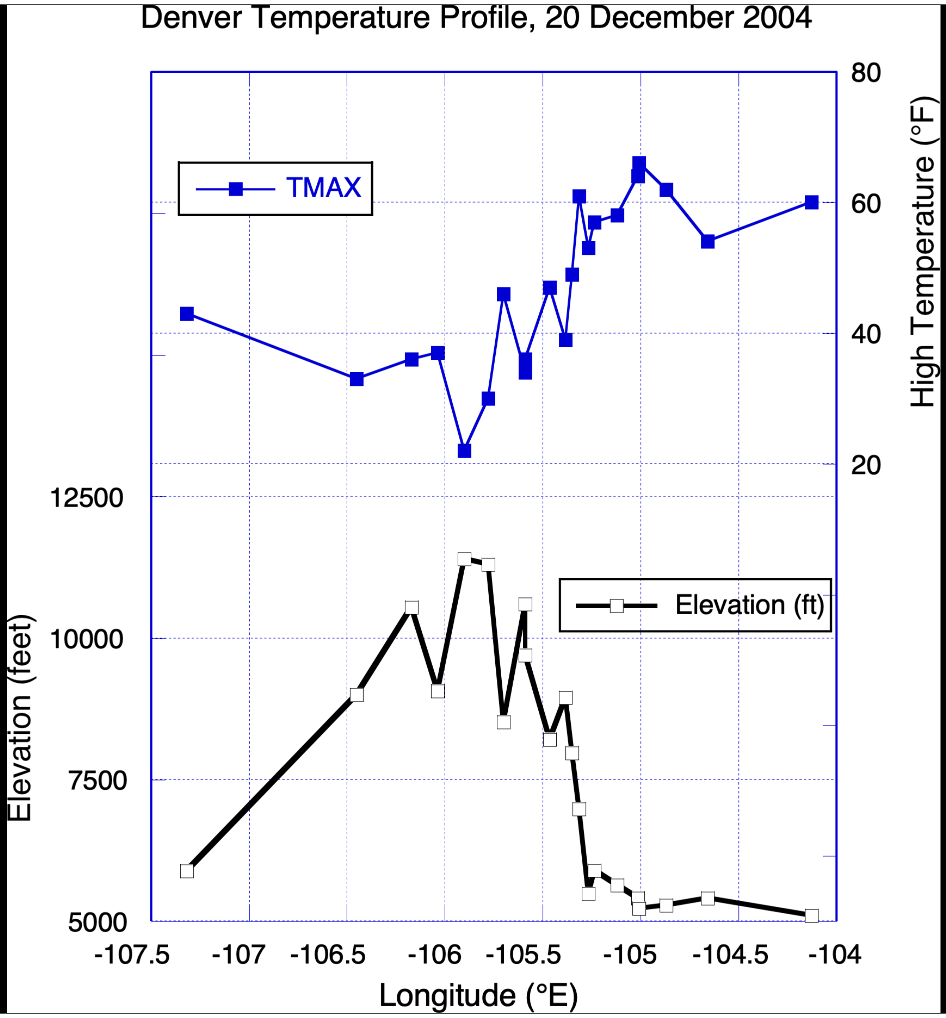
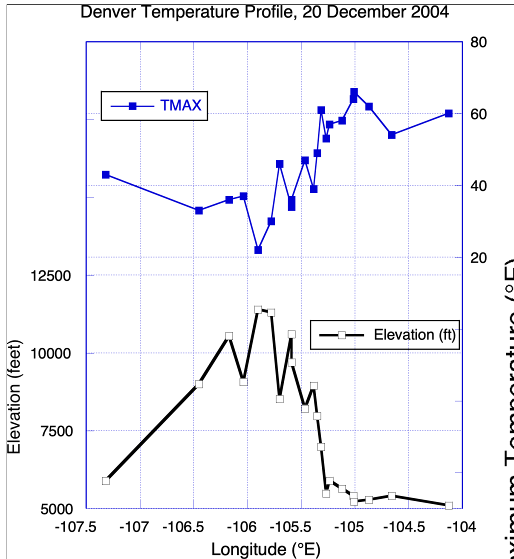
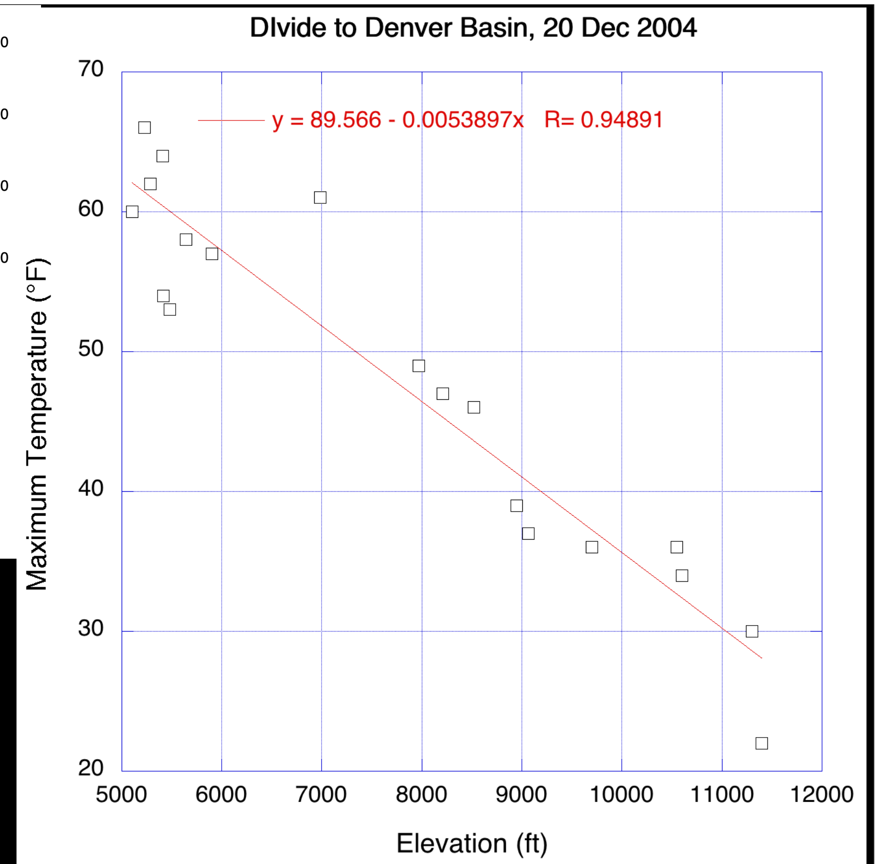
Paleoaltimetry

- What varies with elevation?



Denver Temperature Profile, 20 December 2004
TMAX
Elevation (ft)
Elevation (feet)
High Temperature (°F)
Longitude (°E)
12500
10000
7500
5000
80
60
40
20
-107.5
-107
-106.5
-106
-105.5
-105
-104.5
-104

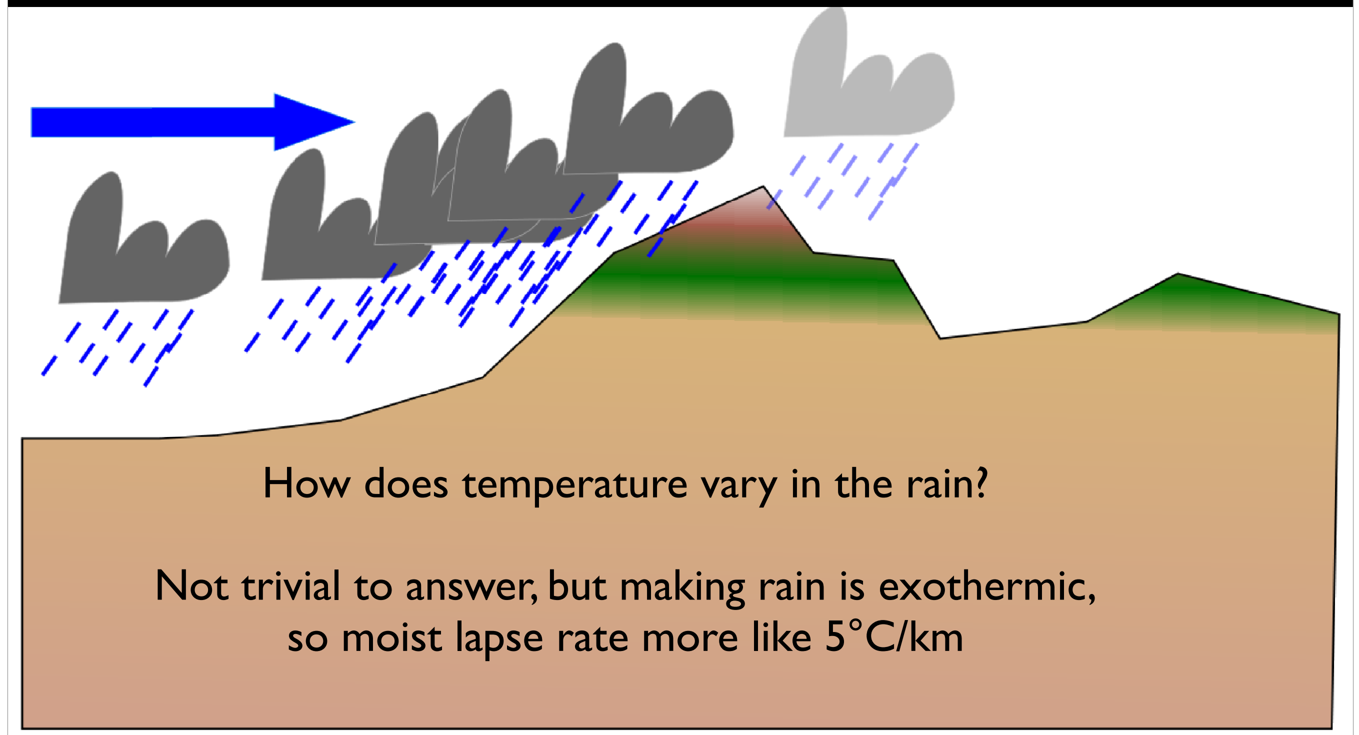

Denver Temperature Profile, 20 December 2004
TMAX
Elevation (ft)
Elevation (feet)
Longitude (°E)
80
60
40
20
12500
10000
7500
5000
-107.5
-107
-106.5
-106
-105.5
-105
-104.5
-104


DIvide to Denver Basin, 20 Dec 2004
y = 89.566 - 0.0053897x R= 0.94891
Maximum Temperature (°F)
Elevation (ft)
70
60
50
40
30
20
5000
6000
7000
8000
9000
10000
11000
12000

Paleoaltimetry

What varies with elevation?

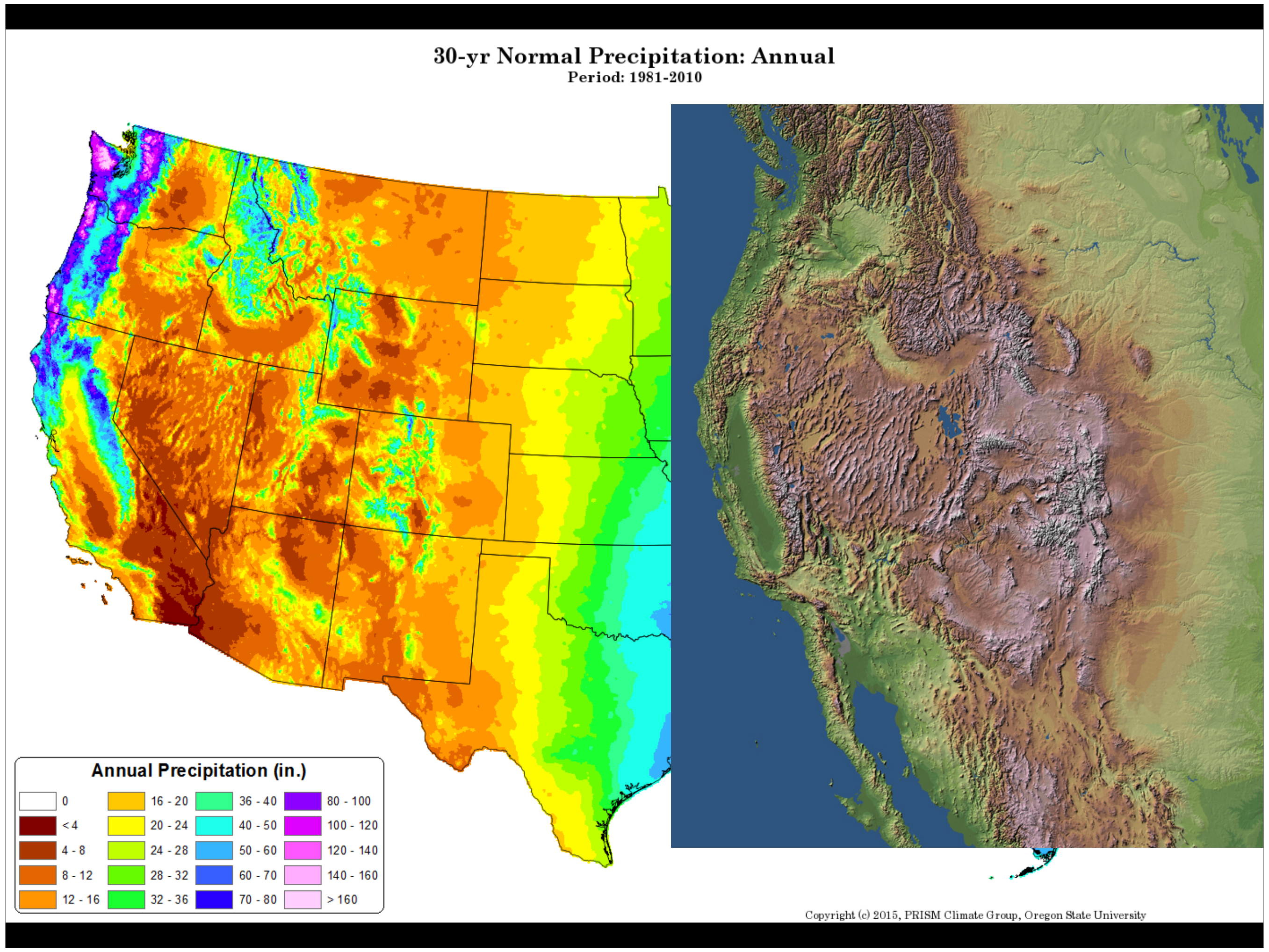
- Temperature (dry lapse rate 9.8°C/km)


How does temperature vary in the rain?
Not trivial to answer, but making rain is exothermic,
so moist lapse rate more like 5°C/km

Paleoaltimetry

What varies with elevation?

- Temperature (dry lapse rate 9.8°C/km, moist ~5°/km)
- Precipitation



Locally well correlated, but at broader scales more going on

Paleoaltimetry

What varies with elevation?

- Temperature (dry lapse rate 9.8°C/km, moist ~5°/km)
- Precipitation
- Radiation
- Air pressure
- Slopes (derivative)

Gravity, too, but nobody has found that to be a tool…

Paleoaltimetry

What varies with elevation?

- Temperature (dry lapse rate 9.8°C/km, moist ~5°/km)
  - Paleobotany
  - Clumped isotopes
- Precipitation
  - Paleobotany
  - Oxygen and hydrogen isotopes (Rayleigh distillation)
- Radiation
  - Cosmogenic isotopes
- Air pressure
  - Plant stomatal density
  - Bubbles in lava
- Slopes (derivative)
  - Erosion, deposition

You'd think with all these that this would be open and shut…but all of them have issues.

Paleoaltimetry

What varies with elevation?

