**GSA Supplemental Data Repository Item 2013103**

# Miocene rejuvenation of topographic relief in the southern Appalachians

## Results and Discussion

The geology of the Cullasaja River basin consists primarily of biotite – to biotite-muscovite gneiss (Fig. DR1). The consistency of rock type coupled with our observations that lithologic contacts have no clear relationship to stream channel position, knickpoint location, or channel steepness (Fig. DR1) leads to the conclusion that bedrock control on hillslope erosion and river incision is uniform at the scale of the basin (Gallen et al., 2011).

The reference concavity ($\theta_{ref}$) was calculated as the average of the eight relict reaches by linear regression through log slope – log drainage area data (Table DR2, DR3; Fig DR2). Three of the relict reaches were excluded because they did not have enough data points to yield statistically significant regressions of slope-drainage area data ($r^2 < 0.7$; Table DR2). All of the concavities extracted from the relict reaches fall within error of the theoretical range (0.3 to 0.6) for equilibrium stream channels (Table DR3; Whipple and Tucker, 1999). The $\theta_{ref}$ and normalized steepness index ($k_{sn}$) were used to reconstruct each relict reach to the mouth of the Cullasaja River (Fig. DR2).

Each of the 28 numerical model runs predicts the positions of the knickpoints very well. The least squares residuals for each model run, however, were not significantly different from one another (Fig. DR3, DR 4). This finding emphasizes the importance of having accurate and precise constraints on the age and/or travel times of knickpoints when using this approach to extract information about the physical meaning of the *C* and *p* parameters with respect to steam channel incision (cf., Berlin and Anderson, 2007).

## EXTENDED METHODOLOGY

### Channel data extraction and knickpoint identification

The surface hydrographic network was defined from a 6-m horizontal resolution digital elevation model (DEM) using the *Flow Direction* and *Flow Accumulation* routines in ArcGIS. From the DEM, flow direction, and flow accumulation grids were used with the ArcGIS and MATLAB StreamProfiler tools package (http://geomorphtools.org). Stream channels were sampled every 3 m vertically. A 100 m smoothing window was applied to remove pre-processing artifacts and noise embedded in the DEM prior to analysis. Only knickpoints present in fluvially-dominated channels were identified. The cutoff between fluvial and colluvial channels followed previous workers in identifying this transport process transition as visible breaks in slope-area space (Montgomery and Foufoula-Georgiou, 1993; Wobus et al., 2006). Using 52 stream channels we selected the maximum drainage where this scaling break occurs as $1.25 \times 10^5$ $m^2$, well within the typical range of drainage areas ($10^5$ - $10^6$ $m^2$) where this shift is observed to occur . Knickpoints are identified as pronounced longitudinal profile convexities that drop > 20 m vertically and with gradients $\geq 0.1$.

**Terrain analysis**

A smoothed slope map was constructed by passing a 100 m radius mean filter over the slope model derived from the DEM within ArcGIS. Similarly, a relief map was generated by passing a 100 m circular radius focal range window over the DEM. Mean local relief and mean slope values were derived by calculating local relief and local slope values over ~ 3 $km^2$ blocks that were then averaged for the relict and active landscapes. The relict surface was delineated as those areas above the elevation of the highest knickpoints (~ 1150 m), characterized by mean slopes < 15° and maximum local relief < 45 m. The standard errors in the mean local relief calculations for the active and relict landscapes were used to assign the 1σ errors to our estimates of the basin average erosion rates based on the Ahnert (1970) dataset (Fig. 2e).

**Longitudinal river profile reconstructions**

Paleo-river profiles were reconstructed by assuming that the modern surface hydrologic network is similar to its past configuration. This simplifying assumption allows us to carry out stepwise calculations with equation (3) for the theoretical elevation of the paleo-river profile using $k_{sn}$, $\theta_{ref}$, and drainage area to determine the local slope for each distance-increment (pixel) downstream from the top of a knickpoint to the mouth of the drainage basin (e.g., Schoenbohm et al., 2004; Clark et al., 2005). Error in the determination of stream steepness and concavity indices using slope-area regressions propagate through into the normalized steepness index values allowing for 2σ errors to be assigned to each longitudinal profile reconstruction (Fig. DR2; Table DR3).

