FINAL TECHNICAL REPORT

IN SOUTHERN CASCADIA, DO UPPER PLATE FAULTS RUPTURE IN CONCERT WITH SUBDUCTION ZONE EARTHQUAKES: A PALEOSESIMIC INVESTIGATION OF THE LITTLE SALMON FAULT ZONE

Collaborative Research with California Geological Survey, Humboldt State University and U. S. Geological Survey

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U.S. Geological Survey
National Earthquake Hazards Reduction Program
Award No. G19AP00045 & G19AP00046
Start date: June 1, 2019; End date: August 31, 2020

November 2020

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Abstract

We excavated two paleoseismic trenches exposing the central segment of the Little Salmon fault (LSF) and central trace of the Goose Lake fault (GLF). We documented earthquake chronologies and deformation characteristics to assess possible fault connectivity between upper-plate faults and the southern Cascadia Subduction Zone (SCSZ). The Little Salmon fault trench exposed three shallow (9^o to 11^o) northeast- to north-dipping thrust faults juxtaposing Pleistocene and Holocene strata of the hanging wall over Holocene alluvium and colluvium in the footwall. Radiometric ages from detrital charcoal obtained within two buried soils, lower (Unit 4) and upper (Unit 7), yielded age ranges of 8170 to 8340 yr BP and 310 to 1890 yrs BP, respectively. We observed direct evidence of at least two Holocene earthquakes preserved in the trench stratigraphy: 1) the latest Holocene earthquake (MRE) and 2) an early Holocene earthquake. There is also equivocal evidence for a third, Late Holocene earthquake. Four ^{14}C ages from an unfaulted colluvial wedge (Unit 8) indicates the MRE occurred prior to 90-480 yr BP (CE 1860-CE 1470). Deformation style of the LSF is similar to that observed in other shallow angle thrust faults during historic earthquakes (i.e., 1988 Armenian earthquake) wherein near-surface sediments are folded around the fault tip and translated as they overrode the footwall. The Goose Lake fault trench revealed discrete faulting within a broad subvertical (~2-meter-wide) zone of deformation with a pronounced vertically imbricated shear fabric that juxtaposed the Carlotta Formation against fluvial terrace deposits. Surface fault rupture was evident in the trench stratigraphy by fissure fills /colluvial wedges. We interpret three earthquakes are permissible based on the trench stratigraphy. The most recent earthquake (MRE) is evident by the presence of unit 7c and the upward termination of fault traces to the bottom of Unit 8. The penultimate earthquake is noted by upward fault termination to the base of Unit 3a and the presence of Unit 7b. The thickness and width of Unit 7b indicates Unit 7b may reflect multiple generations of earthquake slip. Similarly, Unit 7a appears to likely reflect multiple earthquakes and stratigraphy does not permit the identification of individual earthquake events. We identified and sampled six localities for OSL dating as no suitable samples were found for ^{14}C dating within the GLF trench. Our OSL results are still pending. Further age modeling is planned by the research team to assess the plausibility of fault connectivity between the upper-plate fault and the SCSZ.

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This material is based upon work supported by the U.S. Geological Survey under Grant No. G19AP00045 & G19AP00046. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Geological Survey. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Geological Survey.

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1. INTRODUCTION

This technical report summarizes data collected, and initial analysis of data for fault investigations on the Little Salmon fault and Goose Lake fault in northern coastal California. The objectives of the technical report are: 1) summarize the tectonic setting, 2) encapsulate the previous geologic mapping and paleoseismic studies that provide the basis for the motivation of the investigation, 3) summarize the project scope, 4) present results, and 5) discuss findings to date.

The report fulfills deadline-specific reporting requirements under award numbers G19AP00045 and G19AP00046 of the U. S. G. S. National Earthquake Hazards Reduction Program. However, the scientific effort that underlies the Technical Report is a work in progress and finalized results and finalized discussion will subsequently appear in a peer-reviewed publication.

2. TECTONIC SETTING AND PREVIOUS WORK

Our project site is within the complex tectonic regime where dextral shear of the San Andreas fault zone transitions to contraction along the convergent margin of the southern Cascadia subduction zone (SCSZ). At the southern end of the SCSZ, strain accumulation on the megathrust occurs synchronously with contraction of the upper plate. Geodetic investigations (Williams et al., 2006) and tidal marsh subsidence stratigraphy (Clarke and Carver, 1992; Engelhart et al., 2015; Padgett et al., 2020) together support the inferred paired strain accumulation of upper plate faults and the southern Cascadia subduction zone megathrust.

The principle upper-plate faults surrounding the latitude of Humboldt Bay, northern California are the Little Salmon fault zone (LSF), sitting approximately 18-22 km above the shallowly dipping megathrust at latitude ~40.5°N (McCrory et al., 2012), and the Mad River fault zone (Figures 1 and 2). The LSF accommodates slip on one major fault zone and a few in-close proximity (~2 km) related faults. In contrast, the Mad River fault zone is a series of five individual fault strands spread over a ~8 km wide fault zone width (Figures 1 and 2). Whereas the Mad River fault zone has a cumulative slip rate of ~5-7 mm/yr based on slip rates on several individual faults over >10km (Carver and Burke, 1988; Kelsey and Carver, 1988), the northwest segment of the LSF has slip accumulated on one relatively narrow fault zone (< 500 meters).

2.1. Previous Paleoseismic Studies

Previous paleoseismic studies (Carver and Burke, 1988; Clarke and Carver, 1992) within the northwest segment of the LSF infer a late Holocene slip rate of 6-12 mm/yr, which is equal to or up to approximately double that of the Mad River fault zone. The Little Salmon fault zone (LSF) therefore is the major upper-plate structure in the southern Cascadia subduction zone (Ogle, 1953; Kelsey and Carver, 1988; McLaughlin et al., 2000).

Based on prior paleoseismic investigations (Clarke and Carver, 1992; Witter et al., 2002), the northwest segment of the fault zone has ruptured in at least three earthquakes in the last 2,000 years, leaving open the possibility that the Little Salmon fault may rupture in concert with SCSZ earthquakes (Table 1). Poor age control of those three earthquakes renders this correlation speculative. For more than two decades, scientific literature on the Little Salmon fault has discussed the possibility that the fault ruptures in concert with Cascadia subduction zone earthquakes (Clarke and Carver, 1992; Witter et al., 2002). The work reported herein opens that dialog.

Although there have been a number of paleoseismic investigations on the northwest segment of the Little Salmon fault (Carver and Burke, 1988; Clarke and Carver, 1992; Witter et al., 2002), there has been only one prior investigation on the central segment of the Little Salmon fault (Figure 2). Trench excavations by Hemphill-Haley and Witter (2006) yielded evidence for several pre-Holocene-age earthquakes but unfortunately the Holocene record was missing.

Table 1. Chronology of Little Salmon Fault and megathrust earthquakes

Paleoseismic investigation	Number of earthquakes	Ages of earthquakes
Megathrust earthquakes as inferred from buried marsh soils, northern Humboldt Bay: Padgett et al. (2020)	Four	**1**) 1700 AD*; **2**) ~875 cal yrs BP; **3**) ~1120 cal yrs BP; and **4**) ~1,620 cal yrs BP.
Earthquakes observed along Little Salmon Fault, Renner ranch site: Clarke and Carver (1992), as summarized in Witter et al. (2002).	Three	**1**) 1700 AD*; **2**) 500-1200 yrs BP; **3**) 1500-2400 yrs BP
Earthquakes observed along Little Salmon Fault, Swiss Hall site: Witter et al. (2002).	Three	**1**) 1700 AD*; **2**) 540-1,230 yrs BP; **3**) 1,530-1,710 yrs BP

Notes: Ages of earthquakes for the Renner trench site are extracted from Witter et al. (2002) based on G. A. Carver's inferences based on Clarke and Carver (1992). All radiocarbon ages are calibrated age ranges. Megathrust earthquakes ages are calibrated ages further constrained by OxCal modeling.
* In all three studies, the most recent earthquake is assumed equivalent to the AD1700 Cascadia megathrust earthquake.

Approximately 1.8 km south of the Little Salmon fault (LSF), Woodward Clyde Consultants (1980) identified the Goose Lake fault (GLF) as a linear ‘mole-track’ scarp deforming prominent fluvial terraces near Hydesville and trending sub-parallel to the LSF (Figure 3). Two additional sub-parallel strands of the GLF were noted by Woodward Clyde Consultants (WCC) referred to here as the ‘northern’ and ‘southern’ strand (Figure 3).

Paleoseismic trenching by WCC (1980) report the GLF to be a north-dipping bedding plane thrust fault and interpreted three episodes of oblique faulting with the most recent event (MRE) Holocene in age, based on radiocarbon dates. However, radiocarbon sampling only included two samples from the distal edges of the trench and timing of events were extrapolated across the trench. WCC (1980) reported oblique striations within the Carlotta Formation and inferred the sense of motion is south-vergent reverse with a one third component of right lateral strike-slip.

3. PROJECT SCOPE AND RESEARCH APPROACHES

The project scope encapsulates several related-research approaches. First, using new lidar imagery, we re-mapped the Little Salmon fault, focusing on fault-related geomorphology. Second, we identified sites along the Little Salmon fault and Goose Lake fault for a paired paleoseismic trench excavation in the vicinity of Hydesville, California. Third, we excavated two trenches across the LSF and one across the GLF. Fourth, we compiled and interpreted trench stratigraphy in the context of a paleo earthquake history, using age constraints provided by ^{14}C dating of deformed strata in the trenches.

4. RESULTS

4.1. New Geomorphic Mapping

4.1.1. Little Salmon fault: three distinct segments

We exploited a lidar swath of the fault zone area (EarthScope Northern California Lidar Project, 2007) to perform revised mapping of the Little Salmon fault. Our updated geomorphic mapping focused on mapping fault-related geomorphology across the central and east segment of the LSF. Our mapping indicated the LSF is different in trace and fault zone character from original mapping by Ogle (1953) and subsequent mapping (Kelsey and Carver, 1988; McLaughlin et al., 2000). Broadly, the revised mapping indicates that the LSF can be separated into three distinct segments -- northwest, central and southeast -- with each segment about similar in length but different in orientation and underlying geology (Figure 1C).

Swath lidar mapping reveals that the entire LSF manifests youthful west to southwest-facing fault scarps where topography is moderate to gentle sloping. In steeper topography, such as the central and east segment, the LSF was observed through linear drainages, linear hillside benches, uphill-facing scarps, and saddles.

4.1.2. Little Salmon fault: east segment

A review of high resolution lidar imagery across the east segment of the LSF reveals a distinct continuous hillside bench with uphill-facing scarps that traverse the landscape for approximately 9 km, between Wilson Creek and the eastern end of the lidar swath (Figure 4A). Field inspection of these hillside benches found that the benches are asymmetrical grabens or topographic depressions with distinct opposing scarps: northeast- and southwest-facing (Figures 4A and 4B). The grabens range from 5 m to > 30 m wide with sub-vertical northeast-facing scarps up to 4 meters. The southwest-facing scarps varied in height from 3 m to < 10 m. These hillside benches are noted to deform active tributary thalwegs such as Wilson Creek and Cummings Creek tributaries.

We interpret the hillside bench to be the surface expression of the LSF at the contact between Tertiary deposits (Wildcat Group) and Cretaceous sediment (Yager Formation) based on regional mapping (Ogle, 1953; McLaughlin et al., 2000) (Figure 4B). These hillside benches appear conspicuously well preserved across very rugged topography with high hillslope denudation rates through mass-wasting. Hence, we conclude the hillslope grabens must be regenerated by the LSF regularly (i.e. recurrence on the order of hundreds of years) or hillslope aggradation would infill and mute the hillside bench morphology.

Furthermore, these hillside benches or graben features are puzzling geomorphic features for the Little Salmon fault because previous work has documented the LSF to be a northeast-dipping thrust fault (Clarke and Carver, 1992; Witter et al., 2002, Hemphill-Haley and Witter, 2006). In such a tectonic regime, one would anticipate the generation of a southwest-facing scarp as the northeast hanging wall moves up with respect to the southwest foot wall. However, field investigations by Philip and Meghraoui (1983) from the 1980 El Asnam earthquake show that thrust faults can generate hillside benches if contraction is accommodated not only on the master thrust but also on bedding-plane flexural slip faults in the footwall (Figure 4B and 4C). In a model proposed by Philip and Meghraoui (1983) to explain these hillside benches, they note the main fault ruptures contemporaneously with flexural slip of a footwall syncline. Specifically, the master thrust generates south-facing scarps while flexural slip due to contraction on the footwall syncline causes north-facing scarps. Together the two opposing scarps create a mid-slope benched graben within a reverse fault zone.

We propose the hillslope benches and uphill facing scarps observed in the lidar imagery along the east segment of the LSF may be developed by similar kinematics described by Philip and Meghraoui (1983). The Philip and Meghraoui model is also compelling because regional geologic mapping depicts a syncline within the footwall of the LSF across the east segment (Ogle, 1953; McLaughlin et al., 2000). Alternatively, the hillslope benches may be related to hanging wall deformation and the master LSF thrust fault may daylight downslope. Further research would be required to confirm if the LSF is behaving in a similar fashion to that observed by Philip and Meghraoui (1983).

