Figure 3. $\Delta PE$ for lithospheric columns with different crustal thicknesses ($L_c$) as a function of elevation. Two mean density contrasts ($\Delta \rho_m$) between mantle lithosphere and asthenosphere are illustrated. Note that low elevations with 50–70-km-thick crust likely for the early Tertiary Great Basin would require very thick or exceptionally dense mantle lithosphere and imply very negative values of $\Delta PE$. 

Jones et al., Geology 1998
Front Range

River sediments, 5-12 Ma, cobbles from Rockies
Landscape uplift (or baselevel fall)

Ocean (or lake) level falls relative to topography
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.

\[ E = k \left( \frac{\rho gQS}{W} - w_0 \right) \]

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
predictive formula for the given climatic parameters. A least-squares fit is obtained and the estimate of a climate parameter is obtained by projecting the physiognomic scores of a given sample onto the vector obtained for the selection sites for mean annual enthalpy (kJ/kg), temperature (°C), specific humidity (g/kg), and relative humidity.

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. The projections of the physiognomic character states included in multiple regression models for youth physiognomic character states included in multiple regression models. These pro-regression models show the adjusted mean annual enthalpy (MAT) vs. adjusted relative humidity (RH) which should be correlated with both temperature and moisture, as anticipated. Second, the specific humidity is midway between the relative humidity and temperature vectors. This is consistent with relative humidity being a departure from saturation conditions, and implies that the use of axes three and four as components. To use the relative humidity estimate to attenuate contributions from the entire margin (2) (i.e., no teeth), the specific humidity is a measure of enthalpy as the combined specific and latent heat energies. Third, the enthalpy vector is between both specific humidity and temperature, which follows from the definition of enthalpy, specific humidity, and relative humidity are estimates of temperature, specific humidity, and relative humidity are respectively, σ\(H\) = 5.5 g/kg, and σ\(RH\) = 1.7 g/kg, and σ\(T\) = 1.8 °C, determined independently, an alternative estimate of the climate data indicates that mean annual enthalpy can be predicted from fossil leaf apices (20), and long narrow leaves (28). These associations allow us to infer which character states are most important for estimating the importance of the characteristics for explaining the environmental variations along that axis. The environmental variations along that axis represent the relative importances of the characteristics onto a given axis. The axis eigenvalues along the third and fourth axes (see Wolfe, 1995) by removing the outliers as indicated by scores provide visual aids for comparisons between the projections of the physiognomic data. The data set was reduced to thalpy, temperature, relative humidity, and specific humidity (Fig. 8). The number of axes necessary for explaining the physiognomic data set. The vector length along a given climate parameter vector encloses the second axis and accordingly, the second axis is referred to as the moisture stress axis. The first axis (Fig. 11), which is strongly related to the moisture stress, has contributions from the entire margin (2) (i.e., no teeth), signifying that mean annual temperature explains more overall variations in the physiognomic data than do the other variables (see Fig. 10), the first temperature vector aligns more with the first axis than any other climate variable. Because the temperature vector aligns more with the first axis than any other climate variable, the importance of the climate parameter for constraining the physiognomy with an uncertainty of ±1.7° C, ±5.5 g/kg, and ±1.8 g/kg. The axis eigenvalues along the third and fourth axes (see Wolfe, 1995) by removing the outliers as indicated by scores provides a predictive formula for the given climatic parameters. A least-squares fit is obtained and the estimate of a climate parameter is obtained by projecting the physiognomic scores of a given sample onto the vector obtained for the selection sites for mean annual enthalpy (kJ/kg), temperature (°C), specific humidity (g/kg), and relative humidity.
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
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

\[ h = c_p' T + L_v q + g Z = H + g Z \]

So is moist energy \( h \) preserved?
The approach was validated with elevation (Forest et al., 1995; Wolfe et al., 1997). However, the static energy, a parameter that, unlike temperature, changes predictably with latitude, remains almost constant with increasing elevation (Gale, 1972). The SD responses to shade were very similar, the intercepts are significantly different (Fig. 3).