- Temperature (dry lapse rate 9.8°C/km, moist ~5°/km)
  - Paleobotany
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- Radiation
  - Cosmogenic isotopes
- Air pressure
  - Plant stomatal density
  - Bubbles in lava
- **Slopes (derivative)**
  - **Erosion, deposition**

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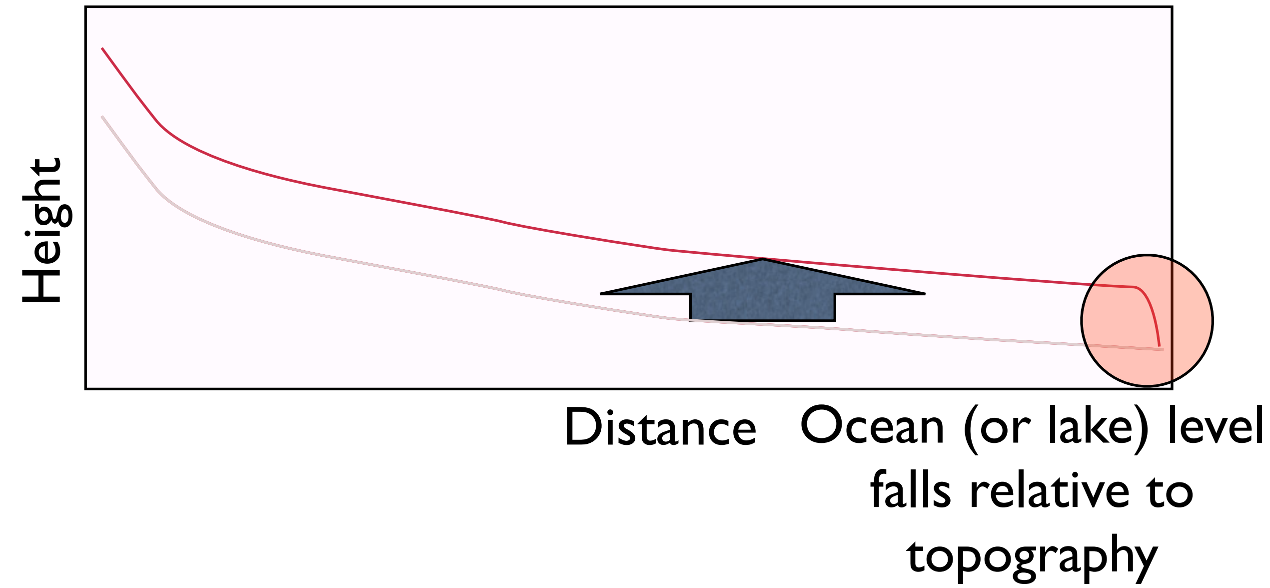
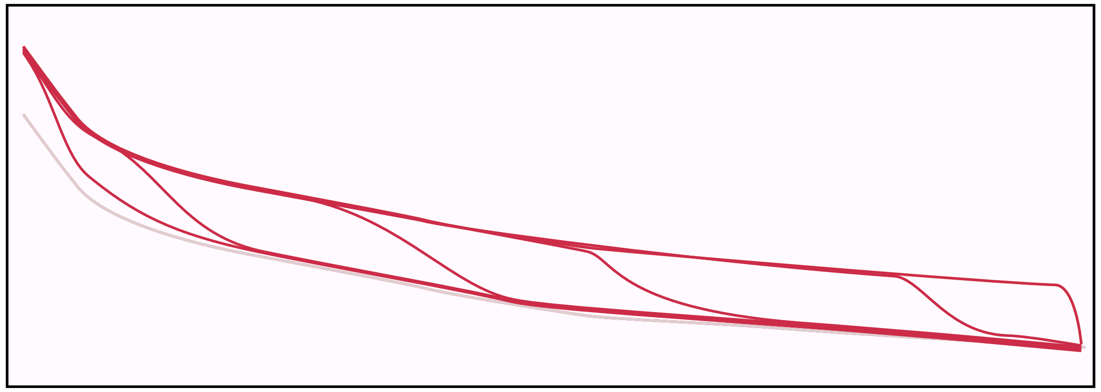
Front Range
River sediments, 5-12 Ma, cobbles from Rockies

Change in Elevation (i.e., uplift)
(or baselevel fall)



River erodes rapidly where gradient is steep...



leading to restoration of original river profile but, for quite some time, leaving remnants of old topography (peaks, canyons)

What makes streams erode?

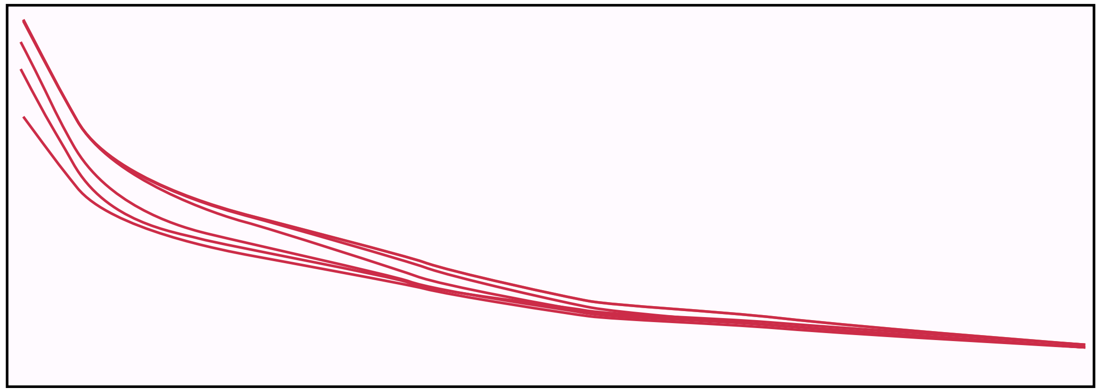
1. Faster water flows, more it can lift and carry.

2. More water flowing, more it can lift and carry.

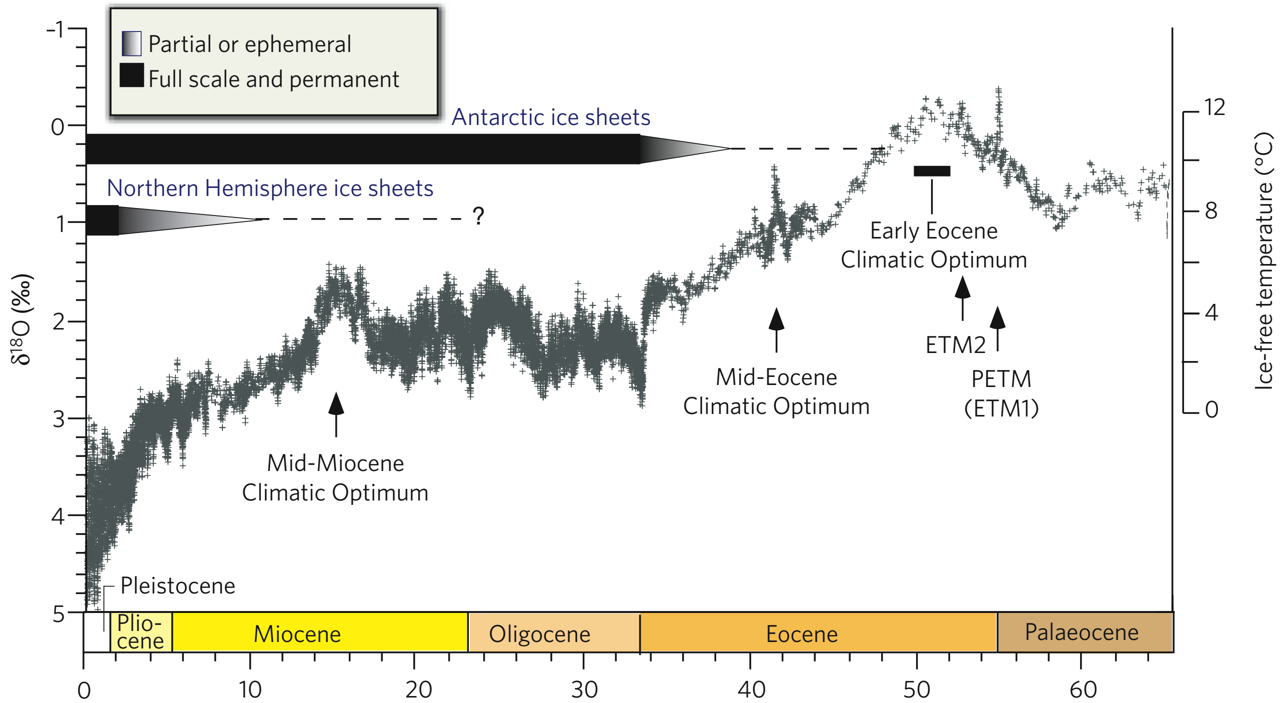
$$E = k\left(\frac{\rho g Q S}{W} - w_0\right)$$

Erosion increases as the flow rate Q (volume/unit time) increases, as W (channel width) decreases, and as S (slope) increases. Other terms constants.

