Modification of wavecut and faulting related landforms

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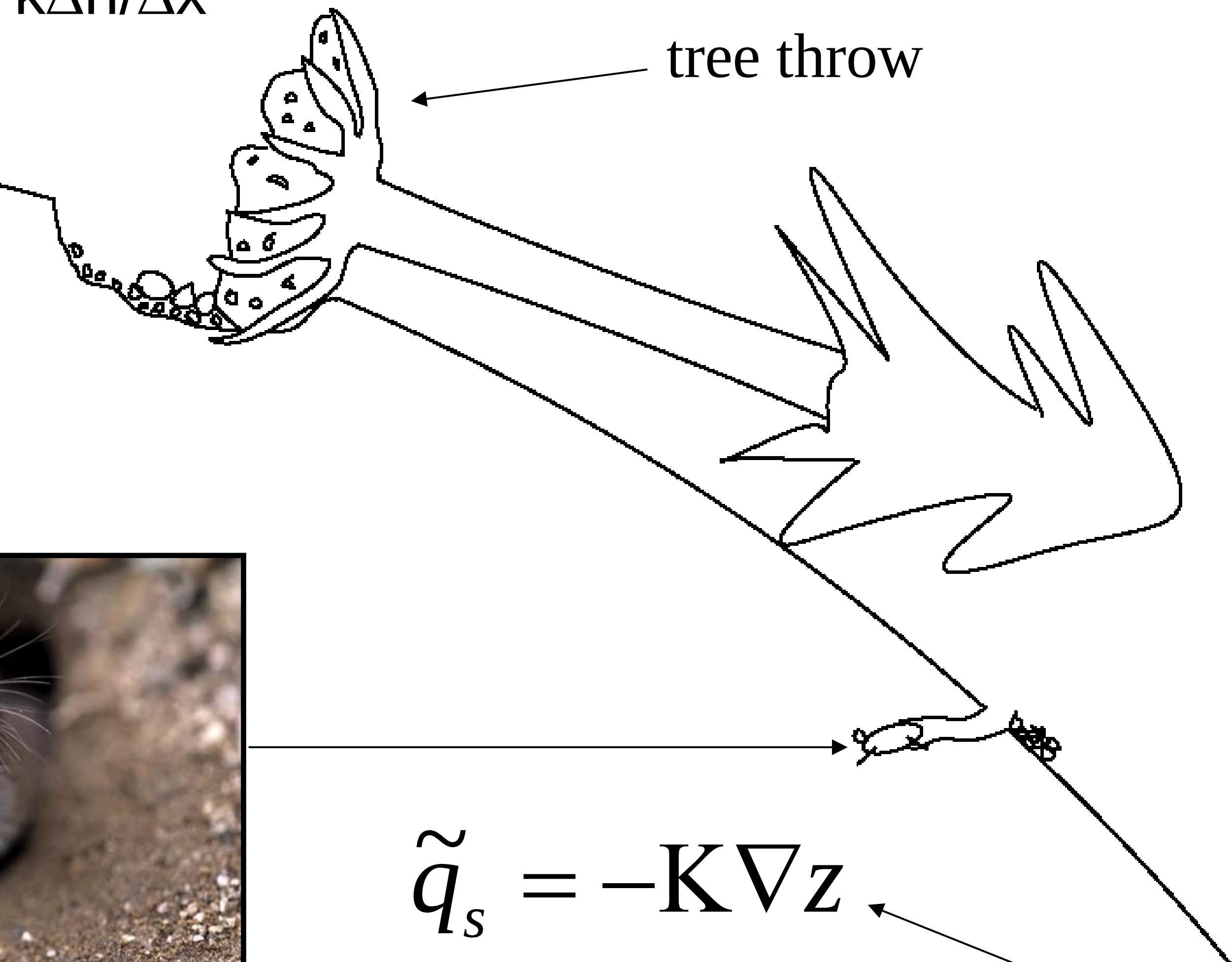
Tutorial notes

Applications of High Resolution Topography to Geologic Hazards in Utah
September, 2017, Salt Lake City, Utah

OpenTopography
High-Resolution Topography Data and Tools

Biogenic transport—slope dependent

Assume $q_s(x) = -k\Delta h/\Delta x$



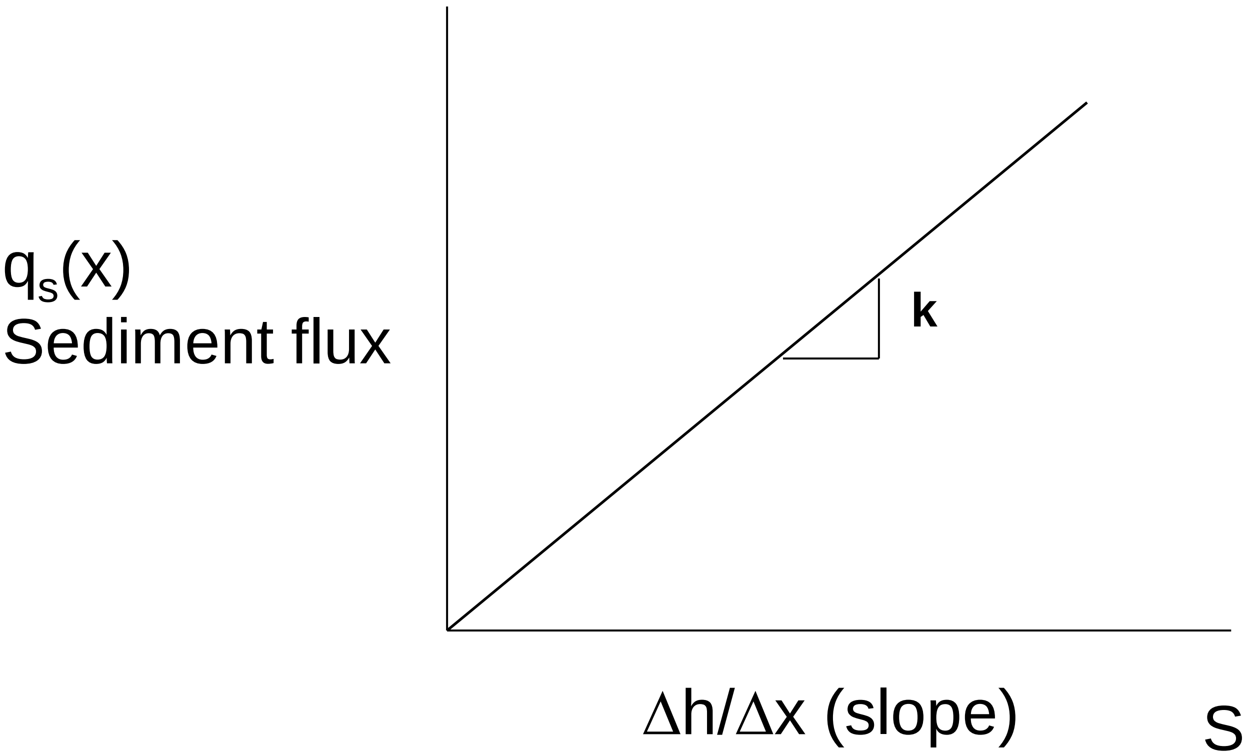
$$\tilde{q}_s = -K\nabla z$$

burrowing

wdfw.wa.gov/wlm/living/gophers.htm

Modified from DiBiase, 2006

Slope dependent transport law



Soil creep
Biogenic processes (burrowing, other animal induced disturbances)
Rainsplash, etc.

Thus, $q_s(x) = k\Delta h/\Delta x$
Assume k constant in time and space

Combine continuity and transport rule

Continuity: $\frac{\Delta H}{\Delta T} = -\frac{\Delta q_s}{\Delta x}$

Transport rule: $q_s = -k\frac{\Delta H}{\Delta x}$

$$\frac{\Delta H}{\Delta t} = -\frac{\Delta\left(-k\frac{\Delta H}{\Delta x}\right)}{\Delta x}$$

$$\frac{\Delta H}{\Delta t} = k\frac{\Delta\left(\frac{\Delta H}{\Delta x}\right)}{\Delta x}$$

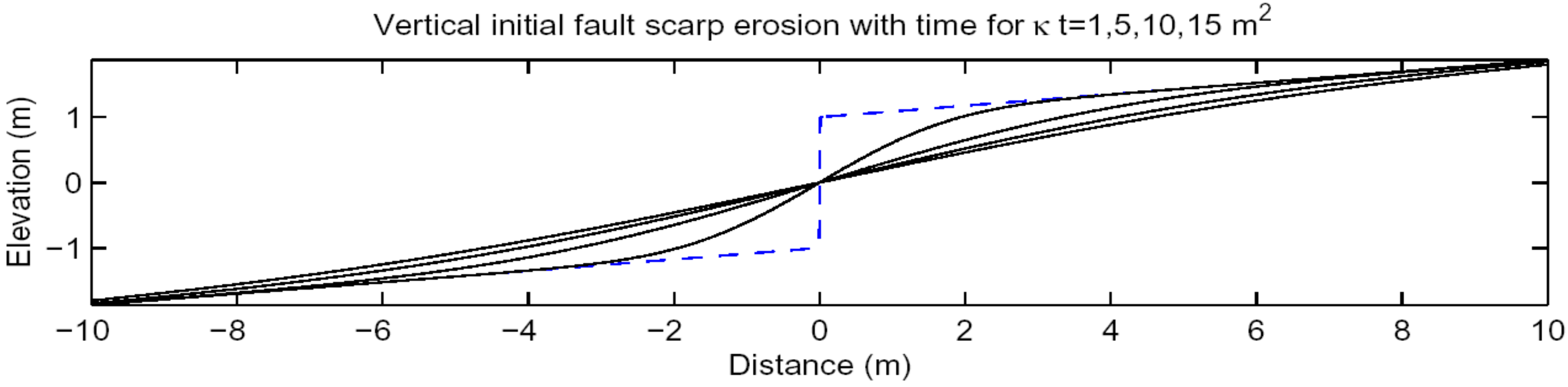
$\lim\ \Delta x \rightarrow dx, \Delta t \rightarrow dt$

$$\frac{dH}{dt} = k\frac{d\left(\frac{dH}{dx}\right)}{dx}$$

$$\frac{dH}{dt} = k\frac{d^2H}{dx^2}$$

“diffusion” erosion

Simple scarp diffusion: Vertical initial form

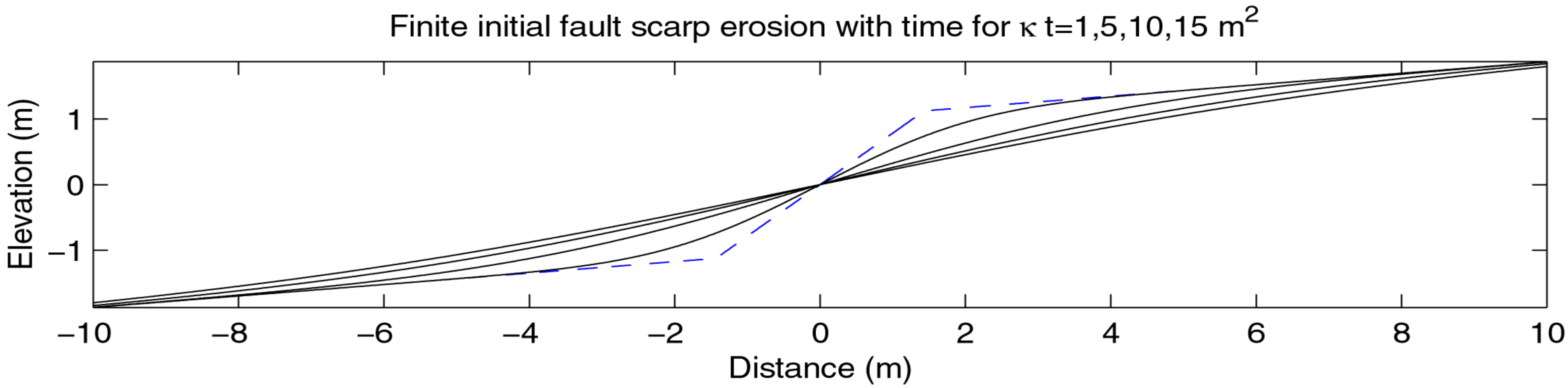


$$H(x,t) = a \operatorname{erf}\left(\frac{x}{2\sqrt{kt}}\right) + bx$$

B = "fan" slope   a = half-offset

"analytic solution"

Simple scarp diffusion: finite slope initial form



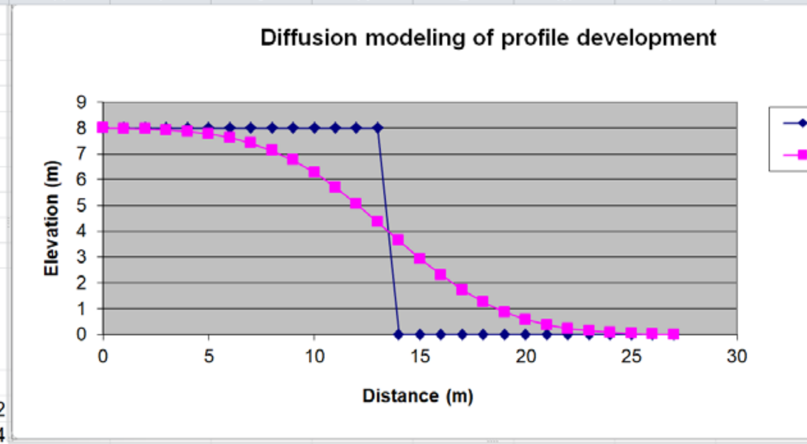
$$H(x,t) = (\theta - b)\left(\frac{\kappa t}{\pi}\right)^{1/2}\left\{\exp\left(-\frac{x + a/(\theta - b)}{4\kappa t}\right)^2 - \exp\left(-\frac{x - a/(\theta - b)}{4\kappa t}\right)^2\right\}$$
$$+\frac{\theta - b}{2}\left\{\left(x + \frac{a}{\theta - b}\right)\mathrm{erf}\left(\frac{x + a/(\theta -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

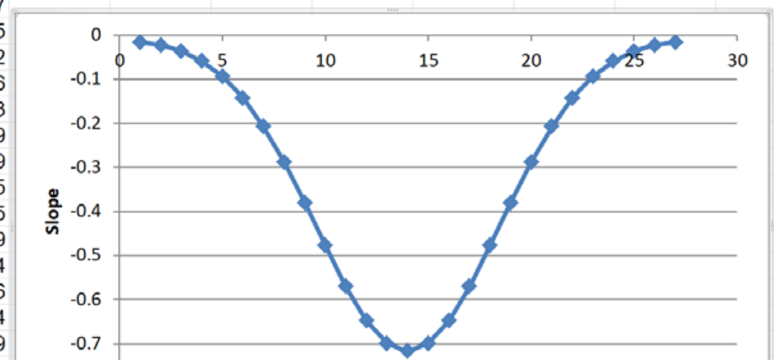
θ = initial scarp slope

"analytic solution"

Spreadsheet to explore diffusion modeling

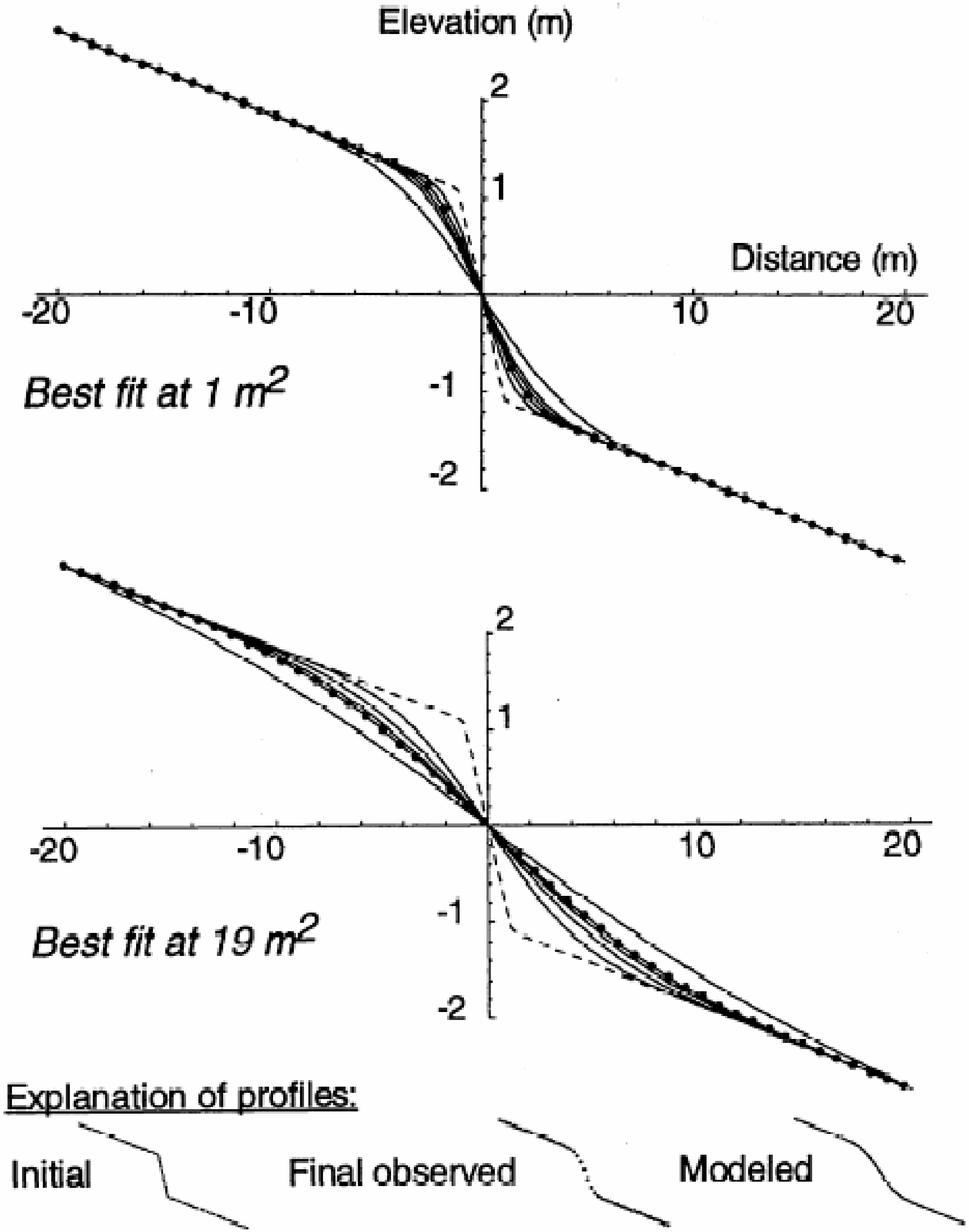
	A	B	C	D	E	F	G
1	Diffusion modeling spreadsheet for UGS September 2017 (J R. Arrowsmith)						
2	**Change cells that are bold**						
3	Constants:		units				
4	dx =	**1**	m				
5	dt =	**0.05**	ky				
6	k =	**1**	m^2/kyr				
7	lambda =	0.05	Keep this below 0.5 or it will blow up!				
8	Age =	10	ka				
9							
10					ModelFinal		
11	Individual change per timestep	x, m	**Initial elevations. Change this column.**		x, m	H, m	dH/dx
12	0	0	**8**		0	8	
13	0	1	**8**		1	7.983583505	-0.01642
14	0	2	**8**		2	7.960946482	-0.02264
15	0	3	**8**		3	7.924772905	-0.03617
16	0	4	**8**		4	7.865725789	-0.05905
17	0	5	**8**		5	7.771904205	-0.09382
18	0	6	**8**		6	7.628943186	-0.14296
19	0	7	**8**		7	7.421008711	-0.20793
20	0	8	**8**		8	7.132814488	-0.28819
21	0	9	**8**		9	6.752520923	-0.38029
22	0	10	**8**		10	6.275017877	-0.4775
23	0	11	**8**		11	5.704769107	-0.57025
24	0	12	**8**		12	5.05727634	-0.64749
25	0	13	**8**		13	4.358431733	-0.69884
26	0	14	**0**		14	3.641568267	-0.71686
27	0	15	**0**		15	2.94272366	-0.69884
28	0	16	**0**		16	2.295230893	-0.64749
29	0	17	**0**		17	1.724982123	-0.57025





