QUATERNARY DEFORMATION OF THE HOG RANCH-NANEUM ANTICLINE REGION NORTHEAST KITTITAS VALLEY, WASHINGTON

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ABSTRACT

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Geomorphic evaluation of the northeastern Kittitas Valley and Hog Ranch-Naneum Anticline (HRNA) region provides new insight into the recent deformation and uplift of Quaternary faults along the northern range front of Kittitas Valley. I conducted LiDAR and landform mapping as well as a suite of geomorphic analyses to assess recent faulting in northeastern Kittitas Valley potentially linked to Quaternary deformation of the HRNA area. Upon generation of normalized channel steepness (K_{sn}) maps, the northeastern basin front was identified as a starting point for additional geomorphic analyses, LiDAR mapping and focused field truthing/mapping. I identified a flight of six strath river terraces near the entrance of Coleman Creek into Kittitas Valley. I also identified knickpoints and knickzones along the southern basin front which I was able to correlate to the knickpoint groupings along Coleman Creek. Based on geomorphic evidence and LiDAR mapping two fault scarps were identified; the Facet fault located at the base of the range front and the Dead Coyote fault located ~2 km south of the range front. Regional geologic mapping and aeromagnetic data suggests that initial tectonic uplift along the HRNA predates the Yakima folds. Exact ages of newly identified faults are unknown. The presence of uplifted strath surfaces within Kittitas Valley suggests a more recent deformation history based on the premise that the landscape within the fold province and HRNA was reset to relatively level relief ~15.6 Ma following the emplacement of the Grand Ronde Basalt member of the CRBG; deformation seems to have continued into the Quaternary (Kelsey et al., 2017 and Reidel, 1989).

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ACKNOWLEDGMENTS

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INTRODUCTION

The Hog Ranch-Naneum Anticline (HRNA) region of northeastern Kittitas Valley (Figure 1) sits on the northern end of the compressional tectonic regime forming the Yakima Folds in central Washington State, east of the Cascade Mountains (Kelsey et al., 2017, Staisch et al., 2018). The Yakima Folds are a series of east-west oriented, parallel, primarily north-verging, asymmetrical fault-cored-folds which deform the Columbia River Flood Basalt Province (Figure 1) (Reidel et al., 1989, Staisch at al., 2018, Crane and Klimczak, 2019). In contrast, the HRNA is a generally north-trending fold that cuts across the Yakima Folds. The Yakima Folds and HRNA are in the back-arc of the Cascadia Subduction Zone, a plate boundary deformation zone between the North American plate and subducting Juan de Fuca plate (Wells et al.,1998) (inset map, Figure 1).

The Columbia River Basalt Group (CRBG) is the predominant lithology within the Yakima Folds and Kittitas Valley. The CRBG consists of thousands of vertical meters of basalt with flow members dating to the mid to late Miocene (Reidel et al., 1989). The primary CRBG flows within the study area include the Grande Ronde, Wanapum and Saddle Mountains basalts (Reidel et al., 1989). The landscape within the Yakima fold province was reset to relatively level relief at 15.6 Ma following the emplacement of the Grande Ronde Basalt member of the CRBG (Kelsey et al., 2017). The CRBG originally erupted and flowed laterally, filling voids, gaps and topographic lows, forming a set of horizontal layers, which provides an excellent datum for recording folding and faulting in this region (Blakely et al., 2011).

This investigation of the northern Kittitas Valley aims to examine, through field investigations and topographic analysis, evidence and mechanisms for Quaternary fault motion and/or deformation within the northeastern Kittitas Valley and HRNA. In doing so, I address outstanding questions such as: what accounts for the topographic expression of the northeastern Kittitas Valley and HRNA/Mission Ridge area? Is there evidence for base level fall and active faulting in the northeastern Kittitas Valley?

The Tabor et al. (1982) geologic map of the Wenatchee quadrangle provides a 1:100,000 map of the northern portion of the study area and documents several faults within the northern Kittitas Valley, and along the HRNA's northwestern flank. Waitt (1979) examined Quaternary geology of the Kittitas Valley and documented faults that offset Quaternary units; however, the study did not examine the relationship of the northern Kittitas Valley and the adjoining range front. Little has been done in recent years to identify faults associated with the northeastern Kittitas Valley. The regional tectonic structures of the Yakima Folds (Reidel et al., 2013), in conjunction with the inferred activity of the HRNA (Kelsey et al., 2017), suggest that a tectonically controlled range front likely occurs in the Kittitas Valley. Inspiration for this investigation comes from fluvial-based neotectonic studies conducted by Staisch et al. (2017; 2018) within the neighboring Saddle Mountains and Manastash Ridge areas (Figure 1). This study expands the previous investigation towards the northern end of the Yakima folds, exploring the interactions between the range front, Kittitas Valley and known structures on the southern boundary of Kittitas Valley.

STUDY AREA

My study focused on the northern Kittitas Valley, and the foothills of the HRNA as the anticline takes a slight bend northwest merging with Mission Ridge and Table Mountain

(Figures 1 and 2). The Kittitas Valley is a roughly trapezoidal shaped valley stretching approximately 135 km from west to east and approximately 20 km from north to south. The Yakima River flows through the western portion of the valley southeastwards toward Yakima, Washington before flowing into the Columbia River. The highest elevation within the project area (~ 2000 m a.s.l.) is near the summit of Mission Peak (Mission Ridge) and the lowest elevation lies within the Kittitas Valley near the Yakima River (~ 500 meters a.s.l). Triangular facets are locally present at the base of the range front and form the intermediary boundary between the northern Kittitas Valley and the HRNA uplands to the north and northeast (Figure 1 and Figure 2).

Several drainage basins within this area drain a large portion of the western and southern flank of the HRNA into the Kittitas Valley. The drainage basin of Coleman Creek was the primary focus of this investigation due to fluvial morphology and the discovery of channel knickpoints, exposures of strath terraces, and proximity to range front faults. Coleman Creek incises through CRBG Grande Ronde normal and reverse polarity flows (Tgn1, Tgr1, and Tgn2) (Tabor et al., 1982). Six topographically spaced strath terraces are apparent near the entrance of Coleman Creek into Kittitas Valley. All strath terraces are underlain by Tgn2.

RESEARCH APPROACH & METHODS

This study focuses on analysis of geology, geomorphology and topography of the northeastern Kittitas Valley range front using both field observations and topographic analysis. The primary research goal was to determine if there was sufficient evidence for base level fall from a range front fault(s) within the major stream channels draining into the northern Kittitas Valley and to identify possible mechanisms of uplift of the HRNA. Toward this end, I created a series of geomorphic maps along the northeastern Kittitas Valley using an array of geomorphic analyses, including creation of a normalized channel steepness index map (K_{sn}), channel longitudinal profiles, channel knickpoint analyses, fluvial terrace mapping and construction of terrace topographic profiles. I also collected bedding attitudes on several of the accessible facet surfaces, bedding attitudes are located in the results section.