Climate change:
Rivers have higher flows

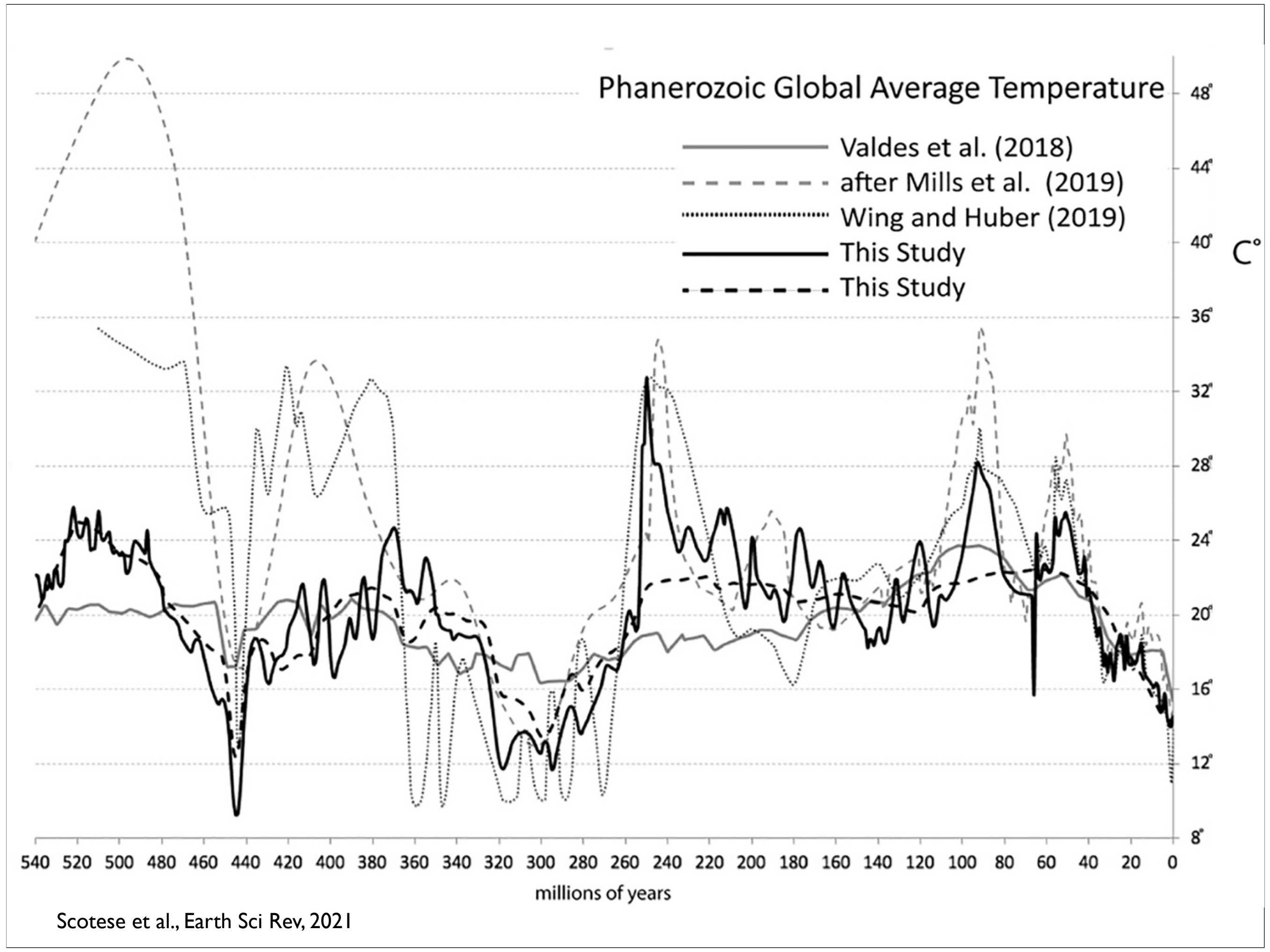


Climate has changed…

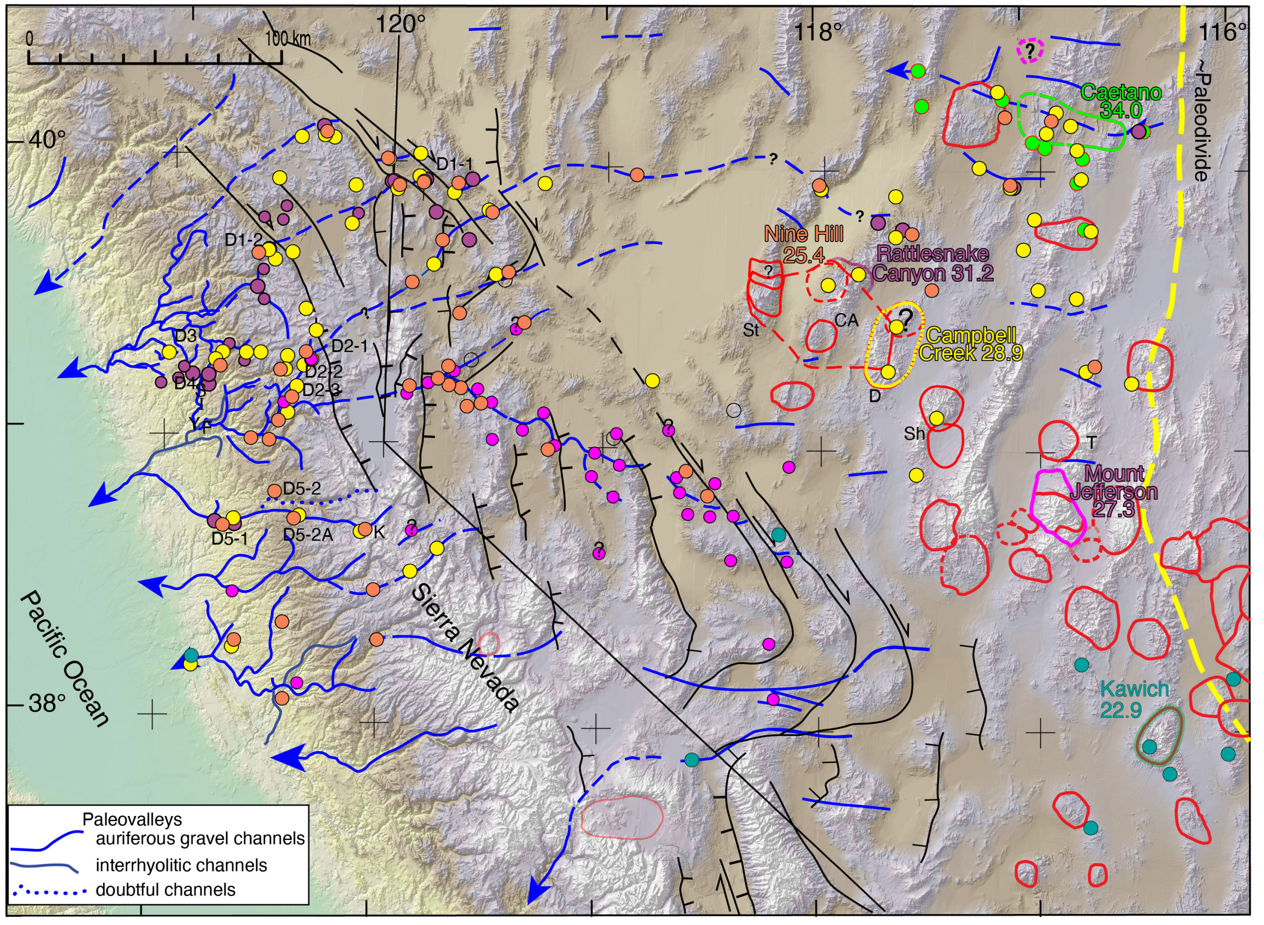


Zachos et al., *Nature*, 2008

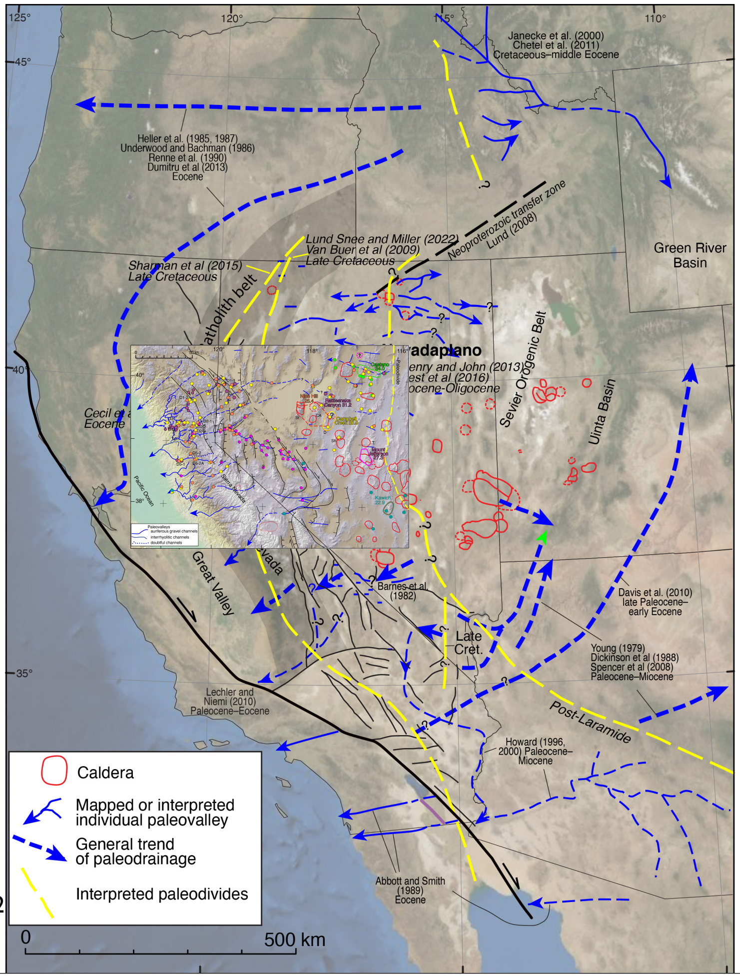
Note these are oceanic measurements…



Note these are global estimates…



Henry, GSA FF Guide, 2022



Henry, GSA FF Guide, 202

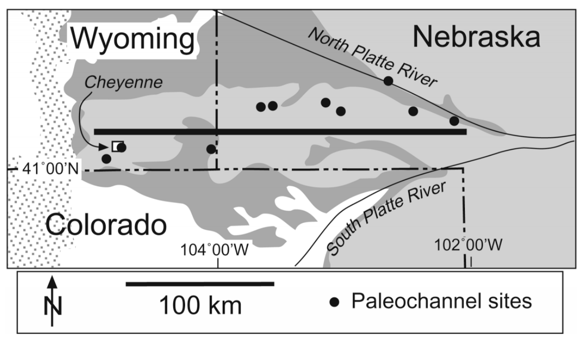


Figure 2. Map of Cheyenne Tablelands showing paleochannel sites (black dots) and transect (solid black line) from which modern slope of Ogallala Group was calculated.

McMillan et al., Geology, 2002

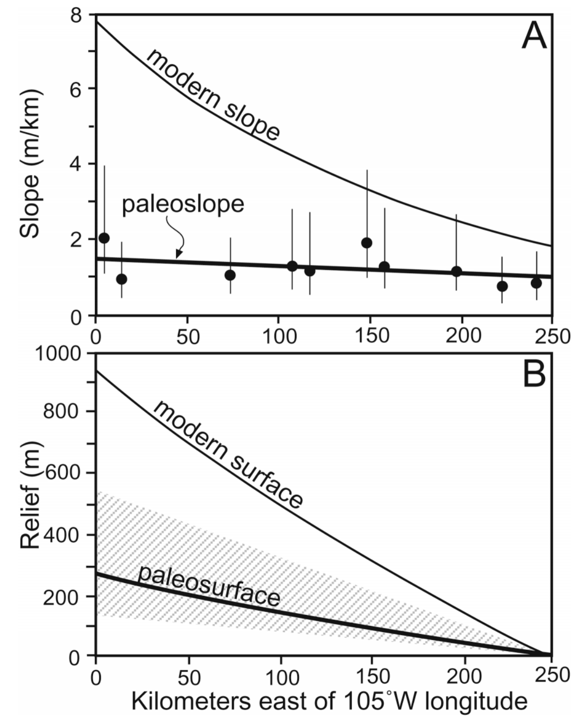


Figure 3. Postdepositional changes in slope and relief of Ogallala surface. A: Paleoslope estimates for each paleochannel site are plotted with linear fit. Vertical bars represent uncertainty (factor of 2) in paleoslope estimates. Modern slope is derived from base of Ogallala Group. B: Paleorelief is derived from integration of paleoslope estimates over 250 km transect. Shaded area represents uncertainty. Relief of modern surface is exponential fit of base topography. Change in relief is relative to fixed hinge point at eastern edge of study area.

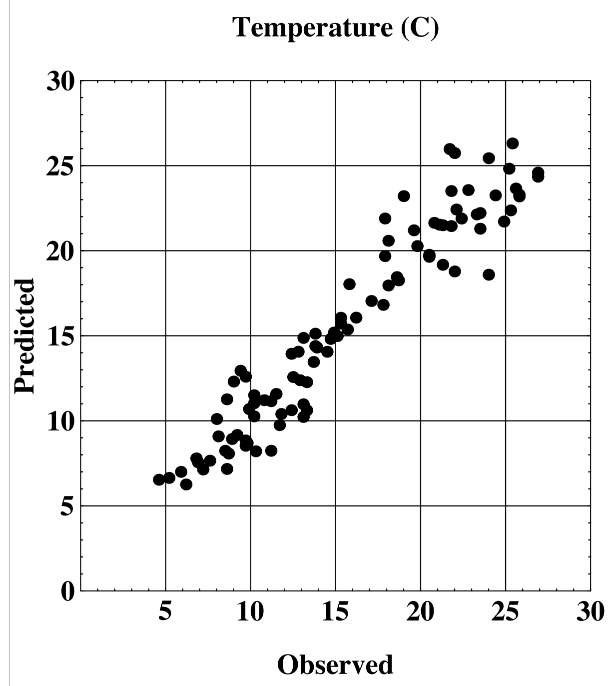
Not exactly paleoaltimeter, but use of sedimentology should tell of tilts (but watch the assumptions carefully).

Paleoaltimetry

What varies with elevation?

- Temperature (dry lapse rate 9.8°C/km, moist ~5°/km)
  - **Paleobotany**
  - Clumped isotopes
- Precipitation
  - Paleobotany
  - Oxygen and hydrogen isotopes (Rayleigh distillation)
- Radiation
  - Cosmogenic isotopes
- Air pressure
  - Plant stomatal density
  - Bubbles in lava
- Slopes (derivative)
  - Erosion, deposition

You'd think with all these that this would be open and shut…but all of them have issues.



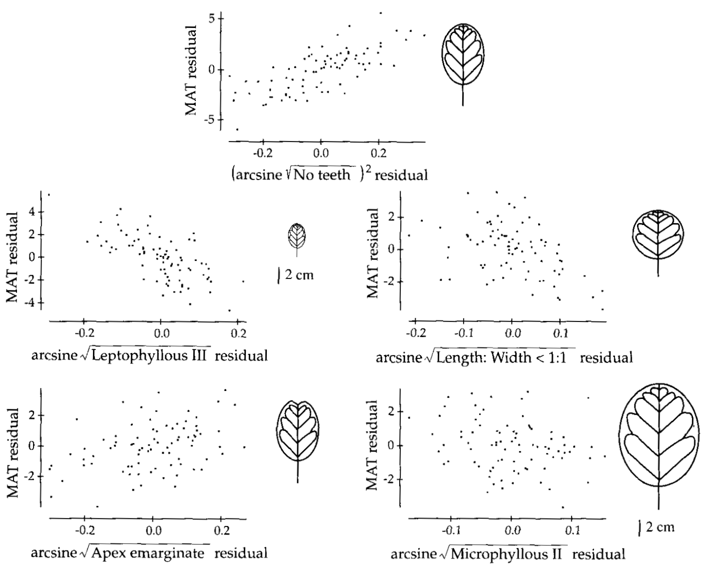


Figure 1. Partial regression plots for leaf physiognomic characters included in multiple regression model. These plot adjusted mean annual temperature (MAT) vs. adjusted *x*, where adjusted = *linear dependency of other xs removed. Plots show variable's individual contribution to regression model after removing multicollinearity.* Characters are arranged by significance as measured by t ratio (see Table 1). Diagram of leaf characteristic is shown to right of corresponding graph.

Forest et al., , GSA Bull 1999

Gregory and Chase, Geology 1992

$$\text{Elevation} = \frac{(\text{sea-level MAT} - \text{flora MAT})}{\text{terrestrial lapse rate}} + \text{sea level,}$$

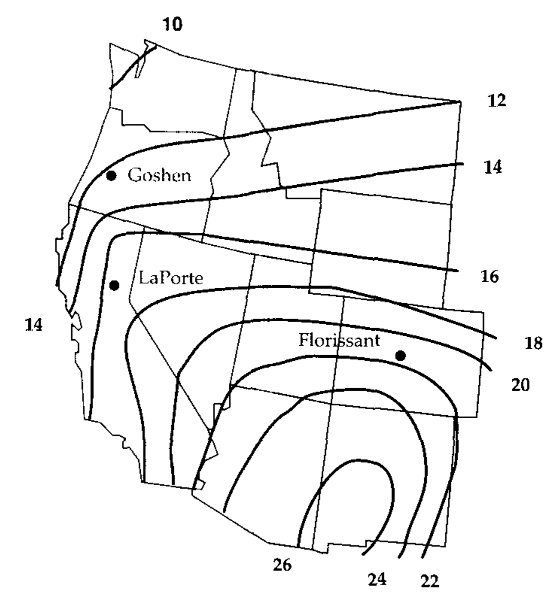


Figure 2. Mean annual temperature (MAT) at sea level in °C for modern western United States. Note that MAT increases inland due to effects of continentality and elevated base level. Redrawn after Meyer (1986).

Gregory and Chase, Geology 1992

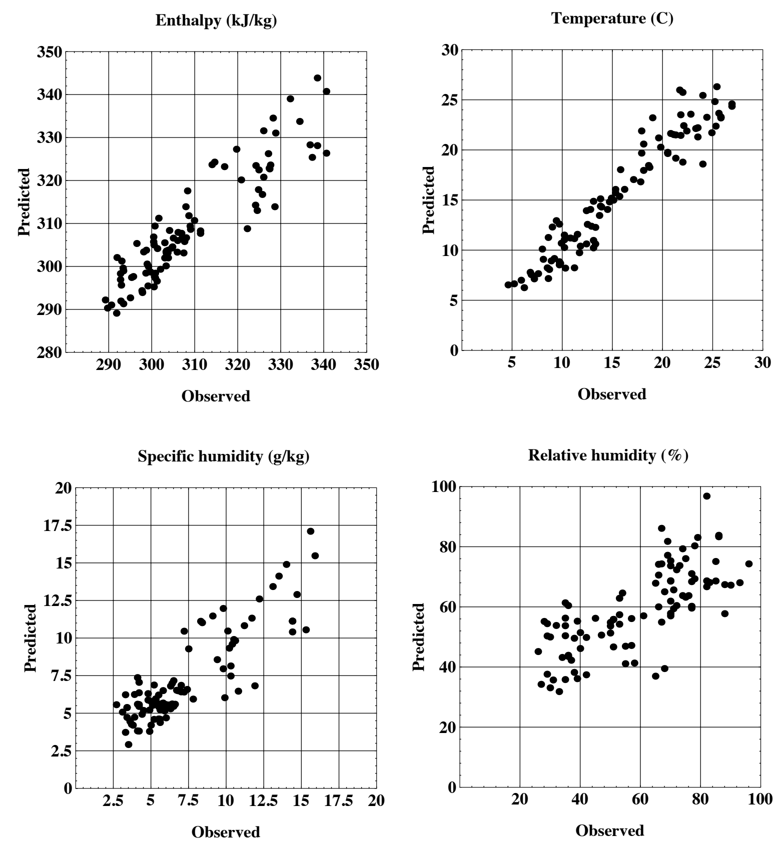


Figure 8. The predictions of the climate parameters from the plant character state variables as given by canonical correspondence analysis are plotted vs. the observations for the plant collection sites for mean annual enthalpy (kJ/kg), temperature (°C), specific humidity (g/kg), and relative humidity.

$$h = c_P' T + L_V q + gZ$$
$$= H + gZ$$

$$Z = \frac{H_{\text{sea level}} - H_{\text{high}}}{g}$$

Forest et al., , GSA Bull 1999

moist static energy (h) is moist enthalpy (H) plus GPE--H is temperature times heat capacity of moist air plus latent heat of vaporization of water times specific humidity. If h is conserved, then differences in H give elevation

Moist static energy in atmosphere today

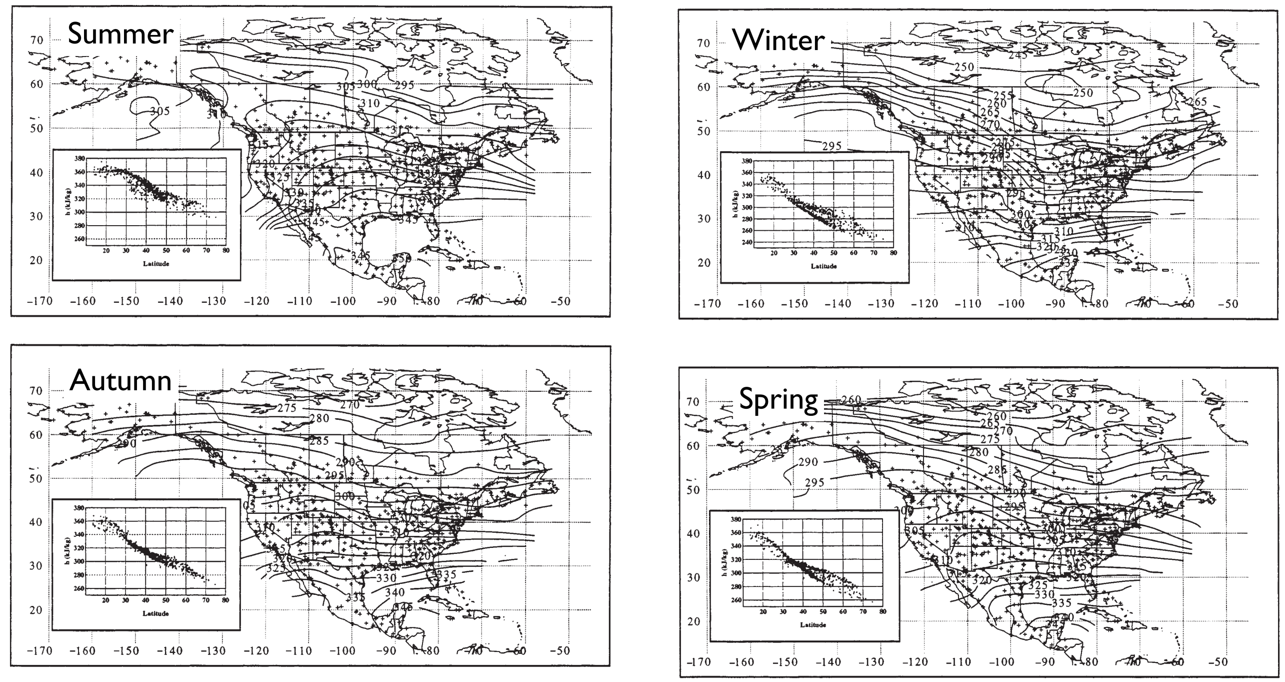


Figure 5. Same as top of Figure 3, except for summer (top) and autumn (bottom).

