Erosion can inform tectonics

Consider the amount of relief on a landscape, R. The mean elevation E of the landscape is greater than the average of R.

Of course creation of relief only has to follow creation of surface elevation

Note can be rates or amounts...
Direct observation of S was paleoelevation, which we discussed before.

House et al., *Nature*, 1998

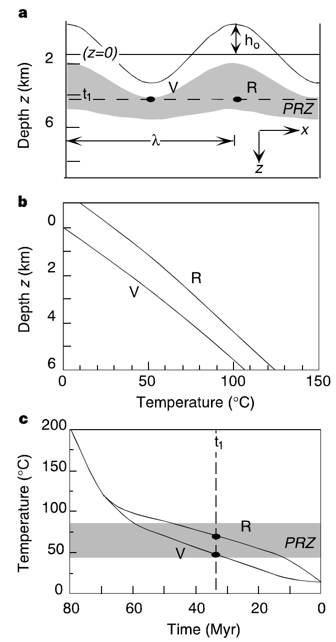


Figure 1 Thermal history of rock samples below periodic topography. **a**, Schematic range-parallel cross-section showing the influence of topography on isotherms bounding the partial retention zone (PRZ, shaded) for helium in apatite (45–85 °C; ref. 11). At time t_1, the sample below the valley (V) is nearly closed to helium diffusion, while the sample below the ridge (R) remains open, resulting in a younger (U–Th)/He age beneath the ridge. **b**, Steady-state geotherms beneath valley and ridge sites described by equation (1) using nominal central Sierran heat-flow parameters[13] of reduced heat flow q_m (21 mW m^{-1}), characteristic depth of heat production h_r (10 km), thermal conductivity k (2.4 W K^{-1} m^{-1}), surface radioactive heat production ρH_s (1 μW m^{-3}), temperature at depth $z = 0$ km T_o (15 °C), and lapse rate of mean surface temperature β (4.5 °C km^{-1}). **c**, Hypothetical cooling histories of valley and ridge samples. Rapid cooling trajectory above ~100 °C based on higher temperature thermochronometers for central Sierra[15,16]. Trajectory through PRZ assumes unroofing at a constant rate of 0.08 mm yr^{-1} of a steady-state topography with $h_0 = 1$ km and $\lambda = 70$ km from a depth $z = 6$ km at 80 Myr, using geotherms from **b**.