Interface | Model Calculation Space

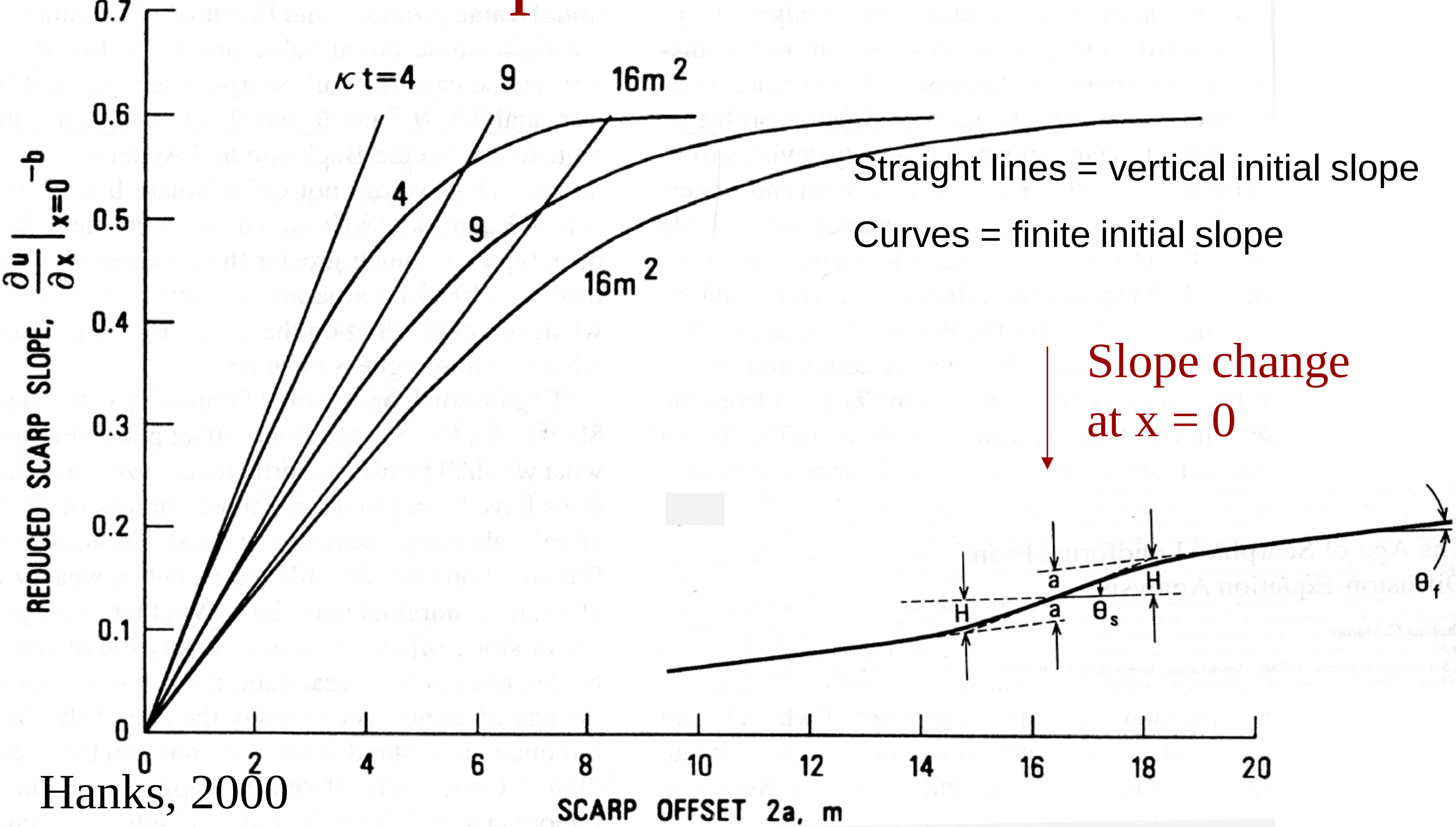
Numerical solution



Morphologic dating: Try to date the landform by finding the best fitting model profile Best fit is in terms of *kt*, so if you know *k*, you can divide through by it and get *t*.

Arrowsmith, et al., 1998

Slope-offset analysis: a good place to start



Hanks, 2000

Slope-offset example

$$\tan\theta_s - b = (\alpha - b)\ \mathrm{erf}\left[\frac{a/(\alpha - b)}{2\sqrt{\kappa t}}\right]$$

$\tan\theta_s$ is the max scarp slope
b is the far field or fan slope
α is the initial scarp slope
κ is the transport rate or diffusivity
$2a$ is the scarp offset
t is time

Bonneville: 14 ka
Lahontan: 12-14 ka
Choose kt = 16m^2
So k = 1.1m^2/kyr

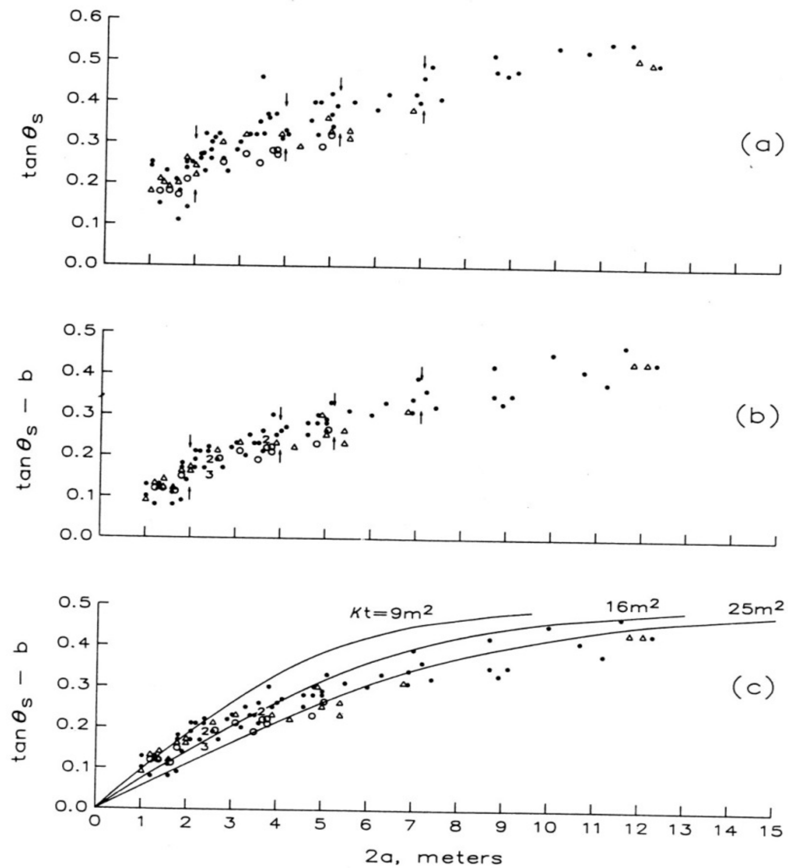


Figure 2.6.3-4. Slope-offset representations of Bonneville (solid circles) and Lahontan (open symbols) shoreline scarps; Bonneville data are from Bucknam and Anderson (1979) and Hanks and others (1984), and Lahontan data are from Hanks and Wallace (1985) (circles) and Hecker (1985) (triangles); (a) tan θ_s versus $2a$ and (b) tan $\theta_s - b$ versus $2a$. In (a) and (b) the facing arrows are meant to indicate the "full range" scatter in θ_s for several values of $2a$; this full range scatter is 5°-6° for (a), 4° for (b). (c) The data in (b) are shown with evaluations of Equation (2.6.3-8b) for the three indicated values of κt and $(\alpha - b)$ = 0.5. Note that the data at larger tan θ_s - b and $2a$ require larger model values of κt, indicative of nonlinear diffusive processes. From Hanks and Andrews (1989).

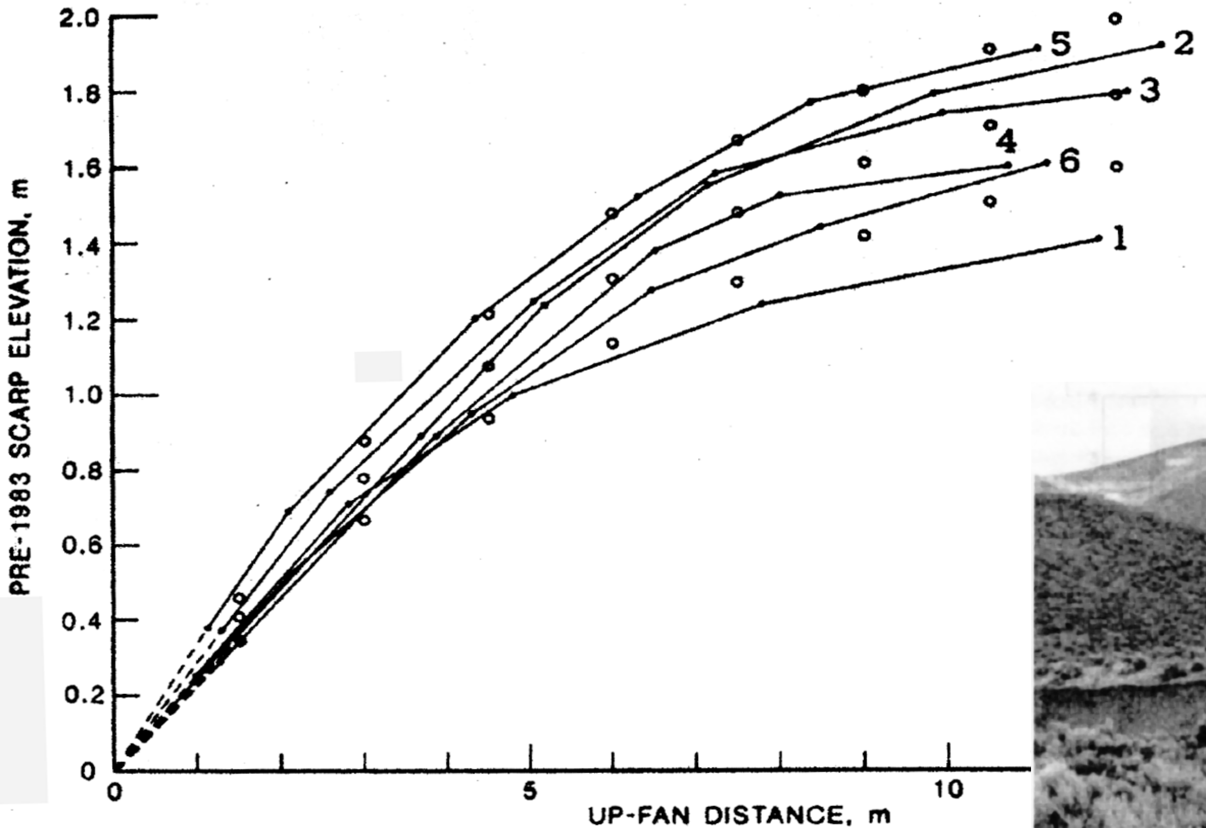
Hanks, 2000

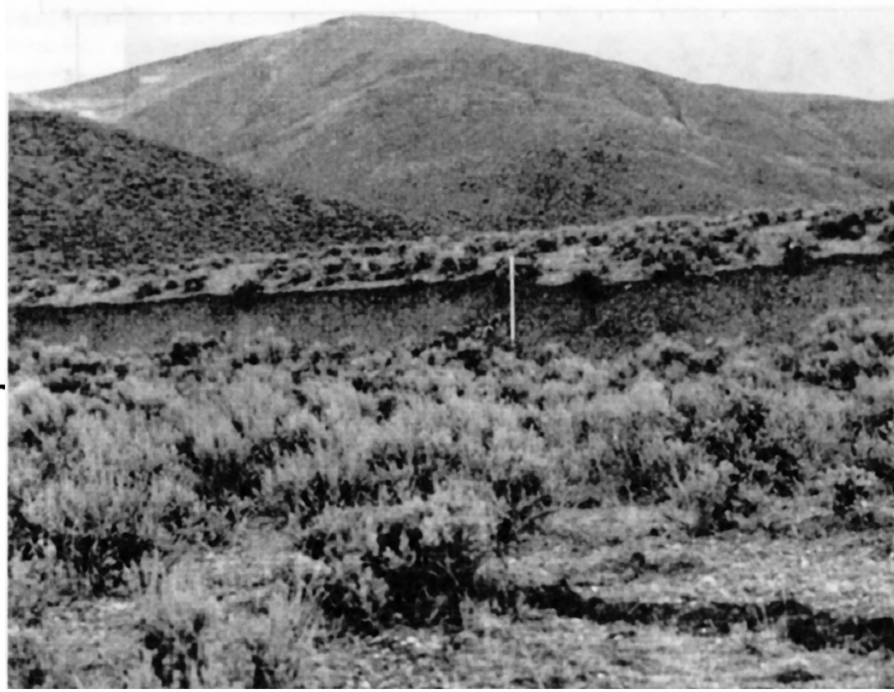
Table 2. Diffusivity Estimates for Weakly Consolidated Materials

Hanks, 2002

Location/Geologic Structure	Age, ka	k, m² ka⁻¹	Range of 2*a*, m	Reference
BASIN AND RANGE, WESTERN U.S.				
Lake Bonneville shoreline, Utah	14.5	1.1	1-12	Hanks and others (1984)
Lake Lahontan shoreline, Nevada	12-14	1.1	1-7	Hanks and Wallace (1985), Hecker (1985)
Combined Bonneville/Lahontan		0.64	≃ 1	Hanks and Andrews (1989)
		1.1	2½-3½	Hanks and Andrews (1989)
		1.8	5-12	Hanks and Andrews (1989)
Fluvial terrace risers, SW Montana	7.1	2.0 ±0.4	1.5-8	Nash (1984)
Lost River fault, antecedent scarps, Idaho	9-10	1.0-0.9	~ 2	This study
Machette Constraint on the "unobservable" scarps	100	≥ 1.2	≤ 2	Hanks and others (1984)
Bare Mountain fault scarps, southern Nevada communication)	100(?)	~ 0.1	0.4-1.9	L.W. Anderson (personal
ISRAEL				
Lake Lisan recessional terraces, Dead Sea area	14	0.4	1-6	Bowman and Gerson (1986)
Fault scarps, northern Arava	<14	>0.4	0.5-1	Bowman and Gross (1989)
Stream terraces, northern Negev				Begin (1992)
higher level	<10	>0.1	1-6	
lower level	<1.4	>0.2-0.7	1-2	
Fault scarps, southern Arava	~ 30	0.2-0.3	2.6-5.6	Enzel and others (1995)
WESTERN CHINA				
Fault scarps, Gansu Province	1.8	3.3 ± 1.7	1.5-4.4	Tapponnier and others (1990)
Fluvial terrace risers, Dzungarian Basin	10	5.5 ± 2	5.5-12	Avouac and others (1993)
Fluvial terrace risers, Tarim Basin	10	3.5 ± 1.2	2.5-10	Avouac and Peltzer (1993)
CALIFORNIA				
Uplifted marine terraces, Santa Cruz	105-370	11	30-50	Hanks and others (1984)
Raymond Hill fault, Pasadena	230	16	25	Hanks and others (1984)
San Andreas fault, Carrizo Plain	17-30	8.5	8-20	Arrowsmith (1995)
MICHIGAN				
Lake Algonquin shoreline	10.5	12	10-20	Nash (1980
Lake Nipissing shoreline	4	12	15-40	Nash (1980)
Netherlands				
Bree fault scarp	<14-19	2-10	1	Camelbeeck, et al. 2001

Profile modeling: example 1

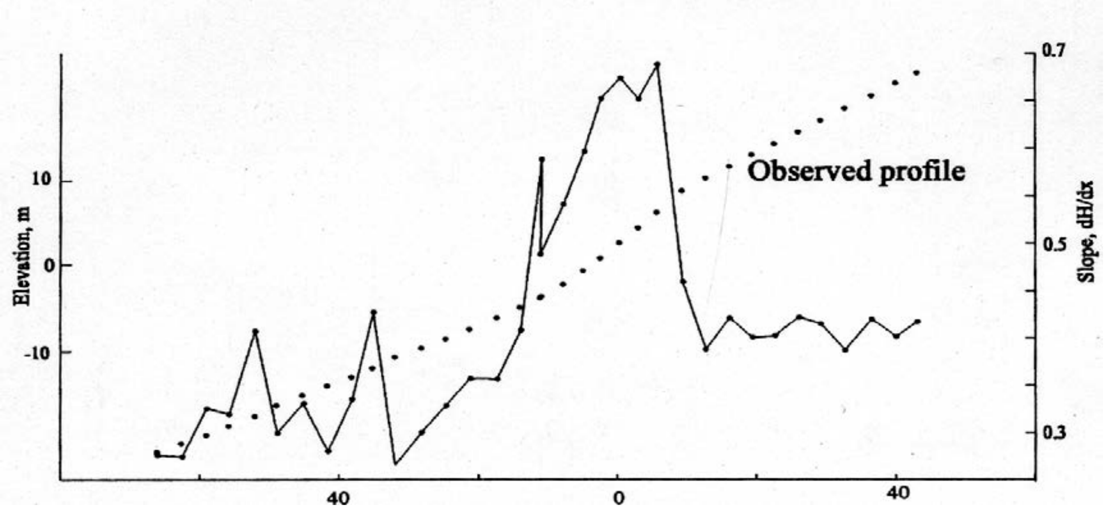


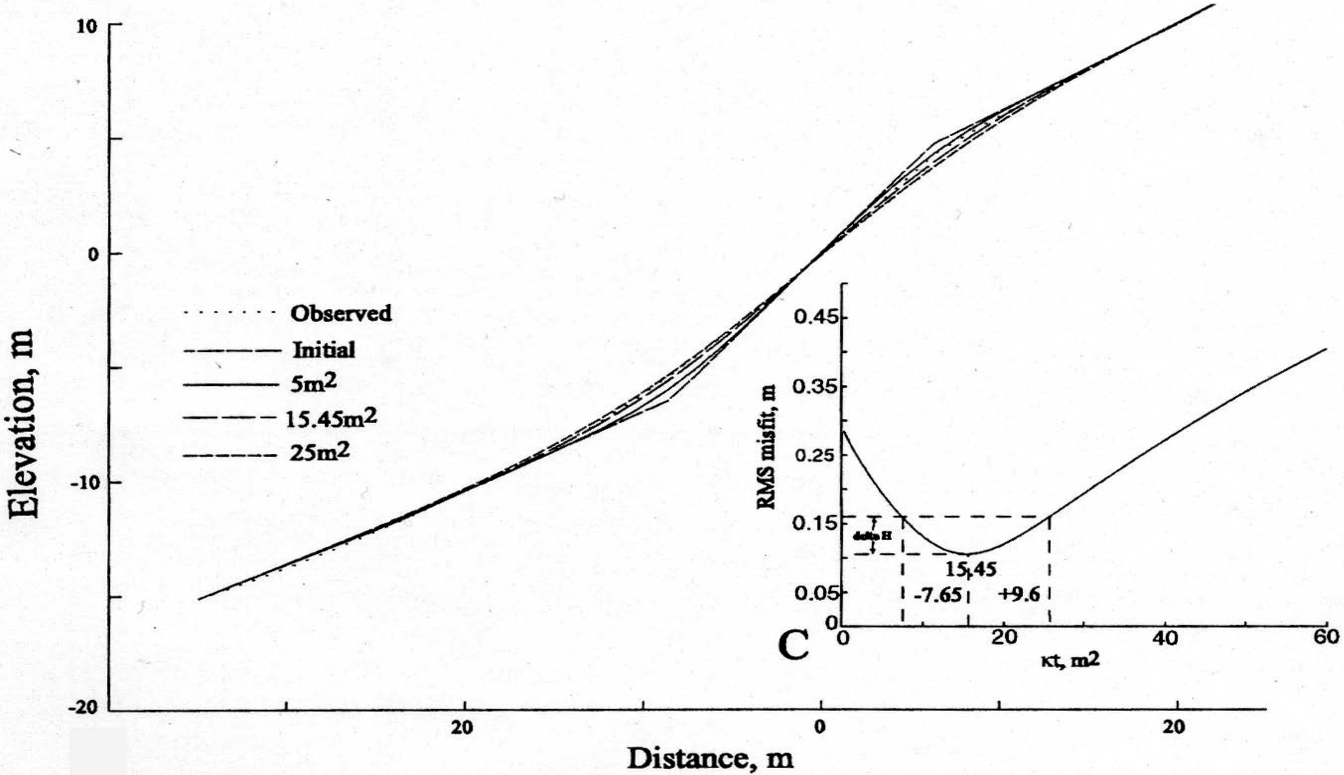


Pre-1983 Borah Peak (ID) Fault scarp.
Scarp offset (a = 1, 1.2, 1.4). $\kappa t = 9 m^2$.
Using k = 1.1 m^2/kyr, t = 8.2 ka.
Confirmed with trenching nearby.

