Recall significance of elevation for body forces...
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.

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

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
The projections of the physiognomic characters included in multiple regression analysis were plotted against the value of the parameter. The relative directions of the four climate parameters are shown. First, the specific humidity vector is nearly parallel to the relative humidity vector. Second, the specific humidity vector is midway between the relative humidity and temperature vectors. This is consistent with the fact that relative humidity should be nearly independent of temperature. Third, the temperature vector aligns more with the first axis than any other climate variable. Because the temperature vector is orthogonal to the relative humidity vector, it indicates that mean annual temperature explains more overall variations in the physiognomic data set. The vector length along a given axis is referred to as the importance of the climate parameter for constraining the physiognomic data set. The vector length along a given axis represents the relative importance of the climate parameter for explaining variations in the physiognomic data. The total length of a climate parameter vector indicates the relative importance of the climate parameter for constraining the physiognomic data set. An outlier indicator should be robust. The estimation is contained in the first six axes (Fig. 9) from CANOCO indicate that significant information is provided by combining the respective energy components. To use the relative humidity estimate to predict mean annual temperature, specific humidity, and relative humidity are determined independently, an alternative estimate of the mean annual enthalpy can be calculated by combining the respective energy components. The relative humidity, as shown, last, the enthalpy vector projects roughly equally between the specific humidity and temperature vectors. This is consistent with the fact that relative humidity should be nearly independent of temperature. In contrast to this, the second axis is related to moisture stress, has contributions from the large leaf sizes (13–16), attenuates the character states (17). In contrast to this, the second axis is related to moisture stress, has contributions from the large leaf sizes (13–16), and implies that the use of axes three and four as components. To use the relative humidity estimate to predict mean annual temperature, specific humidity, and temperature, which follows from the definition of enthalpy as the combined specific and latent heat energies.
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.
So is moist energy $h$ preserved?

$$h = c_p T + L_v q + gZ = H + gZ$$
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.

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.
pp is partial pressure of CO2 as a function of elevation, cd2
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 and from exclusively high altitudes are grouped together. The average $r^2$ value for each category is shown and provides a sense of the linearity of individual studies 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 as and provides a sense of the linearity of individual studies in each group.

Fig. 2. Plots of the change in $\text{P}^{\text{O}}_\text{avg}$ 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 are excluded from these plots. 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 line for the Compilation plot is forced through the origin for purposes of calculating the predictive error. However, this does not change the slope of the regression line. The calculated standard error envelope is also shown on the Compilation plot. The North America data for the Compilation plot is obtained from Poage and Chamberlain.
Bottom panel squares are inferred elevations from the dD values in circles.
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But moisture moves around in complex ways—virtually all these proxies need a solid grounding in the climate
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.
\[ 13C^{16}O_3^{2-} + 12C^{18}O^{16}O_2^{2-} = 13C^{18}O_{16}^{2-} + 12C^{16}O_3^{2-} \]

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.

\[
\begin{align*}
13^\text{C}^{16}_\text{O}_3^{2-} + 12^\text{C}^{18}_\text{O}^{16}_2^{2-} &= \frac{13^\text{C}^{18}_\text{O}^{16}_2^{2-} + 12^\text{C}^{16}_\text{O}_3^{2-}}{=47}
\end{align*}
\]

Favored when colder

<table>
<thead>
<tr>
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<tbody>
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<td>$^{16}O_2$</td>
<td>99.759%</td>
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Ghosh et al., Geochem. Cosmo Acta, 2007

Huntington and Lecler, Tectonophysics, 2015

\[
\text{Reaction 1}
\]

Abundance of isotopologues of CO$_2$ (ppm)

- 12O$_2$: 99.759%
- 18O$_2$: 0.241%
- 16O$_3$: 99.759%
- 18O$_3$: 0.241%

\[
\Delta_{\text{calcite}}(^\text{C}/^\text{O}) = 47
\]

\[
\Delta T(\text{calcite}) = 0.68
\]

\[
\Delta T(\text{calcite}) = 0.68
\]

\[
\Delta T(\text{calcite}) = 0.68
\]
Clumped isotope approach can get temperatures and isotopes...
The problems with clumped isotopes revolve around precipitation of the carbonate (seasonal? which season?) and diagenesis
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 mm³</th>
<th>Pressure atm</th>
<th>Inferred Elevation (m)</th>
<th>Actual Elevation (m)</th>
</tr>
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<tbody>
<tr>
<td>Top</td>
<td>1.65</td>
<td>6044</td>
<td>1.823</td>
<td>0.704</td>
<td>3254</td>
<td>3932</td>
</tr>
<tr>
<td>Base</td>
<td>9300</td>
<td>1.125</td>
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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.

**Figure 9.** Results of analysis of using vesicular basalt as a measure of paleoelevation. Perfect results would lie along the diagonal line.
Not exactly paleoaltimeter, but use of sedimentology should tell of tilts (but watch the assumptions carefully).
nozoic, although for Archean flows this technique may be inverted to changed since the time of eruption. This is probably true for the Ce-
standard atmospheric lapse rate to calculate paleoelevation. Subtracting vesicles are smaller (Sahagian and Maus, 1994). Consequently, samples so that there is the same mass of gas in the bubbles at the top and an erupting magma is homogeneously distributed throughout the lava, derives from the fact that a well-mixed population of bubbles within ambient atmospheric pressure at the time of emplacement (Sahagian berg, 1985). On a shorter time scale, releveling along the Rio Grande graphic arguments have also been used to support recent uplift on the leoelevation (Chamberlain and Poage, 2000). Stratigraphic analysis position of meteoric water and thus can be used as a proxy for pa-
ratios of fluid inclusions in calcite veins that can trap meteoric water and thus uplift and tilting can be inferred from geomorphologic argu-
ments (Small and Anderson, 1995). However, this approach depends strongly on the ability of paleoclimate to be reconstructed for precip-
ments (Small and Anderson, 1995). Our analysis provides a general uplift history for the Colorado Plateau (Reilinger and Oliver, 1976) and 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 ve-
sicular 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-
sults 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.