Active dextral strike-slip faulting records termination of the Walker Lane belt at the southern Cascade arc in the Klamath graben, Oregon, USA

Trevor S. Waldien1,*, Andrew J. Meigs1, and Ian P. Madin2
1College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331, USA
2Oregon Department of Geology and Mineral Industries, 800 NE Oregon Street, Suite 965, Portland, Oregon 97232, USA

■ ABSTRACT

Whether or not northward growth of the Walker Lane belt relates to northward motion of the Mendocino triple junction remains an open question in the study of western North American plate deformation. Uncertainty about the potential linkage arises from an incomplete understanding of how and where dextral transtension in the Walker Lane belt terminates on its northern end. To address this issue, we used bare-earth airborne light detection and ranging (LiDAR) topographic data to reveal the geomorphic record of active dextral transtensional deformation in the Klamath graben in the backarc of the southern Cascade arc, south-central Oregon, USA. Fault scarps in late Pleistocene glacial deposits indicate that at least 0.3 mm/yr of NW-SE dextral shear characterizes slip on the NW-striking Howard Bay fault system within the Klamath graben. Dextral slip on the Howard Bay fault is transferred northward into extension on N-striking normal faults within the Cascade arc. Thus, active faults in the Klamath graben mark the northern terminus of a dextral transtensional fault system spanning the southern Cascade backarc from Crater Lake southward to the northern Sierra Nevada. A review of published geologic slip rates throughout the region of the southern Cascade arc suggests that dextral slip from the Walker Lane belt is transferred both into contractional structures in the northern Sacramento Valley and transtensional structures in the southern ~200 km section of the Cascadia backarc. Termination of transtensional deformation into the southern Cascade arc suggests that the Walker Lane belt propagates independently of the Mendocino triple junction and that, instead, expansion of the Basin and Range Province plays a central role in development of the Walker Lane belt.

■ INTRODUCTION

Western North America evolved from an Andean-type convergent margin to a transform margin over the late Cenozoic (Atwater, 1970; Dickinson and Snyder, 1979). As the last remaining vestige of the Andean-type margin, the Cascadia subduction zone is being replaced with a transform boundary as the Mendocino triple junction migrates northward (Faulds et al., 2005). During the transformation, dextral strike-slip faulting within the San Andreas fault system and distributed dextral transtension in the Walker Lane belt propagate northward and structurally overprint regions previously within the subduction regime (Kelsey and Carver, 1988; Lock et al., 2006; Faulds and Henry, 2008). Although northward growth of the San Andreas fault system has been shown to be geodynamically linked to migration of the Mendocino triple junction and demise of the Cascadia subduction zone (Atwater, 1970; Furlong, 1984), whether or not the northward growth of the Walker Lane belt is also linked to migration of the triple junction remains unclear due to uncertainty in locating the northern termination of dextral transtensional shear (cf. Unruh et al., 2003; Faulds and Henry, 2008).

There are two end-member models proposed to describe the northern terminus of the Walker Lane belt. One model states that dextral slip in the Walker Lane belt is diverted westward across the northern Sierra Nevada and terminates into a series of shortening structures in the northern Sacramento Valley (Unruh et al., 2003; Sawyer, 2015; Langenheim et al., 2016). This first model links the northward growth of the Walker Lane belt to migration of the Mendocino triple junction and predicts a set of northward-younging shortening structures throughout the Sacramento Valley that have tracked the latitude of the triple junction through the Pliocene and Quaternary. Alternatively, the Walker Lane belt has been proposed to terminate into oblique extension in the southern Cascadia backarc (Blakey et al., 1997; Faulds and Henry, 2008; Oldow and Cashmen, 2009). This second model recognizes the continuous structural fabric spanning the Walker Lane belt and southern Cascadia backarc. In this second model, the Walker Lane belt propagates independently of the triple junction. In this study, we used bare-earth light detection and ranging (LiDAR) to provide new geologic and geomorphic evidence demonstrating that active dextral shear deforms the Cascadia backarc as far north as the Klamath graben. We argue that transtensional deformation from the Walker Lane belt reaches the Klamath graben. We combined our findings with data supporting each end-member model described above and created a new tectonic model that reconciles the two competing views on the northern termination of the Walker Lane belt.
ACTIVE TECTONICS IN THE SOUTHERN CASCADE BACKARC

Regional Deformation

Active faulting in the region of the southern Cascade arc results from interaction among the Juan de Fuca, Pacific, and North America plates. Four tectonic domains within the western margin of the North American plate accommodate the relative plate motion in this area. These domains are the Sierra Nevada microplate, the Siletzia block of the Cascadia forearc, the Walker Lane belt, and the Basin and Range extensional province (Fig. 1). The Sierra Nevada microplate translates to the northwest with respect to stable North America (Argus and Gordon, 1991; Wernicke and Snow, 1998). The San Andreas fault system bounds the Sierra Nevada microplate in the west, and the NW-striking Walker Lane belt forms the eastern boundary of the microplate. NW-SE-directed transtensional deformation east of the Sierra Nevada is partitioned into extension on N-striking normal faults of the Basin and Range Province and distributed dextral transtensional shear across the Walker Lane belt (Wallace, 1984). The distributed dextral faults, rotating blocks, and pull-apart basins within the Walker Lane belt accommodate ~20% of current Pacific–North America relative plate motion (Faulds and Henry, 2008; Hammond et al.,...
These graben-bounding fault systems change strike and structural style at the 7 Ma (Walker and Naslund, 1986; Hladky and Mertzman, 2002), yet much of the (Sherrod and Pickthorn, 1992; Braunmiller et al., 1995; Priest et al., 2013). Volcanic strata with alkaline geochemical signatures and angular unconformities in volcanic and clastic strata within the graben record extension as early as ca. 7 Ma (Walker and Naslund, 1986; Hladky and Mertzman, 2002), yet much of the modern Basin and Range–style topography may have formed after the middle Pliocene (Sherrod and Pickthorn, 1992; Priest et al., 2008, 2013). Fault systems bounding the basin control the modern topographic expression of the graben. These graben-bounding fault systems change strike and structural style at the latitude of Mount McLoughlin: Deformation in the southern domain of the graben is dominated by slip on NW-striking faults, whereas deformation in the northern domain of the graben is dominated by slip on N-striking faults (Fig. 2B).

