Last Time...
Stress in the Earth's Crust

** Stress in the Earth's crust seems to indicate that ridge-push forces may dominate stress regime in brittle crust. However, local tectonic conditions may alter this general trend.*

** Weak faults may alter the state of stress around them. The maximum principal compressive stress around these low-friction faults rotates to resolve a shear traction along the fault that is equal to the shear strength of the fault.*

In Today's Class...

Erosion and Uplift Rates

I. Denudation Rates:
- *Definition of erosion rates.*
- *Determining erosion rates.*

II. Uplift Rates:
- *Determining uplift rates.*
- *Removing signal from isostatic response.*
- *Inferring surface uplift.*

Erosion Rates

- Definitions of uplift rates

- Determining erosion rates:
  1) Fluvial sediment flux measurements.
  2) Sediment and structural constraints.
  3) Topography.
  4) Isotopic sediment composition.
  5) Regolith production rates.
  6) Bedrock incision rates.
  7) Landsliding denudation rates
  8) CRN basin-wide denudation rate estimates.
  9) Geochronologic methods.
  10) Tectonic denudation.

Definitions of Uplift

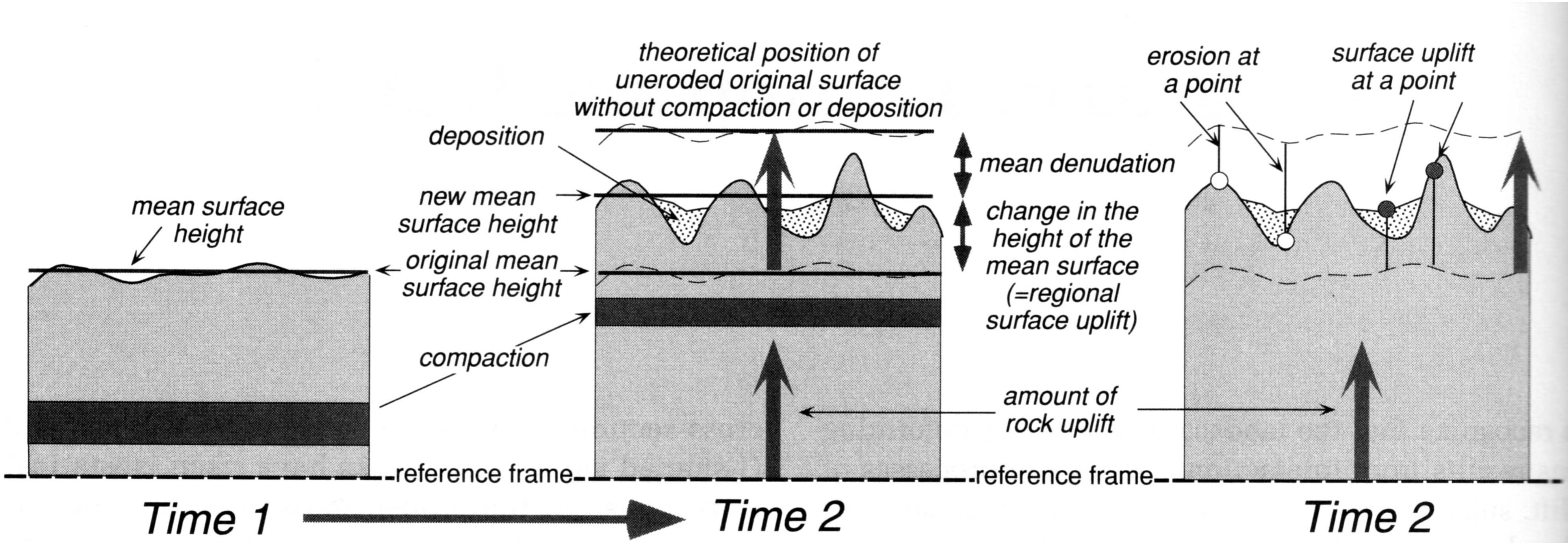


figure take from Burbank and Anderson (2001)

*** Surface uplift is change in surface (referenced to geoid).**

*** Rock uplift is change in the position of a rock (referenced to geoid).**

*** Erosion is change amount of material taken away from top (referenced to geoid; sign is negative for erosion, positive for deposition).**

*** Compaction results in density difference, results in negative movement of surface (referenced to geoid).**

Total Uplift = Rock Uplift + Erosion/Deposition + Compaction

Denudation Rates, Relief, and Elevation

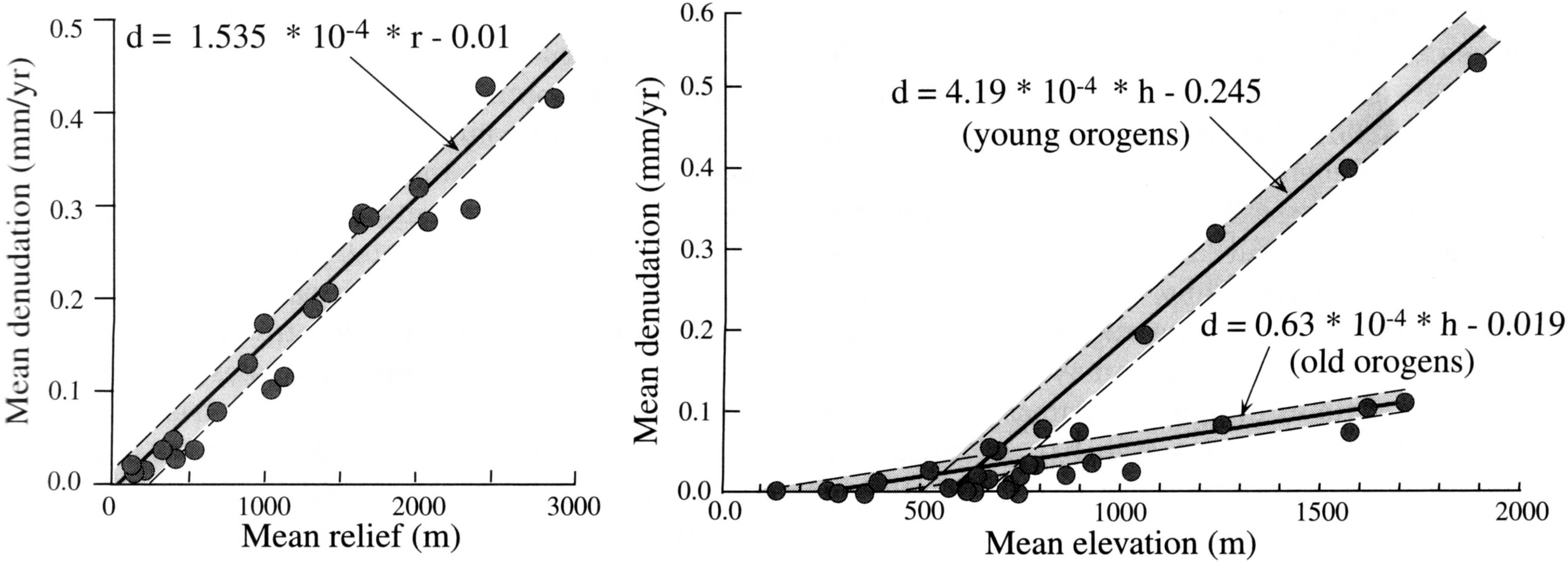


figure taken from Burbank and Anderson (2001) after Ahnert (1970) and Pinet and Souriou (198

- Denudation rates apparently correlate strongly with both basin relief and elevation.

*** Similar elevations produce different denudation rates, depending on age of orogen.**

How does one calculate denudation rates?

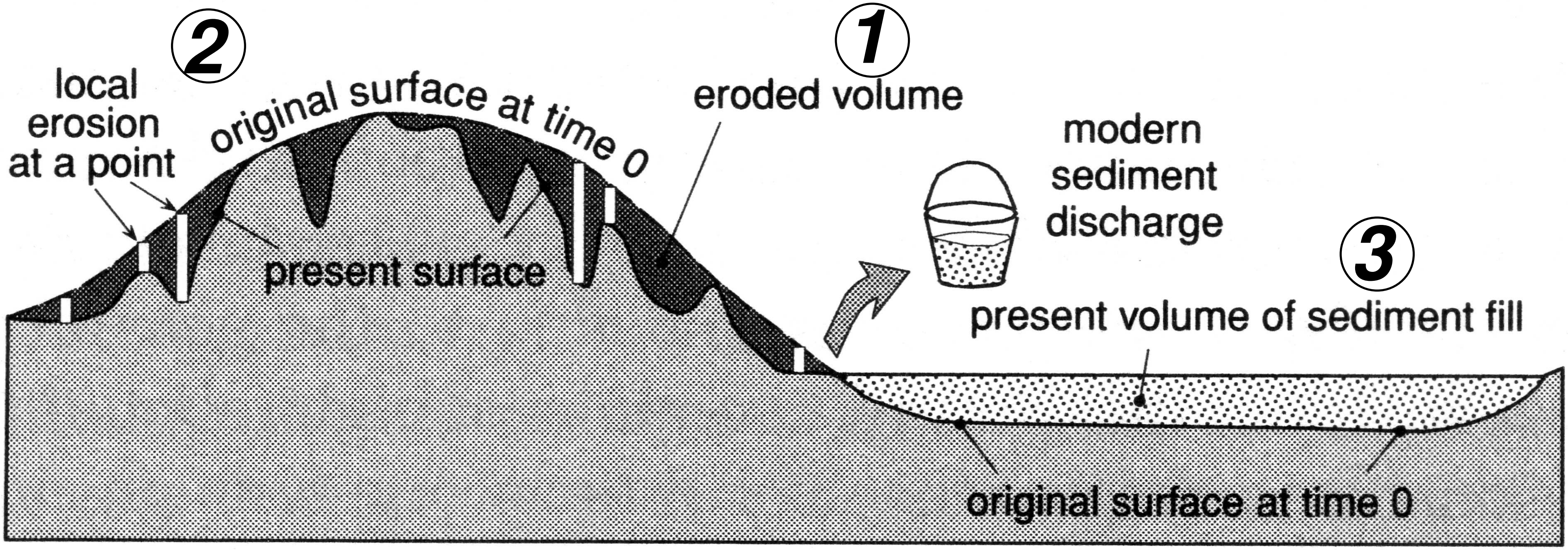


figure taken from Burbank and Anderson (2001)

To measure denudation rates, one can look in one of three places:

1) Sediment flux of rivers

2) Assume some original surface geometry and see how much is missing from topography.

3) Look at sedimentary basins that record erosion to see what the volume of material that went into the basin is.