**Volume and knickpoint travel time calculations**

The volume of rock presumably eroded, or "missing" below the elevation of the highest flight of knickpoints was calculated in two ways. First, the volume between the 1150 m elevation contour, which is coincident with the elevation of the highest trunk channel knickpoint, and the modern surface of the drainage basin encompassed by this contour was calculated to get a maximum volume estimate. Second, a surface cap was created using the modern drainage divide below the 1150 m contour to the mouth of the basin. The volume between this cap and the modern basin surface was calculated and is considered a minimum volume estimate. Knickpoint travel times were determined by using these volume estimates in equation (1) and by assuming basin average erosion rates from 16 to 38 mm $kyr^{-1}$ and calculations carried out at 0.1 mm $kyr^{-1}$ intervals.

**Knickpoint celerity model**

The celerity model equation used to determine the distribution of knickpoints has two unknown parameters. Following previous researchers (Crosby and Whipple, 2006; Berlin and Anderson, 2007), a brute-force search was used to determine the best combination of $C$ (detachment-limited erosion coefficient) and $p$ (drainage area exponent) parameters for the model. This analysis was carried out for the range of knickpoint travel times determined from the volume-for-time substitutions between 4.5 to 18 Ma at 0.5 Ma intervals. The $C$ and $p$ combination resulting in the minimum sum of squared residuals for the 11 modeled knickpoints was assigned as the best fit result for a specified time (e.g., 8.5 Ma) of knickpoint entry into the mouth of the drainage basin (Crosby and Whipple, 2006; Berlin and Anderson, 2007). The $p$-value was allowed to vary from 0.2 to 1.3 over 40 evenly-space increments, while $C$ varied logarithmically between $10^{-10}$ to $10^{-4}$ over 500 increments. The resulting best fit $C$ and $p$ combination for each modeled travel time was used to determine the maximum, mean, and minimum velocity of vertical retreat for the 11 highest knickpoints.

**Data Repository Figure Captions**

**Figure DR1. a**, Shaded relief map of the Cullasaja River basin with mapped landslide initiation points (Wooten et al., 2008). Note how there are fewer observed landslides in the relict-landscape portion of the basin. **b**, Geologic map of the Cullasaja River Basin. Shaded relief map over 1:200,000-scale U.S. Geologic Survey bedrock map (North Carolina Geological Survey, 1985). The majority of the lithologic units are gneisses. The regional foliation mimics lithologic contacts that strike northeast and dip moderately-to-steeply toward the southeast.

**Figure DR2.** Relict-reach regressions and profile reconstructions. Map of the location of the eight relict reaches (the trunk and seven tributary channels) that had sufficient data for least-squares regressions based on log slope-log drainage area data to determine $\theta$ and $k_s$. The longitudinal profiles and slope-area plots of each of these stream channels are shown. The linear least-squares regressions used to obtain θ and $k_s$ for each relict reach is shown by the dark blue line on the log slope-log area data and the longitudinal profile. The forced linear regression through the slope-area data with a $\theta_{ref}$ of 0.5 was used to determine the $k_{sn}$ value for each channel, and is shown in cyan on the log slope-log drainage area and longitudinal profile plots. Reconstructed stream profiles for the trunk and seven tributary channels are shown with their associated 2σ errors for each reconstructed profile. See Table DR3 for statistics.

**Figure DR3.** Top plot shows the sum of square differences between the modeled and observed positions of the upper flight of knickpoints, assuming knickpoint initiation between 4.5 and 18 Ma. There is less than a 2% difference in the minimum residual for any of these model runs. Middle and bottom plots show the best fitting $p$ and $C$ parameter combination for each model run of knickpoint travel time, respectively. The $p$ parameter varies little, while $C$ varies over slightly more than an order of magnitude and progressively decreases to accommodate slower knickpoint travel times.