4.1.3 Goose Lake fault zone: terrace mapping and scarp profiles

New lidar imagery (released publicly in January 2020 by the USGS) surrounding Hydesville allowed us to update Quaternary mapping of the Little Salmon fault near Hydesville, the Goose Lake fault and the adjacent prominent terraces (Figures 3, 5, and 6). These terraces surrounding Hydesville are composed of two distinct fluvial sequences referred to as the younger Yager Terraces (Qyt) and older Van Duzen Terraces (Qvdt) based on the fluvial system responsible for terrace generation (Figure 3). The older Van Duzen terraces are tilted to the north while the lower Yager Creek terrace are both offset and gently tilted to the north by the GLF (Figure 3).

All three strands of the GLF have north-facing scarp morphology with the net scarp relief increasing towards the south, which in part accounts for the overall terrace tilt to the north. Topographic profiles across the central trace of the Goose Lake fault scarp depict an asymmetrical mole-track scarp with a predominate north-facing scarp (>5 meters) and a small (1.5 meter) opposing south-facing scarp (Figure 6).

4.2. Little Salmon Fault Paleoseismic Investigation

4.2.1. Overview

We excavated two trenches (Quail and Swallow trenches) orthogonal across scarps on a major strand of the central segment of the Little Salmon fault. The Quail and Swallow trenches (elevations 153 and 157 m, respectively) were excavated at the northern margin of the Van Duzen valley corridor where terrace cover is influenced by tectonic deformation which is either folding of terrace treads or fault-related scarp development and subsequent diffusion downslope of scarp colluvium (Figures 3 and 5)

Each trench location was intended to capture and document different faulting characteristics of the LSF; the Quail trench was excavated across a large south-facing scarp to expose the main trace of the LSF while the Swallow trench was excavated across a northeast facing scarp that was intended to document hanging wall deformation contemporaneous with slip on the main north-dipping fault. Swallow trench exposures were never fully cleaned and logged because emergent groundwater compromised trench wall stability. Swallow trench was abandoned because of trench collapse in the deepest part of the trench where a fault may have been located. Nonetheless, Swallow trench provided an excellent exposure for soil description and for observing and characterizing the Hookton Formation, which was the oldest unit in the hanging wall of Quail trench.

Investigation of Quail trench (and also of Goose trench, see below) followed the same general protocol. We surveyed the trench to local elevation and emplaced a 1-meter grid on trench walls to enable subsequent logging. We then mapped the trench stratigraphy into lithostratigraphic and/or soil stratigraphic units and photographed trench walls. All units were subsequently described (Tables 2 and 3, Appendix Tables A1-A5). Photomosaics of logged trench walls were produced by importing images into the software program Agisoft (Reitman et al., 2015). Logging of trench stratigraphy was done on overlays on the photomosaics.

4.2.2 Quail Trench

The Quail trench exposed three shallow (9° to 11°) northeast- to north-dipping thrust faults (Tables 4 and 5; Figure 7). The structurally lowest of these faults, Fault A, is the basal hanging wall fault and juxtaposes Pleistocene and Holocene strata of the hanging wall (units 1, 6a, 6b, Table 1) over Holocene alluvium and colluvium in the footwall (units 2 3, 4, 5, 7, 8, Table 2). Because of the shallow fault dips, fault orientation for each of the three faults was determined by measuring trend and plunge of fault plane intersection with trench walls and then a best fit fault plane was determined stereographically (Table 3). Dip of the three faults was uniformly shallow, 9° to 11°, and the structurally lower two faults had strikes of approximately the same northwest orientation (N32°W, N55°W) whereas the structurally higher fault (Fault C) was more east-west (N73°E) in strike (Table 4).

The three thrust faults are distinctly different in fault textures (Table 5). The structurally highest fault (Fault C) is exclusively within unit 1, and S-C foliation is evident by fine sand and silt laminae that have been sheared and strung out at laminae tips. The structurally middle fault (Fault B) is the most conspicuous fault in the trench, although it is not the fault with straightest, nor the longest, exposed expression. Fault B stands out because it juxtaposes tan sediment overlying a black silt loam (Figure 8). Corrugations in the fault surface are up to 2.5 cm in amplitude and the fault zone displays mixing and folding, up to 5-10 cm below the fault surface (Figure 8). The structurally lowest fault (Fault A) is clearly delineated by a linear sandy zone within a black silt loam. The fault zone has minor wavy surfaces, which are manifest by asymmetric flame structures with an amplitude 1-2 mm and a wavelength 10-25 mm. These flame structures show locally developed S-C foliation/fabric, indicating top-to-the-southwest shearing. Taken together, Fault B is more internally deformed relative to the structurally underlying Fault A; Fault A is straighter and is the only fault with a fault tip that projects down-trench into the youngest deformed colluvium.

The shallow nature of the fault dip (<11°) and large scarp height (5.2 meters) suggests large slip-per-event is required to generate adequate scarp relief if fault angle does not increase appreciably at depth. Simplified, first-order calculations of the slip required to create the 5.2-meter-high scarp on a 10° dipping fault surface indicates net slip of 16 meters (Figure 5). The inferred 16 m assumes that all deformation is slip at depth and that folding only occurs near the surface. Alternatively, scarp relief may also be generated, at least in part, by thickening of the hanging wall as the hanging wall sediments are entrained and folded around the fault tip, a scenario that permits the fault geometry to steepen at depth. Specifically, trench logs reveal principal hanging wall units (1c, 1b, 6a, 6b) are folded around the tip of Fault B (Figure 8). We interpret the folding of the hanging wall sediments to be related to folding and dragging along Fault B during displacement. This mode of deformation is similar to that observed in other shallow angle thrust faults during historic earthquakes, such as the Armenian earthquake of December 1988, wherein near-surface sediments are folded and translated as they overrode the footwall (Philip et al., 1992). Similar deformation style has been noted within paleoseismic trenches completed along the Himalayan Frontal Fault (Kumar et al., 2010).

Footwall trench stratigraphy generally consists of fine-grained alluvial deposits that are each separated and overlain by a buried soil (Figure 7). Unit 5 is the most distinct and continuous alluvial unit in the footwall (Figure 7). Three ^{14}C ages were obtained from within Unit 5 and ranged between 1620 to 2120 yr BP (Table 6). Unit 5 was also noted to increase in thickness significantly where it is adjacent to Fault A. We acknowledge an unmapped colluvial unit overlying Unit 5 adjacent to Fault A is possible (Figure 7). However, the lack of notable internal structure within Unit 5 precluded us from identifying a separate colluvial unit.

Age estimates of each buried soil were also determined through detrital charcoal analysis (Table 6). The lower and older buried soil (Unit 4) yielded an age range of 8170 to 8340 yr BP. The age of the upper buried soil, Unit 7, was poorly constrained with two (2) ^{14}C age estimates that ranged from 310 to 1890 yrs BP, discounting an outlier age for sample Qu-3-3. The fact that the older age of Unit 7 is older than the underlying alluvium (Unit 5) suggests the actual age of Unit 7 is likely significantly younger and may be closer to sample Qu-3-4 (Table 6).

Stratigraphy in the hanging wall is distinctly different than units within the footwall. We interpreted the hanging wall sediments to be mainly composed of varying facies of the Hookton Formation (Table 2). The oldest unit exposed in the trench (Unit 1a) consisted of silt and very fine-grained sand that was faulted by Fault C and thrust over Unit 1b (Figure 7). Fault C extended into Unit 1b and offset pebble stringers. In addition, the pebble stringers appeared folded around the fault tip of Fault C. Two alluvial units (Units 6a & 6b) were structurally below the Hookton Formation. We interpreted these alluvial units were entrained into the hanging wall during thrust faulting. We submitted one ^{14}C sample for each alluvial unit within the hanging wall. Age estimates for Unit 6a and 6b were found to be 5320 to 5580 yrs BP and 2000 to 2310 yrs BP, respectively.

No unequivocal piercing points were observed in the trench strata that enables connecting units in the hanging wall with an equivalent unit position in the footwall (Figure 7). Hence, total fault slip is not known. However, we note several observations provide some constraints on fault slip. First, unit 5 is fully tucked underneath the exposed hanging wall, so a minimum slip as determined from trench exposure must be the fault-truncation amount of Unit 5, which is approximately 5-6 meters. Second, we propose that Unit 6b in the hanging wall is possibly correlative to Unit 5 in the hanging wall based on similar lithology and ^{14}C age estimation. Preliminary and simplified line-balanced retrodeformation modeling connecting Unit 6b to the base of Unit 5 yields a heave along Fault A of approximately 4.5-meters. We also note ^{14}C ages for units 6a and 6b span 5580-2000 yr BP, indicating that footwall units 4, 5, and 7 are generally equivalent to the age of hanging wall units 6a and 6b.

4.2.3. Most Recent Earthquake

Units 7 and 8 provide critical insight into constraining timing of the most recent earthquake (MRE). Unit 7, a distinct buried soil developed on top of Unit 5, is the youngest faulted stratigraphic unit observed. Therefore, the age of Unit 7 provides a maximum age constraint on timing of the MRE. Unfortunately, the age of Unit 7 is poorly constrained based on 3 ^{14}C age samples (310 – 1890 yr BP). Unit 8 drapes across the top of Unit 7 and is unfaulted (Figure 8). Hence, we interpret Unit 8 as a scarp-derived colluvial deposit generated during coseismic displacement from the MRE. We submitted 4 ^{14}C samples from within Unit 8 to constrain the minimum age of the MRE, which yielded an age range between 20 to 1060 yrs BP (Table 6). Since unit 8 has a radiocarbon age spanning last-possible prehistory time (CE 1860) back to 1060 yr BP, and if we assume that the oldest detrital charcoal dates have a significant in-built age (Gavin, 2001) and thus can be discarded, then the MRE would be 90-480 yr BP (CE 1860-CE 1470) in age. Alternatively, the younger ages (Qu-4-1 and Qu-4-3) could reflect burrowing and the actual age could be more accurately reflected by sample Qu-39-2. Further age modeling and constraints would be needed to state further conclusions about either option. In summary, our combined age constraints on the MRE provide a maximum age of 1890 yrs BP and a minimum age of 90 yrs BP. Further age modeling is pending by the research team.

We observed direct evidence of at least two earthquakes preserved in the trench: 1) latest Holocene earthquake (MRE) and 2) early Holocene Earthquake. The early Holocene earthquake was noted by a fissure fill above Fault C. An age estimate, obtained from woody material within the fissure fill, produced a minimum age constraint on this oldest earthquake age of 8590 – 8980 yrs BP.

There is also some evidence for a third, Late Holocene, earthquake. As noted above, Unit 5 increased in thickness significantly where it is adjacent to Fault A. We acknowledge an unmapped scarp-derived colluvial unit overlying Unit 5 adjacent to Fault A is possible. If so, this would indicate the penultimate event occurred subsequent to the aggradation of Unit 5. Further indirect evidence for three earthquakes is based on the scarp height and sub-horizontal fault dip. If the scarp height and fault dip (~10°) require a net slip of 16 m (Figure 5), the scarp morphology requires multiple events given the low likelihood that 16 m of slip occurred in one or two earthquakes. If the three faults (Faults A, B, C) each accommodate single-event earthquakes that had equivalent slip, a possibility but by no means required, then three earthquakes could each accommodate a slip of ~5 m, which is reasonable given the 40-km trace length of the Little Salmon fault. Such an estimate is also not inconsistent with the conclusions of Clarke and Carver (1992) of three slip events documented at a site on the northwest segment of the Little Salmon fault each with a slip magnitude of 4-6 m.

4.3 Goose Lake Fault Paleoseismic Investigation

4.3.1 Overview

We excavated one trench across the central trace of the Goose Lake fault (GLF), referred to as Goose trench. The trench site was a re-excavation of a previous paleoseismic trench on the Goose Lake fault by Woodward Clyde Consultants (1980), approximately 20 meters west of their trench location (Figure 2). At the trench site, the fault scarp is predominately composed of a large (>6 meter-high) north-facing scarp with an opposing (south-facing) ~1.5-meter-high scarp (Figure 6). Scarp profiles completed at the trench site and along the central trace of the GLF document the scarp to be an asymmetrical 'mole track' scarp. Our trench was excavated along the south-facing scarp since the previous trench study by WCC found surface fault rupture was predominately confined along the southern scarp.

Geomorphic mapping indicates the GLF has offset the well expressed Yager Fluvial Terrace (QYt5) by approximately 6 meters (northside down). Additionally, it appears the fluvial surface has been deformed by the GLF as evident by a prominent closed depression (down-warping) along the south-facing scarp (Figure 6).

4.3.2 Goose Trench

The Goose trench revealed discrete faulting along a broad vertical (~2-meter-wide) zone of deformation with a pronounced vertically imbricated shear fabric that juxtaposed the Carlotta Formation against fluvial terrace deposits (Figure 9). Surface fault rupture was evident in the trench stratigraphy by fissure fills /colluvial wedges.