Sediment Fluxes from Rivers

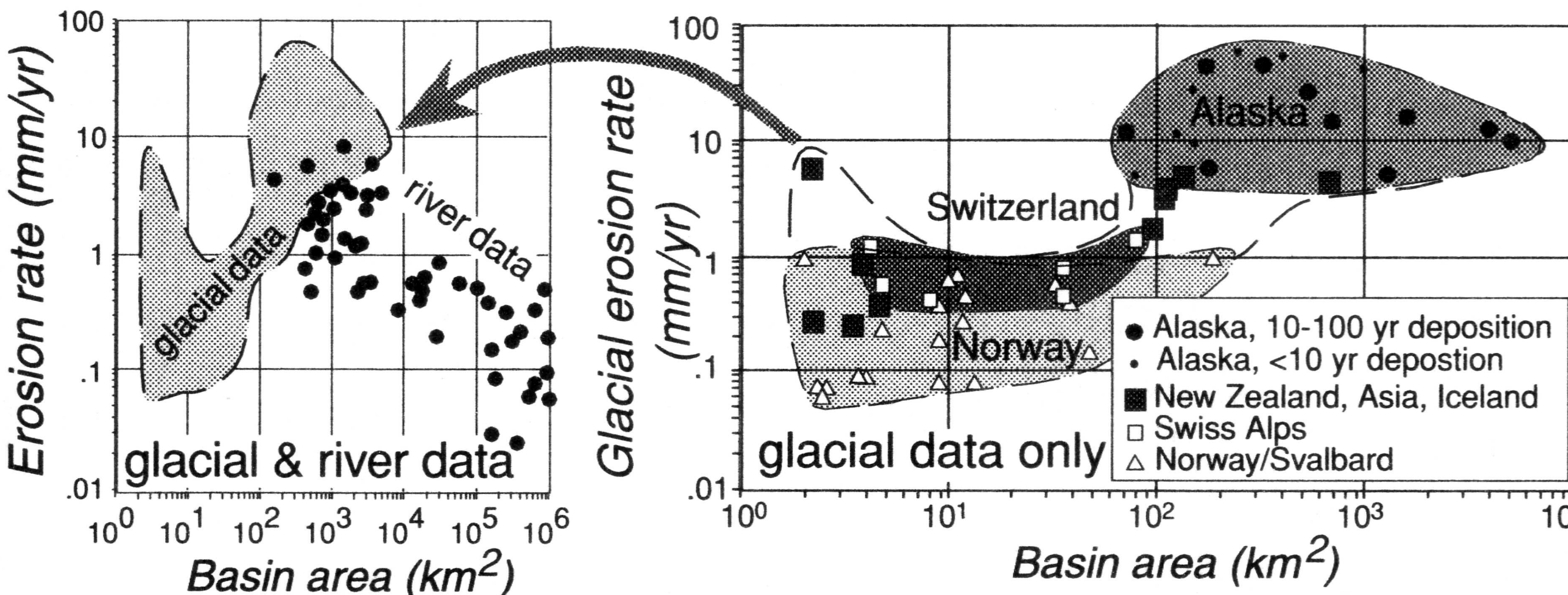


figure taken from Burbank and Anderson (2001) after Hallet et al. (199

- Note that denudation rates in dataset respond differently according to erosion process:

1) Glacial denudation rates increase with increasing basin areas.

2) Fluvial denudation rates decrease with increasing basin areas.

*** Measurements made over 10-100 yr timescales, and so it is unclear if these rates are representative over long timescales of interest to geomorphology.**

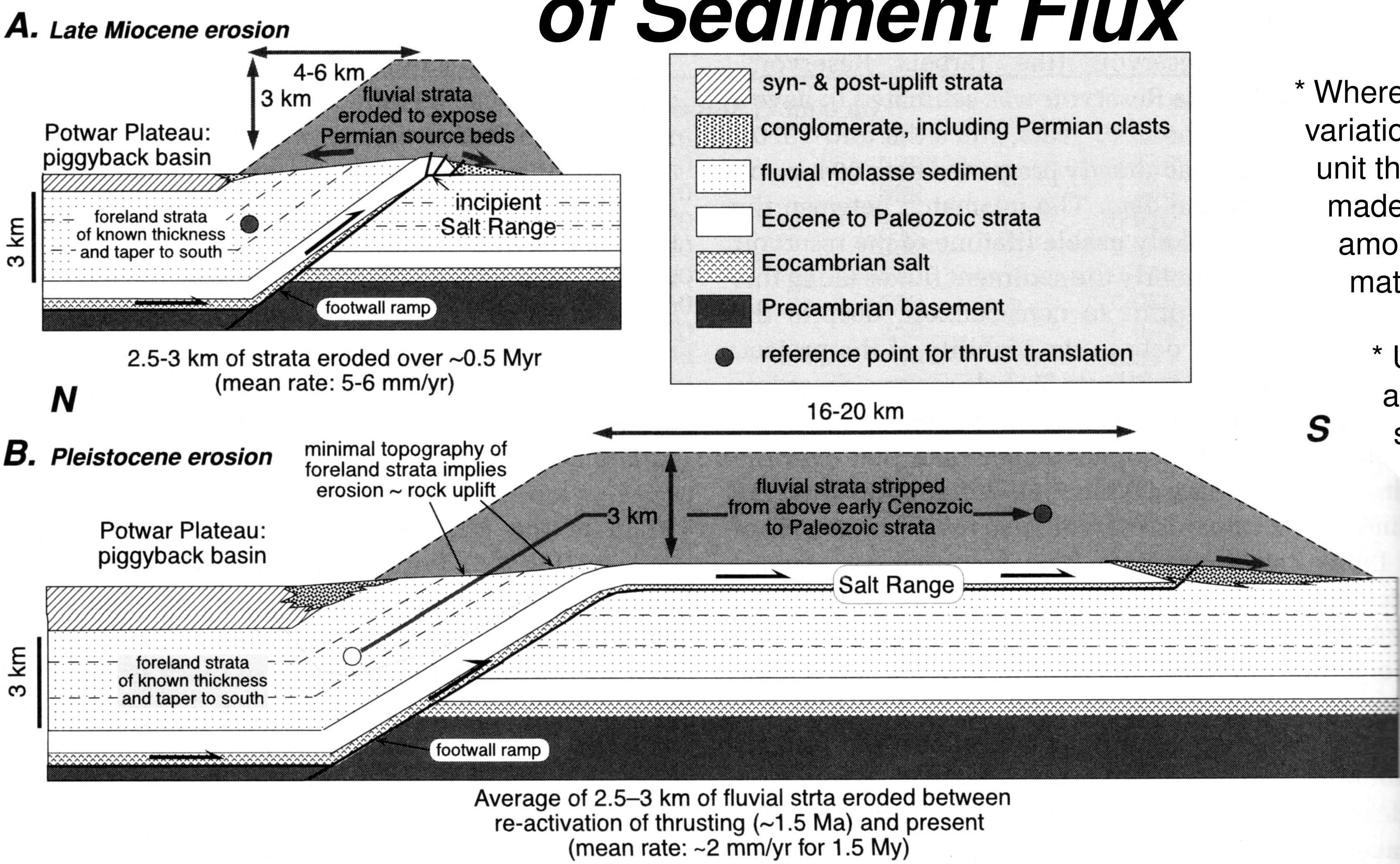
Sediment Fluxes in Rivers Worldwide

TABLE 7.1. Catchment Area, Sediment Load, Sediment Yield, Erosion Rates, and Runoff for World's Rivers with Catchments >250,000 km² (after Milliman and Syvitski, 1992)

River	Area ($\times 10^6$ km²)	Load ($\times 10^6$ t/yr)	Yield (t/km² • yr)	Erosion Rate (mm/yr)	Runoff (mm/yr)
A. High Mountain (>3000 m)					
Magdalena (Col)	0.24	220	920	0.341	990
Irrawaddy (Burma)	0.43	260	620	0.230	995
Brahmaputra (Bangl)	0.61	540	890	0.330	
Colorado (USA)	0.63	120	190	0.070	32
Indus (Pak)	0.97	250	260	0.096	245
Ganges (Bangl)	0.98	520	530	0.196	
Orinoco (Ven)	0.99	150	150	0.056	1100
Yangtze (China)	1.9	480	250	0.093	460
Parana (Arg)	2.6	79	30	0.011	165
Mississippi (USA)	3.3	400	120	0.044	150
Amazon (Braz)	6.1	1200	190	0.070	100
B. Mountain (1000-3000 m): South Asia/Oceania					
Krishna (India)	0.25	64	260	0.096	140
Godavari (India)	0.31	170	550	0.204	270
Pearl (China)	0.44	69	160	0.059	690
Huanghe (China)	0.77	1100	1400	0.519	77
Mekong (Viet)	0.79	160	200	0.074	590
C. Mountain (1000-3000 m): N/S America, Africa, Alpine Europe, etc.					
Fraser (Can)	0.22	20	91	0.034	510
Columbia (USA)	0.67	15	22	0.008	375
Limpopo (Mozam)	0.41	33	80	0.030	13
Rio Grande (USA)	0.67	20	>30	>0.011	
Danube (Rom)	0.81	67	83	0.031	250
Yukon (USA)	0.84	60	71	0.026	230
Orange (SA)	0.89	89	100	0.037	100
Tigris-Euphrates (Iraq)	1.05	>53(?)	>52(?)	>0.019	45
Murray (Austr)	1.06	30	29	0.011	21
Zambesi (Mozam)	1.4	48	35	0.013	390
MacKenzie (Can)	1.8	42	23	0.009	170
Amur (USSR)	1.8	52	28	0.010	180
Nile (Egypt)	3.0	120	40	0.015	30
Zaire (Zaire)	3.8	43	11	0.004	340
D. Upland (500-1000 m)					
Vistula (Pol)	0.20	2.5	13	0.005	165
Uruguay (Urg)	0.24	11(?)	45(?)	0.017(?)	
Pechora (USSR)	0.25	6.1	25	0.009	415
Hai (China)	0.26	14	55	0.020	
Indagirka (USSR)	0.36	14	39	0.014	150
Volta (Ghana)	0.40	19	48	0.018	91
Don (Ukr)	0.42	0.77	18	0.007	
Sao Francisco (Braz)	0.63	6	10	0.004	
Niger (Nig)	1.2	40	33	0.012	116
Volga (Rus/Ukr)	1.4	19	15	0.006	400
Ob (USSR)	2.5	16	6	0.002	130
Lena (Rus)	2.5	12	5	0.002	205
Yenisei (Rus)	2.6	13	5	0.002	220
E. Lowland (100-500 m)					
Yana (USSR)	0.22	3	14	0.005	130
Senegal (Sen)	0.27	1.9	8	0.003	48
Sevemay Dvina (USSR)	0.35	4.5	13	0.005	330
Dnieper (USSR)	0.38	2.1	5.2	0.002	86
Kolyma (USSR)	0.64	6	9	0.003	140
Sao Francisco (Braz)	0.64	6	9	0.003	150
St. Lawrence (Can)	1.1	4	4	0.001	435

table taken from Burbank and Anderson (2001) after Milliman and Syvitski (1992)

