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Exploiting LiDAR for regional morphologic correlation and dating of wave-cut and fault-controlled landforms

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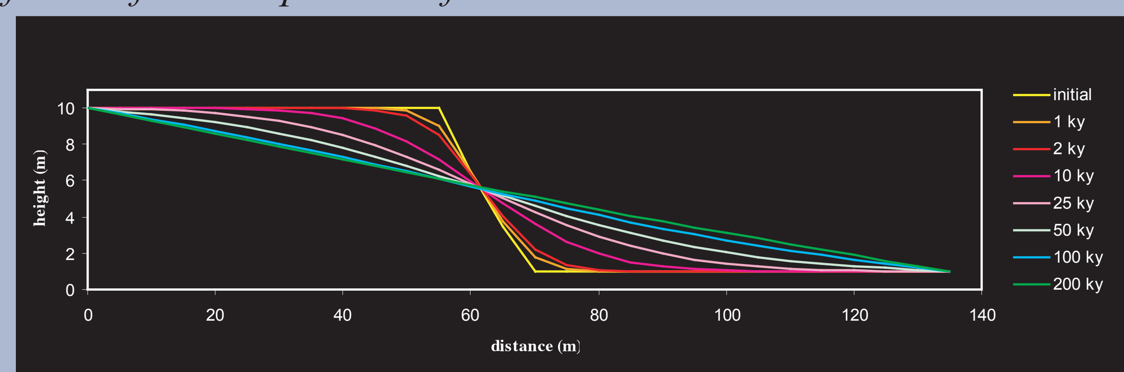
1. INTRODUCTION

- High-resolution Digital Elevation Models (DEMs) from LiDAR data (a.k.a. ALSM) across broad geographic regions offers the opportunity to perform landform correlation of fault scarps, and marine, lacustrine and fluvial shorelines by profile-based morphologic dating (linear and non-linear diffusion).
- Numerous high-resolution topographic profiles can be easily extracted from LiDAR derived DEMs and analyzed for morpholgic age. Broad spatial landfrom correlations can then be established by comparing morphologic age for profiles in the research area.
- This method requires the simplistic assumption that controls on hillslope processes are relatively constant across the region of correlation. Other assumptions include: transport-limited conditions, regolith transport rate increases with increasing slope, simple ramp-shaped initial topography, and no geomorphic transport occurs in or out of the strike of the profile.

Simple scarp diffusion: finite slope initial form

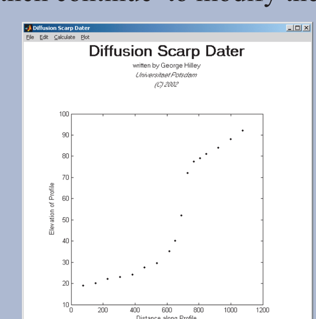


Model of simple linear diffusion of a theoretical scarp-like landform. Our algorithm assumes inital vertical riser morphology rapidly evolves to a steep, ramp-shaped topography via mass wasting processes immediately after formation. Diffusive process then continue to modify the riser (e.g. Rosenbloom and Anderson, 1994; Hanks et al., 1984, Hanks, 2000).

Analytical solution:

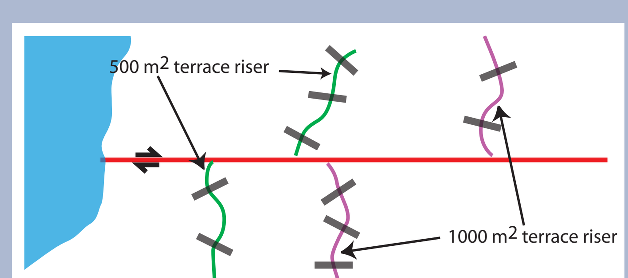
$$H(x,t) = (\theta - b)\left(\frac{\kappa t}{\pi}\right)^{1/2}\left\{\exp\left(-\frac{x + a/(\theta-b)}{4\kappa t}\right)^2 - \exp\left(-\frac{x - a/(\theta-b)}{4\kappa t}\right)^2\right\}$$
$$+\frac{\theta-b}{2}\left\{\left(x+\frac{a}{\theta-b}\right)\operatorname{erf}\left(\frac{x+a/(\theta-b)}{(4\kappa t)^{1/2}}\right) - \left(x-\frac{a}{\theta-b}\right)\operatorname{erf}\left(\frac{x-a/(\theta-b)}{(4\kappa t)^{1/2}}\right)\right\} + bx$$

b = far field fan slope
a= scarp half offset
k= diffusion constant (m^2/1000 yrs)
t= time
θ= initial scarp slope



