Using GIS to appraise lithologic and structural control of streams in the Grabens of southeast Utah

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Introduction

The Grabens of southeastern Utah are a north-south striking arcuate array of normal faults bounding alternate horst and grabens blocks (figure 1). Excellent fault exposure and relatively small size (200 km^2) have prompted geologic study since the mid 20th century. Research has focused primarily on structure geometry and salt tectonics (which controls their formation). Understanding gained through research in the Grabens has been applied in settings ranging from deepwater petroleum traps near Lebanon to the surface of Mars.(Kosi et al., 2012; Schultz et al., 2007).

Patterns and rates of deformation have been inferred from structural interpretations and conceptual models, and have been quantitatively assessed using interferometric synthetic aperture radar (INSAR) data (Furuya et al., 2007). However, patterns and rates have not been determined for the entire history of the Grabens. Structural geologists have attempted to used stream knickpoints as a marker of past movement along structures (Commins et al., 2005), but it is debatable whether these knickpoints actually reflect such movement or are simply a function of lithology. The purpose of this study is to identify, map, and classify knickpoints in order to generate a better understanding of their distribution and determine where future field work might be focused.

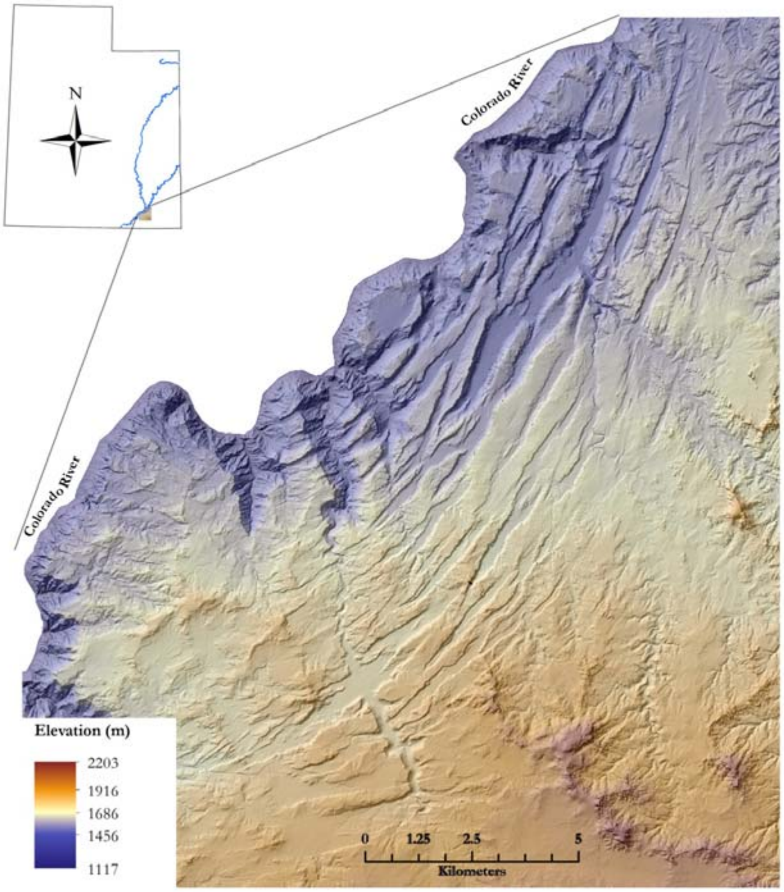


Figure 1. Location map of the Grabens. DEM hillshade map clipped to polygon described in Methods.

Objectives

1. Use GIS to identify anomalies (knickpoints) in stream longitudinal profiles.
2. Overlay results on a geologic map to determine how knickpoints formed.

Stream Long Profile background

Typical streams have a concave-up profile (figure 2). Under ideal conditions, this reflects that the stream's ability to do work—move sediment or incise bedrock—is constant along its length. This is because stream power (Ω) is a function of discharge (Q) and slope (S), and streams initiate in high slope, low discharge areas (headwaters) while terminating in low slope, high discharge areas (mouth):

$$\Omega = \varrho g Q S \tag{1}$$

Geomorphologists quantify long profile metrics using concavity and steepness indexes (θ and ksn, respectively) such that the slope of the longitudinal profile is a function of drainage area, A, and these indexes:

$$S = (ksn)\, A^{-\theta} \tag{2}$$

Streams with this idealized concave up profile are typified by single ksn and θ values over their entire length. However, changes in climate, base level (i.e. the relative elevation of the stream mouth), sediment supply, and geology alter stream slope and/or discharge. These adjustments may manifest as convexities or knickpoints in the typical concave-up longitudinal profile and will require different ksn and/or θ values over the length of the profile for a best fit (Wobus et al. 2006). The Matlab long profile tool requires an input of a reference θ value, meant to approximate the idealized channel profile without knickpoints. Typical concavity index values for the Colorado Plateau range from 0.25—0.45 (Pederson and Tressler, 2012). The user is then required to partition the long profile into subunits that will be best fit using a regression equation with unique ksn and θ values (see Methods—Matlab).