**Figure DR4.** Results from 28 numerical model runs of knickpoint positions using knickpoint travel times from 4.5 to 18 Ma at 0.5 Ma intervals. The data presented are the sum of squares residuals between observed and modeled knickpoint positions. The smallest residual value for each model run is indicated by a star. Minimum residual values fall within 2% of each other. Best fitting p values range between 0.51 and 0.54, and *C* varies over an order of magnitude, depending on the corresponding *p* value needed to reduce the misfit according to the input duration of the knickpoint travel time. Note that the misfits in each model run are minimized within a very narrow range similar to what Berlin and Anderson (2007) observed.

**Additional References for Data Repository Text**


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Crosby, B. T., and Whipple, K. X., 2006, Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River, North Island, New Zealand: Geomorphology, v. 82, no. 1-2, p. 16-38.

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Wobus, C., Whipple, K. X., Kirby, E., Snyder, N., Johnson, J., Spyropolou, K., Crosby, B., and Sheehan, D., 2006, Tectonics from topography: Procedures, promise, and pitfalls: Geological Society of America Special Paper, v. 398, p. 55-74, doi: 10.1130/2006.2398(04).

**Table DR1. Topographic metrics of the active and relict landscape**

| Metric[1] | Active[2] | | Relict[3] | |
|---|---|---|---|---|
| | mean | 1σ | mean | 1σ |
| Relief (m) | 230 | 70 | 106 | 40 |
| Slope (°) | 20 | 2 | 14 | 4 |
| normalized steepness index ($k_{sn}$) | 93 | 34.9 | 29.7 | 16.1 |
| landslide frequency per $km^2$ | 0.84 | 0.47 | 0.28 | 0.35 |

[1] Metrics of mean relief, mean slope, mean channel steepness, and landslide frequency are from 24 tributary basins.

[2] Drainage basins with a mean elevation below 1150 m were categorized in the active landscape.

[3] Drainage basins with a mean elevation above 1150 m were categorized in the relict landscape

**Table DR2. Statistics for the highest flight of knickpoints.**

| Knickpoint distance from divide (km) | Knickpoint distance from tributary mouth (m) | Knickpoint elevation (m) | Upstream drainage area ($km^2$) | Latitude (° N) | Longitude (° W) | Statistically significant regression |
|---|---|---|---|---|---|---|
| 4.8 | 37.15 | 1191 | 4.8 | 35.07093 | 83.17401 | yes |
| 1.89 | 27.91 | 1187 | 1.6 | 35.13163 | 83.20761 | yes |
| 1.83 | 26.4 | 1188 | 1.64 | 35.10807 | 83.21677 | yes |
| 1.32 | 31.44 | 1202 | 0.67 | 35.08895 | 83.22121 | yes |
| 4.35 | 36.4 | 1182 | 7.36 | 35.09091 | 83.19406 | yes |
| 1.62 | 36.33 | 1159 | 1.17 | 35.07560 | 83.18929 | yes |
| 0.66 | 37.22 | 1201 | 0.28 | 35.04410 | 83.18891 | no |
| 0.52 | 31.84 | 1228 | 0.14 | 35.05541 | 83.24320 | no |
| 1.71 | 31.72 | 1235 | 1.09 | 35.04753 | 83.27156 | yes |
| 2.01 | 31.63 | 1225 | 1.03 | 35.05110 | 83.27854 | yes |
| 0.95 | 26.46 | 1209 | 0.3 | 35.08756 | 83.29835 | no |

**Table DR3. Statistics of relict reach regressions and profile reconstructions**

| Stream[1] | Concavity ($\theta$) of stream reach ($\pm 2\sigma$) | Channel reach steepness ($k_s$) | Reference concavity ($\theta_{ref}$) | Channel reach normalized steepness index[2] ($k_{sn} \pm 2\sigma$) | Mean reconstructed profile elevation at Cullasaja River confluence (m $\pm 2\sigma$)[3] |
|---|---|---|---|---|---|
| trunk | 0.56 ± 0.28 | 71.7 | 0.5 | 22 ± 4 | — |
| 1 | 0.55 ± 0.29 | 147 | 0.5 | 38.8 ± 4 | 1085 ± 10 |
| 2 | 0.53 ± 0.21 | 83.1 | 0.5 | 31.7 ± 3 | 1111 ± 6 |
| 3 | 0.25 ± 0.6 | 3.17 | 0.5 | 13.1 ± 12 | 1132 ± 48 |
| 4 | 0.43 ± 0.27 | 9.24 | 0.5 | 16.3 ± 3 | 1153 ± 3 |
| 5 | 0.47 ± 0.16 | 7.84 | 0.5 | 9.9 ± 1 | 1153 ± 2 |
| 6 | 0.65 ± 0.24 | 93 | 0.5 | 30.1 ± 3 | 1122 ± 12 |
| 7 | 0.59 ± 0.42 | 161 | 0.5 | 30.5 ± 6 | 1116 ± 20 |