Structural and Stratigraphic Estimations of Sediment Flux

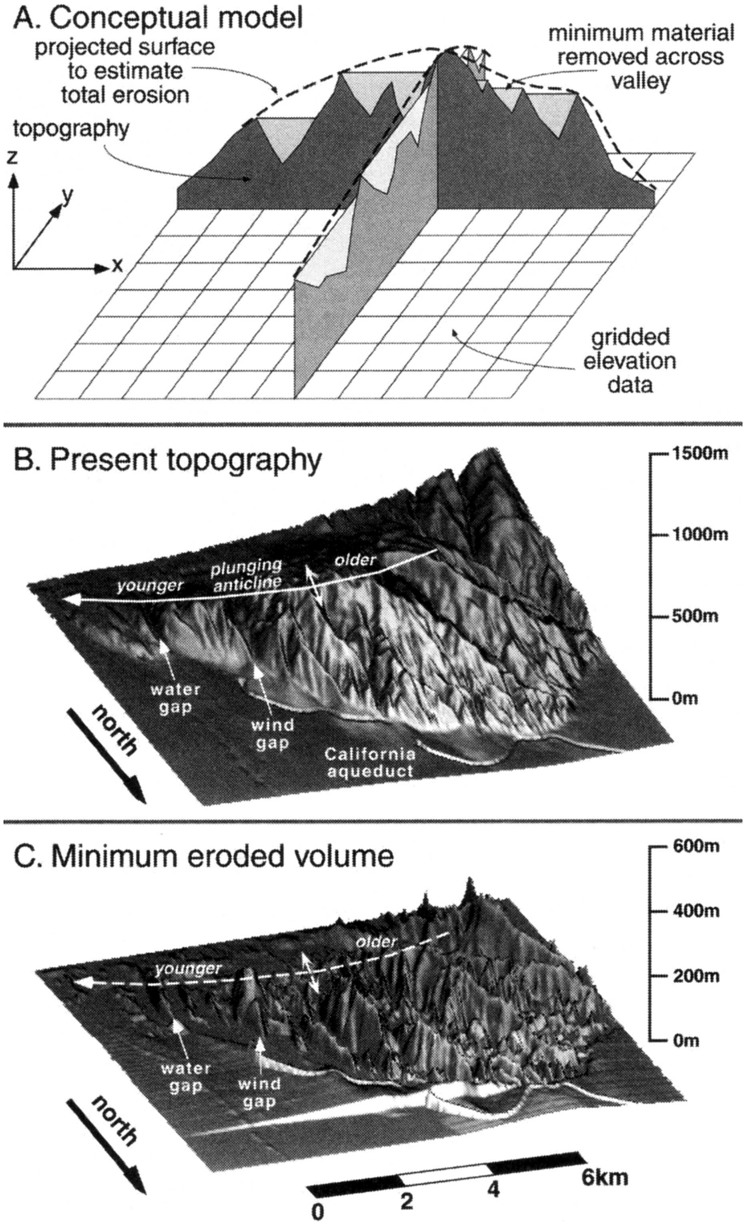


* Where predictable variations in stratigraphic unit thickness can be made, estimations of total amount of eroded material can be inferred.

* Using timing of activity along structure, one can estimate how erosion rates may have varied through time.

figure from Burbank and Anderson (2001) after Burbank et al. (1991).

Sediment Volumes and Denudation Rates from Topography

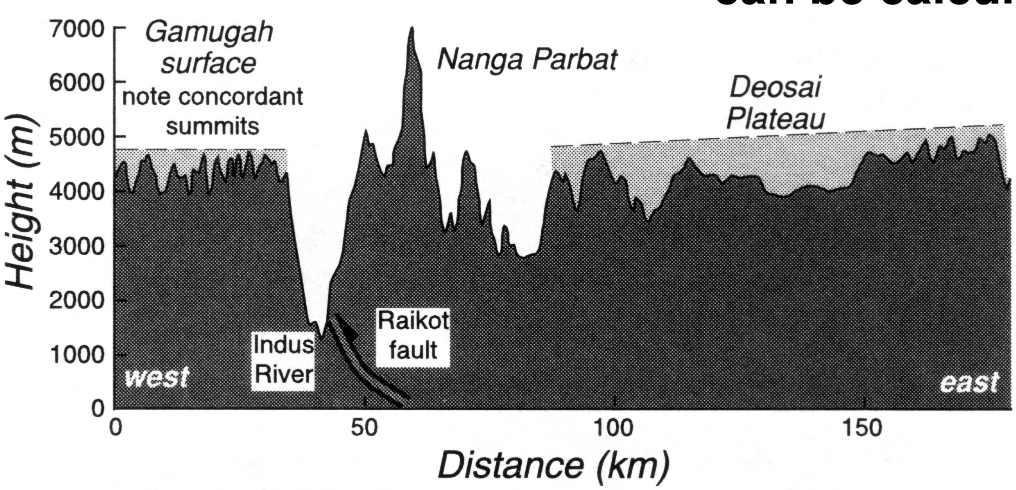


- In some cases, initial geometry of surface (prior to erosion) can be inferred.

* In these cases, extrapolating the highest ridgelines provides an estimate of the prior surface topography.

- Subtracting initial topography from current topography yields volume of material removed by erosion.

- Where start of erosion can be dated, erosion rates can be calculated.



figures from Burbank and Anderson (2001) after Brozovic et al. (1995) [top] and Zeitler (1995) [bottom]

Isotopic Composition of Sediment Load

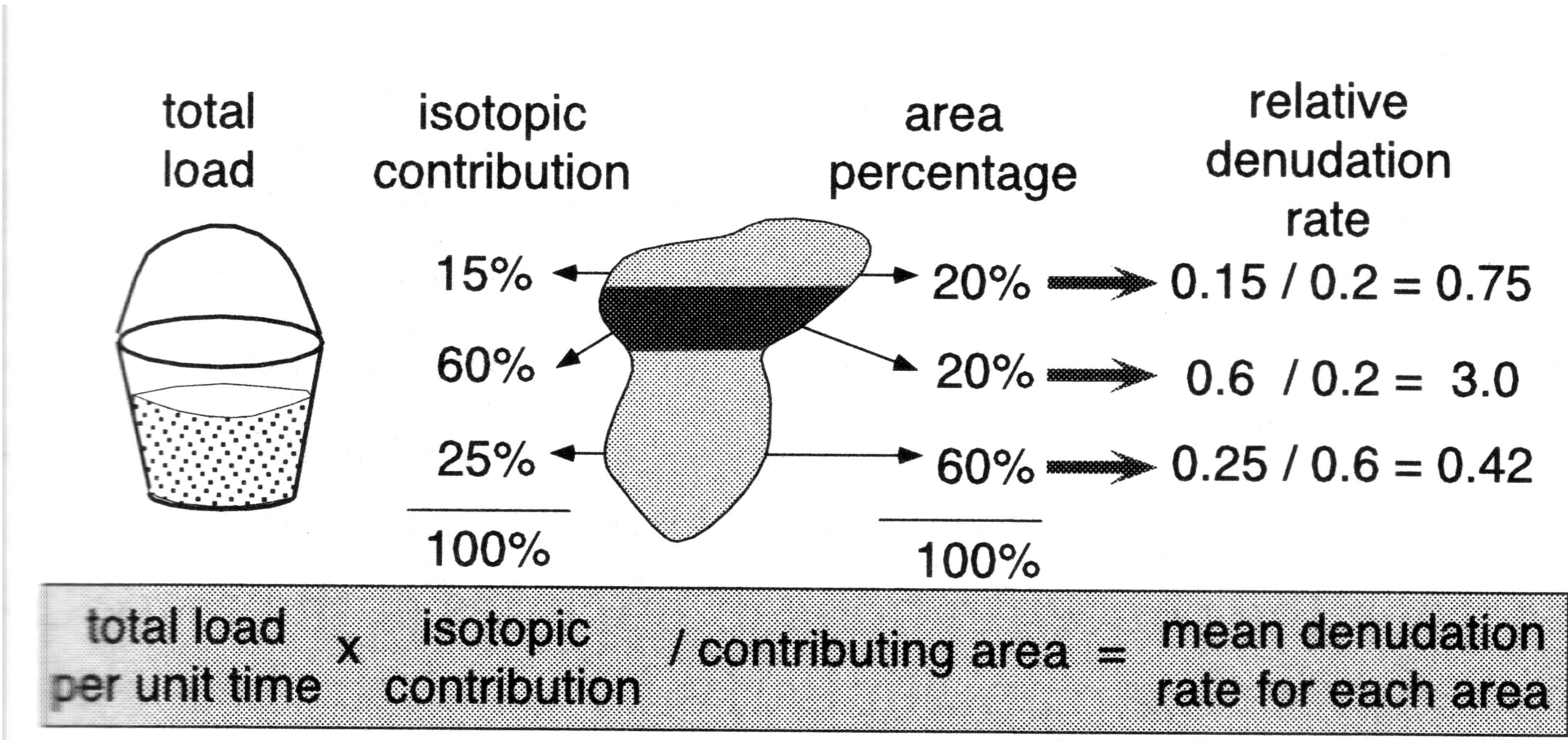
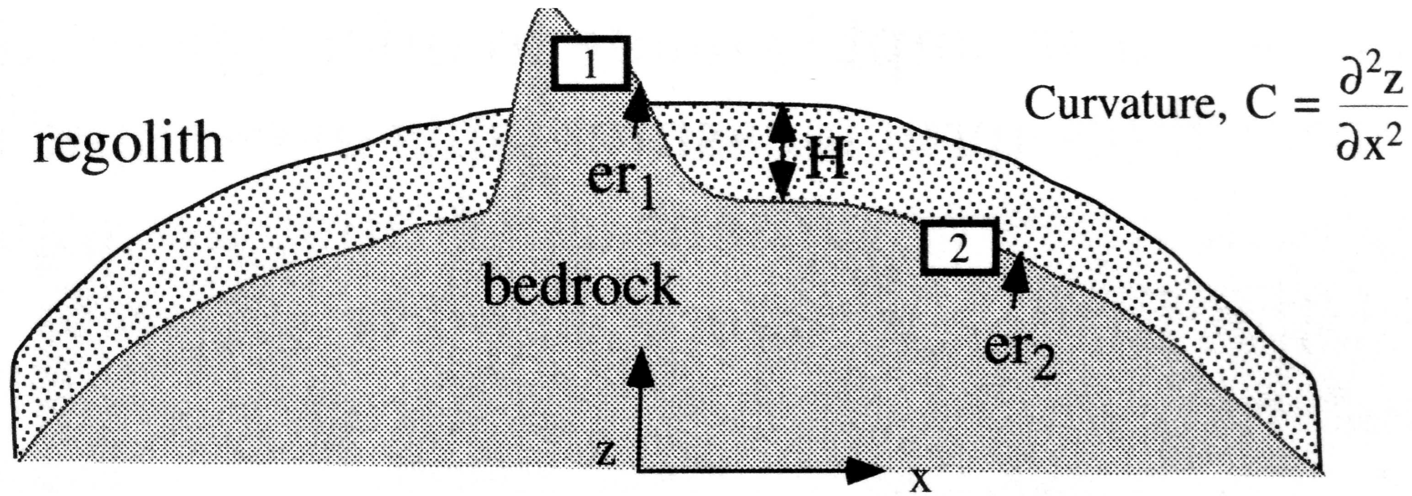


figure from Burbank and Anderson (2001)

- Isotopic composition of sediments may reflect relative rates of denudation within each basin.

