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**Characterizing the Recent Cenozoic Erosional History of the Appalachian
Mountains through Spatial Variation in Stream Profile Metrics across the
Alleghany Front**

A Senior Thesis in Geoscience

by

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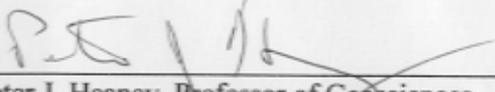
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Characterizing the Recent Cenozoic Erosional History of the Alleghany Front through Spatial Variation in Stream Profile Metrics

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ABSTRACT

Although the east coast of North America has been a passive margin for over 200 million years, throughout the Appalachian Mountains features usually found only in regions experiencing active uplift such as high topographic relief, deeply incised river valleys, landslides, and elevated erosion rates dominate the landscape. Two contrasting hypotheses attempt to explain this contradiction: the Davis hypothesis of rejuvenated Cenozoic uplift along the eastern coast of North America and the Hack hypothesis of dynamic equilibrium where topographic relief is a consequence of spatial changes in surface lithology. I evaluate these hypotheses by characterizing longitudinal stream profiles of tributaries feeding the west branch of the Susquehanna River. Advances in the relationship between active tectonics and signatures that these forces imprint on surface features allow workers to identify dis-equilibrium conditions through perturbations in stream channel profiles called knickpoints. Here, I identify knickpoints, map them spatially, and determine if they are related to spatial variations in lithology (dynamic equilibrium model) or if they are transient signatures left from a pulse of recent uplift underneath the Susquehanna watershed (rejuvenated uplift model).

155 streams were analyzed across the Alleghany Front yielding 95 knickpoints with no correlation to lithology. Streams cutting transversely across synclinal features exhibited trends inconsistent with the dynamic equilibrium model. In these profiles, bedrock lithology from the stream headwaters to the stream mouth is symmetrical about a synclinal axis; however, stream profile metrics, specifically normalized channel steepness and knickpoint location, do not reflect the symmetry seen in stream channel bedrock. This suggests that lithology does not play a primary role in controlling stream profile metrics and the spatial distribution of knickpoints, and indicates that knickpoints represent a transient signal propagating throughout the Susquehanna watershed which could have been generated from a pulse of rejuvenated uplift. However, knickpoints are seen at a variety of elevations above baselevel, the lowest knickpoints occurring in younger, more resistant bedrock and the highest knickpoints occurring in older, less resistant bedrock. It was found that although variation in lithology does not generate knickpoints across the Alleghany Front, these changes significantly control the rate at which transient knickpoints migrate vertically upstream. Finally, it is recognized that the interplay between spatial changes in lithology and changes in knickpoint elevation can be used to estimate a history of how streams transverse plunging synclines evolved. Theoretical models of stream evolution are presented and implications are discussed.

ACKNOWLEDGEMENTS

I would like to thank Penn State University for providing the necessary resources to complete this analysis, my advisor Eric Kirby for educating me in this issue, providing me with edits and suggestions throughout the course of my research, and sharing findings from previously pre-published investigations characterizing broad scale evidence in Pennsylvania for tectonic rejuvenation.

Background

Despite the fact that mountain building along the eastern continental margin of North America ceased nearly 200Ma (Fail, 1998), considerable topographic relief persists today in the Appalachian Mountains (Gallen et al., 2011). Deeply incised stream valleys bounded by high-standing ridgecrests create local relief on the order of a few hundred meters. The origin of these characteristics in an ancient mountain landscape has been the source of an enduring debate between two contrasting schools of thought: the Davis hypothesis and Hack hypothesis. The Davis hypothesis outlines two periods of tectonic rejuvenation in the early and late Cenozoic, the most recent period leading to transient conditions of high topographic relief in the Appalachian Mountains which are still present and adjusting today (Davis, 1889). In contrast, John Hack suggested that the maintenance of topographic relief in the Appalachian Mountains reflects a condition of dynamic equilibrium, where topographic relief arises from difference in the erodibility of bedrock rather than cycles of rejuvenated uplift (Hack, 1957; Hack, 1960).

In the decades since Hack's proposition, measurements of erosion rate from regions in the Appalachians support the Hack hypothesis of a sustained dynamic equilibrium between lithology, sediment flux out of the mountains, and consequent isostatic rebound (e.g., Matmon et al., 2003; Spotila et al., 2004). However, various recent studies provide contradictory evidence supporting the Davis hypothesis. Model simulations suggest that mantle flow could have generated to between 30 and 130 meters of rejuvenated uplift throughout the Mid-Atlantic region during the Miocene (e.g., Moucha et al., 2008); This process may have acted in concert with a flexural response to the redistribution of sediment mass from the Appalachians to offshore basins (Gardner and Pazzaglia, 1994; Erickson, 1998). These propositions are supported by a number of geomorphic anomalies which indicate non-steady state conditions along the North American passive margin including: perched Miocene strath terraces

deposited in the lower Susquehanna River (Gardner and Pazzaglia, 1994), deformation of shallow marine Pliocene sediment groups along the eastern coast of Florida, Georgia, and the Carolinas (Rowley et al., 2010), anomalously low Eocene and Miocene paleoshorelines off of the eastern seaboard of the United States (Spasojevic et al., 2008), and periods of accelerated sedimentation rates in the Baltimore Trough dated to the Miocene (Poag and Sevon, 1989; Pazzaglia and Brandon, 1996).

Indicators of non-equilibrium conditions have been traced into the Appalachian Mountains and corresponding drainage networks, strengthening the Davis hypothesis of rejuvenated Cenozoic uplift (Gallen et al., 2011; Hancock and Kirwan 2007; Portenga et al., 2012). Hancock and Kirwan (2007) demonstrated that river valley bottoms are incising faster than the overall lowering of summit rocks in the Central Appalachians, suggesting that topographic relief in the Appalachians is growing rather than decreasing, contrary to the dynamic equilibrium model (Hancock and Kirwan 2007). Moreover, Portenga et. al used in situ ^{10}Be to quantify erosion rates of ridgelines and drainage basins in the Susquehanna and Potomac River Watersheds and reached similar conclusions (Portenga et al., 2012). With respect to each hypothesis (the Davis and the Hack), mapping spatial variability in erosion rates has generated considerable insight into the erosional state of the Appalachian Mountains.

Using fluvial systems to characterize spatial differences in erosion rates.

In the past decade, significant advancements have been made relating the dynamics of catchment erosion rate, stream channel metrics, and the tectonic setting of fluvial systems (c.f., Whipple, 2004; Kirby and Whipple, 2012). Stream channel metrics of graded streams have been characterized by a power law relationship between local channel slope (S), a channel steepness index (k_s), channel concavity index (Θ), and the contributing upstream drainage area (A) (Hack, 1957).

$$S = k_s A^{-\Theta}$$

eq. 1

The propensity of well-adjusted streams to exhibit this relationship makes stream profiles for graded streams relatively predictable (Hack, 1957; Flint, 1974). Both the concavity index (Θ) and channel steepness variables (k_s) can be determined by plotting a linear regression between local channel gradient (S) and drainage area (A) on a log-log plot (Wobus et al., 2006). The channel steepness (k_s) variable will dictate the y – intercept of the regression, and the concavity index (Θ) will dictate the slope (Wobus et al., 2006). Relatively small discrepancies or uncertainties in concavity index (or regression slope), however, will lead to large changes in channel steepness (or regression y intercept). To correct for this issue, a reference concavity is chosen within an empirically determined range of steady-state channel concavities, $0.4 < \Theta < 0.6$ (Kirby and Whipple, 2012). This reference concavity plots a slope-area regression yielding a normalized stream channel steepness, which is based off of a steady state channel concavity of most mountain stream settings and can be compared to streams of varying catchment size (Wobus et al. 2006; Kirby and Whipple, 2012).

Abrupt spatial or temporal changes in bedrock lithology, rock uplift rate, and/or climate often lead to a segmented stream profile, where each segment has a particular set of k_{sn} and Θ variables (Kirby and Whipple, 2012). Segments are commonly delineated by knickpoints, or local convexities in the channel profile (Whipple, 2004). Knickpoints represent perturbations to a graded stream profile that are caused by a range of processes, including: differential rock uplift, variations in lithologic strength, spatial variations in precipitation within a drainage basin, and/or drainage basin reorganization events (Duvall et al., 2004; Kirby and Whipple, 2001; Snyder et al., 2000; Whipple, 2004; Whipple, 2009; Prince et al., 2011). Knickpoints controlled by changes in lithology are fixed to the lithologic contacts between more resistant and less resistant units (Whipple, 2004); however, knickpoints generated from differential uplift within a catchment migrate upstream from the initial source of perturbation, eventually reaching the headwaters of the stream profile and establishing a steeper equilibrium channel (Whipple, 2004; Wobus et al., 2006).

In a review by Kirby and Whipple (2012), stream profile metrics and corresponding erosion rates from various studies were compiled to reveal a noisy, but consistent, direct relationship between normalized channel steepness (k_{sn}) and the corresponding catchment erosion rate (Kirby and Whipple, 2001; Safran et al. 2005; Harkins et al., 2007; Ouimet et al., 2009; Cyr et al., 2010; DiBiase et al., 2010; Kirby and Ouimet, 2011; Kirby and Whipple, 2012). Correlation between the two variables shows some dependence on climate (Bookhagen and Strecker, 2012; Rossi et al., 2011), incisional process (Sklar and Dietrich, 2006), and lithology (Duvall et al., 2004), but these effects can be controlled by developing a calibration curve from known erosion rates in adjacent watersheds. The resulting calibration curve yields a scaling relationship between k_{sn} and catchment erosion rate that can be applied to neighboring watersheds (Kirby and Whipple, 2012). Under this practice, normalized channel steepness (k_{sn}) measurements attained from DEMs can be used as an effective reconnaissance tool to provide reasonable estimates of spatial erosion rate variation (Kirby and Ouimet, 2011, Kirby and Whipple, 2012).

Applying Longitudinal Profiles to the Erosional History of the Appalachian Mountains.

Erosion rates from fluvial sediment samples in the western branch of the Susquehanna River have been analyzed using cosmogenic ^{10}Be (Reuter, 2005) and can be used to construct a calibration curve relating k_{sn} and catchment erosion rate across the Alleghany front (Portenga and Bierman, 2011; Kirby and Whipple, 2012). With the extraction of longitudinal profiles from streams across the Alleghany front, normalized channel steepness (k_{sn}) of stream profiles can be mapped geographically, illuminating spatial patterns in erosion rates throughout this portion of the Appalachian Mountains (Miller et al., 2013). I will use this method to characterize particular drainage basins which neighbor catchments with known erosion rates from ^{10}Be inventories (Reuter, 2005). By comprehensively mapping stream channel metrics and topographic signatures in the form of stream channel knickpoints, I will generate a

reasonable estimate of how erosion rates change geographically over the Alleghany front, and I will expound upon recent progress in interpreting the significance of stream channel knickpoints. Furthermore, results from this study can be placed in the context of the Davis and Hack hypotheses, distinguishing between transient and equilibrated river profiles combined with corresponding spatial erosion rate patterns.

Methods

The focus of this study was the watershed of Young Woman's Creek (YWC), a tributary of the West Branch of the Susquehanna River with a mouth located near the town of North Bend, PA in the "Deep Valleys" section of Alleghany Front. Erosion rates gathered from two sources: river sediment ^{10}Be by Joanna Reuter (2005) in catchments neighboring YWC served as potential calibrations to estimate erosion rates in the less explored YWC drainage basin.

Geologic Setting.

The bedrock of Young Woman's Creek (YWC) consists of gently folded clastic sedimentary Paleozoic rocks units, containing beds ranging in grain size from silt to pebble-conglomerate. The catchment cuts transversely across a plunging syncline and four formations: the Catskill Formation (Dck), the Huntley Mountain Formation (Mhdm), the Burgoon Sandstone (Mb), the Potsville Formation (Pp), and the Alleghany Formation. Figures 1-2 (next page) are stratigraphic columns and geologic maps of the bedrock lithologies underlying YWC and the surrounding region.

Stratigraphic Column of YWC Bedrock

Age (ma)	Formation	Relative Lithologies	Simplified Description
330	Pottsville Fm. (Pp)		-Sandstone, conglomerate, and coal -Typically forms ridges when dip is near vertical
342	Unconformity		
352	Burgoon SS. (Mb)		-Composed of sandstone, conglomerate, coal, and siltstone -Commonly seen capping plateaued regions of the Allegheny front
362	Huntley Mt. Fm. (MDhm)		-Interbedded sandstone and siltstone (no conglomerate)
	Catskill Fm. (Dck)		-Sandstone, siltstone, and conglomerate -Associated with progradational delta from Taconic Orogenesis -Contains red beds and fossils

Figure 1 (Crude) stratigraphic column of formations that underlie Young Woman’s Creek and surrounding regions. Bedrock consists of Paleozoic clastic sedimentary rocks: shale, siltstone, sandstone, and Conglomerate.

