Analysis of Knickpoint Formation and Characterization of Stream Catchments

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I. Introduction

The earth contains many features in the landscape that can serve as a record of past events. One such feature that can be used to interpret past events is a knickpoint. Knickpoints occur when one reach of a stream is steepened with respect to the adjoining reaches; visually, they can be thought of as waterfalls (Burbank et al.). In an equilibrium environment, the rate of erosion equals the rate of uplift, but the presence of a knickpoint suggests that the environment where the knickpoint is found is not in equilibrium. This means that either uplift is outpacing erosion or vice versa. So what can these knickpoints indicate about the landscape and the geologic processes in an area? In broad terms, these features can tell what has occurred in a landscape, when the changes or events have happened, and how fast those events took place. This paper will focus on the primary causes of knickpoint formation and the implications of knickpoint formation in a landscape.

II. Knickpoint Formation

As previously explained, knickpoints are features that occur in streams and rivers throughout a landscape. The cause of a knickpoint in a stream profile is related to the stream power erosion law which is generally depicted in the form

$$\frac{dZ}{dt} = U - f(Q_s)K\frac{A^m}{W}S^n,$$

(Whittaker et al., 2012). This equation relates change in elevation (Z) over time (t) to other factors of moving water that can alter a landscape. These factors include uplift (U), relative dependency of erosion rates on A and S (m, n), channel width (W), sediment supply (f(Q)), and erodibility (K) (Whittaker et al., 2012). This equation can be used to determine how a stream will change in elevation over time in an actively uplifting area depending on the factors and constraints that are present (Burbank et al.). Gallen et al. suggests another set of equations that can be used to describe an equilibrium stream profile adjusted for current climate and tectonic conditions (Gallen et al., 2013):

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

$$k_s = \left(U / K \right)^{1/n}$$

$$\theta = m/n$$

These equations assume that uplift and erodibility are uniform for the length of the channel, and they can be used to help find the paleo base level when the knickpoint was first created. (Cyr et al., 2014). Using the stream power erosion equations will aid in discovering where uplift and erosion are not in equilibrium.

Knickpoints form in actively evolving, transient streams. Within these streams exist three main reasons for knickpoint formation: tectonics, change in base-level, and lithology. The simplest explanation for a tectonically created knickpoint is local normal faulting where the hanging-wall is in the downstream direction (Burbank et al.). This creates a knickpoint over the fault because the stream is forced to flow in the downward direction. In a more general sense, faulting can be included in the idea of local uplift, where there is a difference in uplift

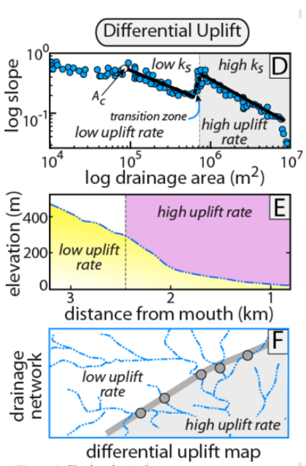


Figure 1: Burbank et al.

above and below the instance of a knickpoint. In **Figure 1**, graph F depicts a drainage network with a differential uplift map (Burbank et al.). The gray circles represent steepend reaches in the landscape as they pass over an area that changes from a low to a high uplift rate. Similarly, graph E in **Figure 1** is a stream profile that highlights the point where there is a difference in uplift rates. In the downstream reach there is a higher uplift rate causing an increase in erodibility as the stream tries to move back into equilibrium, hence the more defined concave shape of the stream (Cyr et al., 2014). Knickpoints are generally associated with tectonic environments, but there are other factors and causes that may also explain their existence.

