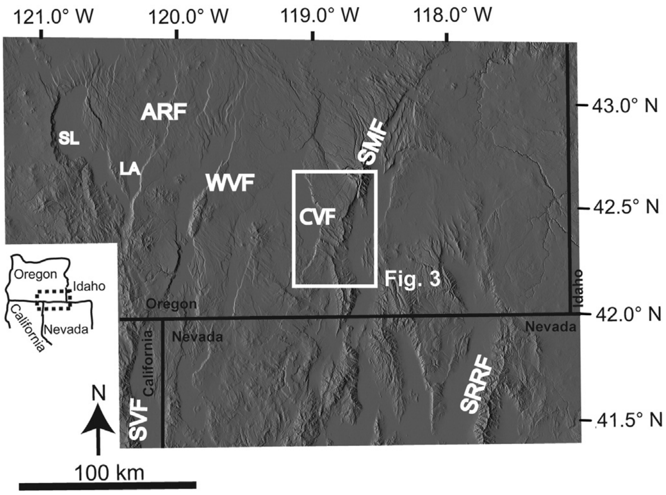

Fig. 2. Location of Catlow Valley fault and other major features within the northwestern Basin and Range, northwestern USA. Shaded relief map created from a U.S. Geological Survey National Elevation Dataset (NED) 30 m digital elevation model (DEM). ARF = Abert Rim fault, BFZ = Brothers fault zone, CVF = Catlow Valley fault, LA = Lake Abert, SL = Summer Lake, SMF = Steens Mountain fault, SRRF = Santa Rosa Range fault, SVF = Surprise Valley fault, WVF = Warner Valley fault.

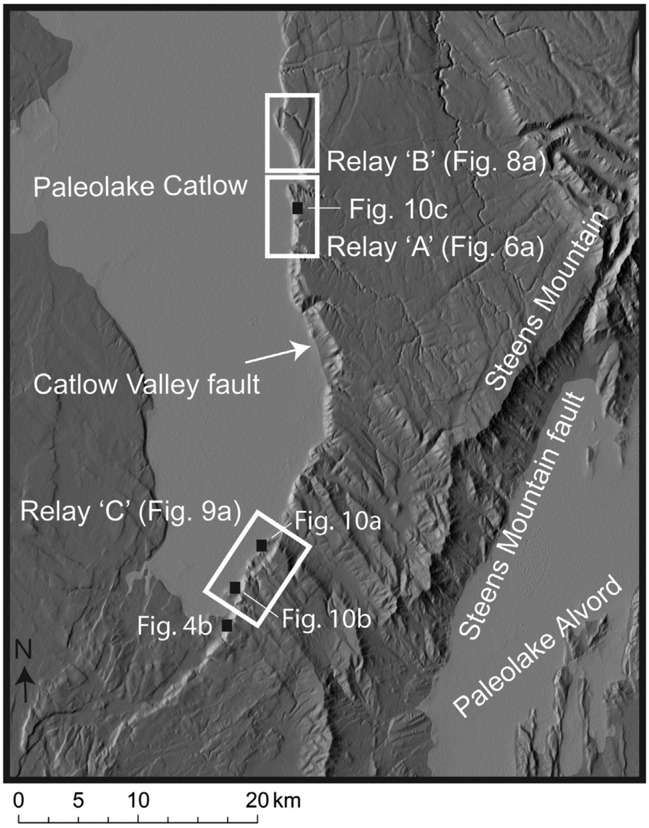

Fig. 3. Shaded relief map of Catlow Valley fault (based on the 10 m DEM), showing the maximum extent of Paleolakes Catlow and Alvord based on the highest late Pleistocene shorelines in the basins. The extent of Paleolake Alvord here is similar to previous interpretations of the late Pleistocene extent of that lake (Reheis, 1999; Reheis et al. 2014).

2.1. Paleolake Catlow and other Pleistocene Northwestern Basin and Range pluvial lakes

Pluvial lake shorelines are present along the Catlow Valley fault escarpment (Vander Meulen et al. 1988); as many as seven can be observed in some locations but not all are spatially extensive (Fig. 4). These shorelines are evidence that a substantial lake (10s of km in width and length and up to 50 m deep) once occupied Catlow Valley in the geologically recent past. The shorelines are prominent features along the Catlow escarpment (Fig. 4a), extending for 10s of km and are visible in aerial imagery and digital elevation models (DEMs). These terraces are likely associated with the ultimate regression of Paleolake Catlow. Little information exists on the paleolake and what work does exist only acknowledges the presence of shorelines