Trench stratigraphy predominately consisted of coarse-grained pebble and cobble alluvium with sub-horizontal imbrication that we interpret to be related to development of the broad fluvial terrace surrounding the trench site. We distinguished several alluvial units (Units 2a, 2b, 3, 3a) based on variation in lithology that relate to individual periods of fluvial aggradation (Figure 9). The oldest fluvial terrace deposits we inferred to correlate across the trench based on lithological characteristics, indicating the total vertical offset across the GLF may be on the order of 3 to 5 meters. The trench stratigraphy also documented laterally discontinuous gravel units across the GLF (i.e. Units 3, 3a) indicating a significant component of lateral motion is plausible. Overlying the fluvial terrace deposits (Units 2a and 2b) was a conspicuous silt deposit devoid of gravel (Unit 4) that we interpreted as a slackwater deposit forming in a closed-depression (Figure 6).

4.3.3. Paleo-earthquakes

We interpret three earthquakes are permissible based on the trench stratigraphy. In order to constrain ages of the paleo-earthquakes, we identified and sampled six localities for optically stimulated luminescence (OSL) dating as no suitable samples were found for ^{14}C dating. Our OSL results are still pending. The most recent earthquake (MRE) is evident by the presence of unit 7c and the upward termination of fault traces to the bottom of Unit 8 (Figure 9). We interpret Unit 7c to be scarp-derived colluvium following coseismic slip on the most recent earthquake. The penultimate earthquake is noted by upward fault termination to the base of Unit 3a and the presence of Unit 7b. Unit 7b was characterized by a sub-vertical shear fabric of aligned pebble and cobbles. The thickness and width of Unit 7b indicates Unit 7b may reflect multiple generations of earthquake slip. Similarly, Unit 7a appears to likely reflect multiple earthquakes and stratigraphy does not permit the identification of individual earthquake events.

Fault deformation style of the GLF appears to facilitate dilation along the fault surface, which allow for the development of colluvial packages / fissure fill deposits. The deformation style, the presence of high-angle fault, and laterally discontinuous gravel units across the fault indicate the GLF is an oblique fault with the potential for a significant lateral component. However, deflected fluvial terrace risers do not provide unequivocal evidence of lateral motion. We propose the GLF and LSF may act to partition strain between contraction and oblique translation across the Van Duzen basin. Alternatively, further research is needed to preclude the possibility that the GLF may accommodate flexural-slip related faulting in association with regional folding within the Eel River/Van Duzen basin as proposed by WCC (1980).

4.4. Relative soil development at the Trench sites

Young A-C soils characterize the Quail trench site whereas better developed soils with a Bt horizon characterize the Swallow and Goose trench sites (Tables A1-A5). The physical setting of the three soil description sites sets the stage for the differences in soils preserved on each. The Goose trench is at an elevation of 109 m, on one of the oldest Yager Creek terraces. In contrast, both the Quail and Swallow trenches are at the elevation of the oldest, highest Van Duzen terrace (Swallow, 153 m; Quail 157 m), although the terrace morphology at each site is modified by faulting.

The Goose and Swallow trenches are both underlain by alluvium and in neither case is there evidence for severe erosional stripping of the surface. The Goose surface is an abandoned river floodplain and the Swallow soil site is on the hinge of a folded terrace surface.

The Quail trench soil sites (two sites, one on the hanging wall and one on the footwall and separated by where the fault cuts upward into the soil zone) are both sites where repeated faulting has severely altered the ground surface. On the hanging wall, each rejuvenation of the scarp has down-tilted the hanging wall surface and promoted erosional back wearing of the surface, while on the footwall the surface receives colluvial deposition following each scarp rejuvenation.

Given the above differences in physical setting, the Quail soil sites have A-C soils of young relative age (i.e., no B horizon development, see Tables A1 and A2), even though the hanging wall of the Quail trench is part of the oldest and highest alluvial terrace. In contrast, the Goose and Swallow soils are approximately similar in relative age even though the soils are described on two terraces that are separated in elevation by 50 m. Both Goose and Swallow soils have Bt horizons, although the relative age of the Swallow soil is older than the Goose soil based on thickness of the Bt horizon and the depth to the base of the Cox (Appendix, Tables A3, A4 and A5).

5. DISCUSSION AND SUMMARY OF RESULTS

5.1. Terrace and fault mapping

The Hydesville terraces (Ogle, 1953; O'Dea, 1992) provide an unusually fertile setting to trace late Quaternary tectonic deformation. The older (Van Duzen) terraces record down-to-the-north tectonic tilts greater than, but in sympathy with, the younger (Yager Creek) terraces. The younger Yager Creek terraces provide inferred Holocene surfaces and alluvial strata whose deformation enables recognition of the distinctly different fault characteristics of the Goose Lake fault from the Little Salmon fault.

5.2. Quail Trench

The Quail trench exposed three shallow (9º to 11º) northeast- to north-dipping thrust faults juxtaposing Pleistocene and Holocene strata of the hanging wall (units 1, 6a, 6b; Table 1) over Holocene alluvium and colluvium in the footwall (Figure 7). Age estimates of the trench stratigraphy were ascertained through detrital charcoal analysis of 14 samples. We recognize that all the ages are based on detrital material that impart a maximum limiting age to the unit.

The most recent earthquake (MRE) was constrained by age estimates on Unit 7, a distinct buried soil that is the youngest faulted stratigraphic unit observed, and Unit 8, a scarp-derived colluvium. Radiometric age estimates of Unit 8 constrain the minimum age of the MRE to be between 20 to 1060 yrs BP (Table 6). Since unit 8 has a radiocarbon age spanning last-possible prehistory time (CE 1860), and if we assume that the oldest detrital charcoal dates have a significant in-built age (Gavin, 2001) and thus can be discarded, then the MRE would occur earlier than 90-480 yr BP (CE 1860-CE 1470).

5.2. Goose Trench

The Goose trench revealed discrete faulting along a broad vertical (~2-meter-wide) zone of deformation with a pronounced vertically imbricated shear fabric that juxtaposes the Carlotta Formation against fluvial terrace deposits (Figure 9). Surface fault rupture was evident in the trench stratigraphy by fissure fills /colluvial wedges. The presence of laterally discontinuous gravel packages across the fault zone, fissure fill/collapse colluvium within the fault zone, sub-vertical dipping faults, and a linear mole-track scarp all indicate that the Goose Lake fault is an oblique-slip fault with a sizable but unknown lateral component. And the distinct difference in deformation style, fault geometry, scarp morphology between the Little Salmon Fault and the Goose Lake fault suggest the two faults may act to partition strain between contraction and oblique translation**.**

5.2. Possible Connectivity between Upper-plate Fault Sources and SCSZ

A goal of our research was to further investigate the question of whether Holocene-age earthquakes on the Little Salmon fault permissibly occur at the same time as earthquakes on the southern Cascadia subduction zone (SCSZ), as described by Engelhart et al. (2015) and Padgett et al. (2020) at northern Humboldt Bay. An earthquake on the SCSZ could have triggered each of the earthquakes that cumulatively generated the scarp at the Quail site but uncertainty in radiocarbon ages of earthquakes (at both at the northern Humboldt Bay site and at the Quail site) leaves open the possibility that the Quail trench earthquake record was in part or entirely out of synchroneity with timing of earthquakes on the proximal southern Cascadia subduction zone. Additionally, further age modeling is needed to assess the possibility whether the most recent earthquake captured at the Quail Trench site may correlate with the 1700AD Cascadia event. Preliminary ^{14}C age estimate indicate it is permissible, but much uncertainty surrounding the age of the youngest units remain.

Because age from our optical stimulated luminesce (OSL) samples are pending, we are unable to assess whether the GLF and LSF may rupture sympathetically or independently. Yet, we suggest the LSF and GLF may be independent seismogenic sources based on the significant differences in fault geometry and deformation style observed in the trenches.

6. ACKNOWLEDGMENTS

This material is based upon work supported by the U.S. Geological Survey under Grant No. G19AP00045 & G19AP00046. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Geological Survey. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Geological Survey. The three PIs (Ladinsky, Kelsey, Micalak) and USGS collaborator Witter together acknowledge and thank the following individuals without whom the field work would not have happened:
Sam Bold: Full-time assistance with every aspect of the field work.
Sue Cashman: Field descprition of fault zones and assistance with unit descpritions.
Brian Sherrod: Provided funding of all age analyses for this project
Jason Buck: Photomosaicing.
Maxime Mareschal: Trench logging and surveying.
Nolan Marshall, John Oswald, Sara Gallagher: Logistical (much thanks for all the help moving trench shores!) and mapping support.
John Cook; Gerry and Matt Beck: Land access to the Quail/Swallow and Goose trench sites, respectively.

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TABLE 2. UNIT DESCRIPTIONS, QUAIL TRENCH

Unit	Color (Munsell)	Texture	Comments
1	Moist:10YR4/2 Dk yellowish brown Mottles:5YR5/8 yellowish red	%si: 65 %vfs: 30-40, tr peb %cl: 5-10 Or… %si:5-15 %vfs:85-90 %cl:tr, rounded pebs > 5%	<u>Structure and sediment observations:</u> Facies A – Sandy silt facies Facies B – Gravelly sand channels, comprise ~20% of unit. Mottles- haloes around iron-oxide tube-like root concretions Rare krotovinas filled with A horizon soil. <u>Deformation</u>: Gravel channels are folded and truncated by basal fault. Possible fractures and fissures filled with gravel. Base of unit is a thrust fault. <u>Summary description:</u> Dark yellowish brown silt loam to loamy sand to sand with channels of rounded pebble gravel. <u>Inferred origin of unit:</u> Hookton Formation, fluvial.
2	Moist:7.5YR3/2 to 2.5Y3/1: dark brown to very dark grayish brown Brown mottling.	Unit 2a: %si:20-30 %vfs:50-60 %cl:15-20 Unit 2b: %si:50-60 %vfs:20-30 %cl:15-20	<u>Structure and sediment observations</u>: there is both a sandy facies and a silty faces (see textures) Contains irregular blebs of clean vfs, blebs cross cut the diffuse boundary betw 2a and 2b. Paleo krotovinas and drab haloed vertical root mottles indicative of paleosol. <u>Deformation</u>: No deformation. Maybe sand blebs the result of liquefaction. <u>Summary description</u>: Mottled very dark grayish brown silt loan to sandy loam; lower sandy loam unit (vfs) and upper silty loam unit (vf sandy silt). <u>Inferred origin of unit:</u> The lower unit (2a) may be sourced from the Hookton. The upper unit (2b) is a paleosol that has drab gleyed-colored vert root mottles and paleo krotovinas.
3	Two colors (moist): 10YR3/2 very drak grayish brown; 5YR2.5/1 black. Weak colored mottles: 2.5YR colors	%si:40-50 %vfs: 30 %cl: 20 5% scattered roun pebs	<u>Structure and sediment observations:</u> Massive; subtle sub ang blocky manifest by desiccation cracks; gradual lower boundary over 15 cm; unit pinches out to south at vertical 25m <u>Deformation:</u> Not internally deformed but probably truncated by fault at north end of trench. <u>Summary description:</u> Massive brown to mottled gray brown clayey silt loam with ≤ 5% rounded pebs, thickest in footwall below faults. <u>Inferred origin of unit:</u> Soil developed in alluvial/colluvial unit – the soil could be the upper part of the paleosol described in unit 2b that, over a gradual contact, directly underlies unit 3.
4	Moist:10R2.5/1 reddish black	%si: 30-40 %vfs: 25-30 %cl: 30-35	<u>Structure and sediment observations:</u> Poorly formed indistinct peds: subtle, coarse sub ang blocky. Rare gravel stringers. Lower contact -smooth, planar and very gradual (>15 cm). <u>Deformation:</u> No obvious deformation. <u>Summary description:</u> Massive reddish black clay loam. <u>Inferred origin of unit:</u> Soil developed on alluvium or colluvium.
5	Moist: 2.5YR2.5/1 reddish black	%si:60-70 %vfs:15-20 %cl:15-20 clay loam; in places: gravel	<u>Structure and sediment observations:</u> Common discontinuous gravel lenses (channels): 10-15% of unit – primarily pebs with rare cobble clasts up to 20x15 cm. Abundance of channels increases to south away from scarp and are more abundant on west wall. channels range from disseminated clusters (several cms) up to large channels on west wall, two examples:150 cm long x 20 cm thick and 170 cm long x 10