The SD responses to shade are limited by large errors (data not shown). For example, a mean July paleotemperature of existing methods. To test the second prerequisite, SD and SI were collected from an aspen stand (fossil) during 1891–1900, 1934–1935, 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 pCO₂ but different intercepts.

\[
pp(z) = 101.325 \left( \frac{m_{air} g}{R} \right),
\]

\[
cd_2(z) = \frac{pp(z)}{101.325} cd_1,
\]

\[
(z) = \ln \left( \frac{cd_2}{cd_1} R^\frac{t}{m_{air} g} \right).
\]

These results suggest that the SD proxy is a potential tool for paleoelevation estimation. Further investigation is needed to confirm the independence of SD responses to altitude and latitude changes.
**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.
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 ($\pm 70^\circ$) and studies from exclusively high altitudes ($\pm 5000$ m) are grouped together. The average $r^2$ value for each category is shown as $\bar{r}^2$, and provides a sense of the linearity of the relationship in each group.
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 and studies from exclusively high altitudes 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 and provides a sense of the linearity of individual studies in each group.

M.A. Poage and C.P. Chamberlain—Empirical relationships between elevation and precipitation change. The North America, Central and South America, and Europe categories are the same as in figure 1. High-altitude studies 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 51 to 54. The best fit regression lines 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 $r^2$ 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.

\[ ^{13}\text{C}^{16}\text{O}_3^{2-} + ^{12}\text{C}^{18}\text{O}^{16}\text{O}_2^{2-} = ^{13}\text{C}^{18}\text{O}^{16}\text{O}_2^{2-} + ^{12}\text{C}^{16}\text{O}_3^{2-} \]

Favored when colder

Fig. 2. Relationship between estimated environmental temperatures at which sampled fishes lived and $\Delta_{47}$ values of CO$_2$ produced from phosphoric acid digestion of fish otoliths (plotted as filled circles). Data for inorganic calcite (plotted as filled squares) grown in the laboratory under controlled conditions (Ghosh et al., 2006) are shown for comparison.
Figure 6. Results of analysis from two flows on Mauna Loa; A refers to location 6, and B to location 7 causing the solidified top to shear away from the emplacement site.

3. There were no sources outside of the flow such as soil moisture or burning vegetation to introduce bubbles into the flow before solidification of the top and bottom.

Fortunately, each of these conditions can be assessed in the field, and appropriate sites can be sampled on the basis of simple emplacement history.

We have used the techniques we have developed with vesicular basalts to "measure" the known elevation of the base and summit of Mauna Loa (as was done earlier using plastic casts; Sahagian and Maus 1994). Figure 8 shows sampling localities on Mauna Loa. The proper vesicularity profile (fig. 1) is so easy to recognize when one is standing in front of a cross section of a lava flow that the most difficult part of the fieldwork is simply finding localities in which the base of the flow is exposed. Potential sampling sites are ubiquitous at the summit.

<table>
<thead>
<tr>
<th></th>
<th>Thickness</th>
<th>N bubbles</th>
<th>Modal size (mm$^3$)</th>
<th>Pressure (atm)</th>
<th>Inferred Elevation (m)</th>
<th>Actual Elevation (m)</th>
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<td>6044</td>
<td>1.823</td>
<td>0.704</td>
<td>3254</td>
<td>3932</td>
</tr>
<tr>
<td><strong>Base</strong></td>
<td>9300</td>
<td>1.125</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

Vesicle size distributions as a function of stratigraphic position in lava flows depend on atmospheric pressure, so it is possible to determine paleopressure and thus paleoelevation of emplacement from analysis of vesicular basalts. A generalized diagrammatic flow chart for determining paleoelevation from vesicular lavas is indicated in figure 7.
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.

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.
Fig. 3. Paleoclimatological 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.
Huntington et al., Tectonics 2010
can be used as a check of paleofloristic interpretations for times of implements traditional floral and other approaches in two ways. First, it be used as a measure of atmospheric development and evolution. This is probably true for the Ce-

This conversion can be done only insofar as sea-level pressure has not standard atmospheric lapse rate to calculate paleoelevation. Subtracting bottom of the flow. However, the pressure at the top is merely atmo-

derives from the fact that a well-mixed population of bubbles within an erupting magma is homogeneously distributed throughout the lava, of paleopressure.'' It is toward that end that we have directed this study.

importance of establishing a technique for the determination of pa-

nitude of epeirogenic activity. This problem with proxies highlights the cause paleoelevation is not the unique factor controlling each proxy across the margin of the Colorado Plateau (Reilinger and Oliver, 1976) has been used to support early uplift of the Colorado Plateau. Strati-

formed in the presence of meteoric water preserve the isotopic com-

sically, depending on climatic factors as well as proximity of oceans, strong on the ability of paleoclimate to be reconstructed for precip-

Our approach of using vesicular lavas as a paleoaltimeter com-

the various approaches discussed here each have limitations be-

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.” Re-

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


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 15–20°C. They then compare with coastal CA estimates of 20–25°C. Snell et al. compare North Horn and Sheep Pass directly.