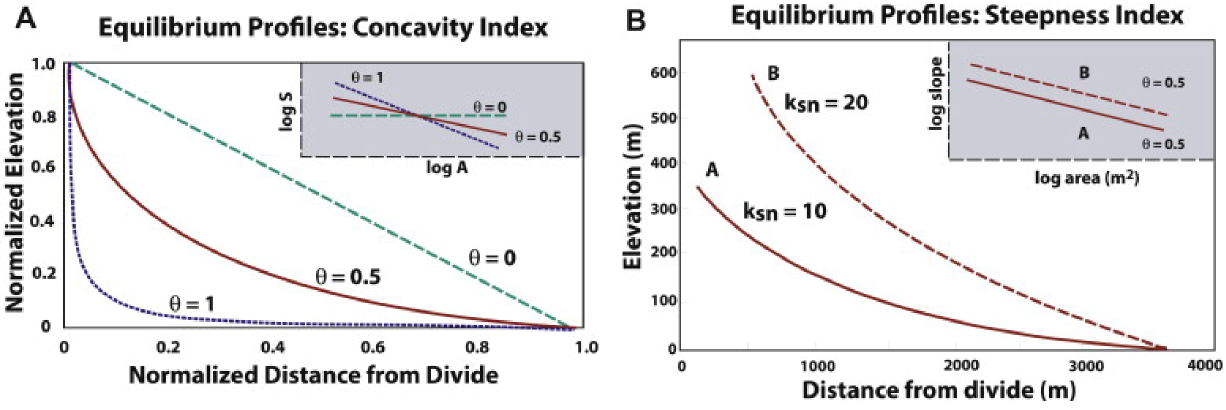


Figure 2. Stream long profiles with various concavity indexes (A) and steepness indexes (B) illustrated. From Burbank and Anderson, 2011.

Because steepness index is a function of uplift rate (U) and erodibility (K):

$$Ksn = (U/K)^{1/n} \tag{3}$$

high values may indicate relative uplift if erodability is held constant along the stream profile; alternatively they may point to changes in erodability (i.e. lithology) if uplift is assumed to be constant.

Knickpoints are classified as either pinned or transient. An example of the former would be a lithologically controlled waterfall that forms due to resistant bedrock (e.g. Niagara Falls); the latter forms due to relative base level fall—which could be initiated through tectonics, decrease in sea level, or stream integration—and migrates upstream after the event (figure 3).