[1] See Fig. DR2 for the location of stream reaches and profile reconstructions.
[2] Units are in $m^{0.9}$.
[3] Errors are associated with the calculation of the $k_{sn}$ values.

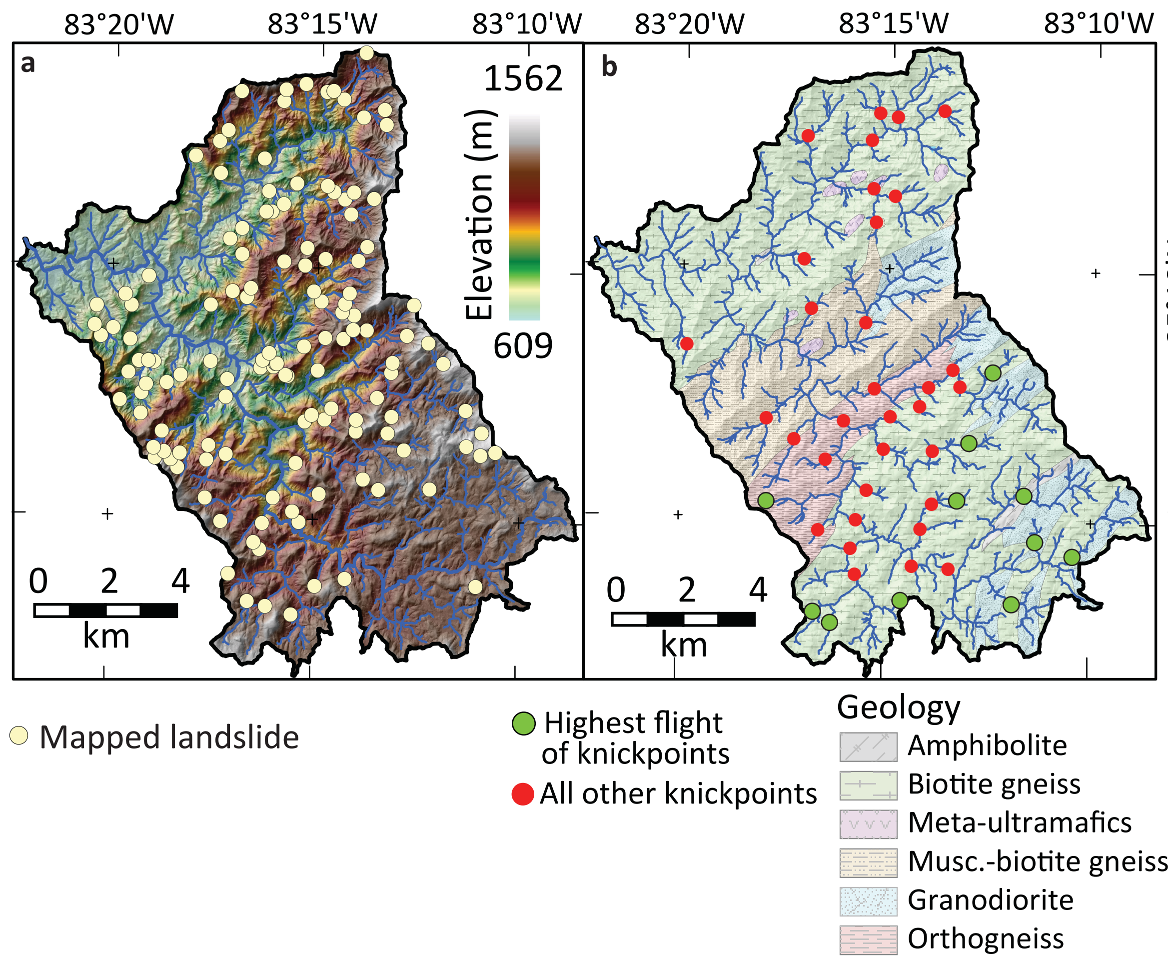

83°20'W
83°15'W
83°10'W
35°10'N
35°5'N
a
b
1562
Elevation (m)
609
0 2 4
km
Mapped landslide
Highest flight of knickpoints
All other knickpoints
Geology
Amphibolite
Biotite gneiss
Meta-ultramafics
Musc.-biotite gneiss
Granodiorite
Orthogneiss