Legend:

	Sandstone		Conglomerate
	Siltstone		Coal

(PA Department of Conservation and Natural Resources Survey, 2011)

Geologic Setting of YWC

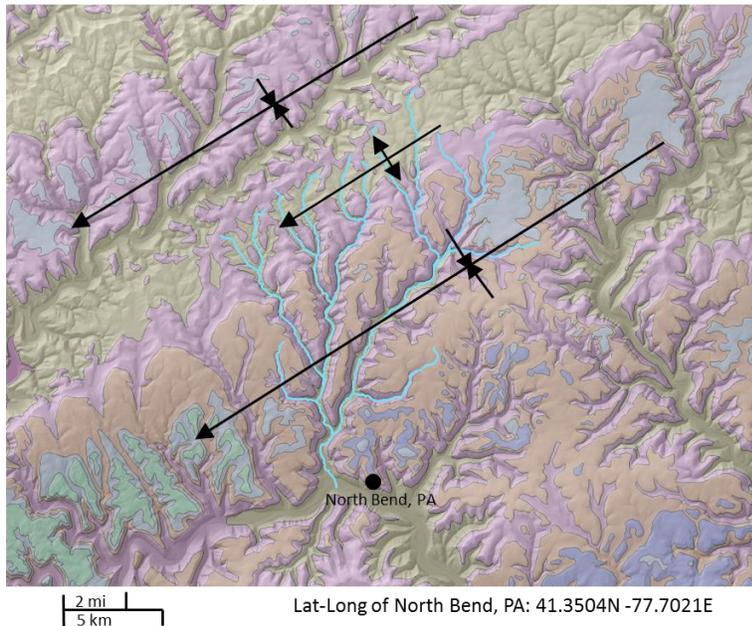


Figure 2 Geologic setting of Young Woman’s Creek (YWC), most of the drainage basin ranges over a syncline plunging roughly to the southwest. Bedrock lithology in gently folded and generally becomes younger moving in the direction of plunge.



Profile Extraction

Longitudinal profiles of Young Woman's Creek, Shavers Creek, and neighboring streams channels were extracted from 10m resolution DEMs (USGS-nationalmap.gov). Using techniques outlined in Wobus et al. 2006, profiles were analyzed according to the stream inverse power law relationship outlined by equation 1, and plotted on elevation vs. distance downstream plots and log local channel slope vs. log catchment area plots (Wobus et al., 2006; Kirby and Whipple, 2012). I used a reference concavity of 0.45 which is suitable for most mountain rivers and consistent with previous studies (Kirby and Whipple, 2012; Cyr et al., 2010; DiBiase et al., 2009; Ouimet et al., 2010; Schoenbohm et al., 2004; Snyder et al., 2000) and a smoothing window of 250m to reduce noise in DEMs. I regressed stream channel segments with similar k_{sn} with a lower limit drainage area between 10^5 m and 10^6 m. In the presence of knickpoints, the profile was split into multiple regressions upstream and downstream of the knickpoint to retain accurate k_{sn} estimates of the profile. A sample regression is detailed in figure 3 on the next page:

Knickpoints or knickzones identified from slope area plots were imported into a GIS (ESRI Arcmap v. 9.3) and plotted spatially on DEMs, noting the vertical elevation above base level of each knickpoint additionally. The mapped region included Young Woman's Creek and was extended to include neighboring streams in order to provide a context for the trends seen in each watershed.

Sampled erosion rates determined by cosmogenic ^{10}Be concentration in quartz grains from river sediment in streams across the Alleghany Front (Reuter, 2005) were used to plot a calibration curve between k_{sn} and erosion rate. Normalized channel steepness (k_{sn}) was regressed over the region of the channel upstream from the ^{10}Be sampling locations and then plotted against erosion rate for each sampled catchment. Each catchment with a normalized channel steepness and erosion rate was categorized by dominant catchment lithology. Data from 24 streams across the Alleghany Front were used to plot the relative relationship between k_{sn} and erosion rate in this region (figure 15).

Figure 3 Sample Regression

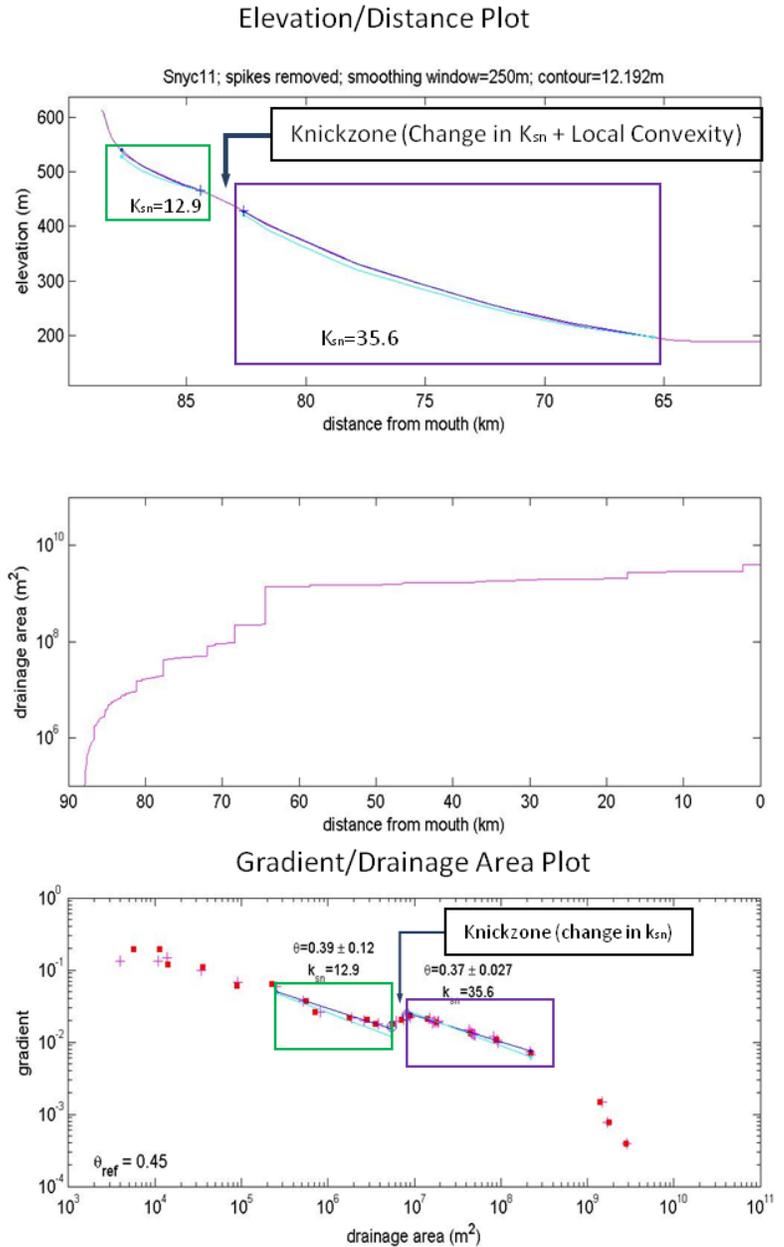
Regressions are picked on the “gradient/drainage area plot.” Each regression outlines a channel reach with similar k_{sn} and concavity, with a drainage area greater than usually 10^5 - 10^6 m. Smaller drainage areas cannot be regressed because they are dominated by hillslope colluvium drainage processes rather than channelized stream flow (Wobus et al. 2006).

A typical channel is characterized as a negatively sloping line formed by data points on a log-log slope area plot (Wobus et al. 2006; Flint 1974). The blue lines cutting through each of the red squares on the gradient/drainage area plot represent a regression line. In a regression, the slope of the line represents the concavity of the reach on the elevation/distance plot and the Y-intercept of the line with respect to a reference concavity (0.45) represents the K_{sn} of the reach.

Slope break knickzones are identified on the slope area plot by a series of data points which would form a positively sloping regression. Slope break knickzones connect two reaches each with negatively sloping regressions, but different y-intercepts, or k_{sn} . Here, a slope break knickzone separates two reaches with different k_{sn} . The knickzone itself is not regressed.

(Green box: $k_{sn} = 12.9$)

(Purple box: $k_{sn} = 35.6$)



Results

155 stream profiles across the Allegheny Front regressed yielding a total of 95 slope break knickzones. A map of the entire region studied is included below. Smaller sub-regions of the full study area are enlarged in some figures to emphasize important findings.

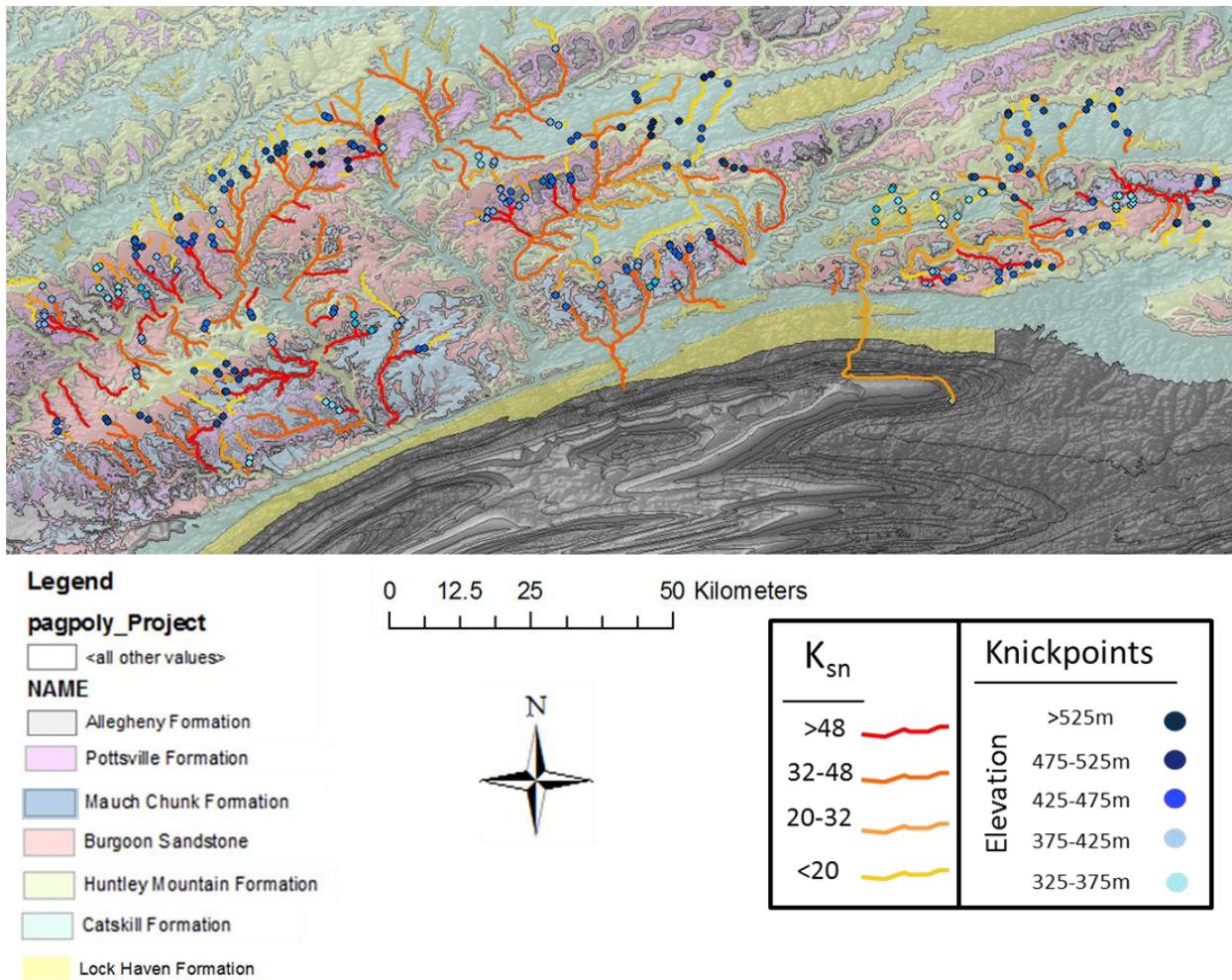


Figure 4 K_{sn} map of the full study area ranging from near Renovo, PA in the west to Williamsport, PA in the east, the colored region is the Allegheny Plateau. K_{sn} is expressed by the color of the channel, and knickpoints are plotted spatially. Each knickpoint is represented by a pair of blue dots delineating the start and finish of a knickzone. The blue hue of the dot corresponds to the height of the knickzone above baselevel.