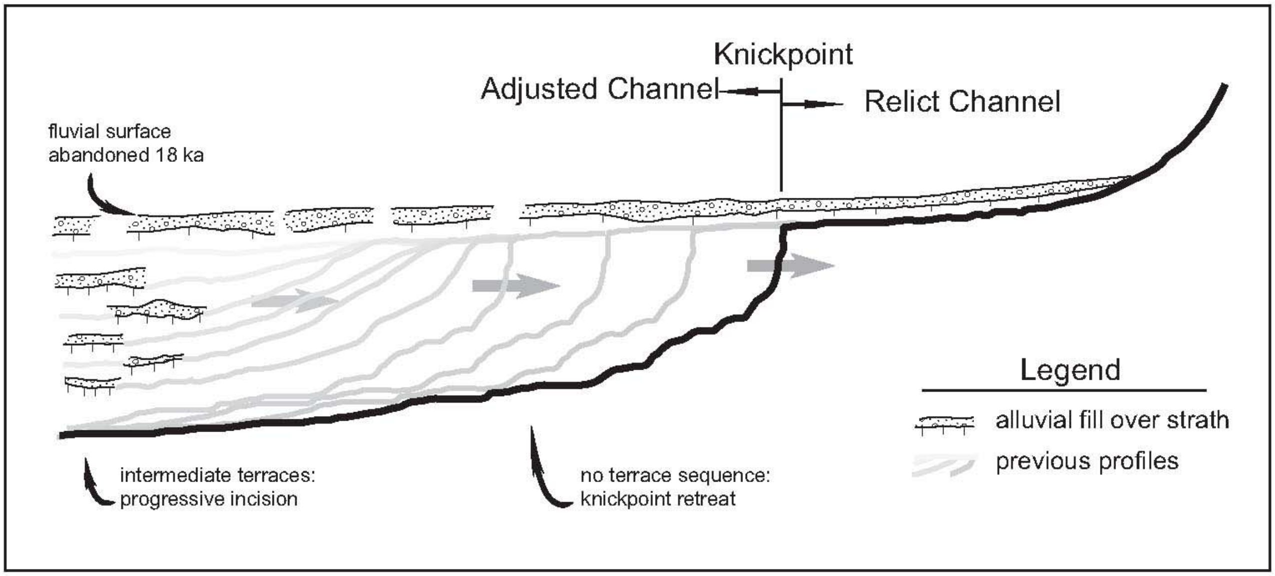


Figure 3. Knickpoint morphology within a longitudinal profile. Light grey lines and arrows show channel adjustment and subsequent upstream migration of knickpoint following base level fall at 18 ka. From Crosby and Whipple, 2006.

Methods—Data Acquisition

1. 5-m autocorrelated DEMs were acquired from the Utah Automated Geographic Reference Center (AGRC). These DEMs are generated through stereoscopic analysis of orthophotos (www.gis.utah.gov).
2. Topographic maps were acquired from the Utah AGRC. These georeferenced digital images of USGS 7.5' quadrangles were used in this project for site identification.
3. A digital geologic map was acquired from the Utah Geologic Survey (UGS). Map was generated in 2004 by H. Doelling.
4. Streamline and watershed data were downloaded from the National Hydrography Dataset, but were ultimately not used in this analysis, because the flowlines artificially connected deranged drainages in the Grabens.

Methods—DEM preparation

1. Mosaic, reference frame, statistics

DEM files were brought into ArcGIS. A new file geodatabase was generated in ArcCatalog, into which a new raster dataset file was created. The spatial reference frame for each DEM had to be added (UTM NAD 83, zone 12N; NAVD1988) and statistics calculated. The Data Management Tool/Converstion Tool was used to convert each ASCII file to Raster; these were then placed in the newly created geodatabase. The four DEM raster files were added to the Data Management Tools/Raster/Mosaic Dataset/Create tool, which mosaicked the DEMs into a new raster file.

2. Clip

In the file geodatabase containing the mosaicked DEM, a new shapefile was added. The Edit

Tool was used to create a polygon outlining the area of interest. Then the Clip tool used this polygon as a mask to which to clip the DEM, so that it was smaller and more quickly analyzed using the Spatial Analyst Tools (figure 1).

Methods—DEM analysis

1. Spatial Analyst Hydrology Tools

Pits were filled in the DEM using the Spatial Analyst Tools/Hydrology/Fill tool. Then the Spatial Analyst Tools/Hydrology/Flow Direction tool was applied, which was input to the Flow Accumulation tool to generate flowlines. The Raster Calculator tool was then used to delineate realistic flowlines; 4 different cell limits were used, with 10,000 resulting in the most satisfactory flowlines. The output from the Flow Accumulation tool and Raster Calculator were used to choose channel heads using the Profiler Tool Add-in (see below). Flow lines were also input to the Spatial Analyst Tools/Hydrology/Watershed tool, along with user-created outlet points, to delineate watersheds for the two drainages selected for analysis, Red Lake Canyon and Cross Canyon (see figure 7).

2. Conversion for Matlab input

The unfilled DEM and Flow Accumulation output raster were converted to ASCII filed using the Data Management Tools/Conversion tool; this output is readable by MatLab, which uses the unfilled DEM and flow direction tool to determine flow accumulation—with user-set flow accumulation limits—and thereby flowlines; these are saved as .shp files and used to generate long profiles with embedded geographic data.

Methods—Matlab

1. Note on ArcGIS compatability

The longitudinal profile tool for Matlab is only compatable with ArcGIS 9.2; not ArcGIS 10.1. Therefore, all the above steps were done twice: once in ArcMap 10.1 for presentation figures, and again in ArcMap 9.2 for input into Matlab.

2. File Management, Profiler Add-in

Steps outlined in the Stream Profiler Tool tutorial available through www.geomorphtools.org were followed to generate a file structure recognized by the Matlab longitudinal profile generator code, to add the Profiler Tool to ArcGIS 9.2, and to subsequently generate long profiles in Matlab. A complete description of these steps is not included this report because they would preclude inclusion of anything else! Please see references for the complete link to the tutorial.

3. Stream selection

The Profiler Tool Add-in allows the user to choose which streams to profile in ArcMap. This is accomplished by clicking on the map where the stream begins; user set "search distance" is used by the program to determine stream head.

4. Profile Analysis

Figure 4 shows an example of the plots generated by the Matlab longitudinal profiler codes. These plots are used to determine regression limits for each stream segment. Most picks were made on the drainage area vs. gradient plot; fit was assessed visually on the long profile plot and using rms values provided by Matlab. Knickpoints were picked by hand on the long profile. Once all segments have been fit, the user saves output files, which consist of: images of plots and .shp files of streams (including regression equation values; elevation and xy data) and knickpoints (figure 5).