Figure 4. Same as top of Figure 3, except for winter (top) and spring (bottom) seasons.

$$h = c_P' T + L_V q + gZ = H + gZ$$

Forest et al., , GSA Bull 1999

So is moist energy h preserved?

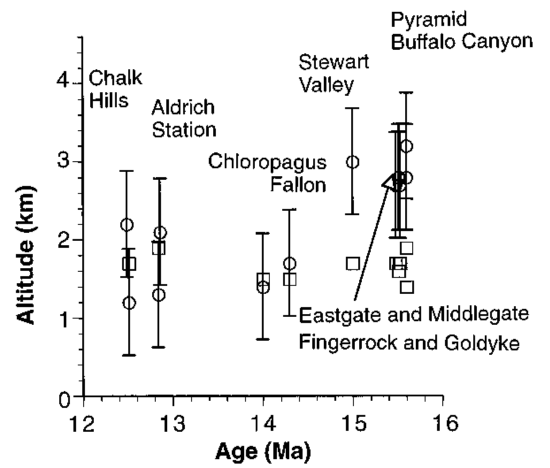


Fig. 3. Paleoaltitudinal estimates for middle Miocene leaf assemblages of western Nevada (circles) versus time. The altitude estimates for assemblages from ~15 to 16 Ma are consistently higher than present-day altitudes (denoted by squares), whereas late middle Miocene (12 to 14 Ma) assemblages have estimates that are close to present-day altitudes.

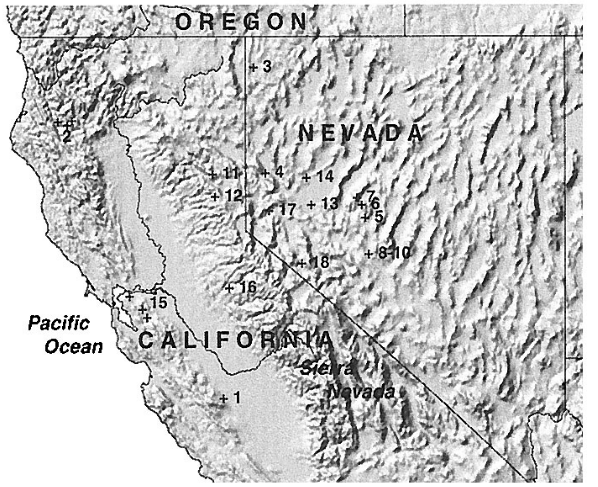


Fig. 2. Map of part of California and Nevada showing the present-day topography and the Miocene fossil sites (+) that produced the collections of leaves analyzed in this report. Numbers coordinate with those in parentheses after the assemblage names in Table 1. Not shown is Molalla, which is about 50 km southeast of Portland, Oregon, on the eastern side of the Willamette Valley.

Wolfe et al., Science 1997

Paleoaltimetry

What varies with elevation?

- Temperature (dry lapse rate 9.8°C/km, moist ~5°/km)
  - Paleobotany
  - Clumped isotopes
- Precipitation
  - Paleobotany
  - Oxygen and hydrogen isotopes (Rayleigh distillation)
- Radiation
  - Cosmogenic isotopes
- Air pressure
  - **Plant stomatal density**
  - Bubbles in lava
- Slopes (derivative)
  - Erosion, deposition

You'd think with all these that this would be open and shut…but all of them have issues.

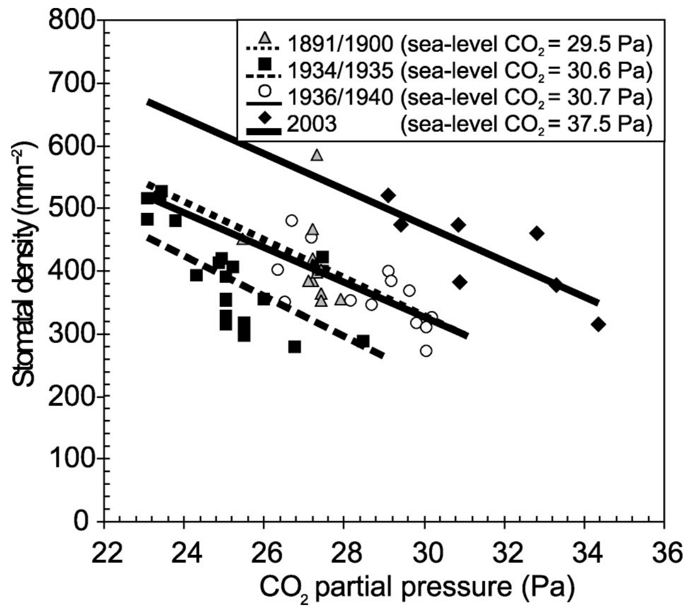


Figure 3. Historical and modern stomatal density (SD) data sets of *Quercus kelloggii* vs. pCO_2 from herbarium leaves (sun + shade) collected in (1) 1891–1900, (2) 1934–1935, (3) 1936–1940, and recent field collections, (4) 2003, demonstrating similar SD response rates—(1) −30.273, (2) −32.046, (3) −27.756, and (4) −28.528, respectively—to decreasing pCO_2 but different intercepts.

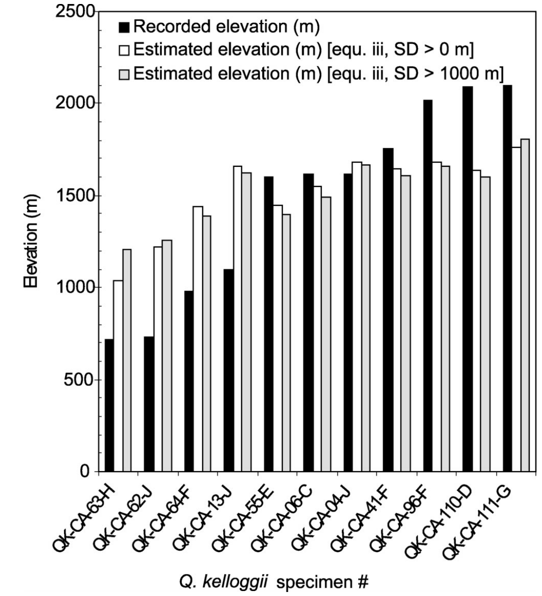


Figure 4. Actual (black bars) vs. estimated elevations of *Quercus kelloggii* collected in 2003 based on mean stomatal density (SD) of one leaf sample per tree or shrub. White and gray bars indicate elevations estimated by using equation 3, where cd_2 was estimated using linear transfer function (SD vs. pCO_2 for 1934–1935 specimens from >1000 m, Fig. 2) and nonlinear shade-leaf transfer function (SD vs. pCO_2 for 1934–1935 specimens from >0 m), respectively. Table DR2 (see footnote 1 in text) gives geographical and ecological setting of each *Q. kelloggii* specimen.

$$pp(z) = 101{,}325^{(-m_{\mathrm{air}} g z / \mathrm{R} t)},$$

$$(z) = \ln\left(\frac{cd_2}{cd_1}\right)\mathrm{R}\frac{t}{-m_{\mathrm{air}} g},$$

$$cd_2(z) = \frac{pp(z)}{101{,}325} cd_1,$$

McElwain, Geology 2004

pp is partial pressure of CO2 as a function of elevation, cd2

Paleoaltimetry

What varies with elevation?

- Temperature (dry lapse rate 9.8°C/km, moist ~5°/km)
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  - Clumped isotopes
- Precipitation
  - Paleobotany
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Deuterium variations in surface water

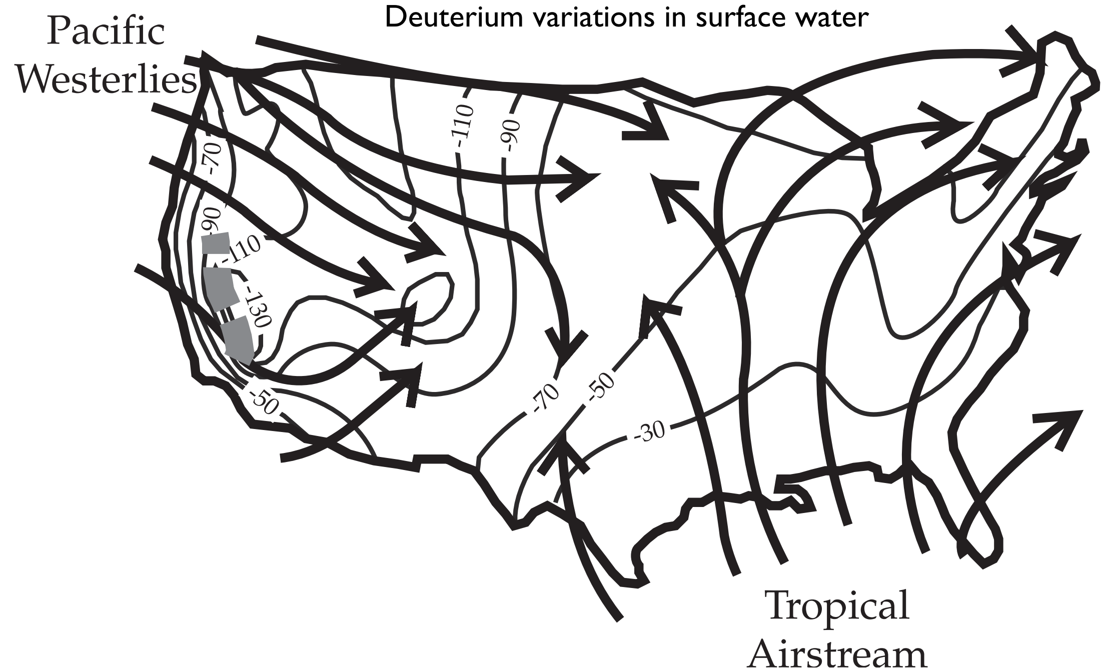


Figure 2. Map showing the principal winter season circulation patterns (arrows) and moisture sources of the United States [from *Bryson and Hare*, 1974]. Also shown are contoured δD values of surface waters and precipitation [from *Dansgaard*, 1964; *Friedman et al.*, 1964]. The approximate position of the Sierran crest is indicated by the thick dashed line. The major isotopic anomaly in eastern California and western Nevada results from the interception of westerly airstreams by the Sierra Nevada and isotopic distillation during rainout in passage across the mountains.

Poage and Chamberlain, Tectonics 2002

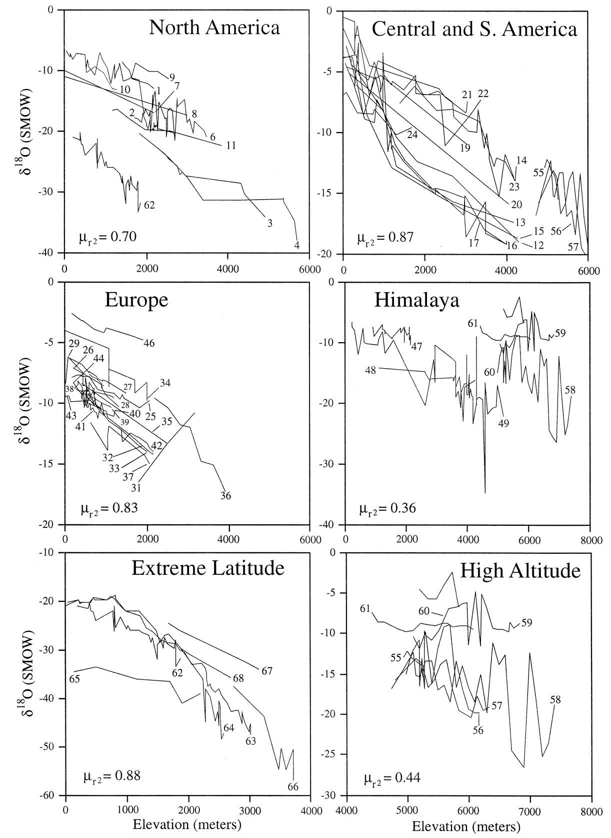
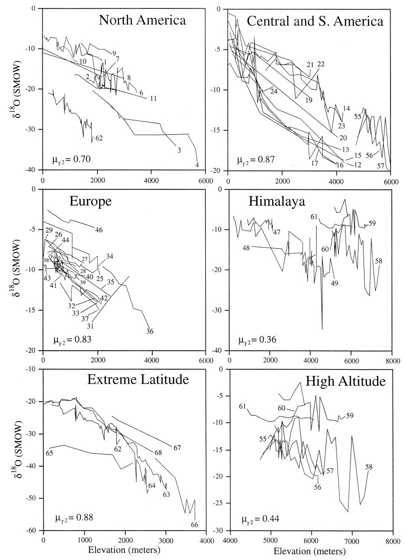


Fig. 1. Raw data for all studies used in this paper. Studies from North America Europe, Central and South America, and the Himalayas are grouped together. In addition, studies from extreme northern and southern latitudes (>70°) and studies from exclusively high altitudes (>~5000 m) are grouped together. Note that there is some overlap between groups as several studies fall into more than one category. The average r^2 value for each category is shown as μ_{r2} and provides a sense of the linearity of individual studies in each group.