Fault and Strath Mapping

Fault and strath mapping was conducted using high resolution 1- and 3-meter LiDAR imagery from the Washington State LiDAR Portal and the United States Army Yakima Training Center (lidarportal.dnr.wa.gov; USARMY, 2009). All LiDAR data is projected in 1-3m UTM Zone 10, NAD 83 coordinate system. I mapped fault lineaments with LiDAR data using a combination of slope, hillshade and DEM (Digital Elevation Model) maps projected in ArcGIS. Mapped fault lineaments were used to help motivate and focus field work and topographic analyses within the project area. I also mapped topographic anomalies with the LiDAR data, later determined to be strath terraces located south of the range front. I collected bedding attitudes on the strath surfaces and along the range front triangular facets to field check previous mapping efforts and generate additional data for this study.

Strath terraces were mapped to measure incision of Coleman Creek, yielding an approximate amount of incision due to base level changes of Kittitas Valley. Strath terraces were mapped initially on LiDAR, then field checked for accuracy. Several potential fluvial terrace surfaces turned out to be landslides and were not mapped. After completing the strath terrace mapping I extracted point data from the strath surfaces using 1-meter LiDAR imagery. I then used the point data to generate longitudinal profiles from the strath surfaces which were eventually used to correlate knickpoints to individual strath terraces.

River Profile Analysis

I performed river profile analyses using the Topographic Analysis Kit (TAK, Forte and Whipple, 2019) to generate K_{sn} maps, channel longitudinal profiles, and knickpoint maps. The TAK functions within the greater platforms of MATLAB and TopoToolbox (Schwanghart and Kuhn, 2010 and Schwanghart and Scherler, 2014). Flint (1974) states that fluvial channels display a change in average gradient of local channel slope, this change in slope can be described by a power-law function; where K_s is the channel steepness and Θ is the concavity (Equation 1). In order to assess channel steepness measures among streams across the landscape, a normalized channel steepness metric (K_{sn}) is calculated using a reference concavity (Equation 2, Wobus et al., 2006). The Reference concavity (Θ_{ref}) for this study was defined as 0.45 which is an average of reginal mean Θ values and consistent with studies performed by Staisch et al. (2018).

1) $S=K_sA^{-\Theta}$

2) $K_{sn}=K_sA_{cent}^{(\Theta ref-\Theta)}$

Upon initiation of this project, I created several regional K_{sn} maps that helped focus the study on the northern Kittitas Valley. After creating several batch K_{sn} maps (similar to Figure 3), I constructed channel longitudinal profiles along several of the larger drainages across northern Kittitas Valley, ultimately focusing the majority of research efforts on Coleman Creek. Longitudinal profiles highlighted breaks in channel slope (knickpoints), leading to a batch knickpoint analysis along the entire range front.

Knickpoints were plotted using the *FindBasinKnicks* tool in the TAK which allows the user to select knickpoint locations on a χ plot; the TAK limits the locations of knickpoints to occurring on a stream node which increases the plotting accuracy and reproducibility. To test whether the knickpoint groups in one drainage were common across the range front, I constructed, using the TAK (Forte and Whipple, 2019), a batch knickpoint map across the range front (Figure 6). In this batch knickpoint map, I could separate knickpoints by elevation based on the knickpoint elevation groupings determined from the Coleman longitudinal profile (Figure 4). Knickpoint/knickzone groupings are discussed in the *River Profile Analysis* results section. A knickzone is a high gradient reach, surrounded by lower gradient reaches (Foster and Kelsey, 2012). In this report, I define "knickzones" by a set of knickpoints occurring within a basin or more broadly within a set of basins which appear at roughly the same elevation or range of elevations.

RESULTS

Fault and Strath Mapping

I identified two new faults located on the northern side of Kittitas Valley (Figure 2). Evidence for the "Facet fault" includes a visible fault lineament (Figure 9a versus Figure 9b), as well as the coincidence in space of the lineament and the range front triangular facets. The triangular facets are composed of unit CRBG TGN-2 (Grand Ronde normal 2) (Tabor et al., 1982). The bedding on the facet surface dips 15-20° to the south, consistent with bedding recorded on the Tabor et al. (1982) geologic maps. The facet surfaces are parallel to bedding and thus have the same 15-20° dip to the south. This suggests that the facets are evidence for an exposed fault at the basin front, discussed further in the discussion section.

The second fault, Dead Coyote fault, is approximately 2 kilometers south of the range front (Figure 2). Evidence for this fault is threefold. First, there is a visible fault lineament on the valley floor in northeastern Kittitas Valley (Figure 9a versus Figure 9b). Second, in two places on the valley floor, the fault exposed strath terraces and large alluvial boulders near Cooke Creek (Figure 10 and 11). The exposed strath terraces along Cooke Creek are described in greater detail in the discussion section. Third, the United States Geological Survey excavated a paleoseismic trench (Dead Coyote trench) on the western end of the fault trace, confirming the presence of a fault on the western end of Kittitas Valley. Evidence from this study suggests that a fault trace connects an uplifted strath surface on the eastern side of the valley to the previously excavated Dead Coyote trench on the western side of the valley (Figure 9).

Six strath terraces were identified in the Coleman Creek canyon, T1 through T6 (Figure 7). Strath terraces were underlain by CRBG units TGN-1, TGR-1 or TGN-2 (Grand Ronde normal and reverse flows). Strath terrace T1 resides approximately 8-meters above the current channel surface whereas T6 resides approximately 80-meters above the modern river. The two strath elevations yield approximately 80 total meters of incision. Terraces T1, T2 and T3 grade upstream to the lowest and largest knickpoint in Coleman Creek (Figure 7). The lowest major knickpoint is approximately 40 vertical meters tall within a larger, deeply incised canyon located at 950 meters elevation (Figures 7). Elevation separation between T1 and T2 is approximately 6.8-meters, elevation separation between T2 and T3 is approximately 7.8-meters.

Terrace profiles T4, T5 and T6 (Figure 7) appear to grade upstream to two higher knickzones in Coleman Creek (Figure 8). Elevation separation between T3 and T4 is approximately 2.1-meters, elevation separation between T4 and T5 is approximately 7.3-meters and elevation separation between T5 and T6 is approximately 18.6-meters.

River Profile Analysis

The batch K_{sn} map (Figure 3) depicts normalized steepness of channels and helped focus research efforts on the northeastern Kittitas Valley because of the presence of overly steep channels (warmer red and orange colors, Figure 3). Coleman Creek, Neneum Creek and Wilson Creek all have high K_{sn} values (Figures 3 and 6). Focusing on Coleman Canyon, Figures 4 and 5 depict the Coleman Creek channel longitudinal profile as well as a χ-area based plot for comparison purposes. χ is a metric used to remove the effect of drainage area through coordinate transformation (χ), yielding an approach which allows for comparison of channel profiles regardless of drainage area (Perron and Royden, 2013). Knickpoints were then identified by both code generated batch analyses and through visual recognition of channel long profiles and field observations within Coleman Creek, noted with white circles on Figures 4 and 5. These knickpoints plot into three distinct elevation-based knickpoint groups, evident on both the longitudinal profile and χ plots (red, yellow and green circles, Figure 4). The lowest knickpoint/knickzone group is between 900-1050 meters, the second knickpoint group is between 1050-1250 meters and the highest knickpoint group is between 1250-1400 meters.