Figure 4. Long profile (top), drainage area relation (middle) and slope vs. A (bottom) plots for Red LakeCanyon. Pink line in the top plot is the Matlab-generated long profile; cyan lines are best fit with reference θ; blue lines are best fit with appropriate θ and ksn values.

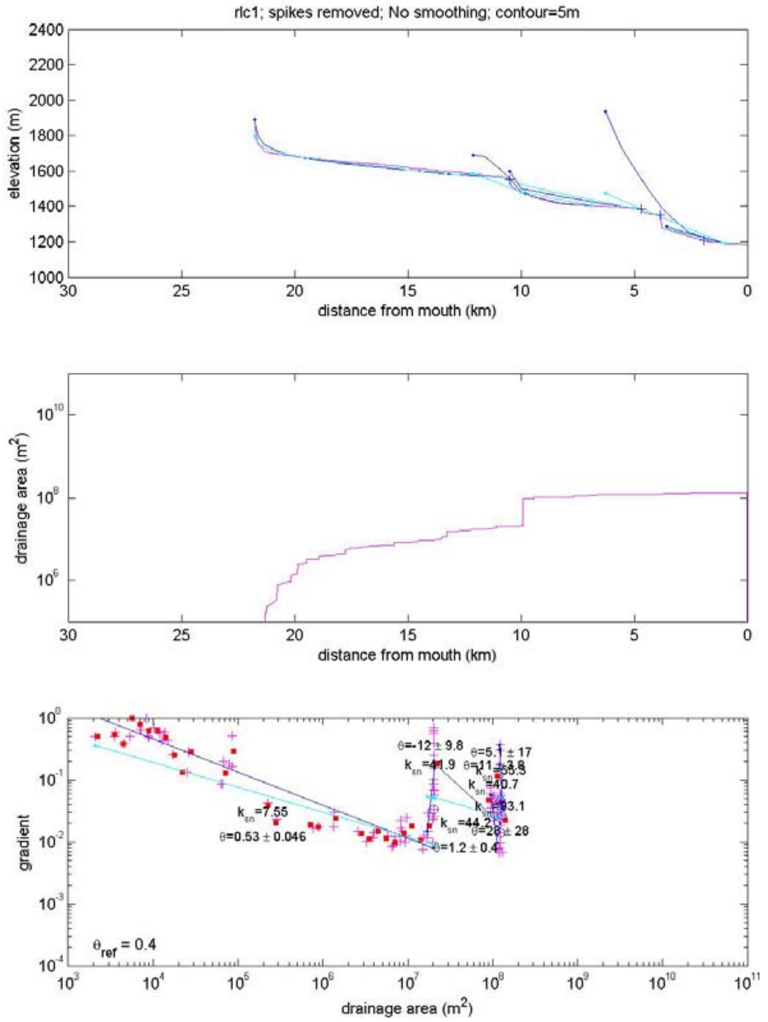
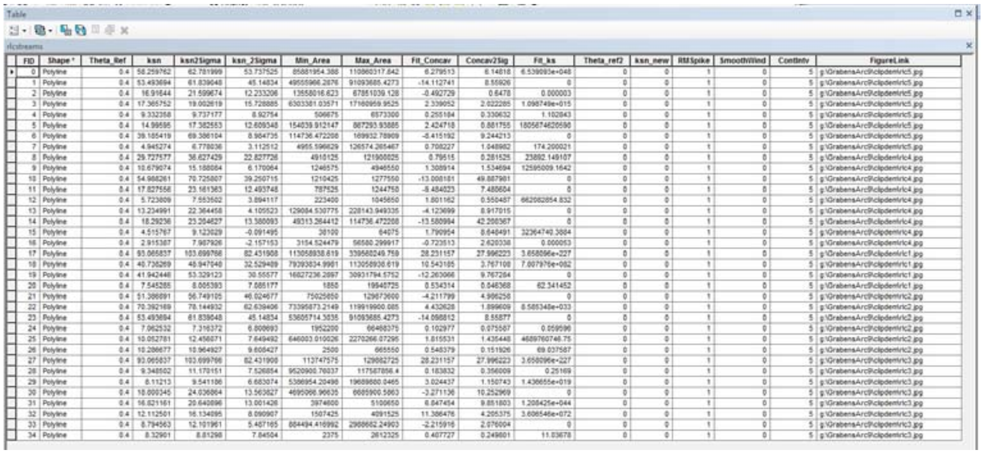


Figure 5. Attribute table from the Red Lake Canyon shapefile.