Poage and Chamberlain, Am J Sci 2001



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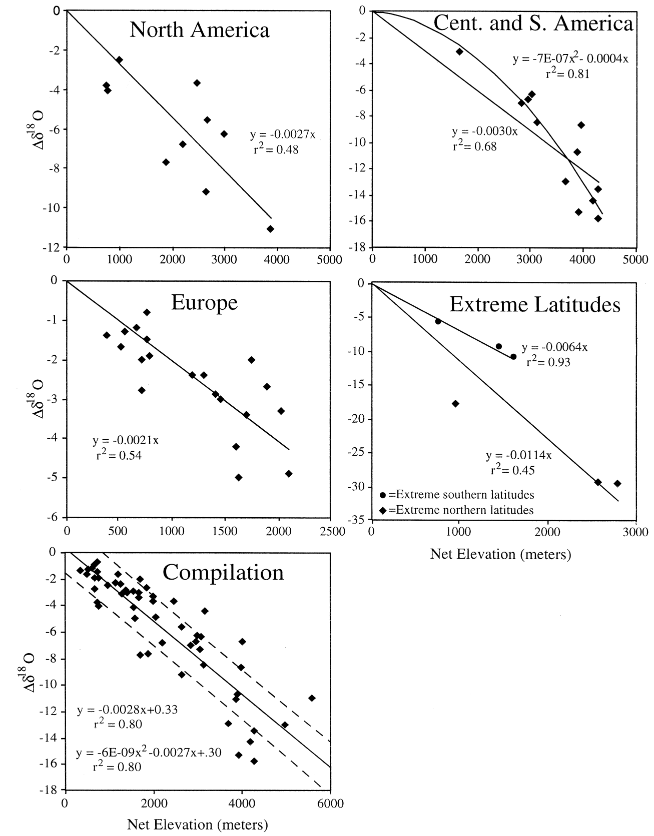
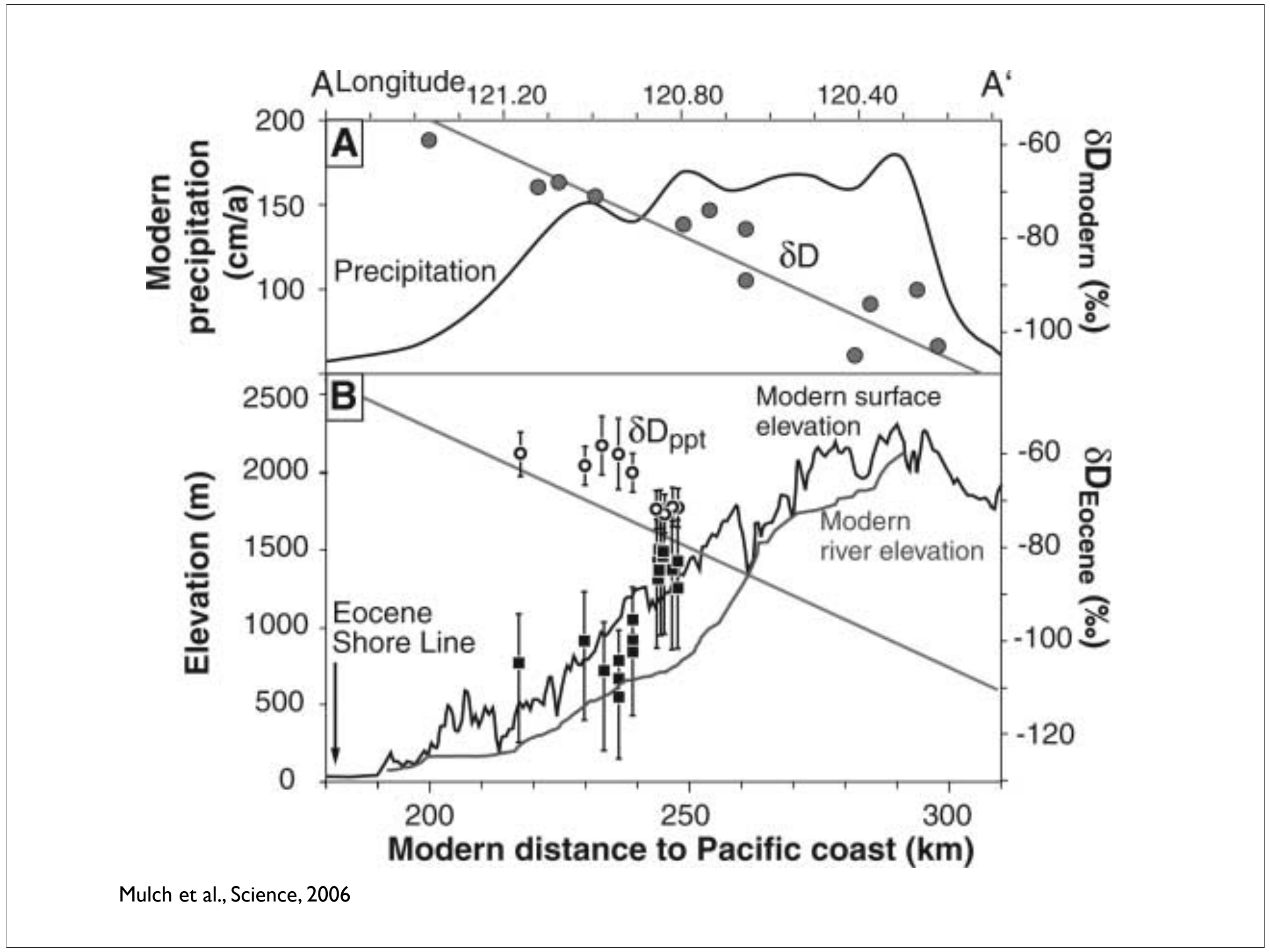
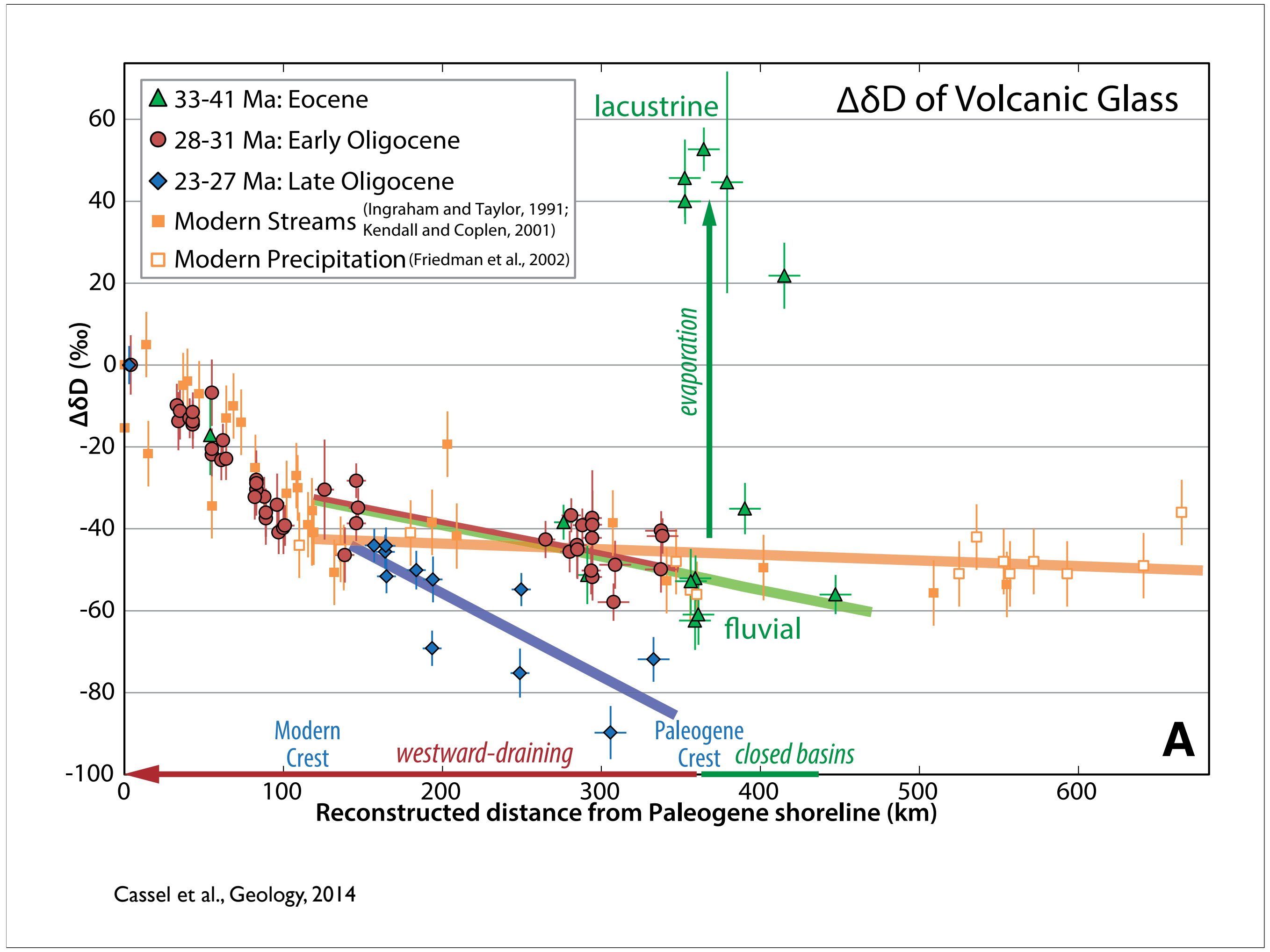


Fig. 2. Plots of the change in $\delta^{18}O$ of precipitation versus net elevation change. The North America, Central and South America, and Europe categories are the same as in figure 1. High altitude studies (#'s 55,56,57) are excluded from the Central and South America plot due to low r^2 values. We include no plot for the Himalayas due to poor r^2 values. The Extreme Latitude grouping of figure 1 is broken into northern and southern groupings. Also included is a Compilation plot showing all the data from North America, Central and South America, Europe, as well as studies 50 to 54. The best fit regression line shown on each graph is forced through the origin except for the Compilation plot. Also shown on the Central and South America category is the best fit polynomial curve. The regression on the Compilation plot is not forced through the origin for purposes of calculating the predictive error; however, this does not change the slope of the regression line significantly. The calculated 1 standard error envelope is shown on the Compilation plot. The best fit polynomial curve for the Compilation plot is indistinguishable from the best linear fit.

Poage and Chamberlain, Am J Sci 2001



Bottom panel squares are inferred elevations from the dD values in circles.



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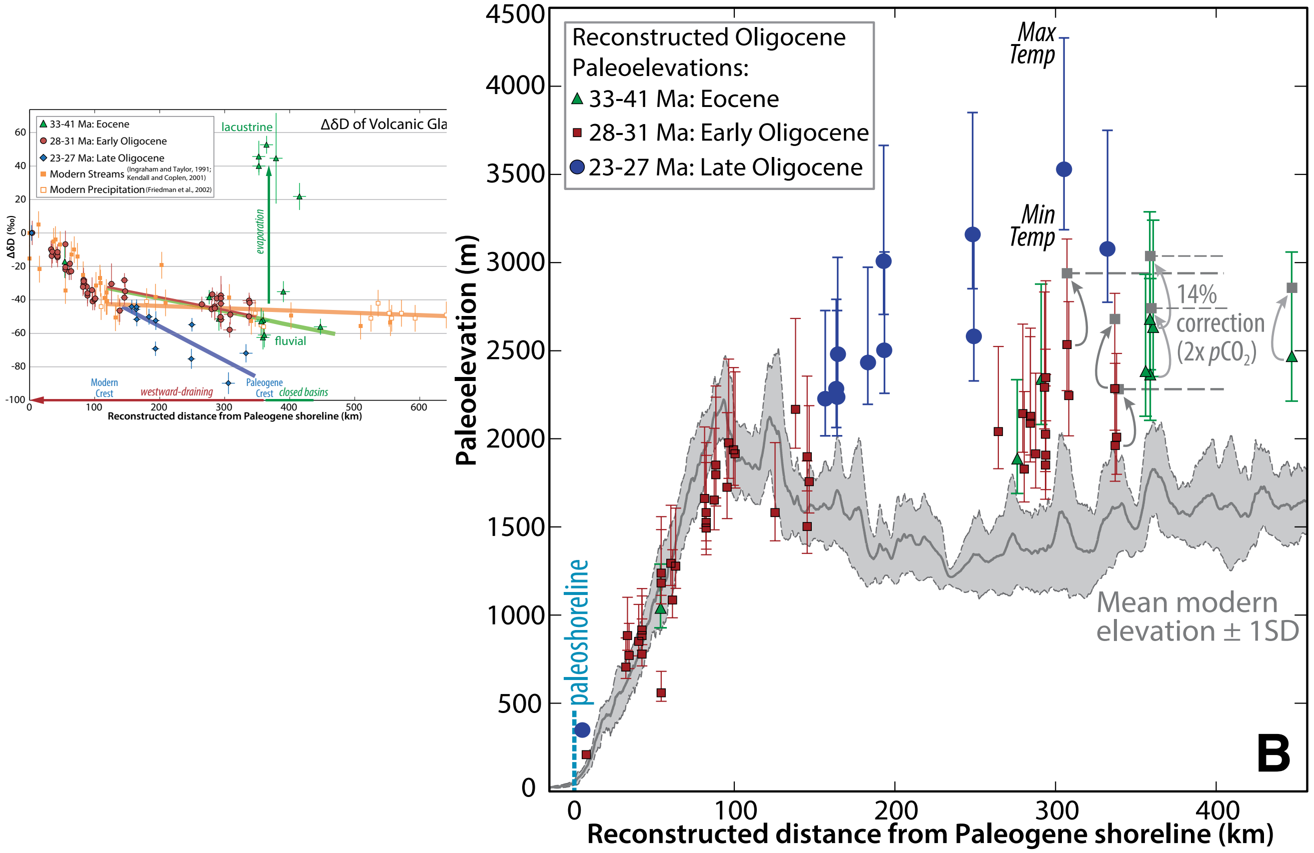
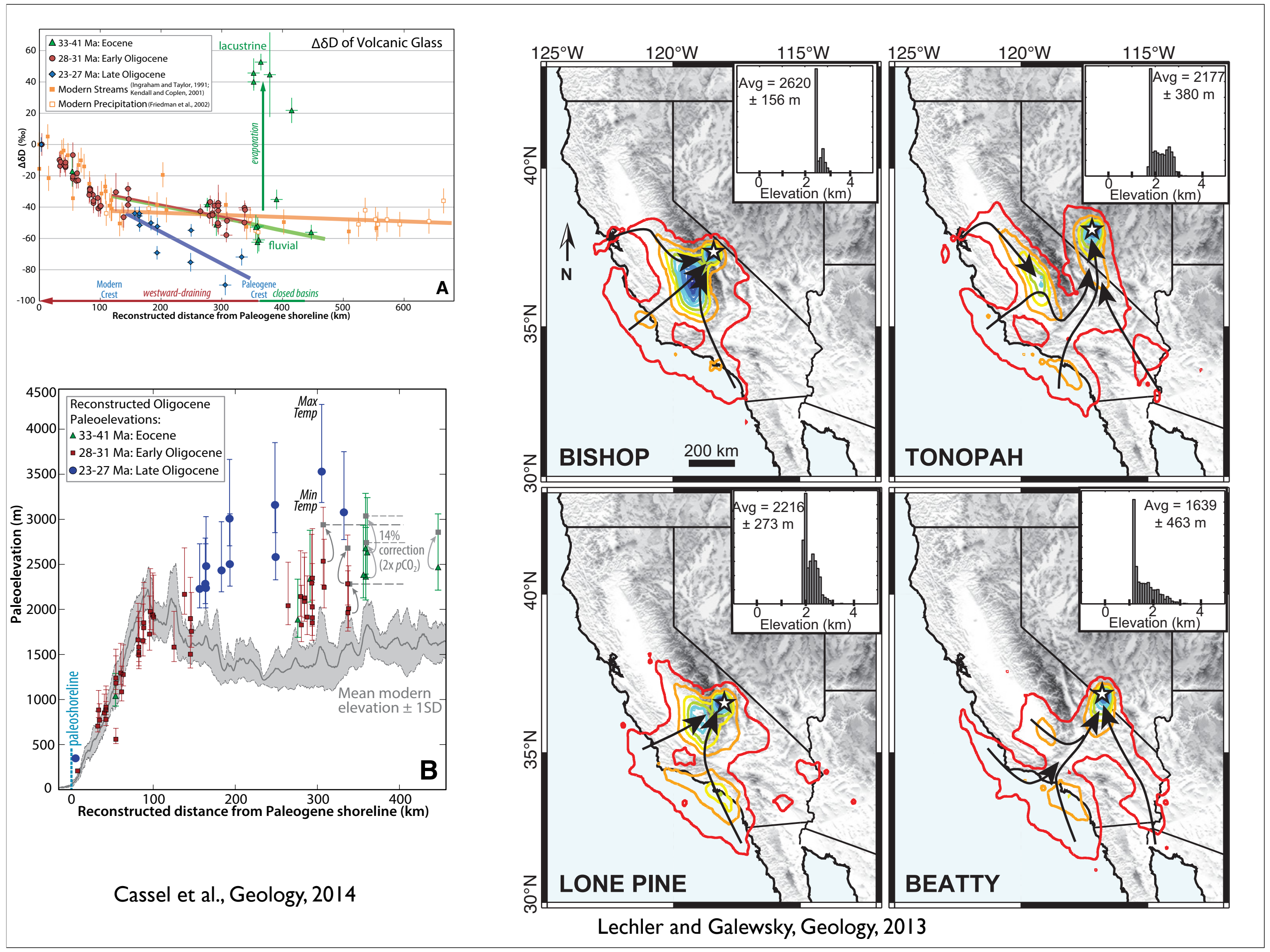