Hanks, 2000

Profile modeling: example 2





Hurricane Fault, NW Arizona

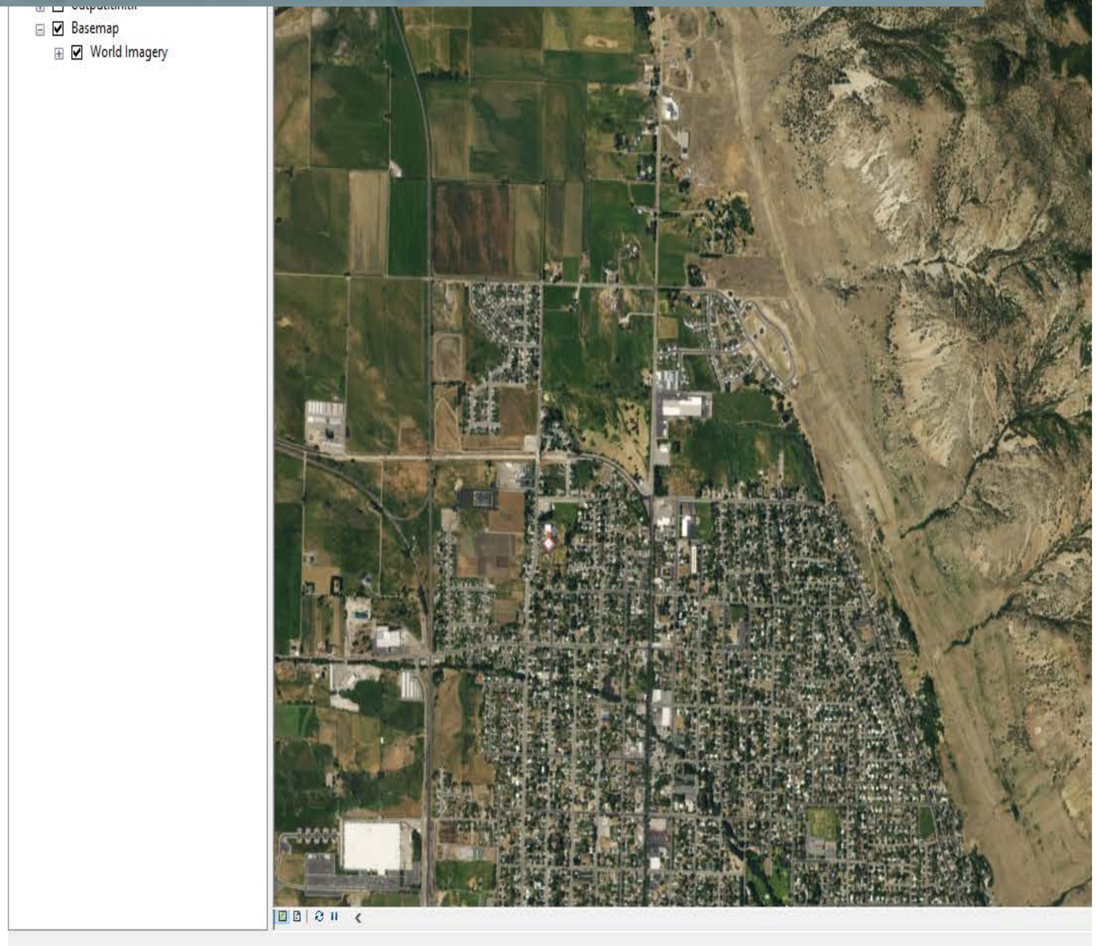
Amoroso, 2001

See also Avouac, 1993 for evaluation of errors in morphologic dating.

PALEOSEISMOLOGY OF UTAH, VOLUME 22

LATE HOLOCENE EARTHQUAKE HISTORY OF THE BRIGHAM CITY SEGMENT OF THE WASATCH FAULT ZONE AT THE HANSEN CANYON, KOTTER CANYON, AND PEARSONS CANYON TRENCH SITES, BOX ELDER COUNTY, UTAH

Christopher B. DuRoss, Stephen F. Personius, Anthony J. Crone, Greg N. McDonald, and Richard W. Briggs



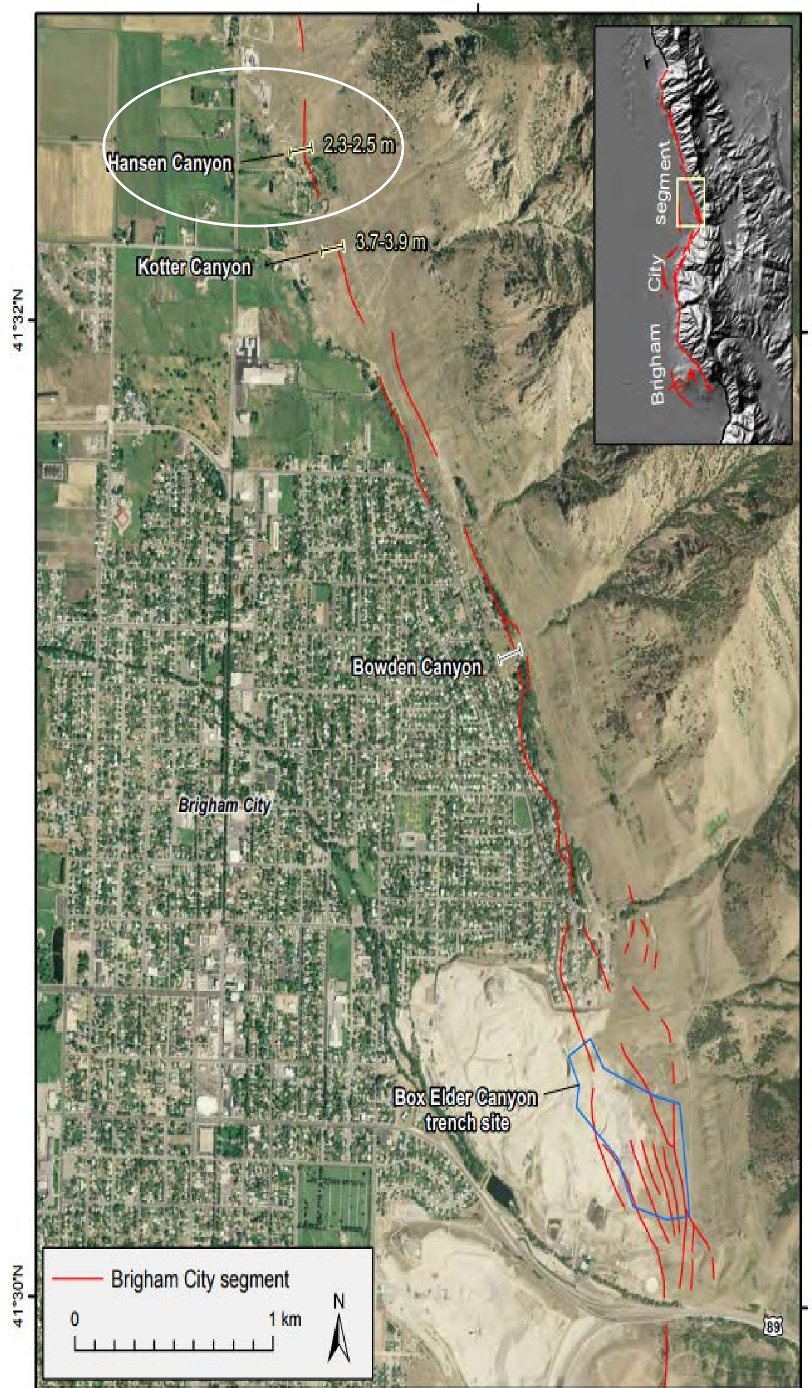


Figure 4. Central Brigham City segment, showing vertical scarp offsets measured at the Hansen Canyon and Kotter Canyon

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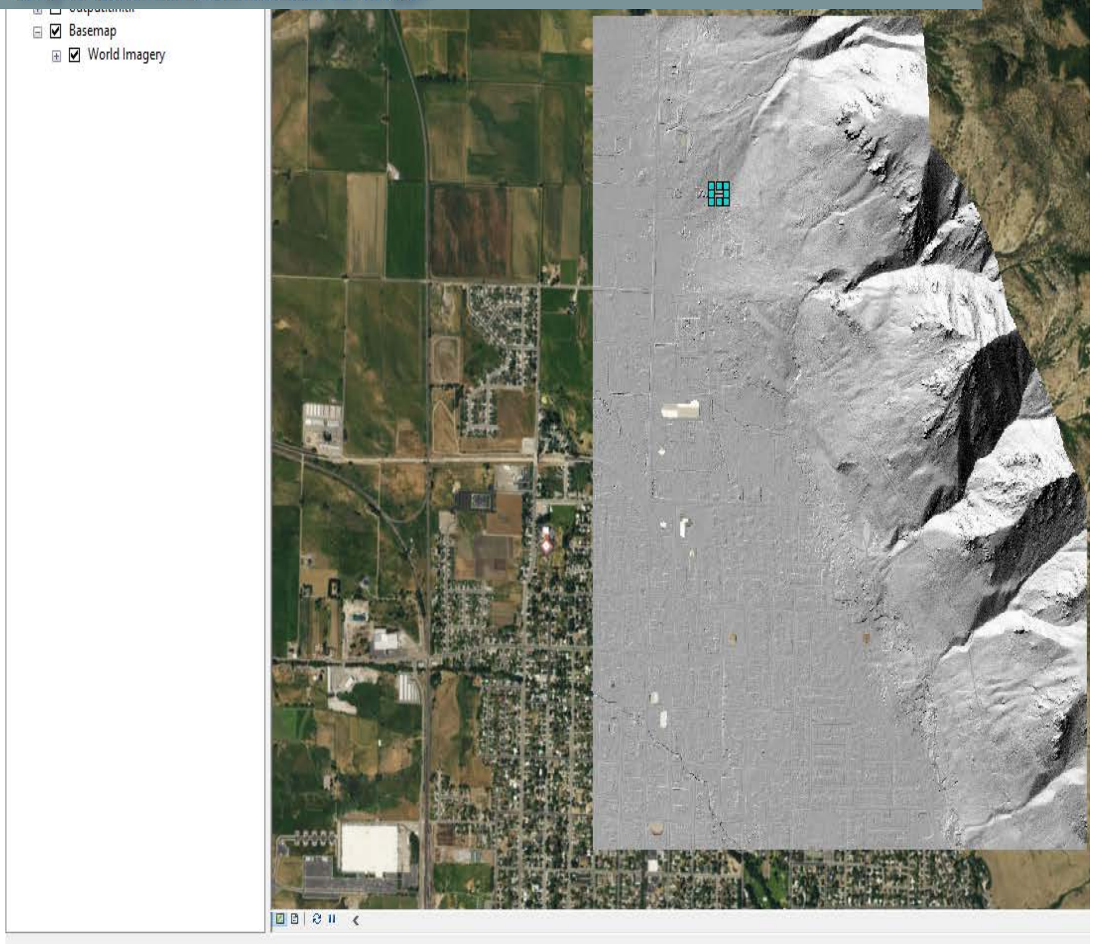


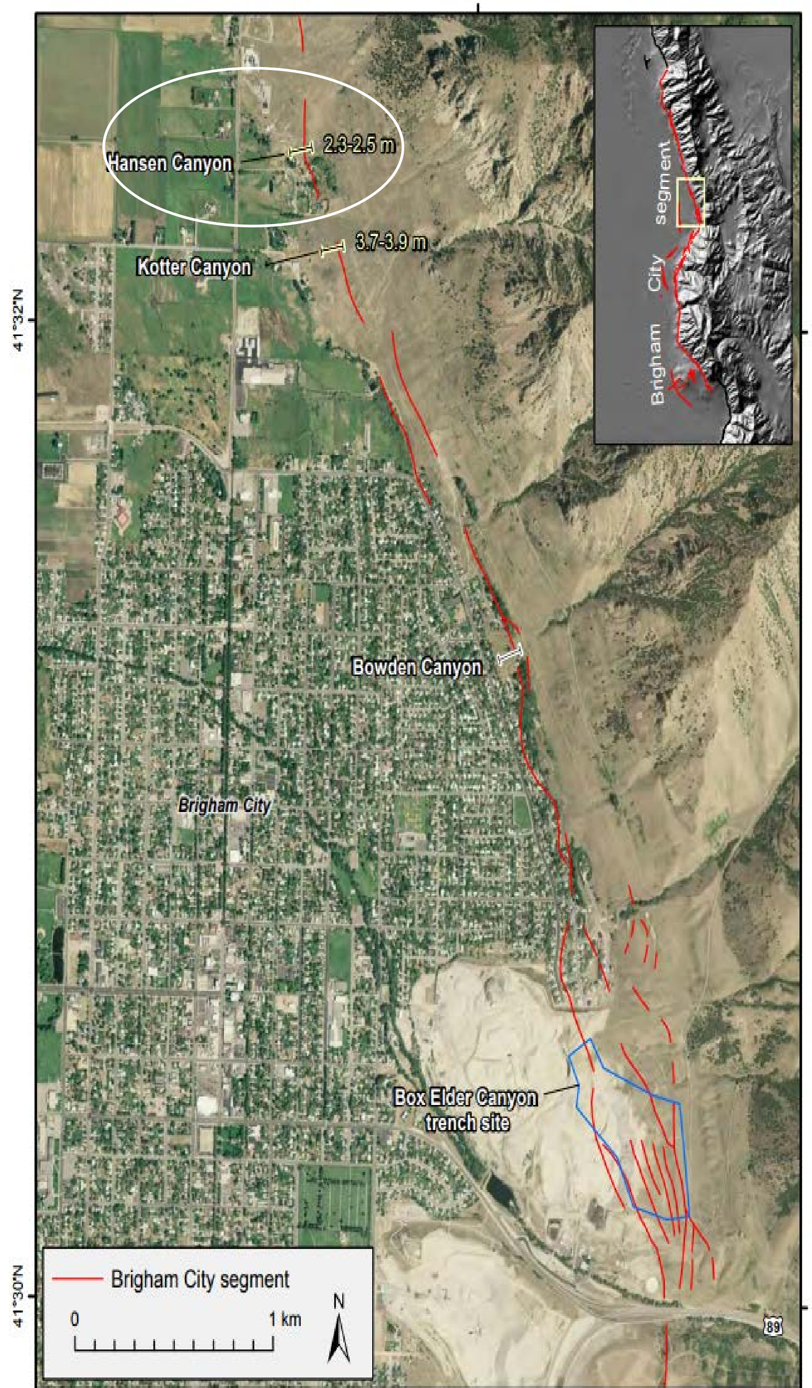
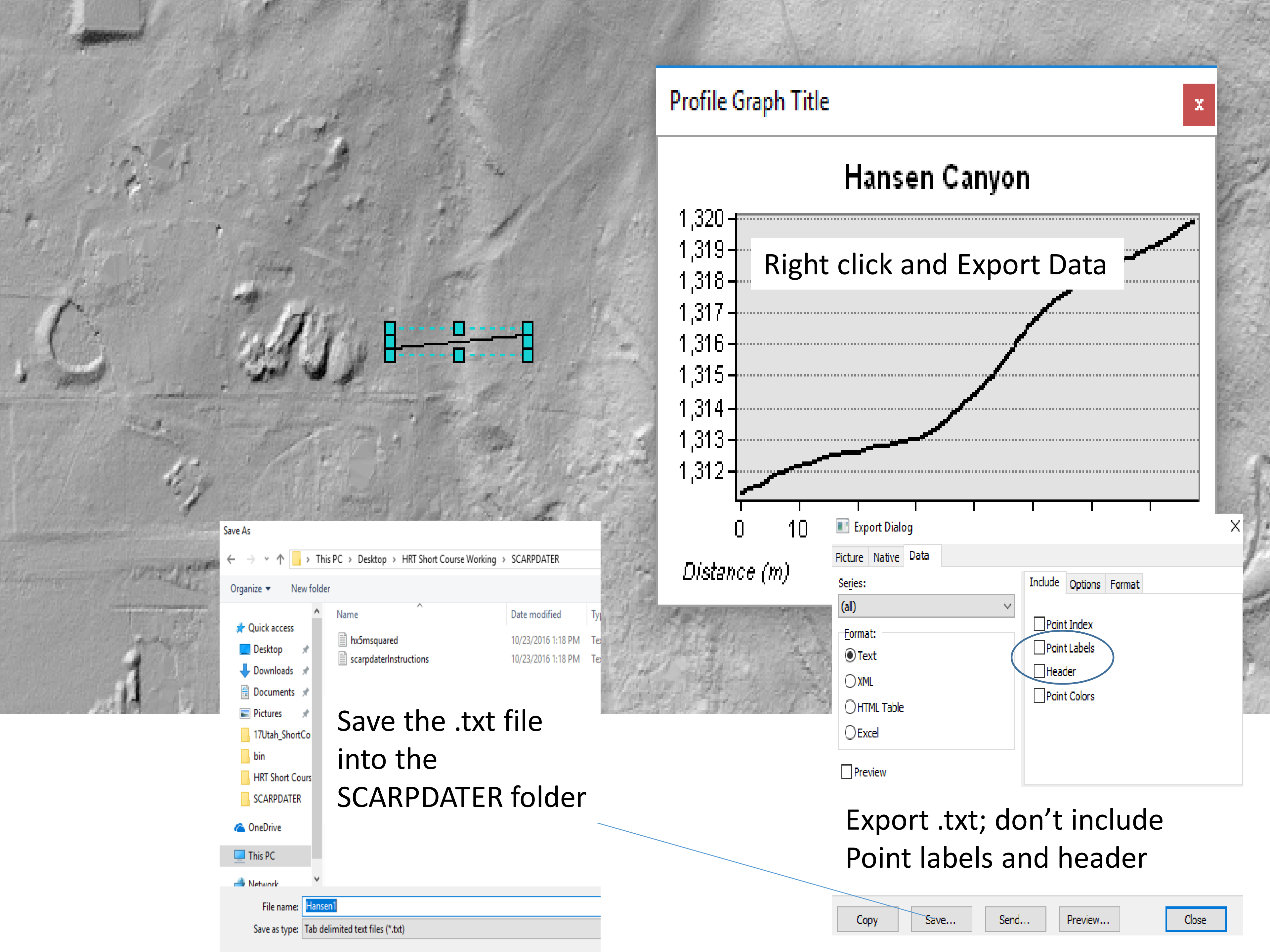
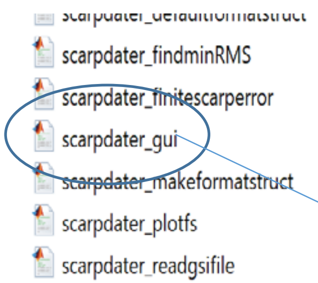
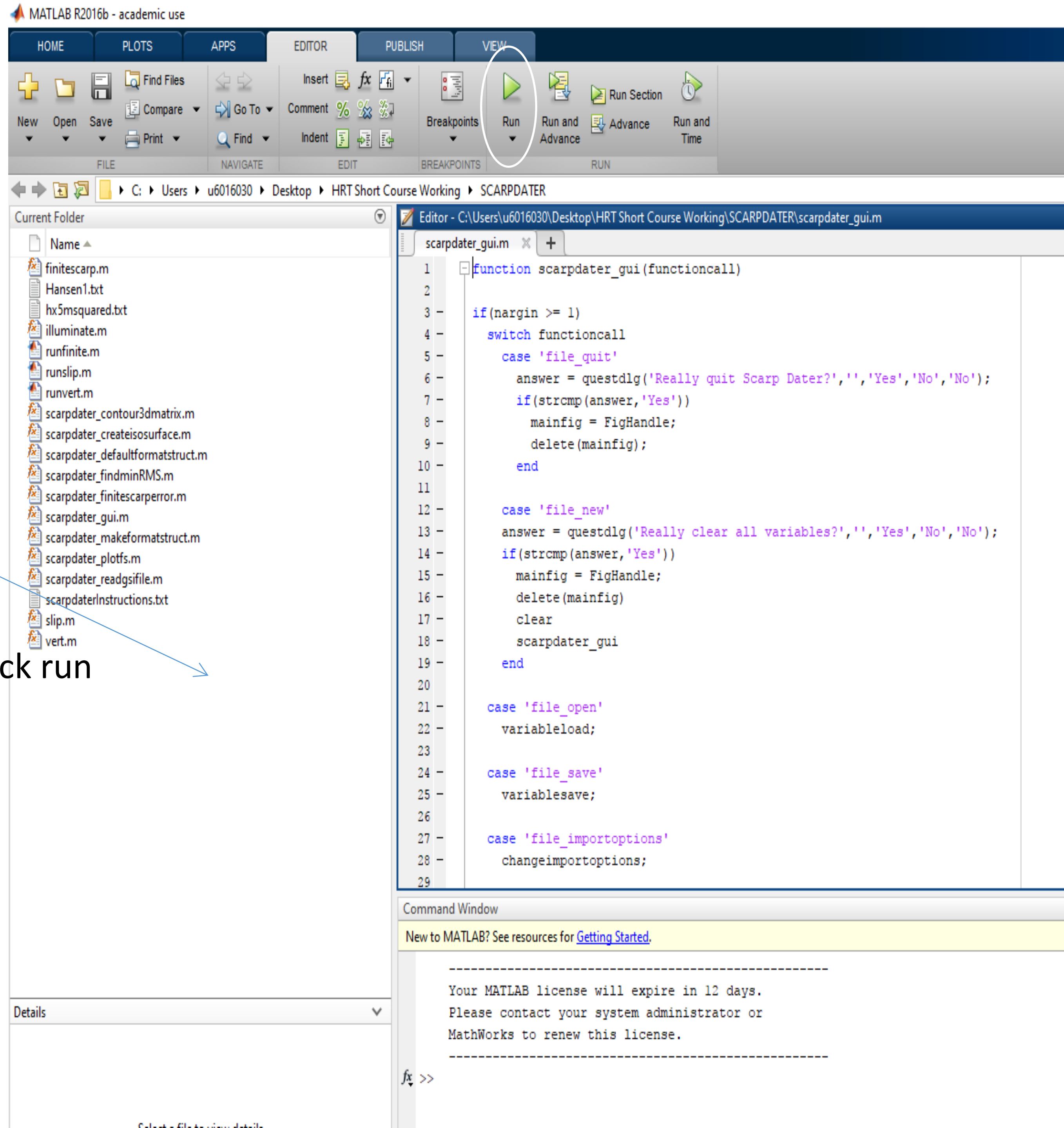