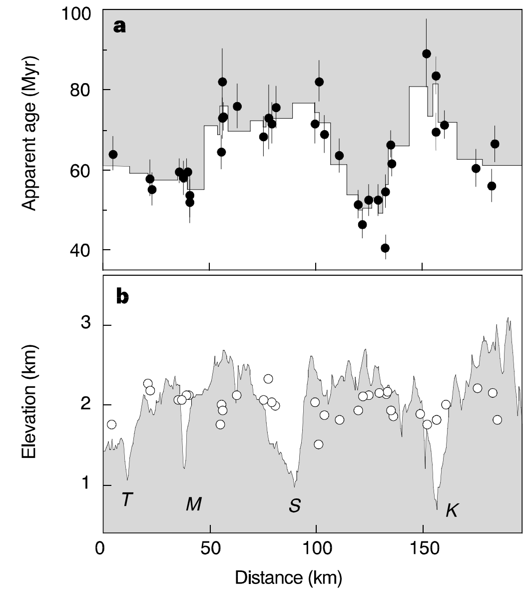
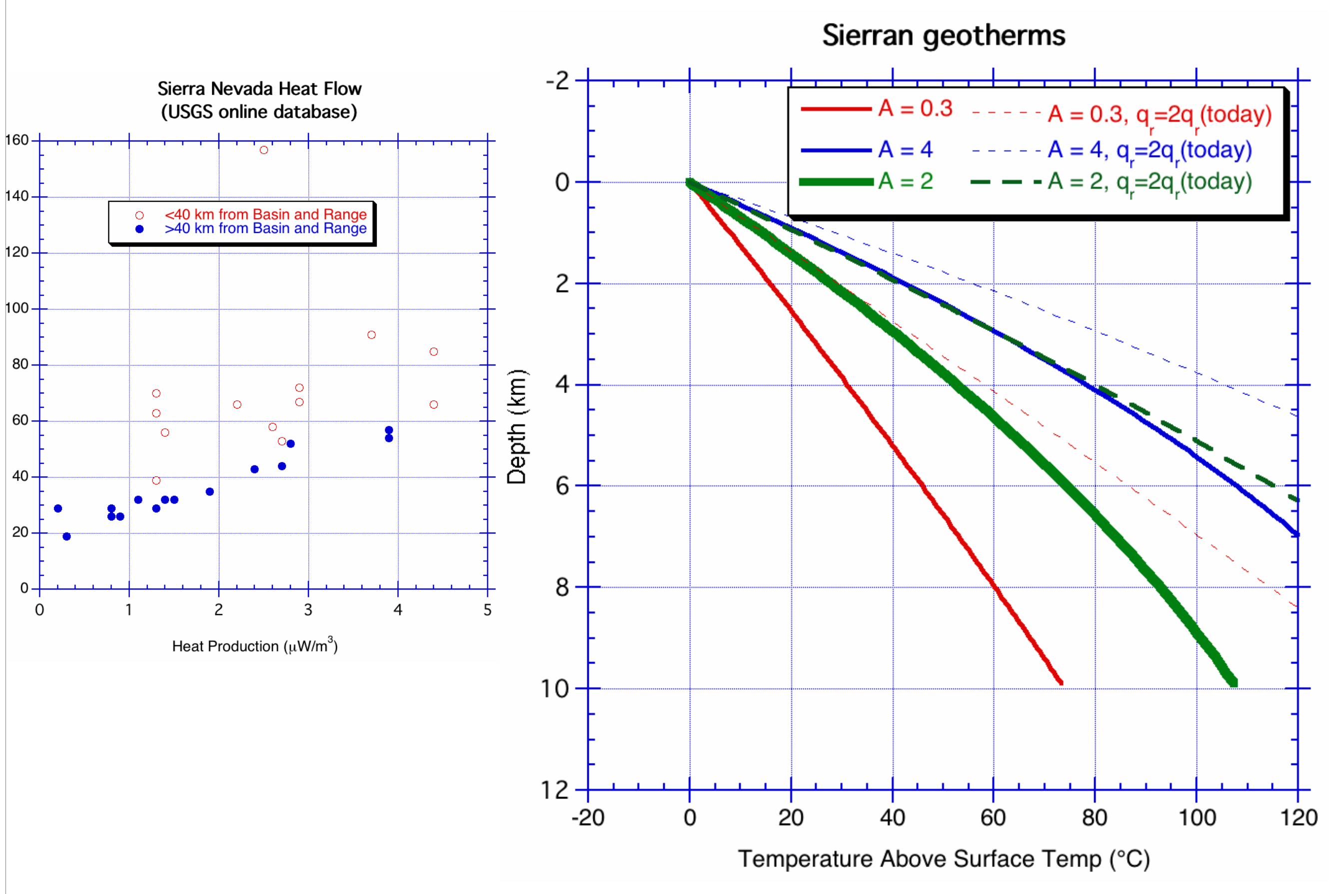


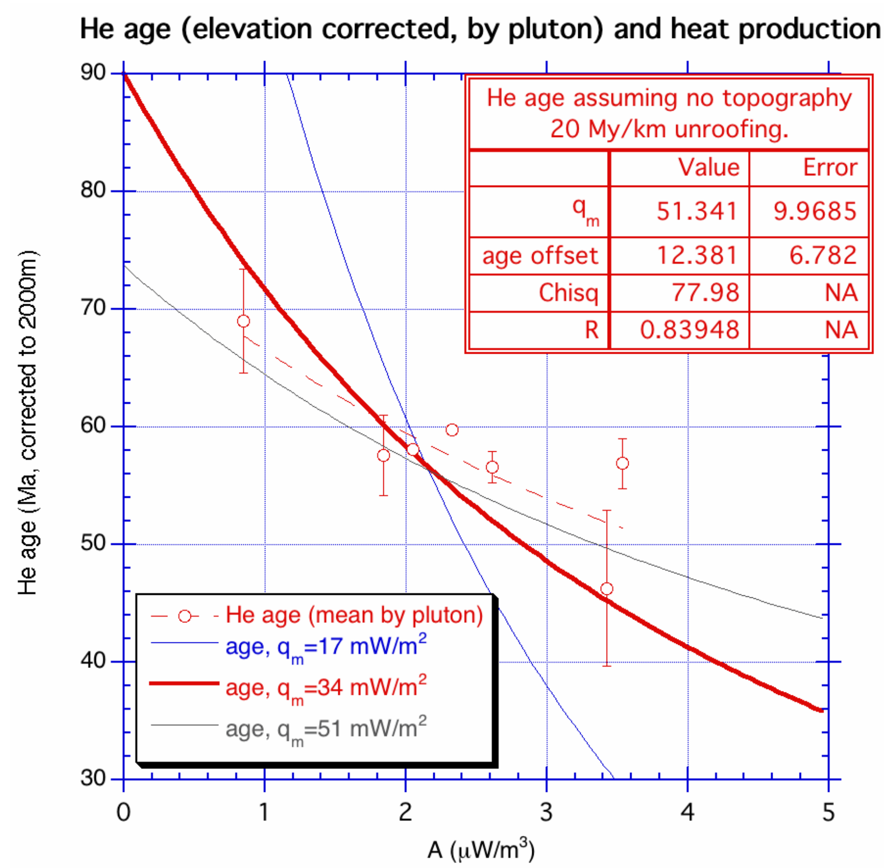
Figure 3 (U–Th)/He ages along range-parallel profile. **a**, Elevation-adjusted helium ages for samples projected onto profile in Fig. 2. Helium and U–Th analyses were performed on the same aliquots at Caltech following procedures in refs 16, 26. Samples of euhedral, inclusion-free igneous apatite from undeformed granitic plutons were analysed in replicate, with mean ages ranging from 44.5 to 84.6 Myr. Errors shown are 1σ and reflect analytical uncertainties in helium and U–Th measurements[16,26]. Ages were corrected for small differences in sample elevation above or below 2,000 m using the observed age–elevation gradient[16]. Stepped curve is defined by three-sample average of elevation-adjusted ages. A complete table of analytical results is available; see Supplementary Information. **b**, Location and elevation of samples projected onto profile in Fig. 2, plotted with topography along profile. Drainages are labelled as in Fig. 2.

