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Workshop on Fluid Mechanics

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Scaling, turbidite deposition, and the morphology of the continental slope

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These are preliminary lecture notes, intended only for distribution to participants

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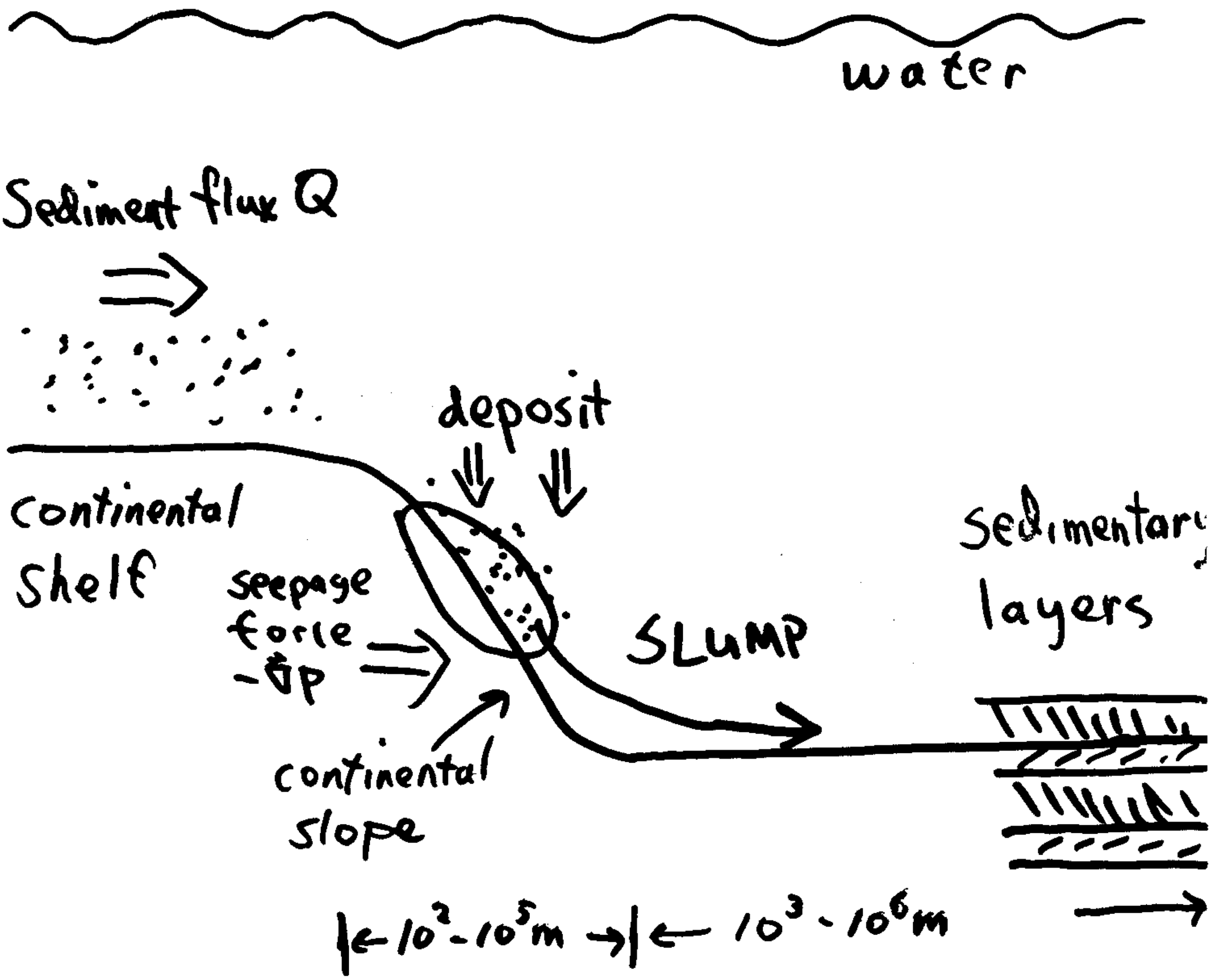
Scaling, turbidite deposition, and the morphology of the contintental slope

D. Rothman MIT
w/ John Grotzinger

and P. Flemings, J. Carlson, O. Mikhailov

Turbidite sedimentation



Duration of slumping "event": 1 minute – 1 day

Time between events: $10^0 - 10^3$ years

Figure 10-35
An artist's representation of the floor of the North Atlantic Ocean based on bathymetric studies of Bruce C. Heezen and Marie Tharp of the Lamont-Doherty Geological Observatory. Depths shown in feet below sea level. [Painted by Heinrich C. Berann; copyright © 1968 National Geographic Society.]

Press a Siever

3

material at the bottom, grading upward to fine

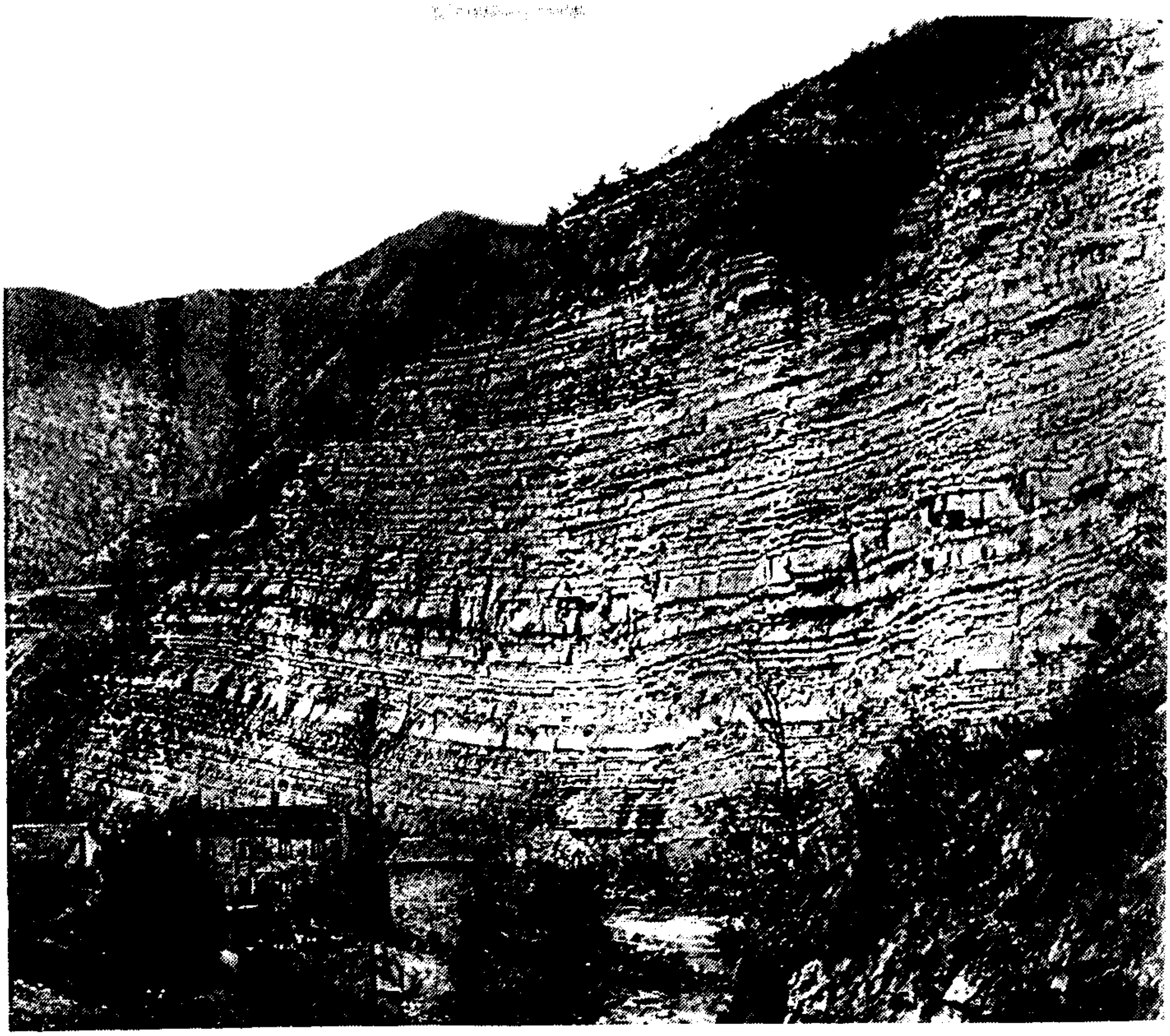


Figure 10-32 Press & Siever

A thick sequence of graded Miocene turbidite beds in the Apennines. The lighter, thicker units are sand stones that are coarsest at an abrupt base and grade upward through finer grain sizes into the darker shale beds. Each pair of sandstone-shale units represents one turbidity flow in a deep marine basin. [Photo by P. E. Potter. From F. J. Pettijohn, P. E. Potter, and R. Siever, *Sand and Sandstone*. Copyright 1972 by Springer-Verlag New York, Inc.]