**Southern Klamath Graben**

Deformation in the southern Klamath graben, south of Mount McLoughlin, is dominated by three NW-striking fault systems (Fig. 2B). From west to east, these fault systems are: the Lake of the Woods, West Klamath Lake, and East Klamath Lake fault zones.

The western limit of faulting in the southern Klamath graben is marked by a series of ≤100-m-high fault scarp s in the Lake of the Woods fault zone southwest of Aspen Butte. East of Aspen Butte, the West Klamath Lake fault zone manifests as an ~15-km-wide zone of generally NW-striking escarpments up to ~200 m high. Both fault systems cut Neogene–Pleistocene volcanic strata and surficial deposits (Smith, 1983; Priest et al., 2008). Measurements from exposed fault planes and seismicity from the 1993 Klamath Falls earthquake sequence show that NW-striking faults in the Lake of the Woods fault zone and West Klamath Lake fault zone generally dip ~40–70°NE and have predominantly dextral-normal oblique displacement (Sherrod and Pickthorn, 1992; Braunmiller et al., 1995; Sagy and Brodsky, 2009).

The East Klamath Lake fault zone marks the eastern limit of deformation in the southern Klamath graben. Escarpments with up to 500 m of topographic relief cut Neogene–Pleistocene volcanic and clastic strata north and east of the city of Klamath Falls, Oregon (Sherrod and Pickthorn, 1992). Exposed fault planes in this zone dip ~50°SW (Priest et al., 2008). Priest et al. (2013) reported an E-W extension rate of ~0.4–0.6 mm/yr across the Lake of the Woods fault zone, West Klamath Lake fault zone, and East Klamath Lake fault zone since the mid-late Pliocene, which is consistent with other slip rate estimates in the graben (Speth et al., 2018).

A system of steeply dipping faults deforms the center of the graben beneath the West Klamath Lake fault zone and East Klamath Lake fault zone. The orientation of the faults is not well known because they have only been observed in seismic reflection data (Colman et al., 2000; Liberty et al., 2009). However, Colman et al. (2000) suggested that the faults strike to the northwest and dip steeply (>60°). Hanging-wall-down separation of the Mazama ash indicates that the faults accommodate Holocene extension.

**Northern Klamath Graben**

Three N-striking fault systems define the northern Klamath graben from the latitude of Mount McLoughlin to Crater Lake. From west to east, these fault systems are: the Sky Lakes fault zone, West Klamath Lake fault zone, and East Klamath Lake fault zone.

A 12-km-wide zone of deformation consisting of the E-dipping Sky Lakes fault zone and West Klamath Lake fault zone intersects the Cascade arc between...
Figure 2. Maps showing the regional fault pattern and related physiography in the southern Cascadia backarc. (A) Hillshade map and Quaternary faults showing the regional fault pattern throughout the southern Cascadia backarc. The transition from N-striking to NW-striking faults generally correlates with the latitudes of major High Cascade stratovolcanoes. The idealized model of N-striking normal faults and NW-striking dextral faults presented by Blakely et al. (1997) is shown in the upper right. Abbreviations of Cascade volcanoes are the same as in Figure 1. (B) Shaded relief map of the Klamath graben. N- and NW-striking Quaternary-active faults define the Klamath graben in the southern Cascadia backarc. Locations of M >3.0 earthquakes from the 1993 Klamath Falls sequence (stars are main shocks; Xs are aftershocks) and locations of fault kinematic measurements (open circles; Figs. 5 and 6) are shown. Focal mechanisms for earthquakes discussed in the text are also shown (Braunmiller et al., 1995). WKLFZ—West Klamath Lake fault zone; EKLFZ—East Klamath Lake fault zone; LoWFZ—Lake of the Woods fault zone; SLFZ—Sky Lakes fault zone; HBF—Howard Bay fault; HB—Howard Bay. The areas of Figures 3 and 7 are outlined, and the outcrop locations for the photos in Figure 4 are indicated with arrows. EQ—earthquake.
Mount McLoughlin and Crater Lake and marks the western limit of deformation in the northern Klamath graben. Individual fault scarps in the Sky Lakes fault zone cut ≤300 ka Cascade arc lavas with up to ~160 m of vertical separation (Bacon et al., 1999). West Klamath Lake fault zone fault scarps display up to ~25 m of vertical separation in late Pleistocene glacial deposits (Hawkins et al., 1988; Speth et al., 2018). Focal mechanisms from the 1993 Klamath Falls earthquake sequence indicate that N-striking faults in the Lake of the Woods fault zone dip ~45° at seismicogenic depths of ~6–9 km and have predominantly normal slip kinematics (Braunmiller et al., 1995). Fault planes exposed at the surface dip ~60°–80° (Smith, 1983; Speth et al., 2018). Published late Pleistocene–Holocene slip rates for N-striking faults in the Sky Lakes and West Klamath Lake fault zones are ~0.3 mm/yr (vertical) and ~0.15–0.5 mm/yr (extension; Hawkins et al., 1988; Bacon et al., 1999; Speth et al., 2018).

An ~30-km-wide zone of distributed faulting in the East Klamath Lake fault zone marks the eastern margin of the northern Klamath graben (Figs. 1 and 2). In this zone, W-dipping bedrock fault scarps with up to 350 m of vertical separation dissect Neogene volcanic and volcaniclastic strata (Sherrod and Pickthorn, 1992), but they have not been demonstrably shown to have Quaternary slip. Using a whole-rock K-Ar age of ca. 2.8 Ma (lava flow age #3; Sherrod and Pickthorn, 1992) and a nearby 260-m-tall scarp cutting the dated lava flow, we calculated a late Pliocene–recent minimum vertical slip rate of ~0.09 mm/yr for individual N-striking faults in the East Klamath Lake fault zone. Assuming the fault scarps were formed by slip on planar faults that dip 45°–60°W, the minimum extension rate for the East Klamath Lake fault zone would be 0.05–0.09 mm/yr.

Methods

Bedrock Fault Analysis

Our bedrock fault slip data set consists of the strike, dip, rake (angle between strike line and striation contained within the fault plane), and hanging-wall transport direction of exposed fault planes at 31 sites in the southern Klamath graben. We used fault strike and dip direction to break the data set into separate populations for structural analysis on a stereonet. These data form the basis of our estimate of the late Miocene–present extension direction across the graben.