DISCUSSION

Evidence from the strath terrace profile analysis and the presence of knickpoints in channels that drain the HRNA suggests multiple instances of baselevel lowering of the Kittitas Valley. My tectonic model posits that baselevel lowering of the northern Kittitas Valley is due to a range-front fault system that periodically uplifts the HRNA/Mission Ridge area relative to the Kittitas valley to the north. Well exposed and tilted triangular facets, in addition to a fault scarp lineament at the base of the facets, provide evidence for an active northernmost range front fault, called the Facet fault, Figures 2 and 9a,b). However, traces of a scarp along the Facet fault are not well preserved in the major or minor stream channels draining the range. The combined evidence of fault scarps and basin-front triangular facets support the contention that a range front fault system is the mechanism of baselevel lowering. Supplementary/conditional evidence for basin front faulting is suggested by, high K_{sn} values in streams draining into the northeastern Kittitas Valley, strath terraces within Coleman Creek which correlate to knickpoints up the channel gradient, abundance of knickpoints within main streams and tributaries, and groupings of knickzones in Coleman Creek. I infer that the range front is tectonically active and that the majority of the knickpoints are related to motion on the Facet fault. Based on the abundance of preserved strath terraces in Coleman Creek and their apparent link to upstream knickpoints, I infer that the strath terraces serve as evidence for a relative incision amount due to base level fall of the Kittitas Valley.

The southern range front fault lineament (Dead Coyote fault, Figures 2 and 9) is exposed in several stream channels and alluvial fans across the northern Kittitas Valley range front. The location of the Dead Coyote fault is additionally inferred based on exposed strath and fluvial boulders along Cooke Creek (Figure 9), by previous paleoseismic trenching and my new mapping from this work. The USGS previous paleoseismic trench in northwestern Kittitas Valley confirmed the presence of a fault, based on my interpretation of the Facet fault, the strath terrace has been uplifted by north up motion on the Dead Coyote fault. The presence of an extensive uplifted strath terrace (Figures 6, 10 and 11) with large, fluvially transported boulders exposed on the surface (Figure 11) suggests a Quaternary uplift history for the strath. I infer the presence of two separate faults, the older, master Facet fault and younger Dead Coyote fault as evidence for Quaternary faulting which has propagated southward as the fault splays and progresses to lower topographic levels.

To better interpret the geology in the norther Kittitas Valley I constructed a geologic cross section (Figure 12) based on evidence suggested by previous studies (Kelsey et al., 2017; Staisch et al. 2018; Crane & Klimczack, 2019), in conjunction with the two new faults located during this project to present a north-south subsurface depiction of the Kittitas Valley's subsurface. The exact dip direction of the two faults is unknown; however, the cross section shows a potential mechanism that drives the uplift of the HRNA and Mission Ridge area. The cross section incorporates regional faulting of the southern Kittitas Valley including the Craigs Hill fault, which Crane and Klimczack (2019) identify in seismic reflection data.

The Cascadia back-arc is home to a unique tectonic environment not generally associated with a traditional subduction zone; compression and rotation exist in each cardinal direction within the back-arc (Wells et al., 1998). Back-arcs above old, thick, cold and denser lithosphere tend to be extensional (Mariana type) due to partial melting of the mantle and weaker stresses applied to the subduction zone and overlying lithosphere, whereas the Cascadia back-arc is contractional and the underlying plate is young, thin, hotter and more buoyant (Chilean type; Stern, 2002). The regional dynamics of the upper-plate rotation within the Cascadia back-arc provides a unique driver for tectonic forcing, a mechanism not present in nonrotating back-arcs. The Cascadia subduction zone promotes east-west contraction from the underlying subducting plate, while also undergoing north-south contraction from the rotation of the North American Plate. The actively deforming thrust environment of the Yakima Fold, HRNA and northern Kittitas Valley is a response to the above pattern of back-arc strain.

CONCLUSION

In this study, I implemented a series of geomorphic metrics in order to evaluate tectonic activity of the northeastern Kittitas Valley and HRNA area. Detailed LiDAR analysis in conjunction with field mapping lead to the recognition of two new faults located at the northern Kittitas Valley range front. The northern most, basin-front Facet fault spans the entirety of the northern range, cropping out near the base of the tilted facet surfaces. The facets were presumably deposited originally horizontal, then subsequently tilted from fault motion on the Facet fault. The second fault, south of the range front (Dead Coyote fault) was recognized by previous paleoseismic trenching (USGS, 2013) as well as the newly recognized uplifted bedrock strath with preserved, fluvially transported boulders on the strath surface described in this report. The most recent earthquake associated with the two newly discovered faults is unknown; however, the uplifted strath with fluvial boulders could suggest a recent deformation history for the Dead Coyote fault. Geomorphic analysis, focused on Coleman Creek, details a flight of six strath terraces encompassing 80 meters of vertical separation. The strath terraces appear to link to two, and potentially three, knickzones apparent on the profile of the main channel of Coleman Creek.

A cross section (Fig. 12) depicts a mechanism for regional uplift of the HRNA through a master thrust fault linked to uplift of the HRNA and Mission Ridge areas. The cross section shows how the two faults evident from the field investigation and geomorphic analyses could project to the subsurface. The cross section utilizes previously published fault orientations (Kelsey et al., 2017; Staisch et al., 2018; Crane and Klimczack, 2019) as well as unpublished paleoseismic data from the USGS. The tectonic model illustrated through the cross section provides a mechanism for baselevel fall of the Kittitas Valley relative to the channels draining the basins to the north. The formation of dipping triangular facets (Fig. 12) can be explained by the thrust orientation of the Facet fault, assumed to have a dip of approximately 25-40°. This model accommodates uplift of the HRNA and Mission Ridge areas as well as growth of the northern Kittitas Valley. Coupled with the knickpoint analyses, terrace profiling, fault mapping and regional tectonics, the cross section (Fig. 12) is the best-case scenario for explaining potential Quaternary deformation of the HRNA and northern Kittitas Valley. Finally, this study contributes to the knowledge of central Washington geology with hopes of leading to further analysis and age determination of faults in Kittitas Valley and central Washington.

LIMITATIONS

My investigation only encompassed a small portion of the HRNA and northern Kittitas Valley. This investigation does not aim to provide an exhaustive explanation for the uplift history and drivers of the HRNA and northern Kittitas Valley or provide exact locations of faults along the northern boundary of the Kittitas Valley. This investigation makes no claims or interpretations for the potential hazards associated with faults located in northern Kittitas Valley.