SE California

"macro" scale

single layer

"meso" scale

"micro" scale

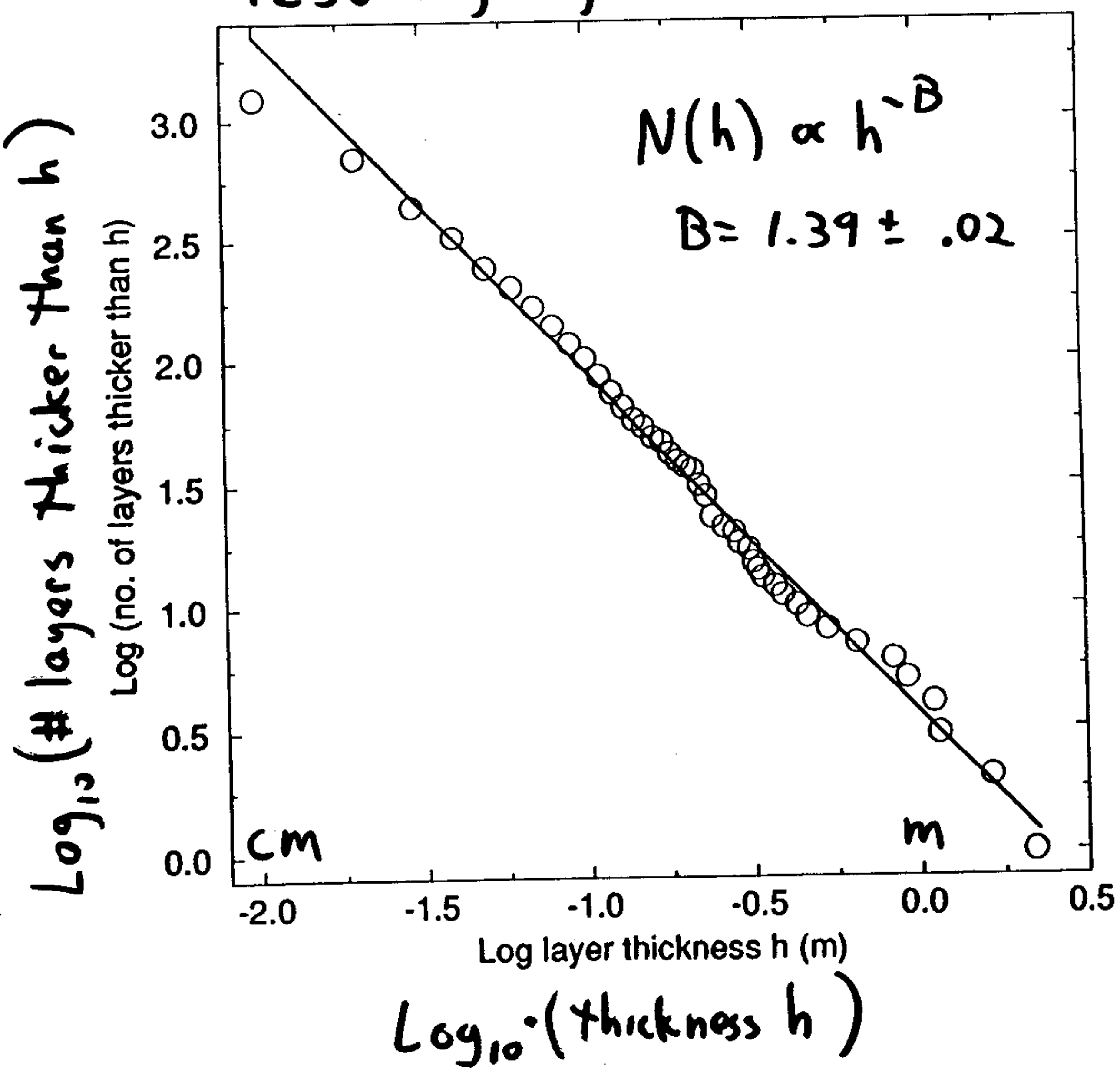
coin

h = layer Thickness

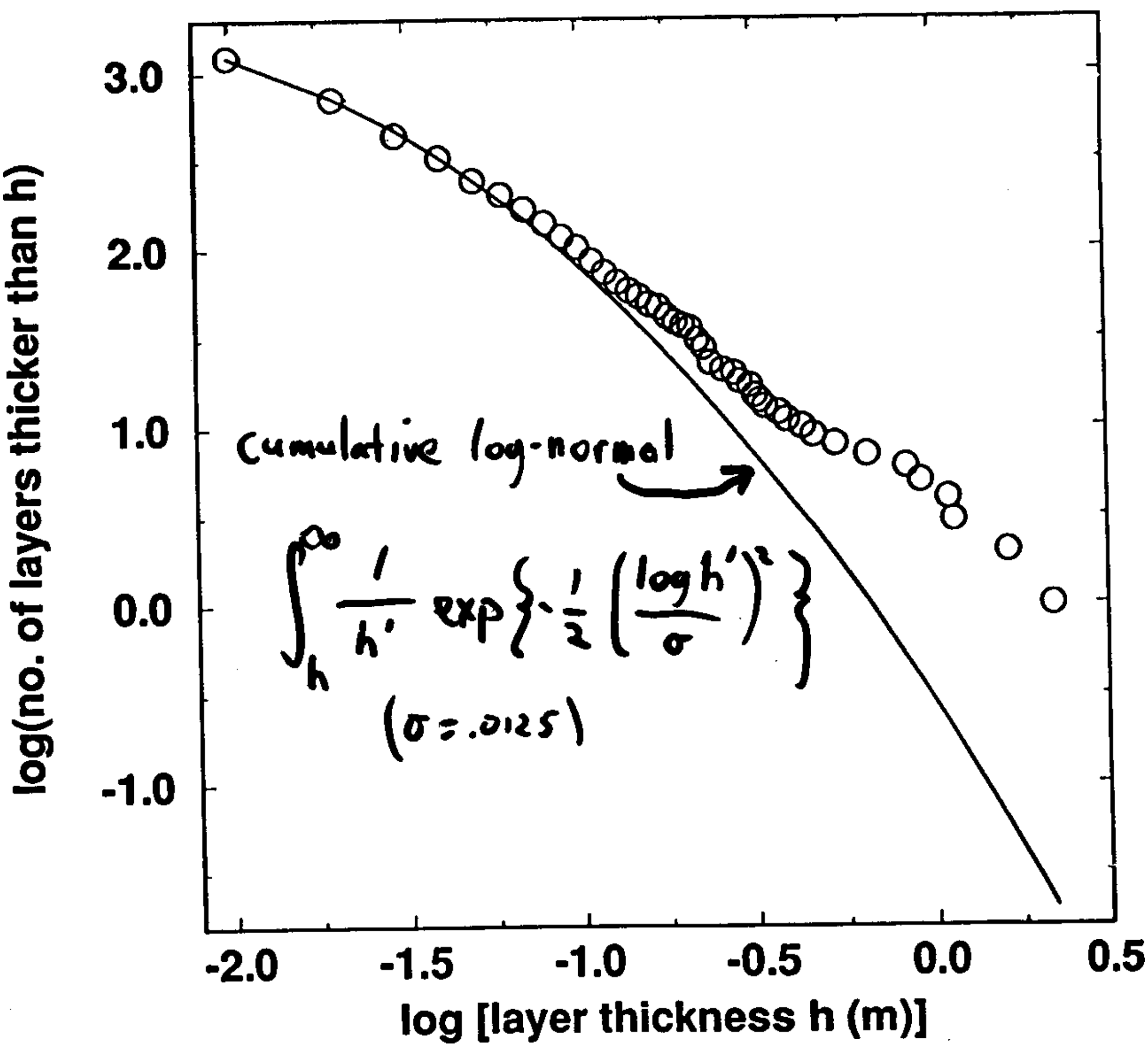
N(h) = # layers Thicker Than h

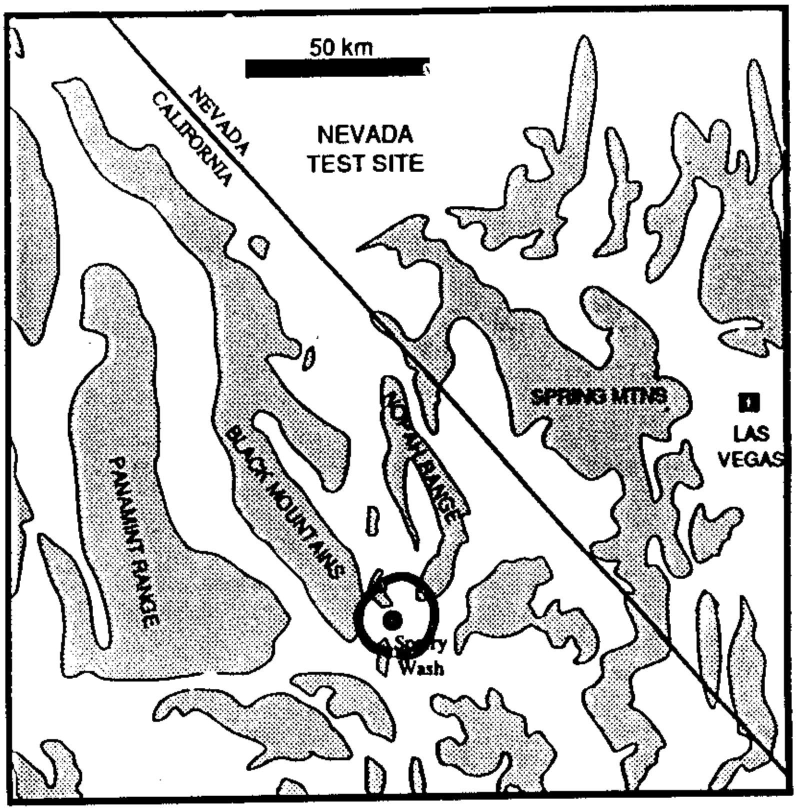
"Direct measurement"

1235 layers, SE California



A log-normal distribution does not fit!