Cassel et al., Geology, 2014

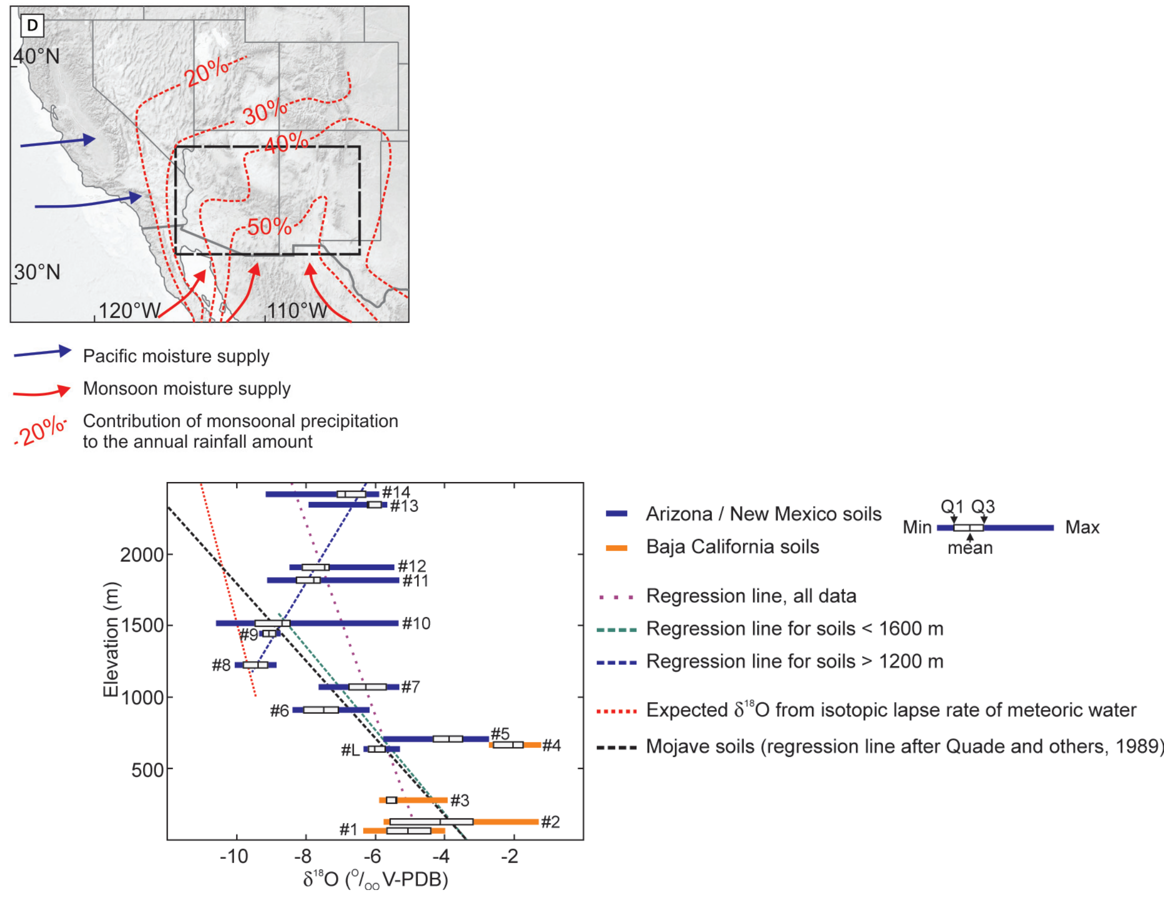
Bottom panel squares are inferred elevations from the dD values in circles.



Cassel et al., Geology, 2014

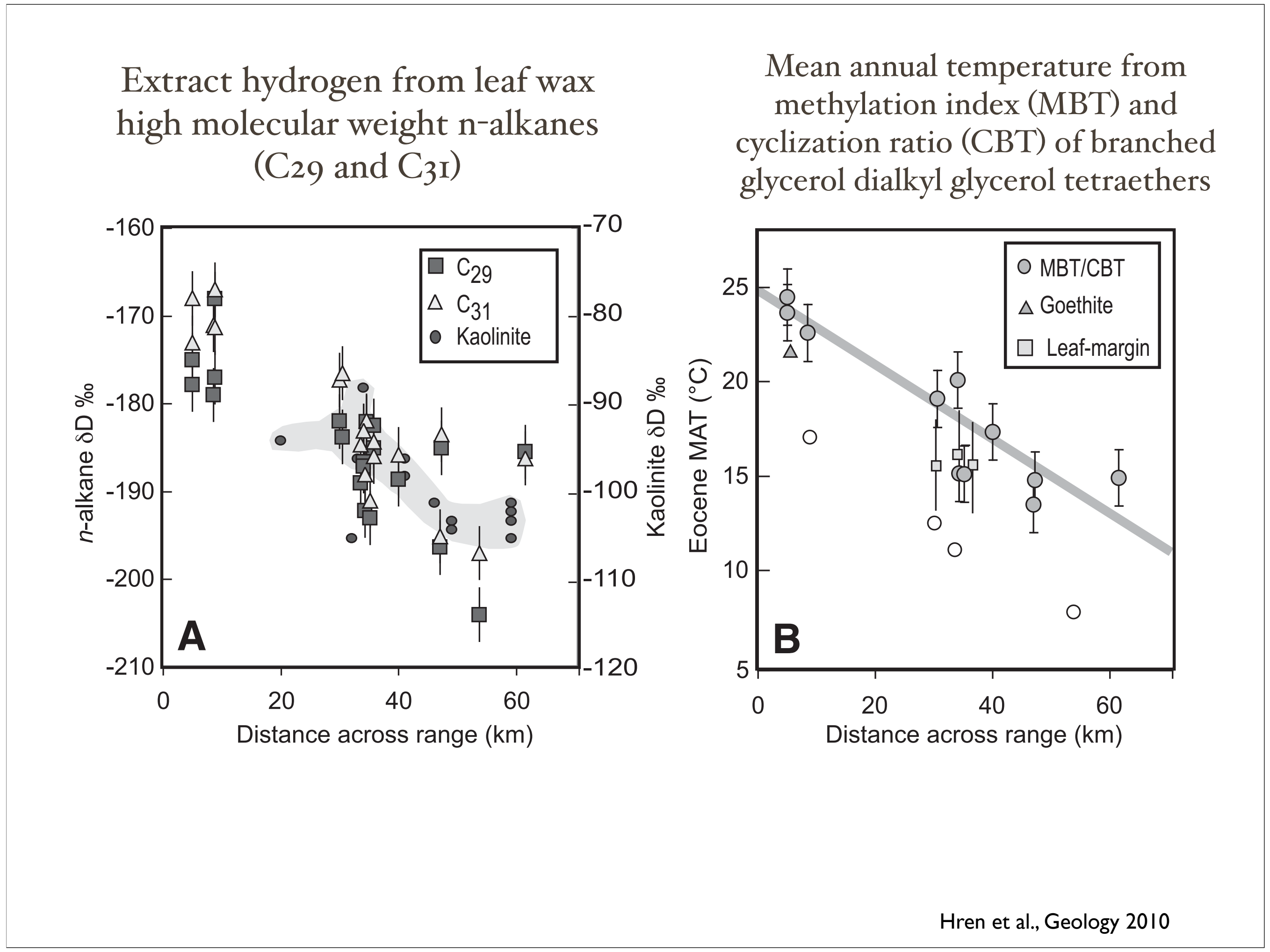
Lechler and Galewsky, Geology, 2013

But moisture moves around in complex ways—virtually all these proxies need a solid grounding in the climate



Licht et al., Am J Sci, 2017

Monsoon in American SW can throw things into serious disarray—these are measurements from pedogenic carbonates (such as might be used for clumped isotope work).



More recent work has indicated that you need to know what kind of vegetation is providing these organic molecules. There is some evidence of some fractionation in some climates as well—quite a literature blooming using this.

Paleoaltimetry

What varies with elevation?

- Temperature (dry lapse rate 9.8°C/km, moist ~5°/km)
    - Paleobotany
    - **Clumped isotopes**
- Precipitation
    - Paleobotany
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You'd think with all these that this would be open and shut…but all of them have issues.

=47

$$^{13}C^{16}O_3^{\,2-} + {}^{12}C^{18}O^{16}O_2^{\,2-} = {}^{13}C^{18}O^{16}O_2^{\,2-} + {}^{12}C^{16}O_3^{\,2-}$$

Favored when colder

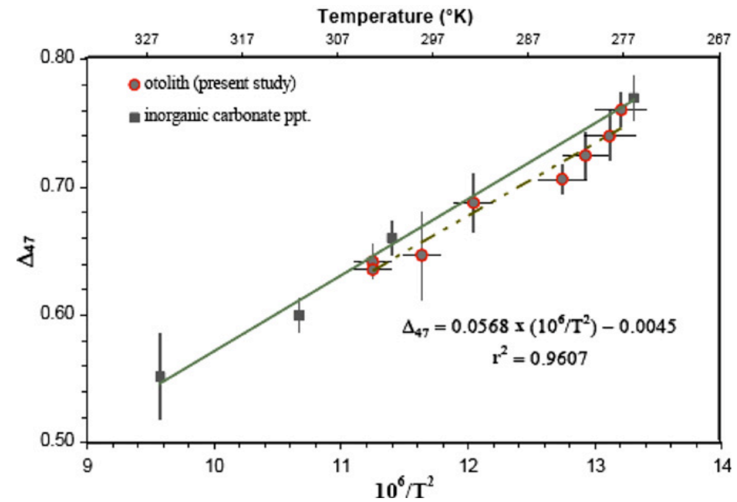


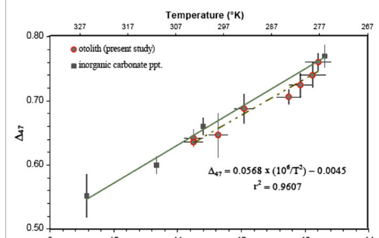
Fig. 2. Relationship between estimated environmental temperatures at which sampled fishes lived and Δ_{47} values of CO_2 produc phosphoric acid digestion of fish otoliths (plotted as filled circles). Data for inorganic calcite (plotted as filled squares) grown in the labor under controlled conditions (Ghosh et al., 2006) are shown for comparison.