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FIGURES

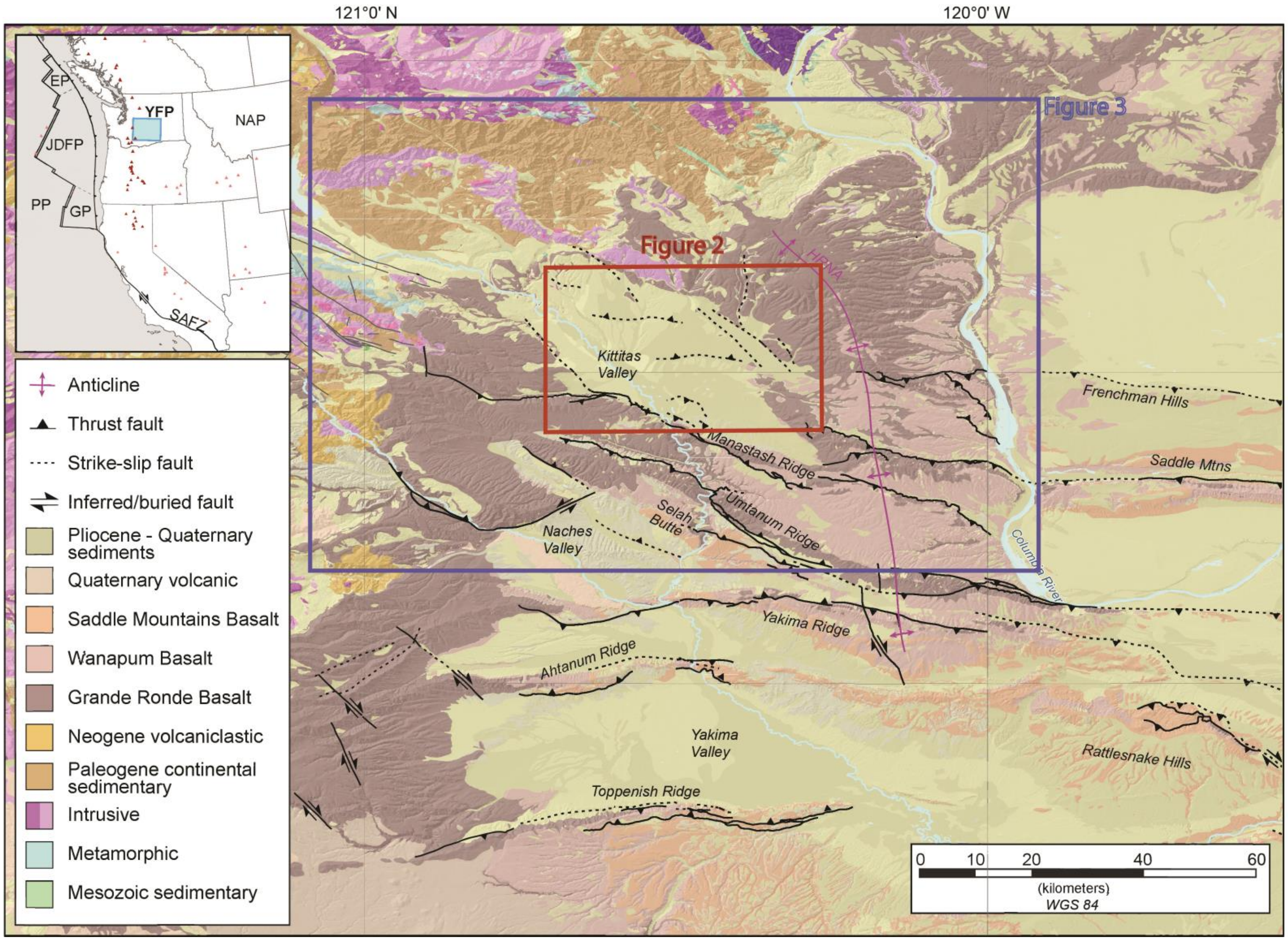

Figure 1. Regional geologic map of the Yakima Folds with inset map of the tectonic setting in the western U.S. drafted by Lydia Staisch, USGS (Staisch et al., 2018). Fault locations sourced from the U.S. Geologic Survey national map database (ned.usgs.gov). Inset: PP, Pacific plate; EP, Explorer plate, JDFP, Juan be Fuca plate. GP, Gorda plate, YFP, Yakima Fold Province, NAP, North American plate, SAFZ, San Andreas fault zone.

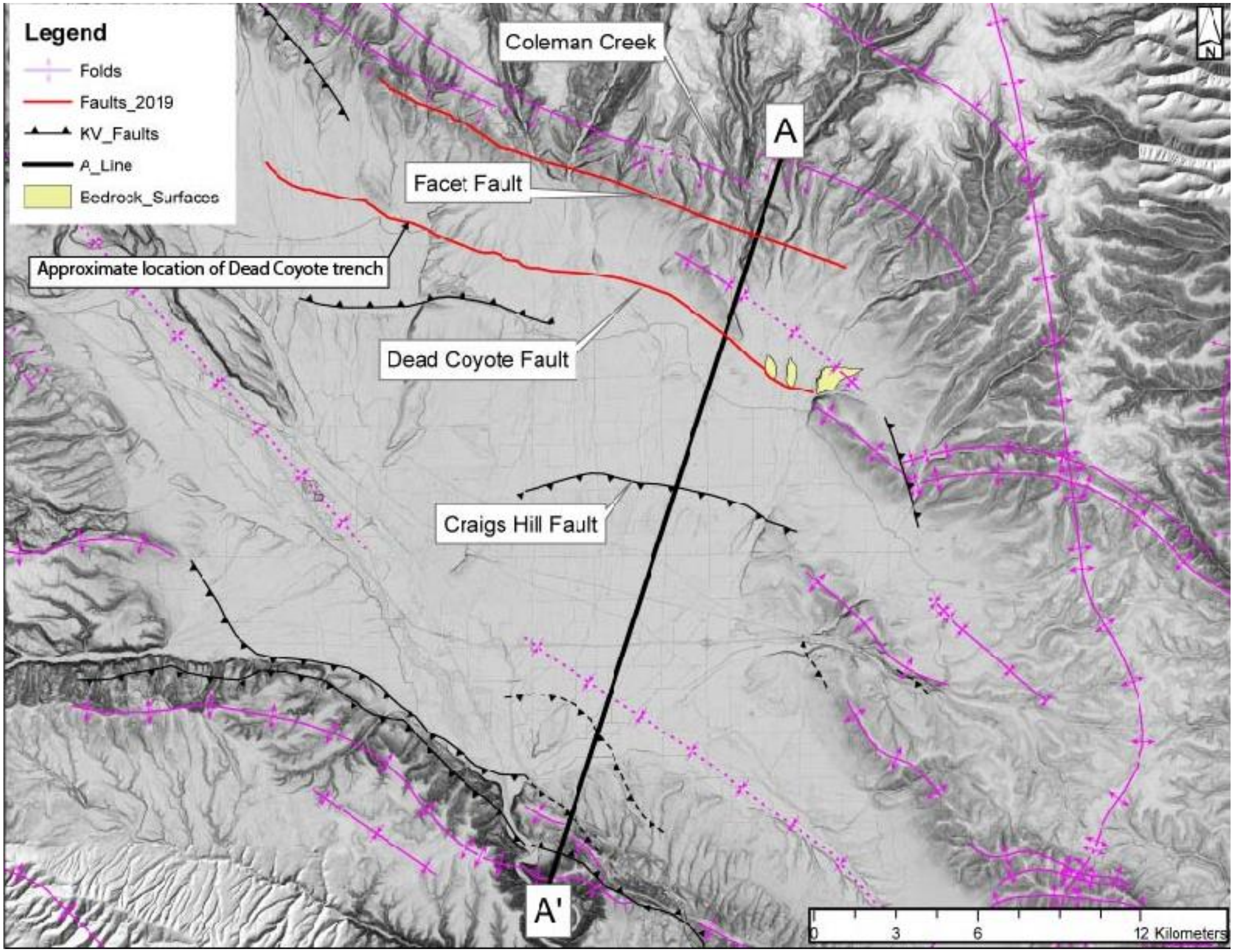

Figure 2. Kittitas Valley fault and fold map. Fault and fold locations sourced from Washington State DNR Geologic Portal (www.dnr.wa.gov/geologyportal); Crane & Klimczak , 2019; Ladinsky et al., 2012; and Staisch et al., 2018. Three-meter DEM data sourced from WA DNR LiDAR portal (www.dnr.wa.gov/lidar).