The second reason that a knickpoint may form in a landscape is due to change in base-level. The most common example of a base-level change is the raising and lowering of the ocean. **Figure 2** is a diagram that illustrates how base-level change knickpoints migrate upstream over time and can record elevations of the base-level (Duran et al., 2019). The visuals in Stage 1 of **Figure 2** show a stream at equilibrium flowing into a body of water at base-level. Stage 2 then shows the result of base-level lowering where a knickpoint is formed and then slowly migrates upslope as the channel grades down to reach equilibrium (Duran et al., 2019). Burbank and Anderson explain how this theory of knickpoint migration can be replicated in a lab setting (Burbank et al.). Their research suggests a complex response showing that a knickpoint can form even when base-level is steadily lowered (Burbank et al.). Although these two explanations account for many knickpoints that exist, there is one simpler explanation.

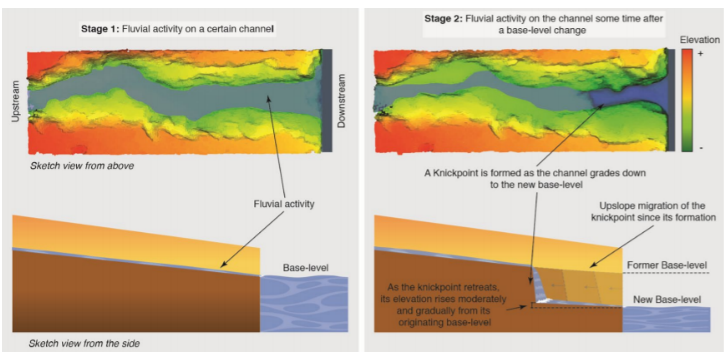


Figure 2: Duran et al., 2019

The third reason that a knickpoint may form is due to a change in lithology. A change in lithology suggests rock type changes can have an effect on the creation of knickpoints (Arkle et al., 2017). As the stream passes over a change in lithology, a knickpoint can be formed when the two geologic units have different characteristics, namely erodibility (Cyr et al., 2014). Rocks that are less resistant to erosion will tend to underlie the shallower reaches of the stream, and in contrast, the rocks that are more resistant will underlie the steeper reaches of the stream (Burbank et al.). A contact between geologic units can often be a location where a knickpoint is formed,

III. Identifying the Cause of Knickpoints

Although there are only three causes of knickpoints outlined in this paper, it can be difficult to distinguish between them without the assistance of other data. **Figure 3** depicts a visual summary of lithologic and uplift that lead to the knickpoint formation explained above:

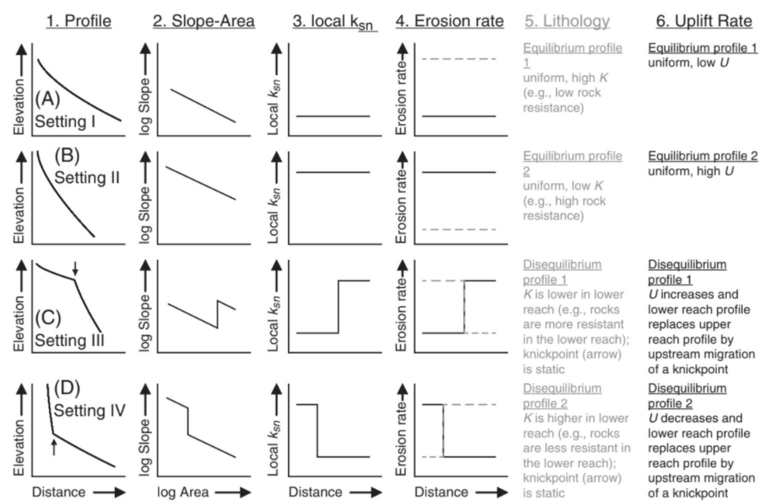


Figure 3: Cyr et al., 2014

In **Figure 3**, each column shows a description for the settings listed in column 1. The purpose of this chart is to explain the differences between lithologic and tectonic controls on knickpoint formation and each are summarized below:

Setting I: Formation due to a low uplift rate or highly erodible rock

Setting II: Formation due to a fast uplift rate or lower erodible rock

Setting III: Formation due to increased uplift where lower reach replaces upper reach by knickpoint migration or more resistant rocks in lower reach