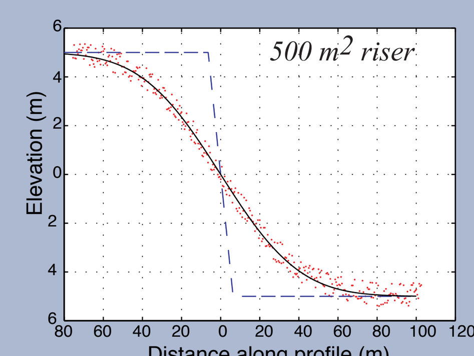
Analysis tool:
Diffusion Scarp Dater MATLAB gui written by George Hilley allows calculation of finite scarp RMS and forward modeling of topographic transect data.
Available at: *http://activetectonics.asu.edu/diffuse*

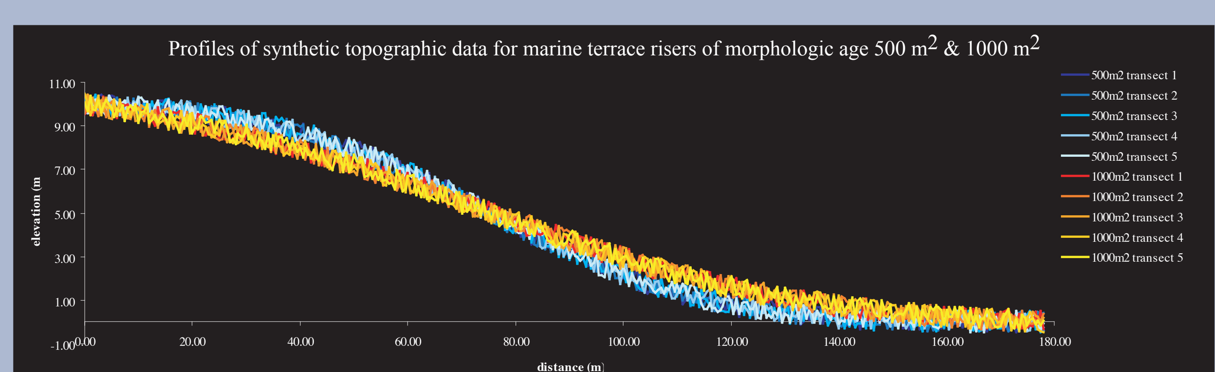
Illustration of morphologic dating method on synthetic "LiDAR data"



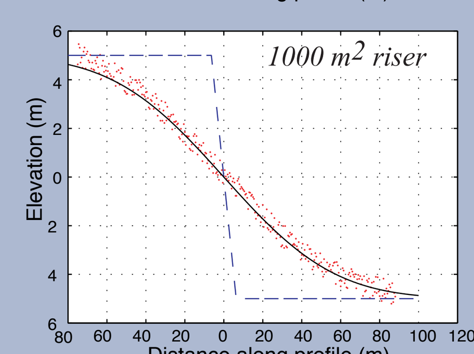
Map view of theoretical field area. 5 profiles from each of the two terrace risers were analyzed to test their correlation across the fault.

= topographic transect location





Synthetic profiles produced by forward model calculations of 500 and 1000 m^2 profiles starting with a 10 m riser and flat tread (for a diffusion constant (k) of 10 m^2/ka the morphologic age (kt) yields an absolute age of 50,000 yrs and 100,000 yrs respectively). To the resulting profiles we added +/- 50 cm of noise to simulate local heterogeneity in the surface as is typically encountered and would be likely in the LiDAR derived profiles.



Best fitting model profiles to the synthetic "data" at left. Initial scarp morphology shown as blue line, topographic "data" is red dots.