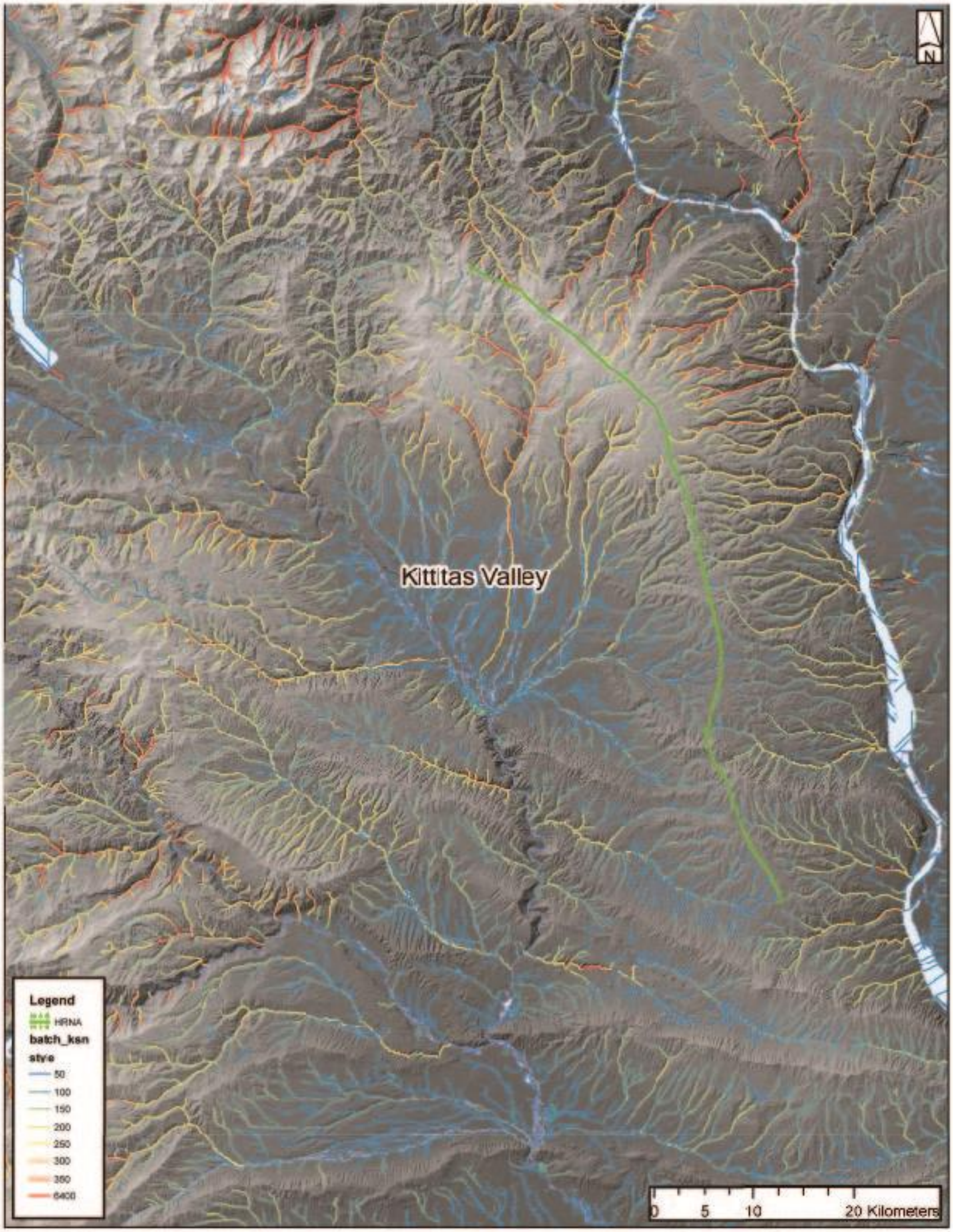

Figure 3. Normalized channel steepness map (Ksn) created using TAK (Forte & Whipple 2019). Red lines represent areas of high channel steepness and blue lines represent areas of lower channel steepness. Hillshade base map using USGS 10m DEM data; hydrology information sourced from ArcGIS online.

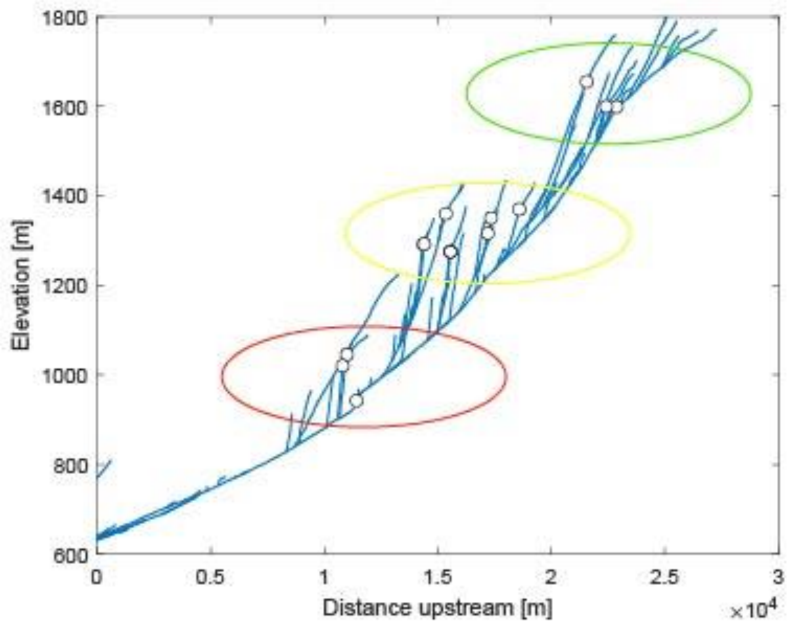

Figure 4. Coleman Creek longitudinal profiles for mainstem and tributaries. Knickpoints denoted with white circles. Red, yellow and green circles indicate three knickpoint/knickzone groupings. (created using TAK, Forte & Whipple 2019).