FID	Shape *	Theta_Ref	ksn	ksn2Sigma	ksn_2Sigma	Min_Area	Max_Area	Fit_Concav	Concav2Sig	Fit_ks	Theta_ref2	ksn_new	RMSpike	SmoothWind	ContInv	FigureLink
0	Polyline	0.4	58.259762	62.781999	53.737525	85881954.388	110860317.842	6.279513	6.14818	6.539093e+048	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc5.jpg
1	Polyline	0.4	53.493694	61.839048	45.14834	49555966.2876	91093685.4273	-14.112741	8.55926	0	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc5.jpg
2	Polyline	0.4	16.91844	21.599674	12.233206	13558016.623	67851039.128	-0.492729	0.6478	0.000003	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc5.jpg
3	Polyline	0.4	17.365752	19.002619	15.728885	6303381.03571	17160959.9525	2.339052	2.022285	1.098749e+015	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc5.jpg
4	Polyline	0.4	9.332358	9.737177	8.92754	506675	6573300	0.255184	0.330632	1.102843	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc5.jpg
5	Polyline	0.4	14.99595	17.382583	12.609348	154039.912147	887293.93885	2.424718	0.881755	1805674820590	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc5.jpg
6	Polyline	0.4	39.185419	69.386104	8.984735	114736.472208	169932.78909	-8.415192	9.244213	0	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc5.jpg
7	Polyline	0.4	4.945274	6.778036	3.112512	4955.596829	126574.265467	0.708227	1.048982	174.200021	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc5.jpg
8	Polyline	0.4	29.727577	36.627429	22.827726	4910125	121900025	0.79515	0.281525	23892.149107	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc4.jpg
9	Polyline	0.4	10.679074	15.188084	6.170064	1246575	4946550	1.308914	1.534694	12595009.1642	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc4.jpg
10	Polyline	0.4	54.988261	70.725807	39.250715	1210425	1277550	-13.008181	49.887981	0	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc4.jpg
11	Polyline	0.4	17.827558	23.161363	12.493748	787525	1244750	-8.484023	7.488604	0	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc4.jpg
12	Polyline	0.4	5.723809	7.553502	3.894117	223400	1045650	1.801162	0.550487	662082854.832	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc4.jpg
13	Polyline	0.4	13.234991	22.364458	4.105523	129084.530775	228143.949335	-4.123699	8.917015	0	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc4.jpg
14	Polyline	0.4	18.29236	23.204627	13.380093	49313.264412	114736.472208	-13.580984	42.298367	0	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc4.jpg
15	Polyline	0.4	4.515767	9.123029	-0.091495	38100	64075	1.790954	8.648491	32364740.3884	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc4.jpg
16	Polyline	0.4	2.915387	7.987926	-2.157153	3154.524479	96580.299917	-0.723513	2.620338	0.000053	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc4.jpg
17	Polyline	0.4	93.065837	103.699766	82.431908	113058938.619	339568249.759	28.231157	27.996223	3.658096e+227	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc1.jpg
18	Polyline	0.4	40.738269	48.947048	32.529489	79393834.9981	113058938.619	10.543185	3.767108	7.807976e+082	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc1.jpg
19	Polyline	0.4	41.942446	53.329123	30.55577	16827236.2897	30931794.5752	-12.263066	9.767284	0	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc1.jpg
20	Polyline	0.4	7.545285	8.005393	7.085177	1855	19946725	0.534314	0.846368	62.341452	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc1.jpg
21	Polyline	0.4	51.386891	56.749105	46.024677	75025850	129873600	-4.211799	4.986258	0	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc2.jpg
22	Polyline	0.4	70.392169	78.144932	62.639406	73395873.2149	119919900.085	4.432628	1.899609	8.585348e+033	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc2.jpg
23	Polyline	0.4	53.493894	61.839648	45.14854	53605714.3835	91093685.4273	-14.698812	8.55877	0	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc2.jpg
24	Polyline	0.4	7.062532	7.316372	6.808693	1952200	66468375	0.102977	0.075587	0.059596	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc2.jpg
25	Polyline	0.4	10.052781	12.456071	7.649492	646003.010026	2270266.07295	1.815531	1.435448	4689760746.75	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc2.jpg
26	Polyline	0.4	10.286677	10.964927	9.608427	2500	665550	0.548379	0.151926	69.037587	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc2.jpg
27	Polyline	0.4	93.065837	103.699766	82.431908	113747575	129882725	28.231157	27.996223	3.658096e+227	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc3.jpg
28	Polyline	0.4	9.348502	11.170151	7.526854	9520900.76037	117587856.4	0.183832	0.356009	0.25169	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc3.jpg
29	Polyline	0.4	8.11213	9.541186	6.683074	5386954.20498	19689680.0465	3.024437	1.150743	1.438655e+019	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc3.jpg
30	Polyline	0.4	18.800345	24.036864	13.563827	4695066.96635	6685900.5863	-3.271136	10.252969	0	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc3.jpg
31	Polyline	0.4	16.821161	20.640896	13.001426	3974600	5100650	6.047454	9.851803	1.208425e+044	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc3.jpg
32	Polyline	0.4	12.112501	16.134095	8.090907	1507425	4091525	11.386476	4.205375	3.606546e+072	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc3.jpg
33	Polyline	0.4	8.794563	12.101961	5.487165	884494.416992	2968682.24903	-2.215916	2.076004	0	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc3.jpg
34	Polyline	0.4	8.32901	8.81298	7.84504	2375	2612325	0.407727	0.249601	11.03678	0	0	1	0	5	g:\GrabensArc9\clipdem\rlc3.jpg