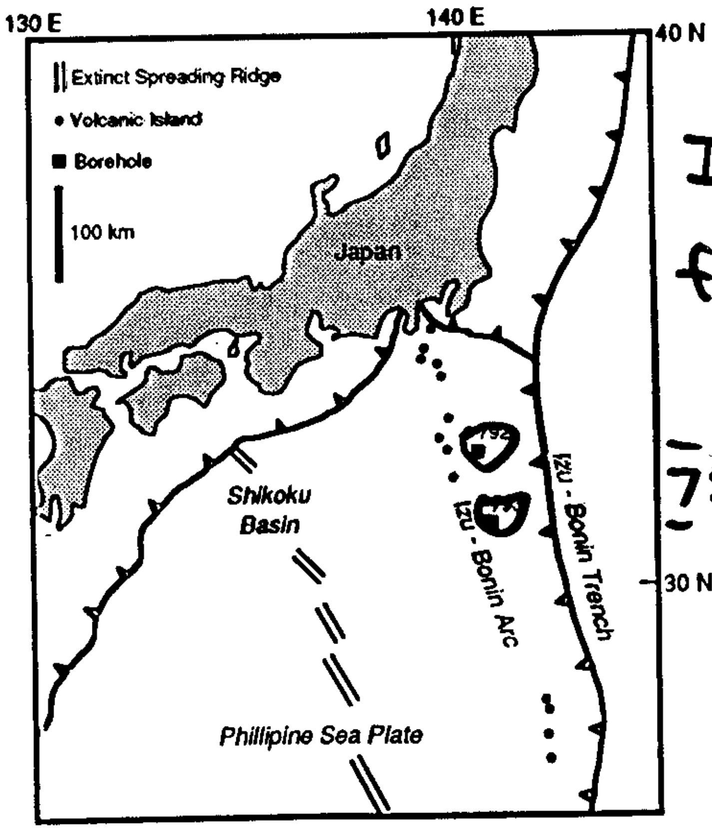




A

SE Calif

~675 Ma



B

Hiscott et al, 1992

Izu-Bonin forearc basin

~75 km

~30 Ma

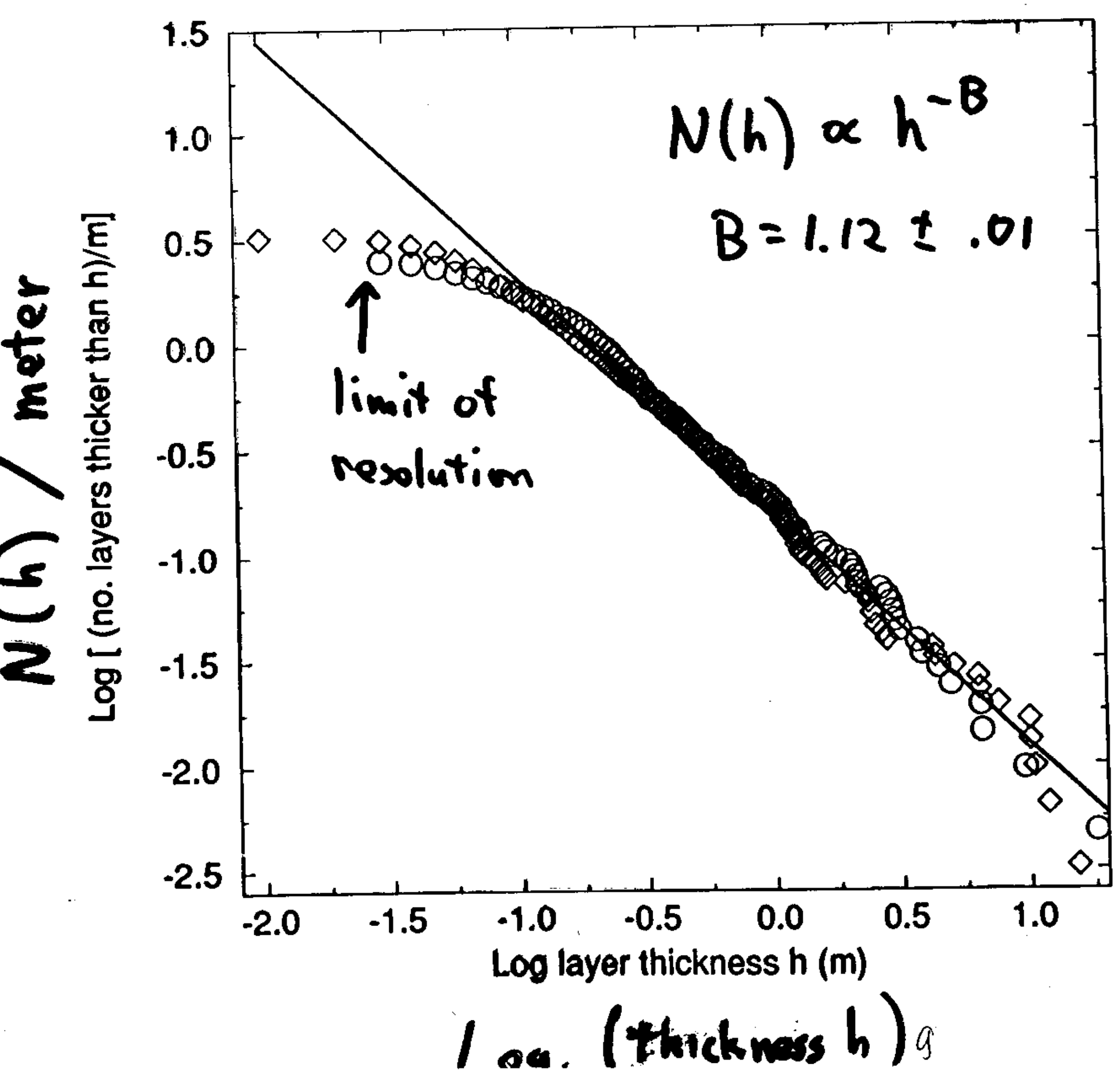
8

Offshore Japan, FMS images

Hiscott, Collela, Pezard, Lovell, + Malinverno, 1992

O : Hole "792" }
◇ : Hole "793" }

~ 75 km apart
Different ages
Different depths

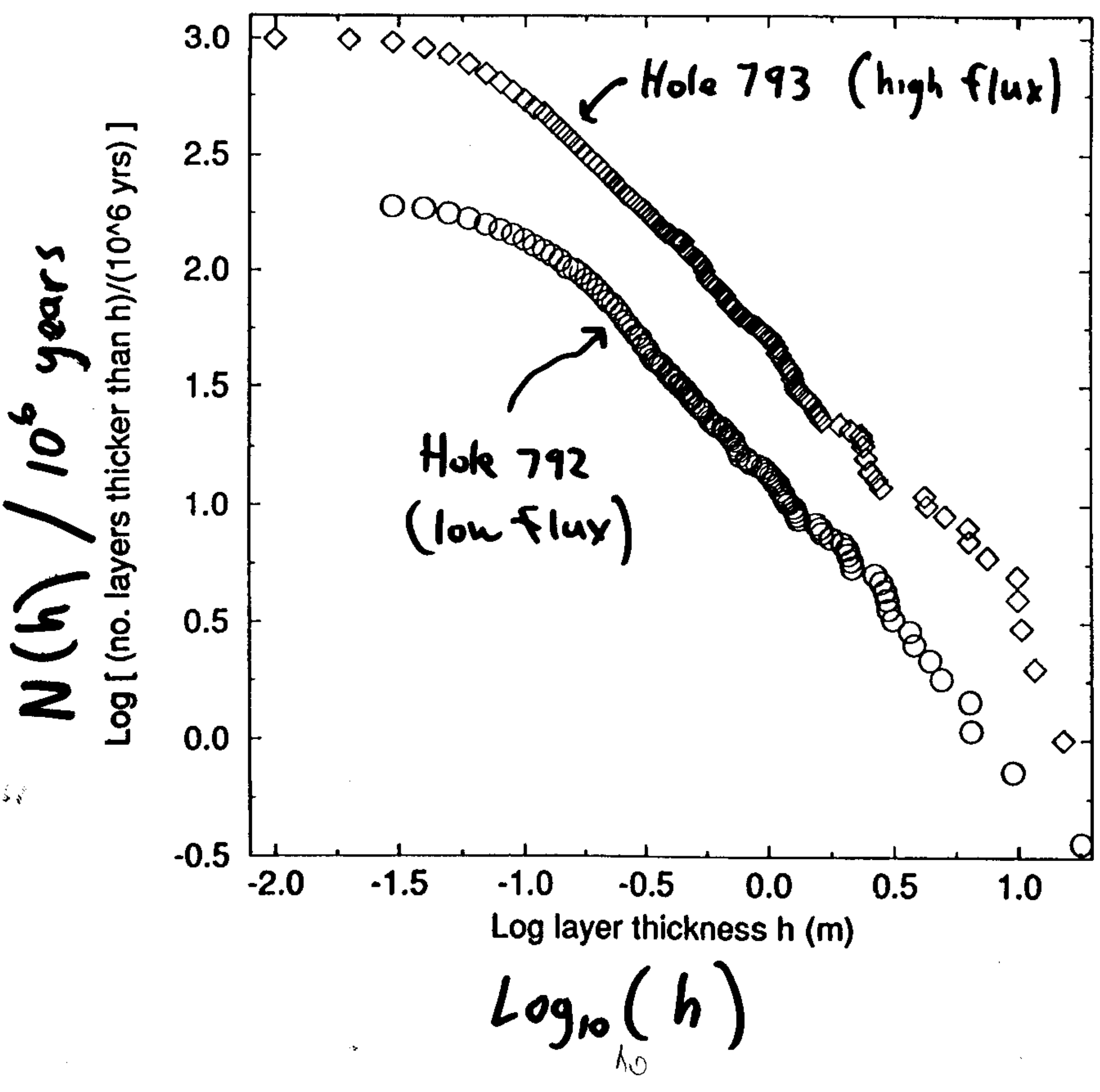


Differential flux: avg. sediment accumulation rate is ~4x greater in Hole 793 than Hole 792.

But: dynamics + system size are ~ same

distance from shelf break ~ same

⟹ Turbidite deposition is slaved to flux, not earthquakes (?)



Implications

1.) Dynamics of turbidite deposition may be scale invariant.
(e.g., <u>nonlinear</u> diffusion)

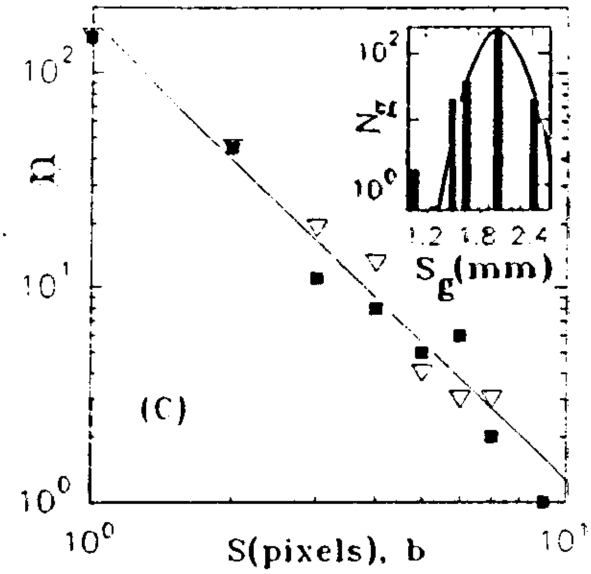
2.) Possible connection with "self-organized criticality" (Bak et al, 1988):
Shelf break may be permanently marginally stable; fluctuations (slump events) occur at all scales.

3.) Unlike many laboratory sandpiles
(Evesque + Rajchenbach, 1988; Jaeger + Nagel, 1989; Held et al, 1990; Bretz et al, 1992; Rosendahl et al, 1993)
turbidite deposition may be an example of a real (underwater) sandpile that does exhibit scale invariance.

Bretz et al, 1992

Flat sandpiles

$N(>s) \sim s^{-1.1}$

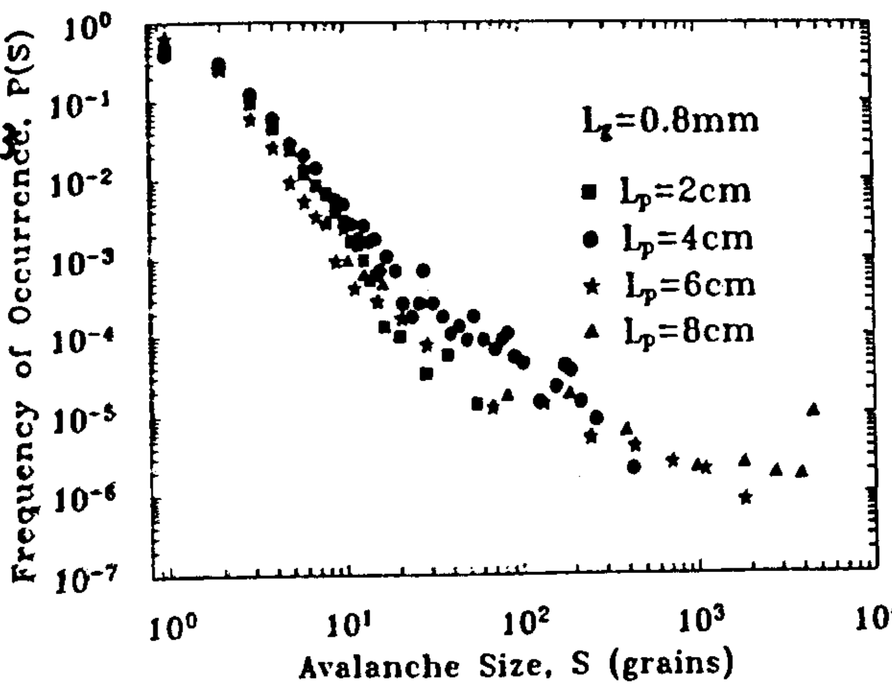


Rosendahl et al, 1993

Conical sandpile

$N(>s) \sim s^{-1.1}$

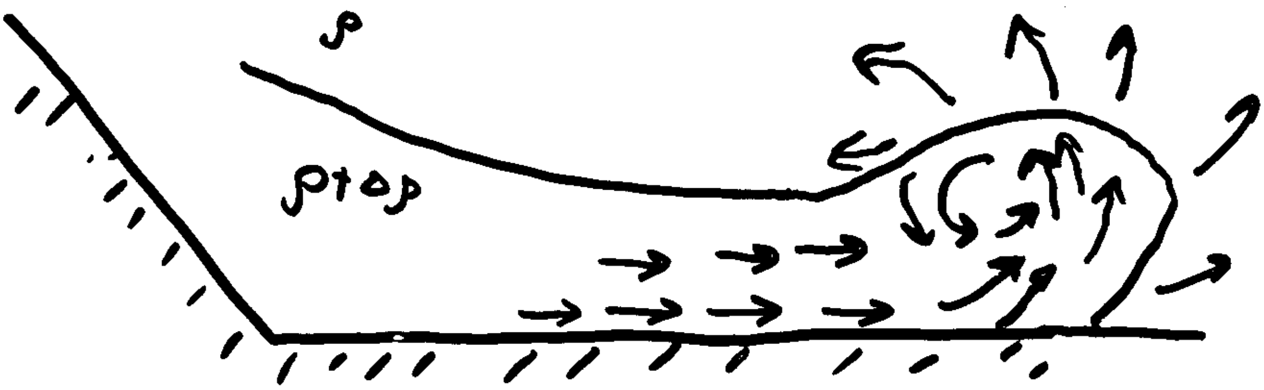
s small



There are, however, large periodic avalanches (relaxation oscillations, i.e., Jaeger et al, 1989)

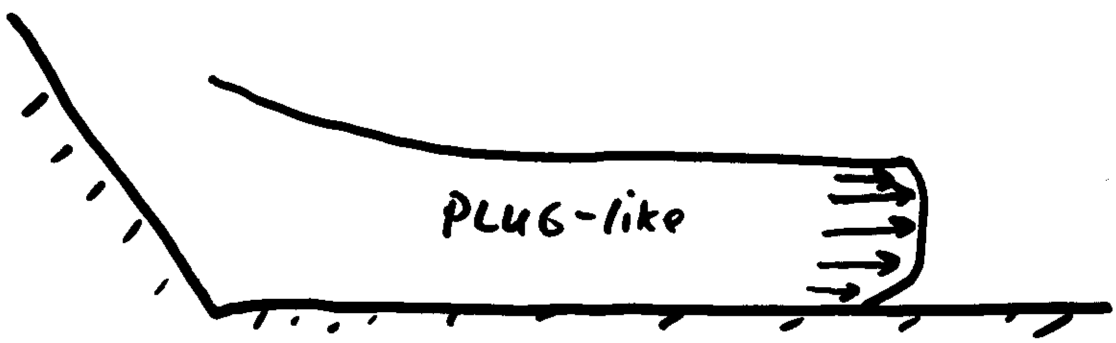
Two types of sediment gravity flows

Turbidity currents



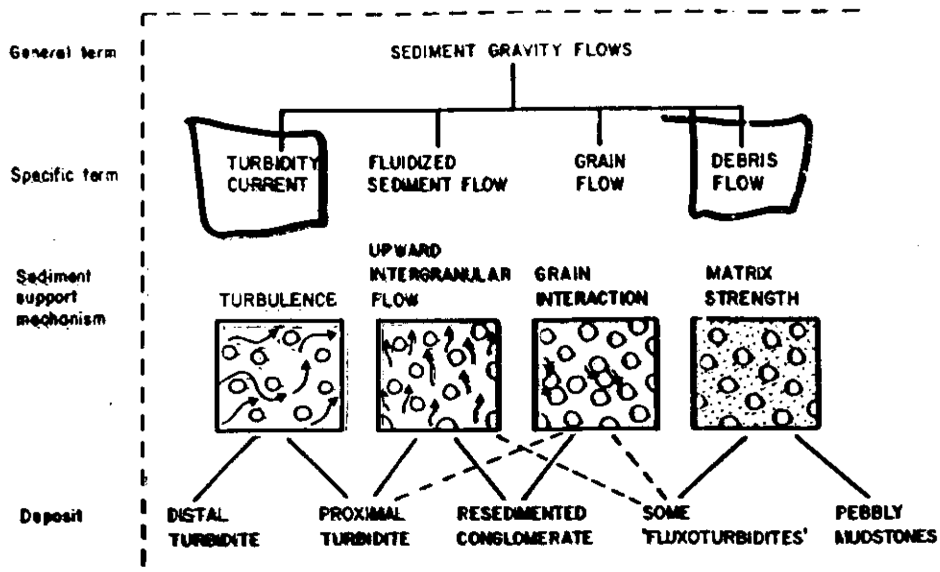
Turbulent vortices at head are sufficiently fast to "lift" or mobilize granular material.