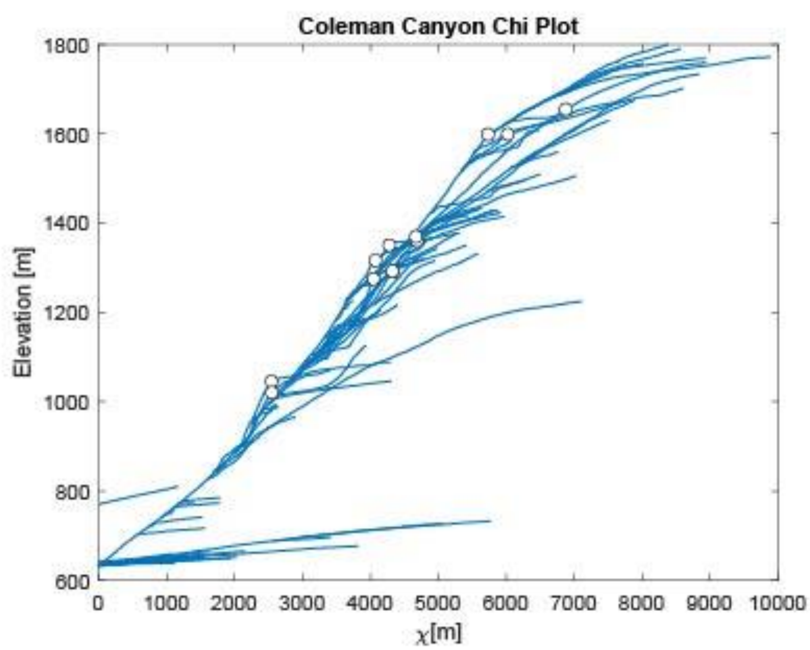

Figure 5 – Coleman Creek χ plot for mainstem and tributaries. Knickpoints, denoted with white dots, coincide with knickpoint locations on figure 4 (created using TAK, Forte & Whipple 2019).

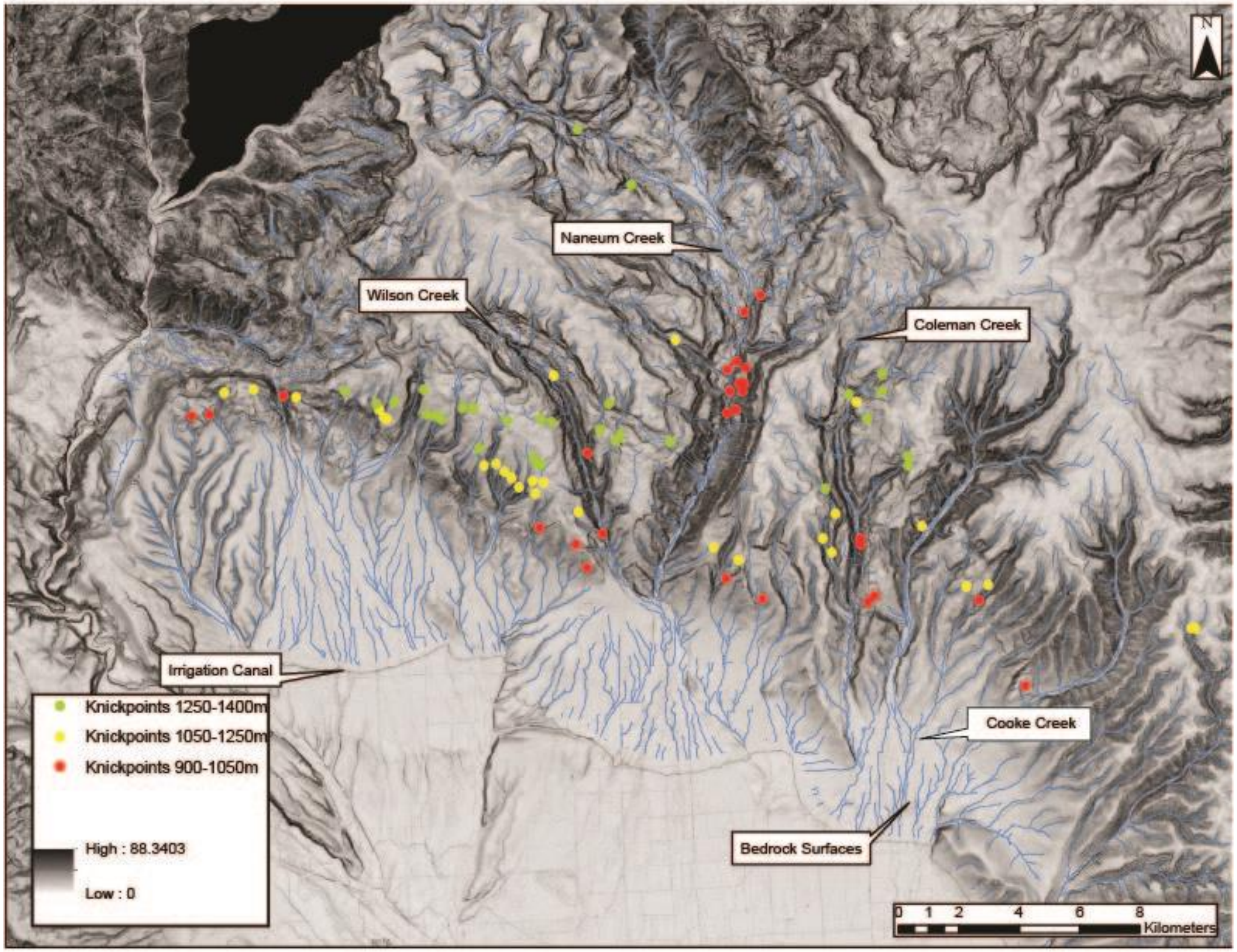

Figure 6 – Batch knickpoint map. Knickpoints are identified and separated into three elevation classes. Created using TAK (Forte & Whipple, 2019).

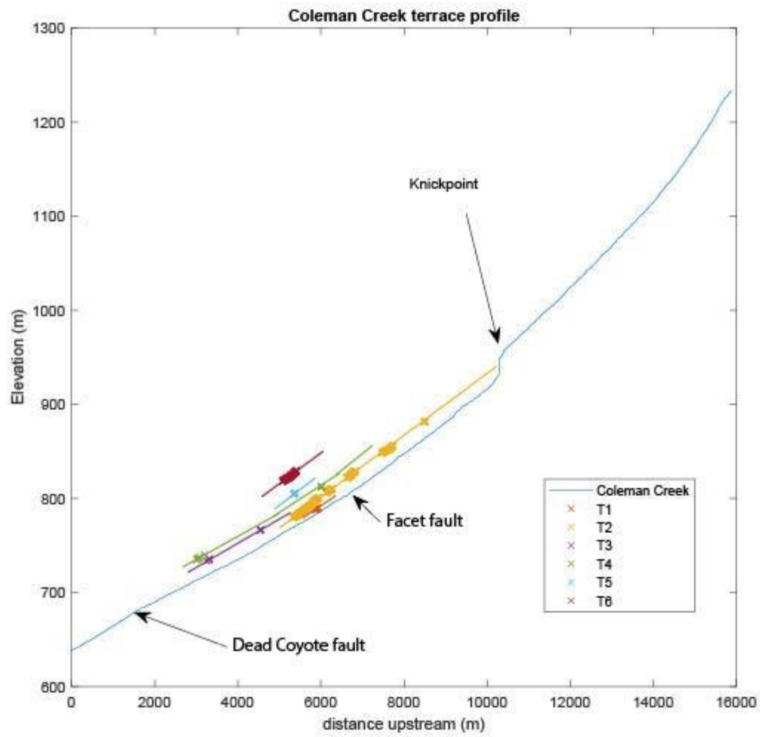

Figure 7 – Profiles for fluvial strath terraces along mainstem, Coleman Canyon. Terrace profile, terrace elevation points and channel longitudinal profile data sourced from 1m LiDAR data (www.dnr.wa.gov/lidar).