Later figures examining specific sub-regions of the full study area will include a small version of this figure with a blue box outlining the sub-region examined. Example:



In the Young Woman’s Creek (YWC) watershed alone, 11 out of 14 regressed channels exhibited a knickzone. Knickzones showed a tendency to be associated with two lithologic units, the upper Catskill Formation and one in the middle Huntley Mountain Formation. Each knickzone delineates a change in k_{sn} , with a mean k_{sn} of reaches above knickzones is 12.5, and the mean k_{sn} of reaches below the knickzone is 41.3; thus, these knickzones are “slope break” perturbations. Knickzones range in elevation above baselevel from near 400m in the southwest portion of the watershed to over 550m in the northeast portion of the watershed.

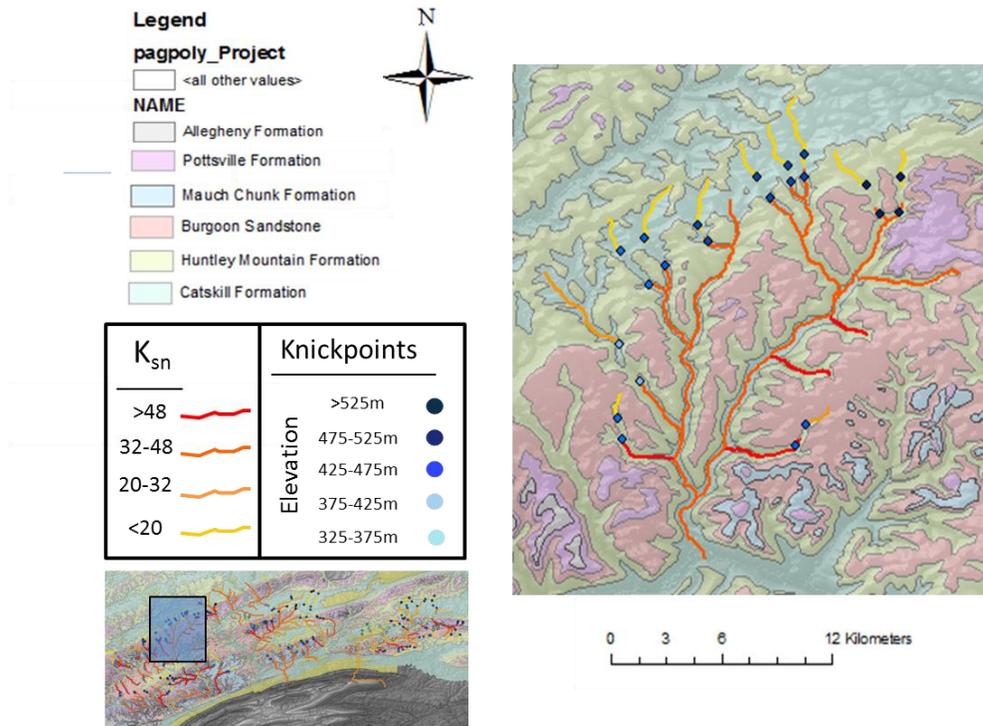


Figure 5 Spatial map of knickzones and k_{sn} in YWC

The study area was expanded to include streams to both the southwest and northwest of YWC, particularly streams which also range through the SW-NE striking syncline underlying YWC. In conjunction to the plunging syncline underlying YWC, bedrock to the SW of YWC (down plunge on the syncline) generally consists of younger lithologic units which bedrock to the NE of YWC (up plunge on the syncline) generally consists of older lithologic units.

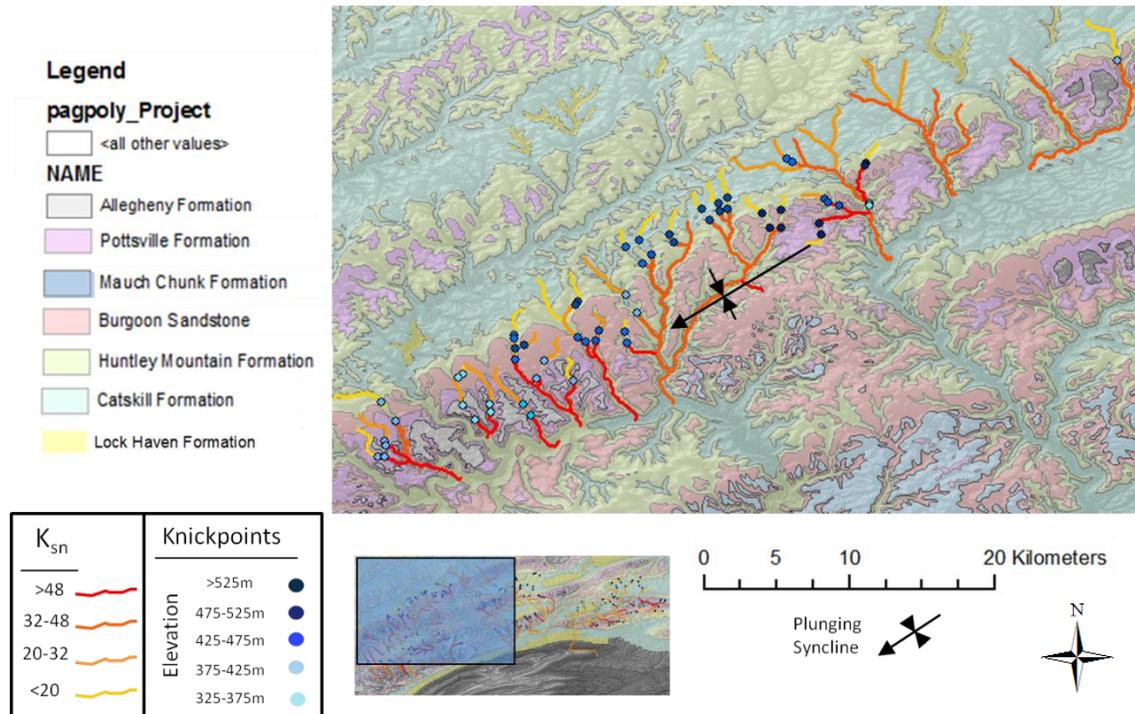


Figure 6 Map of knickzone occurrence in streams ranging over the YWC syncline, notice the trend in knickzone elevation when moving in the opposite direction of synclinal plunge. Generally, knickzones occur at lower elevations towards the southwest portion of the region, then moving northeast, grade into higher elevations in YWC and eventually disappear from stream profiles completely northeast of YWC. This coincides with a shift in lithology; in the southwest corner of this map, channel bedrock is composed of younger units such as the Alleghany, Pottsville, and Burgoon Sandstone and in the northeast, bedrock consists mostly of older units such as the Catskill and Huntley Mountain Formations.

Streams flowing over the youngest rock units in the southwest portion of the syncline display the most distinct slope break knickpoints, separating two, sometimes three reaches or distinct k_{sn} : an upper reach with an average k_{sn} of 10 (often absent), a middle reach, or top reach if the above reach is absent, with an average k_{sn} of 20, and a lower reach with an average k_{sn} of 58. Most knickpoints are located between 300 and 400m above regional baselevel (Atlantic Ocean). Moving in the opposite direction of plunge along the synclinal axis, distinct slope break knickpoints gradually rise in elevation above baselevel, the upper-most reach seen in some streams to the southwest disappears, bedrock lithology consists of generally older units, and differences in k_{sn} across knickpoints shift from values seen to the southwest (20-58) to values seen in YWC to the northeast (12.5-41.3). This transition is outlined in the figure on the next page through a few select profiles:

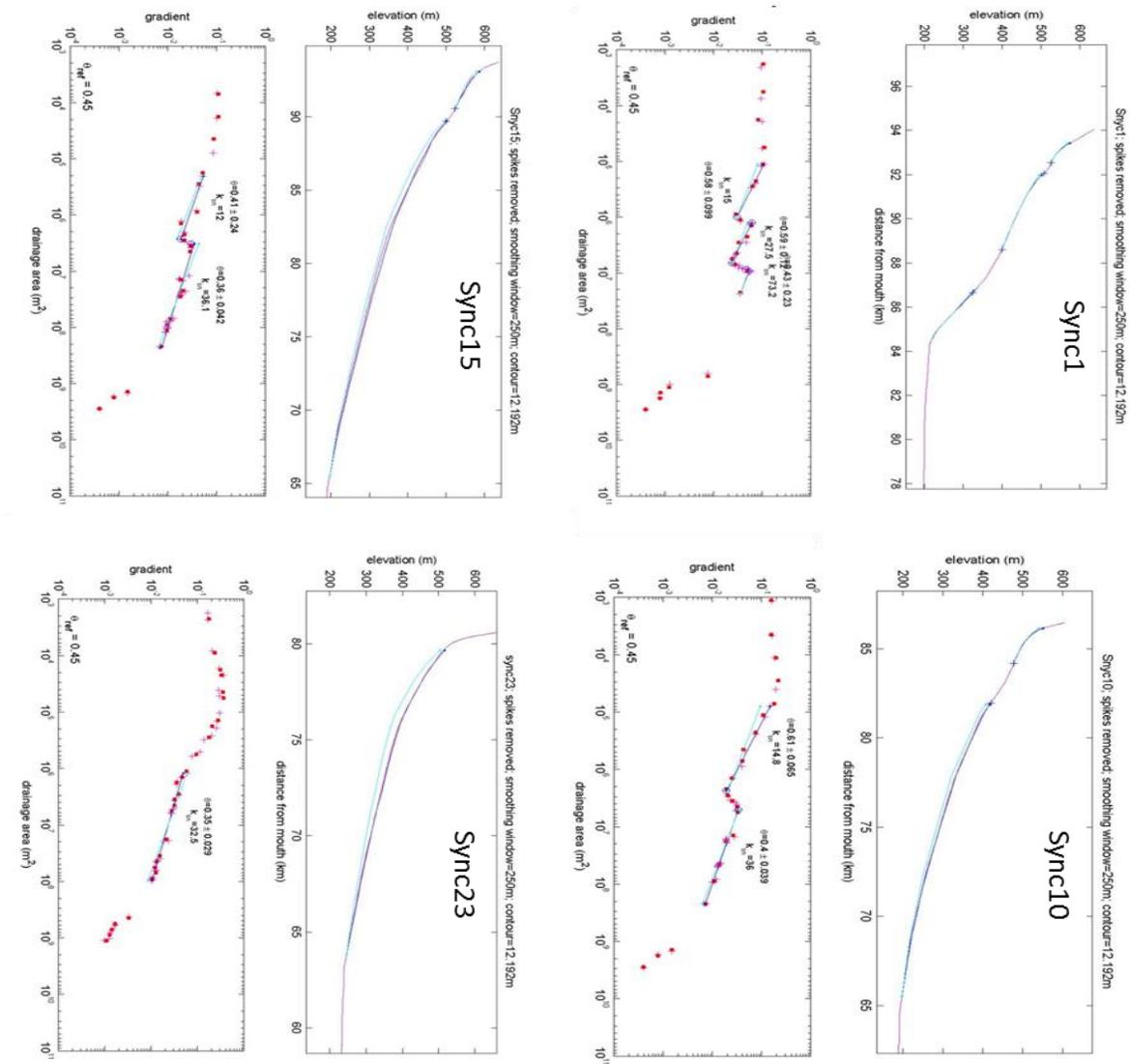
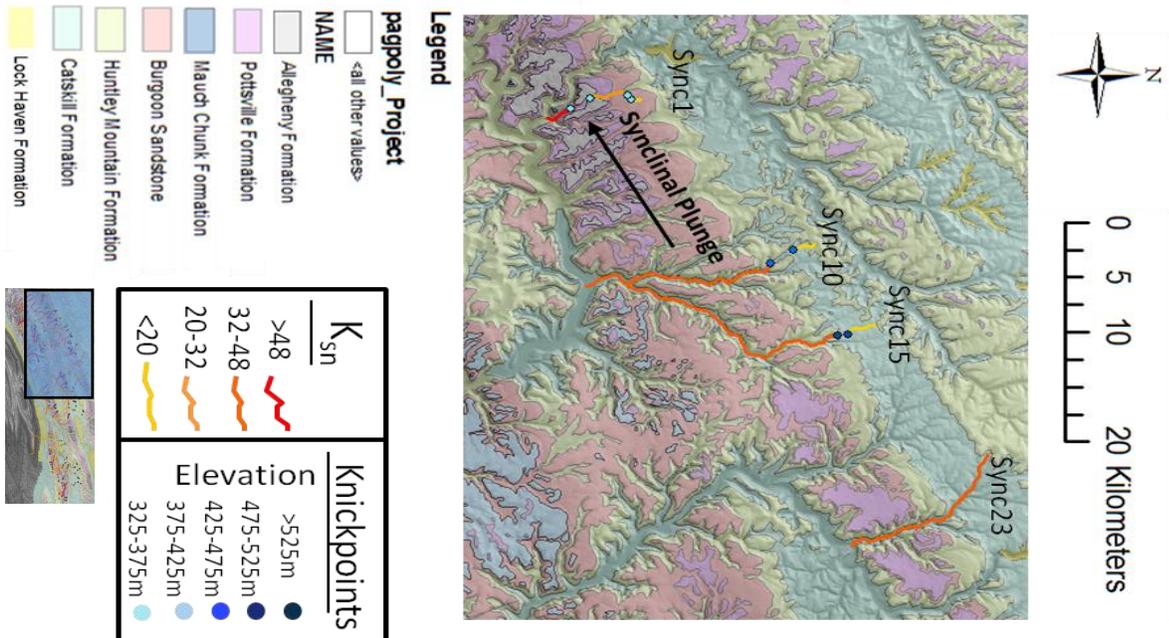