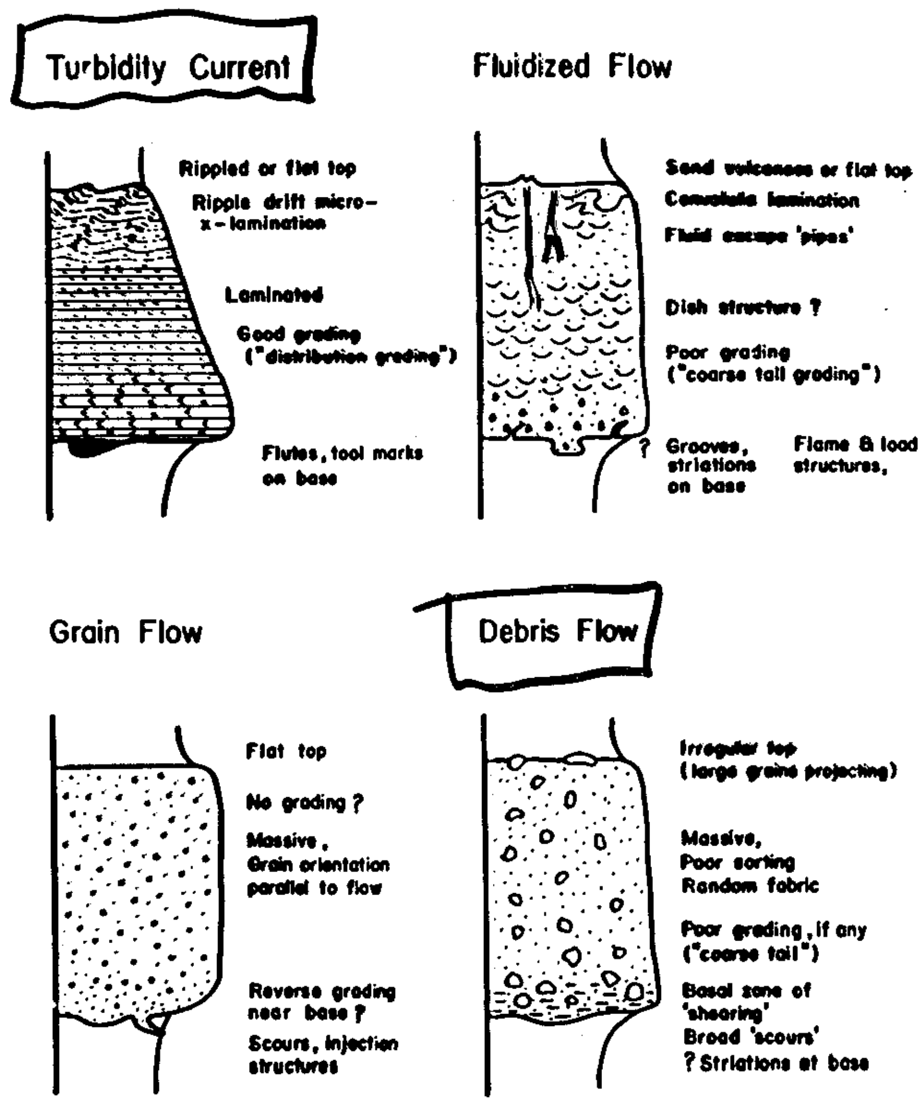
Debris flows



Slow (possibly shear-thinning) flow of dense mud + debris

Mud can be sufficiently dense to almost "float" boulders.

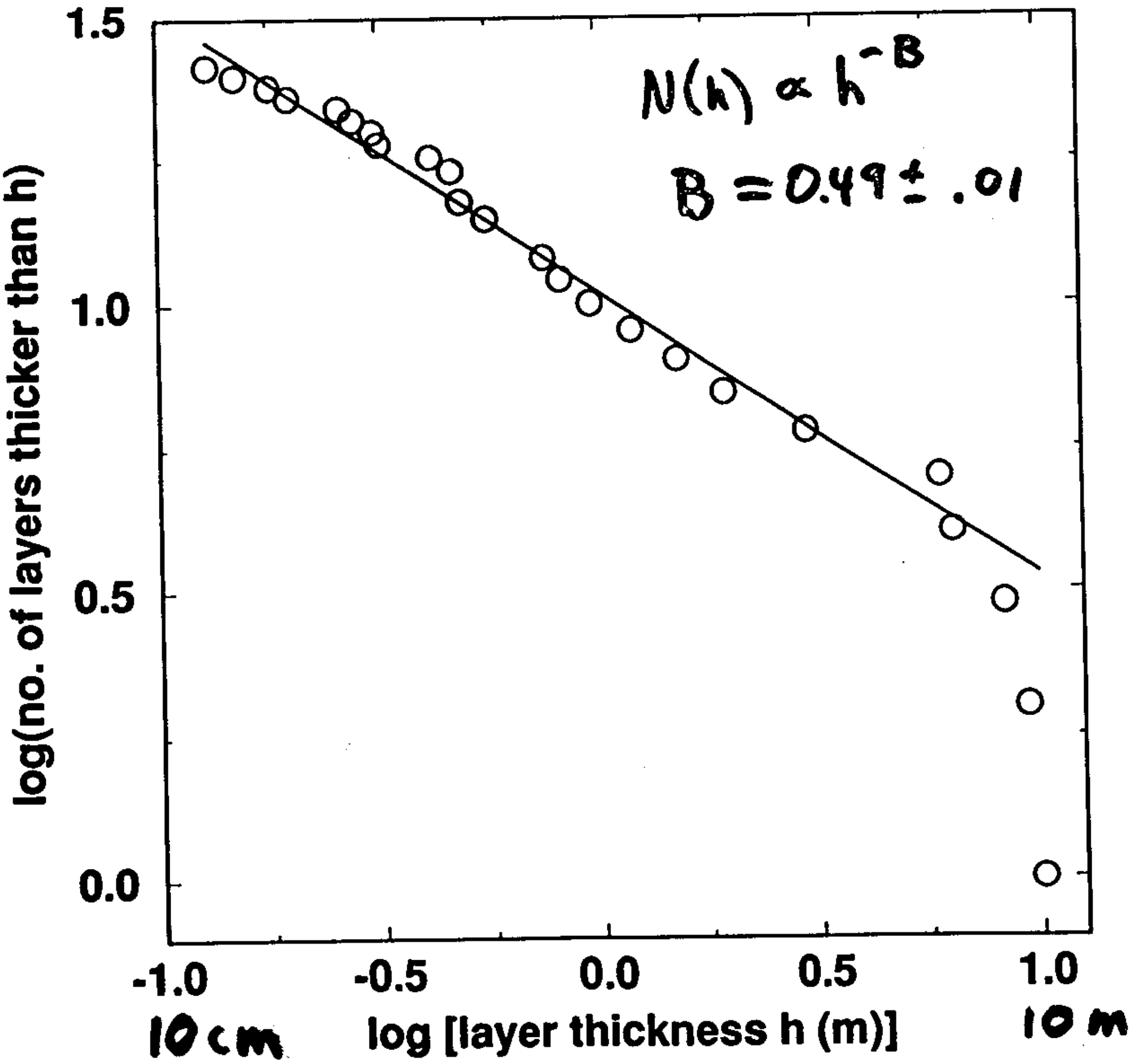




Middleton + Hampton, 1976

In The same sedimentary sequence where $B_{turb} = 1.39$, we find...