Geomorphic Fault Analysis

New kinematic data for Quaternary faults in the Klamath graben were developed from digital elevation models (DEMs) derived from 1-m-resolution airborne LiDAR. The Oregon Department of Geology and Mineral Industries and the Oregon LiDAR Consortium collected and processed the LiDAR data to create a bare-earth DEM. We used the resulting DEM to map an ~25 km² area in the interior of the graben (Fig. 3). Due to thick vegetation, fault scarps and correlative geomorphic features across faults are more accurately mapped remotely using oblique-illumination hillshade, slope, and aspect maps derived from the LiDAR DEM. Accordingly, the LiDAR DEM reveals the vertical and lateral separation of geomorphic features across faults at the submeter scale. Lateral separation across faults in our map area is expressed as offset stream channels and channel walls.

We used LaDiCaoz_v2 (Zielke and Arrowsmith, 2012; Haddon et al., 2016) to identify correlative geomorphic features across the fault scarps, restore slip on the faults, and measure the amount of vertical and horizontal separation recorded by the offset landforms. Using the “backslip” feature in LadiCaoz_v2, we visually inspected the quality of the restoration to iteratively determine the optimal magnitude of vertical and lateral separation (see Zielke and Arrowsmith, 2012). We estimated the uncertainty of the measurements by iteratively restoring the fault and visually inspecting the restorations to determine a permissible minimum and maximum separation of the offset landforms. Supplemental File 1 contains PDFs from LaDiCaoz with back-slipped images of optimal, minimum, and maximum restorations. Combining the inferred fault dip with measurements of lateral and vertical separation of offset landforms yielded the slip vector for faults at three sites within our map area. Vertical separation of the alluvial-fan surface at each site was measured from topographic profiles across the fault scarps extracted from the LiDAR DEM. Uncertainty in the vertical separation was taken as the difference in vertical separation measured at the base and top of the fault scarp. We used the calculated slip vector along with published geochronology to calculate a late Pleistocene–Holocene slip rate for the three sites.

Results

Bedrock Fault Kinematics

Kinematic indicators from bedrock fault planes in the southern Klamath graben show primarily dip-slip motion on both NW- and N-striking faults. Northwest-striking bedrock faults display oblique normal-dextral kinematics (Figs. 4A and 5A), whereas N-striking faults have predominantly normal slip (Figs. 4B and 5B). Striae on E- and NE-dipping fault planes have an average orientation of 120°/60°SE (Fig. 5D). Striae on W- and SW-dipping fault planes have an average orientation of 260°/55°W (Fig. 5D). Because all fault plane measurements record a hanging-wall-down slip sense, the bedrock fault kinematic data indicate that both N-striking and NW-striking faults in the southern Klamath graben facilitate extension of the graben.

Kinematic Analysis of Fault Scarps

Mapping, Stratigraphy, and Age of Quaternary Deposits

New geologic and geomorphic mapping of an ~25 km² area in the interior of the Klamath graben (Fig. 3) provides a record of active dextral faulting in
Figure 3. Geomorphic and geologic maps of the northern tip of the Howard Bay fault. (A) Bare earth light detection and ranging (LiDAR) hillshade image of the map area. Note the distinct generations of glacial moraines, and that bar-and-swale fan surface morphology in the north (Qf2) is better developed than the southern (older; Qf3) portion of the alluvial-fan complex. (B) Hillshade map from A overlain by principal surficial and bedrock units. Mapping has been substantially modified from original mapping in the area by Carver (1972) and Sherrod and Pickthorn (1992).
the graben. There are three key relationships expressed in the map: (1) A set of glacial moraines progrades into an alluvial-fan complex, (2) the alluvial-fan complex is cut by a set of NW-striking scarps, and (3) the scarps decrease in size and quantity to the northwest where the alluvial-fan complex is younger.

We used a chronology based on regional correlation of glacial deposits and surface exposure ages to infer absolute ages of our map units. Carver (1972) identified at least six generations of glacial deposits in the Mountain Lakes Wilderness (Aspen Butte) west of our map area and used clast weathering and deposit morphology to determine a relative age chronology for the glacial deposits. Lateral moraines belonging to three of the six generations of glacial deposits are present within our map area (Fig. 3; Carver, 1972). These moraines are the: Moss Creek till (oldest), Varney Creek till (intermediate), and Waban till (youngest). The high resolution of the LiDAR base map allowed us to use landform morphology to refine the contact locations between these glacial deposits. Speth et al. (2018) used glacial landform morphology, weathering characteristics, and crosscutting relationships to correlate three generations of glacial deposits in the Sevenmile Creek, Cherry Creek, and Dry Creek areas north of Aspen Buttes to the Moss Creek, Varney Creek, and Waban glacial deposits identified by Carver (1972). Speth et al. (2018) used surface exposure age dating to determine absolute ages for the three moraine generations: 17.6 ± 2.6 ka (Waban till), 97.6 ± 12.7 ka (Varney Creek till), and ca. 190–130 ka (Moss Creek till). Assuming that the moraine sequences at Aspen Butte, Sevenmile Creek, Dry Creek, Cherry Creek, and our study area record the same advances, our Qwg, Qvm, and Qmm map units correlate with the 17.6 ± 2.6 ka Waban till (Qwg), the 97.6 ± 12.7 ka Varney Creek till (Qvm), and the ca. 190–130 ka Moss Creek till (Qmm).

A composite alluvial-fan complex in our study area appears to record glacial outwash phases contemporaneous with the lateral moraine sets. High-amplitude bar-and-swale topography and proximity to an active stream suggest the fan surface is younger in the north than in the south (Fig. 3). Poorly preserved bar-and-swale topography on the southern part of the alluvial fan (QIS) appears to be inset into the Moss Creek-aged moraines but interferes with the Varney Creek-aged moraines (Fig. 3B). These map relationships, combined with
the age assignments for the Moss Creek and Varney Creek moraine deposits, bracket the age of the Qf3 deposit to ca. 190–98 ka.