		channels make up 10-15% of unit	cm thick. Burrows penetrate down into this unit. Root pores with ≤ 5 cm diam. Diffuse, smooth lower boundary ≥ 15 cm thick. Deformation: Undeformed except faulted at north end of trench. Summary description: Reddish black clay loam with discontinuous gravel and cobble lenses up to 170 cm long that are more common at south and west end of trench. Inferred origin of unit: Alluvial / colluvial deposits sourced from slope above trench, may be also sourced from the scarp but not specifically sourced from the scarp at N end of trench (except for perhaps a wedge of unit 5 immediately downslope of fault tips of fault A and fault B).
6a	Matrix (moist): 10YR3/1 very dark gray Mottles: 5YR3/4 dk red	%si: 45-55 %vfs:30-40 %cl:10-20 5-10% peb 5% of unit shows mottled color	Structure and sediment observations: no sedimentary structure, no preferred alignment of pebs. Deformation: hanging wall unit: faulted, unit 6a is bound by fault B above and fault A below. Summary description: very dark gray massive loam to silt loam with 5-10% pebs disseminated throughout Inferred origin of unit: unit is younger than Hookton but now is structurally under Hookton; therefore, thrust underneath Hookton during faulting.
6b	Dry:10YR5/3 brown Wet:10YR3/3 dark yellowish brown	%si: 75 %vfs: 20 %cl: 5	Structure and sediment observations: No obvious fabric, sparse krotovina near upper contact of unit. Deformation: No obvious deformation indicators but unit is involved in faulting or roll over of fault tip. Summary description: Msv dk brown vf sandy silt with trace rounded pebs and cobbles. Inferred origin of unit: Unit is a deformed fault tip and was emplaced as a collapse structure or an underthrust folded structure as a consequence of thrust faulting. Unit is sourced from a combo of unit 1 and whatever was the darker unit overlying unit 1 at the time of thrust faulting.
7	7.5YR2.5/1 black	%si:55-65 %vfs:25-35 %cl:10-20 tr rounded pebs	Structure and sediment observations: Poorly formed indistinct peds med to coarse sub ang blocky, trace roots pores. Wavy lower contact over 5-15 cm. Deformation: Faulted – underlies fault tip of fault A Summary description: Black silt loam Inferred origin of unit: Soil developed on unit 5
"plow zone"	7.5YR2.5/1 black	%si:78 %vfs:10 %cl:12 rounded pebs 1-2%	Structure and sediment observations: Massive to weak sub ang blocky structure, blocks 3-6 cm size. Discontinuous vertical fractures, mostly near contact with unit 8. Southern upper boundary is clear over 3 cm. Northern upper boundary is gradual over 10 cm. Deformation: Faulted. Bottom boundary is fault A. Vertical fractures may be related to downslope translation of this unit from next upslope unit (i.e., unit 6b). Summary description: Black sit loam with trace rounded pebs. Inferred origin of unit: Slope colluvium generated by collapse of hanging wall.
8	Three observations: 10R 2.5/1	%si:60-70 %vfs:20-30	Structure and sediment observations: Vertical fracture fabric irregularly developed throughout unit. Irregular vertical fractures repeat like stacked dominoes, 10 cm long.

	reddish black 2.5YR2.5/1 reddish black 7.5YR2.5/1 black	%cl:10-20	Deformation: Not faulted. Summary description: Black to reddish black silt loam with obvious vertical fracture fabric. Inferred origin of unit: Colluvial wedge generated by faulting. Overlies tip of fault A.
9	5YR2.5/1 Black or… 10YR3/1 Very dark gray	%si: 40-80 %vfs: 10-50 %cl:10-20 silt loam to loam in steeper parts of scarp > 5% rounded pebs	Structure and sediment observations: Moderate soil structure – medium granular to med coarse sub ang blocky. Sparse crotovinas. Smooth, clear to abrupt lower boundary over <2 to 5 cm. Lower boundary parallels ground surface and characterized in part by burrows filled with silt from above. Deformation: Not deformed. Summary description: Black loam, has scattered angular clasts of Hookton. Inferred origin of unit: Surface soil on scarp slope; colluvial soil.

TABLE 3. UNIT DESCRIPTIONS, GOOSE TRENCH

Unit	Color (Munsell)	Texture	Comments
8	Wet: 10YR2/1 very dark brown to black	%si:>95 Trace, or less than 5% pebble gravel	Structure and sediment observations: Soil structure is strong, medium to coarse granular structure. Abundant very fine to medium vertical roots. Penetrated by Krotovina. Appears as a till zone. Deformation: No observed deformation. Summary description: Black silt. Inferred origin of unit: Soil A horizon developed in silt.
7 [C1, C2, C3]	Matrix: 10YR4/6 dark yellowish brown Dry: 10YR5/6 yellowish brown	%si:60-70 %ms-cs:30-40	Structure and sediment observations: Mostly disorganized clasts with no obvious preferred orientation, but some subvertical orientation for many clasts. Notable large clast size (Yager Formation ss) is maximum of 80cm, other dimensions of 45cm; the clast is punky, quite weathered. Other large clast is 40cm x 23cm, busted up, weathered. Another large fractured clast 10cm x 5cm completely fractured. Deformation: Faulted: collapsed colluvium generated by faulting. Summary description: Yellowish brown clast-supported rounded to subrounded pebble gravel with 20% cobbles. Inferred origin of unit: Colluvium deposited in an extensional fissure.
6	Wet:10YR3/2 very dark grayish brown	%si:>95 Trace, or less than 5% pebble gravel	Structure and sediment observations: Moderate medium angular blocky soil structure. Penetrated by krotovina. Few very fine vertical roots. Root pores and large diameter tubes. Deformation: No deformation. Summary description: Very dark brown silt. Inferred origin of unit: Weathering from soil formation in parent material forming silt. Aeolian silt.
5	Two colors: 1. Light gray: (wet):10YR6/4 light yellowish brown (dry):2.5YR7/4 pale yellow 2. Medium orange: (wet):10YR5/4 pale yellow (dry):10YR6/8 brownish yellow	1. light gray: %si:85-95 %cs:5 %cl:5 2. medium orange: %si:85-95 %cs:5 %cl:5	Structure and sediment observations: Prominent tongue features are light colored. Their horizontal width is 5-30cm, extending from top of unit to 45cm below top. Separates irregular bodies of mottled silt between tongue features. Rare krotovina. Very fine roots growing along tongue features. Deformation: Undeformed at description and sample location. Possibly folded in northern deformation area. Summary description: Mottled pale yellow to yellowish brown silt, trace coarse sand with a few disseminated pebbles. Inferred origin of unit: Slackwater near alluvial stream because of presence of pebble gravel. Strong soil development.
4	Wet:10YR5/4 yellowish brown	%si:80-90 %vfs:5-15 %cl:0-10 trace rounded pebbles	Structure and sediment observations: Distinctive subvertical tongues lined with Manganese and iron oxide. Tongues cover 10-20% of unit. Deformation: Folded at deformation zone in north end of trench. Southern side undeformed. Lower contact abrupt (>2cm), smooth.

			<u>Summary description:</u> Yellowish-brown silt with vf sand, trace rounded pebbles. <u>Inferred origin of unit:</u> Slackwater deposit, distal to alluvial channel.
3a	Dry:10YR2/2 very dark brown Moist:10YR2/2 very dark brown	%si: 85-95 %cl: 0-10 %vfs: 5 40-50% pebble/cobble gravel, 50-60% matrix	<u>Structure and sediment observations:</u> Matrix-supported gravel deposit, clasts are rounded to subrounded. Crumb structure in very dark brown matrix; strong, fine, granular. Abundant vertical roots. <u>Deformation</u>: South end of deposit collapses into colluvial wedge that buries folded silt beds and other colluvium. <u>Summary description:</u> Very dark brown silt with 40-50% rounded to subrounded pebbles and cobbles. Saturated as a surface soil. <u>Inferred origin of unit</u>: Alluvial deposit that has been isolated from source channel and subsequently mixed with silt.
3	Matrix (dry): 10YR6/4 light yellowish brown Matrix (moist): 10YR5/4 yellowish brown	%vfs-cs:50-60 %si:30-40 %cl:5-15 70% pebble gravel, 20% silty sand matrix, 10% cobble	<u>Structure and sediment observations:</u> Clast-supported, weak to moderate imbrication. Slight inclination of clasts to north, except where clasts are collapsed into fissure to south. <u>Deformation:</u> Flat-lying strath cut-off/truncated by down-to-south faulting <u>Summary description:</u> Clast-supported, weak to moderately imbricated light yellowish brown pebble gravel with minor cobble. <u>Inferred origin of unit:</u> Alluvial deposit.
2b	10YR5/3 brown matrix	%si:70-80 %cs: 20-30 70-80% material coarser than sand to pebble. Rare cobbles.	<u>Structure and sediment observations:</u> Weakly imbricated, lacks clear channel cross-bedding, appears upper unit may have infiltrated gravel downward. Matrix % increases as unit shallows in depth. Varies within unit, but up to 30-40% gravel at top of unit. <u>Deformation:</u> Folded near deformation zone in north area of trench. <u>Summary description:</u> Brown silty pebble gravel, matrix-supported. <u>Inferred origin of unit:</u> Alluvial stream transitioning to slackwater pond.
Red sand Unit	10YR4/4 dark yellowish brown	Matrix: 85-95% sand, 5-15% pebble gravel	<u>Structure and sediment observations:</u> Localized deposit limited between C9 and C14 of grid. Lower contact is abrupt over 2cm and smooth. Pebbles well imbricated. Sand matrix supported. At base cuts black gravels below lime flags. <u>Deformation:</u> No deformation. <u>Summary description:</u> Brown fine to medium sand with coarse sand and granule to pebble-sized gravel. <u>Inferred origin of unit:</u> Alluvial channel sand.
2a; north of inclined clay block	Two colors (dry): 10YR5/4 yellowish brown, minor matrix isolated beneath cobble; (dry): 10YR4/4 dark yellowish brown,	Minor matrix: %cl:70-80 %si:20-30 General matrix: %fs-cs: 65 %si: 20 %cl: 15 55% gravel	<u>Structure and sediment observations:</u> Clast-supported, weakly imbricated cobbles/pebbles. <u>Deformation:</u> Strath on top of unit 1a is tectonically tilted to the north. <u>Summary description:</u> Clast-supported, weakly imbricated, dark yellowish brown pebble cobble gravel with clayey sandy loam matrix. <u>Inferred origin of unit:</u> Alluvium.

	more general matrix color		
2a	10YR4/3 dark brown	%si: 30-40 %vfs: 25-30 %cl: 30-35 60-70% pebble gravel, 20-30% coarse sand, 5-15% cobbles	Structure and sediment observations: Matrix-supported, appears to be cut by strath surface. Weakly imbricated, dipping </=56NE based on one clast. Deformation: Faulted in northern deformation area. Summary description: Dark brown cobble gravel with clay coatings. Inferred origin of unit: Alluvial channel. Carlotta Fm.
1a	Two colors: 4Y4/1 dark gray 10YR4/3 brown	Gray clay: %cl:90-100 %si:<5 Brown clay: %cl:90-100 %si:<5	Structure and sediment observations: Laminations present in brown clay, but not apparent in dark gray clay. Deformation: Shear zone aligned in orientation with laminations, healed fractures filled with light gray clay. In brown clay, steeply dipping (apparent dip = 60N) laminations. Summary description: Steeply dipping brown laminated clay with minor component of unlaminated dark gray clay. Inferred origin of unit: Lake deposit.

TABLE 4. STRUCTURAL MEASUREMENTS OF FAULTS A, B, AND C, FROM QUAIL TRENCH

FAULT NAME	WALL, LOCATION	TREND† of FAULT TRACE ON TRENCH	PLUNGE of FAULT TRACE ON TRENCH	PLUNGE DIRECTION
A	E, top bench	014°	13°	N
A	E, middle bench	346°	02°	N
A	E, middle bench	010°	05°	N
A	E, middle bench	022°	04°	N
A	E, middle bench	024°	04°	N
A	E, middle bench	020°	08°	N
A	E, lowest bench	020°	15°	N
A	E, lowest bench	021°	11°	N
A	W, lowest bench	025°	11°	N
A	W, middle bench	025°	01°	N
A	W, upper bench	018°	01°	N
B	E, middle bench	028°	15°	N
B	E, middle bench	022°	08°	N
B	E, lowest bench	324°	02°	E
B	E, lowest bench	324°	11°	E
B	E, lowest bench	022°	12°	N
B	E, lowest bench	025°	21°	N
B	E, lowest bench	020°	11°	N
B	N, lowest bench	303°	06°	W
B	W, lowest bench	022°	19°	N
B	W, middle bench	353°	02°	N
B	W, middle bench	021°	03°	N
B	W, middle bench	022°	03°	N
C	E, lowest bench	324°	11°	E
C	E, lowest bench	316°	09°	E
C	E, lowest bench	023°	09°	N
C	E, lowest bench	019°	11°	N
C	N, lowest bench	298°	0°	-
C	N, lowest bench	298°	03°	E
C	W, lowest bench	036°	14°	N
C	W, lowest bench	252°	17°	W

†Magnetic declination on Brunton compass set to 14°E

Fault A is the structurally lowest fault in Quail trench, followed by Fault B (middle) and Fault C (structurally highest)

Cylindrical planes of best fits for each data set are:

Fault A: N32°W, 09°NE

Fault B: N55°W, 11°NE

Fault C: N73°E, 11°NW

TABLE 5. FAULT DESCRIPTIONS OF FAULTS A, B, AND C, FROM QUAIL TRENCH

FAULT NAME	WALL, LOCATION	NOTES
Fault A Structurally lowest	E wall, middle bench	Fault A is within black silty loam with scattered disseminated coarse sand grains and small pebbles. Fault is conspicuous because of tan, sandy zone that delineates fault. surface (zone ranges in thickness from 2-60mm, but is generally 5-20mm) An irregular crack with minor wavy surfaces, amplitude 1-2mm, wavelength 10-25mm, runs within, and generally near the base of the tan sandy horizon. At its thickest, fault zone has asymmetric, wavy flow/flame structure with a locally developed S-C fabric. Records dextral, top-to-SW shear.
Fault B Structurally middle	E wall, middle bench	Fault B is conspicuous observed at a distance due to color contrast, tan color over black. Fault places tan (Hookton) over hard black silty loam. Close-up view shows a diffuse fault zone >/= 15cm thick. Fault complexities include corrugations 0.5-2.5cm in amplitude and spaced 5-15cm apart; mixed-color shear zones 5-15cm thick incorporate both tan sand and hard black silty loam; lenses of tan sandier material within black silt loam unit and 5-10cm below fault trace. Texture is reminiscent of S-C fabric. Hanging all of fault displays a rounded, overturned anticline. Fold is evident by tan sand- black silty loam contact and by pebble-rich beds that are folded in the tan sand unit.
Fault C Structurally highest	W wall, middle bench	Shear fabric developed at southernmost tip of Fault C on west wall of trench. Tan, fine sand interbedded with dark brown silt shows S foliation, strung-out tips of sandstone laminae shows C foliation.

