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Evidence for late Quaternary surface rupture along the Leech River fault near Victoria, British Columbia, Canada

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Abstract: *We present results of new geomorphic and structural mapping of the Leech River fault near Victoria, British Columbia, Canada providing the first evidence for Quaternary surface ruptures on Vancouver Island. Based on new field and aerial mapping aided by 2m LiDAR DEMs, we identify >60 individual, sub-parallel, linear scarps, sags and swales in en echelon arrays that offset bedrock and late Pleistocene-Holocene deposits. Reconstruction of fault slip across an offset post-last glacial maximum (~15 ka) colluvial surface near the center of the fault zone requires ~6 m of dip displacement of the colluvial surface, and ~4 m of displacement of intervening channels. These data argue that the Leech River fault experienced at least two surface-rupturing (~M6) earthquakes since ~15ka. We interpret the mapped scarps as part of a steeply dipping fault zone that is 500-1000m wide and 30 - 60 km long that accommodates transpression across the northern Cascadia forearc.*

***Key words**: Quaternary rupture, forearc faults, British Columbia*

INTRODUCTION

In the Cascadia forearc of southwestern British Columbia (Fig. 1), active forearc strain related to eastward subduction of the Juan de Fuca plate and northward motion of the Oregon block (e.g., McCaffrey et al., 2013) may be accommodated along a network of crustal faults. Microseismicity and geodetic data do not easily elucidate planar crustal faults in the region, however, (e.g., Cassidy et al., 2000; Balfour et al., 2011), and direct evidence for Quaternary faulting in British Columbia has remained ambiguous. Geomorphic, trenching, and geophysical studies have contributed to the recognition of several major active fault systems in the Cascadia forearc of Washington and Oregon (McCaffrey & Goldfinger, 1995; McCaffrey et al., 2013; Personius et al., 2014), including the Southern Whidbey Island Fault, the Utsalady Point Fault, the Darrington-Devil's Mountain Fault (Fig. 1) (Johnson et al., 1996, 2001; Sherrod et al., 2008; Personius et al., 2014), but no active structures of similar significance are currently formally recognized in southern British Columbia (e.g., Halchuk et al., 2015).

Here we focus on documenting new evidence for Quaternary ruptures along the Leech River fault (Fig. 1), an Eocene terrene-bounding fault located in southern Vancouver Island that separates schists of the Leech River complex from basalts of the Metchosin Fm. (Fig. 2) (Muller, 1977; MacLeod et al., 1977). The potential Quaternary activity of the Leech River fault has been the focus of several recent investigations because of the seismic hazard it may pose to the nearby population of Victoria, British Columbia (Fig. 1) (see Cassidy et al., 2000; Mosher et al., 2000; Balfour et al., 2011). The fault has a strong topographic expression on Vancouver Island, facilitating the construction of several hydroelectric dams along its trace (Fig. 2). It trends into the city of Victoria and into the submarine expression of the Devil's Mountain fault zone (Fig. 2; Barrie and Greene, 2015). Some authors have suggested that the Leech River fault was last active in the Eocene, given a lack of observed offset Oligocene and younger sediments along some portions of the fault (MacLeod et al., 1977; Fairchild, 1979). However, we document new geomorphic and structural data that indicate the Leech River fault zone has been active during the Quaternary.

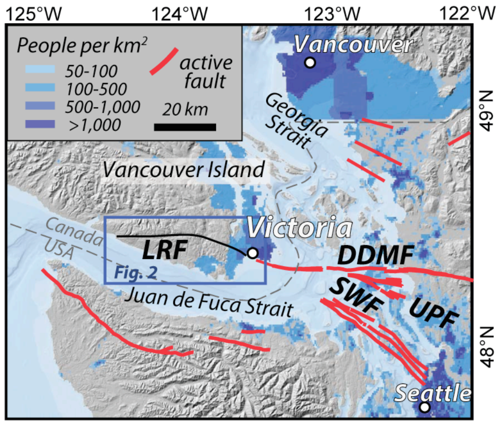

Figure 1: Tectonic setting of the Leech River fault, showing population centers (Balk et al., 2006) relative to active faults (Barrie and Green, 2015; Sherrod et al., 2008; USGS Quaternary fault and fold database for the United States, 2010; Kelsey et al., 2012; Personius et al., 2014). The Leech River fault (LRF) is shown in black. DDMF, Darrington-Devil's Mountain Fault; SWF, South Whidbey Island Fault; UPF, Utsalady Point Fault.