Ghosh et al., Geochem. Cosmo. Acta, 2007

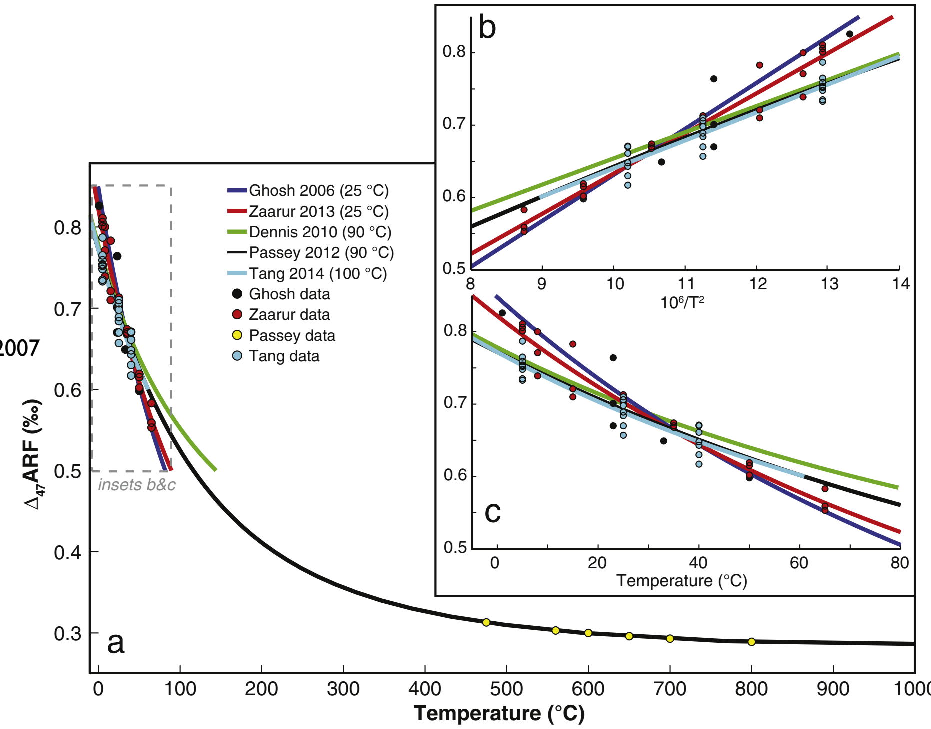
=47

$$^{13}C^{16}O_3^{2-} + {}^{12}C^{18}O^{16}O_2^{2-} = {}^{13}C^{18}O^{16}O_2^{2-} + {}^{12}C^{16}O_3^{2-}$$

Favored when colder

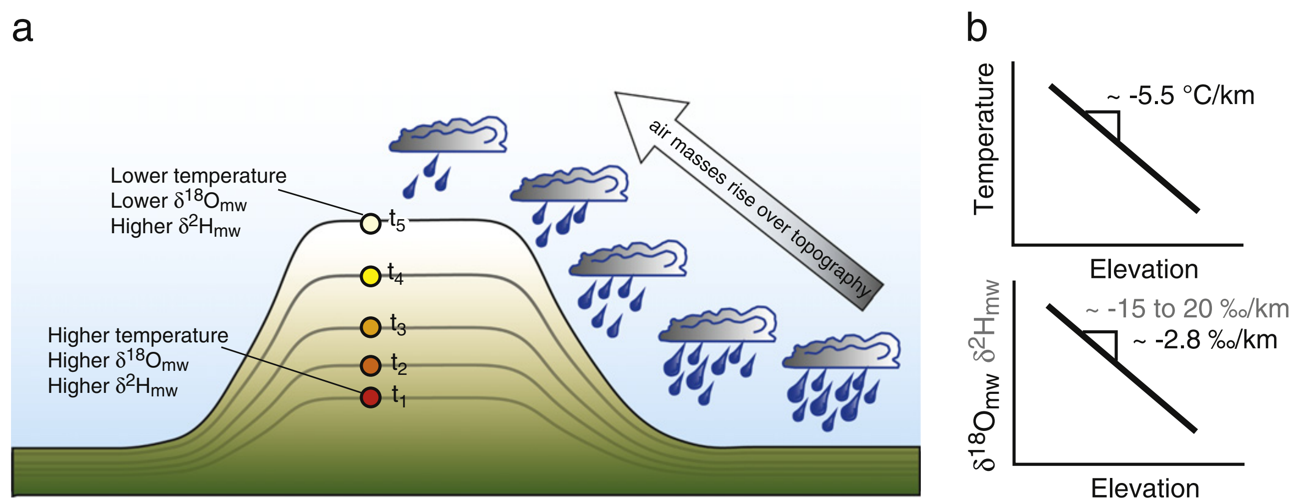


Ghosh et al., Geochem. Cosmo. Acta, 2007

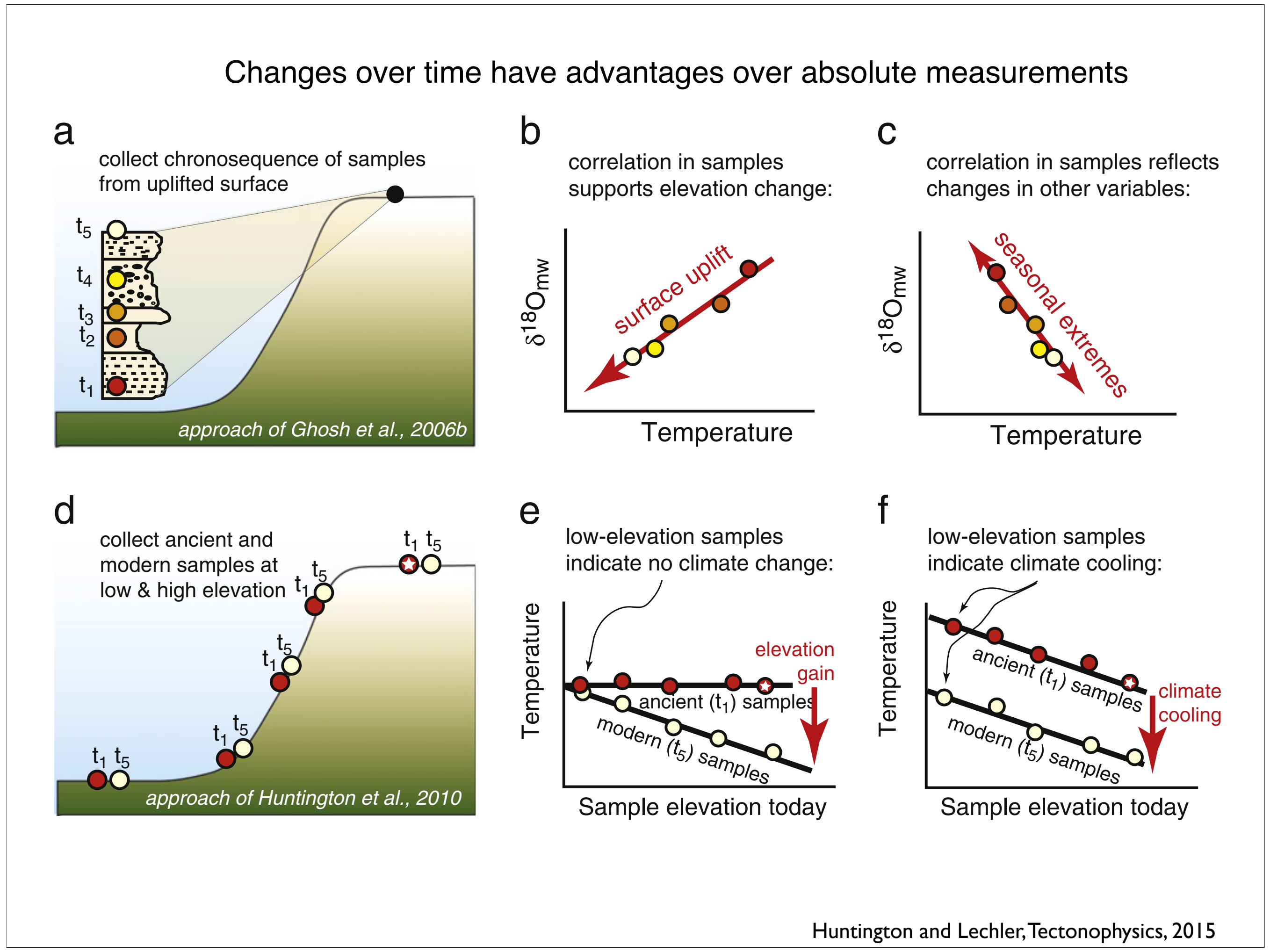


Huntington and Lechler, Tectonophysics, 2015

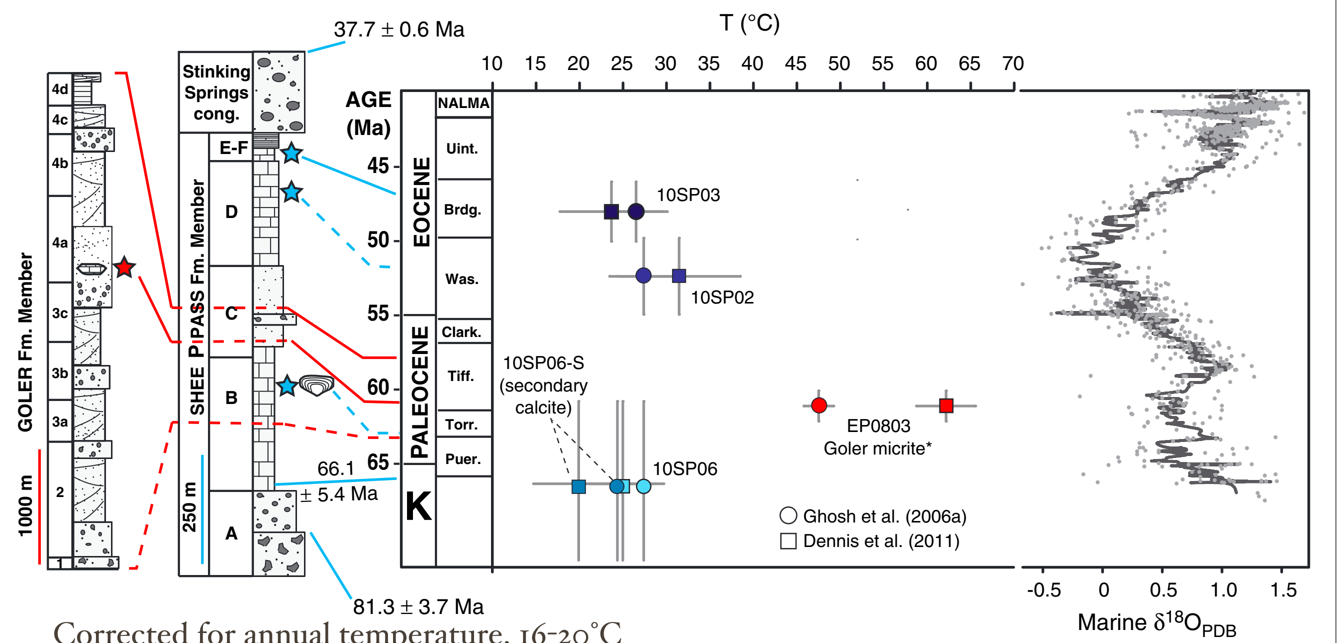
Clumped isotope approach can get temperatures and isotopes…



Huntington and Lechler, Tectonophysics, 2015

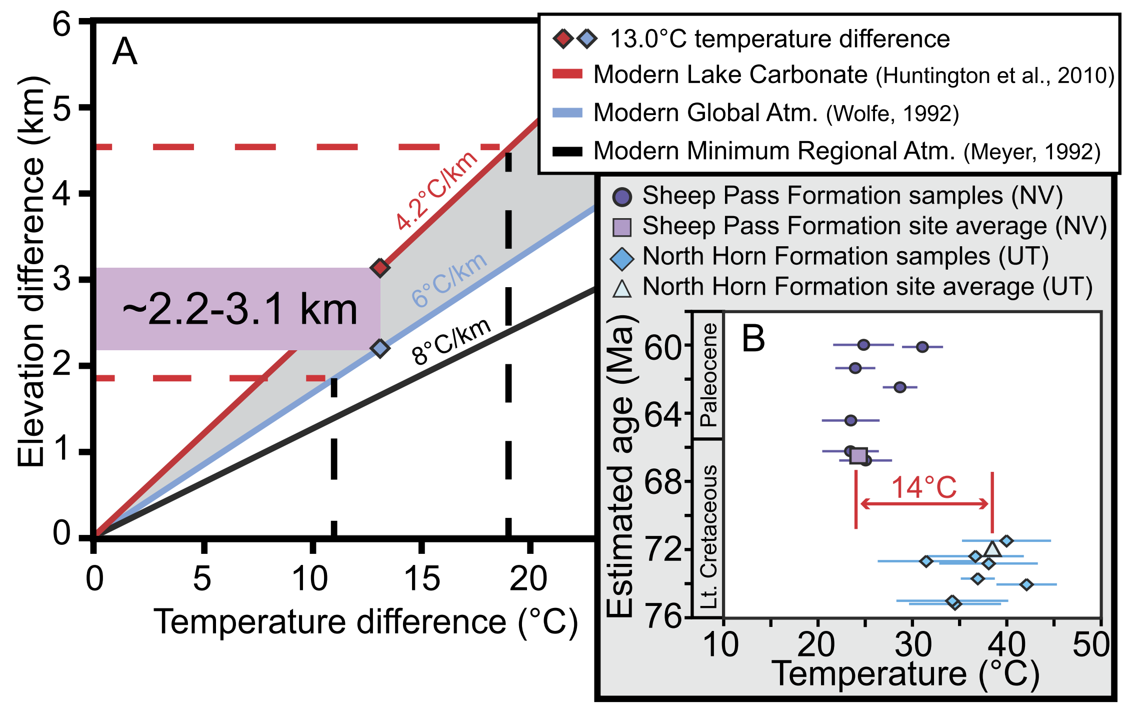


The problems with clumped isotopes revolve around precipitation of the carbonate (seasonal? which season?) and diagenesis



Corrected for annual temperature, 16-20°C
Compared to Eocene shoreline in Sierra 20-25°C from various proxies yields elevations <2 to ~2 km

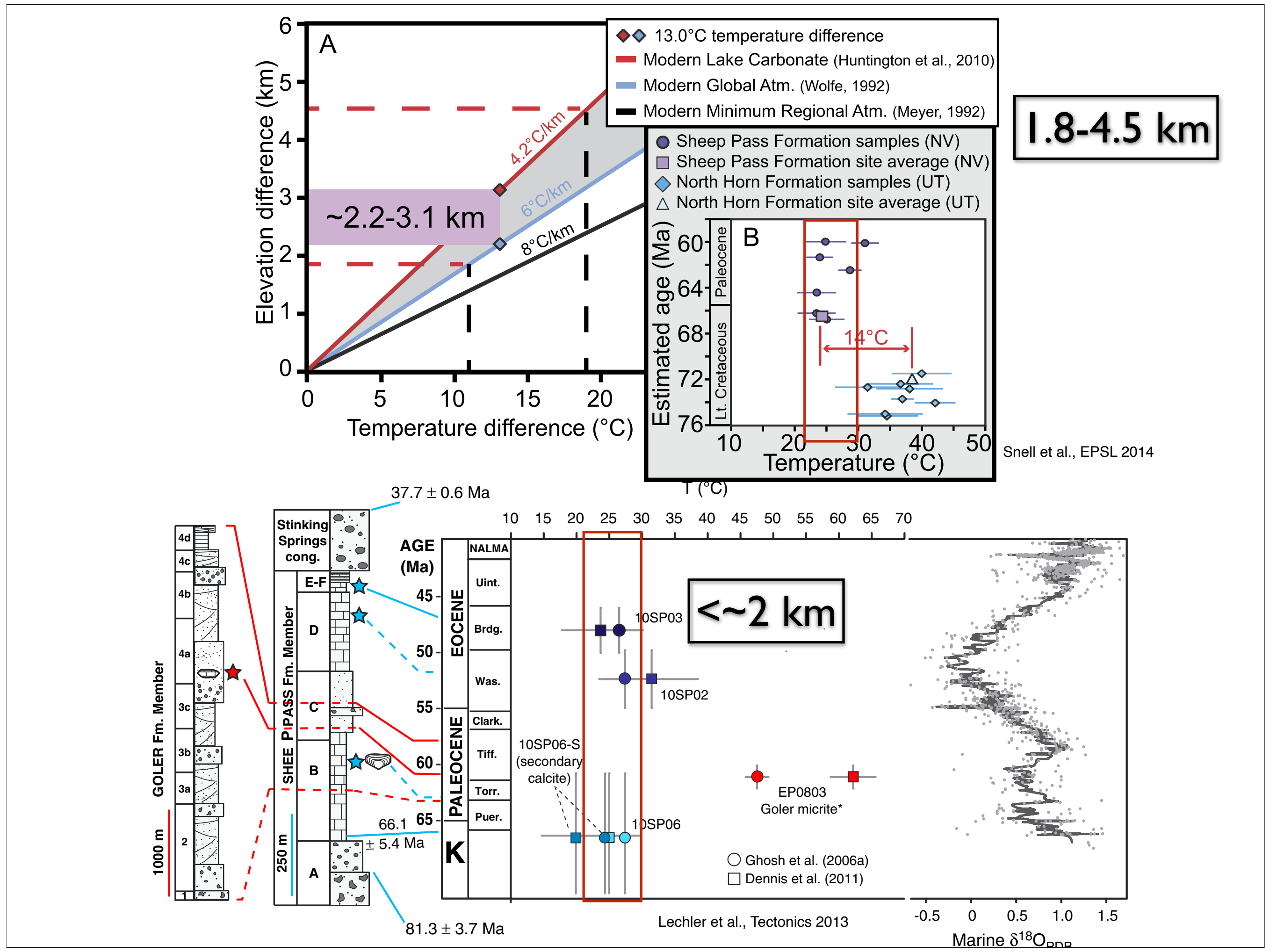
Lechler et al., *Tectonics*, 2013



Compared to nearshore (?) deposits to east (North Horn) yields elevations 2.2-3.1 km

Snell et al., *EPSL*, 2014

Now you could say these agree at 2 km, but each paper argues away from that number. But note the raw temperatures are



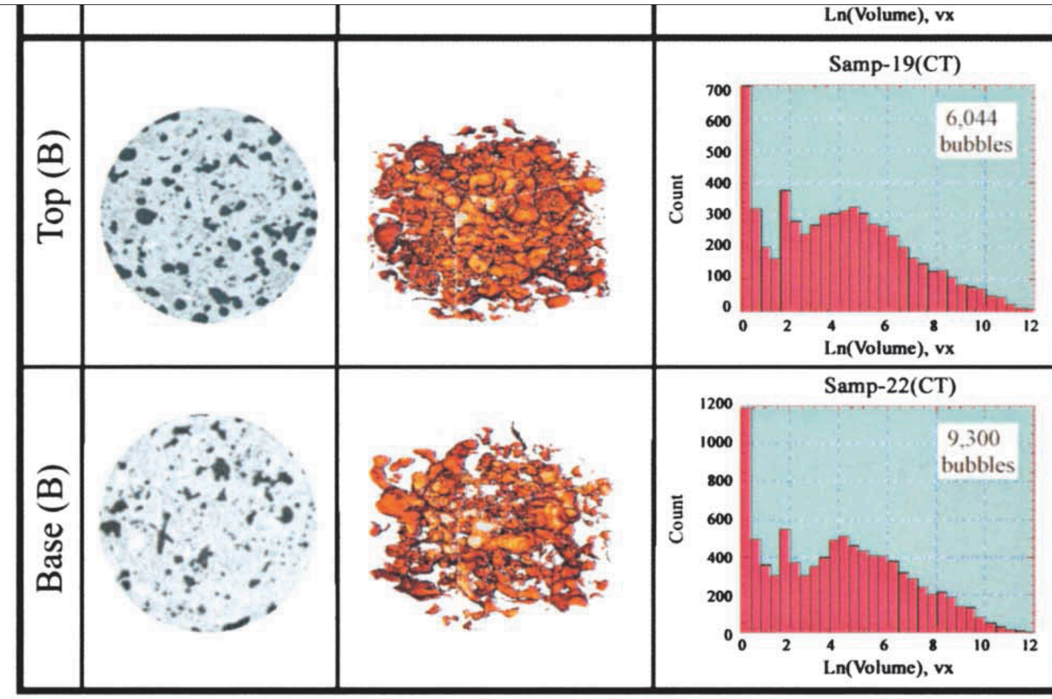
OK, so why the two different results. Lechler et al. then correct these values, which are assumed to be summer season, to a mean annual temperature of 15-20C. They then compare with coastal CA estimates of 20-25C. Snell et al. compare North Horn and Sheep Pass directly

Paleoaltimetry

What varies with elevation?