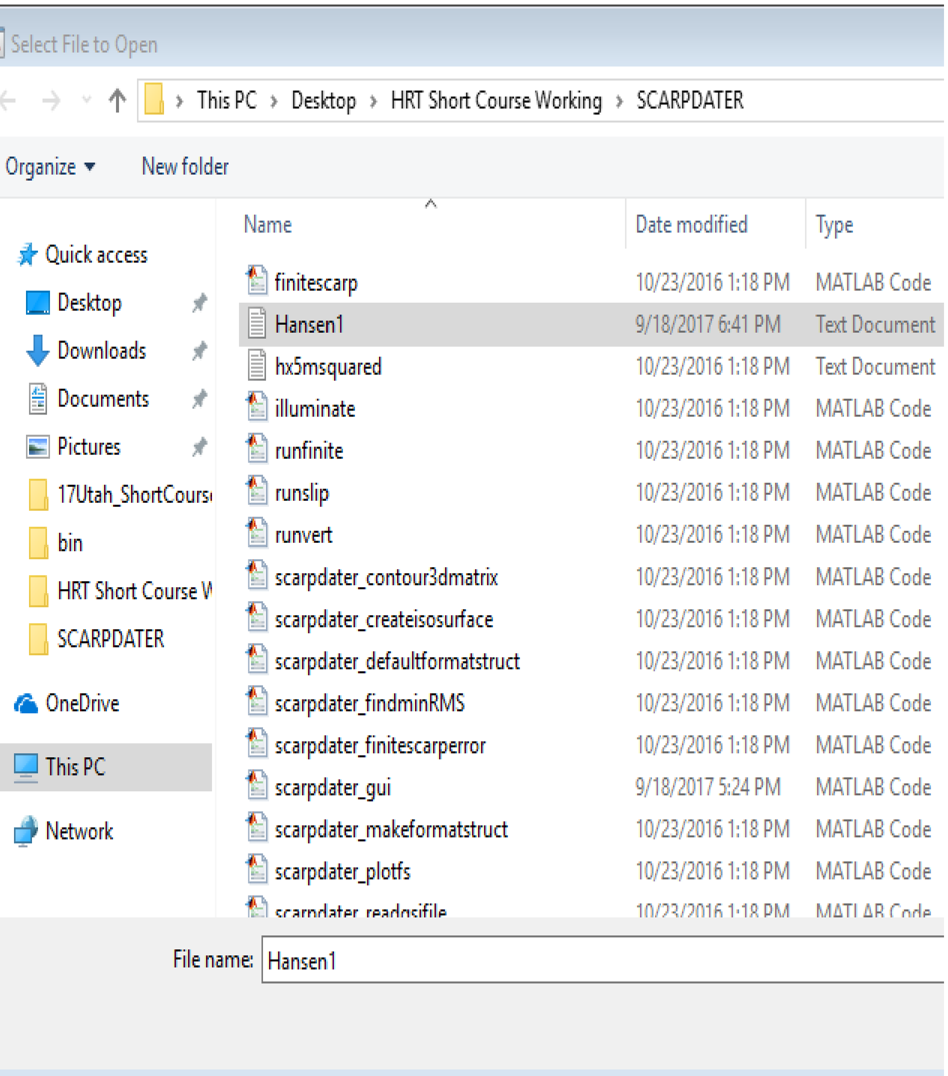
Figure 4. Central Brigham City segment, showing vertical scarp offsets measured at the Hansen Canyon and Kotter Canyon

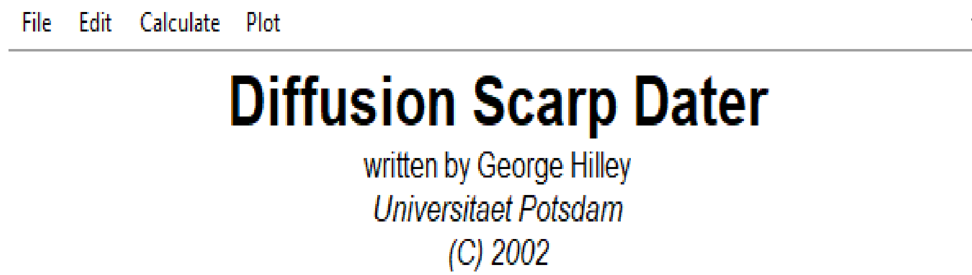

Profile Graph Title
Hansen Canyon
1,320
1,319
1,318
1,317
1,316
1,315
1,314
1,313
1,312
0
10
Distance (m)
Right click and Export Data
Save As
This PC › Desktop › HRT Short Course Working › SCARPDATER
Organize
New folder
Quick access
Desktop
Downloads
Documents
Pictures
17Utah_ShortCo
bin
HRT Short Cours
SCARPDATER
OneDrive
This PC
Network
Name
Date modified
hx5msquared
10/23/2016 1:18 PM
scarpdaterInstructions
10/23/2016 1:18 PM
File name: Hansen1
Save as type: Tab delimited text files (*.txt)
Save the .txt file into the SCARPDATER folder
Export Dialog
Picture
Native
Data
Series:
(all)
Format:
Text
XML
HTML Table
Excel
Preview
Include
Options
Format
Point Index
Point Labels
Header
Point Colors
Export .txt; don't include Point labels and header
Copy
Save...
Send...
Preview...
Close



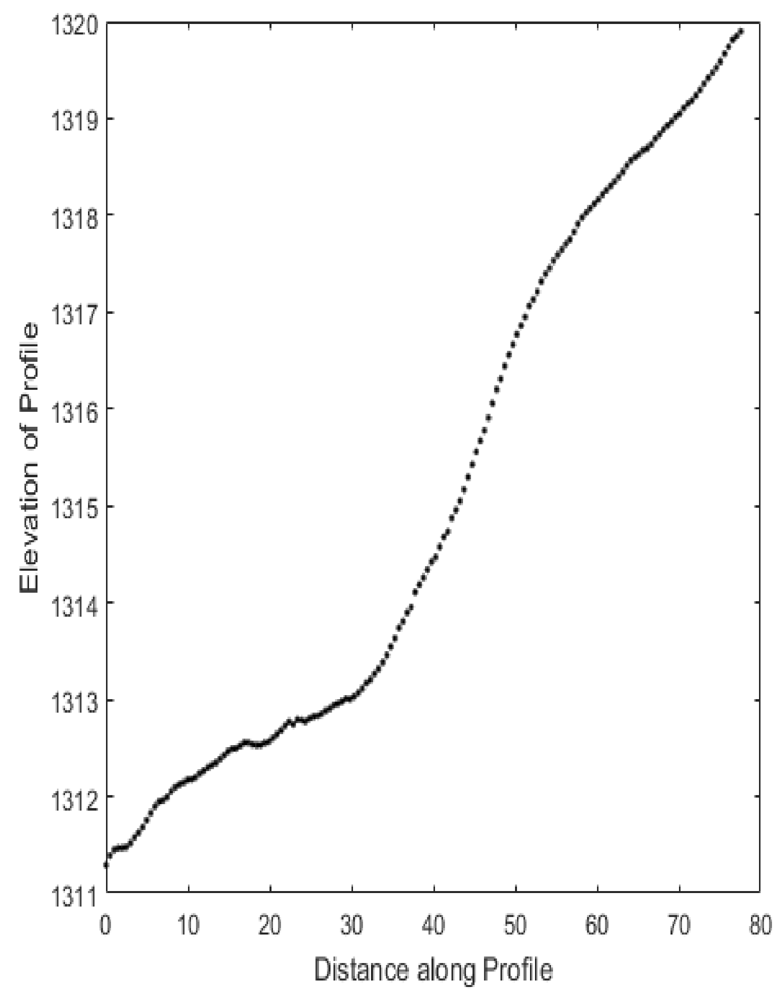
Double click on Scarpdater_gui and then click run