TABLE 6. RADIOCARBON AGES AND CALIBRATED AGE RANGES FROM QUAIL TRENCH SITE, HYDESVILLE, CALIFORNIA

Sample no.	Unit	Sample material	Analytical age*	Calibrated age†	δ13C (‰)§	Laboratory number #
Qu-4-1	8	Single charcoal fragment 4x1.5x1 mm	115±15	20-260	NR	OS-156814
Qu-4-3	8	Single charcoal fragment 4x3x1 mm	340±30	310-480	NR	OS-155090
Qu-39-1	8	9 charcoal fragments, 6 seed fragments 3 conifer needle fragments, 1 small stem	modern	modern	NR	OS-156818
Qu-39-2	8	Approximately 50 charcoal fragments	1070±20	920-1060	NR	OS-156819
Qu-2	7	16 charcoal fragments, two seed fragments	1920±15	1740-1890	NR	OS-156817
Qu-3-3	7	Conifer needle, 9 mm long	modern	modern	NR	OS-156813
Qu-3-4	7	Single charcoal fragment, 5x2x1 mm	330±20	310-460	NR	OS-156775
Qu-33-1	6b	Single charcoal fragment 6x3x2 mm	2160±30	2000-2310	NR	OS-155088
Qu-15-1	6a	Single charcoal fragment with branch node, 3x2x2mm	4720±20	5320-5580	NR	OS-156816
Qu-40-1	5	Single charcoal fragment 4x4x1 mm	2070±25	1940-2120	NR	OS-155091
Qu-40-2	5	Single charcoal fragment, woody fabric, 4x2x1mm	1820±25	1620-1820	NR	OS-155089
Qu-9	5	Single charcoal fragment	2060±30	1930-2120	-28.0	B-542429
Qu-6-3	4	Single charcoal fragment, woody fabric, 9x2x1.5mm	7420±30	8170-8340	NR	OS-156815
Qu-1	1	Wood fragment	7880±30	8590-8980	-22.2	B-542428

* Age reported by Beta Analytic, Miami, Florida, or by the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS), Woods Hole, Massachusetts, USA.
† Calibrated age range (cal yr B.P.) in solar years before 1950 CE (95% probability distribution at 2s), calculated using OxCal version 4.2.4 (Bronk Ramsey, 2009) employing the IntCal13 data set of Reimer et al. (2013).
§ NR: δ13C values measured on the accelerator but were not reported; however, the analytical radiocarbon result was corrected for isotopic fractionation.
\# B- Beta Analytic laboratory number; OS- Accession numbers supplied by the National Ocean Sciences Accelerator Mass Spectrometry Facility.

APPENDIX A:

Soil Descriptions: Tables A1, A2, A3, A4 and A5

Table A1. Quail Trench soil profile: description at 0.85 m vertical on trench log, Sept 30, 2019; Elevation: 157 m, H. Kelsey describing; S. Bold taking notes.

Horizon	Interval (cm)	Roots	Color	Structure	Texture	Comments
A	0-15	Common Very fine vertical	Dry: 10YR3/3 Wet: 10YR3/1	Weak to moderate, Fine to med crumb	Silt loam 10-12% c 80% si <10% vf sa	Clear, smooth lower boundary over 5 cm
AC	15-29	Very few, very fine	Dry: 2.5Y4/2 Wet: 10YR2/2	Massive	Silt loam 10-12% c 70% si 20% vf sa	Lower boundary is over 5 cm, gradual to clear. Bedrock attributes at C horizon, 65% C horizon and 35% A horizon. Plentiful root casts filled with A horiz material. A horiz roots casts, 0.5-1.5 cm.
1Cox	29-97	No roots	Dry: 2.5Y5/4 Wet: 2.5Y4/2	Msv with scattered rounded to subrounded granules and pebbles, which define discontinuous horizontal beds	Silt loam 8% c 25% sa 67% si	Lower boundary smooth, clear over 2-3 cm.
2Cox	97-123	No roots	Dry: 2.5Y5/4 Wet: 2.5Y4/2	Granule pebble horizontal beds, matrix supported	Matrix same as 1Cox: Silt loam 8% c 25% sa 67% si With 40% matrix and 60% granule/pebble beds	Lower boundary not visible b/c at base of bench tread. Intbd vf sand and granule -to-peb beds, horizontal, in part clast supported.

Table A2. Quail Trench soil profile: description at 5.7 m vertical on trench log, Sept 30, 2019; Elevation: 155 m, H. Kelsey describing; S. Bold taking notes.

Horizon	Interval (cm)	Roots	Color	Structure	Texture	Comments
A	0-20	Few to common, vf to f, vert	Dry: 10YR2/1 Wet: 10YR2/1	Weak to moderate, Fine to vf crumb	Silt loam 10-12% c 86% si 5% vf sa	Clear, smooth lower boundary. This soil is thicker and more colluvial than soil described at 0.85 m vertical
AC	20-36	Few vf vert	Dry: 10YR3/1 Wet: 10YR2/1	Weak, med-fine crumb	Silt 8% c 87% si 5% vf sa	Gradual smooth lwr bound, distinctly more msv than horiz A. 1-2 cm clasts of unit 1 make up 5%. Colluvium parent material.
CA	36-55	No roots to trace vf	Dry: 10YR3/1 Wet: 10YR3/1	Msv to very weak, fine crumb. Distinct clasts of tan colored unit 1, 0.8-2 cm, makes up 10-15% of unit	Silt 8% c 5% vf sa 87% si Rounded to sub round pebbles make up 2-3%, scattered throughout	Lower boundary: over 9 cm, gradual, smooth to wavy. Lower contact of unit 7 is at 48 cm depth. Colluvium parent material.
Cox1	55-69	No roots	Dry: 10YR4/2 Wet: 10YR2/2	Massive	Silt loam 10% c 15% vf sa 75% si	Lower boundary: over 5cm, clear to gradual, smooth
Cox2	69-111	No roots	Dry: 2.5YR4/2 Wet: 10YR3/1	Massive	Silt loam 12% c 78% si 20% f-vf sa	Lower boundary: not observed, base of upper tread

Table A3. Swallow Trench soil profile: top of profile is 100 cm up and 25 cm north of grid point A/5 Sept 18, 2019; Elevation: 153 m, H. Kelsey describing; R. Witter taking notes.

Horizon	Interval (cm)	Roots	Color	Structure	Texture	Comments
A	0-21	Common f-vf	Dry:10YR3/3 Moist:10YR3/2	Moderate-Fine crumb structure	Silt loam 5% c 95% si Tr vf sa	Clear, smooth lower boundary
AB	21-32	Few vf vert	Dry:10YR7/6 Wet:10YR5/4	Weak, f-vf sub ang blocky	Silt loam 10% c 10-15% fn sa 75-80% si	Clear to gradual smooth lower boundary
Bt	32-74	Trace vf vert	Dry: 2.5Y7/4 Mottles: 10YR6/8 10YR2/1 Wet: 10YR6/6	Weak; Fine to med prismatic	Silt loam 15%c 20% sa 65% si	Abrupt, smooth. yellow brown mottles; black manganese mottles deposited along root pores?
Bt2	74-85	No roots	Dry: 2.5Y7/4 Mottles: 10YR6/8 10YR2/1 Wet: 10YR6/6	Weak; Fine to med prismatic	Pebble gravel	Abrupt smooth lwr bound; Clast-supported peb gravel wi Bt
Bt3	85-133	No roots	Dry: 2.5Y8/4 Mottles: 10YR5/6 10YR3/2	Weak, fine sub ang blocky to massive	Silt loam 12% cl 25% sa 63% si	Gradual, sooth; Rounded to sub roun peb float in deposit and in beds up to 3 cm th. soil tongues
Cox	133-333	No roots	Dry: 7.5YR5/8 Wet: 10YR5/6	Massive	10-12% cl 35-40 % sa 48-55 % si	Grey soil tongues <5% of deposit: 3-6 cm clast-supported pebble beds.

Table A4. Goose Trench soil profile: description at 14 m vertical on trench log. Sept 18, 2019; Elevation: 109 m, H. Kelsey describing; R. Witter taking notes.

Horizon	Interval (cm)	Roots	Color	Structure	Texture	Comments
A1	0-19	Common vf vert	Dry:10YR4/2 Moist:10YR3/1	Moderate-Fine-med crumb structure	Silt loam 10% c 70% si 20% vf sa	Abrupt to clear lower boundary, smooth
A2	19-39	Few vf vert	Dry: 10YR3/1 Wet: 10YR2/1	Weak, med-fine crumb	Silt loam 12% c 70-75% si 10-15% vf sa	Abrupt irreg lwr bound, amplitude 10 cm, relief 20 cm (amp = 1/2 wave height)
AB	39-54	Few vf vert	Dry: 10YR4/2 Wet: 10YR2/2	Weak, fine crumb to sub ang blocky	Silt loam 15% c 15% vf sa 70% si	Clear wavy lower boundary, relief of 8 cm
Bt1	54-80	Zero to trace vf vert	Dry: 2.5YR6/3 Wet: 2.5YR4/2	Weak; Fine to med sub ang blcky	Silt loam 15%c 15% f-vf sa 70% si	Clear, irregular bound with relief of 20 cm. Weak visible orange mottles, Incipient E-horizon??
Bt2	80-122	No roots	Grey-brwn chunks Dry: 10YR4/4 Wet: 10YR5/4 The rest: Dry: 2.5YR6/3 Wet: 2.5YR4/2	Msv to Weak fine to med sub ang blocky	Silt loam 15% c 70% si 15% sa	Clear smooth boundary, Orange and dark brown mottles
2Cox	122-149	None to tr vf vert	Dry: 10YR4/3 Wet: 10YR6/6	Massive: Sandy silt	Loam 8% cl 45% vf sa 47% si	Abrupt to clear, sooth; vertically oriented black blebs possibly along roots
3Cox	149-174	No roots	Wet: 10YR5/64	Massive: 45% gravel	Matrix texture: Sandy loam 8% cl 32 % si 60 % vf to c sa 45% gravel	Clear, smooth boundary, Matrix supported gravel, 45% gravel
4C	174-240	No roots	10YR4/3 Brown Looks dk brown	Massive:	Stratigraphic unit 2: 60-70%. peb 5-15% cob 20-30% cs Matrix: cs with clay coats	Parent material is strat unit 2a: clast-supp dark yellowish brwn cobbly peb grvl with clayey coating on clasts

Table A5. Summary of field soil observations, trench sites near Hydesville, CA

Trench site, vert (m) grid location	Elevation	Parent material	Bt thickness (cm)	Depth to base of Bt (cm)	Max clay in Bt (%)	Depth to top of Cox (cm)	Depth to base of Cox (cm)
Quail, 0.85 vert	157 m	Hookton Fm	No Bt	No Bt	No Bt	29	>123*
Quail, 5.7 vert	155 m	Colluvium	No Bt	No Bt	No Bt	55	>111*
Swallow, 5.0 vert	153 m	Hookton Fm	101	131	15	133	333
Goose, 14 vert	109 n	Clast-supported alluvium	68	122	15	122	174