Figure 7 Here selected stream regressions are displayed with their corresponding position mapped on a regional DEM. Notice the trend in increasing knickpoint elevation, and decreasing slope break magnitude (change in k_{sn}) while moving NE opposite the direction of synclinal plunge. **Sync 1** (top left), **Sync 10** (top right), **Sync 15** (bottom left), and **Sync 23** (bottom right)



The trend of prevalent slope break knickzones, increasing in elevation above baselevel as streams progressed into older bedrock lithologies was investigated in several other regions of similar geological structure, see figure 8 below:

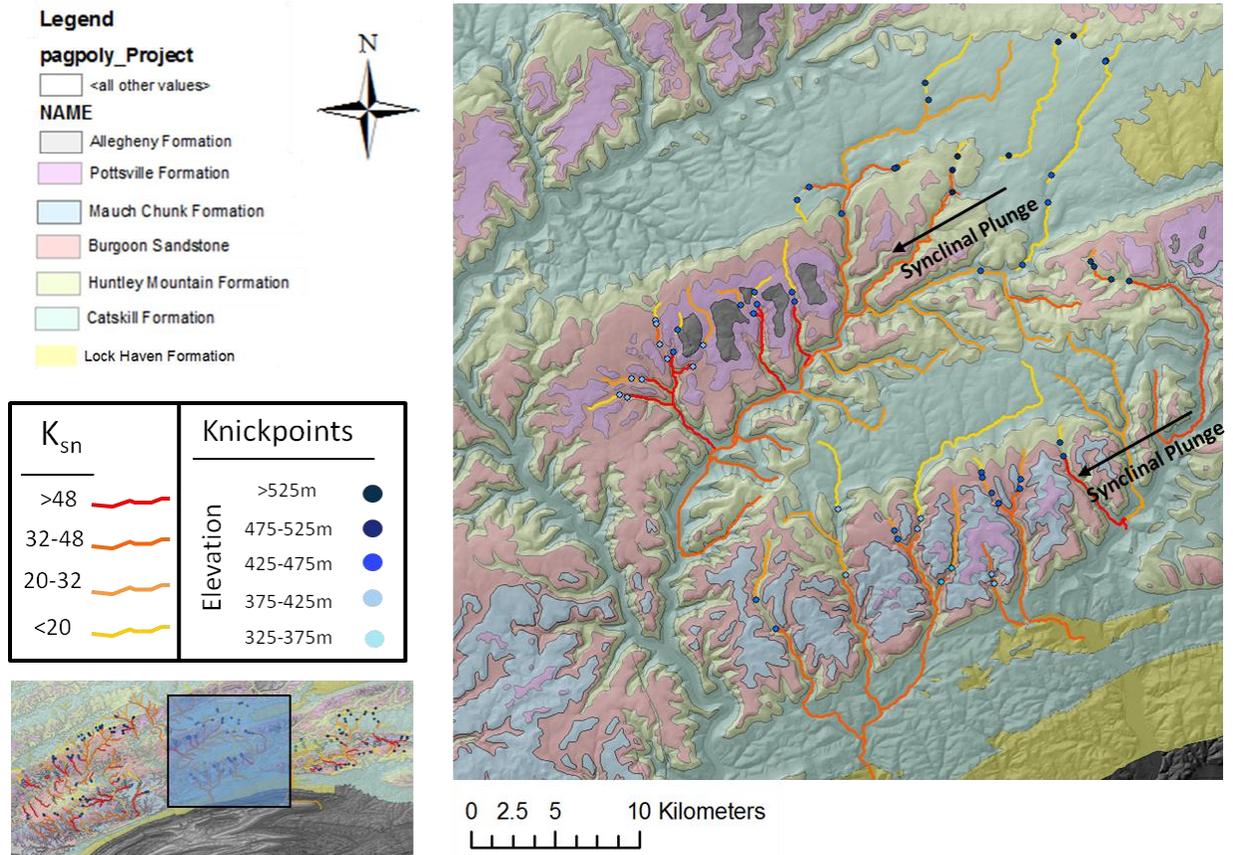


Figure 8 Knickpoint and k_{sn} map of a region about 30km east of YWC. Two synclines plunge in a direction roughly WSW. Knickpoints are distributed across all lithologies, and a distribution pattern similar to the YWC syncline is seen along these structures; streams with younger bedrock lithology have knickpoints at elevations of around 400-450m above baselevel, while streams with older bedrock lithology have knickpoints generally 500m+ above baselevel or no knickpoints at all. In long stream profiles stemming from high elevations in the northeastern portion of this region, two knickpoints are preserved in the profile similar to “Snyc1” (figure 10); however, these paired knickpoints are significantly higher in elevation in these streams.

The next collection of figures focuses specifically on synclinal structures which contain bedrock characteristics similar to the syncline analyzed in figure 7.

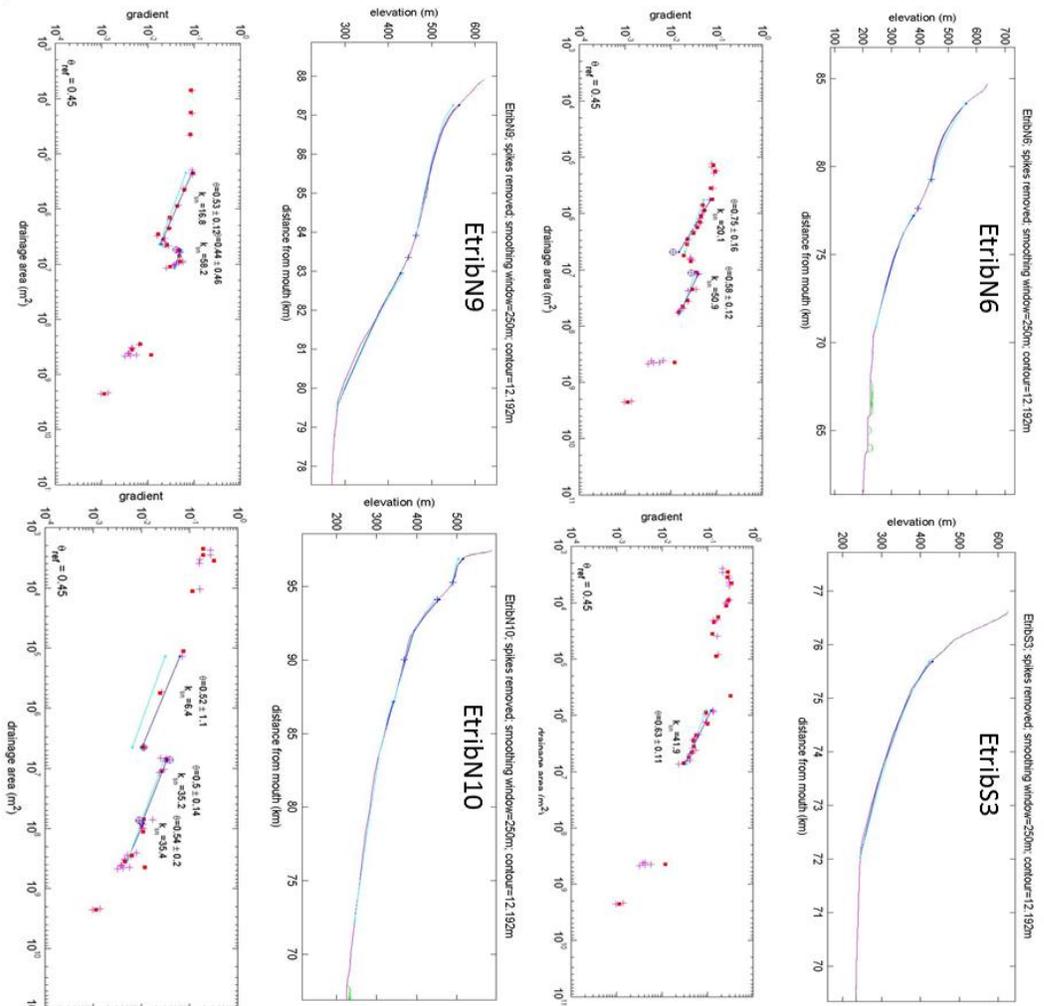
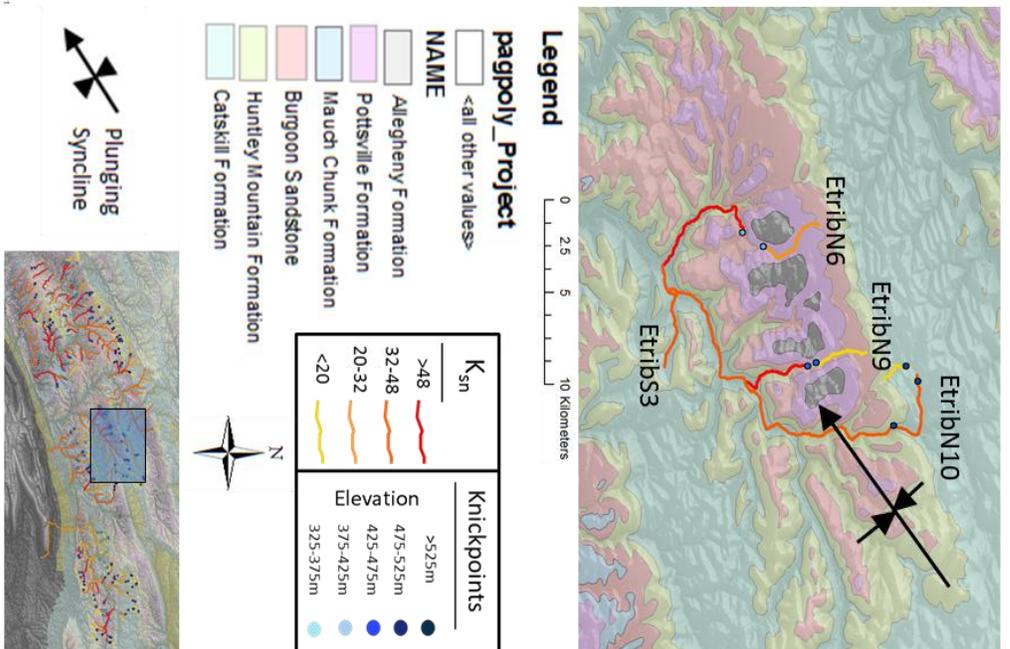


Figure 9 These stream profiles are associated with a syncline east of VWC. The bedrock lithology is similar to the syncline studied in figure 7. The profiles and knickzones in the Matlab figures on the left are plotted on the DEM on the right. A transition of slope-break knickpoint elevation is seen through EtribN6 and EtribN10. Knickpoints have lower elevations in the EtribN6 and EtribN9 which have generally a younger bedrock than EtribN10. Notice however, that even though EtribS3 has a profile lying at roughly the same elevation as EtribN6 which contains knickpoints, EtribS3 is a smooth profile. Equally significant, EtribS3 lies entirely in the Catskill Formation, which tends to be less resistant bedrock.