House et al. interpreted variations in ages as deflections of a steady-state isotherm—older ages under ancient canyons cooled first.

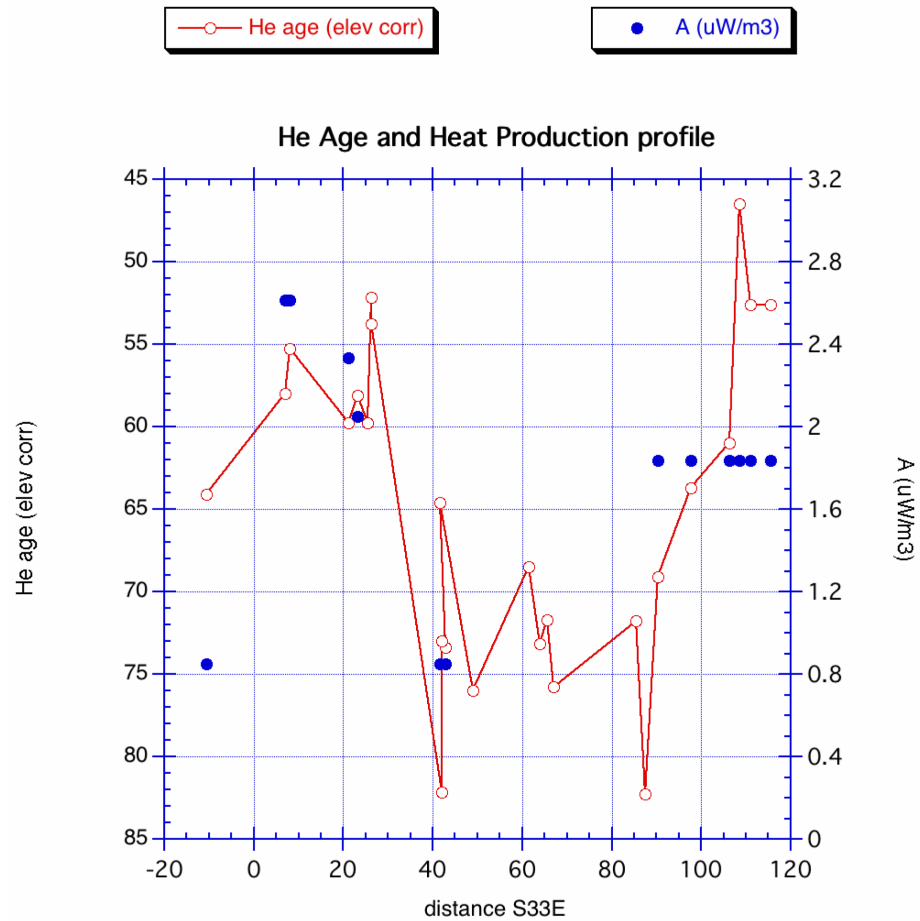


Jones et al., *Geosphere*, 2004

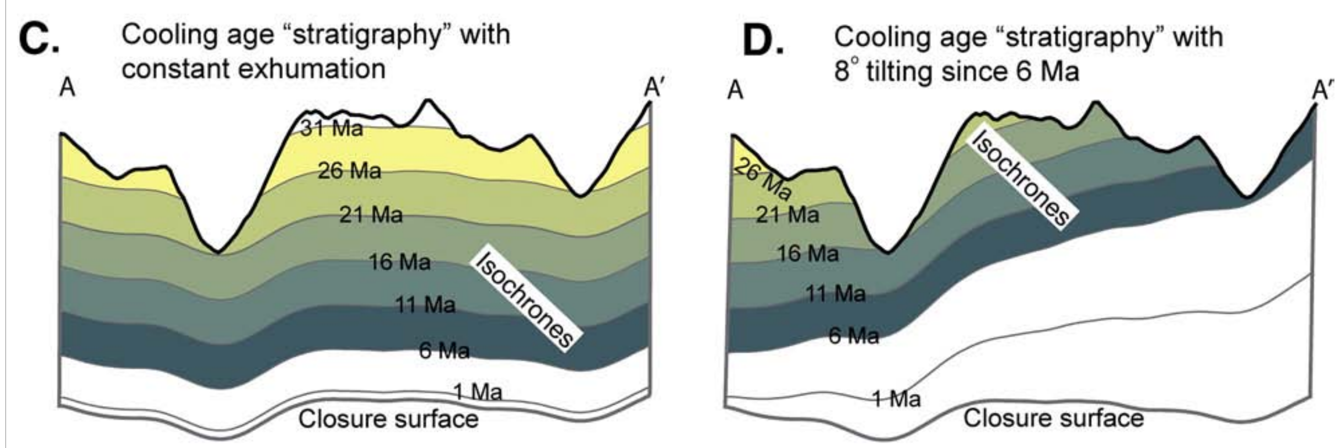
We know there is a big variation in heat production (left)--what is the impact on shallow geotherms