Well-preserved bar-and-swale topography characterizes the northern part of the alluvial-fan complex (Qf2), which overlies the Varney Creek-aged moraines (Fig. 3B). An alluvial fan at Cherry Creek to the north has a similar surface texture as our Qf2 map unit and yielded a surface exposure age of 20.4 ± 5.3 ka (Speth et al., 2018). This age is within uncertainty of the 17.6 ± 2.6 ka Waban moraine set and a ca. 18 ka massive influx of glacial flour to Upper Klamath Lake, which implies that local Cascade Range glaciers were receding at that time (Rosenbaum and Reynolds, 2004). Because the Waban moraines and influx of glacial flour both yield ages of ca. 18 ka, we assigned an age of 18 ka to the Qf2 fan deposit.

**Fault Slip Measurements from Offset Landforms**

Northwest-striking scarps cut the Qf3 and Qf2 alluvial-fan deposits in the map area. The scarps in the alluvial-fan complex are continuous for several hundred meters and display a right-stepping pattern (Fig. 3). The scarps are more sparsely distributed and display less topographic separation in the northwest, where the alluvial-fan complex is younger. Hillshade and slope maps constructed from the LiDAR DEM reveal three right-deflected stream channels inset into the Qf3 alluvial-fan surface. Because the stream deflections are coincident with down-to-the-northeast topographic scarps in the alluvial-fan surface, we interpreted the scarps and stream deflections as offsets due to fault slip. We refer to this fault as the Howard Bay fault, and we used the deflected streams to determine the kinematics of the fault at three locations within the Qf3 deposit.

Two fault strands offset an active stream channel at site A (Fig. 6). The western fault strand offsets both the active thalweg and the SE-facing channel wall. Reconstructing the channel with the “backslipping” tool in LaDiCaoz resulted in 6 ±5/–4 m of dextral separation and no vertical separation across the western fault strand. Although the eastern fault strand lacks clear evidence of lateral offset of the active thalweg, a linear, subtly NW-facing slope terminates into the fault scarp southeast of the active channel. This lineament is likely the displaced NW-facing channel wall for the stream prior to incision of the active channel. Restoration of the NW-facing channel wall on the eastern fault strand using LaDiCaoz resulted in 38 ±7/–6 m of dextral separation and 1 m of vertical separation. The Qf3 fan surface has 11.5 ± 0.3 m of vertical separation summed across both scarps at site A (Fig. 7).

Site B displays a high-quality example of a right-laterally offset stream channel, where both the SE-facing channel wall and active thalweg are offset (Fig. 6). Restoration of the SE-facing channel wall using LaDiCaoz yielded 36 ± 4 m of dextral separation and ~5.5 m of vertical separation across the fault scarp. The lateral separation recorded by the offset channel wall likely underestimates the true lateral separation due to erosion along the channel wall east of the fault by the active stream. Vertical separation of the Qf3 alluvial-fan surface is 9.4 ± 0.8 m across fault scarps at site B (Fig. 7).

As is the case for site A, site C does not exhibit clear evidence of lateral offset of an active stream channel. Nonetheless, intersection of a linear NW-facing slope with the scarp does suggest truncation due to faulting. Interpreting this linear slope as the displaced NW-facing channel wall yielded 56 ±9/–6 m of dextral separation and ~2 m of vertical separation at site C after restoration with LaDiCaoz (Fig. 6). The Qf3 alluvial-fan surface displays 13.6 ± 0.5 m of vertical separation across the fault scarps at site C (Fig. 7).

In addition to the measurements of vertical and lateral separation, the orientation of the Howard Bay fault is required to fit the fault into the structural framework for the Klamath graben. Fault scarps at sites A–C strike ~320°, but the fault dip cannot be determined from the scarps alone. Strike-slip aftershocks from the 1993 Klamath Falls earthquake sequence plot along the projected trace of the Howard Bay fault and have a nodal plane that also strikes ~320°. The strike-slip aftershocks have been interpreted to record slip on a plane dipping steeply to the southwest (Braunmiller et al., 1995; Cridel et al., 2001). A southwesterly dip seems unlikely for the section of the Howard Bay fault at sites A–C because the SW-side-up component of slip expressed in the Qf3 alluvial-fan surface (Fig. 7) would require a component of convergence. Instead, a vertical or steeply NE-dipping fault plane could allow for a component of extension and thus seems more probable for the Howard Bay fault at sites A–C. Given these constraints, we infer that the fault scarps in the alluvial-fan complex record slip on a fault oriented at 320/80°NE.

**Dextral Slip Rates**

We combined the lateral slip measurements from sites A–C and the inferred age of the Qf3 alluvial-fan surface to calculate a strike-slip rate for the Howard Bay fault since the late Pleistocene. Sites A–C are suitable to calculate a slip rate because: (1) the channels are incised into the Qf3 deposit and therefore likely formed after fan surface abandonment; (2) similar magnitudes of lateral separation at sites A–C suggest the channels were incised as offset accumulated on the Howard Bay fault; and (3) the magnitudes of the vertical and horizontal offsets measured from the LiDAR DEM require that the separation of landforms accumulated over multiple surface-rupturing earthquakes. The extension rate on the Howard Bay fault is negligible due to the probable steep dip for the fault as revealed by seismicity (Braunmiller et al., 1995). Similarly, the landform restorations (Fig. 6) suggest the stream channels and channel walls record limited vertical separation, despite the observation that the cumulative topographic relief across the scarps is ~10 m (Fig. 7). Thus, the lateral component of slip represents nearly the entire fault slip vector between the offset landforms (Fig. 5C).

Coupling the measurements of lateral separation with a 190–84.9 ka age (total range in ages of bracketing deposits) for the Qf3 surface yields site-specific oblique slip rates of 0.4 ± 0.2 mm/yr (site A), 0.3 ± 0.2 mm/yr, (site B), and 0.5 ± 0.3 mm/yr (site C). Taking the average of the three sites yields an oblique rate of 0.4 ± 0.1 (1σ) mm/yr for the Howard Bay fault. Given that the highest-quality
Figure 6. Hillshade maps and landform reconstructions at sites A–C (Fig. 3). (Left) Hillshade maps of each site marked with a fault (cyan line), and two fault-parallel topographic profiles (red and blue lines) across the offset landform intended for restoration. Yellow arrows indicate the landform used for each restoration. Profile lines for Figure 7 are shown. (Center) Fault-parallel profiles (red and blue profiles) showing the offset landforms that are restored by matching the shape of the profiles. Arrows indicate the part of the profile that was used for reconstruction. (Right) Images of “backslipped” fault offset using optimal values determined by matching the fault-parallel profiles. Note that the hillshade maps for each site are at slightly different scales.
offset of the three sites is the SE-facing channel wall offset preserved at site B, the overlap between the site-specific rates, and the likelihood that the offset channels formed following abandonment of the fan surface, we suggest that the 0.3 ± 0.2 mm/yr dextral slip rate at site B is the most representative rate and is a minimum.