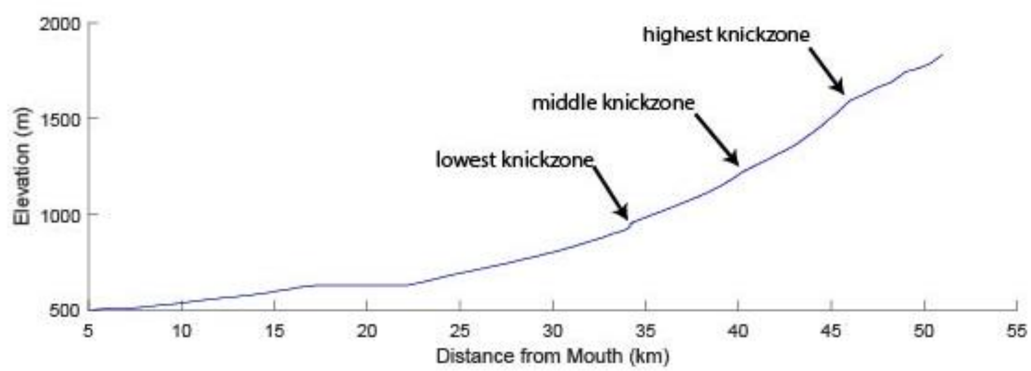

Figure 8 – Coleman Creek longitudinal profile showing locations of the three primary knickzones. Terraces T1, T2 and T3 grade upstream to the lowest knickzone. Terraces T4 through T6 grade to one of the two higher knickzones. Profile extracted using TAK (Forte & Whipple 2019).

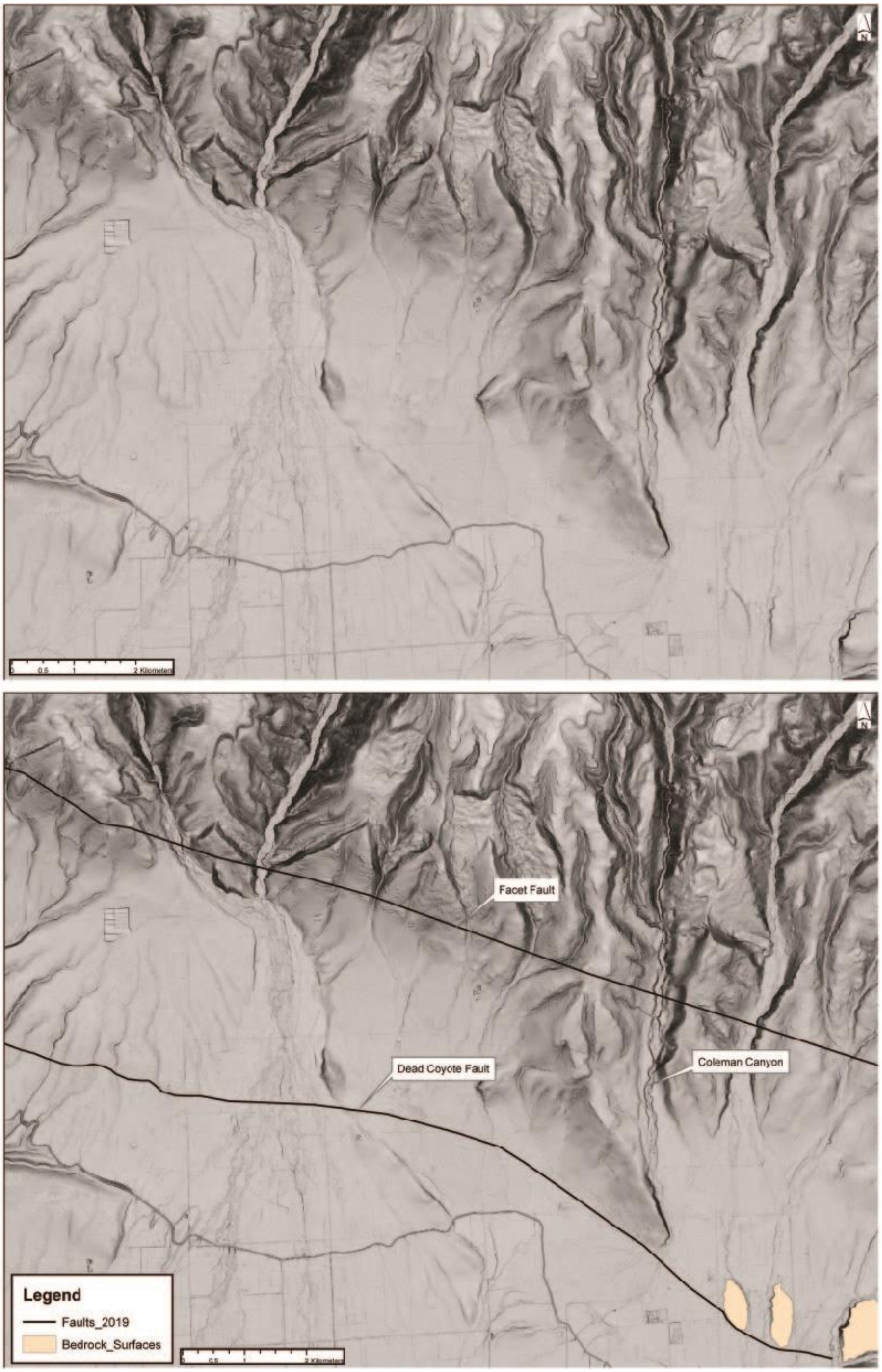

Figure 9. (a) – Unannotated slope map displaying triangular facets, fault exposures, terrace surfaces and valley bedrock surfaces. Three-meter DEM data sourced from WA DNR LiDAR portal (www.dnr.wa.gov/lidar). (b) – Annotated slope map displaying triangular facets, fault exposures, terrace surfaces and valley bedrock surfaces. Three-meter DEM data sourced from WA DNR LiDAR portal (www.dnr.wa.gov/lidar).