Jones et al., *Geosphere*, 2004

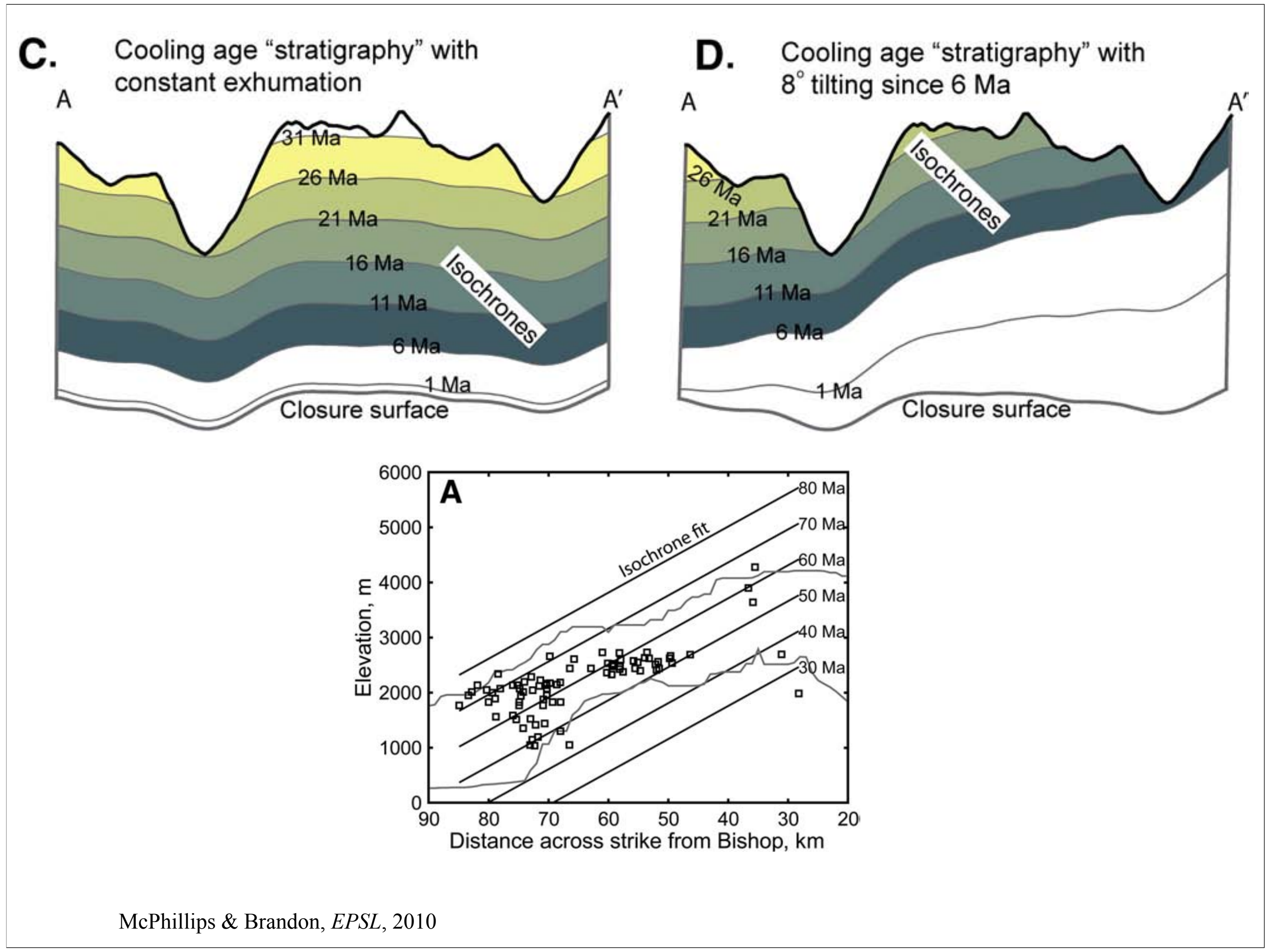


Jones et al., *Geosphere*, 2004

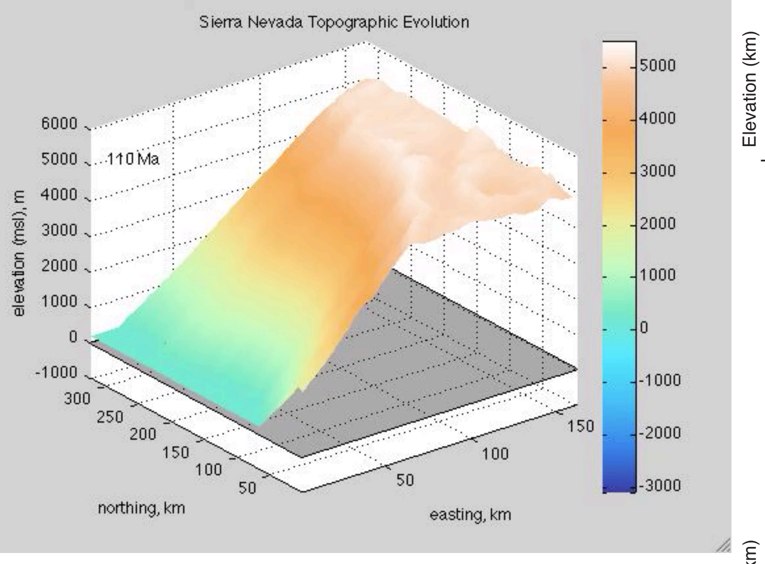


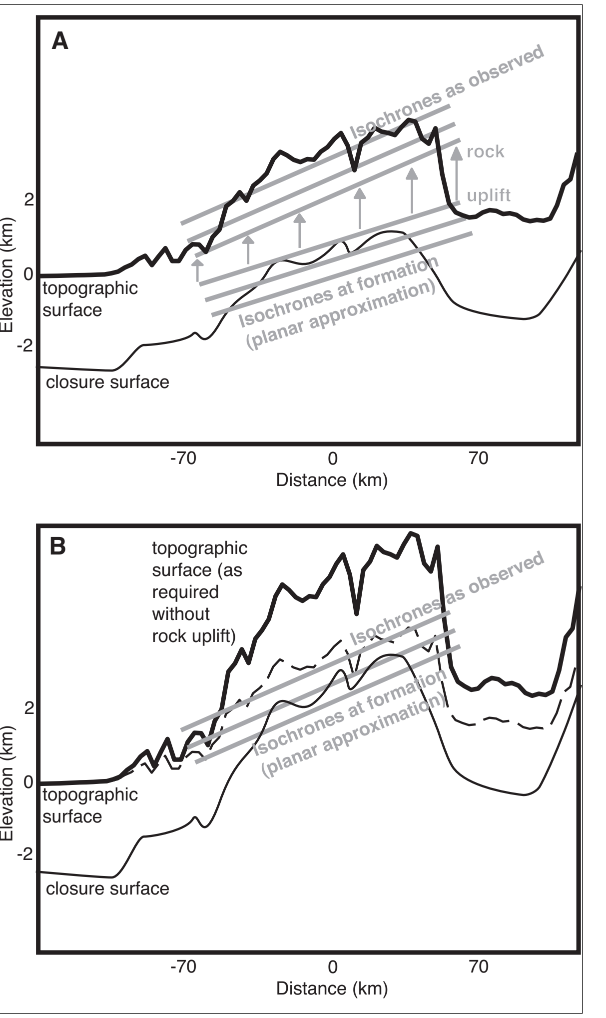
McPhillips & Brandon, *EPSL*, 2010

A different approach to using low-T geochron was to see if varying tilts of surfaces through available measurements