*Soil description is truncated at the depth of tread in the benched trench

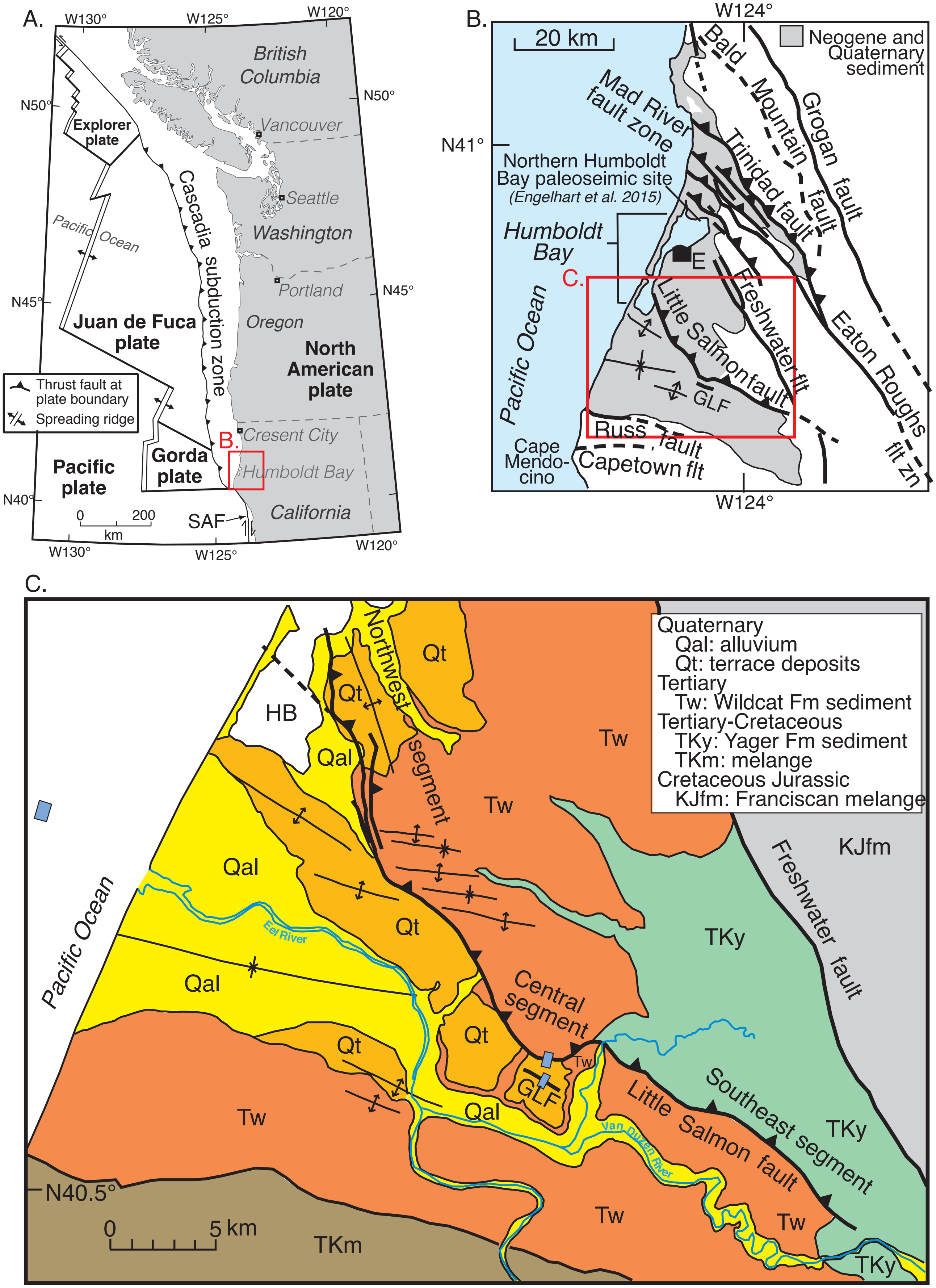


Figure 1. (A) Plate tectonic location map SAF, San Andreas Fault. (B) Upper plate faults and folds in the Humboldt Bay, northern California area. E, Eureka; GLF, Goose Lake Fault. (C) Geologic map of the Little Salmon fault. Blue boxes depict study areas. GLF, Goose Lake Fault; HB, Humboldt Bay.

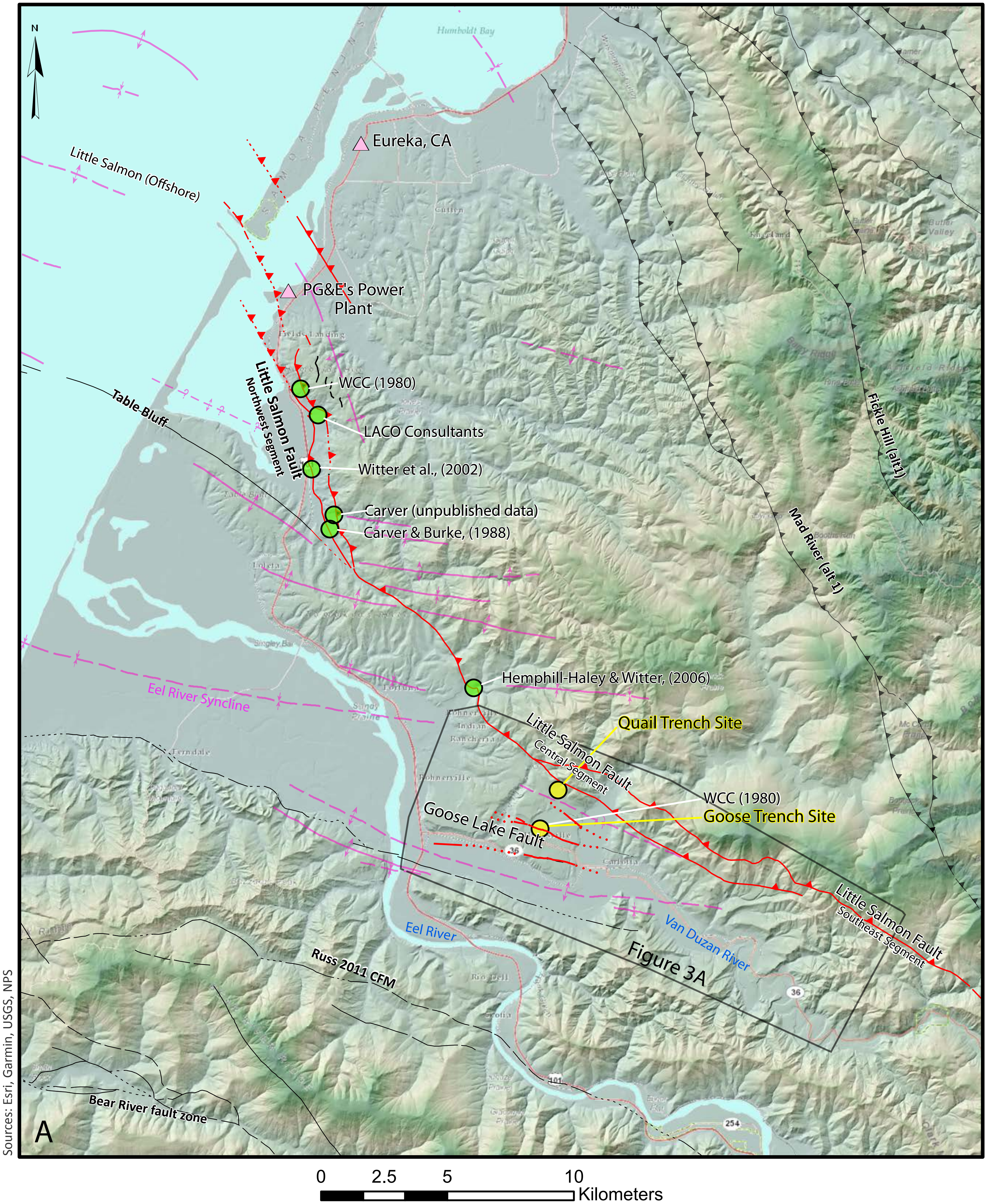


Figure 2. 10-meter hillshade map of southern Humboldt Bay, California. Red lines depict fault scarp mapping of the Goose Lake fault and Little Salmon fault; dotted where approximated or inferred. Black lines denote regional Quaternary faults as depicted by Jennings (1994). Purple lines represent regional folds from McLaughlin et al. (2000) at 1:100,000. Green circles denote prior paleoseismic investigations along the Little Salmon Fault Zone. WCC- Woodward Clyde Consultants.

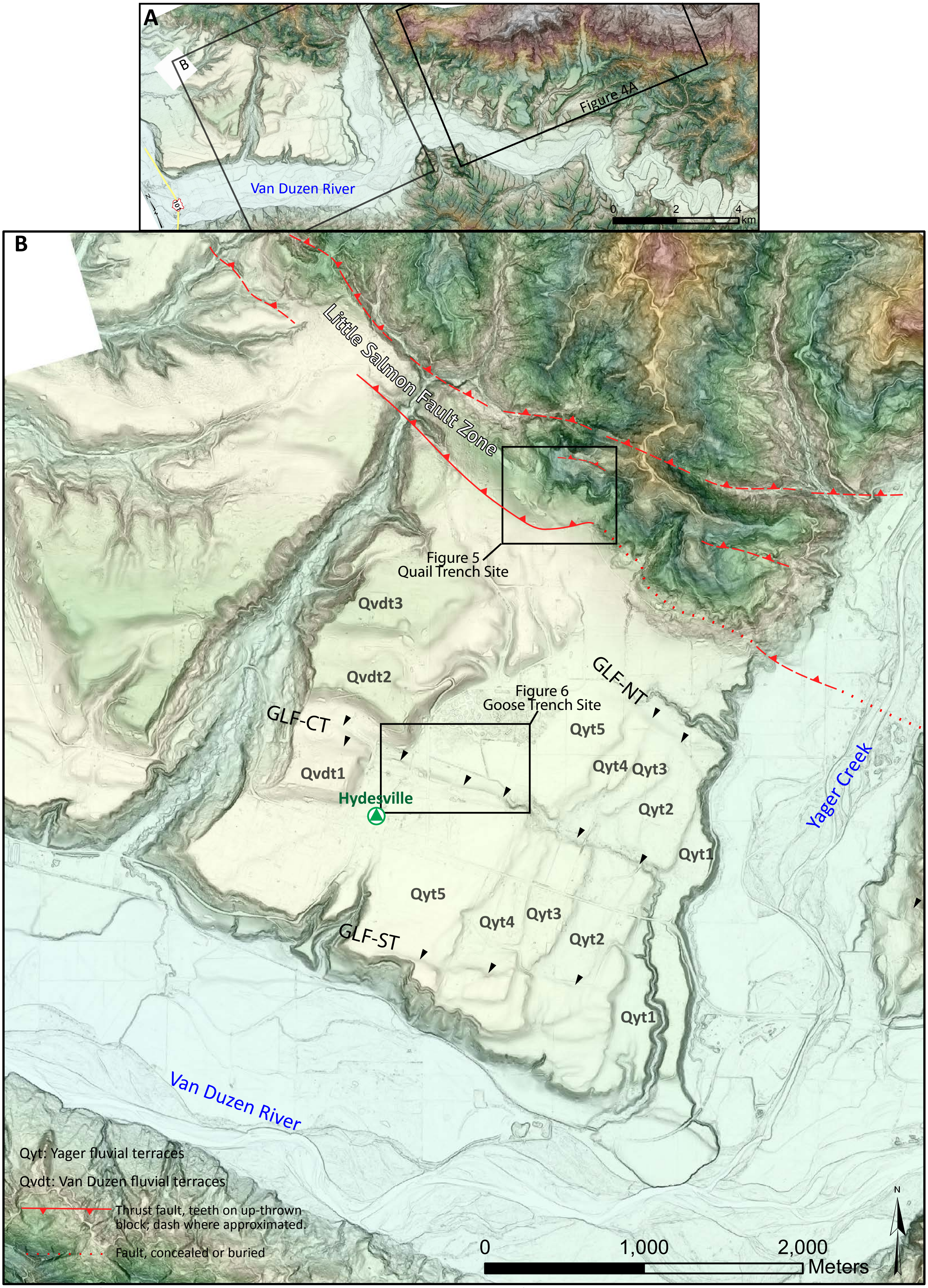


Figure 3. A) Lidar slope-map of the Van Duzen River Basin. B) Lidar slope map of Hydesville, California. Red lines denote revised mapping of the LSF from the NCALM Earthscope NorCal (2007) lidar data. Black arrows delinate geomorphic expression of the Goose Lake fault traces, GLF-NT, Goose Lake fault, northern trace; GLF-CT, Goose Lake fault, central trace; GLF-ST, Goose Lake fault, southern trace.