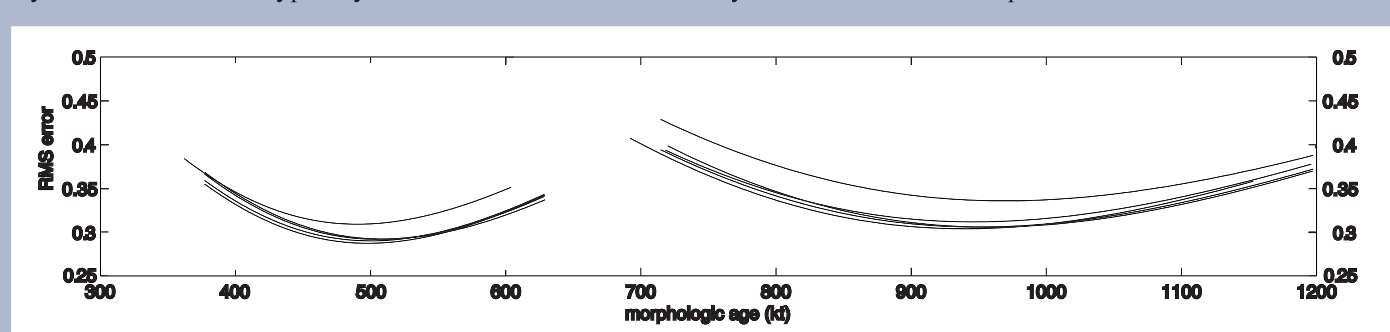
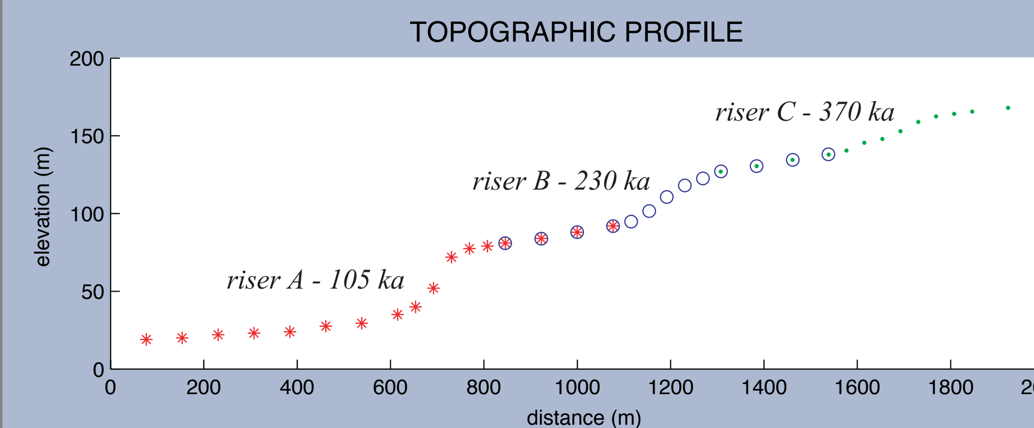


Illustration of the relationship between RMS and morphologic age for the 5 different profiles of the two different risers. This analysis demonstrates the ability of morphologic dating to differentiate landforms of morphologic age 500 m^2 from ones of 1000 m^2.

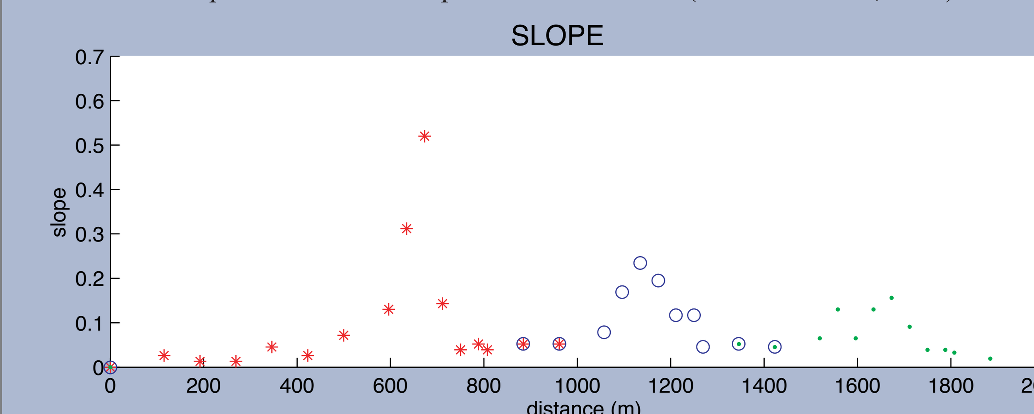
2. CLASSIC MORPHOLOGIC DATING STUDIES REVISITED

Hanks et al., 1984 - Profile modeling of the Santa Cruz, CA marine terrace risers:

- Using the topographic profiles published in Hanks et al., 1984, we recreate this Santa Cruz terrace study to test our methodology and demonstrate the technique's utility for morphologic dating of marine terrace risers.