Initial attempt at fitting planar isochrons for the Kings and San Joaquin drainage





McPhillips & Brandon, *AJS*, 2012

Consider relationships near the surface

S = surface uplift (relative to sea level)
D = denudation (erosion)
R = rock uplift (relative to sea level)

On average, $D = R - S$ (or $S = R - D$)

Generally we observe *D* either through low-temperature geochronology or geologic relations (e.g., incision of older rocks). We'd like *S*.

Following England and Molnar, *Geology*, 1990

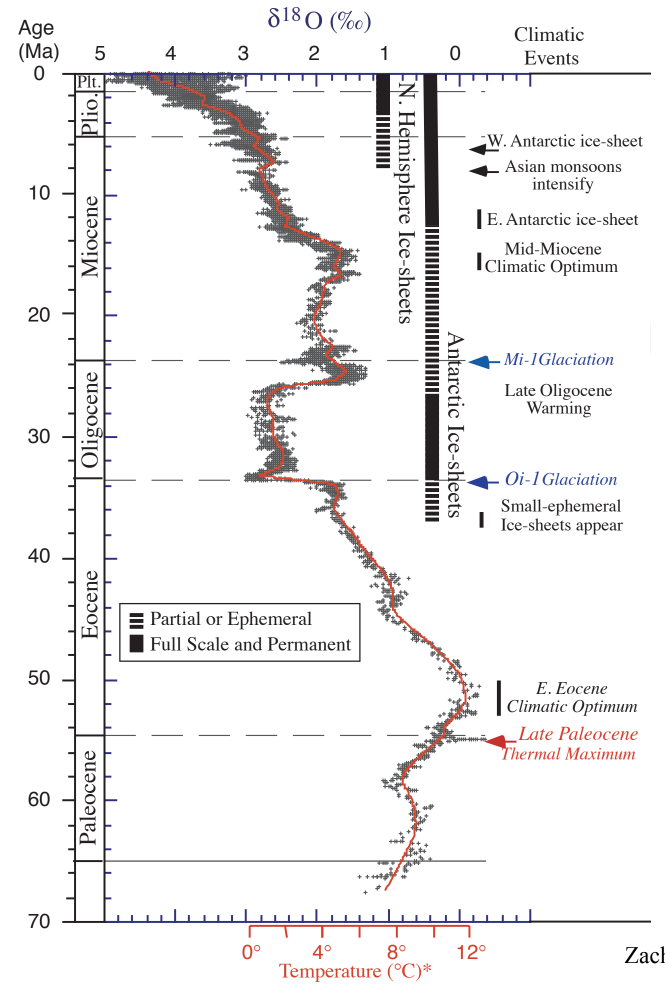
Note can be rates or amounts...
Direct observation of S was paleoelevation, which we discussed before.

Since we can infer D, what might it mean in terms of mean elevation E?