*** Based on different isotopic signatures of different lithologies.**

CRN Measurements of Regolith Production Rates



*** Erosion rates are estimated both for regolith created under regolith mantle and along exposed bedrock.**

- These measurements may provide good estimates of the erosion rate at point locations of sampling (usually on hillslopes) over the time-range represented by the CRN isotope system.

*** Extrapolation to basin and orogen scale rates may be problematic.**

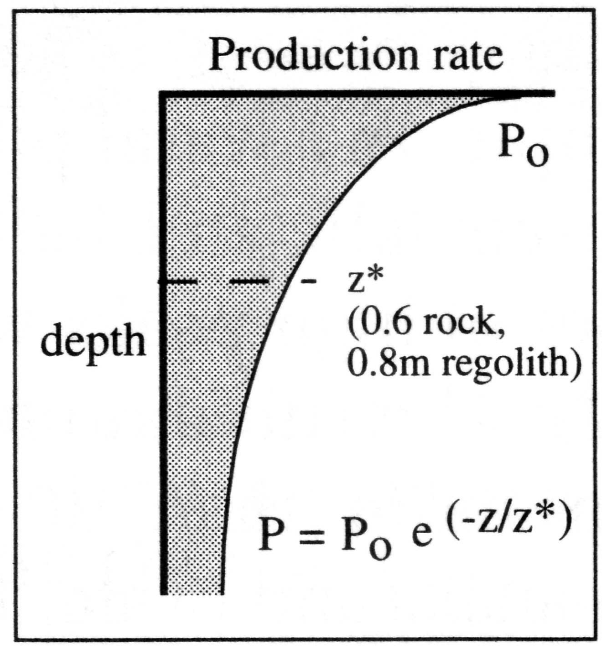
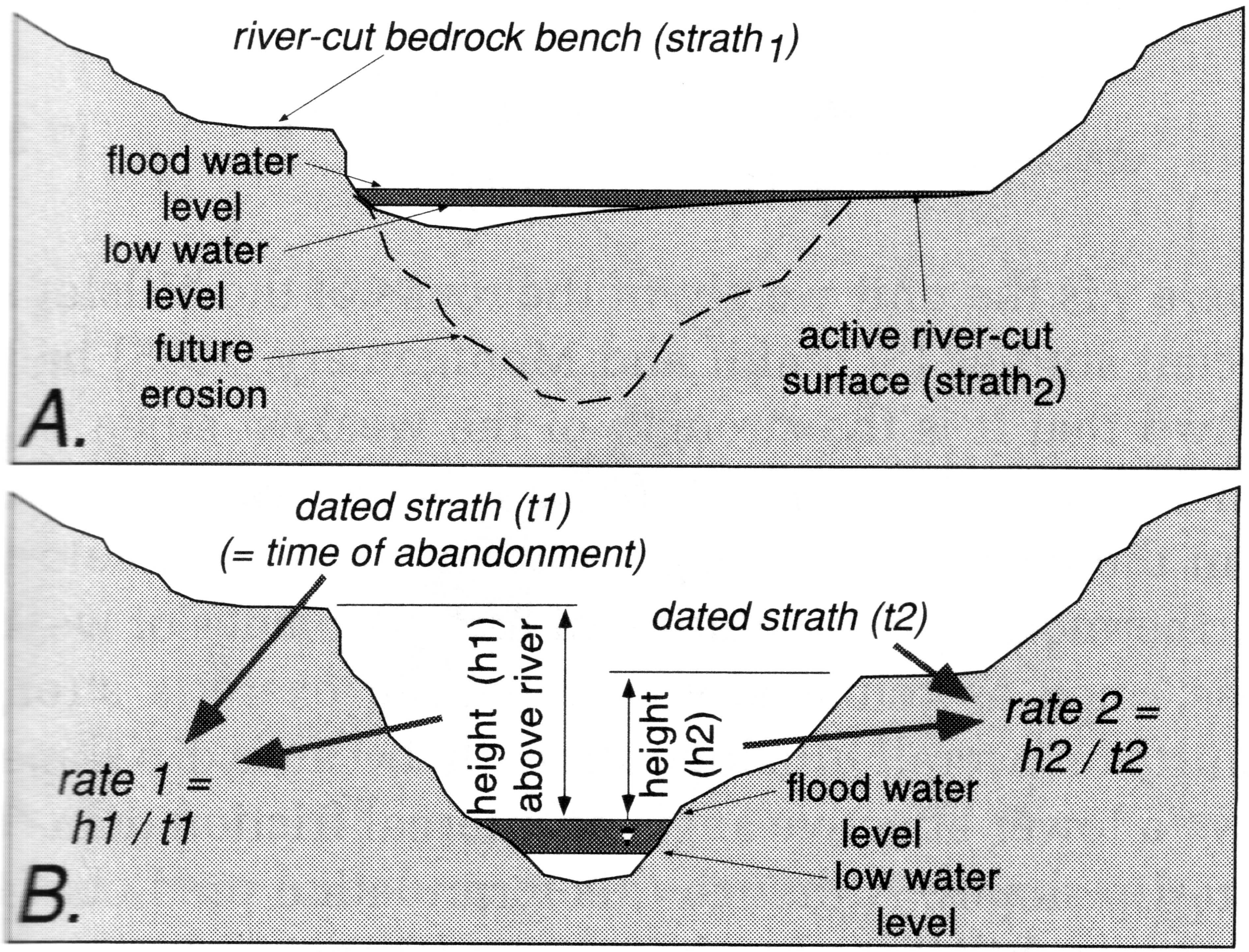


figure taken from Burbank and Anderson (2001).

CRN Estimates of Bedrock Incision Rates



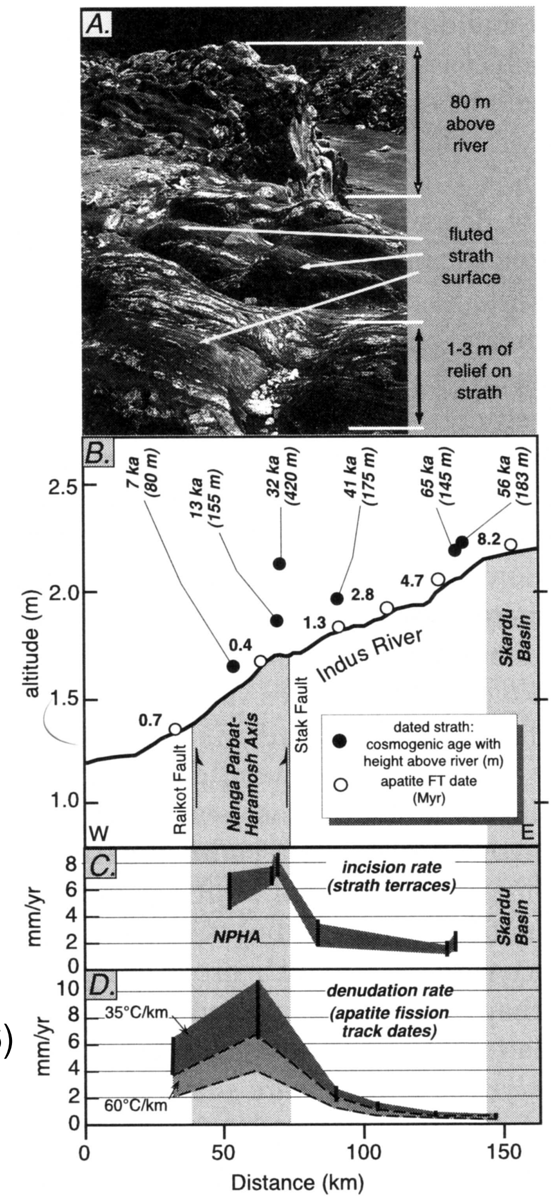
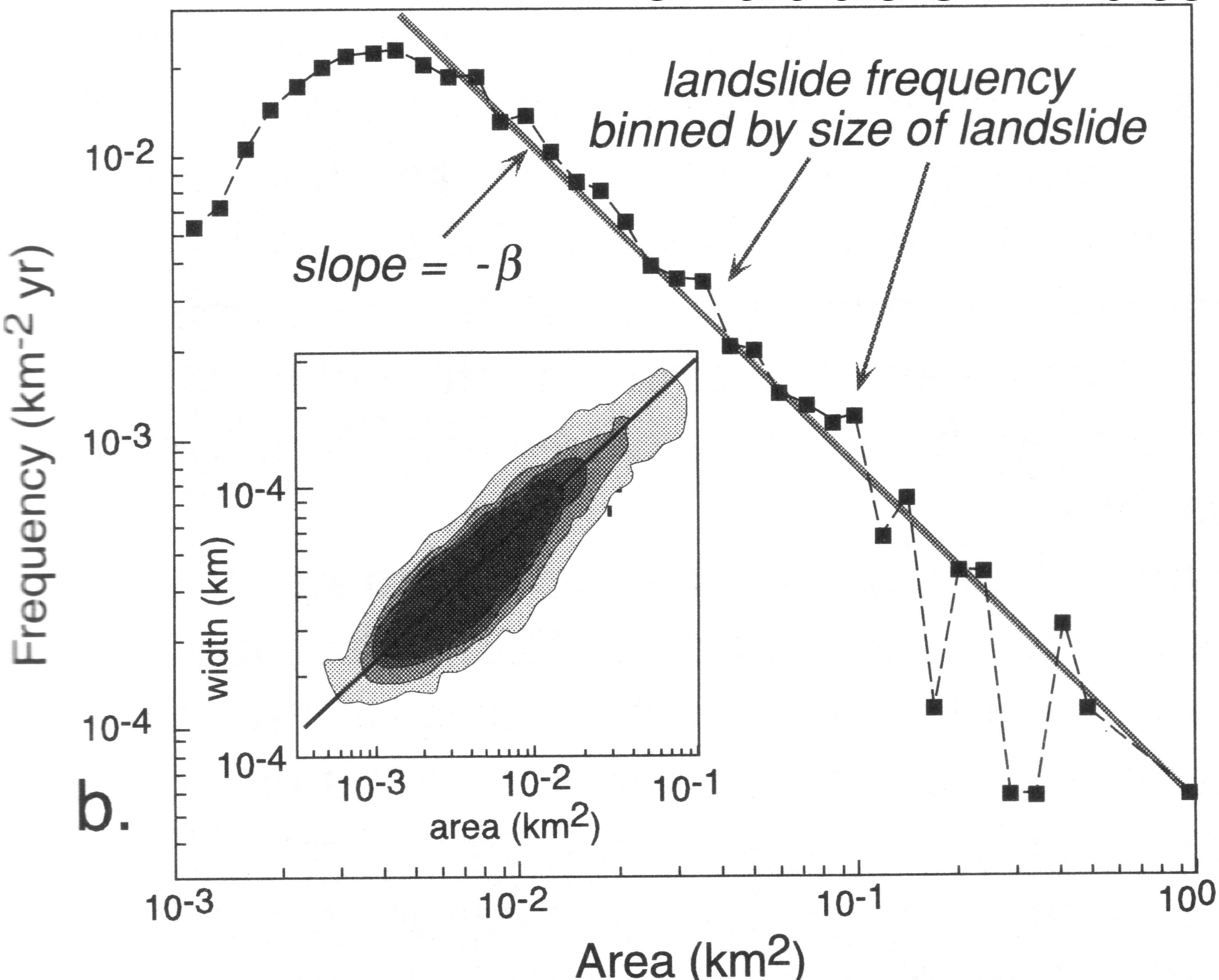


figure from Burbank and Anderson (2001). Right figure after Burbank et al. (1996)