**North-Striking Normal Faults**

In addition to the dominant NW-trending structural fabric, the southern Klamath graben also contains a set of N-striking fault scarps (Fig. 8). The N-striking faults appear to be restricted to the West Klamath Lake fault zone in the southern domain of the graben, near the projected trace of the Howard Bay fault. The faults cut SW-dipping tilt blocks comprising late Miocene and Pliocene basalt flows (Sherrod and Pickthorn, 1992). Fault throw on the N-striking fault set is equal to or less than throw on the NW-striking faults. The NW-striking and N-striking faults in the West Klamath Lake fault zone display multiple structural relationships. In some locations, the fault sets form a continuous topographic escarpment that marks the change in fault strike. Elsewhere, the fault sets appear to link, or the N-striking faults cut the NW-striking faults (Fig. 8C). Distinguishing between the crosscutting and linking fault relationship is complicated by the observation that lake sediments commonly bury the hanging walls of NW-striking faults (Fig. 8B). Such burial makes it unclear if the N-striking faults are restricted to the footwall blocks of NW-striking faults or if the N-striking faults cut completely through both fault blocks. The down-to-the-east separation across the N-striking faults records primarily normal slip, which is consistent with other N-striking faults in the Klamath graben.

**DISCUSSION**

**Kinematics and Timing of Deformation in the Southern Cascadia Backarc**

**Klamath Graben**

Kinematically linked sets of N- and NW-striking faults characterize active deformation in the Klamath graben (Fig. 2). Bedrock kinematic indicators and earthquake focal mechanisms show that N-striking structures have primarily normal dip-slip motion. Dextral-normal oblique slip occurs on NW-striking faults (Fig. 5; Braunmiller et al., 1995). Regionally, E-W extension initiated at ca. 7 Ma (Walker and Naslund, 1986; Hladky and Mertzman, 2002) and was under way in the Klamath graben by ca. 4 Ma (Priest et al., 2013). Multiple-event fault scarps in late Pleistocene glacial deposits and historic seismicity indicate that active normal faulting is concentrated in the west and is distributed between the Lake of the Woods fault zone, Sky Lakes fault zone, and West Klamath Lake fault zone (Hawkins et al., 1989; Braunmiller et al., 1995; Speth et al., 2018). The extension direction inferred from historic seismicity is consistent with that given by bedrock fault data (Fig. 5), which implies that the extension direction and structural style of faulting have varied little as the graben developed. Seismic reflection data also reveal steeply dipping faults with normal separation of Holocene strata in the graben center beneath Klamath Lake (Colman et al., 2000; Liberty et al., 2009). Although they dip steeply, only normal separation is documented for these faults.
Figure 8. (A) Hillshade map of the West Klamath Lake fault zone and Howard Bay fault (HBF; red line) in the southern Klamath graben emphasizing the presence of N-striking fault scarps (yellow lines). Inset in the upper right shows that the NW-striking Howard Bay fault and N-striking normal faults are compatible with a dextral shear deformation regime (inset; see Sylvester, 1988). (B) Several N-striking normal faults have an ambiguous relationship with NW-striking oblique faults in the West Klamath Lake fault zone because lake sediments bury the hanging walls of several NW-striking faults. (C) One location south of the projected trace of the Howard Bay fault clearly shows a N-striking normal fault cutting a NW-striking oblique fault.
Data presented here provide the first geological evidence for dextral faulting in the Klamath graben. Reconstructions of landforms offset by the Howard Bay fault are consistent with historic seismicity (Crider et al., 2001) showing that strike-slip deformation accompanied late Pleistocene–present extension within the Klamath graben. Although extension in the graben has been ongoing since at least the Pliocene (Priest et al., 2013), evidence of strike-slip faulting at that time is unknown. Yet, the landform reconstructions across the Howard Bay fault and inferred ages of the alluvial-fan deposits cut by the fault indicate that dextral faults were deforming the interior of the graben by the late Pleistocene.

North-striking normal faults in the West Klamath Lake fault zone appear to be structurally associated with the Howard Bay fault. The N-striking normal faults in the southern domain of the graben are kinematically compatible with a deformation regime dominated by NW-SE dextral shear (Fig. 8A; Sylvester, 1988). The clear example of a N-striking fault offsetting a NW-striking fault in the West Klamath Lake fault zone (Fig. 8C) yields the possibility that at least some of the N-striking faults are younger and thus may have developed in concert with dextral slip on the Howard Bay fault after the NW-striking oblique faults were established. The Howard Bay fault projects northwestward to the southern tip of the Sky Lakes fault zone and West Klamath Lake fault zone in the northern Klamath graben. Because these fault systems display the strongest evidence for Holocene surface rupture in the graben, we infer that NW-SE dextral shear on the Howard Bay fault is transferred into E-W extension in the Sky Lakes fault zone and West Klamath Lake fault zone north of Mount McLoughlin. Speth et al. (2018) observed an increase in the slip rate of the northern West Klamath Lake fault zone dated at ca. 100 ka, which they suggested could have been related to volcanic processes. Given the similarity in post–ca. 100 ka slip rates (~0.3 mm/yr) between the Howard Bay fault and the northern West Klamath Lake fault zone and the potential development of the Howard Bay fault system in the Pleistocene, it seems equally possible that the slip rate increase in the West Klamath Lake fault zone could have related to initial linkage with the Howard Bay fault. Together, the West Klamath Lake fault zone and Howard Bay fault account for ~0.3 mm/yr of late Pleistocene–Holocene WNW–ESE oblique extension in the Klamath graben. This rate is a minimum and underestimates the regional rate because it does not account for Quaternary slip on faults in the Sky Lakes fault zone, East Klamath Lake fault zone, or near the graben axis beneath Klamath Lake.