Classically, geologists assumed $D \propto E$

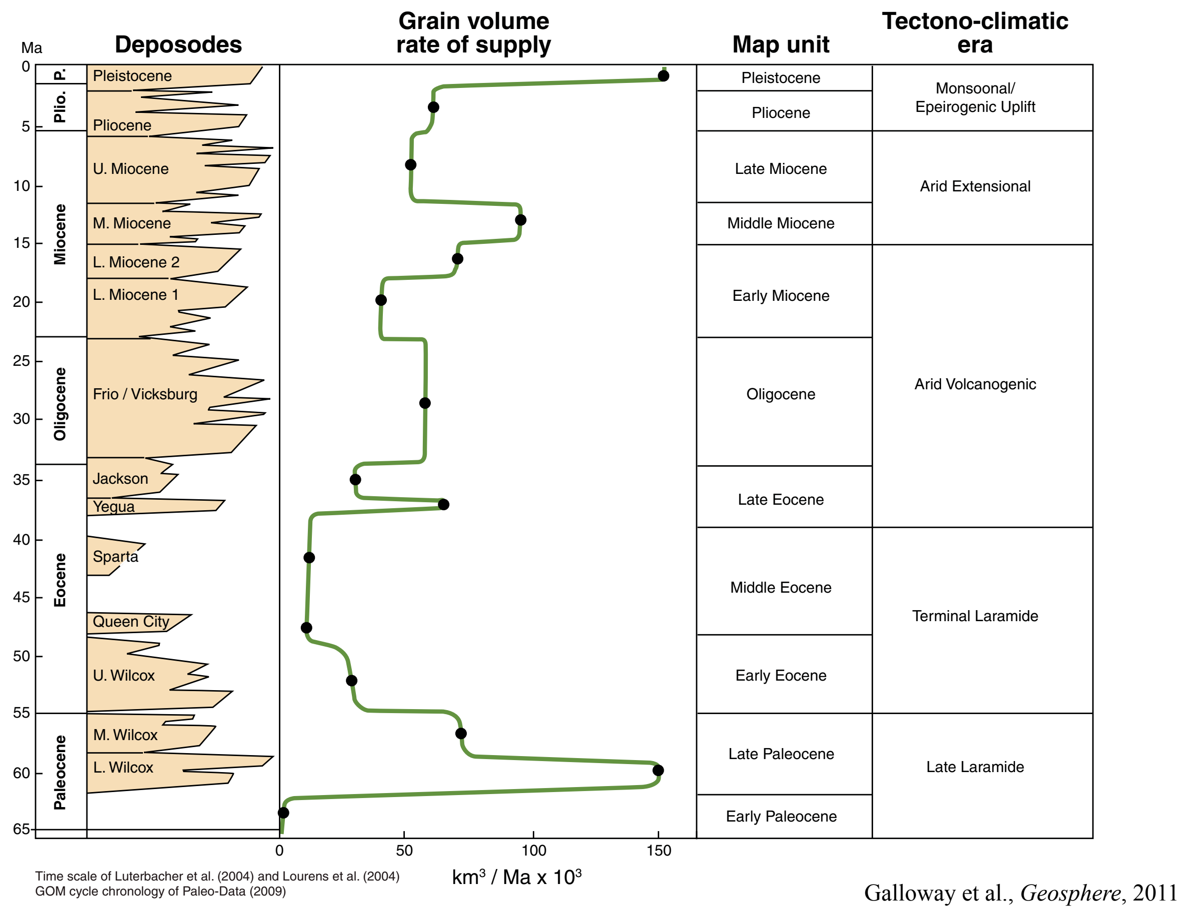
But examples like Tibetan Plateau and Altiplano suggest this is imperfect....

Even if there is some orogen-scale basis for this, is this a constant factor?