- Temperature (dry lapse rate 9.8°C/km, moist ~5°/km)
  - Paleobotany
  - Clumped isotopes
- Precipitation
  - Paleobotany
  - Oxygen and hydrogen isotopes (Rayleigh distillation)
- Radiation
  - Cosmogenic isotopes
- Air pressure
  - Plant stomatal density
  - **Bubbles in lava**
- Slopes (derivative)
  - Erosion, deposition

You'd think with all these that this would be open and shut…but all of them have issues.



	Thickness	N bubbles	Modal size mm^3	Pressure (atm)	Inferred Elevation (m)	Actual Elevation (m)
Top	1.65	6044	1.823	0.704	3254	3932
Base		9300	1.125			

Sahagian et al., J. Geol., 2002

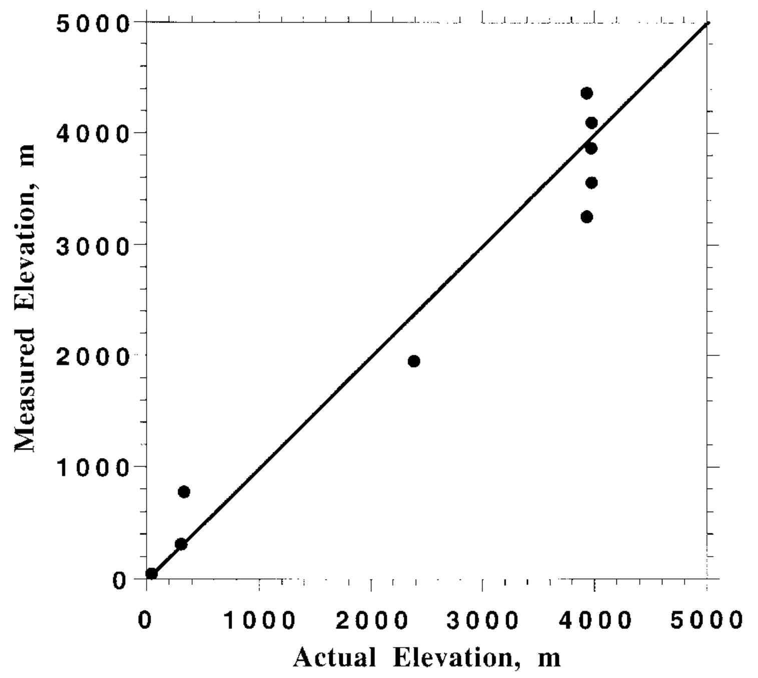


Figure 9. Results of analysis of using vesicular basalt as a measure of paleoelevation. Perfect results would lie along the diagonal line.

Sahagian et al., J. Geol., 2002

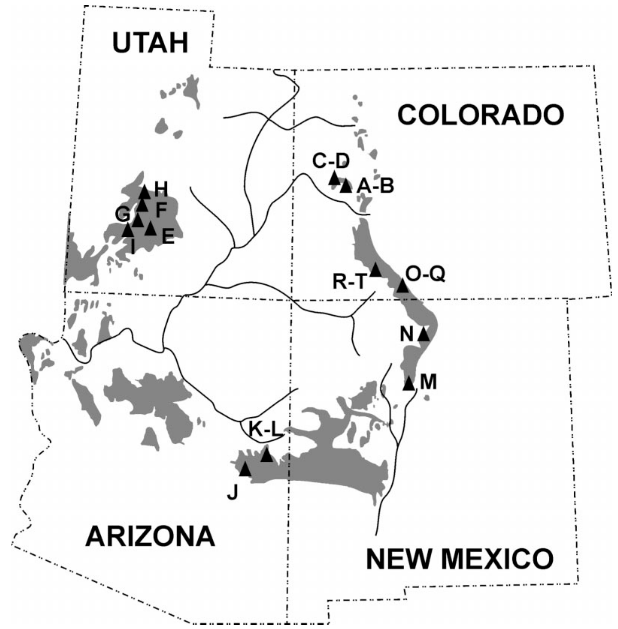


Figure 1. Sampling localities throughout perimeter of Colorado Plateau. Lava fields are shaded. In general, southern localities are limited to relatively young flows, while older flows can be found in northern sections. Oldest flows are andesitic. There is no relationship between paleoelevation and age (see Fig. 2).

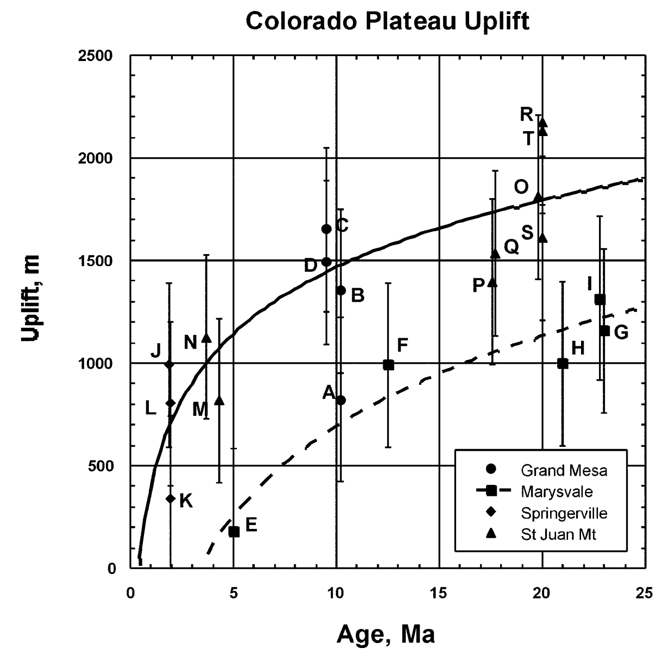
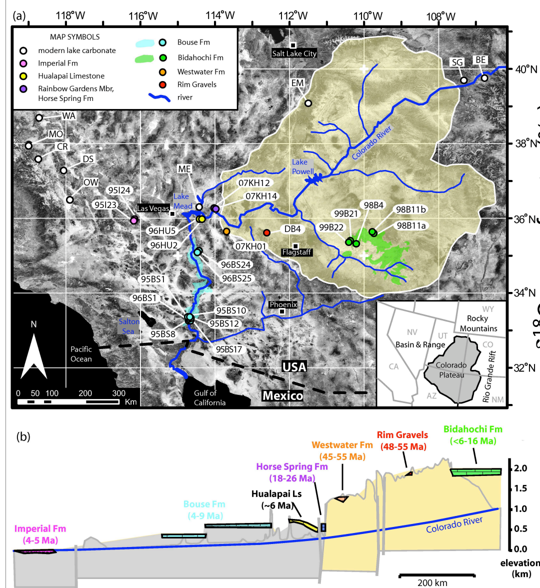
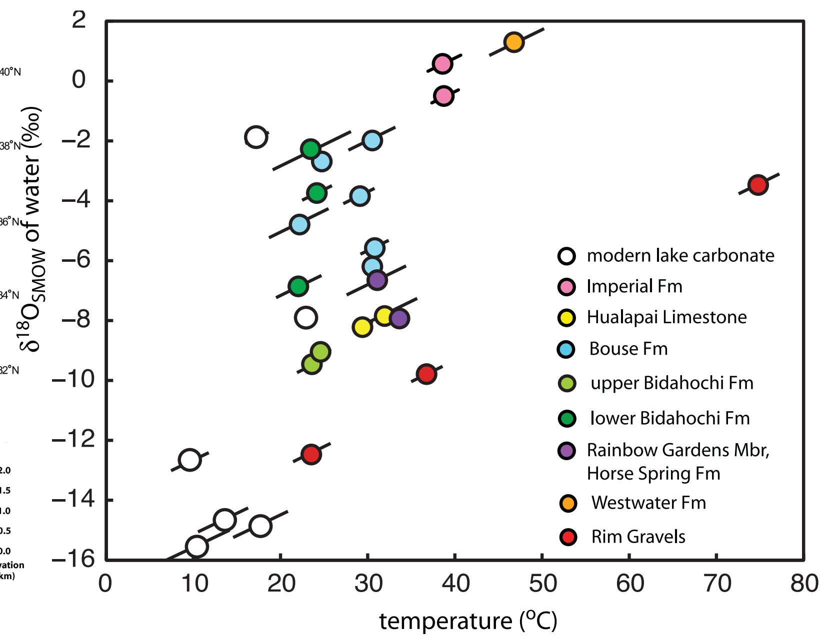


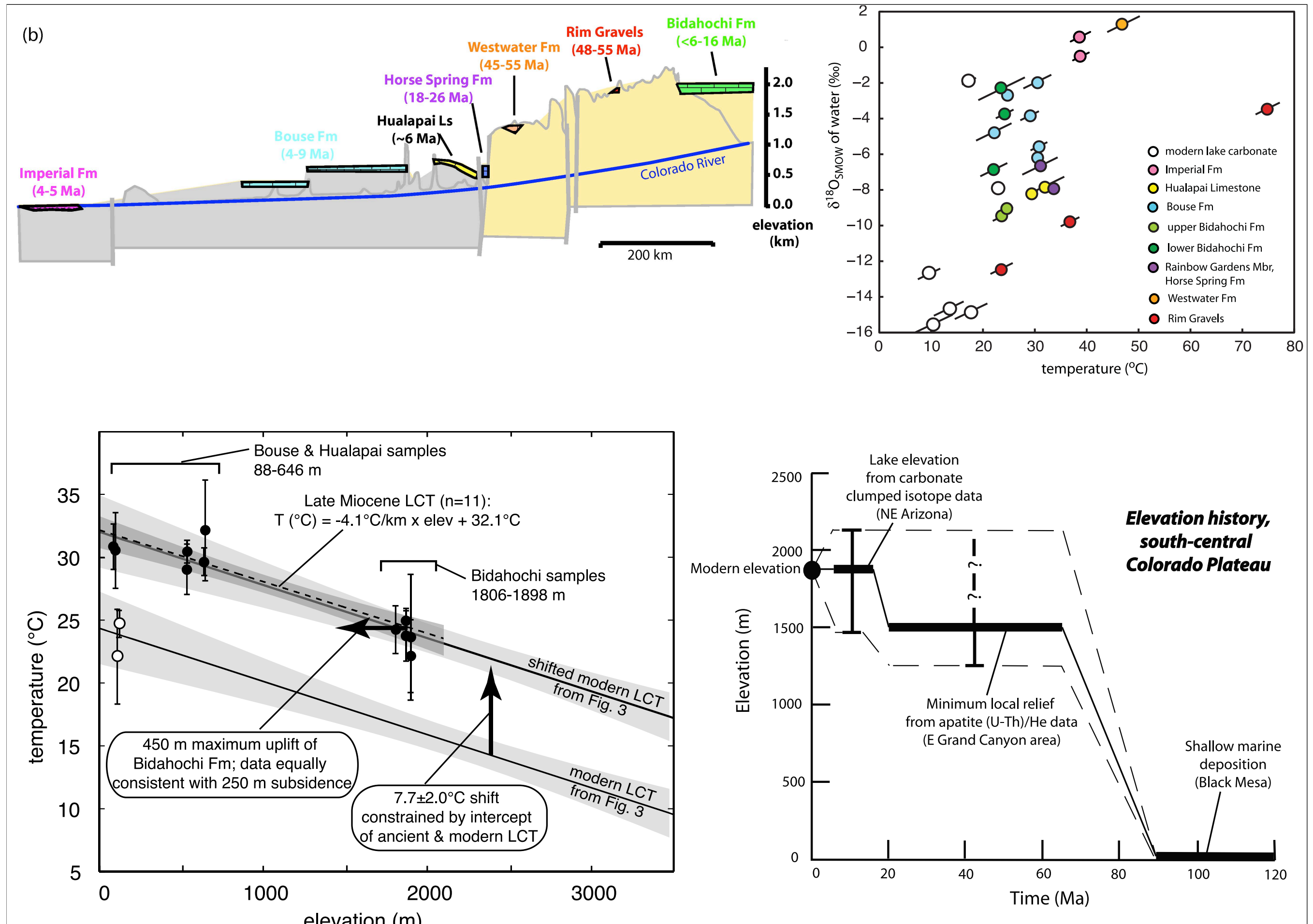
Figure 3. Uplift history of Colorado Plateau based on vesicular basalt paleoaltimeter. Logarithmic curve provides highest r-value (solid curve) relative to other curve fits. However, a logarithm passes through (0,0) even though this point is actual value of "no uplift since present." Results indicate that slow uplift (40 m/m.y.) commenced at least 25 m.y. ago, but accelerated (to 220 m/m.y.) in past 5 m.y. Dashed line is for Marysvale samples collected from downfaulted blocks of transition zone to Basin and Range.

Sahagian et al., Geology 2002

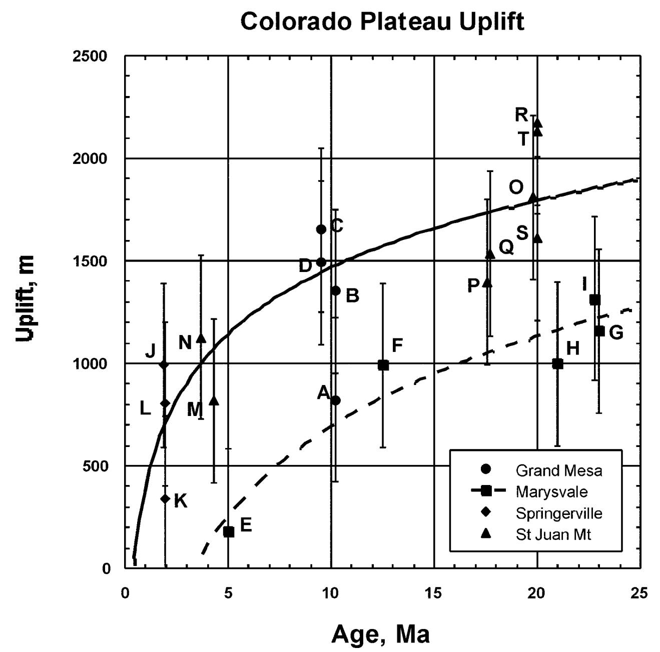




Huntington et al., Tectonics 2010



Huntington et al., Tectonics 2010



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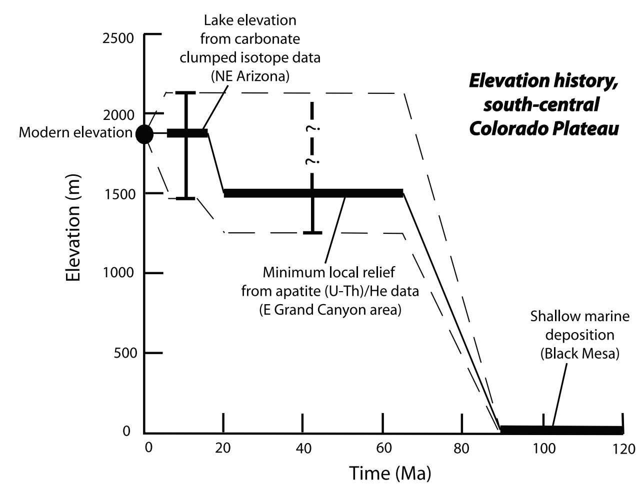

Huntington et al., Tectonics 2010