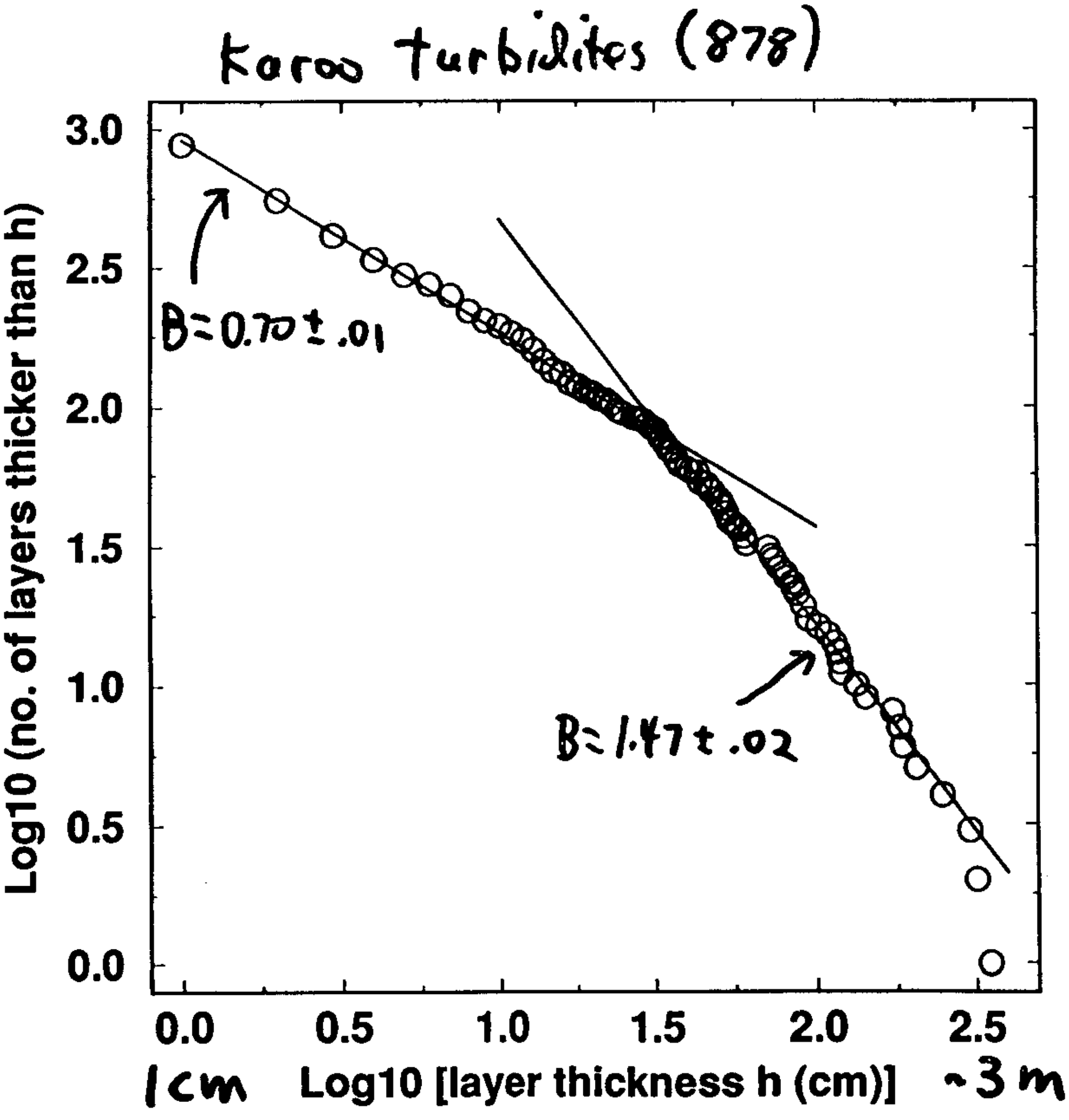
24 Debris flows, SE Calif



878 layers

Cape fold belt (Karoo), South Africa

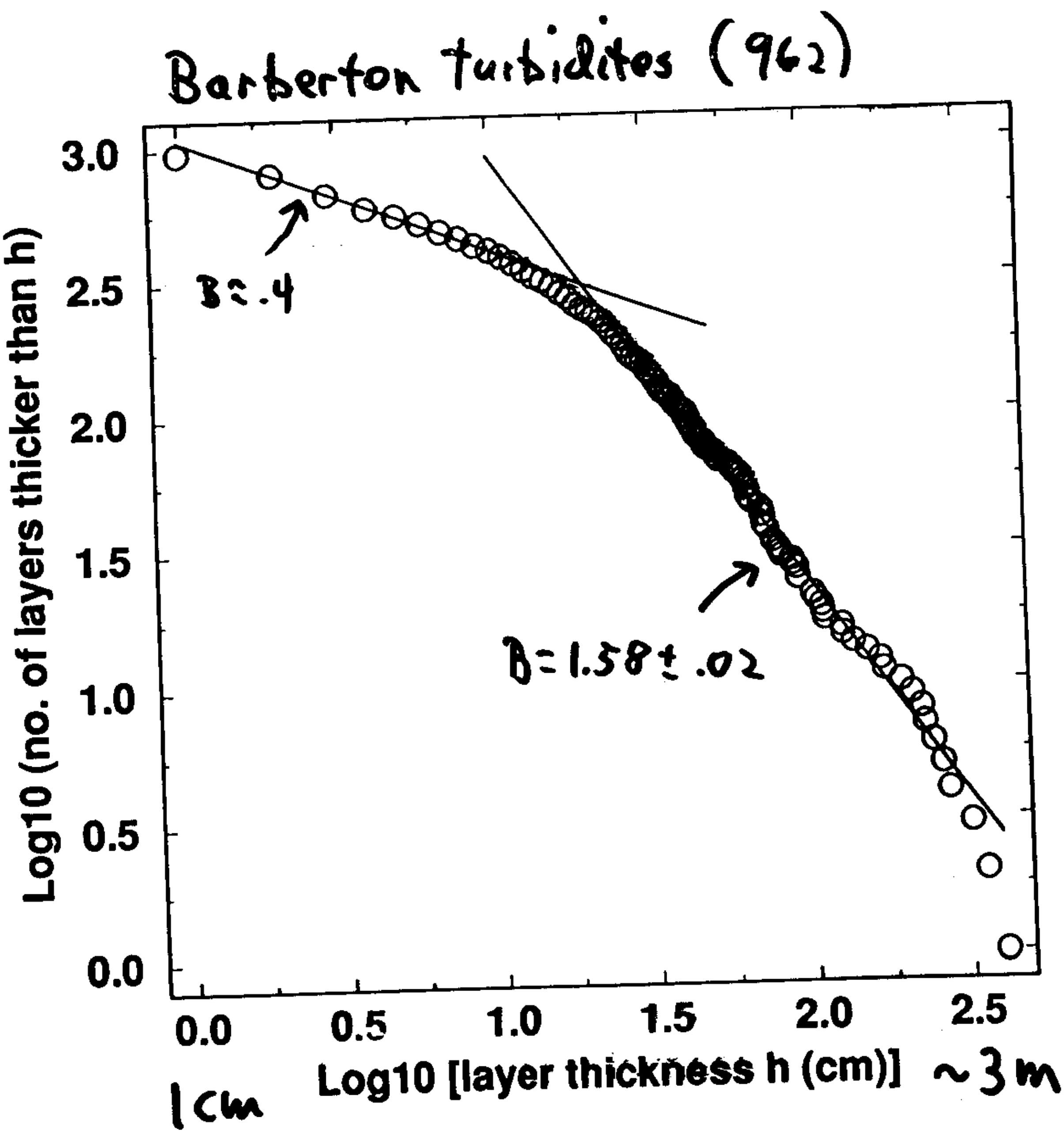
Continental subduction zone, ~ .25 billion years old.



962 layers

Northern South Africa (Barberton)

rift basin, 3.5 billion years old



Some scaling and dimensional analysis

Since $N(h) \propto h^{-B}$

we may define the frequency distribution

$$p_h(h) \propto h^{-B-1}$$

Define

volume of sedimentation event $= V$

deposition area $= S$

$V = Sh$

Assume $h \propto V^{\alpha}$ <u>OR</u> $S \propto V^{1-\alpha}$

$\alpha = 1/3$ => self-similar areal spreading

$\alpha = 2/3$ => self-similar channelized flow

$\alpha = 1$ => NO spreading

The use of the apparent coefficient of friction H/L_T to characterise sturzstrom behaviour has invariably resulted in a great deal of data scatter (see e. g. Fig. 6, after Scheidegger, 1973; Hsü, 1975), as has the use of the potential energy expended in the event (Howard, 1973; Lucchitta, 1978). This is not unexpected when measurements of the physical quantities involved are necessarily rather approximate, but it may also indicate that friction coefficients and energy expenditure may not, at this stage, be appropriate variables for characterising and understanding sturzstroms.

The ingenious "simulation" by Hsü (1975) of the Elm sturzstrom suggests an alternative approach to the mechanics of debris streams. Hsü found that by using a bentonite — clay suspension, which can resist low shear stresses but flows as a fluid at higher shear stresses, he was able to reproduce, to kinematic model scales, the geometry and motion of the Elm event. This suggests that sturzstroms may flow at high shear stresses and become rigid when shear stresses reduce. Hsü (1975) also found that the height of the initial fall of his clay suspension did not affect the motion or extent of the

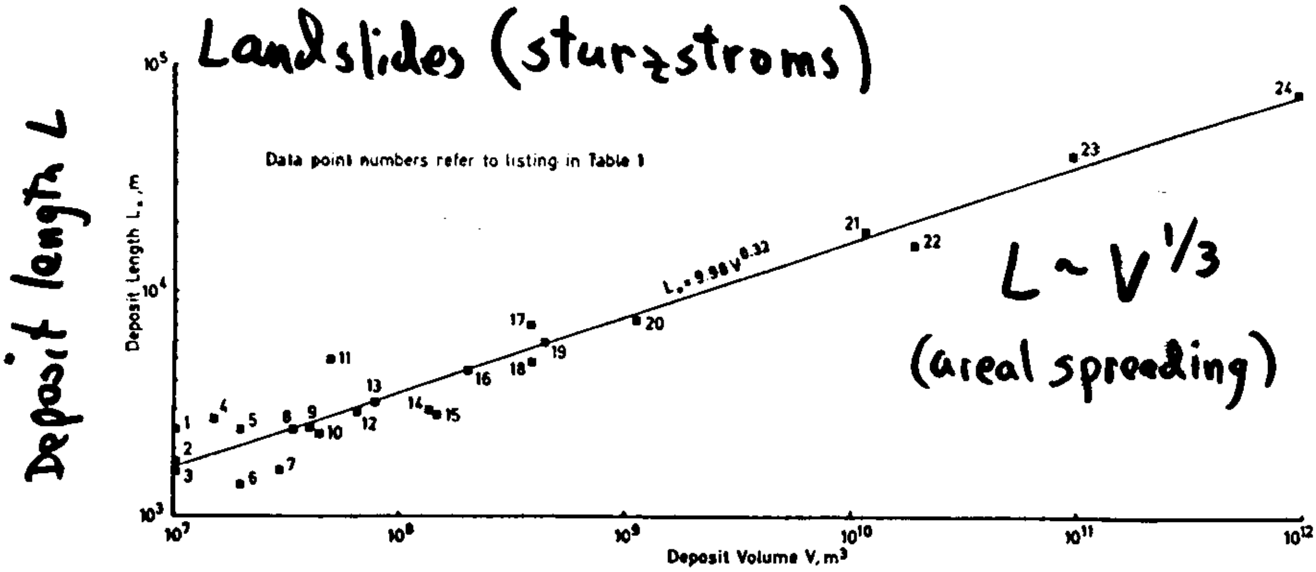


Fig. 1. Deposit length L_* (m) plotted against deposit volume V (m³)

Deposit volume V

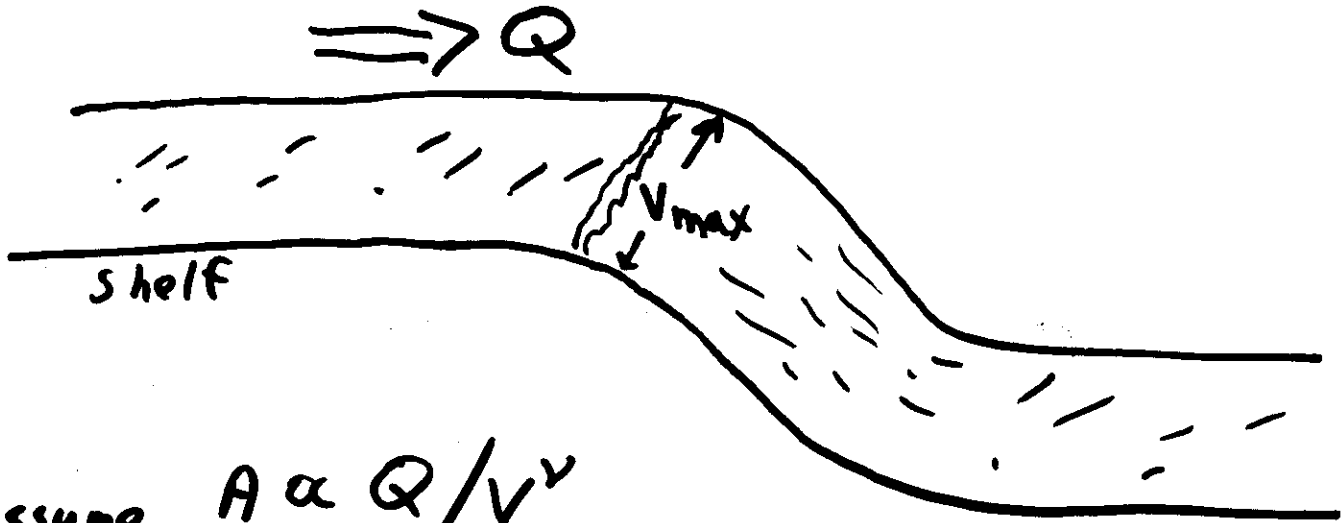
model deposit; this suggests that the areal extent of the deposit was related only to the volume of material involved, provided that the stresses were high enough to fluidise it, and that the height and kinetic energy of the fall did not significantly affect the final deposit characteristics. If this were also true for sturzstroms, then the inclusion of fall height in behaviour plots would merely cause data to scatter, rather than giving any insight into processes;

Davies, 1982

From $h \propto V^{\alpha}$, the volume frequency distribution is

$$\rho_V(V) = A\, V^{-\alpha B - 1}$$

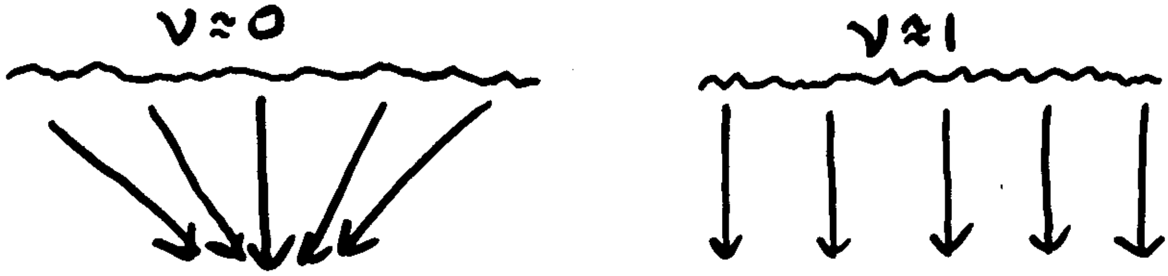
The prefactor A depends on the total volume flux Q to a shelf break of system size V_{max}.