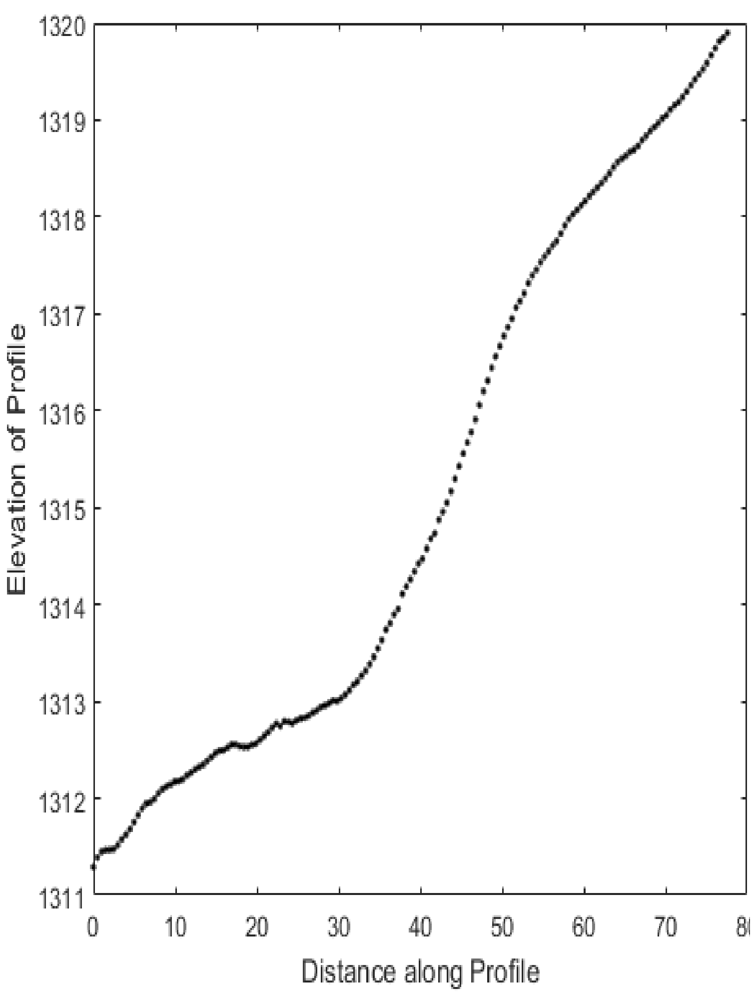


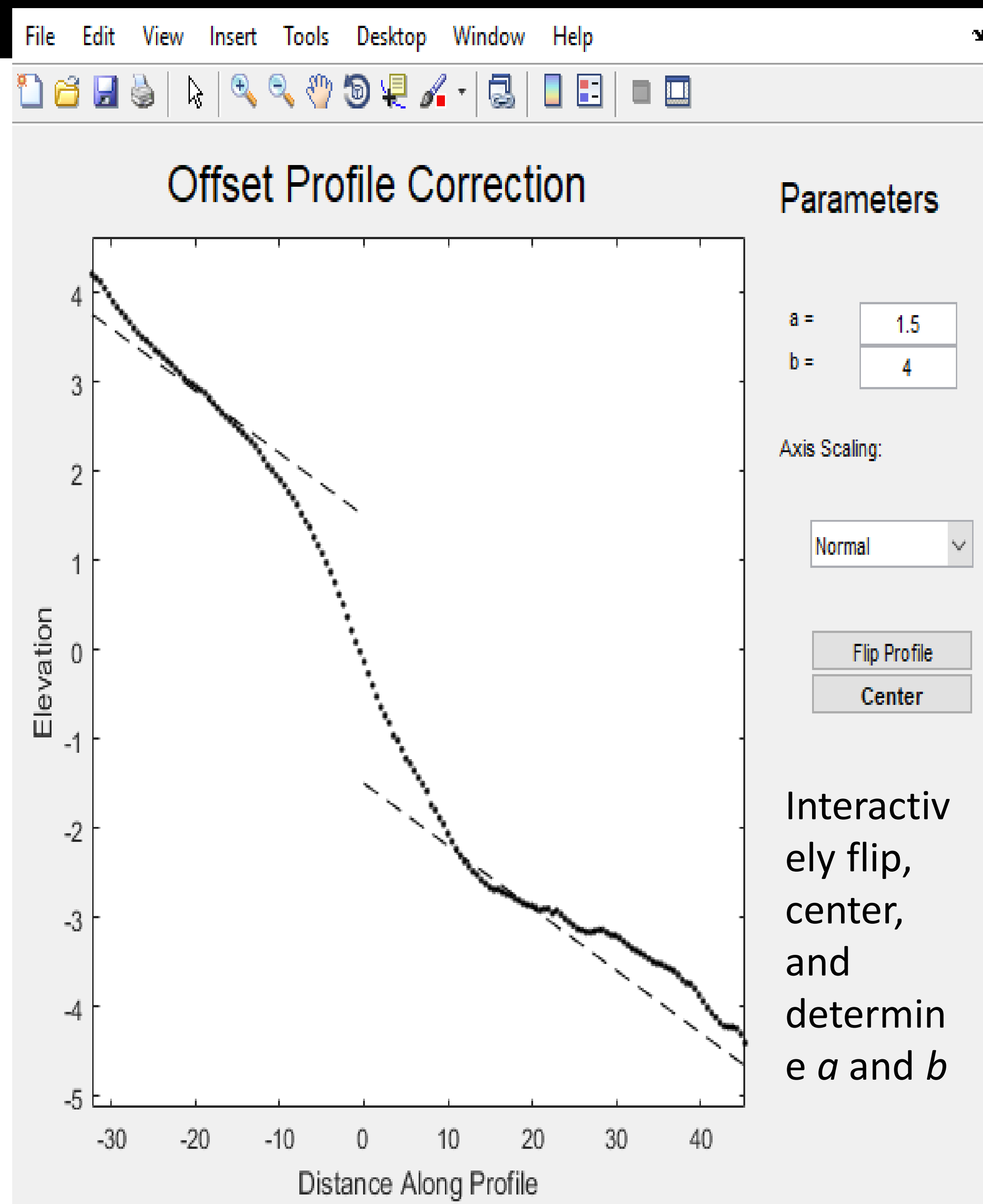


File->Import->Text X-Z format

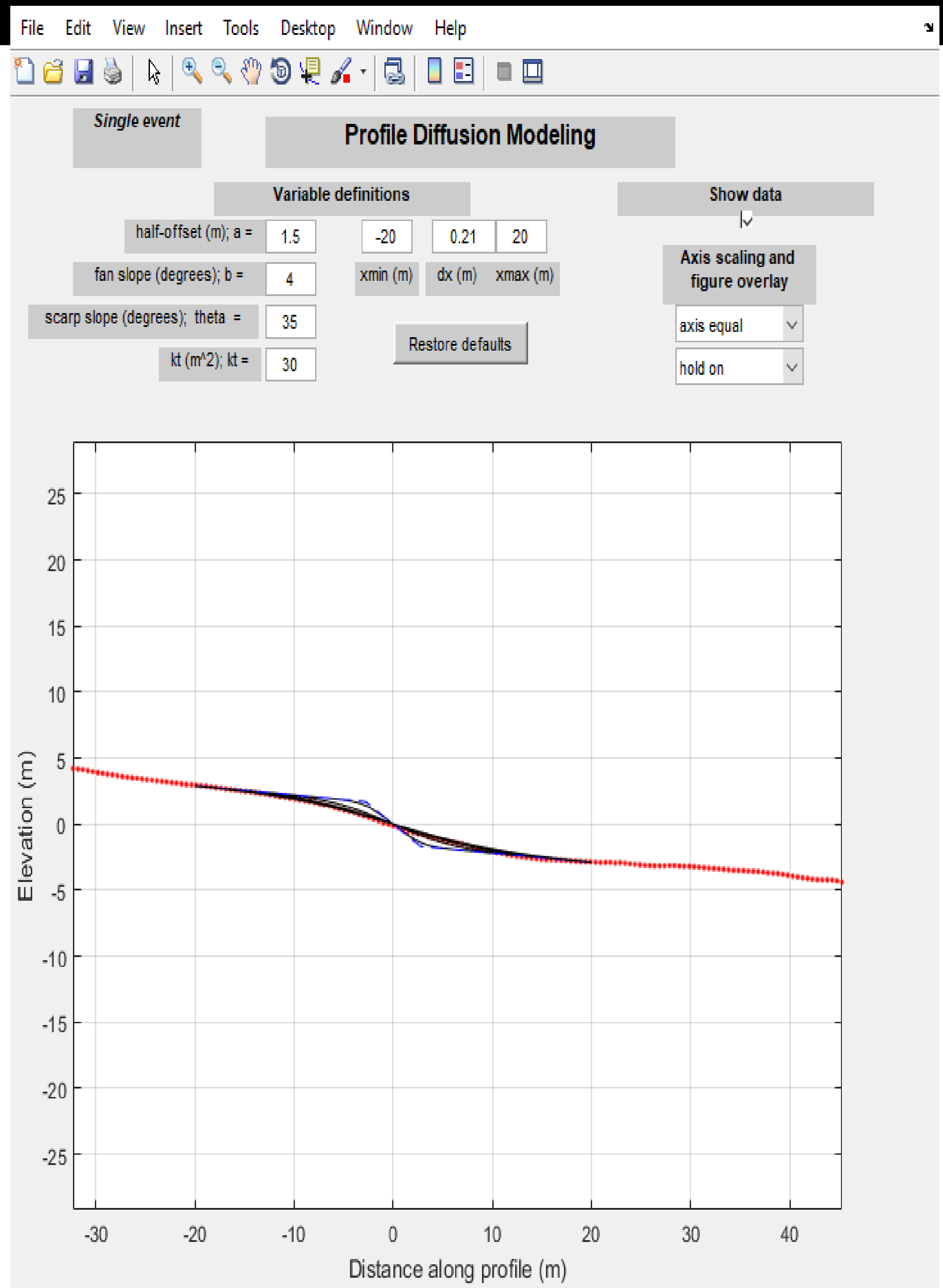


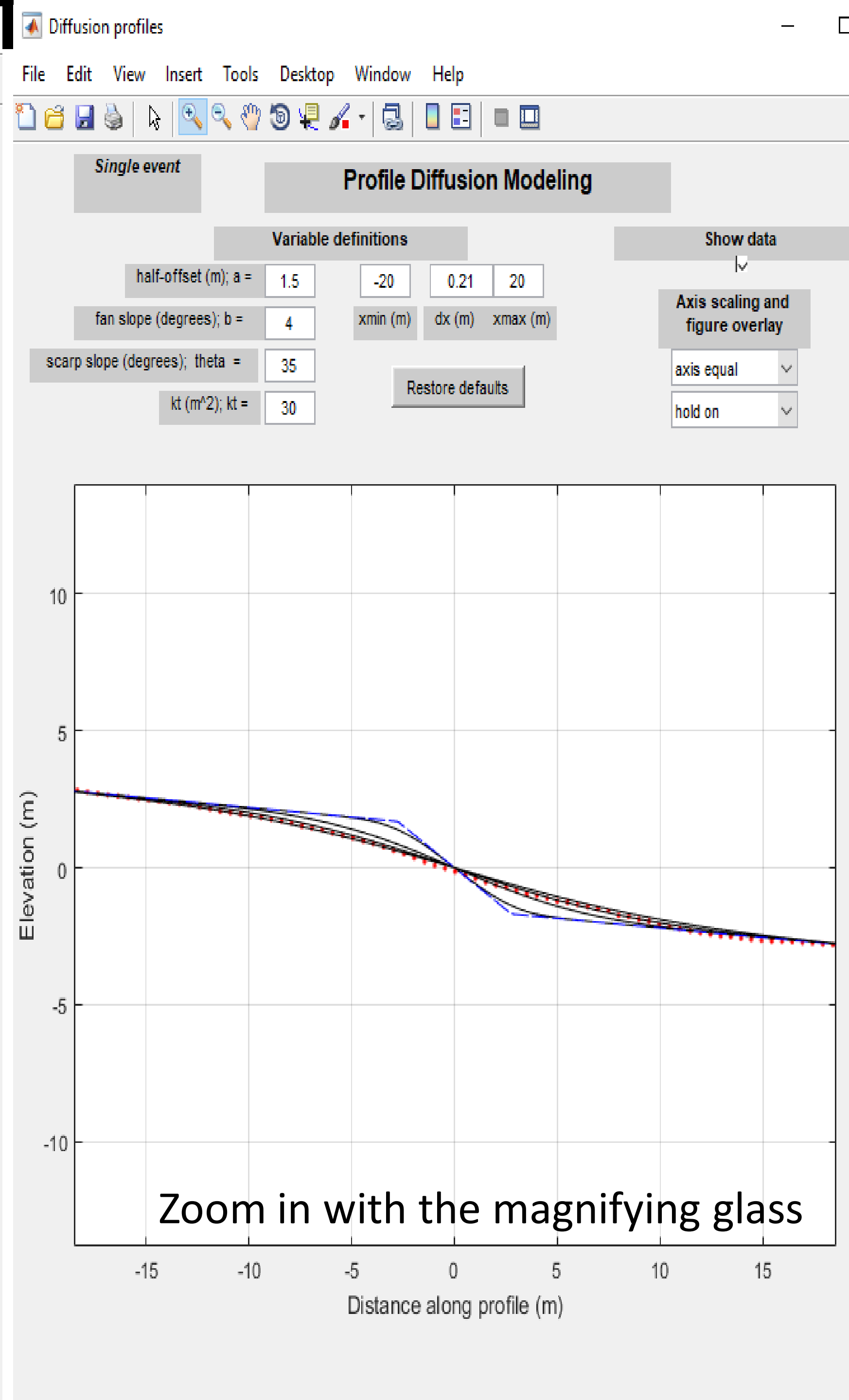
Edit->Offset Data



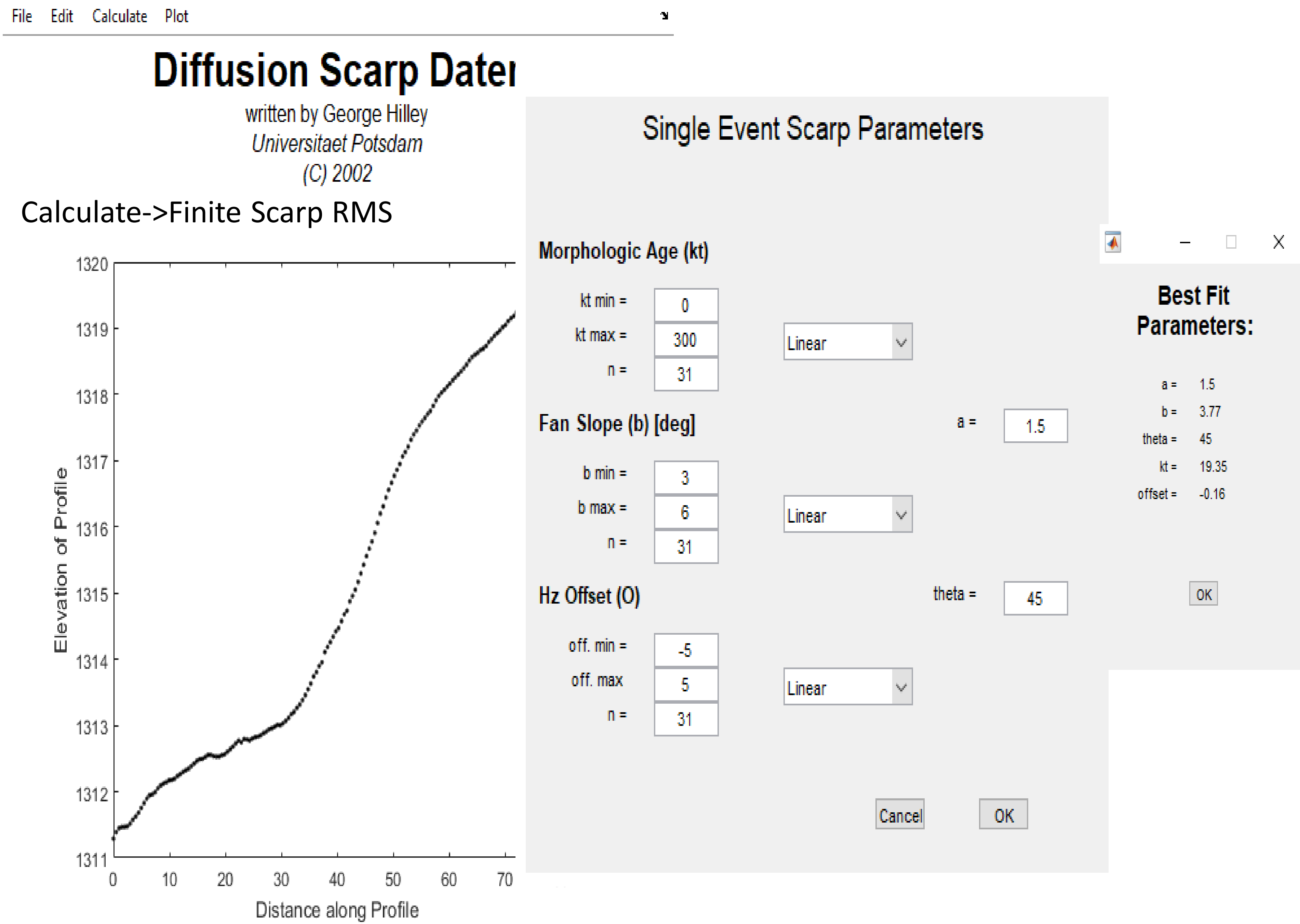


Interactively flip, center, and determine *a* and *b*


File Edit View Insert Tools Desktop Window Help
Single event
Profile Diffusion Modeling
Variable definitions
Show data
half-offset (m); a =
1.5
-20
0.21
20
fan slope (degrees); b =
4
xmin (m)
dx (m)
xmax (m)
scarp slope (degrees); theta =
35
kt (m^2); kt =
30
Restore defaults
Axis scaling and figure overlay
axis equal
hold on
Elevation (m)
Distance along profile (m)

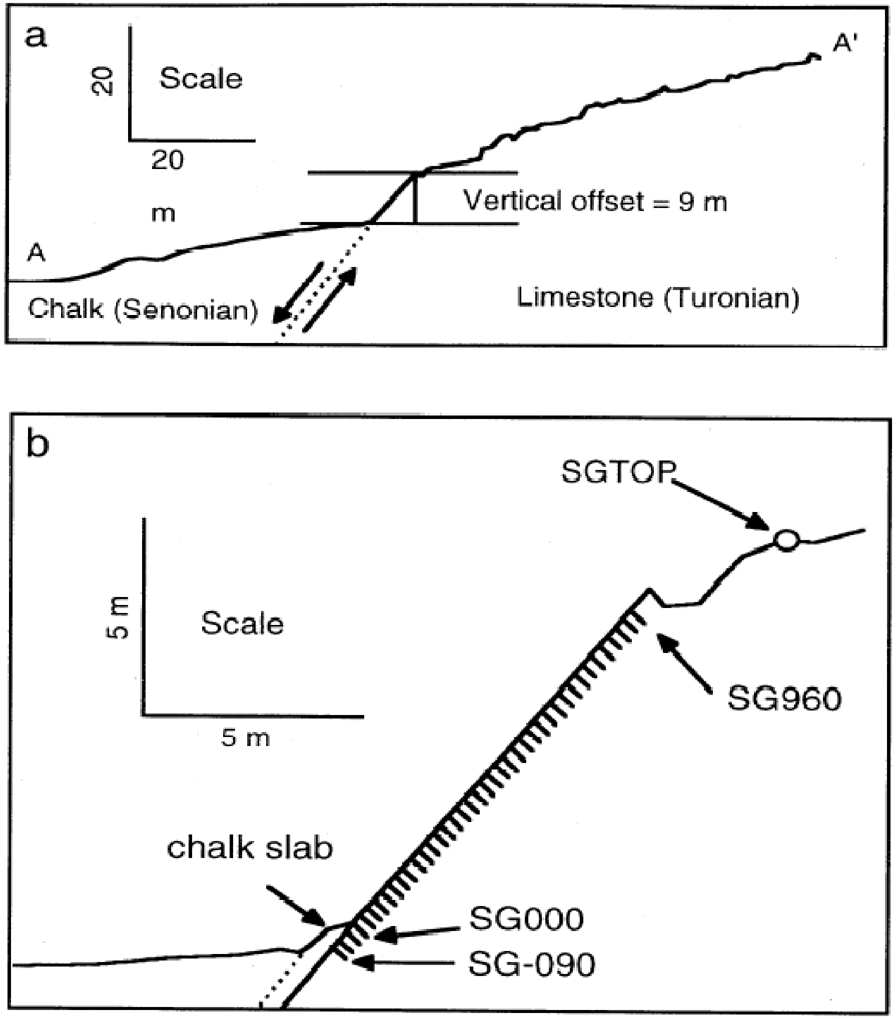

Diffusion profiles
File Edit View Insert Tools Desktop Window Help
Single event
Profile Diffusion Modeling
Variable definitions
Show data
half-offset (m); a =
1.5
-20
0.21
20
fan slope (degrees); b =
4
xmin (m)
dx (m)
xmax (m)
scarp slope (degrees); theta =
35
kt (m^2); kt =
30
Restore defaults
Axis scaling and figure overlay
axis equal
hold on
Elevation (m)
Distance along profile (m)
Zoom in with the magnifying glass

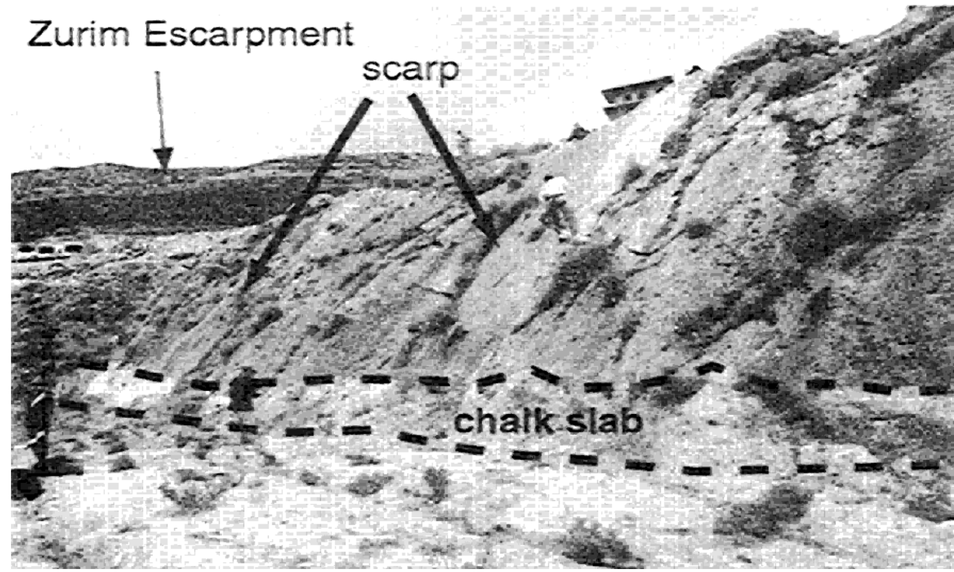
Calculate->Finite Scarp RMS



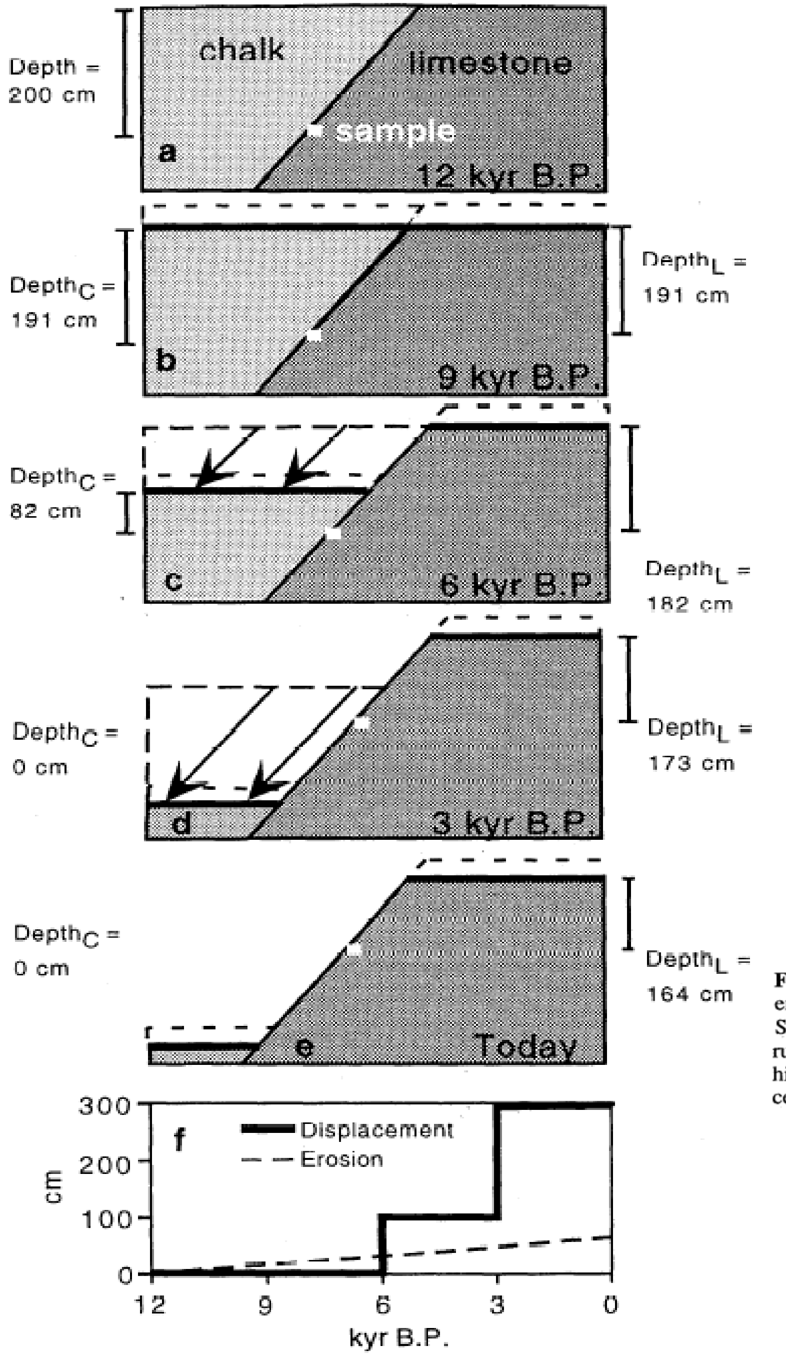
Direct dating of fault scarps

- Mitchell, et al., 2001
  - Cosmogenic dating of progressive fault scarp exposure
- Also:
  - Benedetti, et al., Zreda and Noller, and Phillips, et al.
- Promising, but be cautious and its expensive





Mitchell, et al., 2001



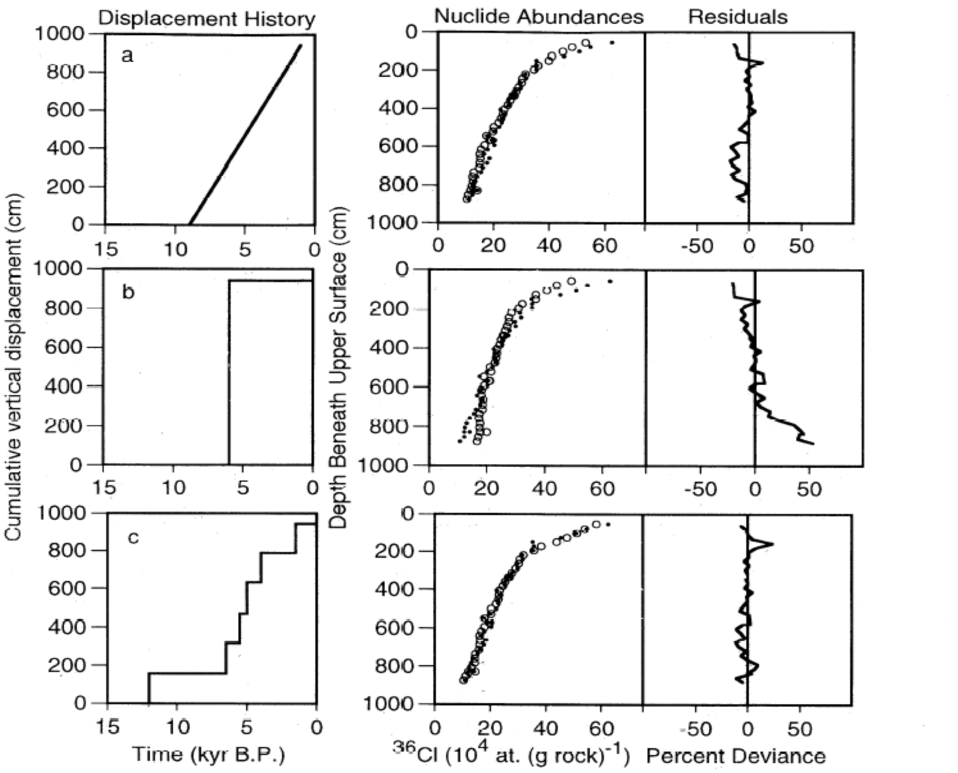


Figure 11. Three different displacement scenarios with resulting model ^{36}Cl values and residuals (percent difference between measured and model ^{36}Cl values). Model ^{36}Cl are open circles; measured ^{36}Cl data are small dots. (a) Steady creep from 9 to 1 kyr B.P. results in model ^{36}Cl values that are too low for much of the scarp. (b) A single rupture event occurring at 6.5 kyr B.P. results in model ^{36}Cl values that are too low at the top of the scarp and too high at the base. (c) The best fit scenario from the six-event series (with maximum displacement in the mid-Holocene) results in a reasonable fit down the entire profile.