Modoc Plateau

To the south, faulting throughout the Modoc Plateau displays characteristics similar to the Klamath graben. The Pliocene–Quaternary structural fabric of the Modoc Plateau is characterized by normal slip on approximately N-striking faults and oblique slip on NW-striking faults, which accommodate NW-SE dextral transtension throughout the region (Fig. 2A; Blakely et al., 1997; McCaffrey et al., 2013). Although fault slip studies indicate primarily normal slip on faults in the Modoc Plateau (White and Crider, 2006; Kattenhorn et al., 2016), seismicity indicates that NW–SE-oriented dextral transcurrent or transtensional deformation regimes characterize a significant portion of the region (Unruh and Humphrey, 2017). Moreover, the Likely fault and Eagle Lake faults are regional NW-striking structures in the Modoc Plateau with demonstrable Pleistocene dextral displacement (Pease, 1969; Sawyer and Bryant, 1995; Colie, 2003). Whereas normal separation across faults is well represented by regional topography, the relative magnitudes and loci of strike-slip faulting are less well understood. Factors that may obscure the signal of dextral shear in the southern Cascadia backarc include: (1) the low strike-slip rates; (2) topographic resurfacing by sedimentary and volcanic processes; (3) locations of strike-slip faults beneath lakes within grabens; and (4) the potentially recent onset of strike-slip deformation in the region (Faulds and Henry, 2008).

Termination of the Walker Lane Belt in the Klamath Graben

Coexistence of active normal, oblique, and dextral faults as seen in the southern Cascadia backarc also characterizes deformation in the Walker Lane belt to the south of Lassen Peak (e.g., Wallace, 1984; Faulds and Henry, 2008). Active dextral faults in the Walker Lane belt are commonly present in structural lows in the interiors of established grabens (Henry et al., 2007; Dong et al., 2014; Eisses et al., 2015). In some places, extension continued after strike-slip deformation initiated (slip partitioning; Walker et al., 2005; Dong et al., 2014; Eisses et al., 2015). Elsewhere, extension predated strike-slip faulting (Henry et al., 2007). Dextral slip on the Likely and Eagle Lake faults north of Lassen Peak in the Modoc Plateau, for example, appears to crosscut extended regions and link zones of generally N-striking normal faults (Fig. 9). Although the absolute timing of initial strike-slip faulting is not well known, seismicity (Unruh and Humphrey, 2017) and geomorphic evidence (Gray et al., 2017) display clear coexistence among active dextral, normal, and oblique faults in the Modoc Plateau. In the Klamath graben, dextral slip on the Howard Bay fault deforms the interior of the graben (Fig. 2B) and likely initiated after the graben developed. Both active tectonic evidence (Liberty et al., 2009; Speth et al., 2018; this study) and seismicity (Braunmiller et al., 1995; Crider et al., 2001) show that dextral, oblique, and normal faults in the graben have been active in the Quaternary. Thus, the observations of structural style and deformation regime throughout the southern Cascadia backarc match observations from the Walker Lane belt.

Dextral transtension throughout the Walker Lane belt and southern Cascadia backarc is linked to the motion of neighboring crustal blocks within western North America. South of the latitude of the Mendocino triple junction, northwestern migration of the Sierra Nevada microplate and extension in the Basin and Range Province result in a zone of dextral transtension along the eastern margin of the microplate (Unruh et al., 2003). Northwestward motion of the Sierra Nevada microplate is transferred through the Klamath Mountains into clockwise rotation of the Siletzia block in the Cascadia forearc.
Figure 9. Hillshade and active fault map of the southern Cascadia arc, backarc, northern Sierra Nevada, and northern Walker Lane belt. Latest Pleistocene–Holocene dextral (ellipses), contraction, and extension (rectangles with arrows) rates in mm/yr are shown for major structures. Long-term (longer than ~15 k.y.) slip rates are indicated by an asterisk (*). Fault traces are from the U.S. Geological Survey Quaternary fault database, except for those added to the map (dashed). Physiographic features: KG—Klamath graben; TL—Tule Lake. Cascade stratovolcanoes are the same as in Figure 1. Geologic features: HBF—Howard Bay fault; LF— Likely fault; SVF—Surprise Valley fault; HCF—Hat Creek fault; ELF—Eagle Lake fault; PLF—Pyramid Lake fault; WSF—Warm Springs Valley fault; HLF—Honey Lake fault; MVF—Mohawk Valley fault; GVF—Grizzly Valley fault; SN-CRBZ—Sierra Nevada–Cascade Range boundary zone; ICFB—Inks Creek fold belt; BCF—Battle Creek fault. Slip rate sources: A—Speth et al. (2018); B—Sawyer and Bryant (1995); C—Personius et al. (2009); D—Blakeslee and Kattenhorn (2013); E—Hammond and Thatcher (2005); F—Sawyer (2015); G—Sawyer et al. (2013); H—Gold et al. (2014); I—Gold et al. (2017); J—Gold et al. (2013a); K—Angster et al. (2016). lit.—literature.
north of Mendocino triple junction (Fig. 1; Wells et al., 1998; Savage and Wells, 2015). As the result of the forearc rotation, deformation in the Cascadia backarc transitions from convergence in the north to oblique extension in the south (McCaffrey et al., 2013). N- and NW-striking faults defining the western limit of deformation in the southern Cascadia backarc strike oblique to forearc motion (Fig. 1) and thus serve as a transtensional breakaway zone between the rotating forearc and the backarc. The zone of backarc transtensional deformation continues as far north as the Klamath graben, where N-striking graben-bounding faults in the northern domain of the graben are partially buried beneath the southern flank of the Crater Lake volcano. North of Crater Lake, N-striking normal faults define the breakaway fault system within and west of the High Cascade stratovolcanoes (Smith et al., 1987; Keach et al., 1989; Bacon et al., 1999). Geodetic velocity vectors from Crater Lake northward nearly parallel the Walker Lane Belt (Smith et al., 1987; Conrey et al., 2002).

In the Klamath graben and south, the Cascade arc axis lies in the footwall of the E-dipping oblique breakaway fault system. The arc thus moves with the forearc block. To the north, the arc volcanoes are localized on faults that mark the breakaway (Fig. 1). The subtle westward deflection of the southern Cascade arc axis south of Crater Lake may have partially developed due to clockwise forearc rotation and the position of the arc axis west of the backarc oblique breakaway (Wells and McCaffrey, 2013).