Figure DR1

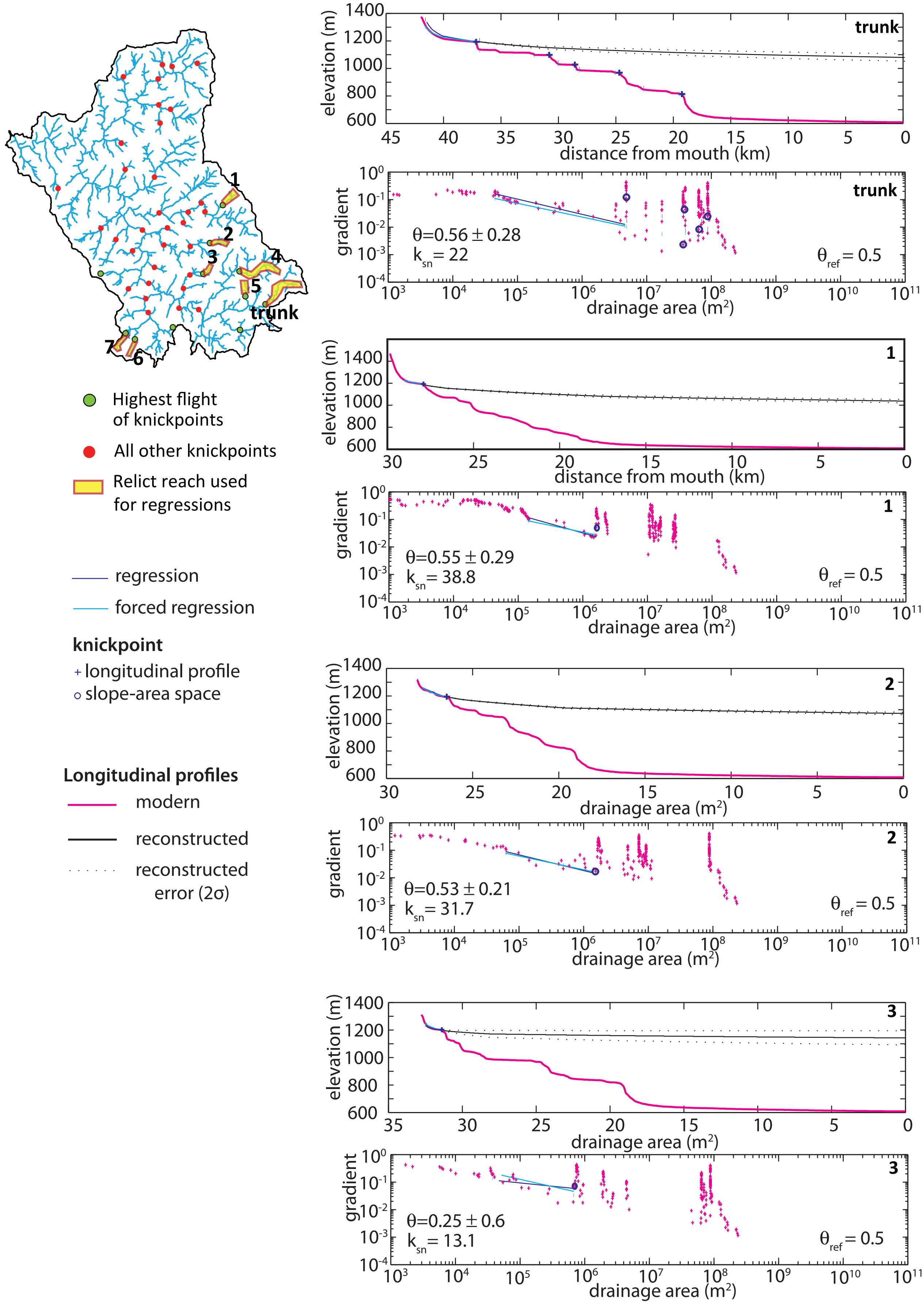

trunk
1
2
3
4
5
6
7
Highest flight of knickpoints
All other knickpoints
Relict reach used for regressions
regression
forced regression
knickpoint
+ longitudinal profile
o slope-area space
Longitudinal profiles
modern
reconstructed
reconstructed error (2σ)
elevation (m)
distance from mouth (km)
gradient
drainage area (m²)
θ=0.56 ± 0.28
k_sn = 22
θ_ref = 0.5
θ=0.55 ± 0.29
k_sn = 38.8
θ=0.53 ± 0.21
k_sn = 31.7
θ=0.25 ± 0.6
k_sn = 13.1