Santa Cruz, CA marine terrace topographic profile recreated from Hanks et al., 1984. Ages for the three risers come from U-Th and amino acid racemization data, global sea level curves and the assumption of a constant uplift rate of 0.35 m/ka (see Hanks et al., 1984) .



Plot showing slope calculated along the marine terrace topographic profile. Plot illustrates qualitative observation that the older risers have more subtle topography - peak slope diminishes and the scarp widens.

PARAMETERS / RESULTS

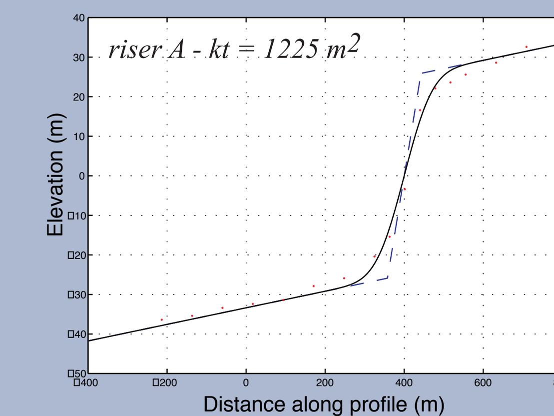
k for Santa Cruz terraces: 11 m^2/ka

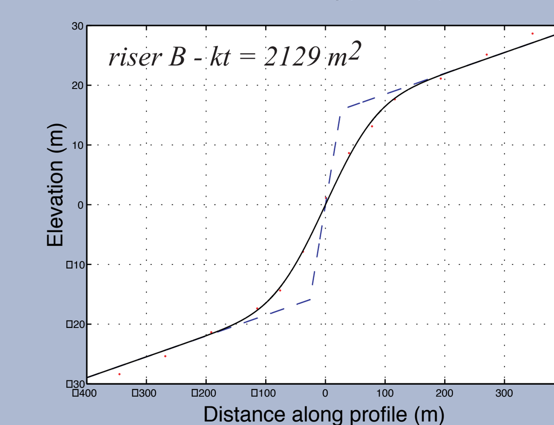
Hanks et al., 1984

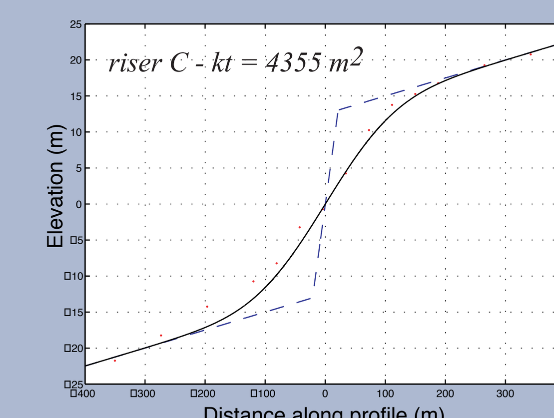
Sea Cliff	2a (m)	age (ka)	b (upper)	b (lower)	kt (m^2)
A	50	105	0.04	0.02	1200
B	30	230	0.05	0.02	2500
C	31	370	0.03	0.02	4100

This study

Sea Cliff	2a (m)	age (ka)	b (setup)	b (calculated)	kt (m^2)	theta
A	50	105	0.03	0.021	1226	35
B	30	230	0.035	0.035	2129	35
C	31	370	0.025	0.021	4355	35