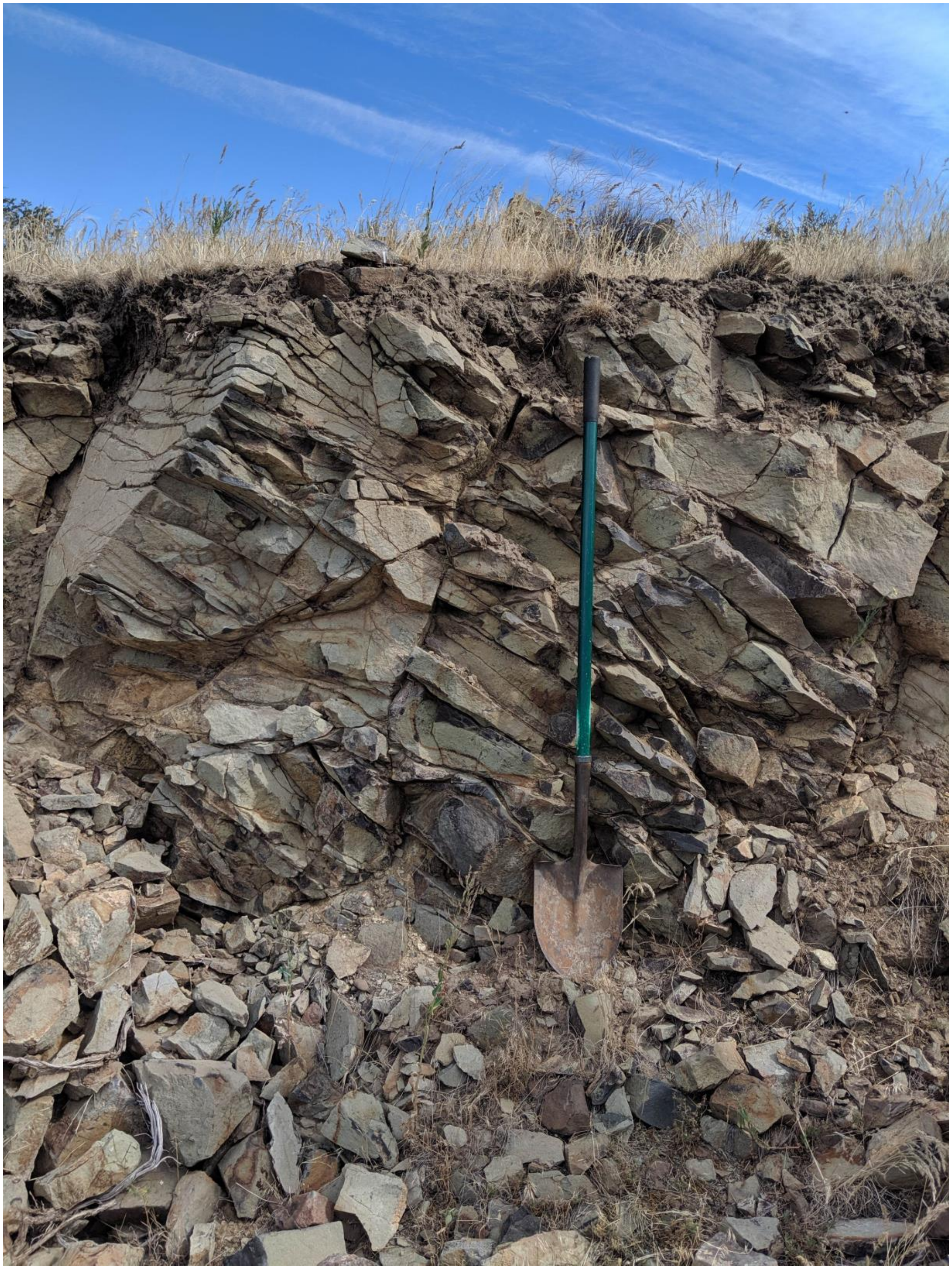

Figure 10 - Photograph of borrow pit, view to northwest, that exemplifies that the fluvial strath at this location. Image shows Grande Ronde TGN2 basalt columns dipping ~30° to northeast.

Figure 11 - Photograph facing southwest taken on the uplifted bedrock surface that is depicted in Figure 9b. Geologists are standing on individual fluvially transported boulders resting on top of the uplifted strath surface.

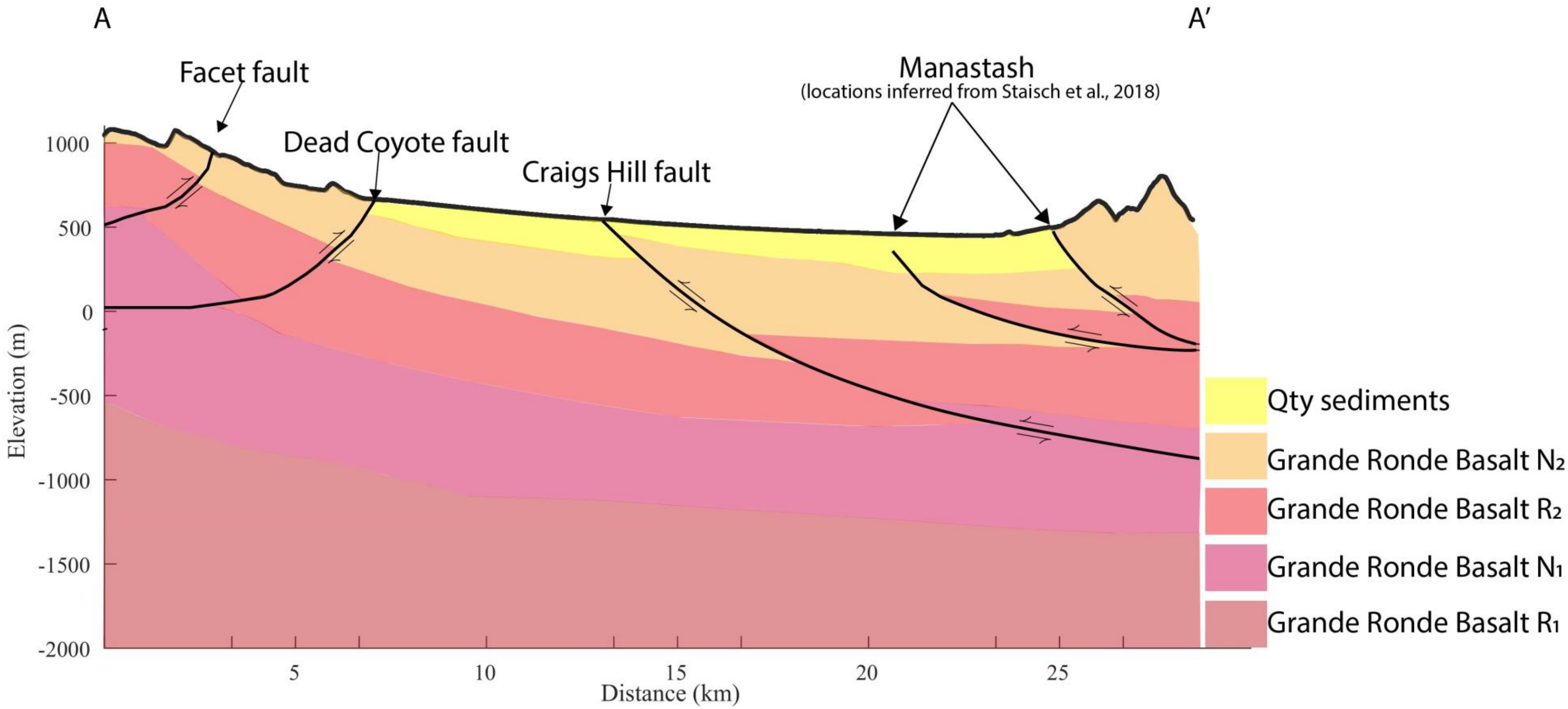

Figure 12 – Geologic cross section from A-A' (reference figure 2 for location).