Mitchell, et al., 2001

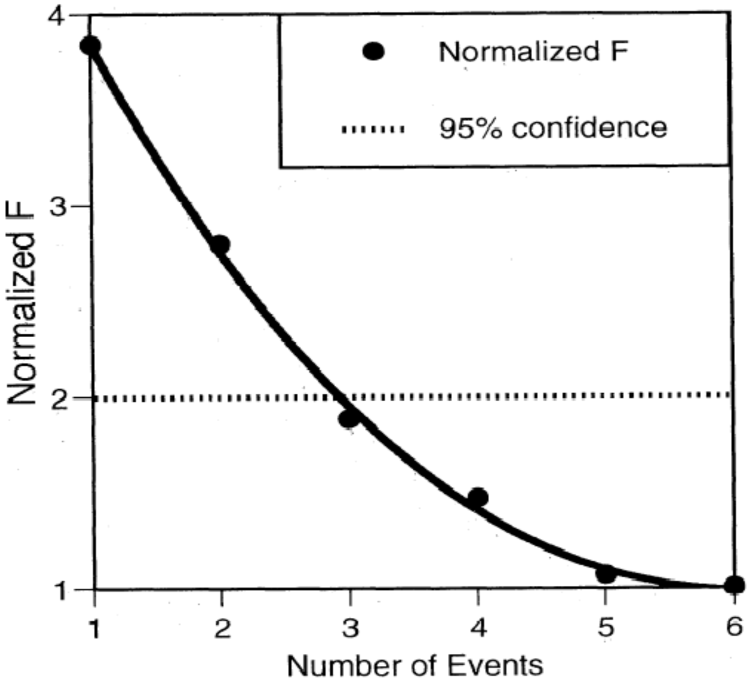


Figure 12. Lowest residual (F) value for each displacement history series. For comparison, F values have been normalized to the lowest residual. Higher numbers of events result in better F values; however, the change in F decreases with an increasing number of events.

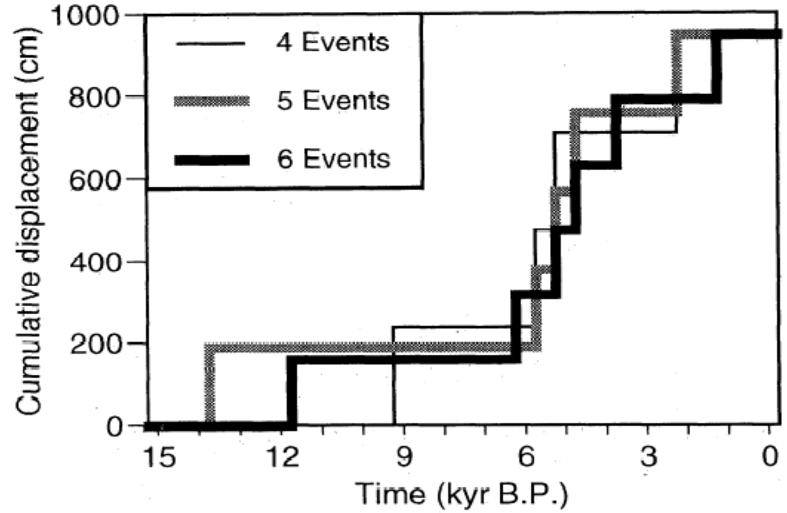
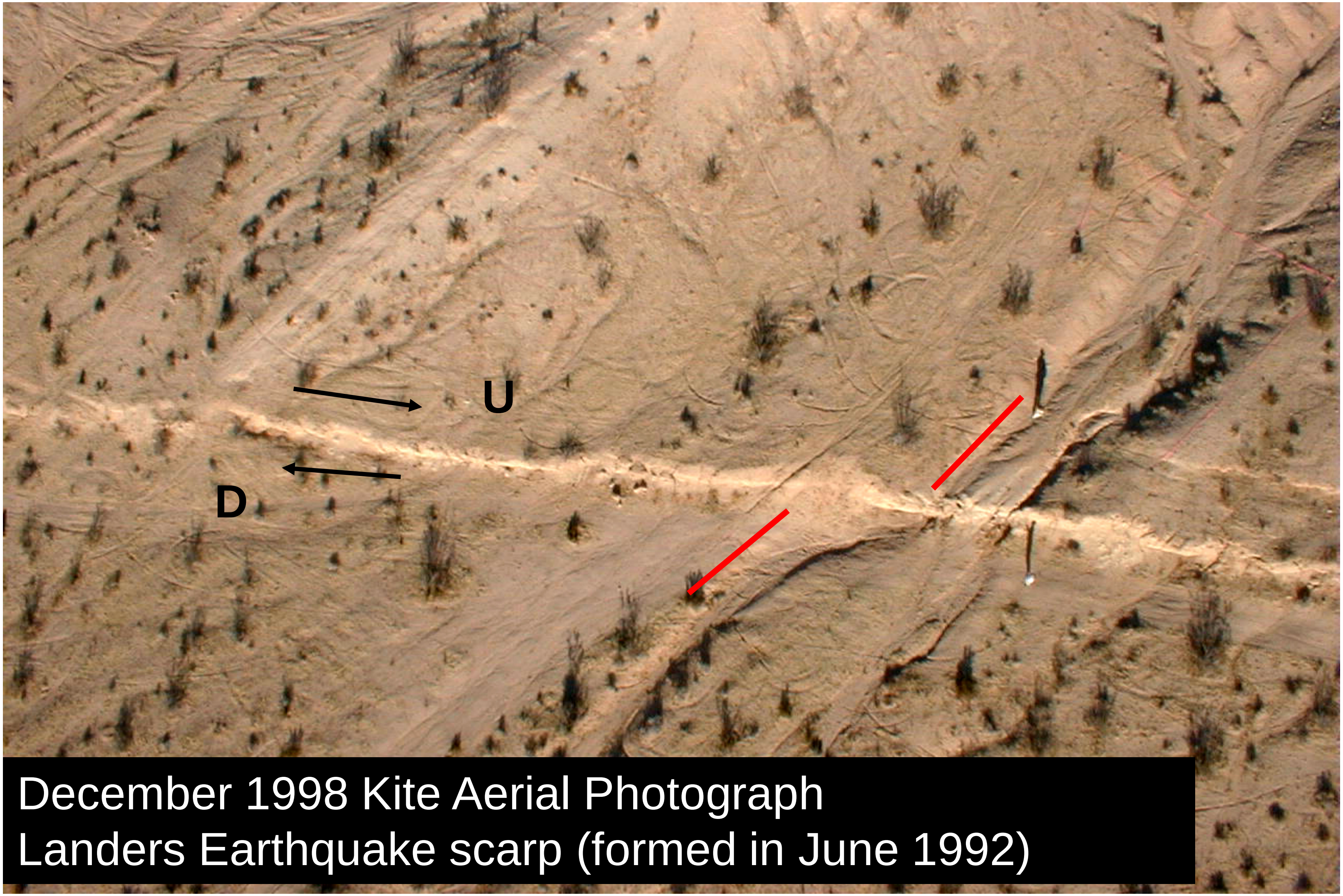
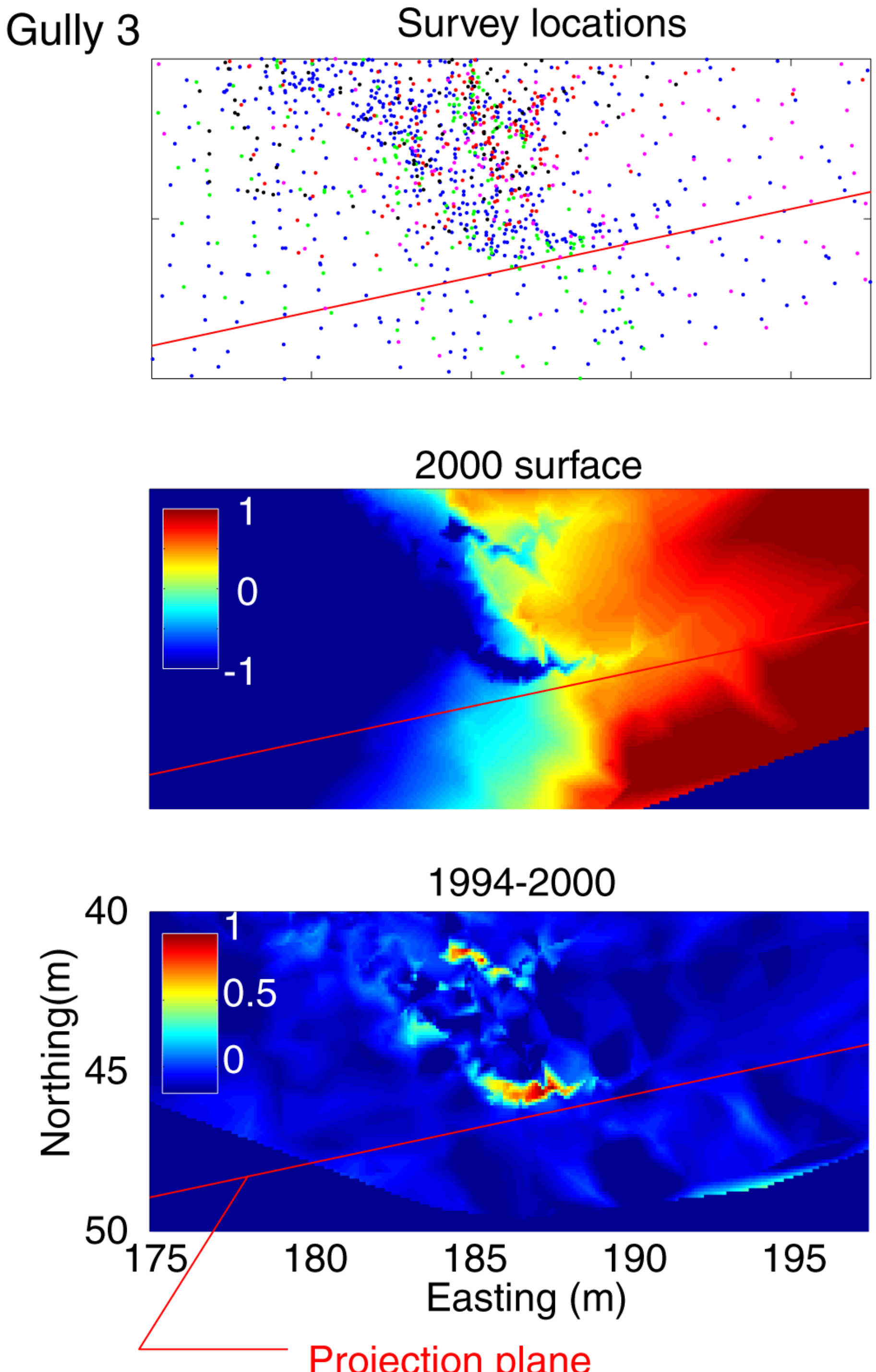


Figure 14. Cumulative displacement versus time for best fit histories of four, five, and six events. All three of these histories show most displacement occurs in a relatively short period of time, centered around 5 kyr BP. Lesser amounts of displacement occur in the time periods 13-11 and 2.5-0.5 kyr B.P.

Mitchell, et al., 2001

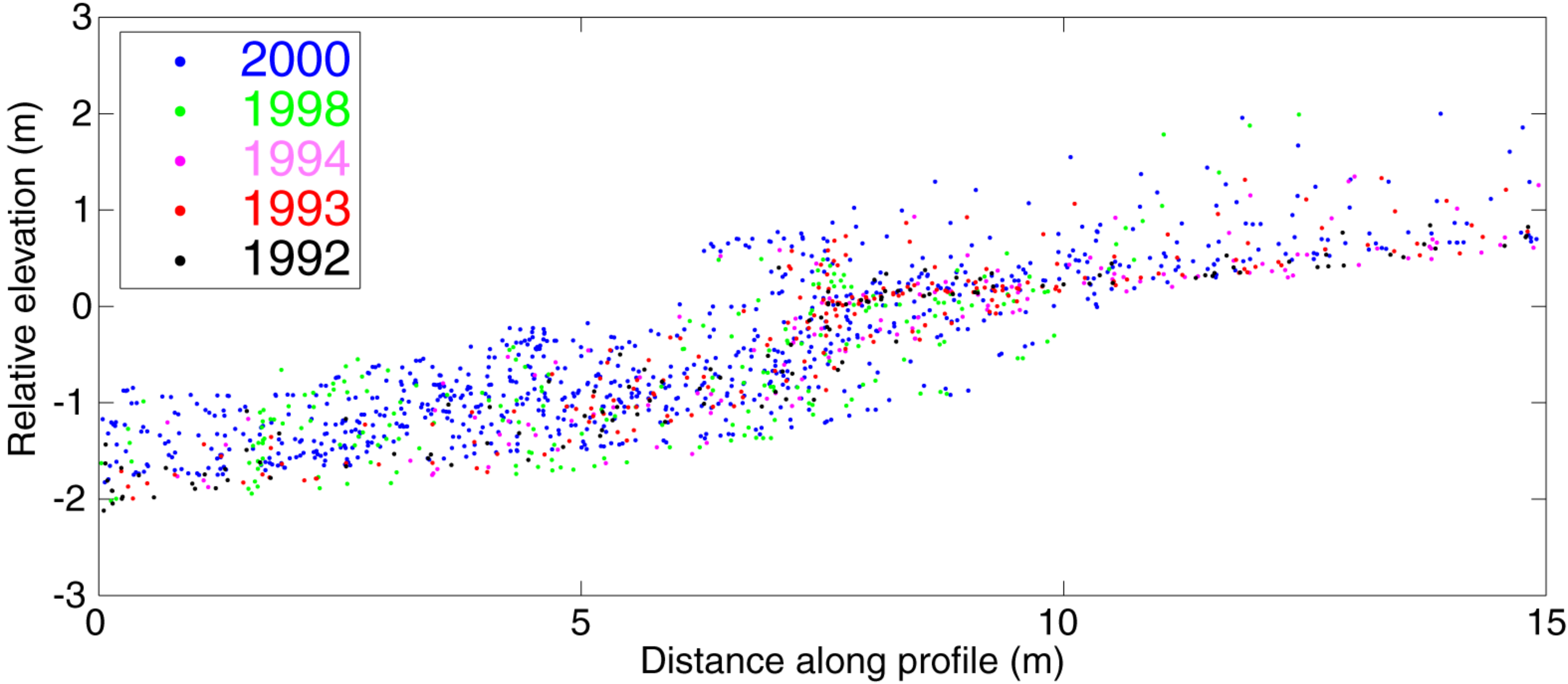
Fault scarp erosion monitoring

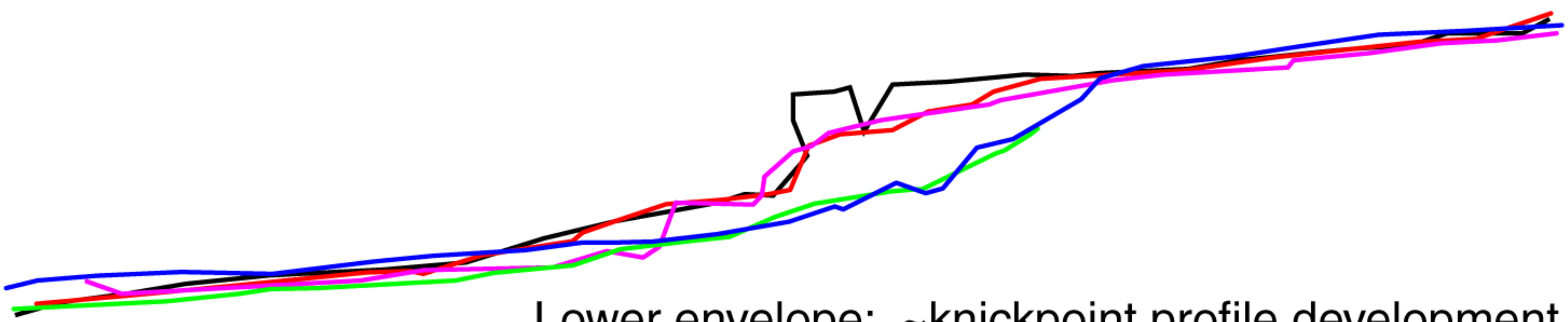




Gully 3
Survey locations
2000 surface
1
0
-1
1994-2000
1
0.5
0
40
45
50
Northing(m)
175
180
185
190
195
Easting (m)
Projection plane

Gully 3 projected topographic data and profile





Lower envelope: ~knickpoint profile development

Evidence for nonlinear, diffusive sediment transport on hillslopes and implications for landscape morphology

Joshua J. Roering, James W. Kirchner, and William E. Dietrich

WATER RESOURCES RESEARCH, v. 35, p. 853–870, 1999

$$\tilde{q}_s = \frac{K \nabla z}{1 - (|\nabla z|/S_c)^2}$$

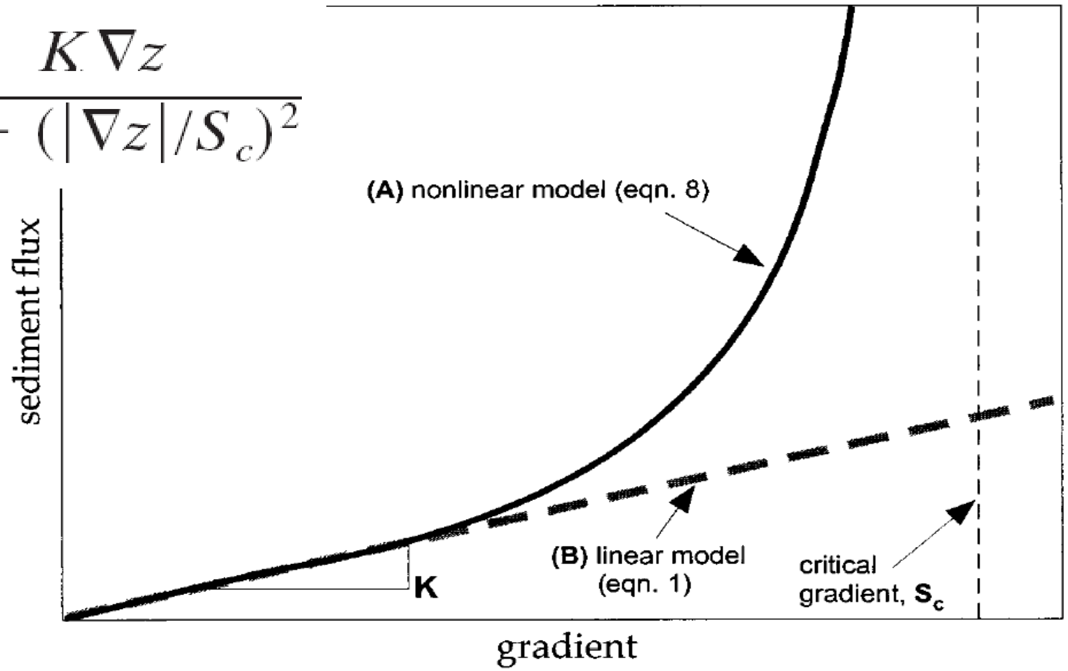


Figure 3. Theoretical relationships between sediment flux and gradient. (curve a) Nonlinear transport law (equation (8)); (line b) linear diffusion law (equation (1)). The critical gradient S_c is the gradient at which flux becomes infinite for the nonlinear transport law.