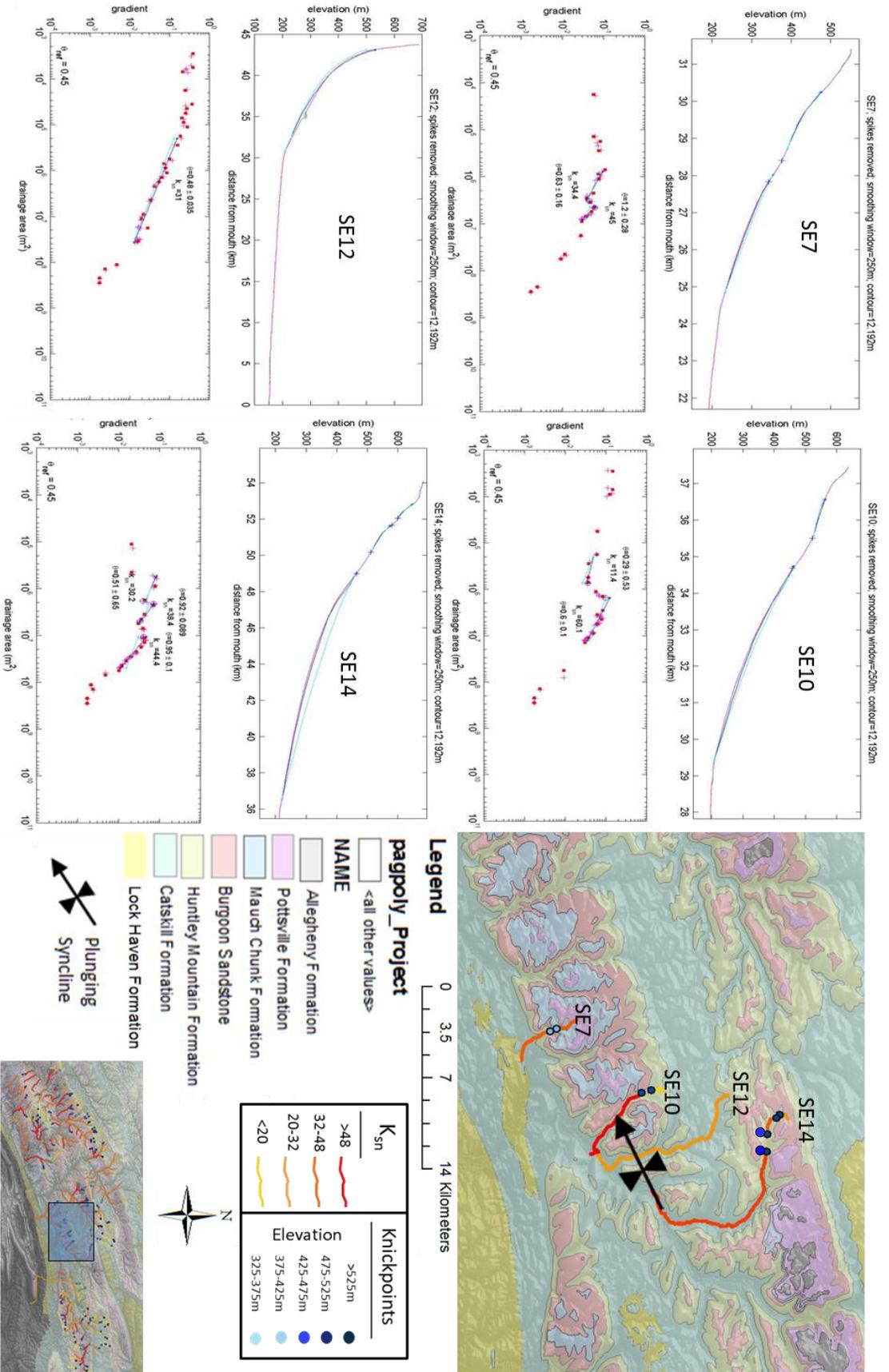


Figure 10 These stream profiles are selected from another plunging syncline east of WVC. Bedrock lithology is similar to the synclines studied in figures 10 and 13. A transition of slope-break knickpoint elevation is seen through EribN6 and EribN10. The knickpoint in SE7 is significantly lower in elevation than the knickpoint in SE10; likewise, SE7 encounters younger bedrock than SE10. SE 12 lies entirely in older bedrock, the Catskill Formation, and does not have any knickpoints; however, SE14 lies predominantly in the Catskill Formation, but in the upper reaches of the channel, lies in the Huntley Mountain and Burgoon Sandstone units. In the upper reach of SE14 knickpoints are again present and actually at a lower elevation than the knickpoint in SE10.

A calibration curve was constructed from erosion rates that were derived from cosmogenic Be10 (Reuter, 2005) and a corresponding k_{sn} that was determined by regressions performed on each individual stream channel above the Be10 sampling location for that catchment. The plot can be used to put stream channel metrics into the context of catchment erosion rate.

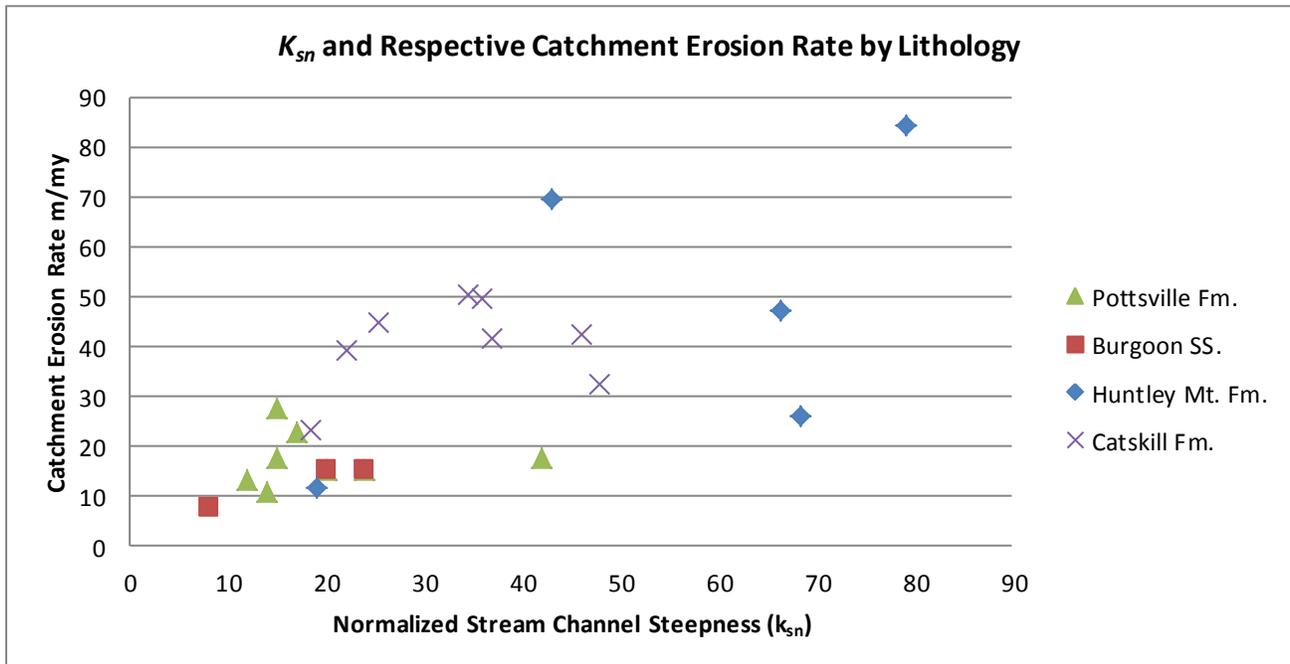


Figure 11 This is a calibration plot of k_{sn} against catchment erosion rate, sorted by lithology. These points were categorized by dominant bedrock lithology; if a catchment had a relatively even mix of two or more lithologies, that point was discarded. Younger lithologic units such as the Burgoon Sandstone and Pottsville Formation tended to have lower erosion rates and lower k_{sn} values; however, more data points and field site sampling may be required to comprehensively judge erosive resistance between rock units.

Discussion

The prevalence of widespread slope-break knickpoints throughout the study area provide suggest that channels have experienced a deviation from equilibrium conditions during the recent erosional history of the Alleghany Front. It is unlikely that these perturbations are a direct result of spatial changes in lithology, because these knickpoints are not fixed to lithologic contacts or specific

stratigraphic zones within lithologic units (Whipple, 2004; Kirby and Whipple, 2012). Furthermore, spatial changes in k_{sn} do not reflect spatial changes in lithology. For example, observe tributaries in the study area that flow over symmetrical synclines with headwaters in one lithologic unit, a middle section of the stream underlain by flow a package of younger lithologic units at the core of the syncline, and finally a mouth at a confluence with a larger stream underlain by the same lithologic unit which was present at the headwaters of the stream. In these tributaries, knickpoints are commonly found towards the headwaters of the stream, but as the tributary flows across the axis of symmetry of the syncline, the tributary flows again over the same stratigraphic section which contained the knickpoint that existed near the headwaters of the stream. If the lithology of a stratigraphic zone was the cause of the knickpoint located near the headwaters of the stream, it would be expected that a duplicate knickpoint would be in the same stratigraphic zone located across the axis of symmetry of the syncline, towards the confluence of the tributary with the trunk stream (Kirby and Whipple, 2012; Burbank and Anderson, 2012). In all instances, this is not the case.

Likewise, if lithology had strong controls on stream profile metrics, k_{sn} should vary spatially according to changes in bedrock lithology (Kirby and Whipple, 2012); however, as tributaries range over symmetrical synclines, this is not the case. Channel steepness is low towards the headwaters of the stream above a knickpoint (usually $<20\text{m}^{0.9}$), and k_{sn} is high below the knickpoint and towards the mouth of the tributary (usually $>35\text{m}^{0.9}$). Across these synclines, the bedrock lithology is the same at the headwaters of the tributary and at the mouth of the tributary, but the k_{sn} is drastically different at both of these locations, so it is likely that lithology is not the primary factor controlling stream profile metrics in the study area (Duvall et al., 2004; Kirby and Whipple, 2012). Figure 16 on the next page demonstrates the last two points:

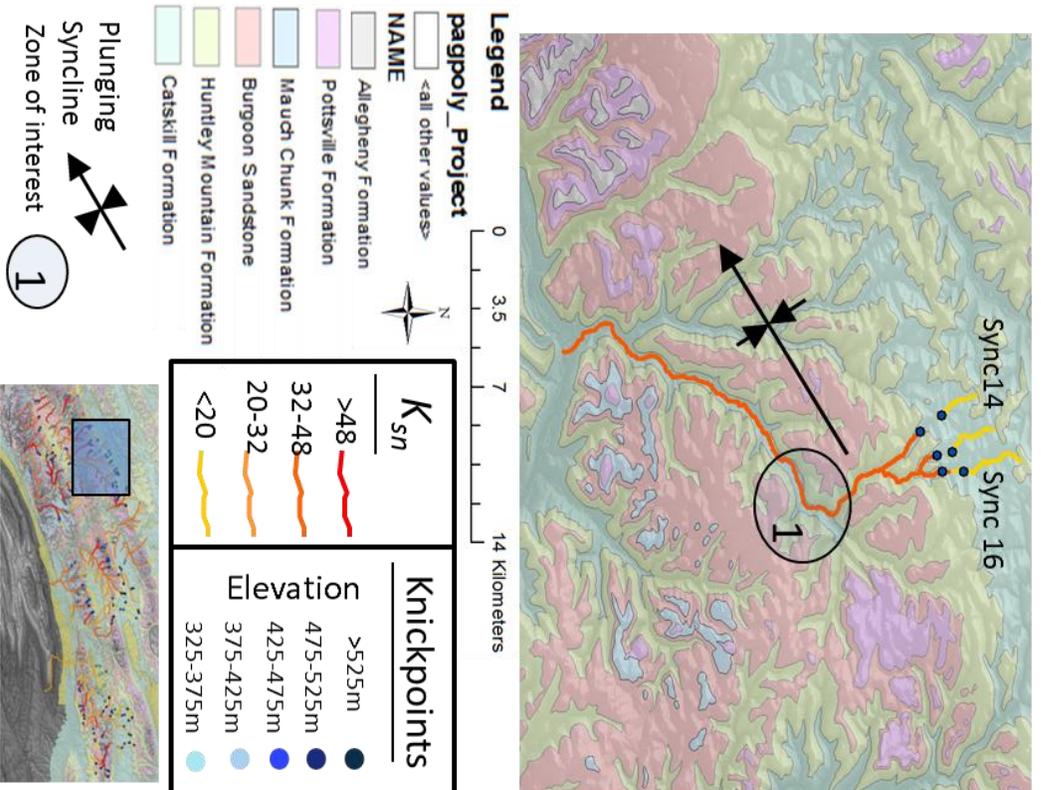
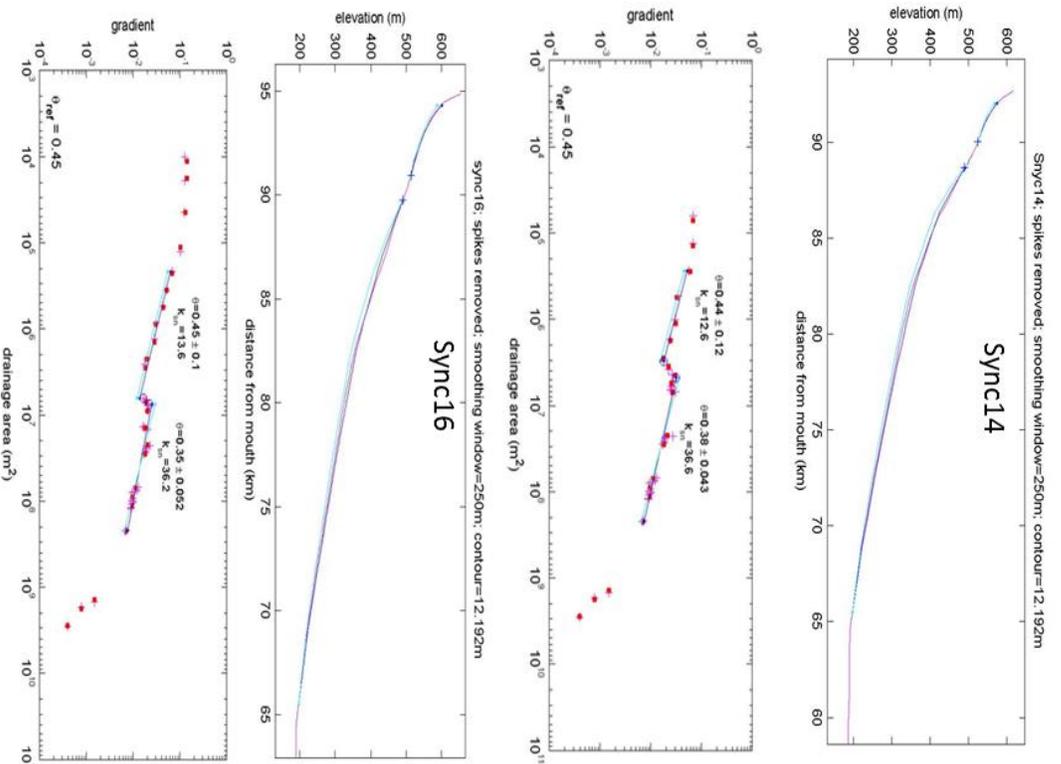


Figure 12 Select profiles from WWC that range over a syncline. Notice the locality labeled “zone of interest” marked by the symbol “1”. No knickpoints exist in the zone of interest even though it lies in the same bedrock lithology as the knickpoint containing region located across the axis of symmetry of the syncline. Additionally, K_{sn} is near 13 upstream from the knickpoints, and 36 in the zone of interest. Because the K_{sn} of the stream profile in zone of interest is considerably steeper than a region above the knickpoints which is in the same stratigraphic zone, it is unlikely that the observed knickpoints are a resultant of a change in bedrock lithology (Kirby and Whipple, 2012).

Because these knickpoints are not fixed on particular stratigraphic zones, these perturbations likely represent a deviation from equilibrium conditions which manifested in the form of the observed slope-break knickpoints and are currently migrating throughout the tributaries of the Alleghany Front (Kirby and Whipple, 2012; Whipple, 2004). The mechanism which initiated this transient wave of knickpoint perturbations cannot be distinguished from this study alone. Differential rock uplift and precipitation within a drainage basin and/or drainage basin reorganization events can all generate a similar wave of migratory knickpoints (Kirby and Whipple, 2001; Snyder et al., 2001; Whipple, 2001; Whipple, 2004). And in a theoretical case, even differences in overlying bedrock lithology of a finite extent could generate a migratory knickpoint, see figure 13 for an explanation:

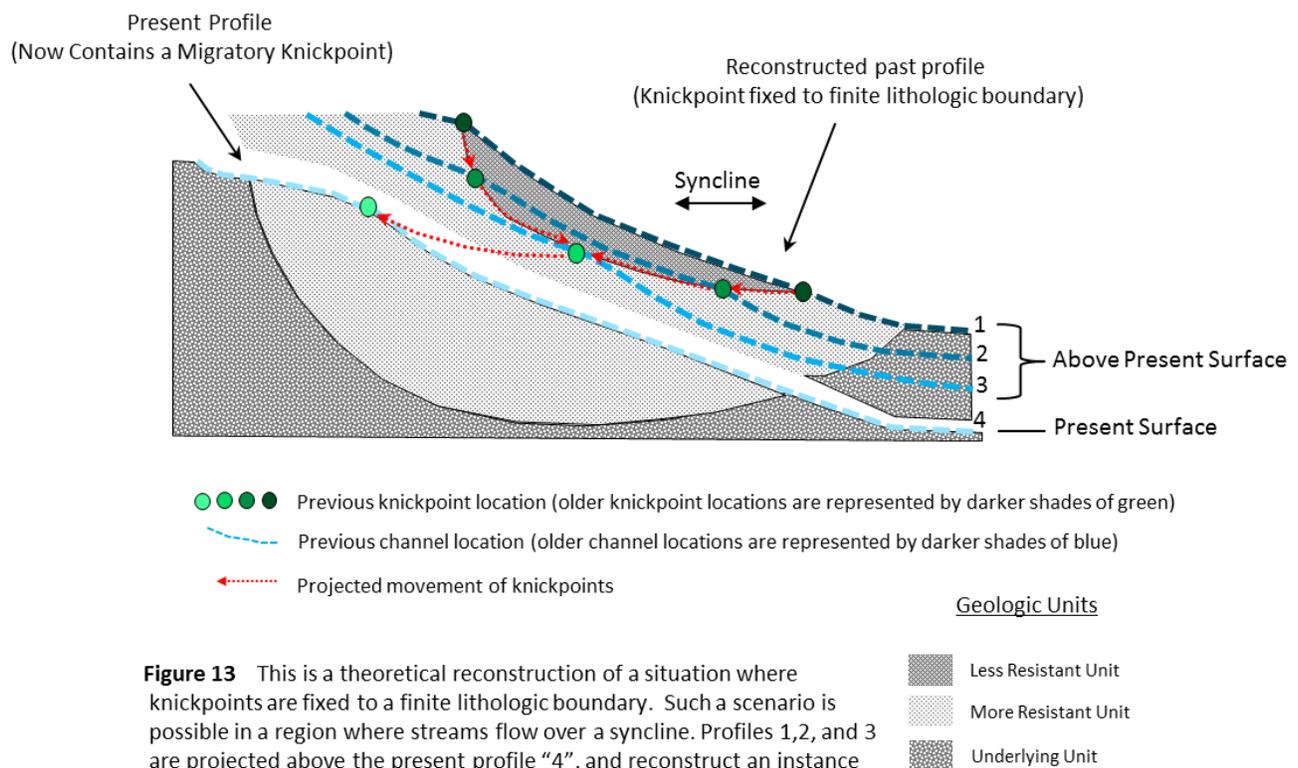


Figure 13 This is a theoretical reconstruction of a situation where knickpoints are fixed to a finite lithologic boundary. Such a scenario is possible in a region where streams flow over a syncline. Profiles 1, 2, and 3 are projected above the present profile “4”, and reconstruct an instance when the stream cut through a lithologic boundary between two units of different resistance. During the time of profiles 1 and 2, two knickpoints would be fixed to the contact between the less and more resistant units (Whipple, 2011). As the stream down-cut through both units, the knickpoints would theoretically migrate, fixed to the contact until they combined at the termination of the contact at the time of profile 3. Any time after profile 3, the bedrock lithology would be uniform; no lithologic boundary would exist because all of the overlying unit would be eroded away, a single knickpoint would exist, it would no longer be fixed to a lithologic contact, and it would be able to freely migrate up the channel (Anderson and Burbank, 2012).

Although applicable to the structural geology underlying YWC, this particular scenario where lithologic variation may have led to the generation of migratory knickpoints is not likely a likely cause for the widespread distribution of slope-break migratory knickpoints across the Alleghany Front.

Highlighted in figures 14 and 15 are a number of profiles ranging over the syncline under YWC rule out overlying lithologic variation as a causal mechanism.

Figure 14 on the next page shows regressions of streams which range over the YWC syncline, starting with streams in the southwest and moving northeast in the opposite direction of synclinal plunge. Bedrock lithology of each stream is interpreted from geological maps provided by the Pennsylvania Geological Survey. Notice that in both Sync2 and Sync3-2 a knickpoint exists downstream the estimated fold axis of the syncline. Based on the theoretical generation of a knickpoint from weathering of an overlying more or less resistant lithologic unit (the process outlined in figure 13), knickpoints should be seen either at or upstream the fold axis. Furthermore, by the process outlined in figure 13, the knickpoint in profile Sync2 would have had to have been generated by the erosion of a unit overlying the Burgoon Sandstone; however, the Sync7 profile still exhibits two slope break knickpoints in the Huntley Mountain Formation which underlies the Burgoon Sandstone. This cannot be possible if knickpoints were originally generated from a lithologic contact between an overlying unit, because we would expect all knickpoints to have already migrate along the lithologic contact and to have consolidated into one knickpoint by the time the stream down-cut to the Burgoon Sandstone forming a profile with only one single knickpoint (like Sync2) ([Whipple, 2011](#); [Kirby and Whipple, 2012](#)). However, because Sync7 still contains two knickpoints in bedrock consisting of the Huntley Mountain Formation which underlies the Burgoon Sandstone, it is impossible that any lithologic variation of overlying units could have generated these knickpoints. Figure 15 on page23 examines a more likely propagation method for these knickpoints.

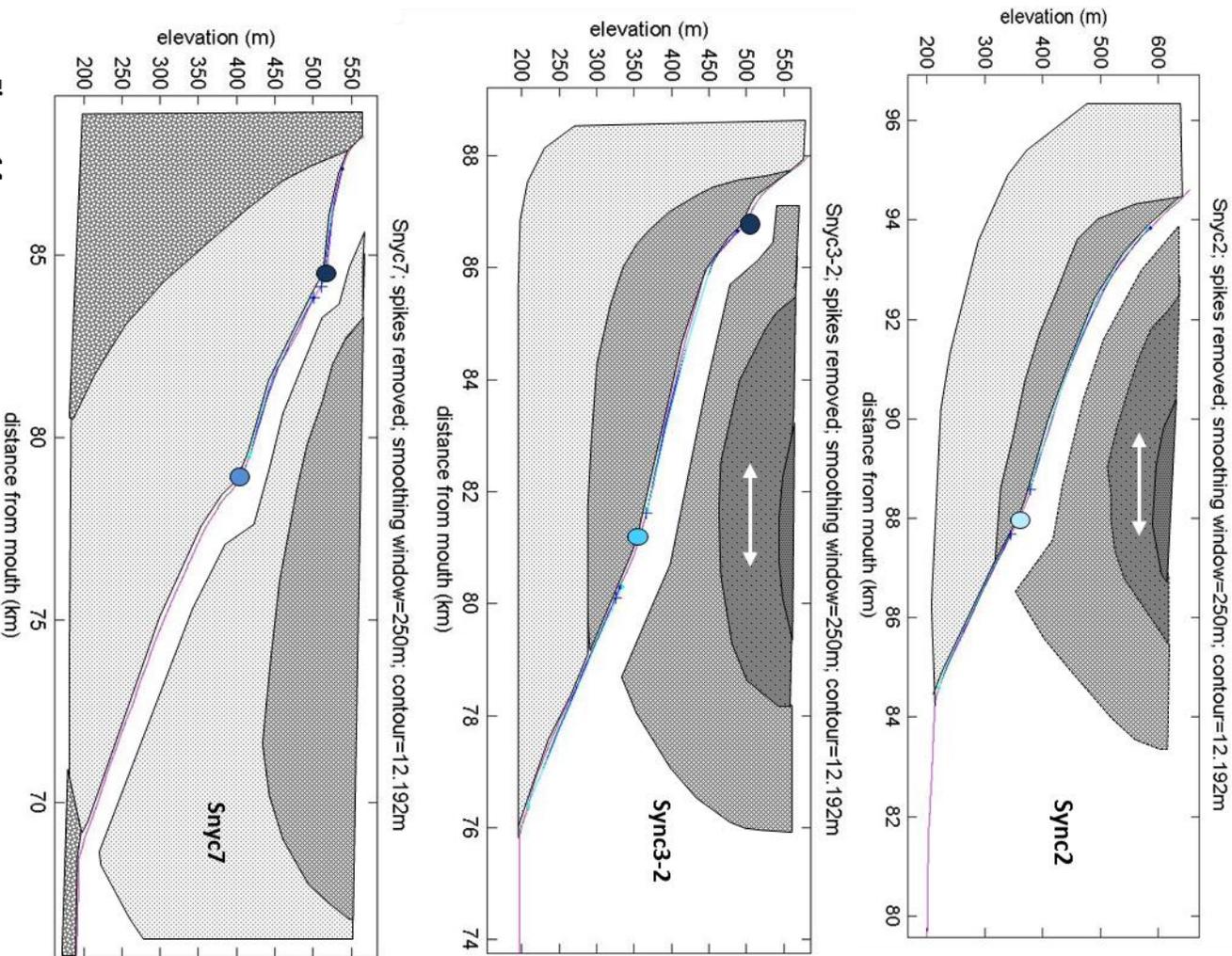


Figure 14 Cross sections of bedrock underlying and overlying longitudinal profiles, the thin blue-pink line represents the current surface. Each profile is vertically exaggerated; relative dips may be skewed.