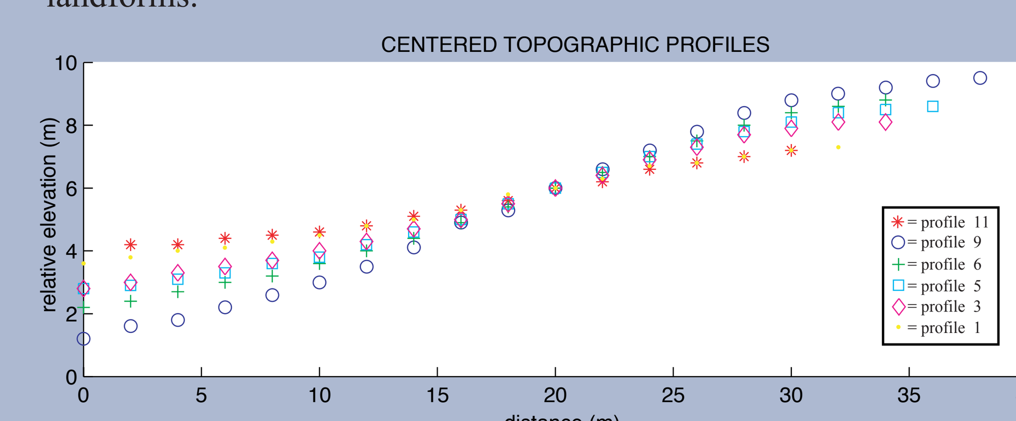




Model calculations (solid lines) for the Santa Cruz terrace risers. Assumed initial morphology shown as dashed blue line. Actual topography shown as red dots. Model parameters are summarized in the table at left.

Hanks and Wallace, 1984 - Morphological analysis of Lake Lahontan shoreline scarps:

- From topographic profiles of Lake Lahontan high stand shorelines published in Hanks and Wallace, 1985, we revisit their quantitative comparison of profiles to demonstrate how morphologic dating can be used to correlate landforms.



Lake Lahontan shoreline topographic profiles recreated from Hanks & Wallace, 1985. Shown are the profiles for which Hanks & Wallace performed model calculations.

PARAMETERS / RESULTS

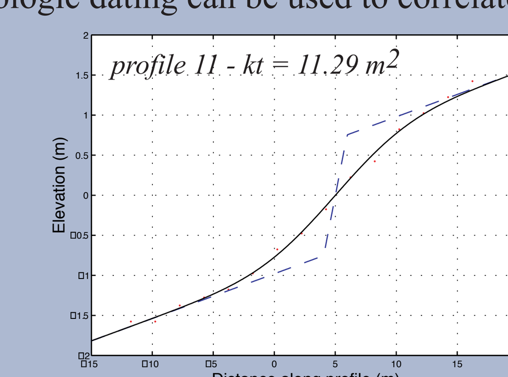
k for Basin and Range: 1.1 m^2/ka

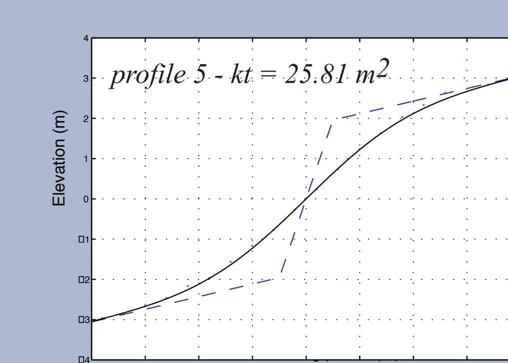
Hanks & Wallace, 1985

profile #	a	b (deg.)	kt (m^2)
11	0.7	3.5	16
9	2.5	3.5	25
6	2	3.5	25
5	1.8	3.5	25
3	1.6	3.5	25
1	0.7	3.5	16

This study

profile #	a	b (setup)	b (calculated)	kt (m^2)	theta
11	0.7	3.5	3.2	11.29	45
9	2.5	3.5	4	20.97	45
6	2	3.5	4	25.81	45
5	1.8	3.5	3.6	25.81	45
3	1.6	3.5	3.6	25.81	45
1	0.7	3.5	4	14.52	45





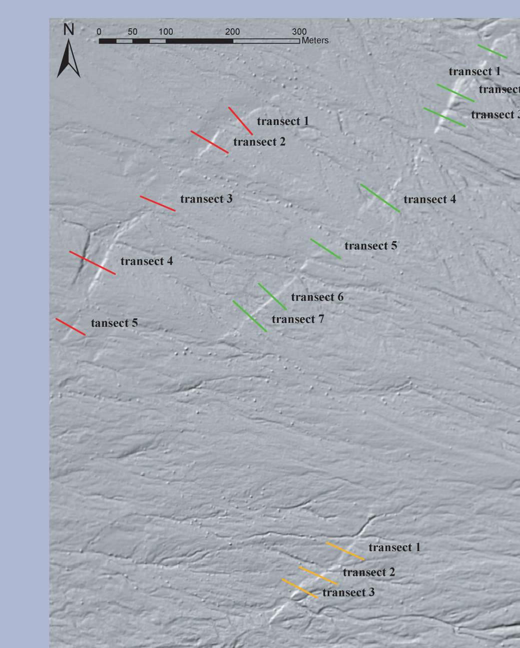
Model calculations (solid lines) for two Lake Lahontan shorelines. Assumed initial morphology shown as dashed blue line. Actual topography shown as red dots. Model parameters are summarized in the table at left.