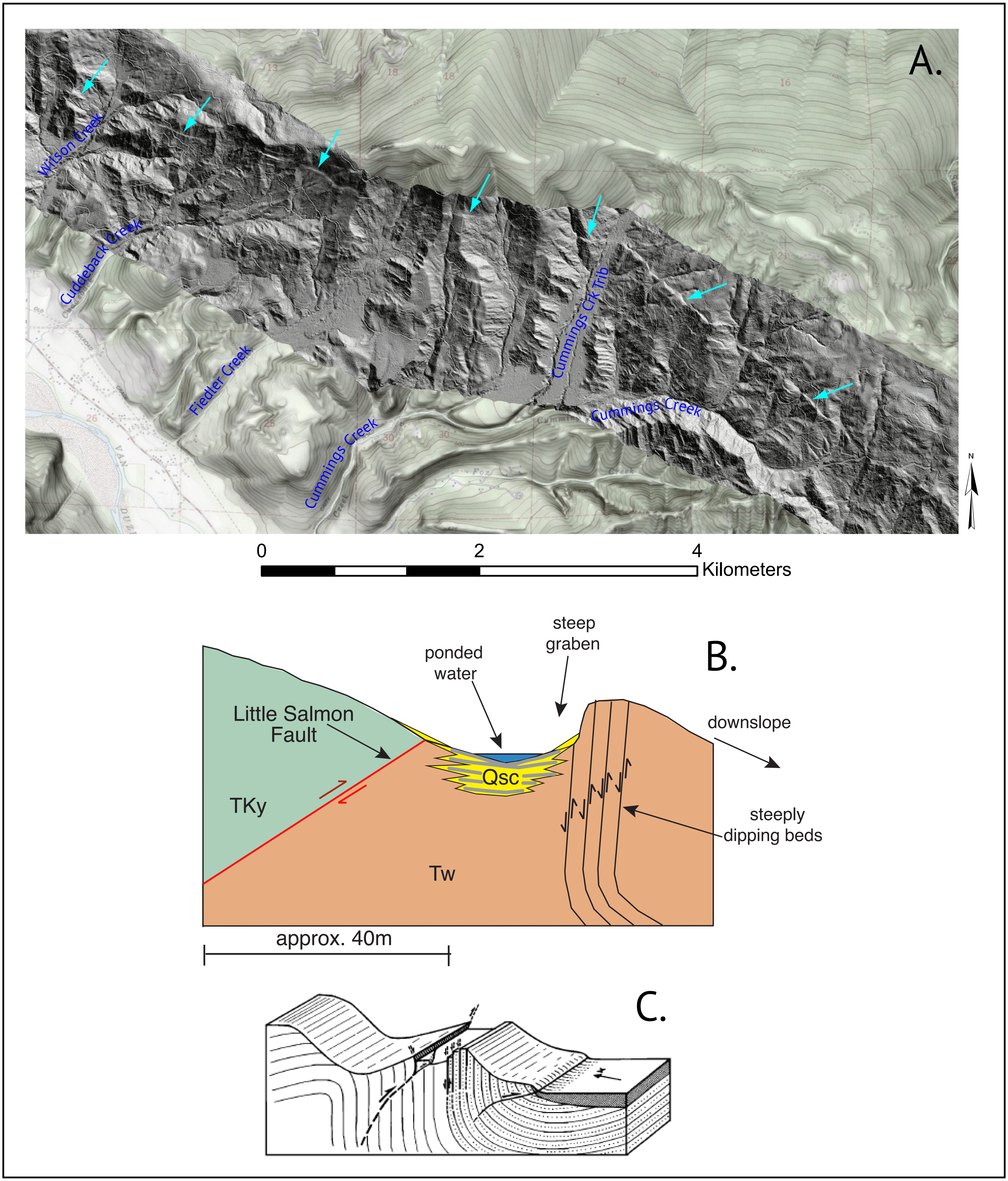
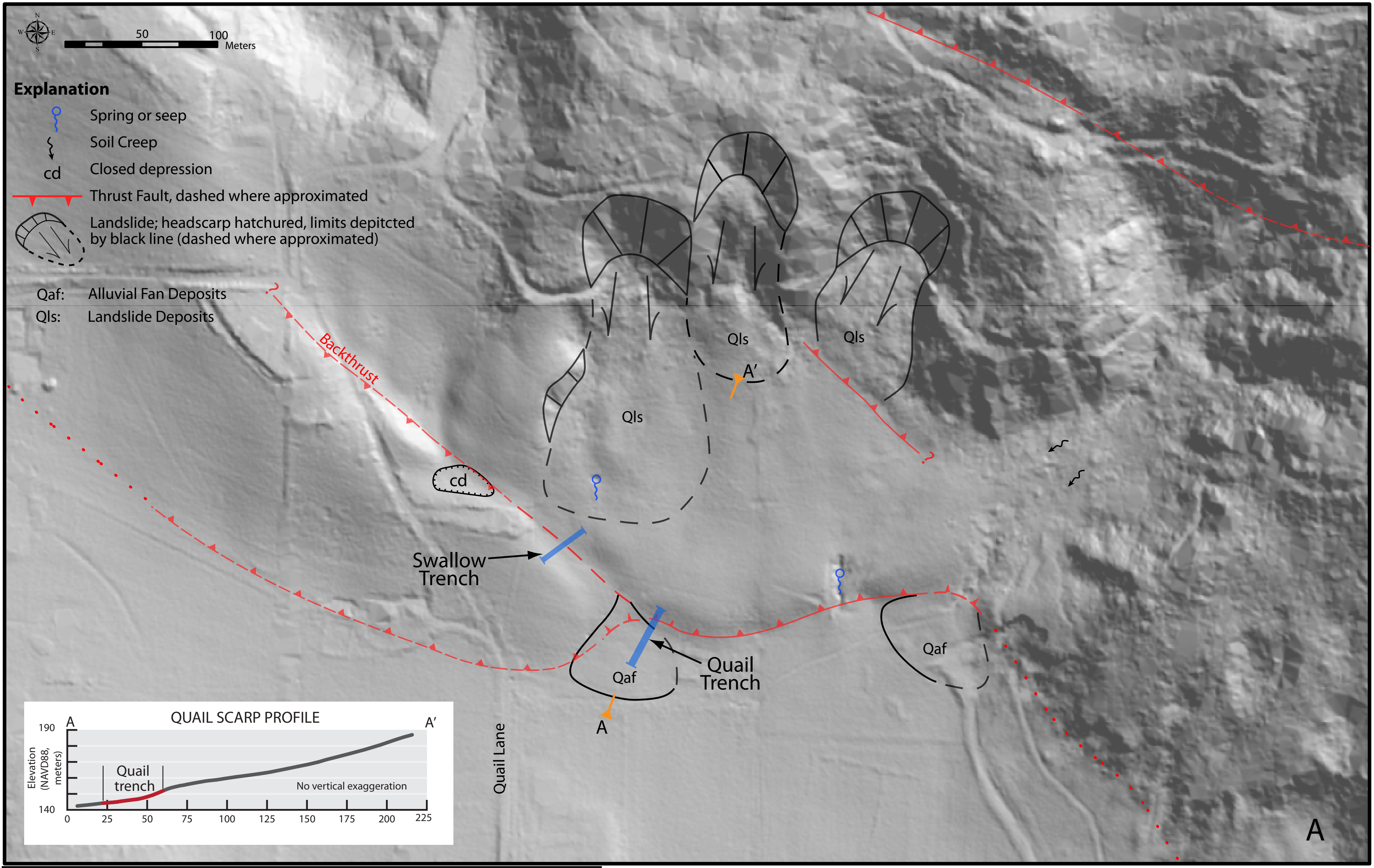


Figure 4. A) lidar swath (hillshade, 1-meter resolution) of the southeastern segment of the Little Salmon Fault (LSF) shown on backdrop of a 10-meter DEM basemap. Teal arrows denote prominent hillside bench traversing the landscape; the bench is the Holocene scarp expression of the LSF. B) Field sketch of geomorphic cross section across hillside bench in southeastern segment. Tw, Tertiary Wildcate Group Neogene Sediment. Tky, Tertiary-Cretaceous Yager Formation sediment. Qsc, Quaternary scarp-derived colluvium. C) Schematic model from Figure 24 of Philip and Meghraoui (1983) showing compressional setting with apparent normal geometry.



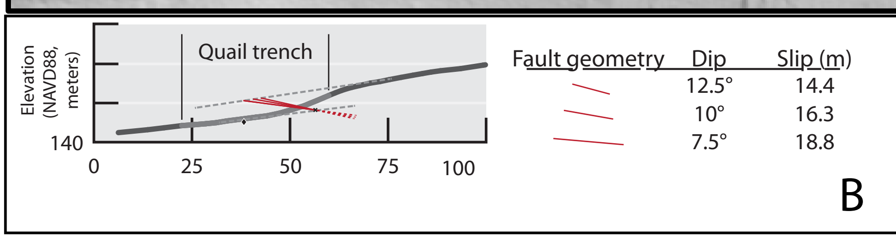


Figure 5. A) Quail trench site geomorphic map. Basemap composed of hillshade image. Basemap layers derived from 1-meter LiDAR ditigal elevation map NCALM Earthscope 2007. B) Calculations of total slip on the LSF based on three different fault angles and a given scarp height of 5.2 meters.

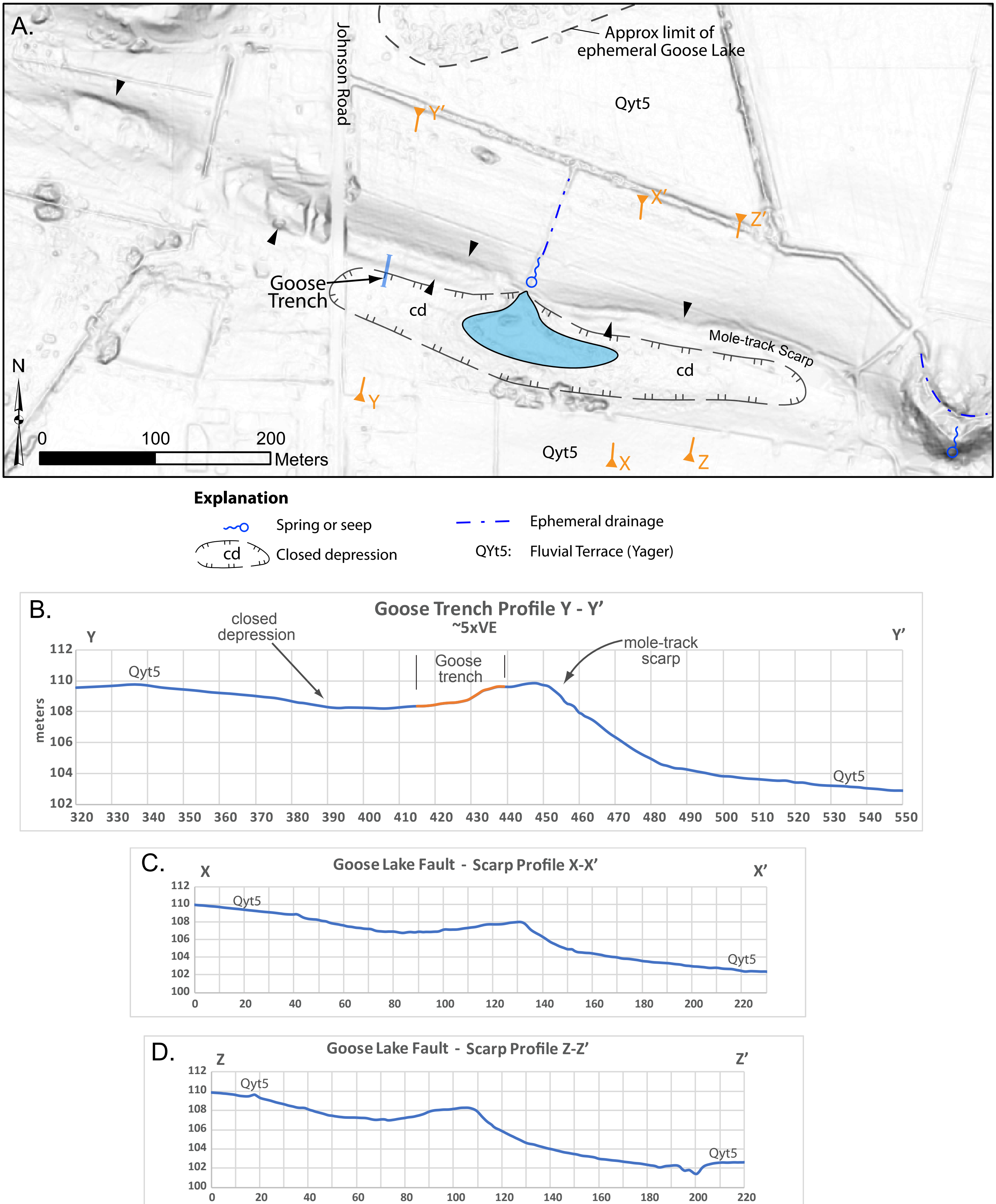


Figure 6. A) Geomorphic map of the Goose trench site. Black arrows depcit north and south-facing scarp of the GLF - central trace. Basemap composed of slope-shade. B) Scarp profile of Goose Lake fault - central trace based on Trimble 7X GPS mapping. C) GLF scarp profile of central trace. D) GLF scarp profile of central trace.