We use a combination of mapping of topgraphic scarps from a high resolution LiDAR digital elevation model (James et al., 2010), bedrock and surficial field mapping, and collection of structural, geomorphic and stratigraphic data to delineate Quaternary fault-related features along the Leech River fault. We identify several strands of the Leech River fault that displace late post-glacial (Clague and James, 2002), Pleistocene to Holocene sediments and record at least two earthquakes since ~15 thousand years ago. These data provide the first evidence for Quaternary surface rupture along a crustal fault in the Cascadia forearc in southern British Columbia, and suggest that the Leech River fault is only one of a network of active faults that accommodate forearc transpression in southwestern Canada.

OBSERVATIONS

We map fault-related topographic and structural features within a ~60 km long by 1 km wide region along the Leech River fault to provide evidence of Quaternary slip and reactivation of the Eocene terrane boundary fault (Fig. 2A). Individual topographic features range in length from hundreds of meters to several kilometres long, are up to five meters high, and form linear ridges, sags and scarps with both north and south facing directions (Fig. 2B). The roughly east-west oriented topographic features occur at a high angle to the southerly regional ice flow direction during the last glacial maximum, confirmed locally from glacial striae and streamlined drumlinoids (Fig 2B). Along the eastern half of the fault, where we have focused current mapping, topographic features coincide with displaced geomorphic surfaces, brittle fracture networks, and up-hill facing scarps. We discuss three key sites from the eastern half of this fault system where field and LiDAR data indicate tectonic offset of bedrock and Quaternary deposits (Fig. 2B, sites A-C).

Site A is located on the south side of the Leech River valley, ~5 km west from the abandoned town of Leechtown (Figs. 2 and 3). Here, we identify an approximately east-west striking, >200-m-long and up to 2 m high topographic scarp that is uphill (southward) facing across a relatively steep, north-facing slope. The surface trace of this scarp is located ~100-m south of the fault contact between the Metchosin Fm. and Leech River Complex. The surficial geology at the site consists of a dense, matrix-supported subglacial till with numerous striated clasts, overlain by a ~1 m thick apron of colluvium. This colluvial surface is incised by several steep, linear channels. Field and LiDAR data indicate that both the colluvial surface and the channels incising it are vertically displaced by several meters across the scarp. Scarp heights measured in the field at site A are systematically lower within the incised channels (~1m) than on the colluvial surface (~1.2 m). The vertical separation across the scarp, estimated from regressions through LiDAR-derrived topographic profiles, is ~6m at interfluve profiles but only ~4 at channel profiles. This observation requires at least two surface rupturing events at site A. The scarp at site A is nearly linear in map pattern, but deviates northward into channels and topographic lows, requiring a steeply (60-90°) north-dipping fault plane. The uphill facing scarps at Sites A and the lack of consistent lateral offset of displaced channels imply thrust-type displacement with minor to no lateral slip along this strand of the fault.