3. APPLICATION OF MORPHOLOGIC DATING TO LiDAR/ALSM DATA

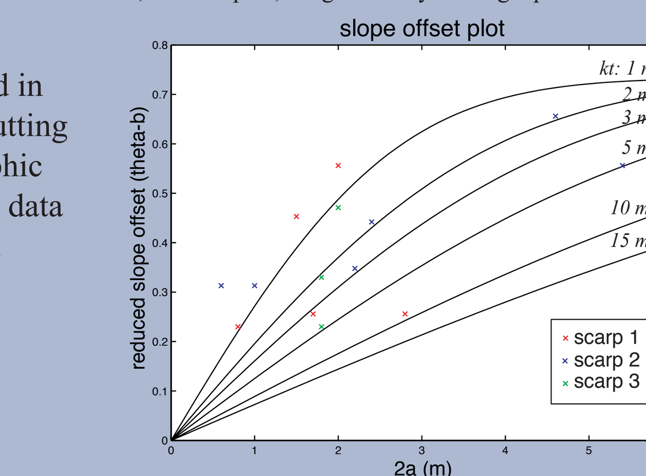
Sheep Creek fan fault scarps - Death Valley, CA

(Thanks to Thad Wasklewicz, U. Memphis, for generously sharing a portion of his Death Valley ALSM dataset)

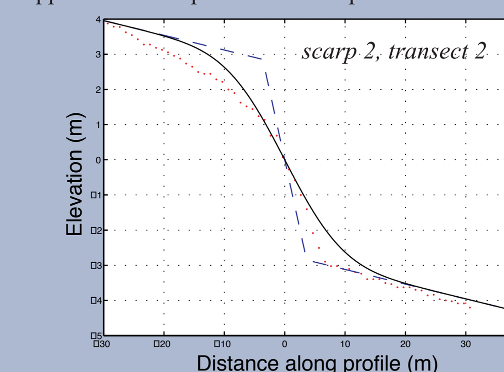
- In this analysis, we blindly apply the morphologic dating technique discussed in sections 1 & 2 (at left) to fault scarps cutting the Sheep Creek alluvial fan. Topographic profiles were extracted from the ALSM data and then analyzed for morphologic age.



Hillshade of 1 m DEM derived from ALSM data. Three fault scarps clearly offset the Sheep Creek fan. Locations of topographic profiles extracted from the DEM are shown as colored lines (red: scarp 1, green: scarp 2, orange: scarp 3).



ABOVE: Slope offset plot for topographic transects across the three Sheep Creek fan scarps. Transect data shown as colored Xs. Also shown are model calculations for a variety of kt values. The transects generally plot at low kt values (< 5 m^2/ka) however the significant scatter in the data makes it difficult to associate any scarp with a single kt value. BELOW: Calculated model fit to a select topographic profile. Note relatively poor fit to the data in the upper and lower parts of the scarp.



PARAMETERS / RESULTS

Scarp 1

transect #	a (m)	b (setup)	b (calculated)	kt (m^2) qualitative	kt (m^2) calculated
1	0.85	2.5	2	5 - 21	9.68
2	1	2.5	2.4	1	1.61
3	0.75	2.7	2.8	15	17.74
4	1.4	2.5	0.8	2 - 15	4.84
5	0.4	4	3.2	0.3 - 2	-

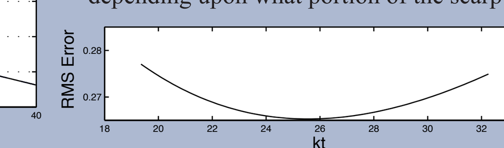
Scarp 2

transect #	a (m)	b (setup)	b (calculated)	kt (m^2) qualitative	kt (m^2) calculated
1	1.2	3.3	3.2	2 - 15	48.39
2	2.7	2.5	2.4	10 - 60	25.81
3	2.3	2.5	2	1	16.13
5	0.3	5	-	1	-
6	0.5	5	4	0.3	-
7	1.1	3	2.8	7	32.26