<u>Assume</u> $A \propto Q / V_{max}^{\nu}$

i.e. 1.) (Frequency of events of size V) $\propto Q$

2.) ν specifies geometry of transport downslope



Focused downslope flow (by, say, a canyon)

Parallel downslope flow (ie, no canyon)

The flux Q is related to the event-size distribution by

$$Q = \int_{V_{min}}^{V_{max}} V \rho_V(V)\, dV$$

$$\propto A V_{max}^{1-\alpha B} \quad , \quad V_{min} \to 0, \quad \alpha B < 1$$

$$\propto Q V_{max}^{1-\nu-\alpha B}$$

Thus $1 - \nu - \alpha B = 0$

OR

$$\boxed{B = \frac{1-\nu}{\alpha}} \qquad (\nu > 0)$$

For SE Calif turbidites and debris flows:

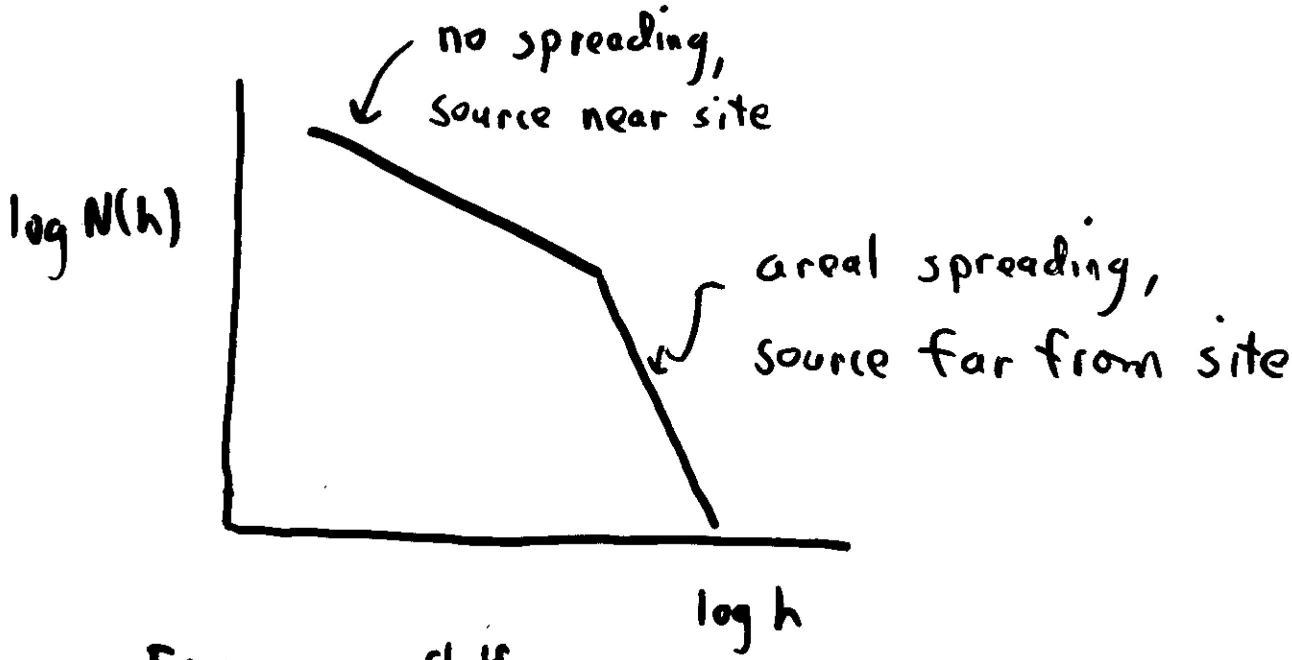
Assume $\nu \approx 1/2$, say. Then

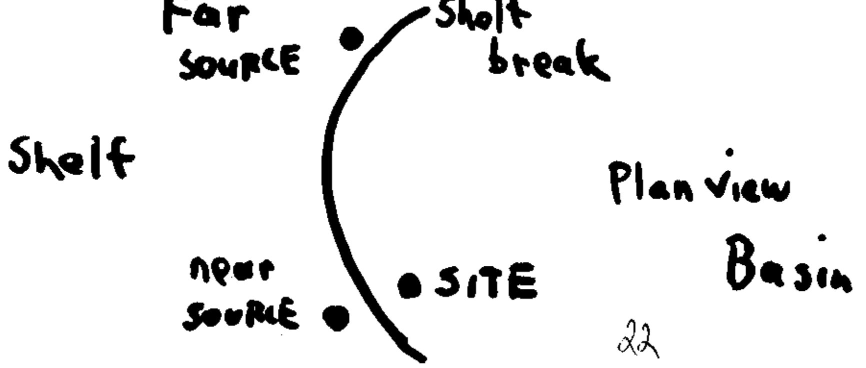
$B_{turb} \approx 1.4 \Rightarrow \alpha_{turb} \approx 1/3 \Rightarrow$ areal spreading

$B_{debris} \approx 1/2 \Rightarrow \alpha_{debris} \approx 1 \Rightarrow$ no spreading

For the crossover turbidites:

One possible interpretation is constant $\nu \approx 1/2$, and





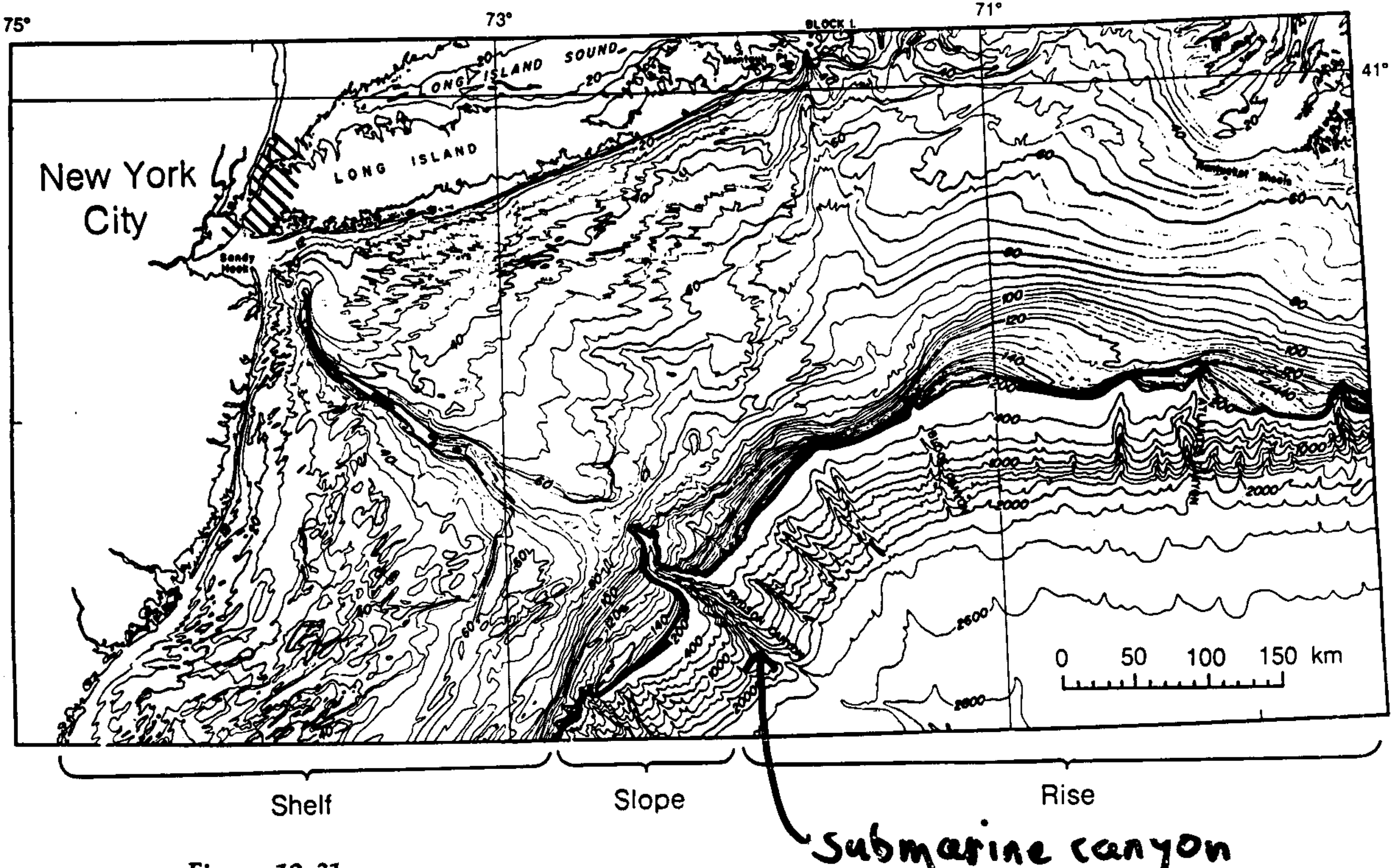


Figure 10-31
Map of continental shelf, slope, rise, and Hudson Canyon off New York City. [From K. O. Emery, Woods Hole Oceanographic Institution.]

Q. Can the power-law distribution of avalanche sizes be related to the morphological features of the continental slope?

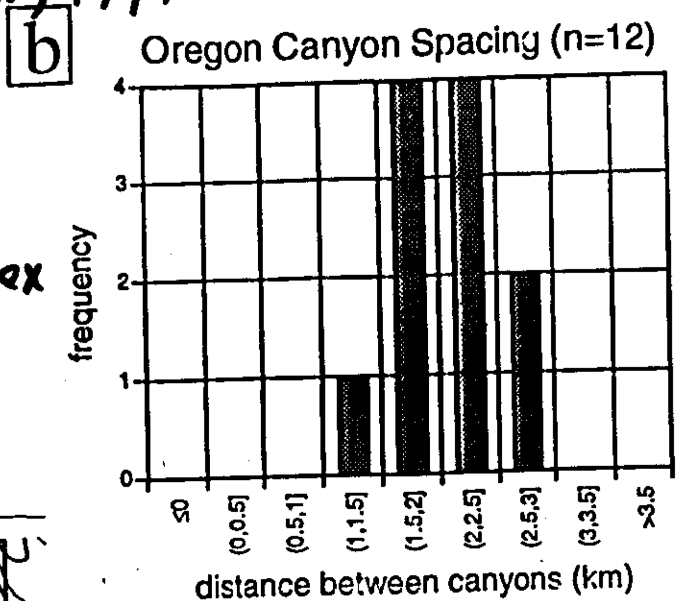
A. Maybe. Some possible approaches:

1. Ask if the topography is fractally rough.
If so, perhaps the power law in avalanches is related to topographic "roughness".