Deformation Style and Rates at the Northern Termination of the Walker Lane Belt

Dextral faulting related to the Walker Lane belt has been variably argued to terminate into contractional structures in the northern Sacramento Valley or to continue north of the Mendocino triple junction into the southern Cascadia backarc.

The first end-member model argues that dextral slip from the Walker Lane belt is absorbed by shortening in the Inks Creek fold belt at the latitude of the Mendocino triple junction (e.g., Unruh et al., 2003). The Inks Creek fold belt is a Quaternary-active system of NE-striking blind thrust faults and associated folds in the northern Sacramento Valley (Fig. 9; Harwood and Helley, 1987; Angster et al., 2015). In this model, all of the dextral slip from the Walker Lane belt is transferred across the northern Sierra Nevada to the Inks Creek fold belt via the Sierra Nevada–Cascade Range boundary zone, a series of young and discontinuous dextral faults in the northern Sierra Nevada south of Lassen Peak (Fig. 9; Sawyer, 2015). The model implicitly requires strong geodynamic linkages among motion of the Sierra Nevada microplate, location of the Mendocino triple junction, and the northern termination of the Walker Lane belt.

The model favoring termination of the Walker Lane belt into the Inks Creek fold belt, however, fails to account for the distributed dextral transtension in the southern Cascadia backarc. Thus, a second option for the northern termination of the Walker Lane belt proposes that dextral shear is transferred into oblique extension in the Cascadia backarc (Faulds and Henry, 2008). This model calls upon the identical structural style and deformation characteristics between the two regions and does not assume strong linkages among Sierra Nevada microplate motion, Mendocino triple junction location, and Walker Lane belt deformation. In this view, the Walker Lane belt evolves independently of the Mendocino triple junction and Sierra Nevada microplate by accommodating dextral transtension between the Basin and Range in the east and the Sierra Nevada and Siletzia crustal blocks to the west.

A compilation of late Pleistocene–Holocene slip rates from the northern domain of the Walker Lane belt, southern Cascadia backarc, and northern Sacramento Valley (Fig. 9) shows how active deformation transitions from the strike-slip margin to the Cascadia subduction margin. Using the nomenclature of Faulds and Henry (2008), the northern domain of the Walker Lane belt comprises a set of NW-striking dextral faults at approximately the latitude of the Mendocino triple junction in eastern Nevada. From east to west, faults in the northern domain of the Walker Lane belt are: the Pyramid Lake, Warm Springs Valley, Honey Lake, and Mohawk Valley faults. Published latest Pleistocene–Holocene dextral slip rates for these faults (Fig. 9) are: Pyramid Lake fault = 0.5–1.6 mm/yr (Angster et al., 2016), Warms Springs Valley fault = 0.2 mm/yr (Gold et al., 2013a), Honey Lake fault = 1.4–1.9 mm/yr (Gold et al., 2017), Mohawk Valley fault = 0.3 mm/yr (Gold et al., 2014). Other faults in the region with documented Quaternary dextral slip, but lacking published slip rates, include the Eagle Lake fault (Colie, 2003) and Grizzly Valley fault (Gold et al., 2013b). Assuming the Mohawk Valley fault slips no faster than 1 mm/yr and the Warm Springs Valley fault slips no slower than 0.1 mm/yr during the Holocene, the published geologic data afford a latest Pleistocene–Holocene dextral slip rate of ~2.3–4.7 mm/yr summed across the northern domain of the Walker Lane belt (see Fig. 9). This sum of dextral slip rate does not account for additional slip on the Eagle Lake fault, Grizzly Valley fault, unidentified faults, or distributed dextral shear and thus underestimates the ~7 mm/yr of dextral shear across the region indicated by geodetic measurements (Hammond et al., 2011; see discussion in Gold et al., 2014).

The summary of fault slip rates suggests that an appropriate tectonic model describing the northern termination of Walker Lane belt requires both shortening in the northern Sacramento Valley and dextral shear in the southern Cascadia backarc (Fig. 9). From the northern Walker Lane belt, >2.5 mm/yr (long-term rate since ca. 1.4 Ma) of dextral shear is routed across the northern Sierra Nevada via the Sierra Nevada–Cascade Range boundary zone and transferred into shortening in the Inks Creek fold belt (Sawyer, 2015). This long-term rate for the Sierra Nevada–Cascade Range boundary zone is consistent with the geodetic
shortening rate of 2.5 ± 1.5 mm/yr in the Inks Creek fold belt (Hammond and Thatcher, 2005), but it may not account for all of the dextral slip summed across the northern domain of the Walker Lane belt. Moreover, strike-slip seismicity (Crider et al., 2001; Unruh and Humphrey, 2017) and geomorphic evidence for oblique and strike-slip deformation (Gray et al., 2017; this study) require that a portion of the dextral slip from faults in the northern domain of the Walker Lane belt must be transferred into the southern Cascadia backarc. Although slip rates are not well known for most faults in the Modoc Plateau, a conservative summation of slip on the Likely, Hat Creek, and unnamed distributed faults results in ≥1 mm/yr of dextral shear across the region. The data presented herein reveal that at least 0.3 mm/yr of dextral shear is present on the Howard Bay fault and other NW-striking oblique faults in the Klamath graben, which is transferred into extension on N-striking normal faults within the Cascade arc to the north. The diffuse faulting at the northern tip of the Walker Lane belt may variably reflect: (1) poor organization due to the incipient nature of the fault system (e.g., Wesnousky, 2005; Faulds and Henry, 2008); (2) the style of Neogene–Quaternary faulting at the northern tip of the Walker Lane belt that is largely controlled by basement crustal structure inherited from pre-Cenozoic terrane accretion (e.g., Blakely et al., 1997; Langenheim et al., 2016); (3) landscape evolution wherein resurfacing due to volcanism outpaces the development of structurally controlled topography; and/or (4) regional oblique extension that is accommodated primarily by magmatism (Parsons and Thompson, 1991).