Scarp 3

transect #	a (m)	b (setup)	b (calculated)	kt (m^2) qualitative	kt (m^2) calculated
1	0.9	4	4	3 - 15	19.35
2	1	4.5	4	2	9.68
3	0.9	4	3.6	2	9.68

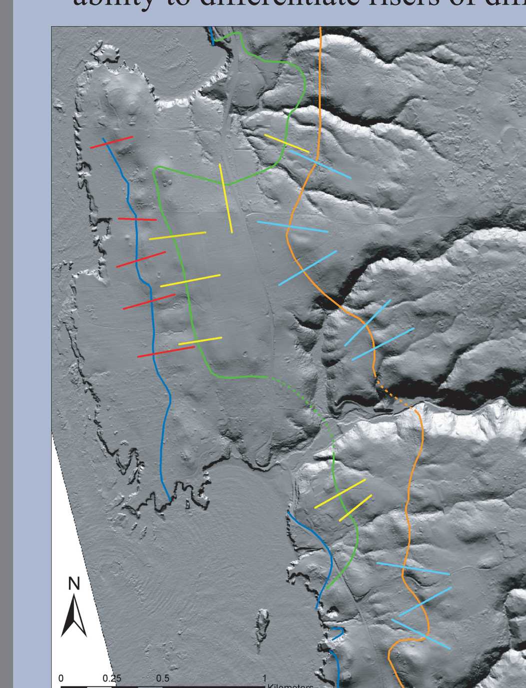
- Plotting the topographic transects in the slope offset space reveals significant variation in kt along strike for all three scarps.
- In general, the slope offset plot suggests low morphologic ages (< 5 m^2/ka) for the Sheep Creek scarps. However it is difficult to assign any scarp to a single kt.
- Many of the topographic profiles reveal an over-steepening of the scarp near its base and a bevel in the upper scarp. Qualitative forward modeling of these transects may yield a very different kt than that of the analytical solution, depending upon what portion of the scarp you choose to fit.



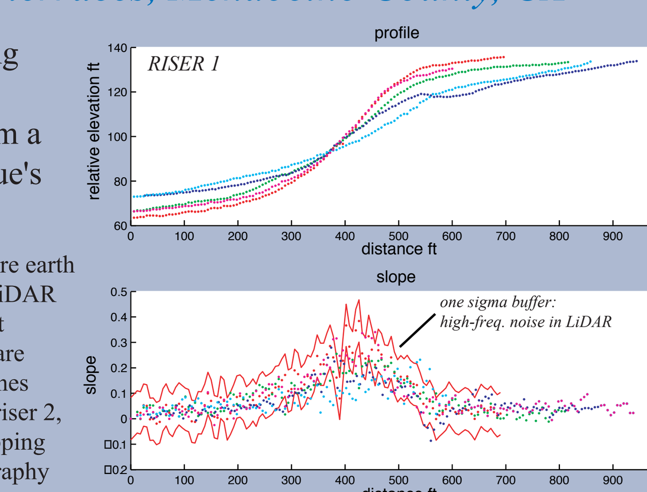
Relationship between RMS and kt for model calculation shown at left. Note range of potential kt values that fit the topographic data.

Marine terraces, Mendocino County, CA

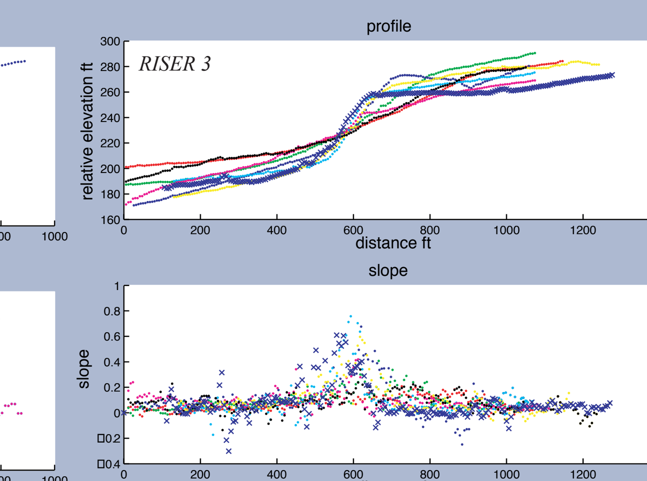
- Morphologic dating has potential utility for correlating marine terraces over significant lengths of coast line. Here we compare topographic transects extracted from a small piece of coastal LiDAR data to test the technique's ability to differentiate risers of different ages.