2. Do "drainage" features on the slope satisfy power-law scaling?

3. Quantify force(s) that cause slope failure.
Do those imply power-law avalanches?

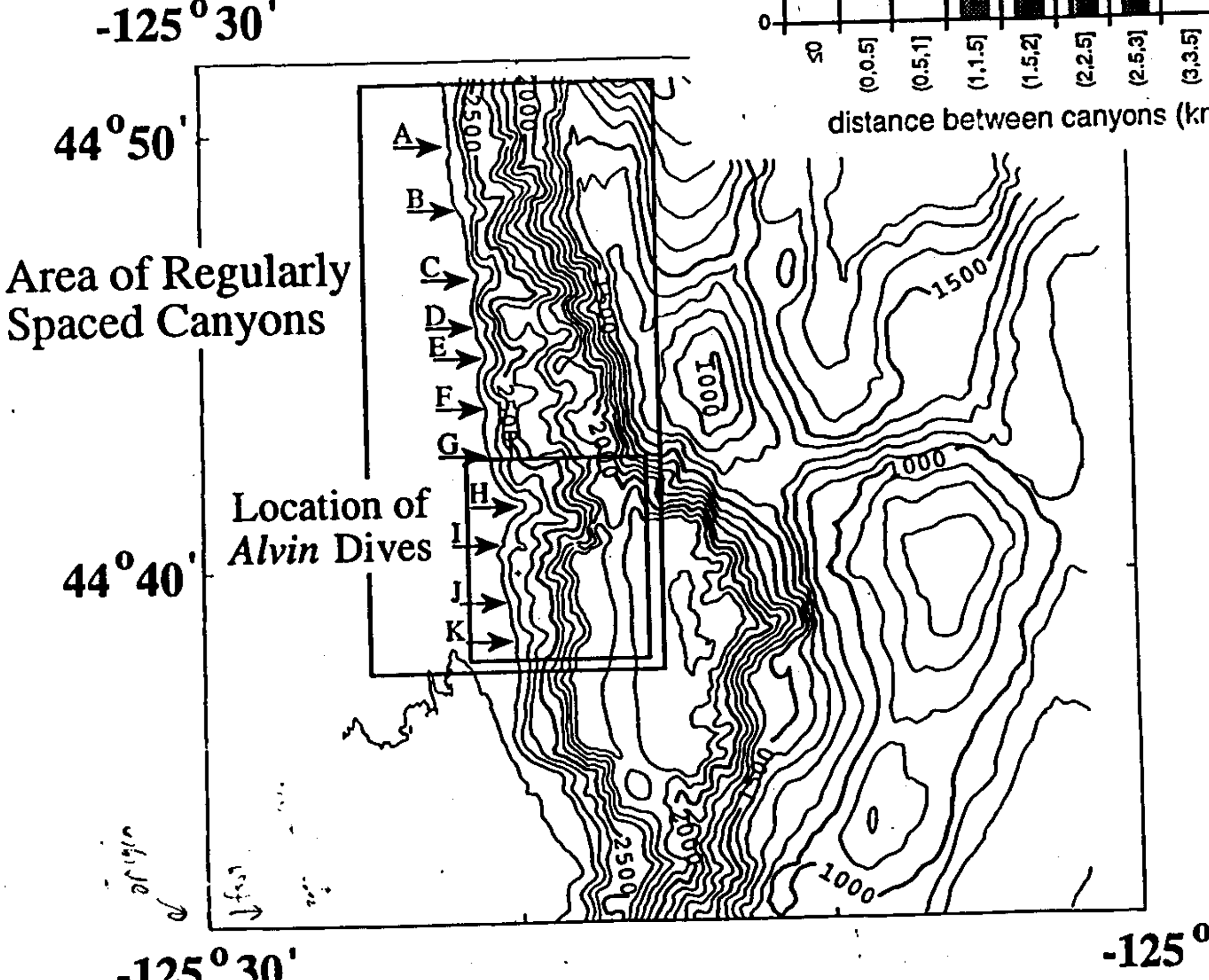
Orange, Anderson, & Breen, 1994



Offshore Oregon

Cascadia accretionary complex

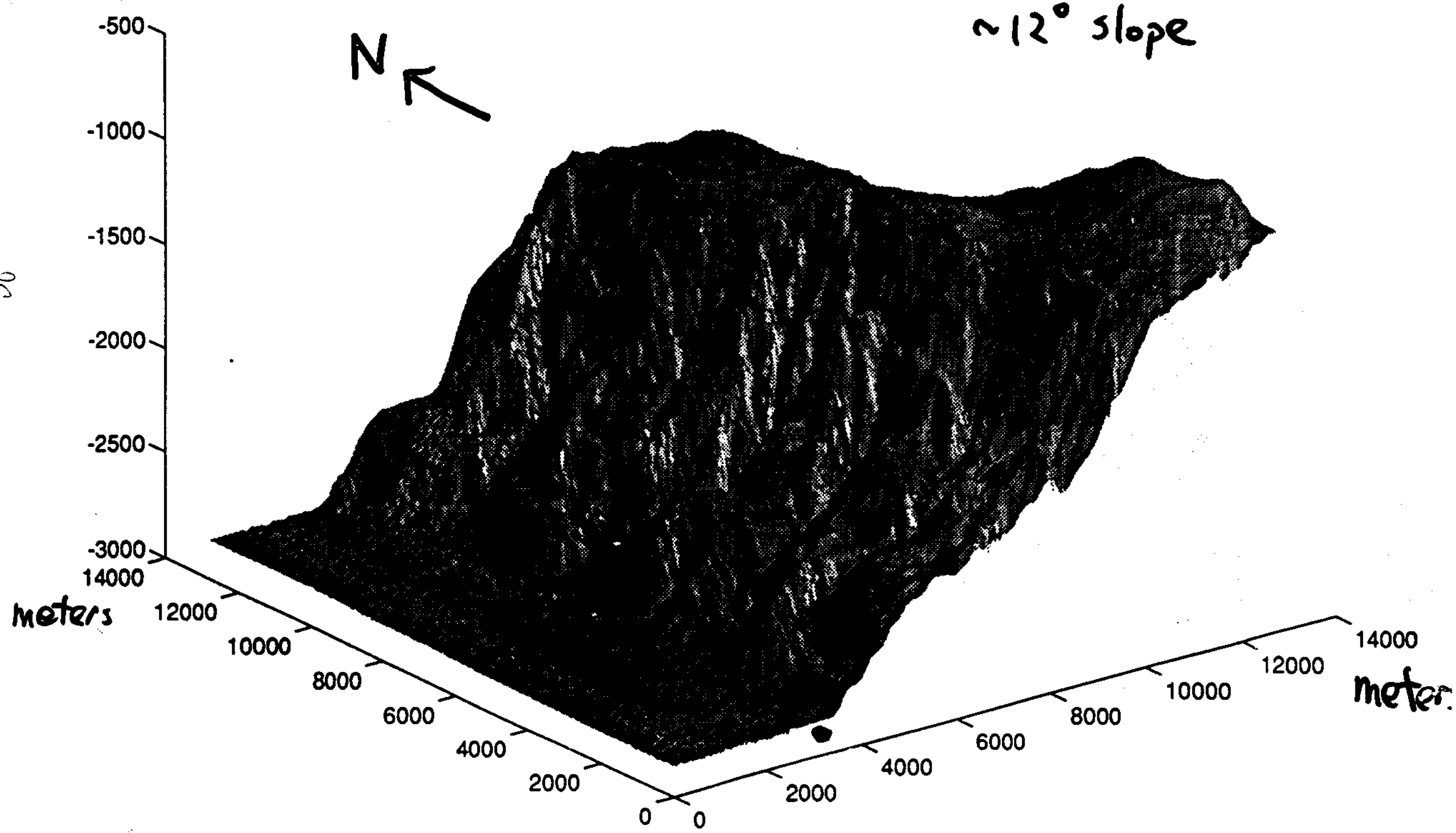
a "Headless" canyons



A scale would be helpful.

10 min lat = 10 nmi!

Orange Fig 10, b.

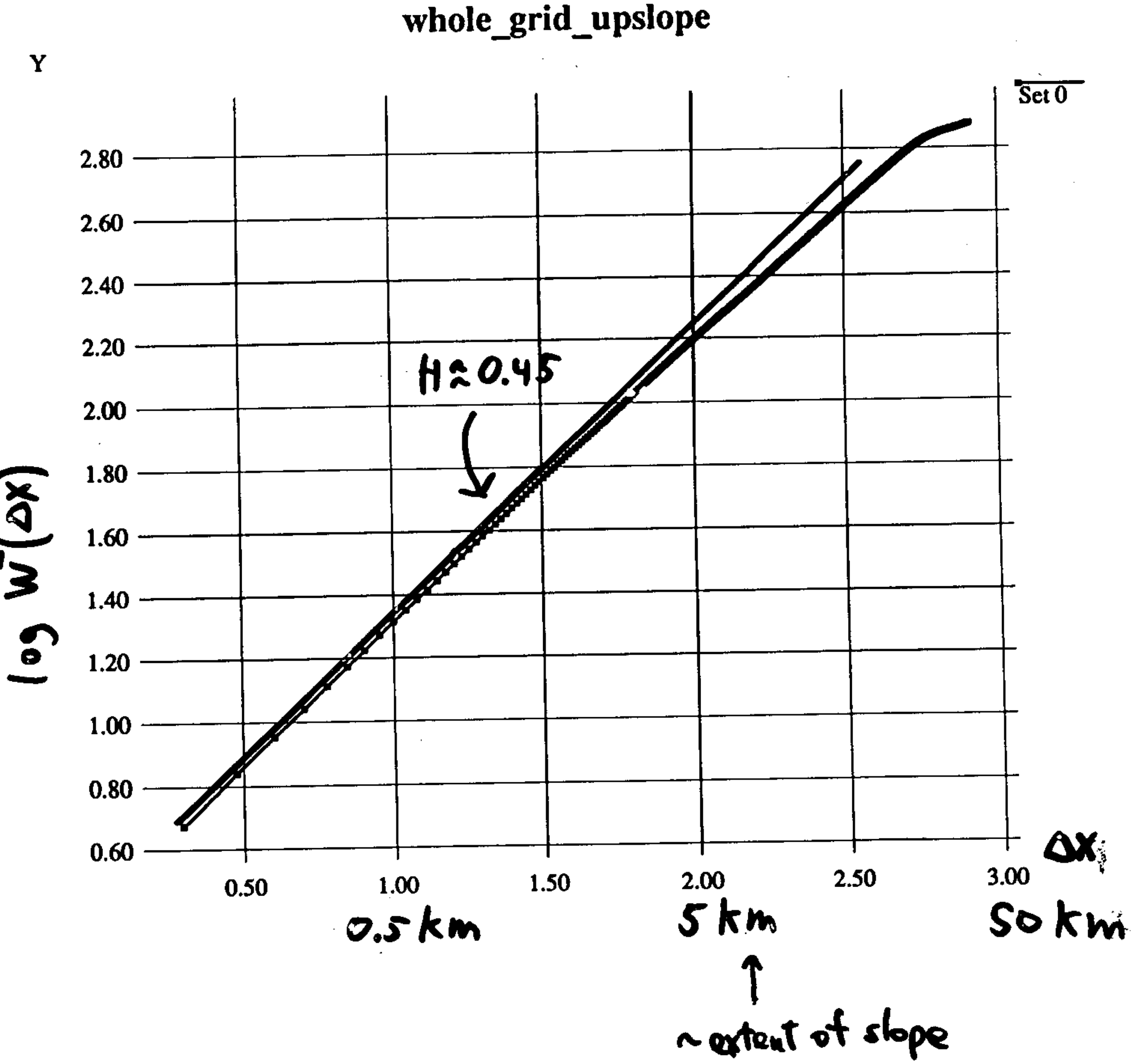

~12° slope
N
-500
-1000
-1500
-2000
-2500
-3000
14000
12000
10000
8000
6000
4000
2000
0
meters
0
2000
4000
6000
8000
10000
12000
14000
meter

26

Average upslope width as function of length

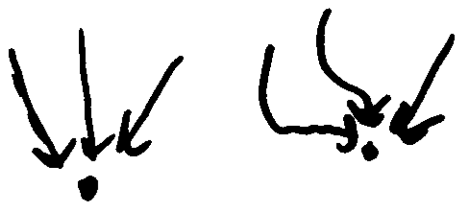
$$W(\Delta x) = \left\langle \left(\langle z^2 \rangle - \langle z \rangle^2 \right)^{1/2} \right\rangle_{[x, x+\Delta x]}$$

$$\sim (\Delta x)^H$$



"Drainage" features of the slope (à la Bros et al)