Site B is located approximately 5 km to the east along strike from site A, where we identify a prominent south-facing bedrock scarp that intersects the now-abandoned town of Leechtown near the confluence between the Sooke and Leech Rivers (Fig. 2). The Leechtown scarp can be traced relatively continuously for ~1.5 km along strike and is located ~100 m south of the Metchosin Fm-Leech River Complex contact. An exposure of the fault in rock quarry near the center of this scarp exposes several steeply north-dipping sub-parallel faults cutting relatively undeformed Metchosin Fm. basalt. Faults exposed in this quarry have a 1-2-mm-wide gouge zone and one contains sub-horizontal slickenlines consistent with strike-slip. At the eastern end of site B, the scarp is defined by an ~4 m high, uphill facing bedrock scarp, where the northern (upthrown) side of the scarp consists of fractured and brittly-deformed Metchosin Fm. basalt, and the southern (downthrown) side of the scarp contains moisture-rich, fine-grained sediment. The apparent north-side-up displacement across the scarp and the northward divergence of the scarp trace into topographic lows argue for displacement along a steeply north-dipping reverse fault, and kinematic indicators at the site argue for a strong oblique component to slip.

Site C is located ~5 km to the east of site B, where we identify several hundred meter long linear sags, swales and benches that cut across relatively smooth, till-mantled hillslopes. These scarps have a nearly linear trace across topography, but they do not exhibit clear upthrown fault blocks, nor a consistent increase in surface elevation across the scarps. Features at this site consist of 10-15 m wide disrupted zones that are up to ~5 m higher than the surrounding landscape, and the facing direction of scarps changes along strike. We interpret this *en echelon* stepping of topographic ridges and the lateral juxtaposition of topographic highs and lows as pressure ridges and mole tracks, produced during strike slip or oblique slip faulting.

DISCUSSION

The topographic scarps we identify occur parallel to the mapped location of the Eocene Leech River fault (Fairchild and Cowan, 1982; Massey et al., 2005), but none of the mapped fault scarps coincide with the lithologic terrane boundary between the Leech River Complex schists and Metchosin Fm basalts (Fig. 2), nor with local lithologic contacts. Instead, individual topographic scarps occur as much as hundreds of meters north or south of the lithologic fault boundary. Thus these features cannot be explained by differential erosion across lithologic contacts. In addition, where we have mapped the litholgoic contact between the basalt and schist units, we find evidence for mylonitc fabrics and foliated fault fabrics, but do not find evidence for discrete brittle structures or fault gouge. Conversely, where we identify fault planes in bedrock associated with topographic scarps, we do not identify any mylonitic fabrics, but instead observe discrete fractures and gouge-bearing fault zones. The active fault zone, therefore, does not likely exactly re-occupy the Eocene terrane boundary fault.

We suggest that the identified scarps together delineate an active fault system that is up to ~1 km wide and 30-60 km long (Fig. 2). Within this zone, we observe near vertical faults, variable scarp facing directions, laterally discontinuous surface scarps, and field evidence for strike-slip and reverse faulting. These observations of scarp morphology, fault orientations and fault kinematics suggest that the active strands of the Leech River fault accommodate strike and dip slip motion within a steeply dipping fault zone or flower structure. Such characteristics are typical of strike slip systems (e.g. Sylvester, 1988) and are similar to features observed along active oblique-reverse faults in the Pacific Northwest (e.g. Johnson et al., 2001; Sherrod et al., 2008; Personius et al., 2014).

The offset geomorphic features, faulted bedrock and surficial deposits, and prominent bedrock scarps mapped along the Leech River fault collectively argue that several strands of the fault were active since the late Pleistocene. The strongest evidence for late Pleistocene to Holocene ruptures along the Leech River fault come from Site A, where the colluvial apron overlying basal till morphologicaly remains both in situ and intact. The colluvial surface and incised channels must therefore be no older than the deglaciation following the last glacial maximum (~15 ka; Clague and James, 2002), and faulting at site A must postdate ~15 Ka. In addition, the difference in scarp height and estimated vertical separation between interfluve and channel profiles implies multiple episodes of fault activity, with at least one event occurring after the formation of the colluvial apron, but before channel incision, and at least one additional event following formation of the channels. Assuming a 60-90° dipping fault plane, vertical separations across the scarp equate to approximate total dip slip magnitudes of >6.5m for interfluve surfaces and >4.5 m for channels. These data indicate ~2m of dip displacement occurred during the first event, and ~2 to ~4m of displacement occurred during a subsequent event or events. Assuming first order displacement length scaling (e.g. Wells and Coppersmith 1994), these dip displacement magnitudes and fault length collectively suggest the Leech River fault has experienced at least two ~M6 earthquakes since ~15 Ka.