Figure DR2

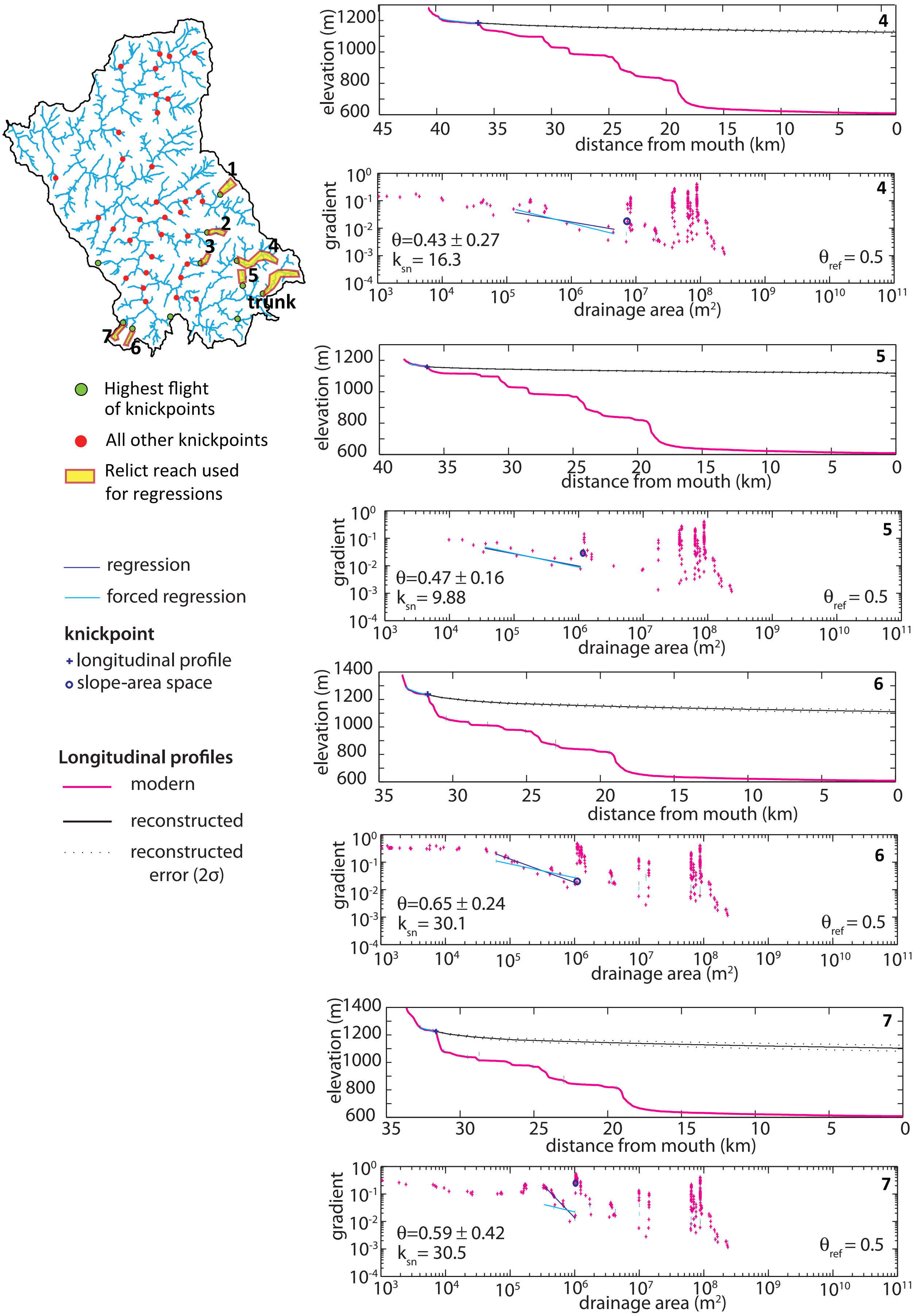



Figure DR2 cont.