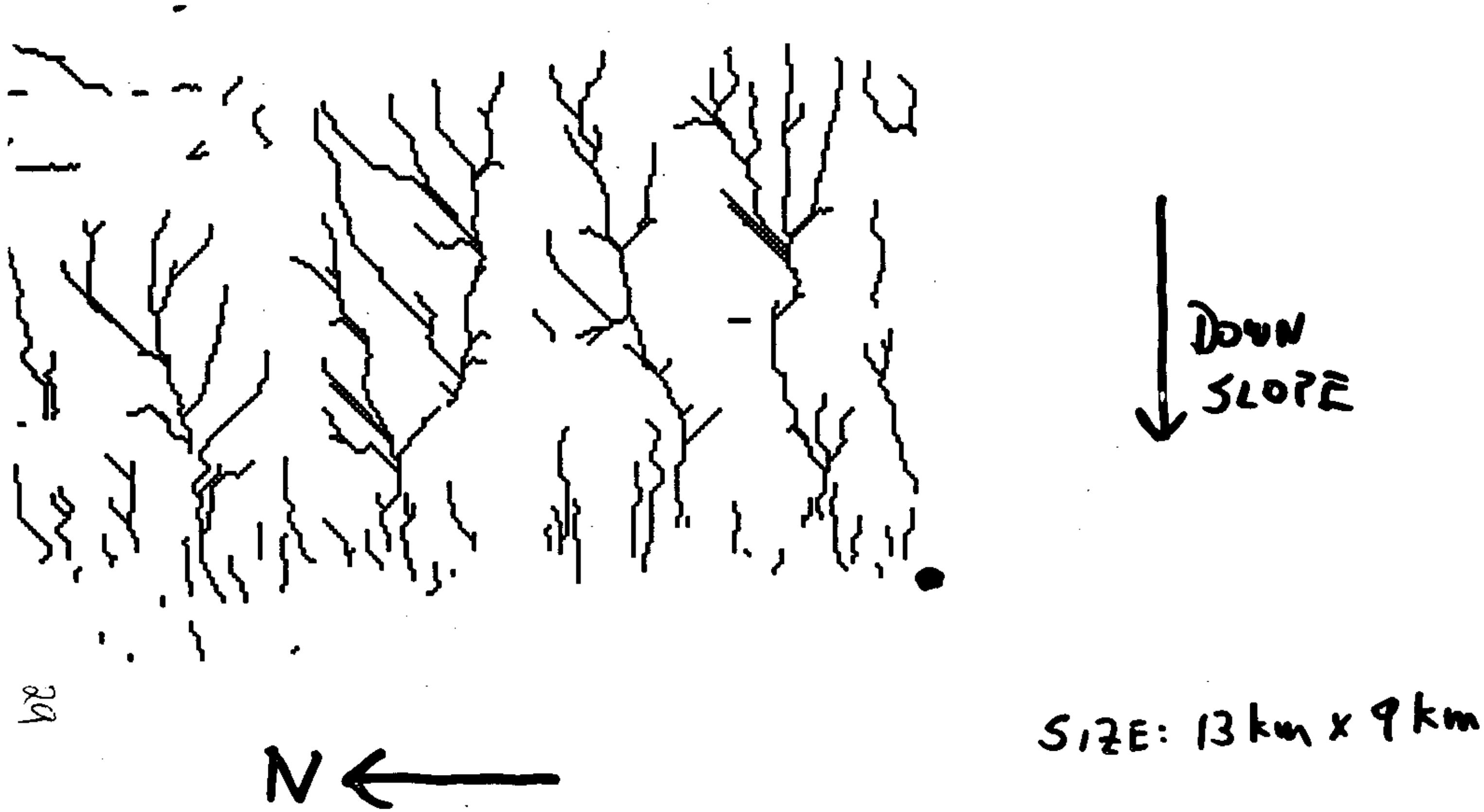
Imagine that each "pixel" of the bathymetric map collects any sand that would fall into it if the slope above were unstable.



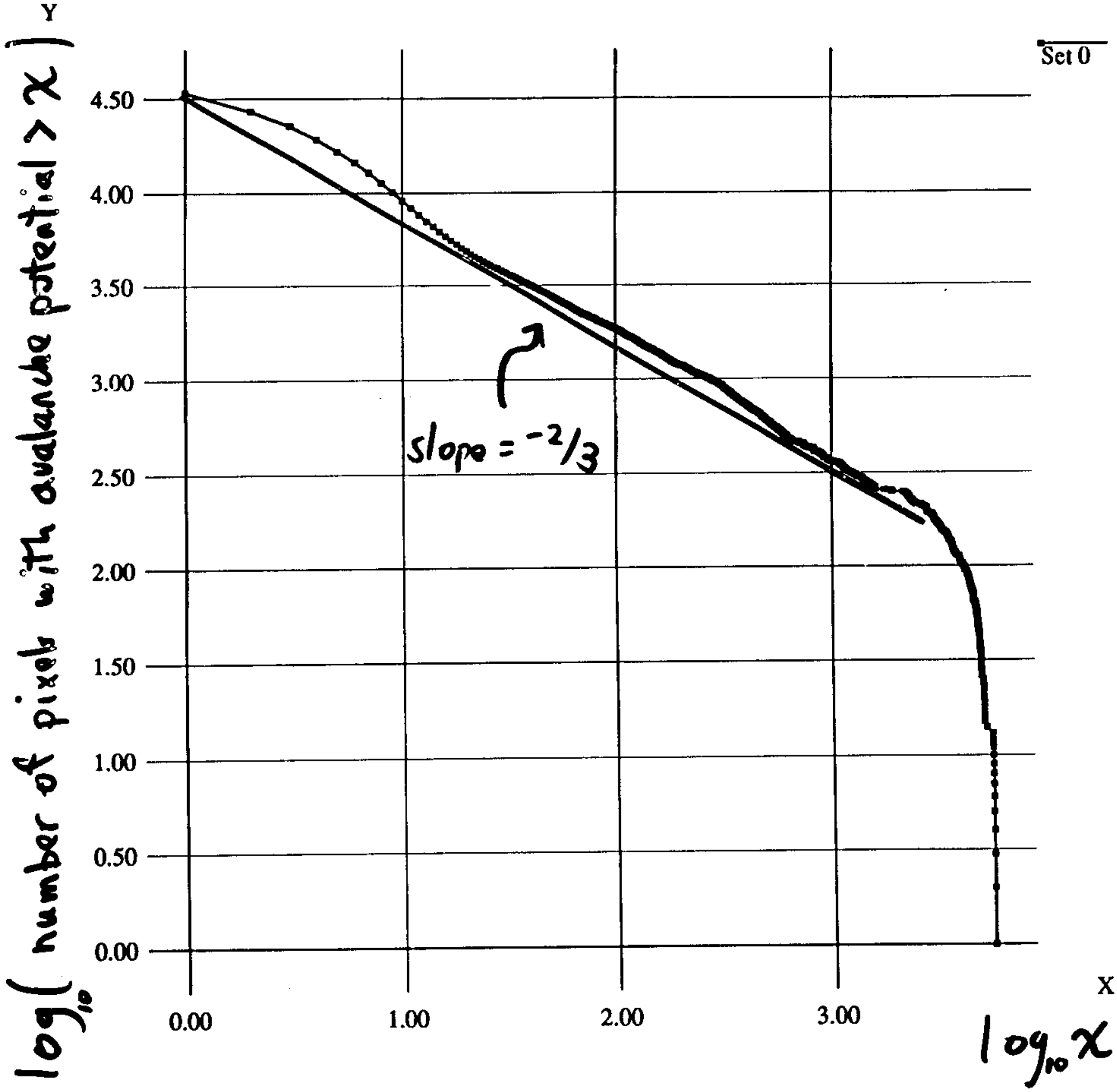
Each pixel may then be assigned a drainage area, or "avalanche potential."

A map showing only those pixels with the greatest avalanche potentials forms a dendritic network.

And the avalanche potentials satisfy a power-law distribution.


DOWN
SLOPE
SIZE: 13km x 9km
N

Cumulative distribution
of avalanche potentials

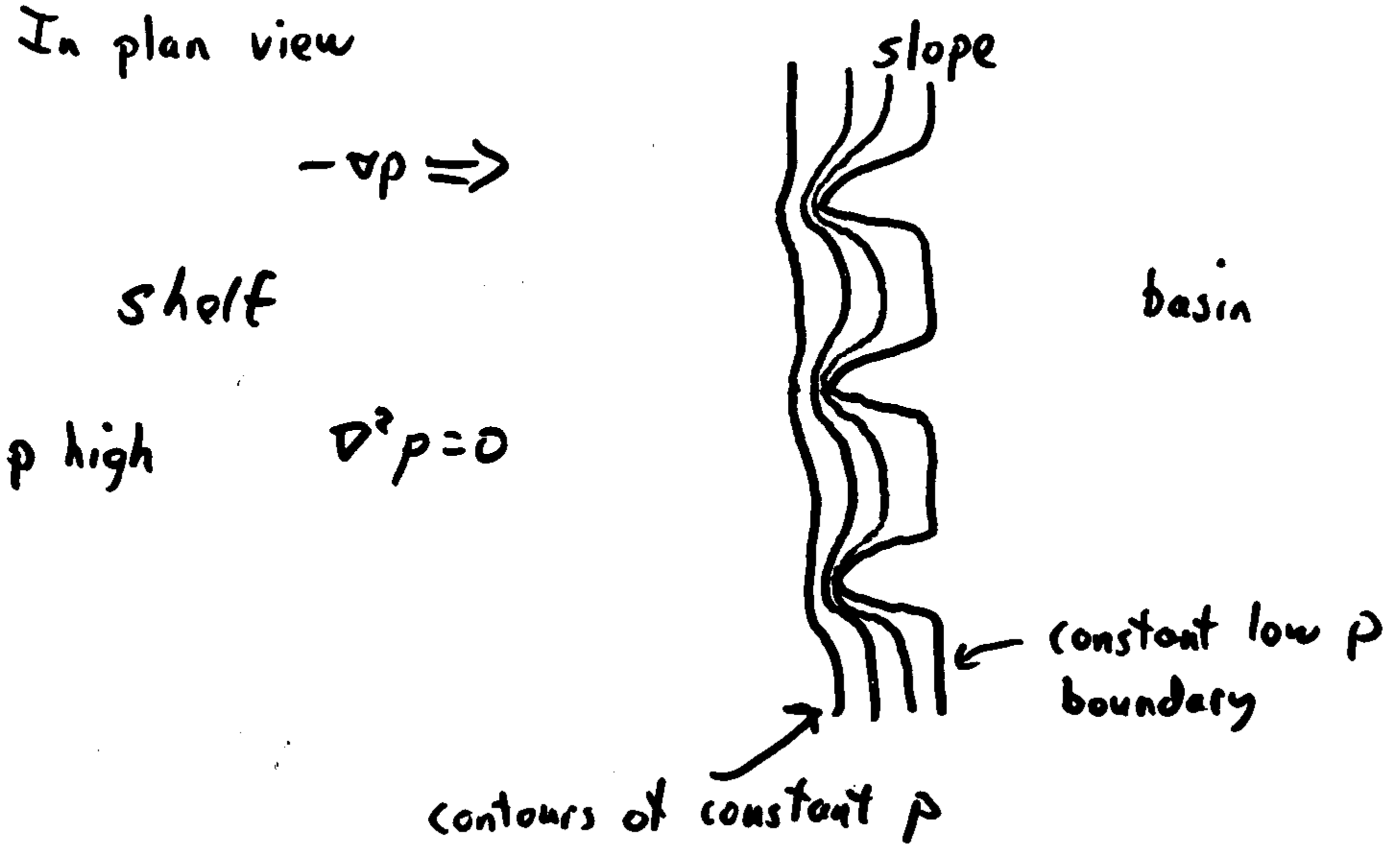


A dynamical model

Assume that the primary destabilizing force is the seepage force $-\vec{\nabla} p$.

i.e., when $|\hat{\nabla} p| > |\vec{\nabla} p|_c$, The slope fails.

In plan view



- Solve $\nabla^2 p = 0$ in bulk
- Evaluate $\vec{\nabla} p \big|_{\text{boundary}}$
- What is The distribution of $\vec{\nabla} p \big|_{\text{boundary}}$

Conclusions

1. There are lots of power-law turbidite deposits.

2. We have the beginnings of some testable scaling laws. (by 3-D seismic imaging)

3. The shelf-slope-turbidite system provides nice opportunities to

   - relate dynamics to geometry

   - better understand slowly forced, rapidly relaxing systems