- Exposure age of strath surfaces are compared with relief of modern stream channel to calculate incision rate.
*** Measures fluvial bedrock incision rate, rather than mean denudation rate.**

Using Landsliding Frequency to Estimate Denudation Rates



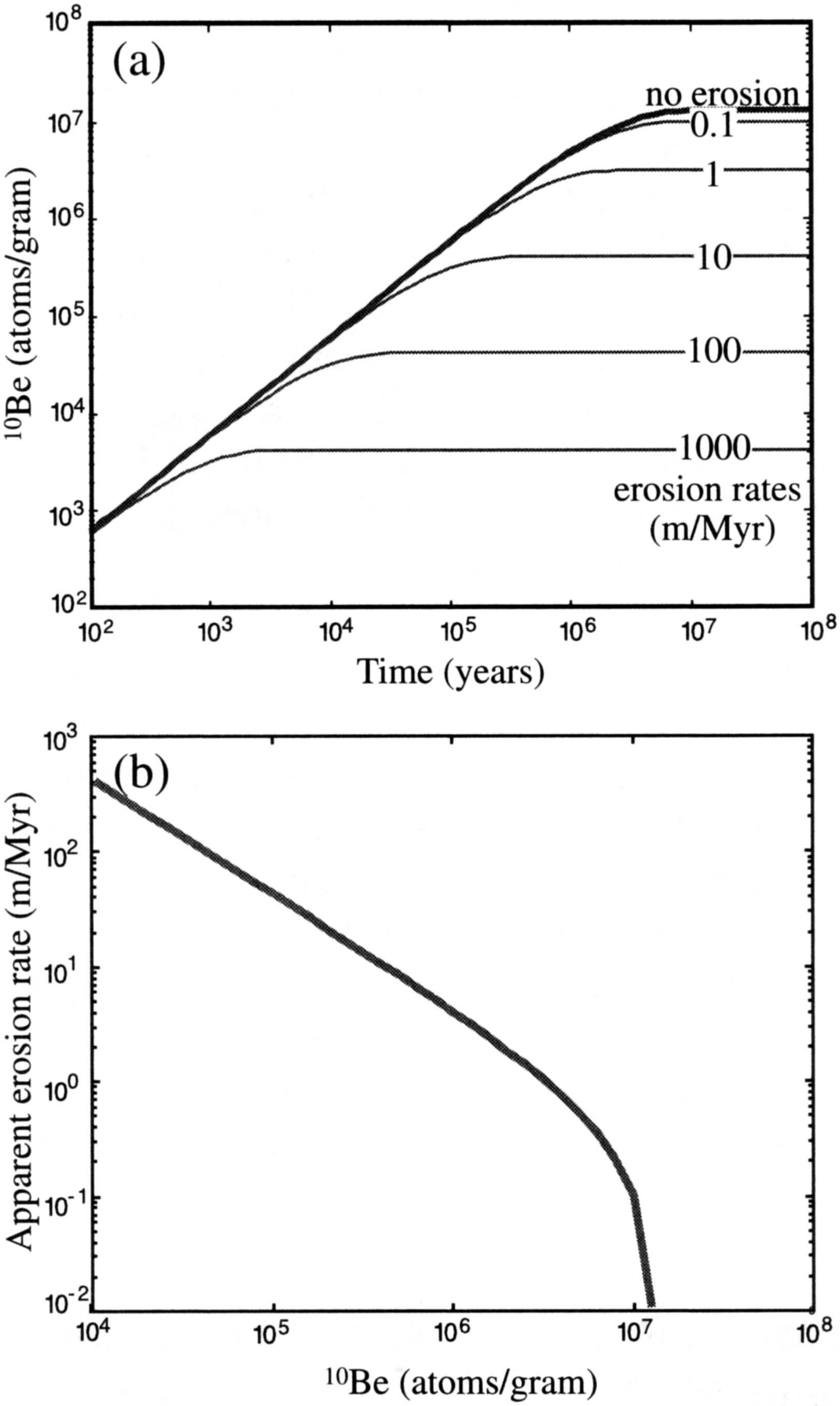
- Landsliding frequency may be combined with slide volume for each side in the frequency magnitude distribution.

*** From these estimates, a landsliding denudation rate may be calculated.**

**** Do large, infrequent landslides constitute the dominant transport agent, or do frequent, small slides do most of the work?**

figure from Burbank and Anderson (2001) after Hovius et al (1997)

CRN Estimates of Basin Denudation Rates



- CRN content of sands found in fluvial systems record erosion rate on hillslopes in catchment. In theory, by measuring this content, a basin-averaged erosion rate may be estimated.

Advantages:

1) Rates are estimated over the entire basin.

2) Rates are representative of erosion over timescale of isotope sensitivity (up to 100s kyr to Myr).

Disadvantages:

1) Must have correct mineralogy.

2) Signal may be contaminated by short-duration, large mass movements on hillslopes.

3) Need relatively uniform lithology (i.e., quartz content) for good rate determinations.

figure from Burbank and Anderson (2001) after Brown et al (1995)

Denudation Rates Using Thermochronometers

- Some minerals retain evidence of fission events only below a "closure" temperature.

- By dating a rock with one of these minerals, the time at which the rock cooled below that temperature may be inferred.

*** By assuming a temperature distribution in the crust, one can calculate the depth at which the sample cooled below its closure temperature, and infer an erosion rate.**

TABLE 7.2. Radiometric dating systems and closure temperatures for some minerals

Mineral and dating system	Closure temperature
hornblende (K-Ar)	525±25°C
muscovite (K-Ar)	325±25°C
biotite (K-Ar)	300±25°C
k-feldspar (K-Ar)	200±25°C
sphene (fission-track)	275±55°C
zircon (fission-track)	300±55°C
apatite (fission-track)	120±20°C
muscovite (Rb-Sr)	500±25°C
biotite (Rb-Sr)	275±25°C
monazite (U-Pb)	525±25°C

figure from Burbank and Anderson (2001).

Using Thermochronometers to Estimate Cooling Rate of a Sample

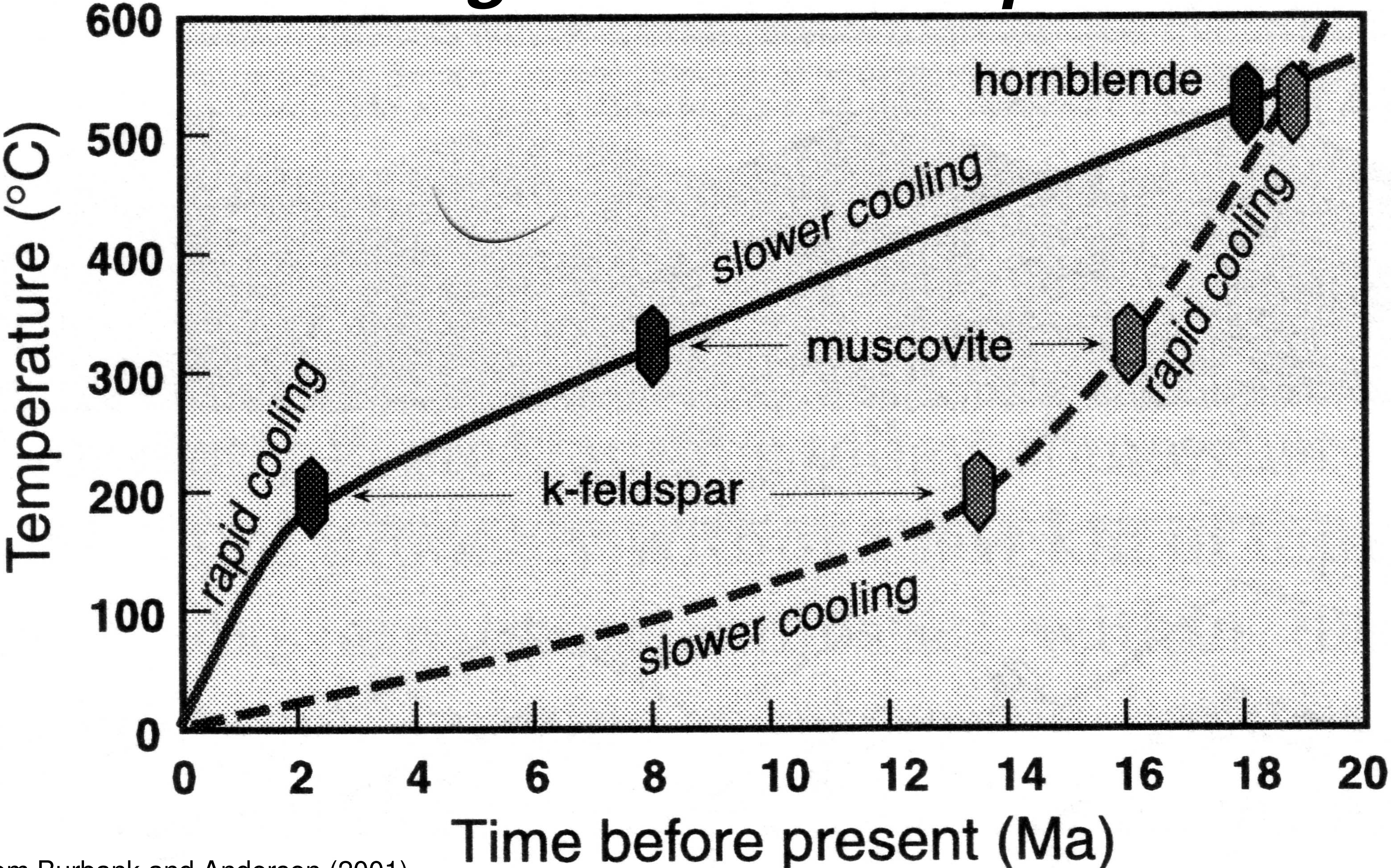
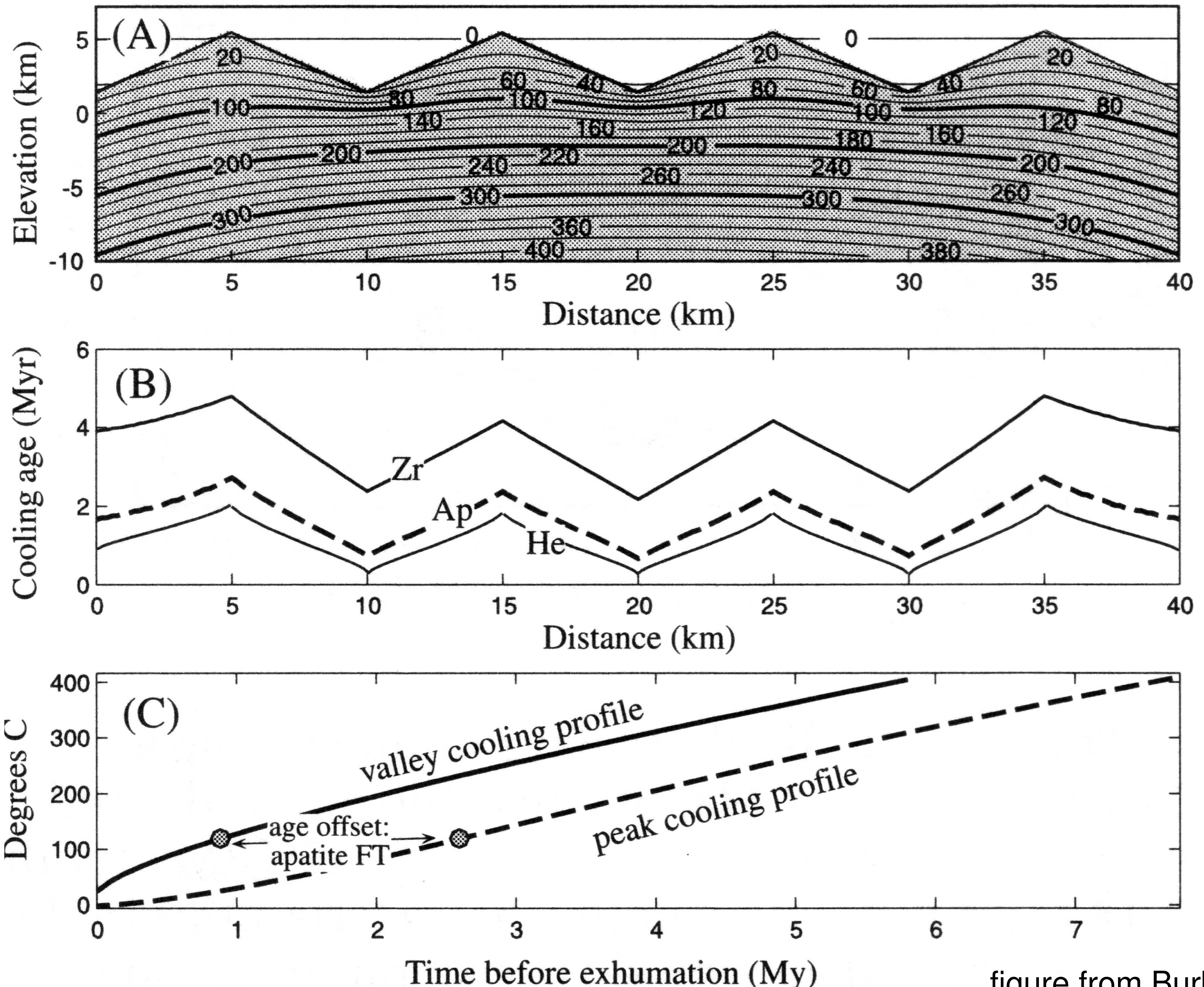