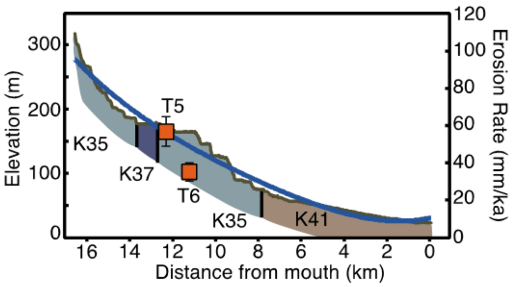
Setting IV: Formation due to decreased uplift where lower reach replaces upper reach by knickpoint migration or rocks are less resistant in lower reach

It is often difficult to determine the difference between lithology and tectonic controls simply based on digital elevation data, hence the need for more information about local slope area, erosion rate, and lithologic erodibility (Cyr et al., 2014). In order to tell the difference between these two causes, compare the k_{sn} graph to the erosion rate graph; this will show that the cause is either due to an uplift rate, or a lithologic control. For example in setting II, if the river channel is steep because the local rock is resistant to erosion, then the channel incision and hill slope erosion rates would be low. However if it is steep due to rapid uplift, then both channel incision and hill slope erosion rates would be high.

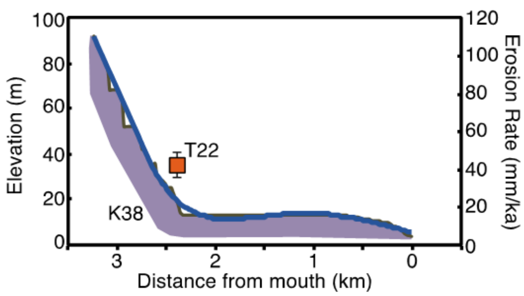
In **Figure 3**, several of the columns are plotted in log space because it shows the relationship of a graph as a straight line, and any points that do not follow this trend can highlight differences in one variable compared to another (Frost, J). Log-log plots are useful in identifying the setting and cause of knickpoints because it gives a clear visual of the relationships between variables, and can be used to easily compare to each of the four settings.

The settings from **Figure 3** and the three main causes of knickpoint formation can be used to identify the cause of knickpoint formation in the field. To demonstrate the process of hypothesizing a knickpoint cause, three stream profiles from the Northern Range in Trinidad will be analyzed. Each of these stream profile graphs can be found in the supplementary material (Arkle et al., 2017).

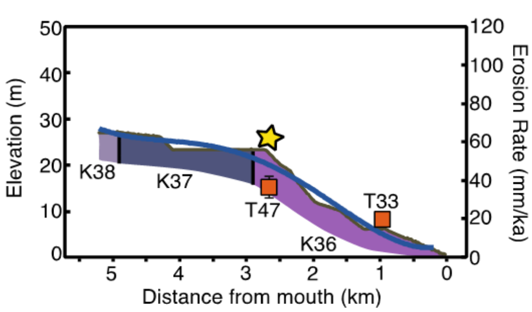
The first step in determining the cause of the knickpoint formation is to compare the shape of the smoothed profile to column 1 in **Figure 3**. The shape mostly resembles setting I or



III (when comparing the raw data). Next, looking at erosion rate, it appears to resemble the lithology erosion rates of setting III where erosion is high until it crosses the knickpoint and the erosion rate decreases. It is also important to note that the change in steepness is not at a geologic contact, but rather it occurs within the rock unit. Based on these interpretations, the most likely explanation of knickpoint formation in this profile is a lithologic control where there are more resistant rocks in the lower reach.



For this stream profile, comparing the smoothed profile to each setting, it most closely resembles setting IV. There is also only one rock unit that underlies the stream profile, so that rules out a lithologic cause because a rock unit will not change erosion resistance in the middle of a unit. Further, the local k_{sn} graph matches the tectonically controlled erosion rate graph because we have ruled out a lithologic cause. This stream profile is most like setting IV which implies that the knickpoint was caused by a tectonic environment characterized by low uplift where the lower reach profile replaces the upper reach profile by upstream migration.