5. Bringing data into ArcGIS

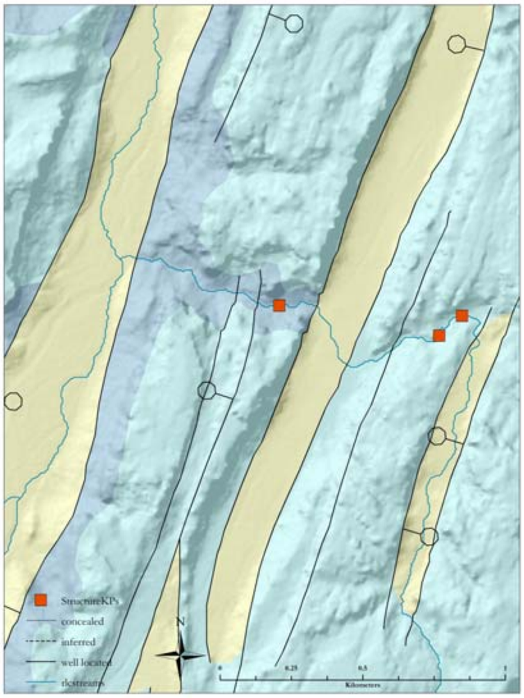
Shape files of streams (lines) and knickpoints (points) were opened in ArcGIS using the Profiler tool extension. Files had to be merged using the Data Management Tools/General/Merge tool in order for them to become readable by ArcMap 10.1.

Methods—Analysis in ArcGIS

1. Classifying knickpoints

The geologic map was brought ito ArcMap 10.1 along with the stream and knickpoint shapefiles from Matlab. All files were projected into the same data frame (see Methods—DEM Preparation). Each knickpoint was examined: those just upstream of a fault were classified as structurally controlled (figure 6) and those plotting on a bedrock contact were classified as bedrock controlled (Figure 7). Where both factors were present, or neither, knickpoints were unclassified.

Figure 6. Knickpoints classified as structurally controlled. Note two eastern knickpoints on horst, just upstream of two similarly space graben-bounding normal faults. Cedar Mesa sandstone is light blue, Lower Cutler beds are sky blue, Quaternary eolian and alluvial material is buff.



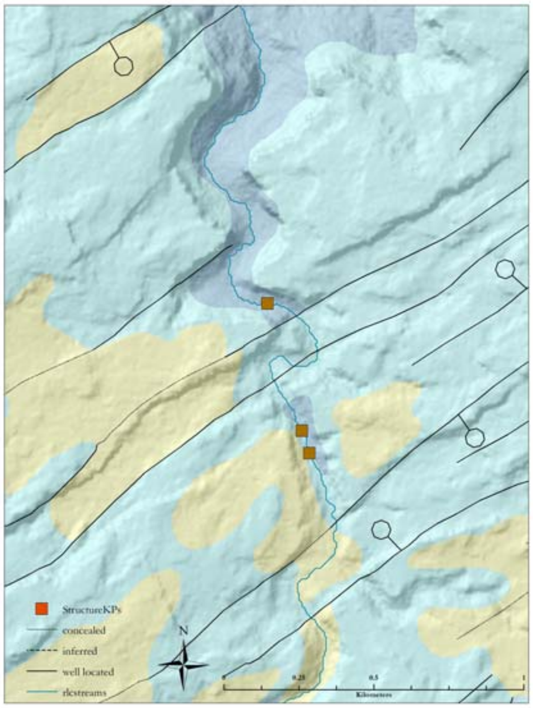


Figure 7. Knickpoints classified as bedrock controlled. Cedar Mesa sandstone is light blue, Lower Cutler beds are sky blue, Quaternary eolian and alluvial material is buff.