figure from Burbank and Anderson (2001)

Problems with Inferring Denudation Rates from Thermochronometers



- To convert to denudation rate from cooling rate, temperature distribution must be assumed.

*** Geothermal gradients may be steepened by high denudation rates. Topography may also bend the isotherms such that the age distribution reflects the topography.**

*** Multiple thermochronometers may help to constrain the approximate geothermal gradient.**

figure from Burbank and Anderson (2001)

Inferring Denudation Rates from Track Length Distribution

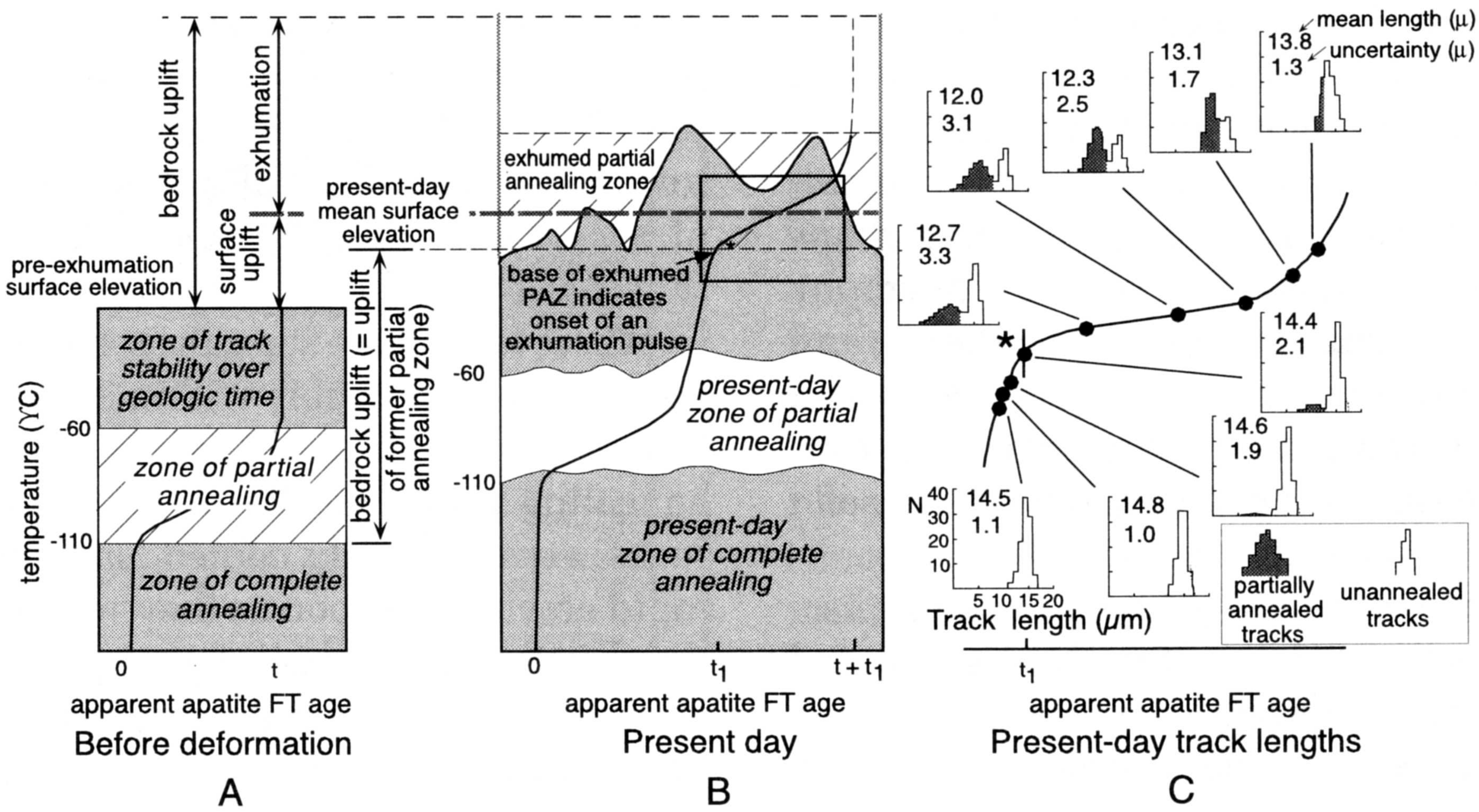


figure from Burbank and Anderson (2001) after Fitzgerald et al. (1995)

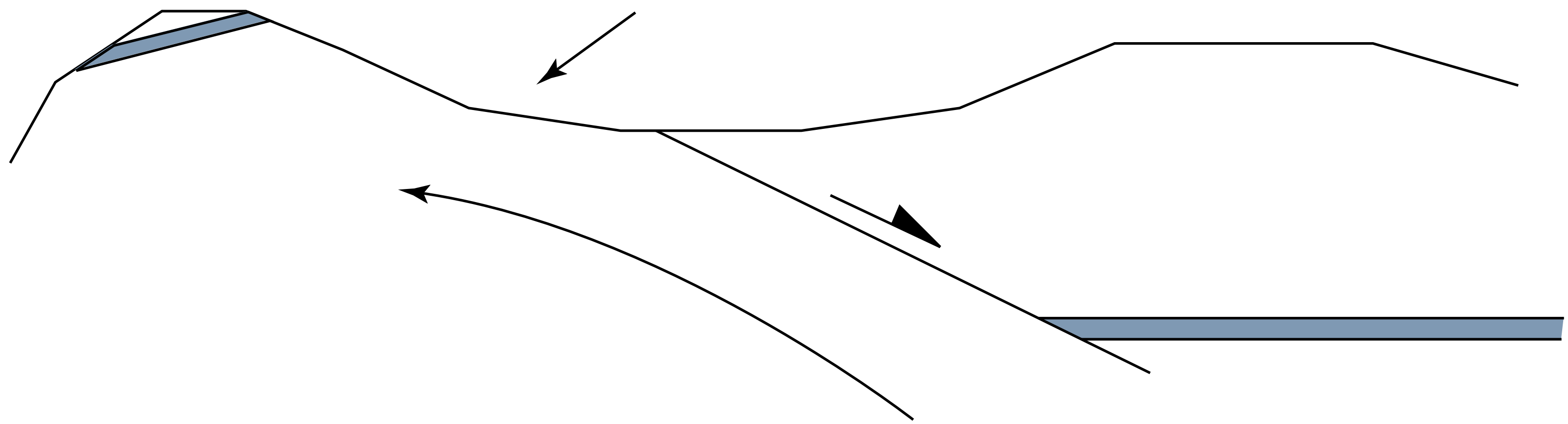
- Some minerals have damage tracks related to fission events. These are tracks in the mineral lattice (apatite and zircon are common minerals where this damage is observed).

- These tracks heal over time within a temperature range.

- By measuring the distribution of track lengths, one can estimate how quickly the mineral cooled through this "partial annealing zone".

Tectonic Denudation

Exposure of Footwall Rocks



*** Tectonic denudation may bring rocks to the surface relatively quickly from large depths.**

- While tectonic denudation was invoked to explain most rapid cooling in the past, measured erosion rates seem sufficient to account for all measured denudation rates inferred from thermochronometers.