CONCLUSIONS

Our observations of linear fault scarps and offset Quaternary geomorphic features delineate a >30 km long section of the LRF that has been tectonically active since the end of the Cordilleran glaciation. This active fault zone contains numerous sub-parallel, mesoscale faults with variable orientations that together comprise a steeply-dipping ~1 km wide fault array or flower structure. While slip sense along individual fault strands is highly variable, the orientation and surface morphology of fault-related features across the entire fault zone strongly suggest that this active fault system accommodates forearc transpression. Reconstruction of an offset post-glacial colluvial landform requires at least two surface rupturing events, each with at least ~2m of dip displacement, to have occurred since ~15 Ka. These estimated displacements suggest that the Leech River fault is capable of hosting earthquakes of ~M6 within kilometers of Victoria, BC. We suggest that the Leech River fault is part of a network of active faults that accommodate forearc deformation in the northern Cascadia forearc.

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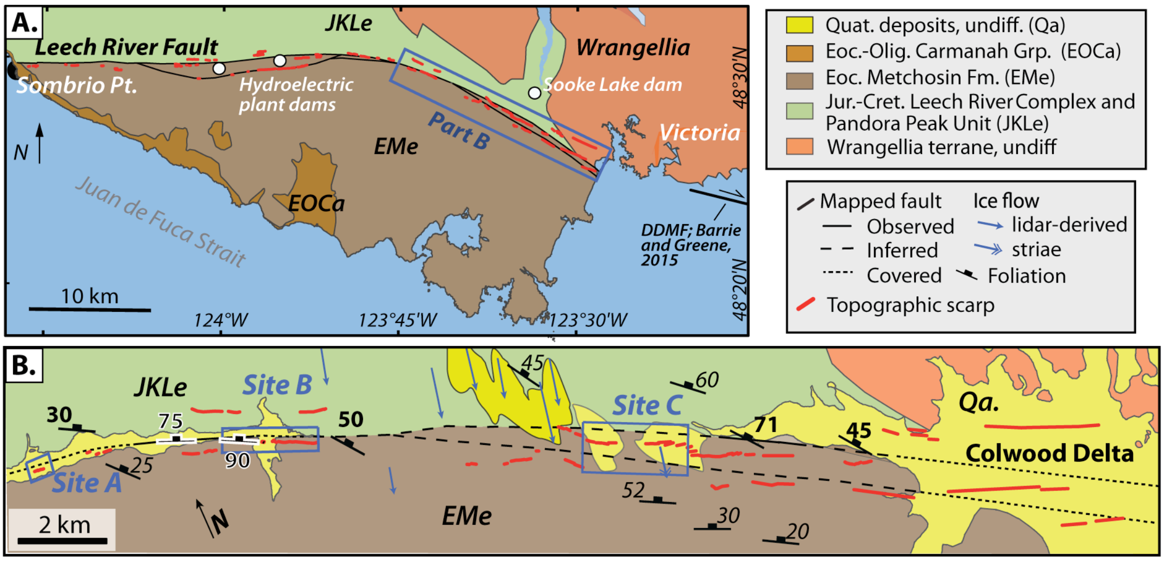

Figure 2. A. Simplified geologic map of the Leech River fault and surroundings (after Massey et al., 2005). Red lines denote topographic scarps, pressure ridges, topographic benches and linear swales and sags identified in this study. B. Map showing trace of identified features relative to bedrock (Massey et al., 2005), surficial deposits (Blyth and Rutter, 1993) and local ice flow indicators (blue arrows, this study). Foliation measurements from this study are shown in bold and those from Muller (1983) are shown in italics. Foliation data outlined in white are at the lithologic contact (this study).