Classification was accomplished by creating two new point shapefiles within the geodatabase and adding points with the Edit tool. X and Y coordinates were determined using the Data Management Tools/Features/Add XY Coordinates tool.

2. Display streams

Streams from the Matlab line shapefile were classified by ksn index in order to assess where the normalized steepest reaches fell relative to knickpoints.

Results

The location of the Red Lake Canyon and Cross Canyons is shown in figure 8. Figure 9 shows the long profiles of each stream and its tributaries; numerous knickpoints are evident in both drainages.

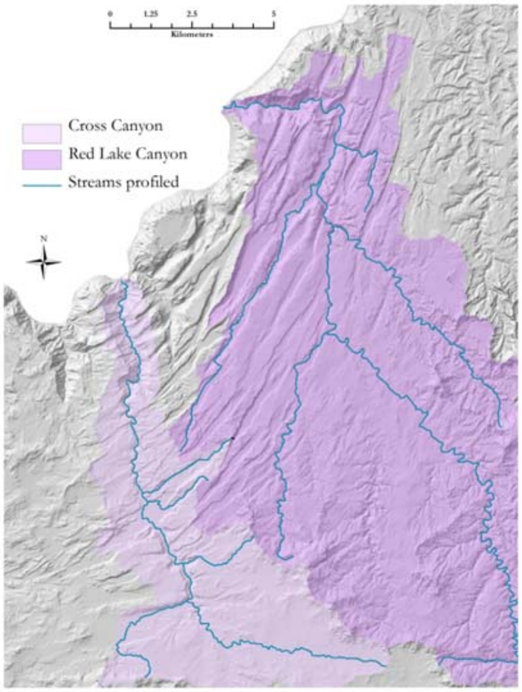


Figure 8. Red Lake Canyon and Cross Canyon watersheds with streams profiled in Matlab.

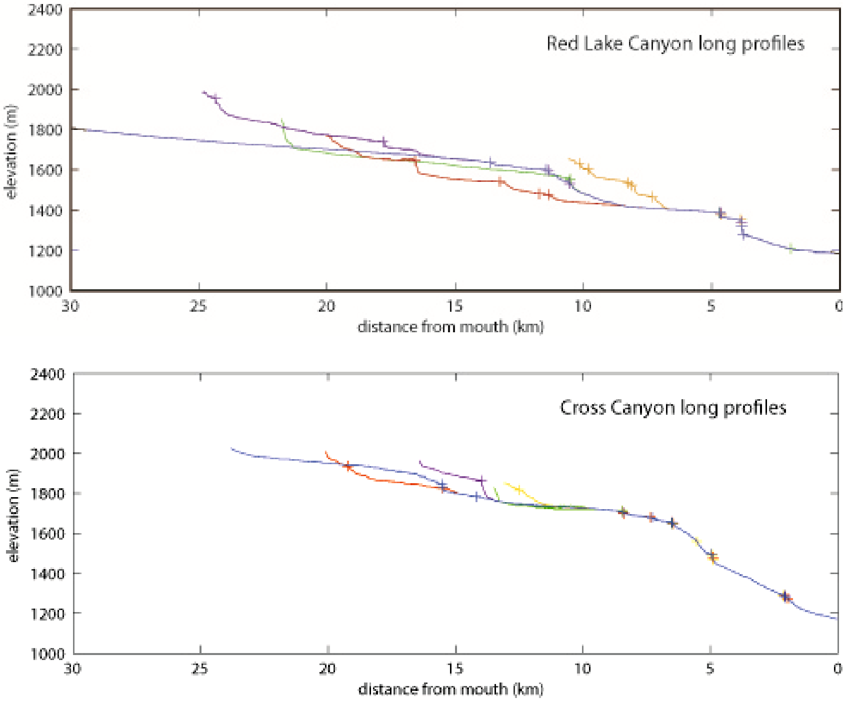


Figure 9. Longitudinal profiles of Red Lake Canyon and major tributaries (top) and Cross Canyon and major tributaries (bottom). Crosses indicate convexities of knickpoints in each profile.

30 knickpoints were identified through the long profile analysis and of those, 13 were determined to be structurally controlled; 5 were classified as forming due to lithology, and 11 were unable to be classified (figure 10). A correlation between steepness index and knickpoints was not evident.

Discussion

Three different reference θ values were input for three separate long profile analyses in Matlab; these results show the best fit. However, choosing the parameters for the Profiler Tool is clearly an art and ksn values may not be as accurate as those picked by a worker with more experience in this “art”. Knickpoint picks, on the other hand, are accurate, based on comparison of location with orthophotos and topographic maps.