Uplift Rates

- Determining uplift rates using:
1) Stratigraphic constraints.
2) River profiles.

- Removing istostacy from total uplift rates to estimate tectonic component.

- Paleoaltitude estimations.

- Topographic barrier inferences from oxygen isotopes

Constraining Uplift and Uplift Rate From Stratigraphic Data

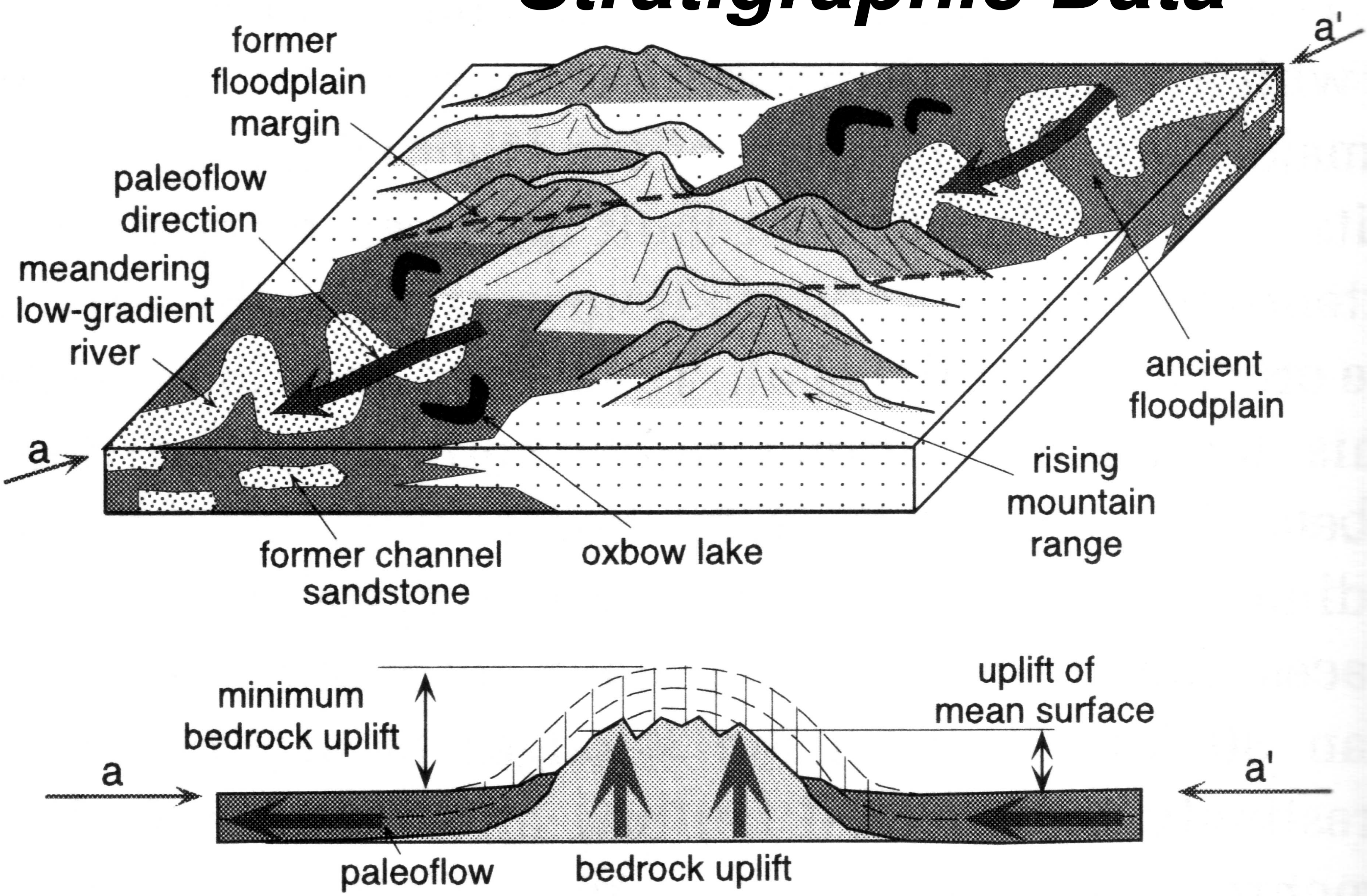


figure taken from Burbank and Anderson (2001)

- Depositional systems or unconformities may provide good markers for constraining total offset.

- Where deformation can be dated, rates may be inferred and compared to denudation rates.

River Profiles as Indicators of Uplift Rates

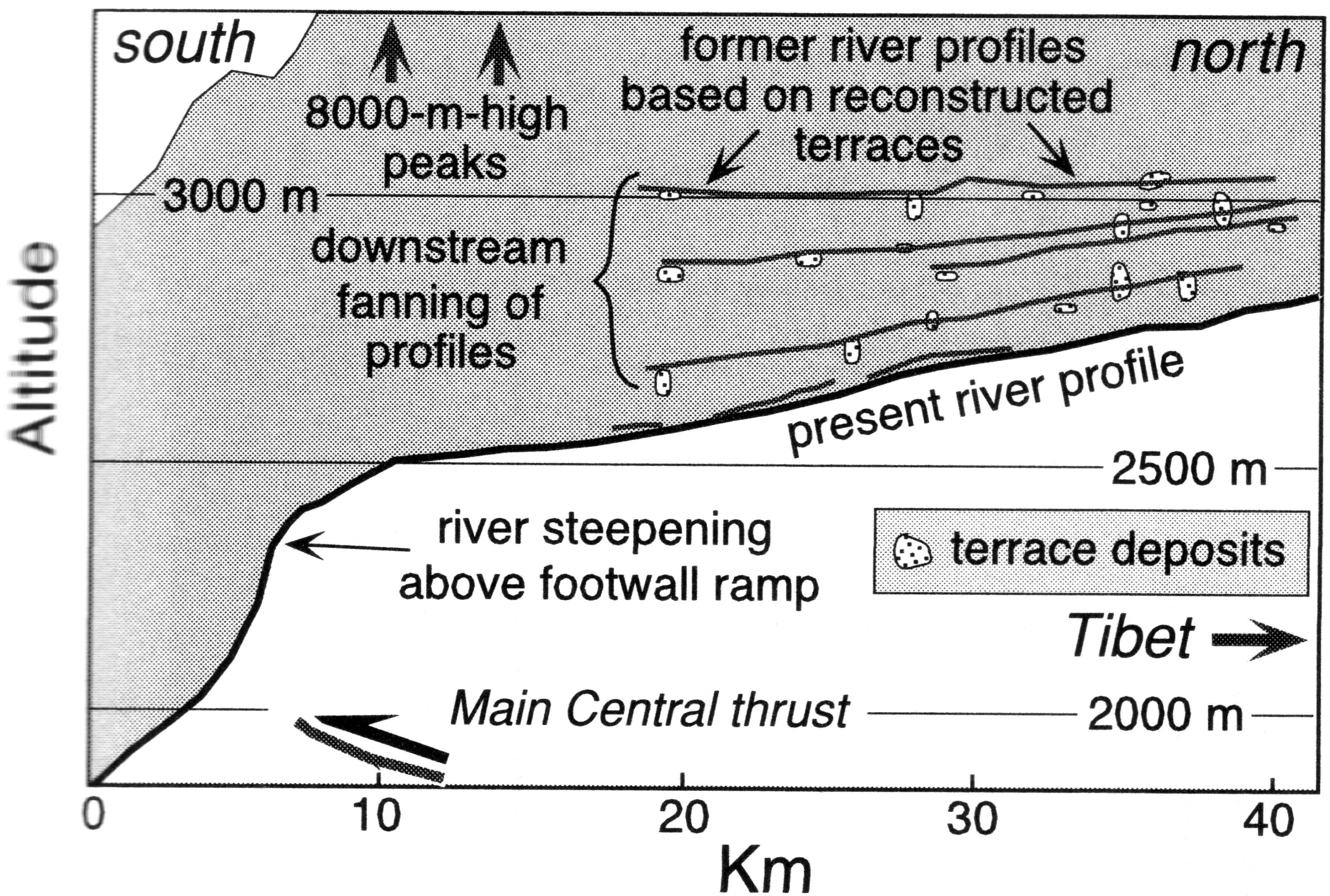


figure from Burbank and Anderson (2001) after Iwata et al. (1987)

Calculating Tectonic Uplift Over Large Spatial Scales

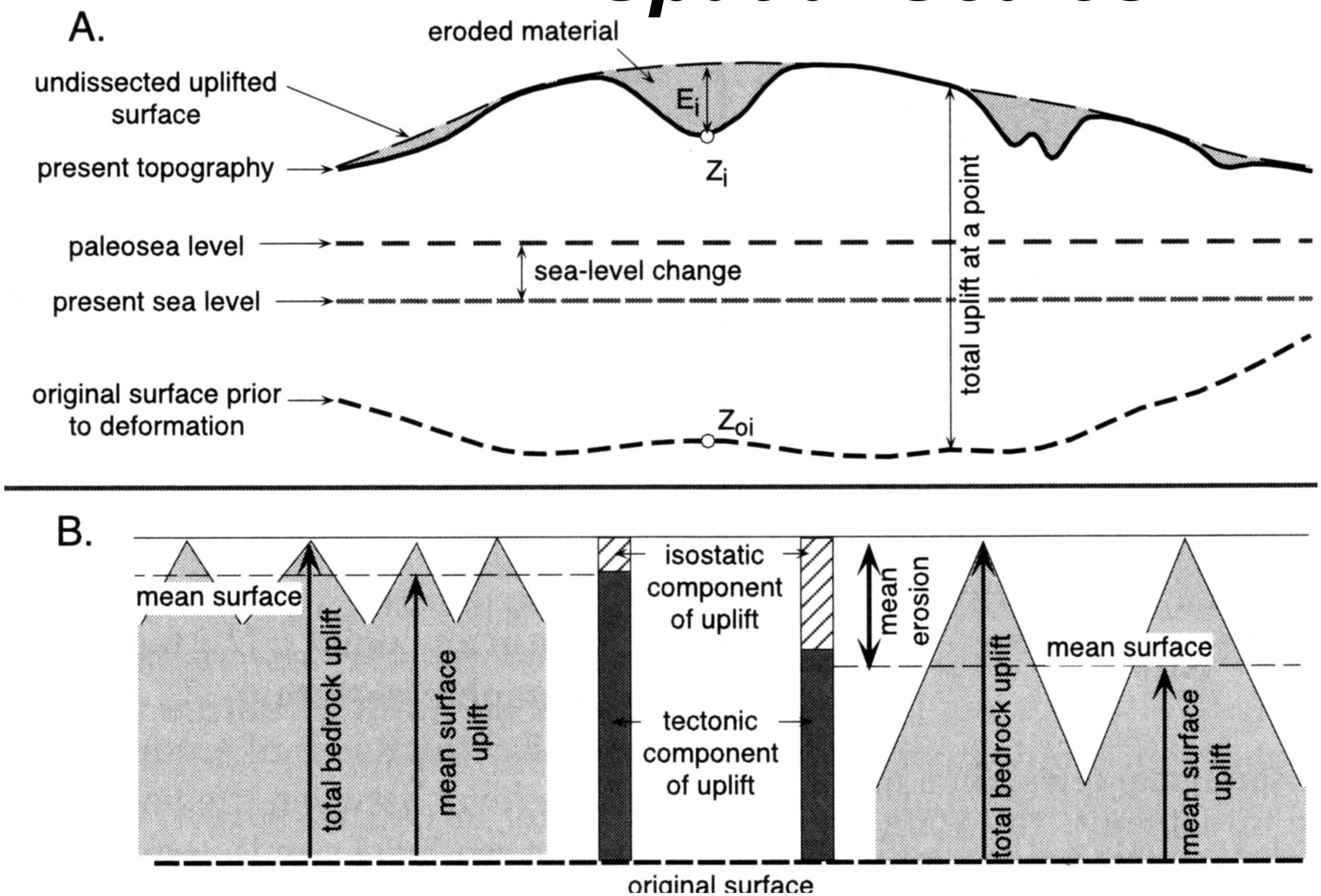


figure from Burbank and Anderson (2001)

- Apparent uplift consists of three components:

1) Isostatic component

2) TECTONIC COMPONENT!!!