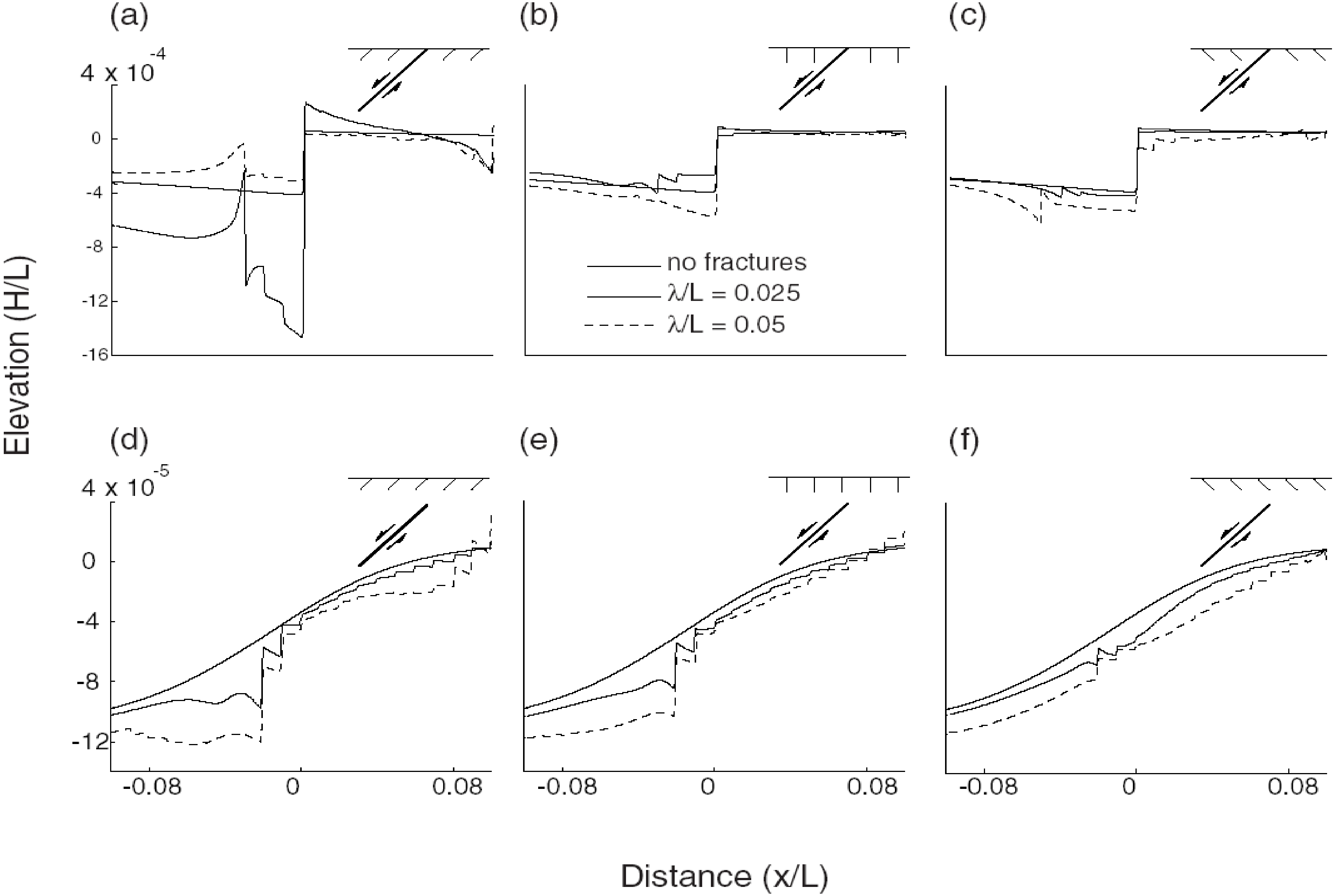
Mattson and Bruhn, 2001:

Calibrated K_0 = 1.2 m^2/kyr and and S_c = 0.9 for Lake Bonneville shoreline scarp.

Nonlinear approach improves model fits by removing most dependence of K_0 on scarp height.

Distributed deformation

- Block faulting versus distributed deformation
- Simple 2D dislocation models as sources of deformation
- Activation of secondary fractures in the near surface

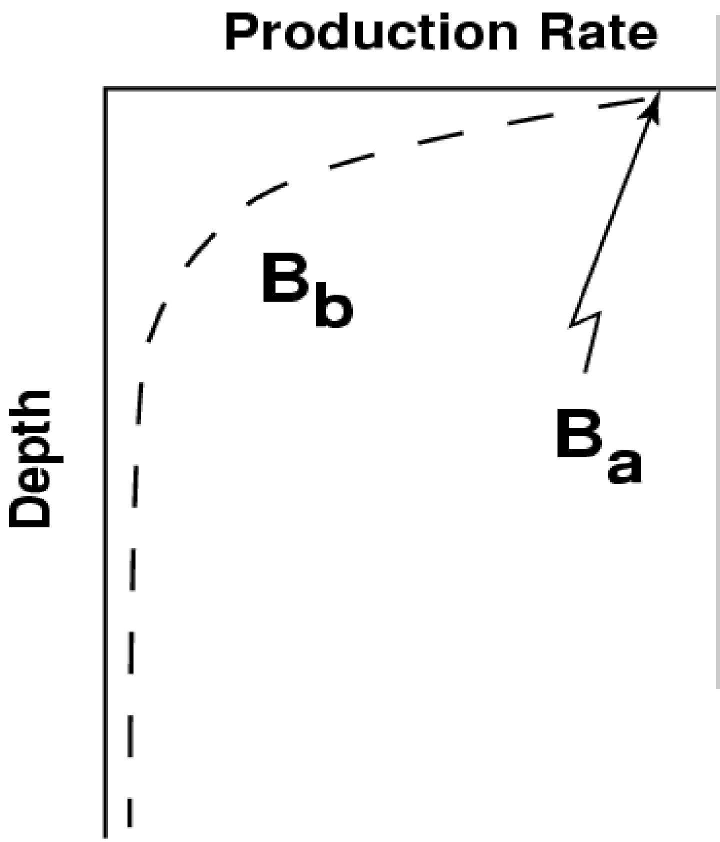


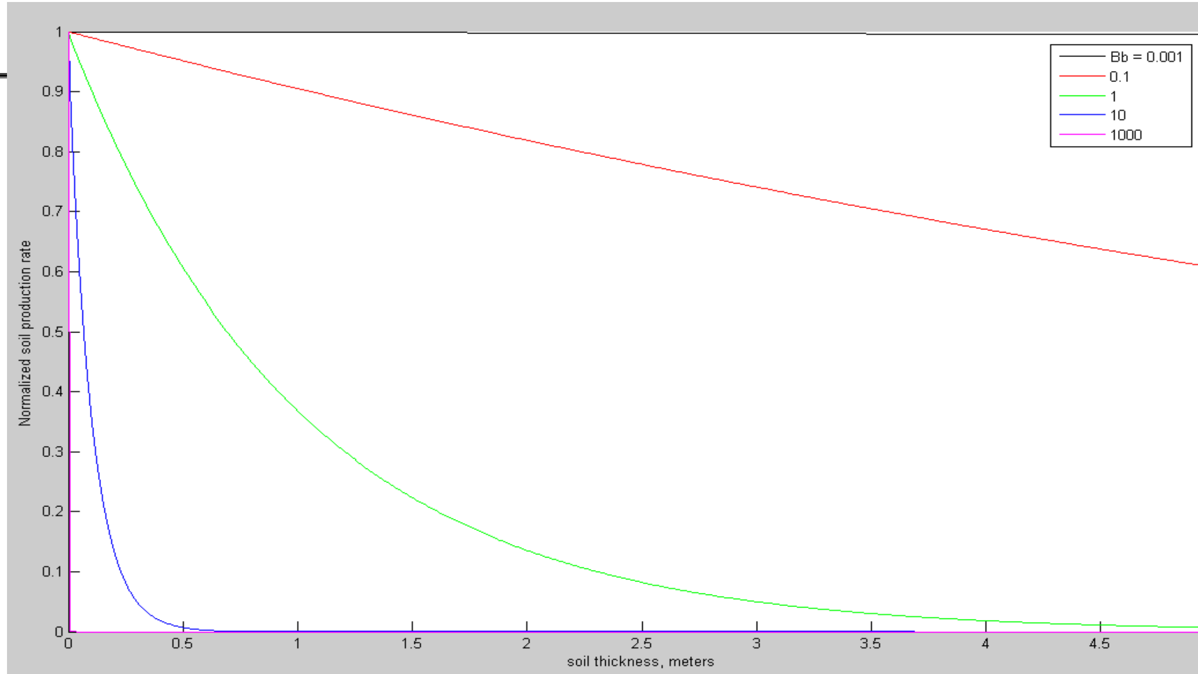
Slip along main normal fault activates shallow fractures, modifying the deformation at the surface

Hilley, et al., 2001

Transport vs. Production limited?

- Simple models of fault scarp development can be extended by accounting for regolith production and thus the availability of transportable material.





$$\frac{\partial B}{\partial t} = -B_a e^{-B_b(H-B)}$$

where, B_a	is the production rate of regolith when bedrock is exposed (L/T),
and B_b	is the thickness sensitivity of production rates (1/L).

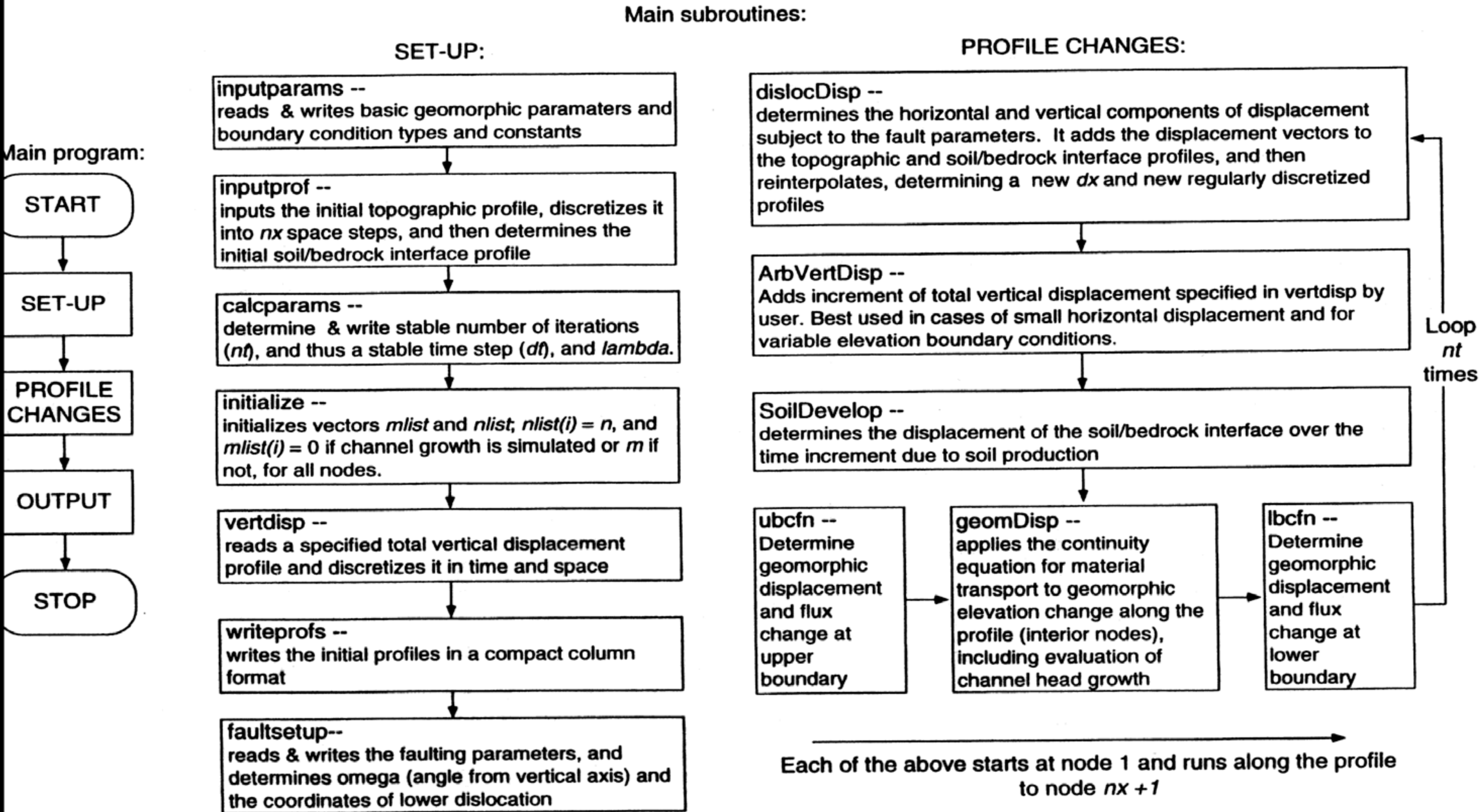
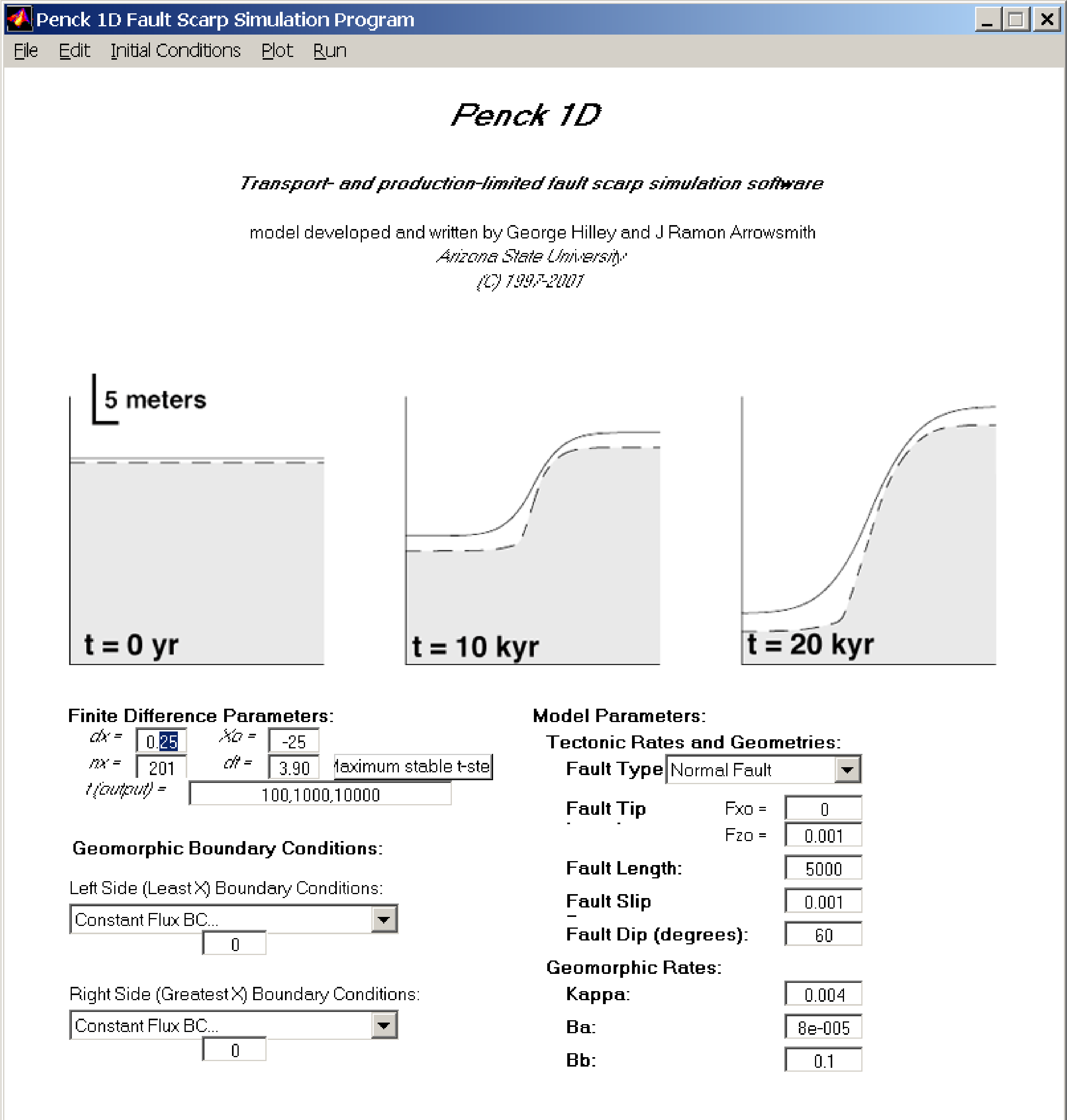


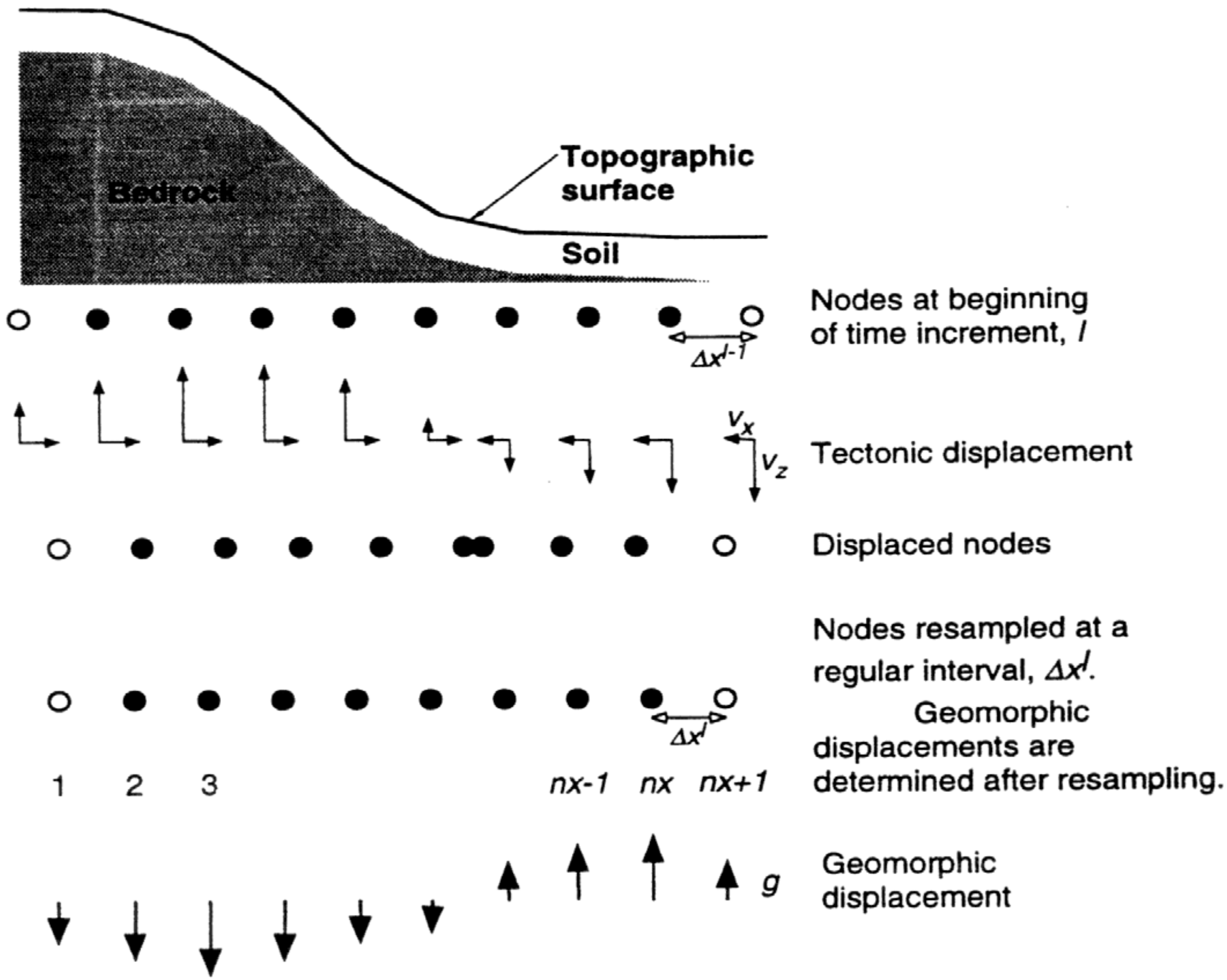
Figure B.12. Flow chart for PENCK. Main program flow is shown on left, and flow of main subroutines in the middle and on the right. Each routine of PROFILECHANGES determines elevation change along the profile from upper end to lower end and the entire loop is repeated *nt* times.