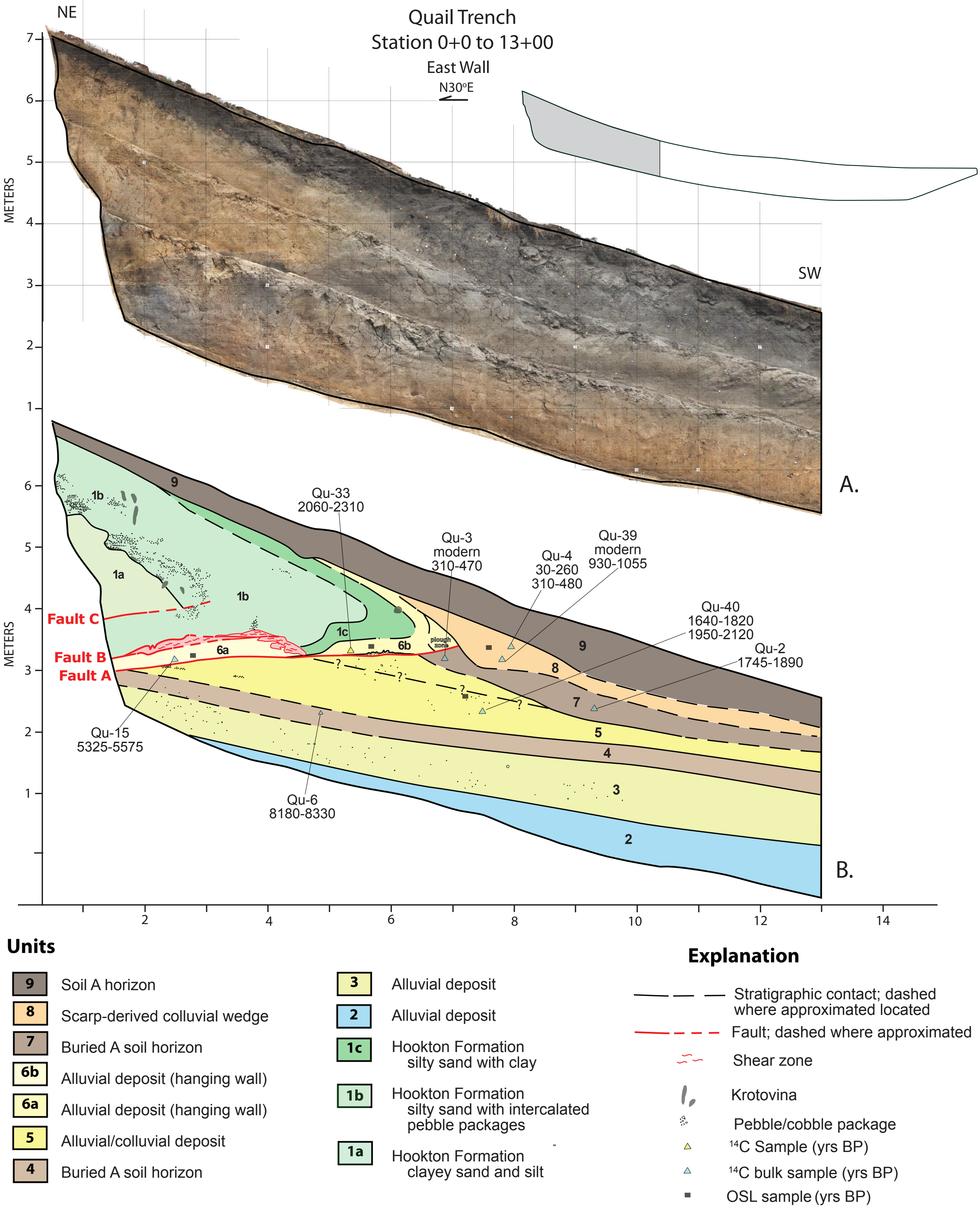


Figure 7. A) Uninterpreted photomosaic of Quail trench. B) Interpreted trench log. ^{14}C ages represent calibrated age with 2-sigma standard deviation displayed in years before present (BP).

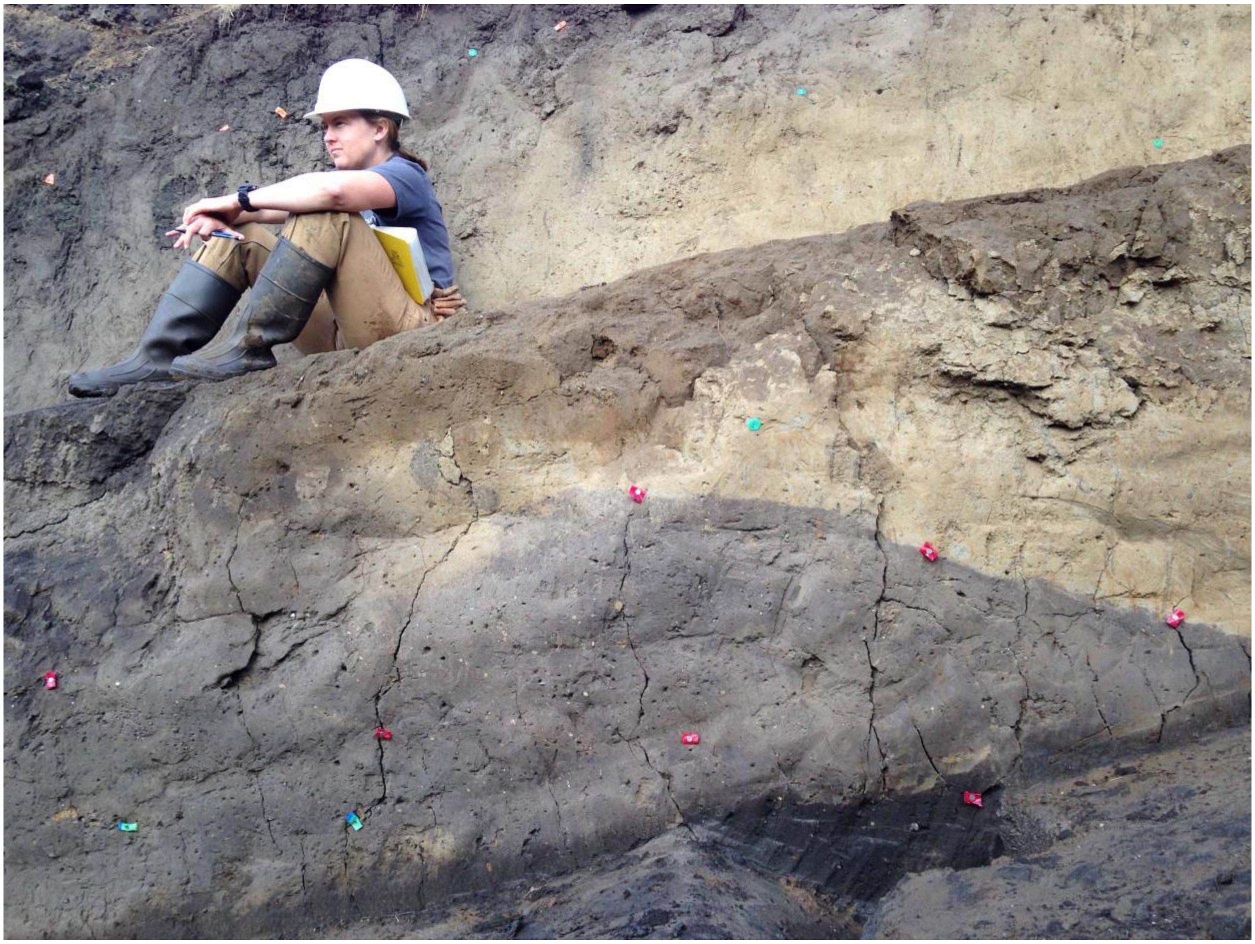
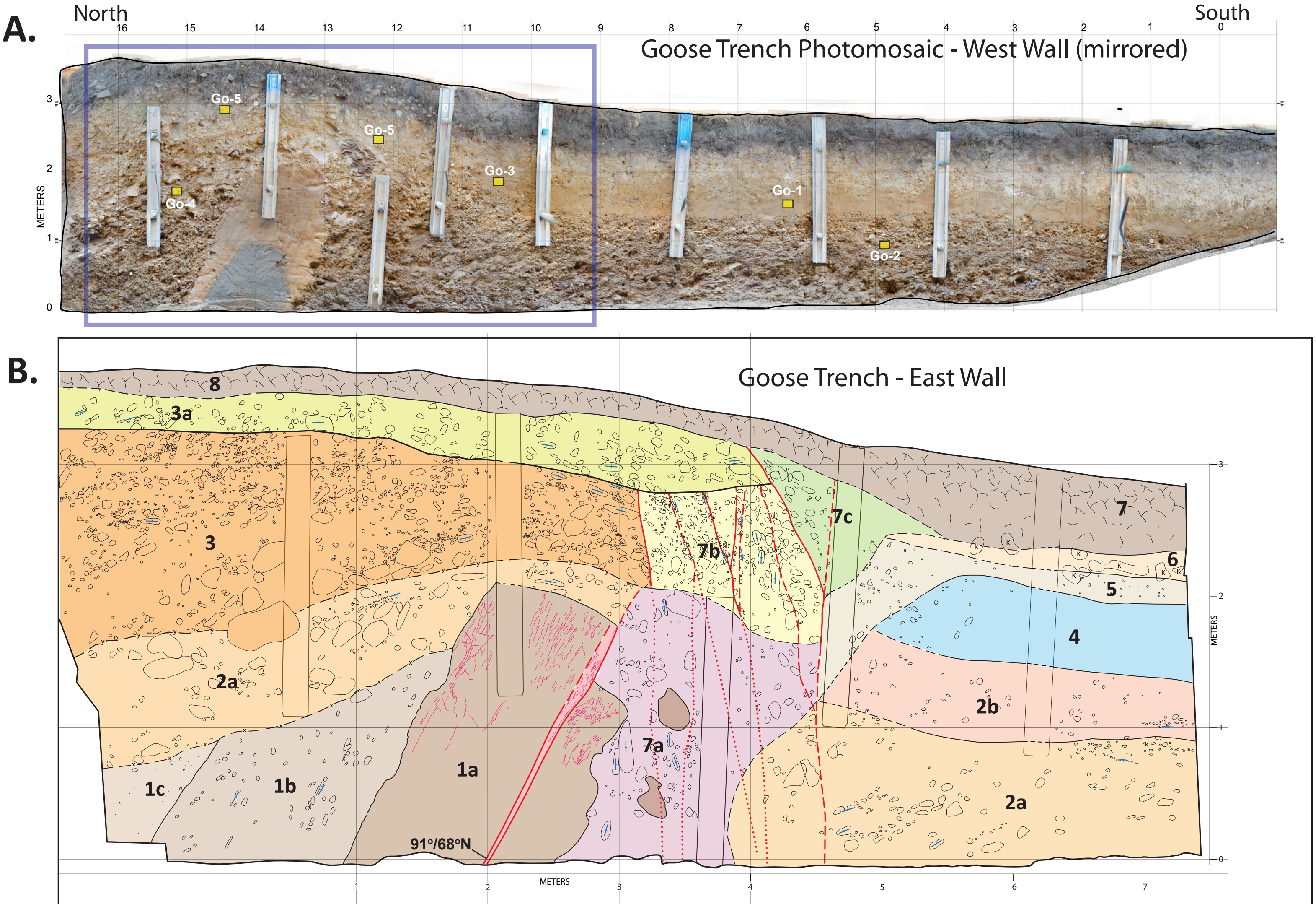


Figure 8. Photograph showing two low angle thrust faults, fault A (structurally lowest) and fault B, both exposed in the west wall of Quail trench. Both faults are flagged with red flagging tape. Fault B is obvious from the color change. Fault A juxtaposes black silt on black silt with a thin, discontinuous selvage of sand at the fault contact, and is less obvious. Photo shows fold in hanging wall of fault B (below seated person). The fold, depicted both by tan sand-black silt loam contact and by pebble-rich beds in the sand unit, is a rounded overturned anticline. Co-PI Michalak for scale. Photo by S. M. Cashman



Units

8	Soil A horizon
7c	Fissure fill/ sub-vertical imbrication
7b	Fissure fill/ sub-vertical imbrication
7a	Colluvium/alluvium; choatic internal structure
6	AB soil horizon
5	Slackwater deposit; few pebbles
4	Slackwater deposit; silt with clay
3a	Fluvial terrace deposit; matrix supported gravel
3	Fluvial terrace deposit; clast supported gravel
2b	Fluvial terrace deposit; matrix supported gravel
2a	Fluvial terrace deposit; clast supported gravel
1c	Carlotta Formation Sand, medium to coarse-grained
1b	Carlotta Formation Pebble gravel
1a	Carlotta Formation Claystone

Explanation

- Stratigraphic contact; dashed where approximated located
- Fault; dashed where approximated, dotted where inferred
- Shear zone
- —x— x Strath surface
- —y— y Strath surface
- Pebble/cobble clasts
- Clast imbrication orientation
- Rootlets
- (K) Krotovina
- OSL sample s

Figure 9. A) Uninterpreted mirrored photomosaic of Goose Trench with OSL sampling locations. B) Interpreted trench log of east wall of Goose Trench.