Active dextral transtension and termination of the Walker Lane belt in the Cascadia backarc suggest that the latitude of the Mendocino triple junction and the northern termination of the Walker Lane belt are not strongly linked. The continuity in structural style and deformation kinematics between fault systems east of the Sierra Nevada microplate and those in the southern Cascadia backarc shows that transtensional Walker Lane–style deformation is present at a latitude ~200 km north of the triple junction (Fig. 10). Although the Walker Lane belt and Mendocino triple junction are both migrating northward (Faulds and Henry, 2008; Busby, 2013), our integrated model argues that the Walker Lane belt is propagating independently of the triple junction. This conclusion supports the probable recent development of the Sierra Nevada–Cascade Range boundary zone and Inks Creek fold belt at the latitude of the triple junction.
The geomorphic expression of active normal faulting in the Klamath graben suggests that historic seismicity underrepresents the earthquake hazard in the southern Cascadia backarc. In September 1993, two Mw 6.0 earthquakes struck the Klamath Falls area (Wiley et al., 1993). Although no surface rupture was identified, the earthquakes were attributed to the Lake of the Woods fault zone (Braunmiller et al., 1995; Dreger et al., 1995). Aftershocks from the 1993 Klamath Falls earthquake sequence showed predominantly normal focal mechanisms, except for a cluster of strike-slip events to the southeast of the main shocks (Fig. 2; Braunmiller et al., 1995; Crider et al., 2001).

The evidence for strike-slip surface rupture on the Howard Bay fault makes it a candidate structure for the sequence of late strike-slip aftershocks in the 1993 events (Fig. 2). Crider et al. (2001) favored a steeply SW-dipping fault as the slip plane for the strike-slip aftershocks. Given the hypocenter depths of ~6 km and epicenters ~2–8 km south of Howard Bay, the cluster of strike-slip aftershocks appears to fall on the projected trace of the Howard Bay fault if it dips to the southwest at that locale. However, ~15 km to the northwest, Howard Bay fault scarps at sites A–C have consistent SW-side-up separation where they cut the proglacial alluvial-fan complex (Figs. 3 and 7). If the fault plane cutting the fan dips to the southwest, the SW-side-up separation recorded by scarps at sites A–C would require a component of reverse slip. Since the Neogene–recent deformation of the Klamath graben is dominated by extension and dextral slip, it seems unlikely that the northern section of the Howard Bay fault dips to the southwest. Therefore, we infer that the Howard Bay fault changes dip direction along strike between the eastern flank of Aspen Buttes and the location of the 1993 strike-slip aftershock cluster.

The 1993 main shocks appeared to be segmented normal fault events; the first ruptured a patch of a NW-striking fault in the southern domain, and the second event ruptured a patch of a N-striking fault in the northern domain of the graben (Braunmiller et al., 1995; Crider et al., 2001). Fault segmentation is argued as the reason that the Klamath Falls earthquakes ruptured as two Mw 6.0 events rather than a single Mw 6.2 event (Braunmiller et al., 1995; Dreger et al., 1995). Importantly, neither event is known to have produced a surface rupture, nor did the faults rupture in a single, presumably larger, event through the change in fault strike. However, the surface expression of active faults in the Klamath graben strongly implies continuity between N- and NW-striking fault scarps (Fig. 2). Moreover, the clear surface expression of both normal and dextral faults suggests that coseismic linkage between variably oriented faults likely occurred during past earthquakes. Coseismic linkage between faults of different strike implies that faults in the graben are capable of producing surface-rupturing earthquakes larger than Mw ~6.2 (Wells and Coppersmith, 1994; Braunmiller et al., 1995). Seismic reflection data reveal multiple-event faults and growth strata in un lithified Holocene strata beneath Klamath Lake in the southern domain of the graben (Colman et al., 2000; Liberty et al., 2009). Speth et al. (2018) mapped and dated Holocene deposits that are cut by ~1.5-m-tall fault scarps belonging to the northern domain of the West Klamath Lake fault zone, and they suggest an earthquake recurrence interval up to ~10 k.y. These data together reveal the Holocene activity on normal faults in both the southern and northern domains of the graben.

Whether fault slip in larger earthquakes is segmented or through-going between individual faults remains an open question. The smallest fault scarps in the youngest part of the alluvial-fan complex (Qf2; Fig. 3) are ~1 m high and hundreds of meters long, which are comparable to the size of Holocene scarps in the West Klamath Lake fault zone (Speth et al., 2018). Fault linkage between the Howard Bay fault and the West Klamath Lake fault zone during a surface-rupturing earthquake is implied by the similarity in fault slip rates and height of the youngest scarps on the faults. Static stress modeling implies, however, that slip on the Howard Bay fault triggered by the Lake of the Woods fault zone may actually shift the northern West Klamath Lake fault zone away from failure (Crider et al., 2001). If correct, this could imply that: (1) the West Klamath Lake fault zone and Howard Bay fault are kinematically linked; (2) coseismic slip may alternate between the two fault systems, rather than link them; or (3) rupture segmentation depends on which of the two faults nucleates an earthquake. Regardless of the potential for fault linkage, the presence of ~1-m-tall scarps on faults with observed historic seismicity indicates that both dextral and normal faults are active. If we use empirical scaling relationships (Wells and Coppersmith, 1994) and interpret the smallest scarps on the Howard Bay fault as single-event scarps, we suggest that combined rupture on the two fault zones could potentially generate earthquakes as large as ~Mw ~7, which is consistent with magnitudes inferred for the West Klamath Lake fault zone by Hawkins et al. (1989) and Bacon et al. (1999).

**CONCLUSION**

New bare-earth LiDAR topographic data reveal the geomorphic expression of active NW-striking dextral faulting in the Klamath graben in the Cascadia backarc, south-central Oregon. NW-striking dextral faults and kinematically linked N-striking normal faults together accommodate >0.3 mm/yr of NW-SE dextral transtension across the graben. Dextral transtension in the Klamath graben forms the northern terminus of transtensional deformation throughout the southern Cascadia backarc, which mimics the structural style observed in the Walker Lane belt to the south. The continuous belt of dextral transtension east of the Sierra Nevada microplate (classically defined Walker Lane belt) and
southern Cascadia backarc (the herein proposed northern continuation of the Walker Lane belt) suggests that the Walker Lane belt development is linked to the motion of both the Sierra Nevada and Siletzia crustal blocks relative to the Basin and Range. Termination of the Walker Lane belt into the Cascade arc >200 km north of the latitude of the Mendocino triple junction implies that the Walker Lane belt propagates northward independently of the Mendocino triple junction and is instead partially controlled by expansion of the Basin and Range Province.

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