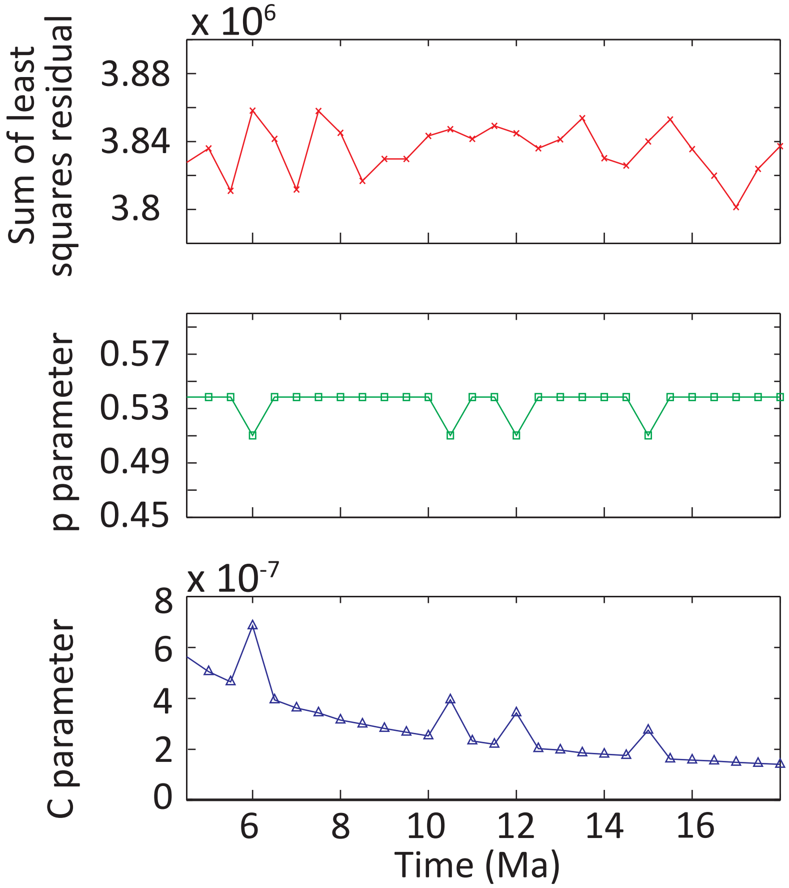
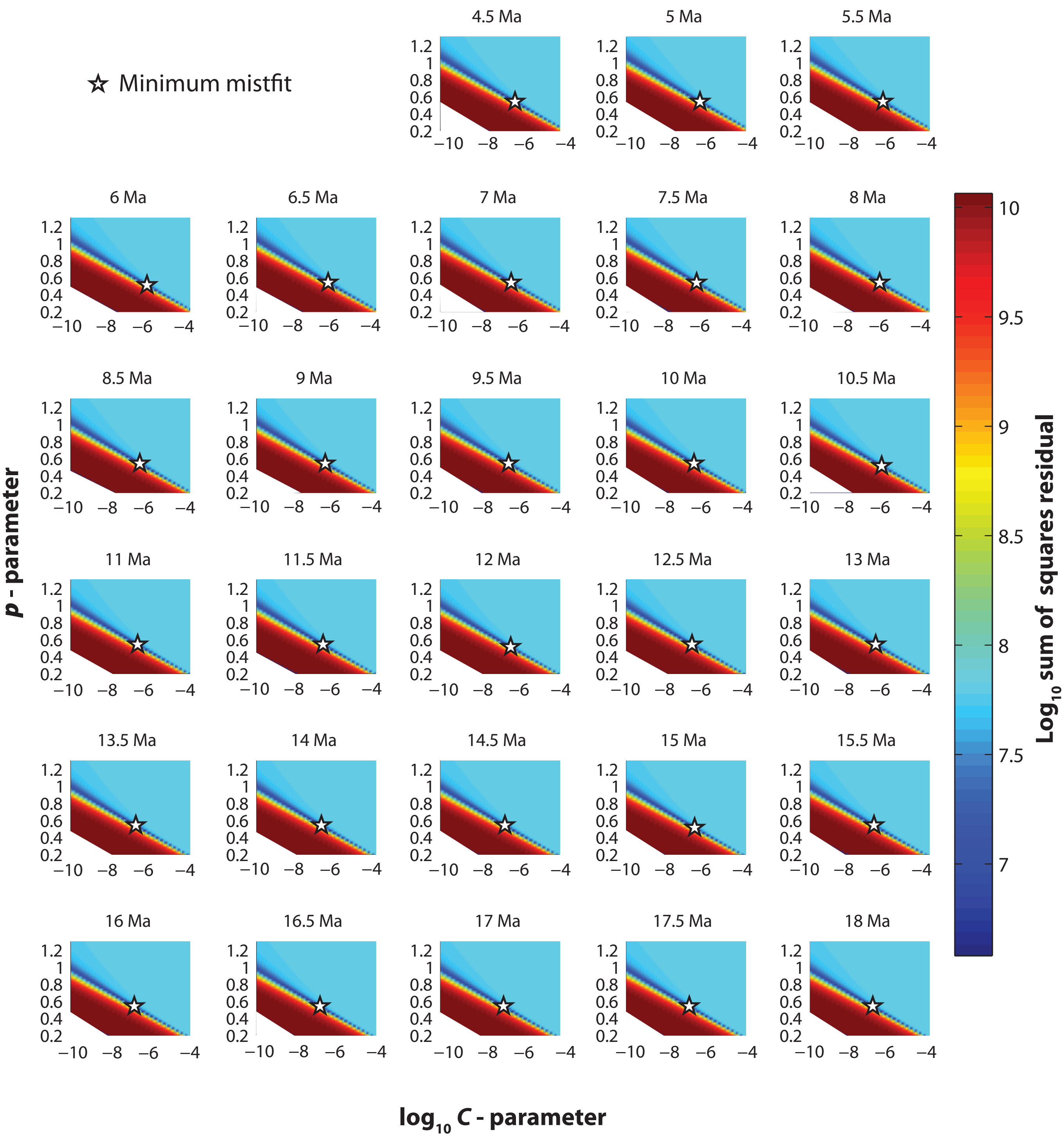

x 10^6
Sum of least squares residual
3.88
3.84
3.8
p parameter
0.57
0.53
0.49
0.45
x 10^-7
C parameter
8
6
4
2
0
6
8
10
12
14
16
Time (Ma)

Figure DR3



☆ Minimum mistfit
4.5 Ma
5 Ma
5.5 Ma
6 Ma
6.5 Ma
7 Ma
7.5 Ma
8 Ma
8.5 Ma
9 Ma
9.5 Ma
10 Ma
10.5 Ma
11 Ma
11.5 Ma
12 Ma
12.5 Ma
13 Ma
13.5 Ma
14 Ma
14.5 Ma
15 Ma
15.5 Ma
16 Ma
16.5 Ma
17 Ma
17.5 Ma
18 Ma
p - parameter
$\log_{10}$ C - parameter
$\text{Log}_{10}$ sum of squares residual


Figure DR4