3) Apparent uplift due to sea level changes.

*** To calculate the tectonic component of uplift from total apparent uplift, we must subtract the effects of the other two.**

Erosional Unloading and Isostatic Response

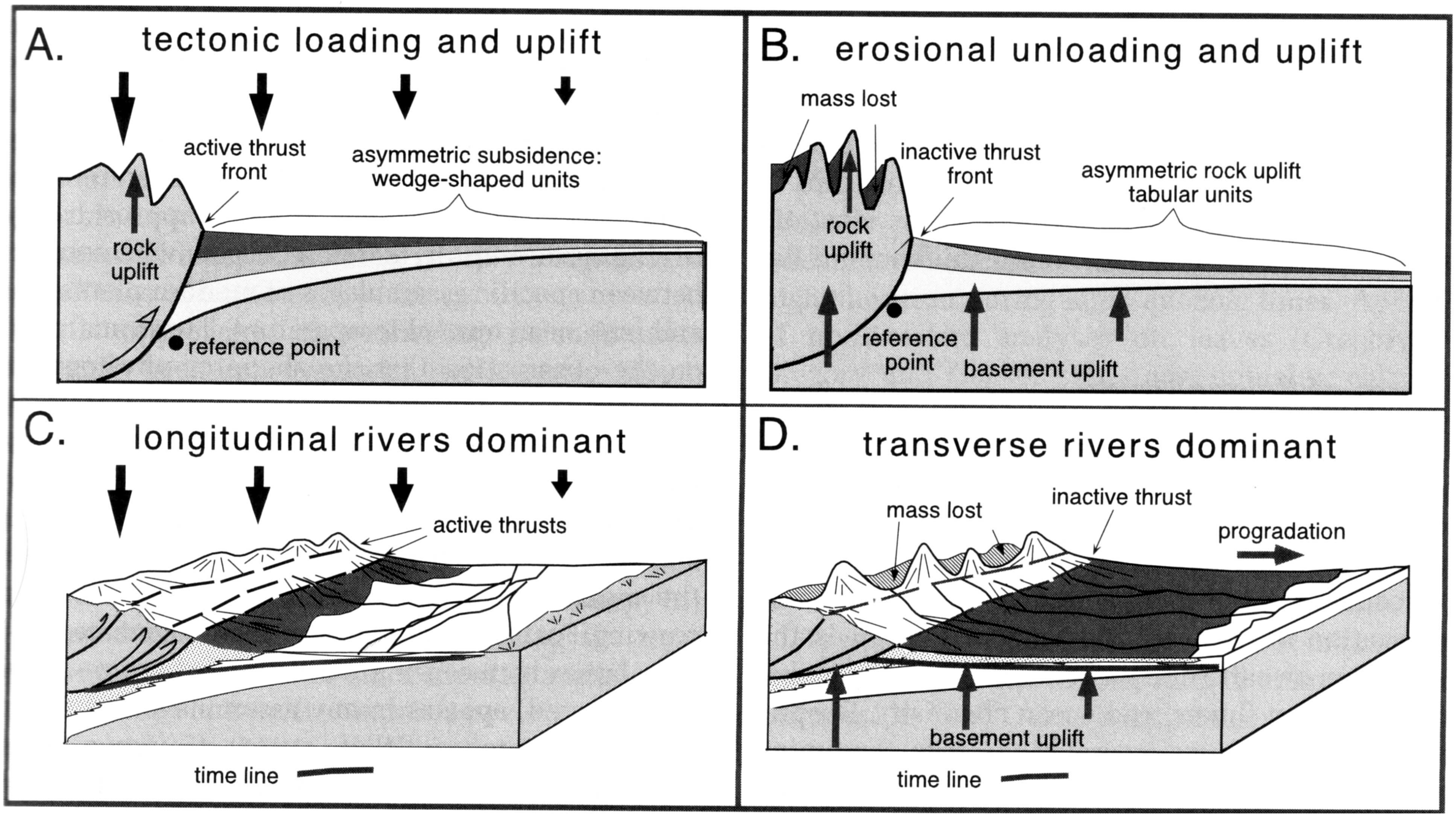


figure from Burbank and Anderson (2001) after Burbank (1992)

Paleoaltitude Estimations

- Estimations are often based on assemblages of different fauna that reflect environmental temperature and precipitation conditions.

** Must convert temperature and precipitation to elevation. Often this is done using a thermodynamic approach where the potential energy in a rising air mass (related to altitude) is converted to thermal energy and latent heat.*

** Often, this approach yields only crude estimates of paleoelevation, whose estimated uncertainties (700-950 m) may often be greater.*

Inferring Surface Uplift from O Isotopes

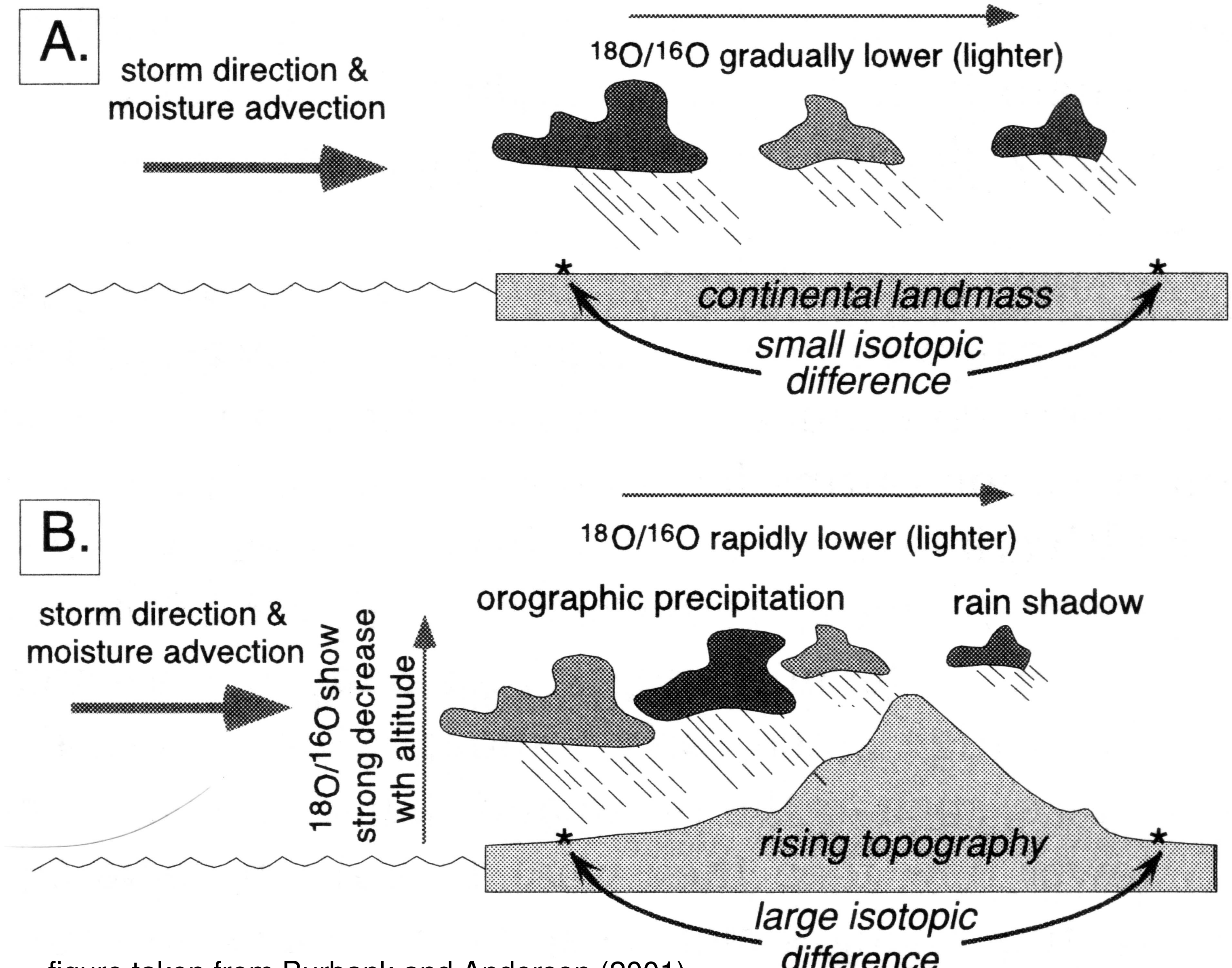


figure taken from Burbank and Anderson (2001)

- 18O preferentially comes out in rainwater.

- Orographic barrier is therefore recorded by isotopic fractionation.

*** Areas downwind of topography will have lighter isotopes than those upwind. Where this fractionation can b calibrated, the surface elevation of the upwind topographic barier can be estimated.**

Important Points:

- Uplift can be grouped into three major types:

** Erosion/Sedimentation*

** Surface uplift*

** Rock uplift*

- Erosion rates can be measured using several techniques:

1) Fluvial sediment flux measurements.

2) Sediment and structural constraints.

3) Topography.

4) Isotopic sediment composition.

5) Regolith production rates.

6) Bedrock incision rates.

7) Landsliding denudation rates

8) CRN basin-wide denudation rate estimates.

Important Points:

9) Geochronologic methods.
10) Tectonic denudation.

- Uplift Rates may be determined by:
1) Stratigraphic constraints.
2) River profiles.

- Istostacy may play an important role in deformation and erosion.

- Paleoaltitude estimations may be made from faunal assemblages.

- Topographic barriers may be recorded by oxygen isotope records in sediments.

Next Time...

Short Time-scale (Holocene) Deformation and Landscape Response