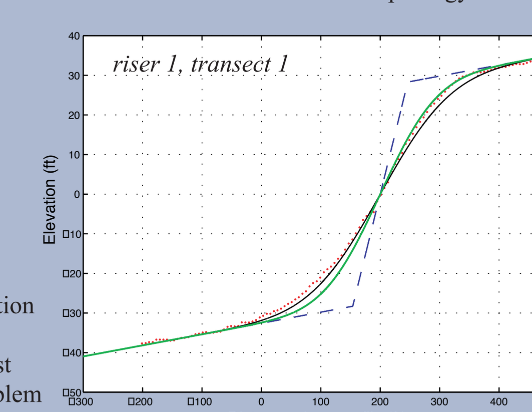
Hillshade of 1.8 m bare earth DEM derived from LiDAR data. The three lowest marine terrace risers are mapped by colored lines (blue: riser 1, green: riser 2, orange: riser 3). Mapping is from aerial photography and the LiDAR data. Topographic profiles extracted for this study are shown as straight line segments, colored by riser.



Upper plot shows centered topographic profiles across riser 1. Lower plot shows slope along the topographic profile. Red lines denote one sigma buffer around the red profile to demonstrate the extent of the high-frequency noise in the LiDAR data. Note the along strike variation in riser morphology



Upper plot shows centered topographic profiles across riser 3. Lower plot shows slope along the topographic profile. Note the along strike variation in riser morphology - risers shown with blue, yellow and cyan dots and blue x's all show evidence for rejuvenation



Calculated model fit to transect across riser 1 (black line). The green line shows a qualitative best fit to the upper portion of the riser. The analytical solution is driven to higher kts due to excess mass on the terrace platform. We favor a best fitting model of the upper riser where the mass excess problem exists.

PARAMETERS / RESULTS

RISER 1 - stage 5a (~83 ka)

transect #	a (ft)	b (setup)	b (calculated)	qualitative kt (m^2)	calculated kt (m^2)	k (m^2/ka)	theta	
1	27	1.5	1.6	2300	3710	27.71	35	excess mass
2	22.5	1.6	1.6	3500	5161	42.17	35	excess mass
3	14.5	2	2	2742	2742	33.04	35	
4	15	2	2	3500	7742	42.17	35	excess mass
5	24	1.5	1.6	2000	3226	24.10	35	

RISER 3 - stage 7 (~194 ka)

transect #	a (ft)	b (setup)	b (calculated)	qualitative kt (m^2)	calculated kt (m^2)	k (m^2/ka)	theta	
1	24	1.8	1.6	10323	10323	53.21	35	
2	29	2.5	2.4	6000	9032	30.93	35	excess mass
3	23	5	-	1000	-	5.15	35	rejuvenated
4	26.5	2	2	600	645	3.09	35	rejuvenated
6	31	2.5	2.4	1500	2581	7.73	35	rejuvenated
7	17	3	3.2	7742	7742	39.91	35	
8	27	2	1.2	871	871	4.49	35	rejuvenated

4. CONCLUSIONS

- Application of morphologic dating techniques to LiDAR/ALSM datasets offers an opportunity to correlate landforms over broad geographic regions.
- This study demonstrates that diffusion equation analysis is an over-simplified technique that is highly dependent on transect selection. The abundance of high-resolution topographic data provided by LiDAR creates a new suite of complications that need to be addressed in order to make morphologic correlation effective. Ultimately, these complications provide insight into the geomorphic process.
- Complications in the morphologic age analysis can be traced to these causes: landform rejuvenation, non-transport limited conditions, non-linear diffusion, and non-diffusive conditions.
- High-frequency noise in the LiDAR data effects slopes along the profile. Undersampling the DEM for the slope calculations helps with this problem.
- Further statistical analysis of the profile data will quantify correlation and help to resolve some of the complications that LiDAR data introduces to morphologic analysis

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