For this final stream profile, the convexity under the star indicates that this most closely resembles setting III. The knickpoint is not at a geologic contact, but it does appear that there is an increase in rock resistance in the downstream reach. If we were to compare the local k_{sn} with the erosion rate, it may resemble the lithology controlled erosion rate where erosion decreases after the knickpoint. If the cause was due to tectonic controls and a migrating knickpoint, it is expected that the erosion rate would increase after the knickpoint.

IV. Knickpoint Implications

Knickpoints can form in a landscape due to several different factors which can help explain and describe what is happening in an environment. As previously explained, knickpoints can hint at tectonic activity in an environment. In fact, these knickpoints in the landscape can be viewed as an archive of tectonic rates, past ocean levels, and changes in climate through time (Whittaker et al., 2012). Using the knickpoints to decipher past and current tectonic activity is helpful to better understand the geologic processes in an area. In the Northern Range in Trinidad, Bandera used catchment data and identified knickpoints in a localized area to locate a fault (Bandera et al., 2021). Identifying faults in a region helps interpret the geologic past of an area.

Knickpoints can also be used to decipher the timing of geologic movement or uplift. After collecting catchment data from the Northern Range of Trinidad, Arkle et al. found that the Northern range underwent a tectonic inversion, resulting in a current east side up tilting of the island (Arkle et al., 2017). Not only were they able to determine a tectonic inversion, but they were able to use the stream power erosion laws and stream catchment data to suggest a rough timing of when the inversion occurred (Bandera et al., 2021). Recall that the stream power erosion law is change in elevation over change in time based on several factors including uplift and erosion. Knowing these other factors, the equation can be rearranged to determine the timing of an inversion.

V. Conclusion

The focus of this paper is to discuss the primary causes of knickpoint formation and the implications of knickpoint formation in a landscape. Knickpoints are generally created by tectonic forces, changes in base-level, or a change in lithology. These knickpoints can then be used to better understand a landscape and to construct an estimated timeline of geologic deformation in an area. Further study in the theory of knickpoint formation will likely find that these features can be used to further decipher the geologic past.

References

Arkle, J.C., Owen, L.A., Weber, J., Caffee, M.W., and Hammer, S., 2017, Transient Quaternary erosion and tectonic inversion of the Northern Range, Trinidad: Geomorphology, v. 295, p. 337–353, doi:10.1016/j.geomorph.2017.07.013.

Bandera, A., 2021, Timing and Nature of Uplift of the Northern Range, Trinidad: An Analysis with Knickpoint Indices: Geological Society of America, v. 53, doi:10.1130/abs/2021NC-362861.

Burbank, D., and Anderson, R. Holocene deformation and landscape responses, *in* Tectonic Geomorphology, John Wiley & Sons, Ltd, p. 243–273, doi:10.1002/9781444345063.ch8.

Cyr, A.J., Granger, D.E., Olivetti, V., and Molin, P., 2014, Distinguishing between tectonic and lithologic controls on bedrock channel longitudinal profiles using cosmogenic 10Be erosion rates and channel steepness index: Geomorphology, v. 209, p. 27–38, doi:10.1016/j.geomorph.2013.12.010.

Duran, S., Coulthard, T.J., and Baynes, E.R.C., 2019, Knickpoints in Martian channels indicate past ocean levels: Scientific Reports, v. 9, p. 15153, doi:10.1038/s41598-019-51574-2.

Frost, J. Using Log-Log Plots to Determine Whether Size Matters: Statistics by Jim, https://statisticsbyjim.com/regression/log-log-plots/ (accessed April 2021).

Gallen, S.F., Wegmann, K.W., and Bohnenstieh, D.R., 2013, Miocene rejuvenation of topographic relief in the southern Appalachians: GSA Today, v. 23, p. 4–10, doi:10.1130/GSATG163A.1.

Whittaker, A.C., 2012, How do landscapes record tectonics and climate? Lithosphere, v. 4, p. 160–164, doi:10.1130/RF.L003.1.