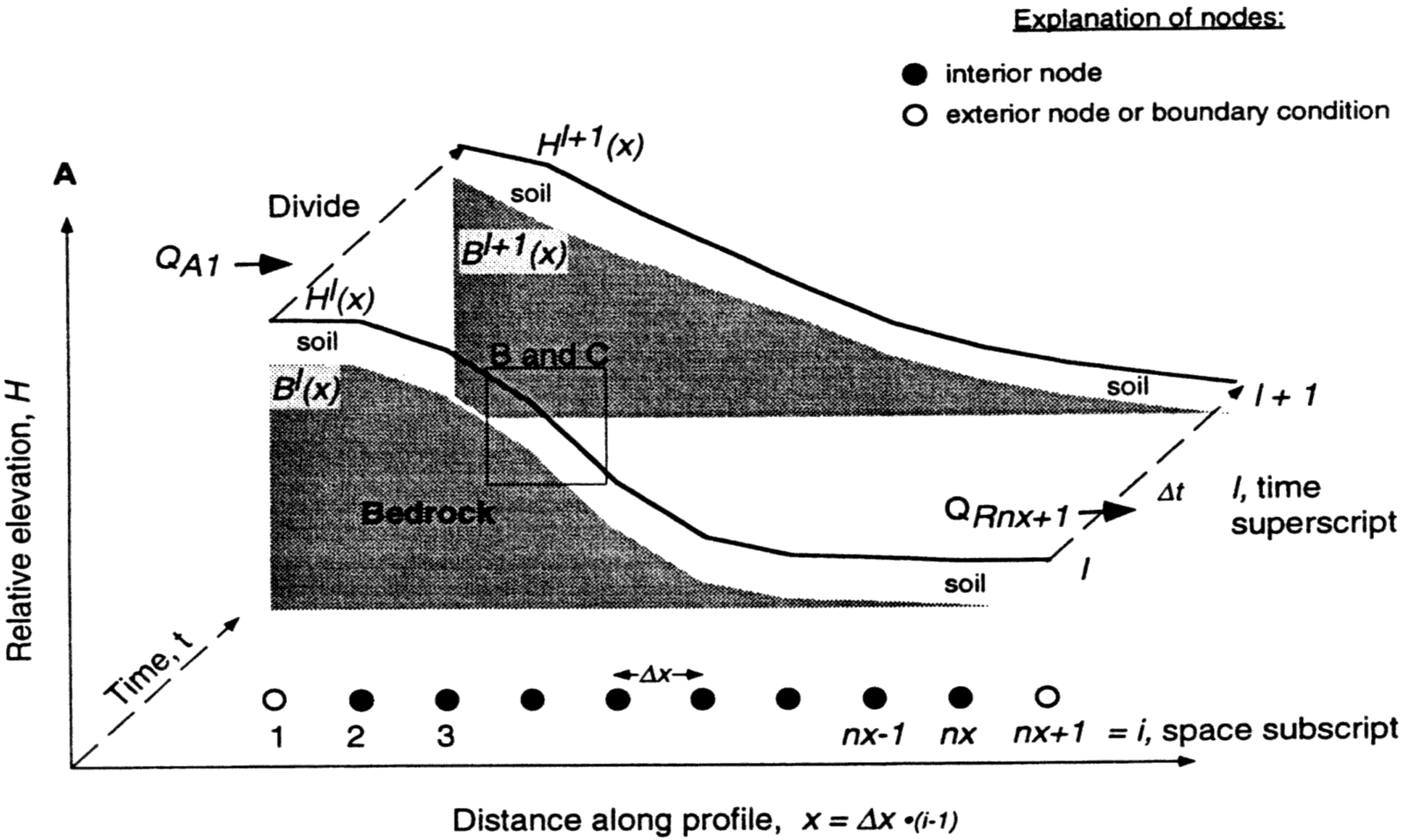
MATLAB modeling tools

Hilley, 2001;

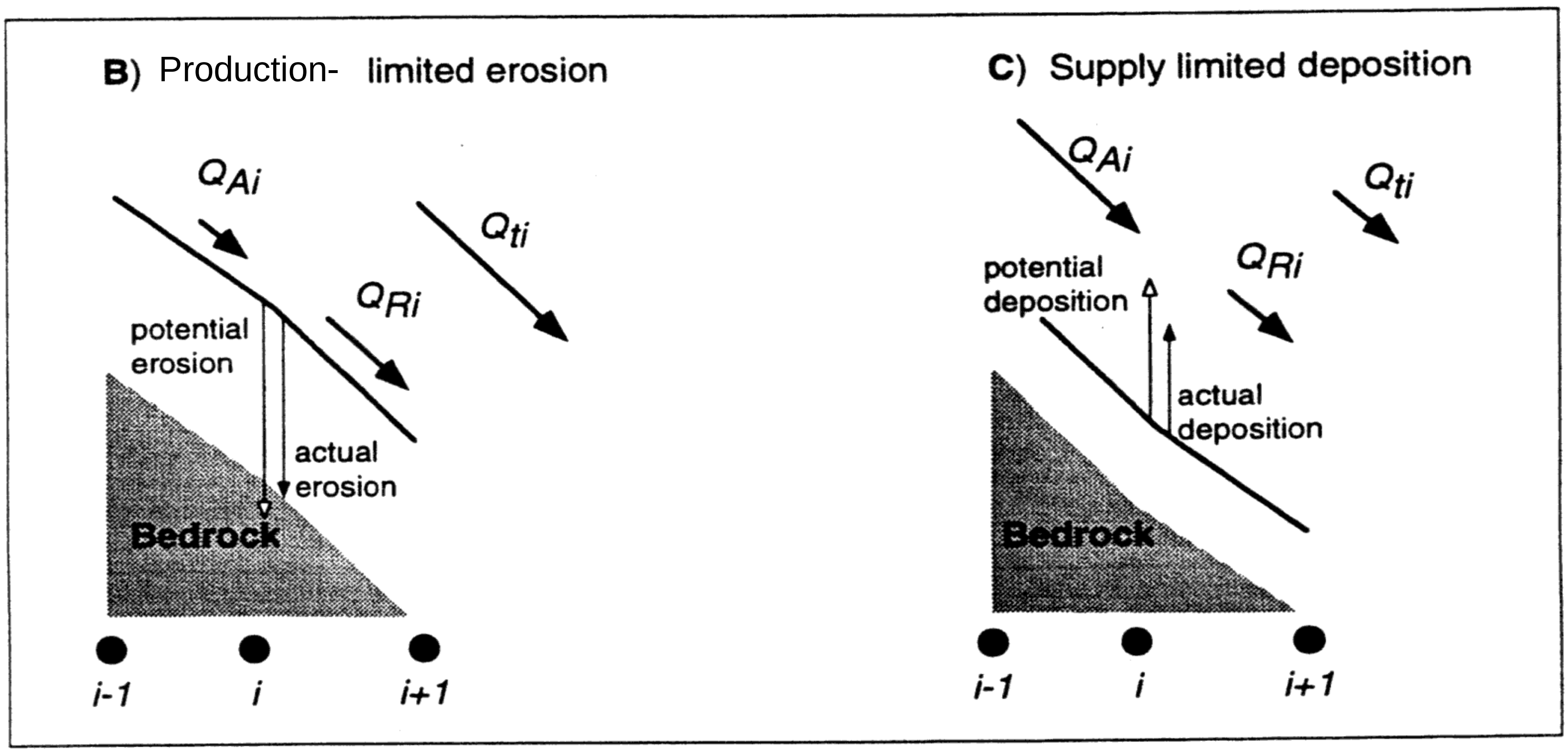
Hilley and Arrowsmith, 2001, 2002



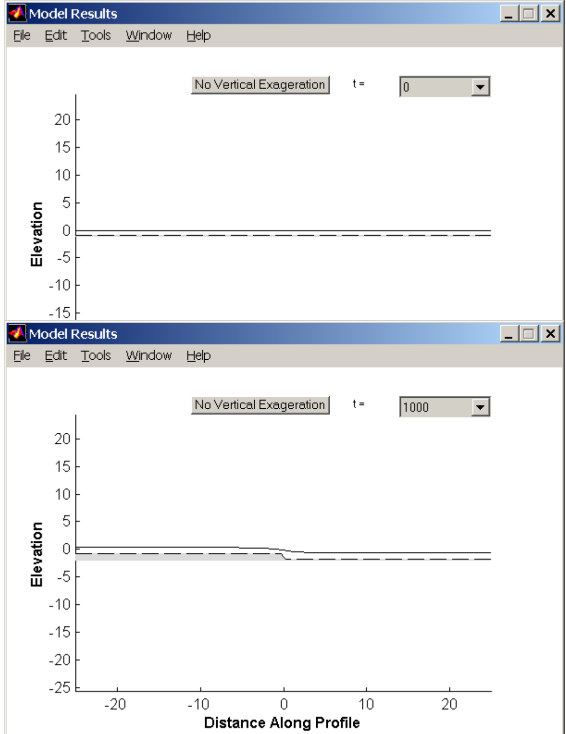
Topographic surface
Bedrock
Soil
Nodes at beginning of time increment, l
Δx^{l-1}
v_x
v_z
Tectonic displacement
Displaced nodes
Nodes resampled at a regular interval, Δx^l.
Geomorphic displacements are determined after resampling.
Δx^l
1
2
3
$nx-1$
nx
$nx+1$
g
Geomorphic displacement

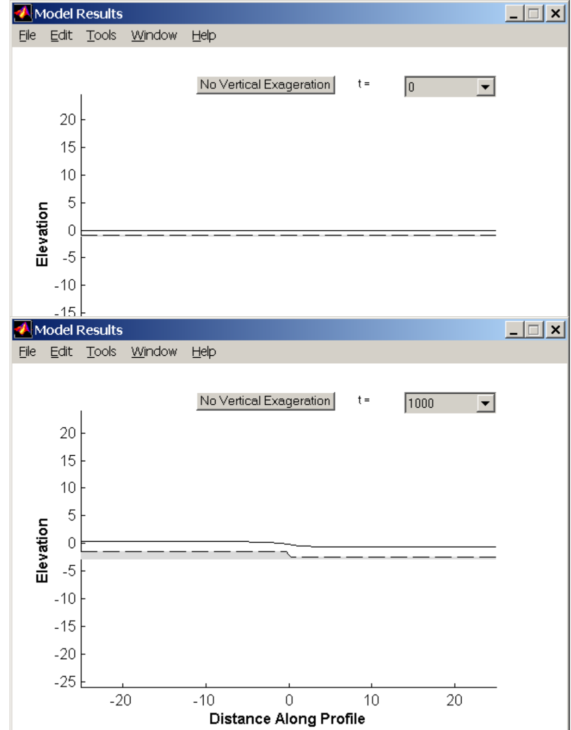


A
Explanation of nodes:
interior node
exterior node or boundary condition
Divide
Q_{A1}
$H^{l+1}(x)$
soil
$B^{l+1}(x)$
$H^{l}(x)$
soil
B and C
$B^{l}(x)$
Bedrock
soil
soil
$l + 1$
Δt
l, time superscript
Q_{Rnx+1}
l
Relative elevation, H
Time, t
Δx
1
2
3
$nx-1$
nx
$nx+1$
= i, space subscript
Distance along profile, $x = \Delta x \cdot (i-1)$

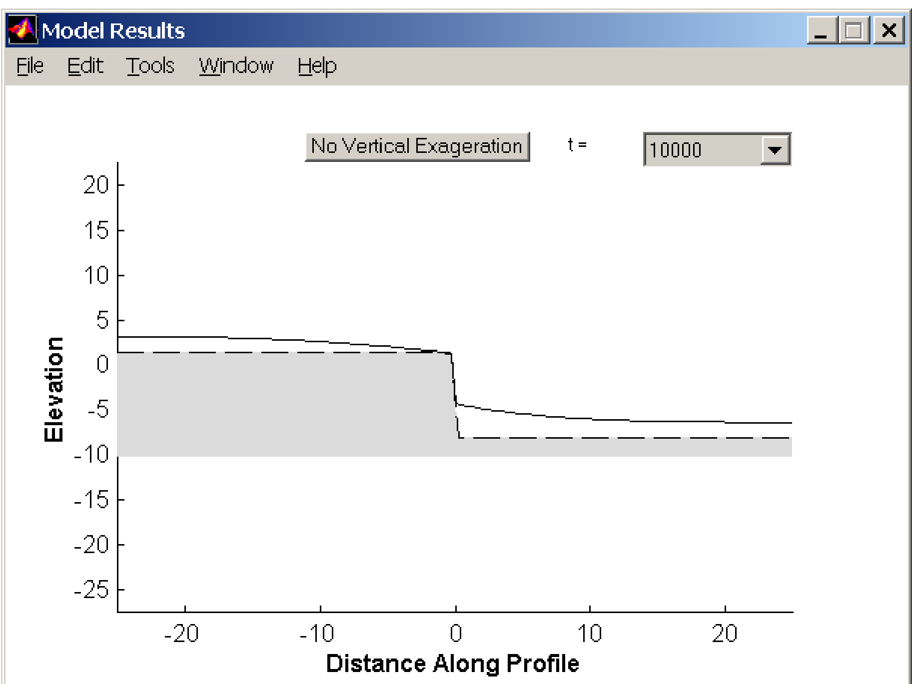

B) Production- limited erosion
Q_{Ai}
Q_{ti}
Q_{Ri}
potential erosion
actual erosion
Bedrock
i-1
i
i+1
C) Supply limited deposition
Q_{Ai}
Q_{ti}
Q_{Ri}
potential deposition
actual deposition
Bedrock
i-1
i
i+1

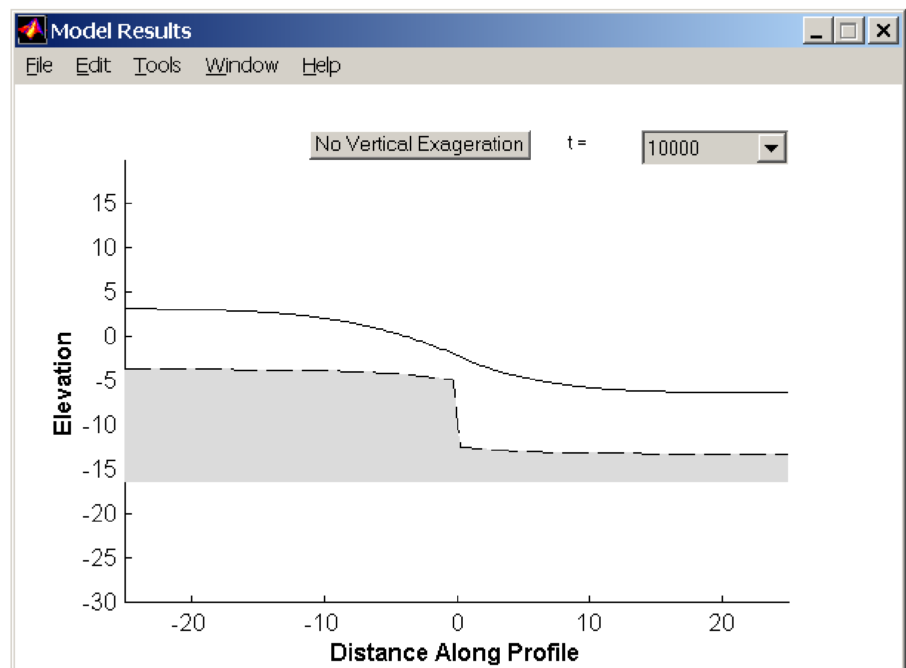
Ba = $8x10^{-5}$ m/kyr



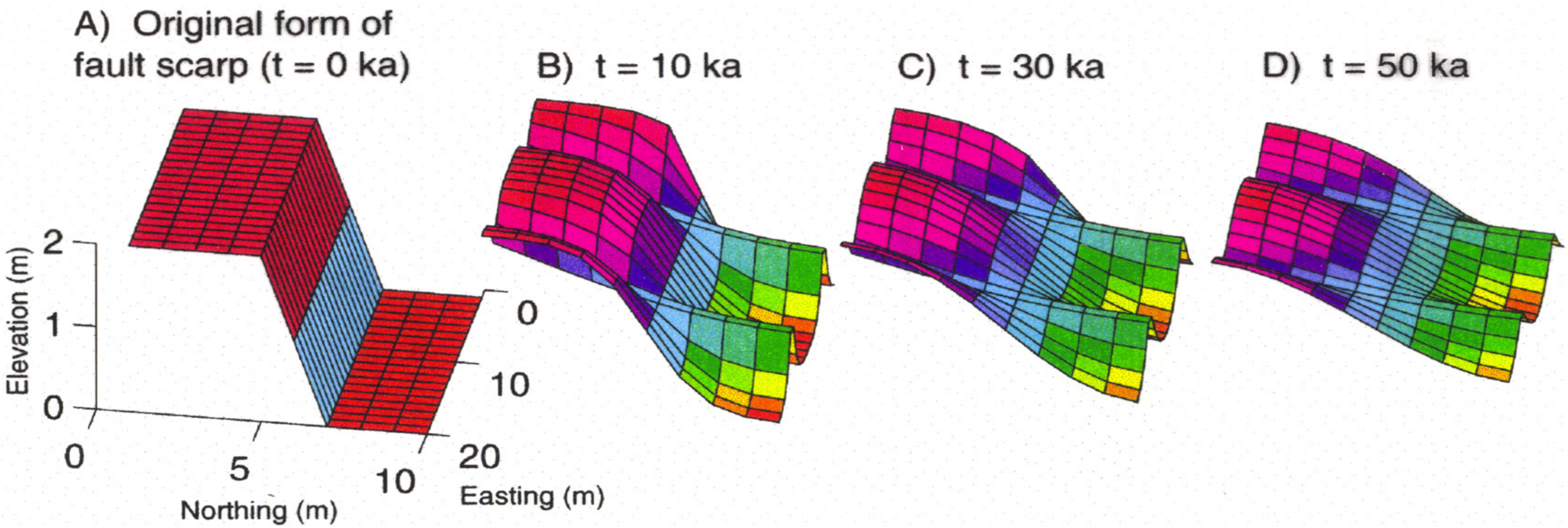


Ba = $8x10^{-4}$ m/kyr





Adding another spatial dimension and more processes



Simulation of the development of landforms resulting from incision into a fault scarp. In this model, two channels are specified in order to transport material across the scarp. The surrounding hillslopes respond to the incision by processes such as creep and rainsplash (diffusive). This model includes the processes of channelization, rainsplash and creep, and the interaction between these processes. Values for the diffusivity of hillslope materials is 10 m^3/ka, the horizontal and vertical unit scales is 10 meters.

-Hilley and Arrowsmith unpublished

Prospects and cautions

- Tectonic geomorphology studies provide important information about the timing and distribution of past earthquakes when used as a part of integrated studies.
- The theoretical basis for these studies continues to develop; however, morphological modeling is useful for better interpreting the processes responsible for observed fault scarps.
- True morphologic dating remains challenging because of the difficulty in calibrating geomorphic transport rate constants.
- When considering the plan-view development of scarps, two dimensional studies may be useful; however, realistic models require the inclusion of fluvial processes whose rates must be calibrated for each site if a meaningful morphologic age is to be calculated.