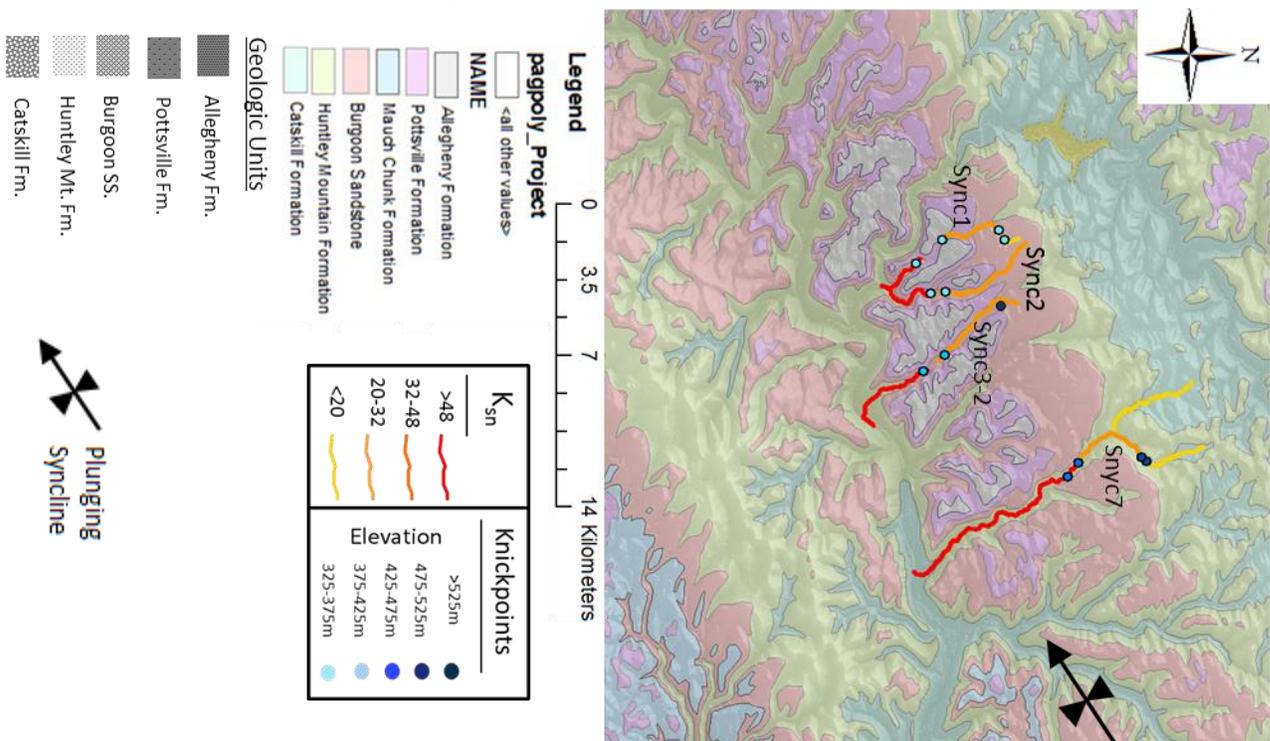
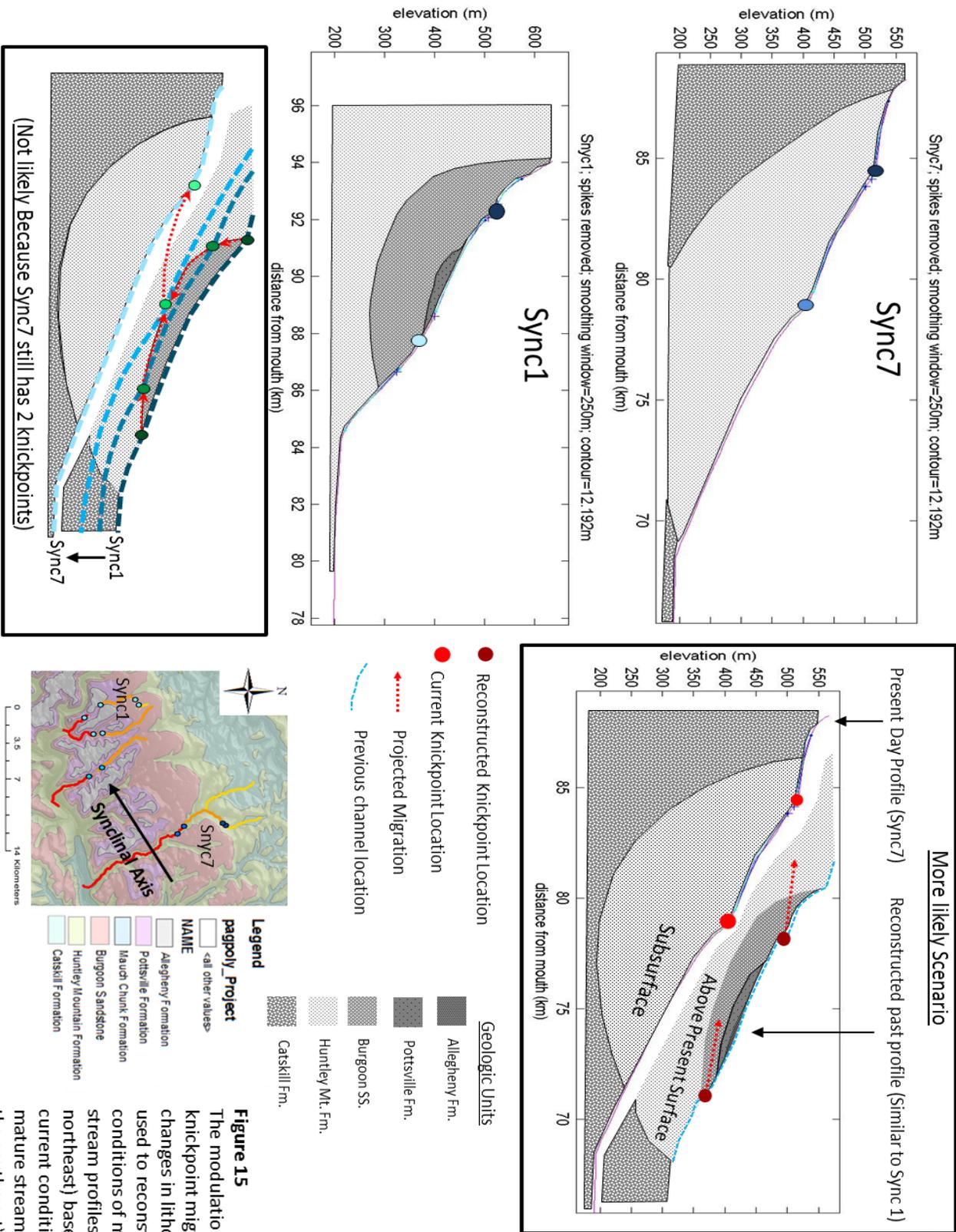


Figure 15 compares cross sections of the lithology underlying two profiles, sync1 and sync7. Sync1 is located about 15km southwest of sync7 and is underlain by younger bedrock, which would overlie the bedrock underneath sync7. If these streams have been incising down through the regional bedrock over time, it is a reasonable estimate that the sync1 profile resembles a past version of the sync7 profile, when the sync7 profile sat atop the same younger bedrock that currently underlies the sync1 profile. The sync1 profile can be used to reconstruct a past version of the sync7 profile, and difference in the position of the knickpoints in sync1 and sync7 can be used to interpret a possible migration route of the knickpoints. Figure 15 illustrates that the knickpoints in reconstructed sync7 must have migrated freely (not fixed to a lithologic boundary) to the position that they are currently at in sync7.

With it well established that this region exhibits slope-break knickpoints which were not generated along lithologic boundaries characterized by abrupt changes in erosive resistance, these knickpoints must represent migratory signals left in stream profiles from waves of transient conditions (Kirby and Whipple, 2012). However, the equilibrated slope break knickpoints seen across the Alleghany Front are expected to have been migrating at a consistent vertical rate above baselevel (Niemann et al., 2001) (Kirby and Whipple, 2012). In the study area, knickpoints range nearly 300 meters in elevation above regional baselevel suggesting that the vertical migration rate is differentiated, in this case seemingly by spatial variations in lithology. Across the Alleghany Front, younger units such as the Alleghany, Pottsville, and Burgoon Sandstone tend to form resistant ridges and plateau features whereas older units such as the Catskill and Huntley Mountain Formations tend to weather into valleys (Levine and Slingerland, 1987). Additionally, catchment erosion rates gathered from cosmogenic ^{10}Be indicate that younger units, the Pottsville Formation, and the Burgoon Sandstone, are eroding slower than older units, the Catskill and Huntley Mountain Formations, refer to figure 11 (Reuter, 2005).



Streams flowing perpendicular to the axis of plunging synclines throughout the study region provide the best visualization when characterizing the observed relationship between knickpoint migration rate and bedrock lithology. Moving down-plunge along a synclinal axis, bedrock lithology consists of younger more resistant units. Streams ranging across younger more resistant units have knickpoints at a lower elevation above regional baselevel, and moving up-plunge along a synclinal axis, streams ranging across less resistant units have knickpoints at a higher elevation above regional baselevel. The climb in knickpoint elevation is gradual as is the transition from younger bedrock to older less resistant bedrock, suggesting a correlation between knickpoint elevation and bedrock strength (Duvall et al., 2004). Figures 6, 7, 8, 9, and 10 emphasize this transition; figure 6 is revisited below:

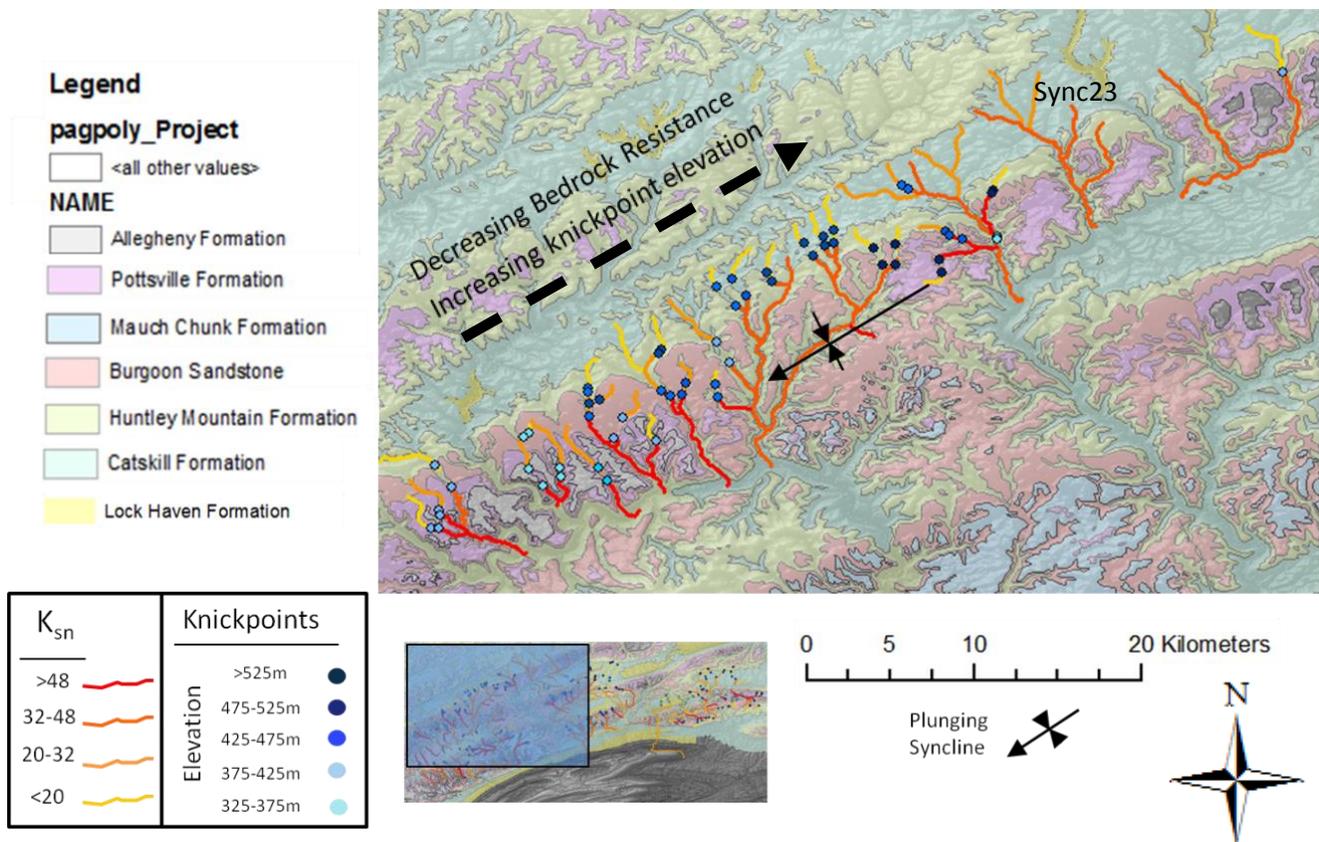


Figure 6 (revisited) The elevation of knickpoints above regional baselevel is lowest in streams which are underlain by the youngest units. Moving up plunge, the elevation of knickpoints gradually climbs as streams are underlain by older weaker units. The resistant younger units are inhibiting the vertical migration rate of knickpoints. As streams incise into older units beneath the Burgoon Sandstone, vertical migration rate increases, and knickpoints rapidly migrate upstream, eventually migrating through the profile entirely, resulting in a steepened channel with no knickpoints (streams near sync23).

The interplay between changing lithology, stream profile metrics, and estimated erosion rate along the axis of synclinal plunge in this region could be used as a powerful tool to reconstruct past conditions of certain stream profiles and quantify how this landscape has evolved since the onset of the transient perturbation. Assuming that changes in lithology have largely controlled knickpoint migration rate and stream channel morphology since the onset of incision, stream profiles currently flowing over younger bedrock lithology resemble past conditions of stream profiles which now flow over older bedrock (figure 15) (Duvall et al., 2004)(Whipple, 2011). Comparing stream profiles that transverse plunging synclines reveals a chronology of how stream profile metrics and correlated erosion rate changed over time with respect to changing lithology as these streams down-cut into older bedrock.

In figure 6, stream profiles in the northeast portion of the region represent the most mature streams which have down-cut into the oldest bedrock. Each stream to the southwest represents a snapshot of a northeastern stream's erosional history (Figure 15 and Figure 16, next page). For example, Ssync23 used to have roughly the same characteristics as Ssync10 when Ssync23 was situated in the past on top of the same bedrock which currently underlies Ssync10. This chronology can be used to estimate how erosion rates have changed since the transient wave began migrating throughout the study region. But, if additional external forces other than bedrock lithology have changed during the course of a stream's incision since the initiation of the transient wave, such as additional fall in baselevel, changes in climate, or vegetation cover (Wobus et al., 2006; Synder et al., 2003; Portenga and Bierman, 2011; Whipple, 2009), then this estimate will be skewed. The chronology only accounts for changes in stream profile metrics and erosion rates which would be influenced by changes as these streams down-cut through different lithologies (Duvall et al., 2004; Kirby and Whipple, 2012).

Based on the small amount of data points correlating between k_{sn} and catchment erosion rate plotted in figure 15, we are limited in how much we can characterize spatial changes in erosion rates. It is evident that the k_{sn} above knickpoints is significantly lower than the k_{sn} below knickpoints, which indicates that portions of stream catchments above knickpoints are eroding slower than portions below knickpoints (Kirby and Whipple, 2012).

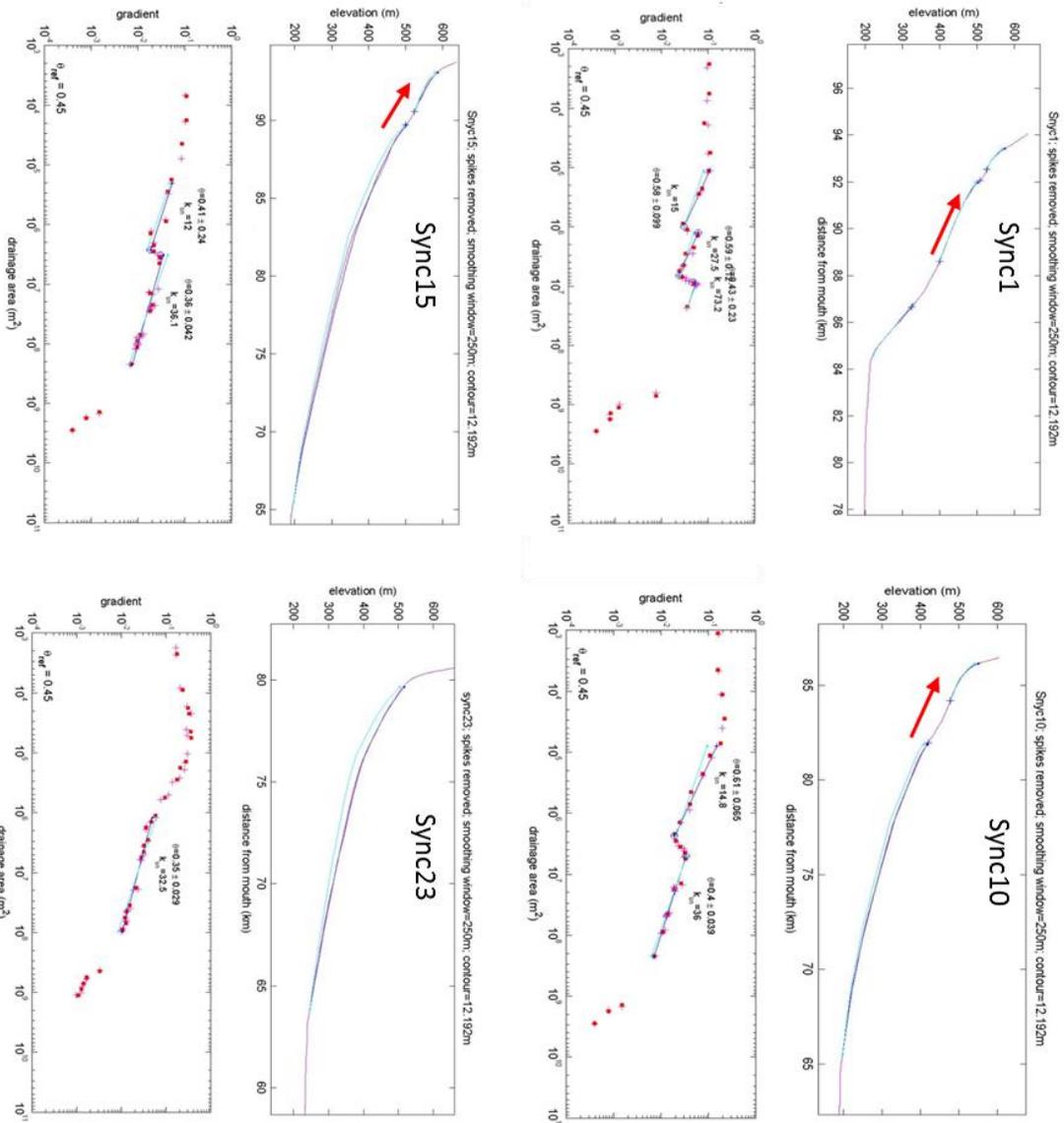
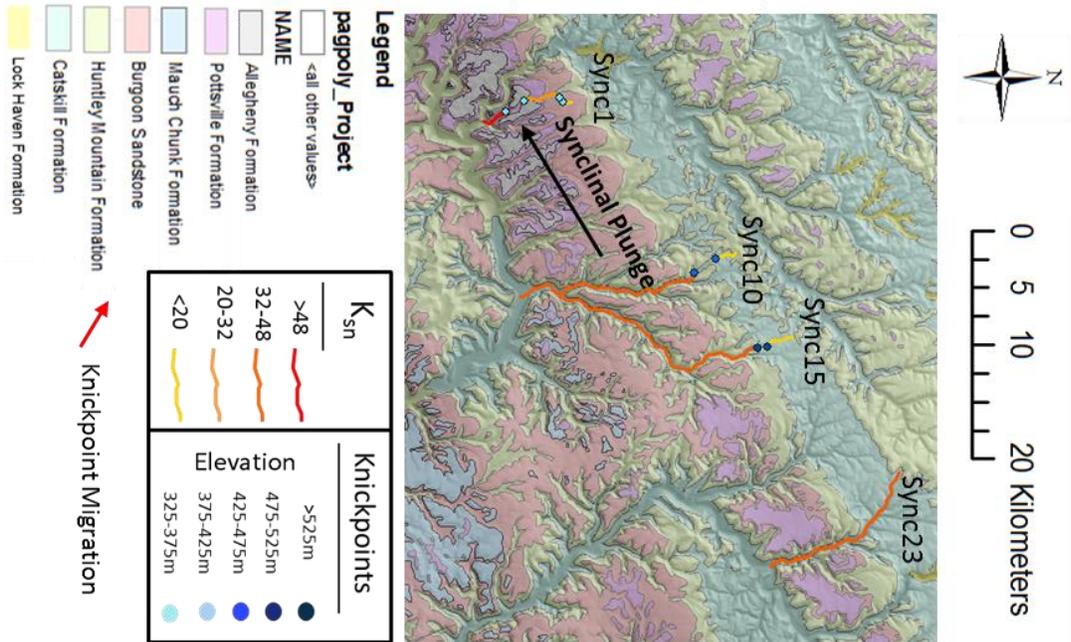


Figure 16 This figure demonstrates how stream profiles ranging over the WVC syncline have evolved over time. Sync23 represents the most mature stream profile, where the transient signal has migrated through the profile entirely. Each stream southwest of Sync23 could represent a snapshot of sync23 during a past stage in its evolution as the transient signal migrated up stream. Previously, when sync 23 was cutting through the bedrock that is now underneath sync15, we would expect the sync23 to have roughly a similar profile and erosion rate to sync15, same with when sync 23 was cutting through the bedrock underneath sync10 and sync1. All of these estimates are only possible under the assumption that the estimated condition takes place after the transient wave entered the channel and that no other changes in baselevel fall or stream discharge occurred thereafter (Kirby and Whipple, 2001, 2003; Snyder et al., 2001; Whipple, 2001; Whipple, 2004).



Conclusion

The prevalence of slope-break knickpoints distributed with no spatial dependence on bedrock lithology is evidence of a transient signal migrating throughout stream channel networks in the Alleghany Front. Numerous stream profiles contain a pair of knickpoints, which may indicate two pulses of transient conditions. Spatial differences in lithology are not a likely the source which generated these knickpoints, but differences in substrate erodibility appear to influence the vertical migration rate of the knickpoints. From this study alone, the mechanism that created these perturbations cannot be distinguished. Future studies which measure erosion rates in specific catchments that range over regional plunging synclines can be employed to establish a chronology of how stream channel erosion rates have changed since the onset of transient conditions. A chronology of erosion rates can be used to revise the estimated timing of incision throughout the Susquehanna Watershed, in light of how erosion rates have changed over time in accordance to lithologic changes which are encountered as streams have down-cut through bedrock. Accurately estimating the timing of incision throughout the Susquehanna River will elucidate which mechanism produced current migratory knickpoints: rejuvenated uplift, climate change, or stream capture/drainage basin reorganization events. In further research, the interplay between drainage systems and regional geologic structure can be an effective tool in reconstructing recent degenerative histories of relict mountain chains.

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