Knickpoint classification is limited by the resolution and accuracy of the geologic map. The Cedar Mesa sandstone and underlying Lower Cutler Beds are lithologically diverse, with cyclic carbonate units, and there may therefore be more bedrock control than identified in this study (Jordan and Mountney, 2010)

Conclusions

Classification was possible for 60% of knickpoints, which suggests that this method is a useful first step toward structuring a field campaign to investigate knickpoints. While the results support the use of knickpoints for inferring past displacement along faults, caution is urged in applying this reasoning carte blanche, as bedrock variability controls at least 12% of knickpoints in these two drainages.

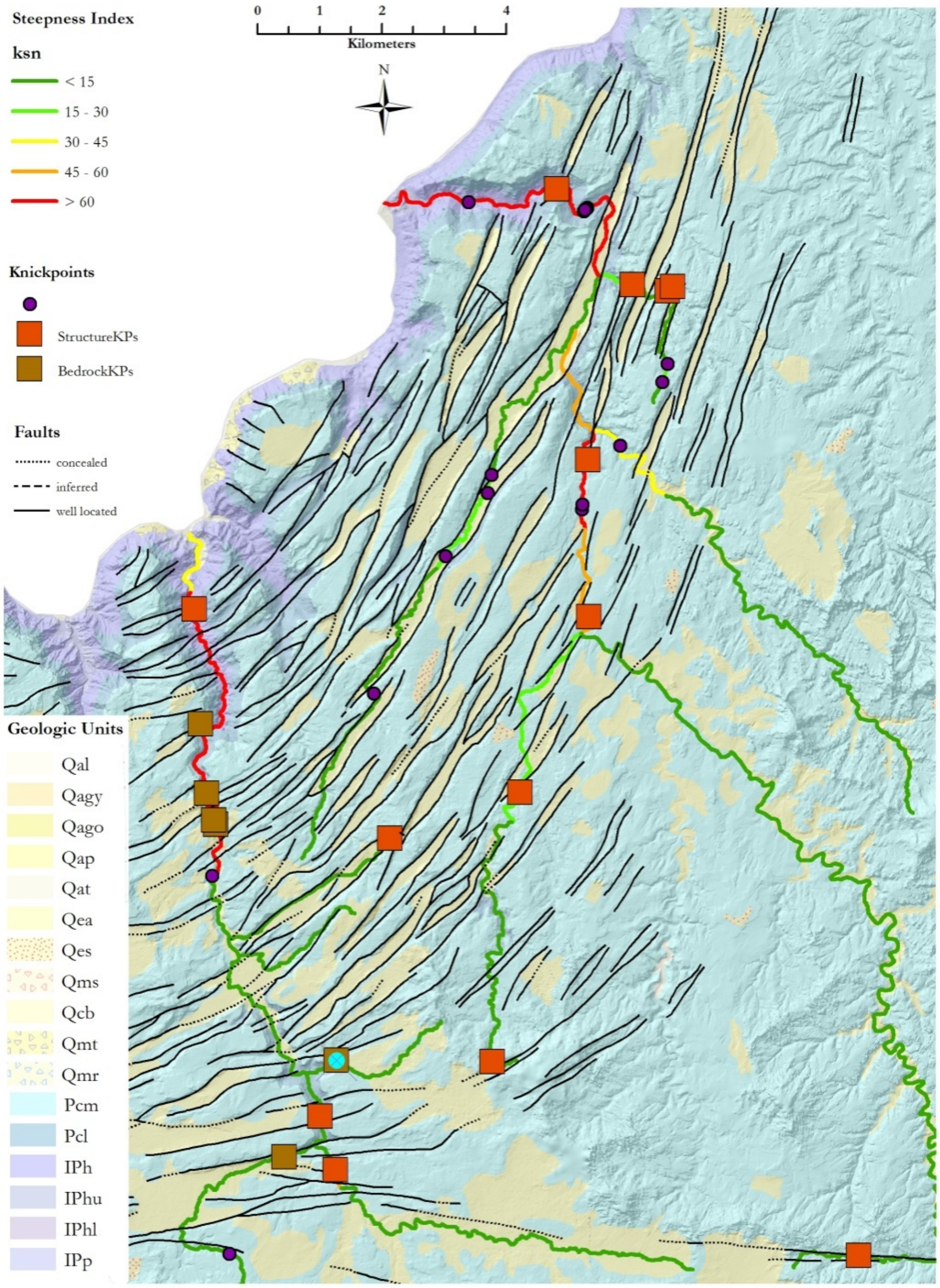


Figure 10. Classified and unclassified knickpoint distribution, surface geology and structures, and stream reaches classified by steepness index. Geologic units influencing knickpoint formation are P_{cm} (Cedar Mesa sandstone) P_{cl} (Lower Cutler Beds), and IP_{h} (Honaker Trail Fm)

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