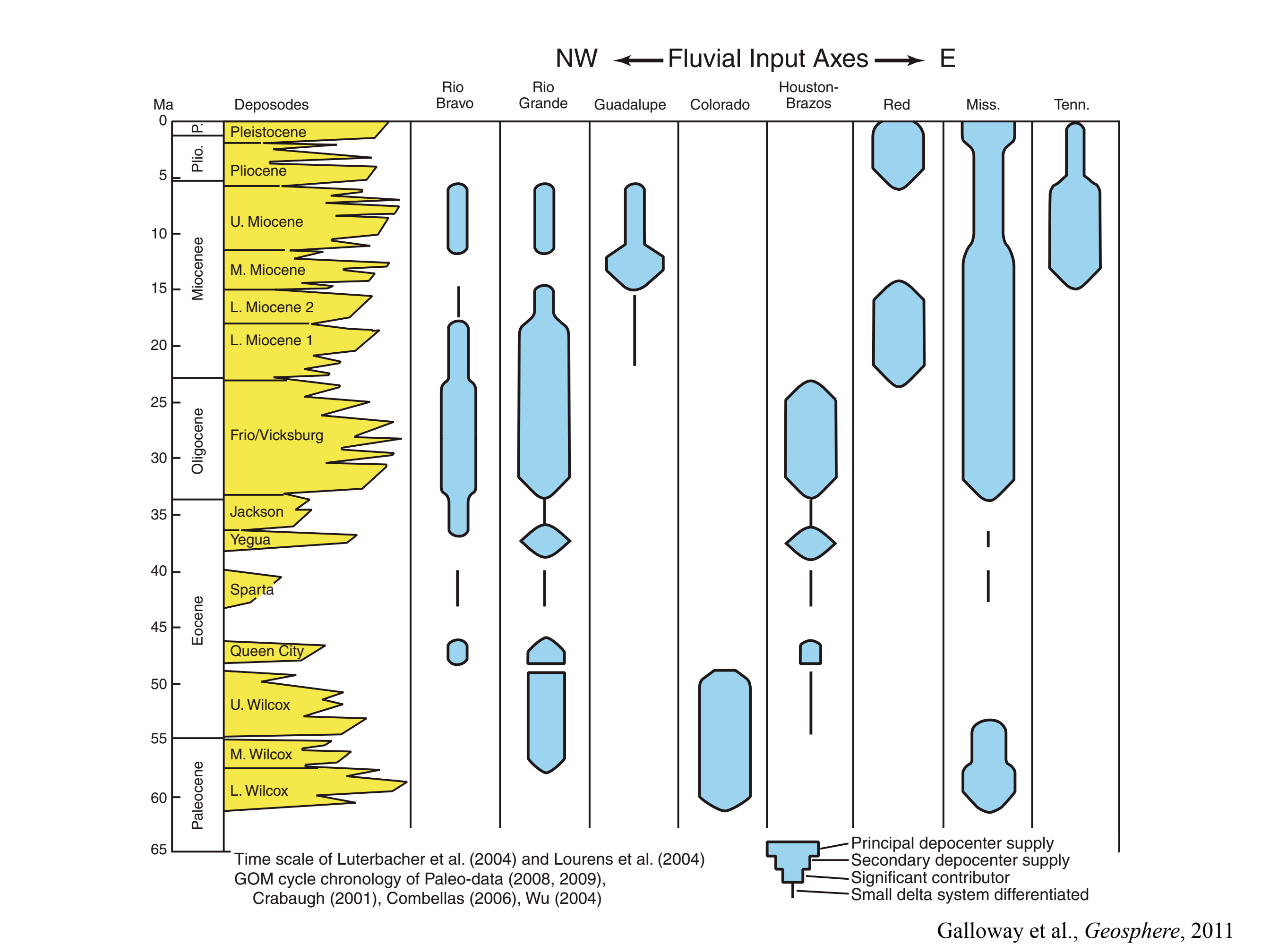
Zachos et al., *Science*, 2001

Sediment supplied to Gulf of Mexico



Galloway et al., *Geosphere*, 2011

Now we saw this before when we were discussing the Laramide, so carry it the rest of the way...



Note “Colorado” here isn’t the river we are usually thinking of. Note large pulse on Rio Grande in Oligocene–Miocene

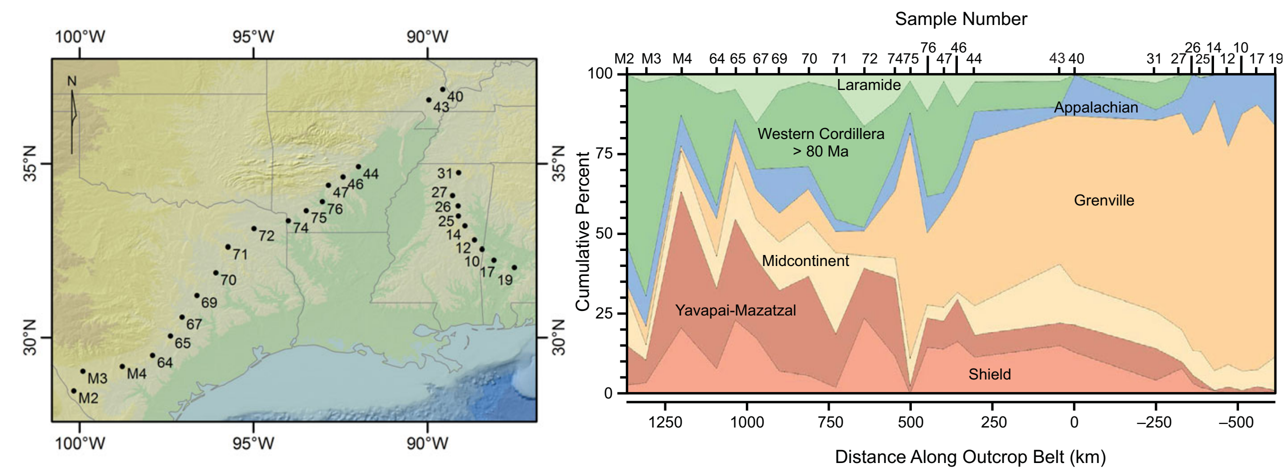
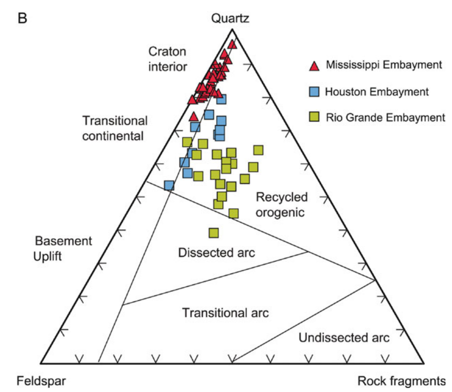


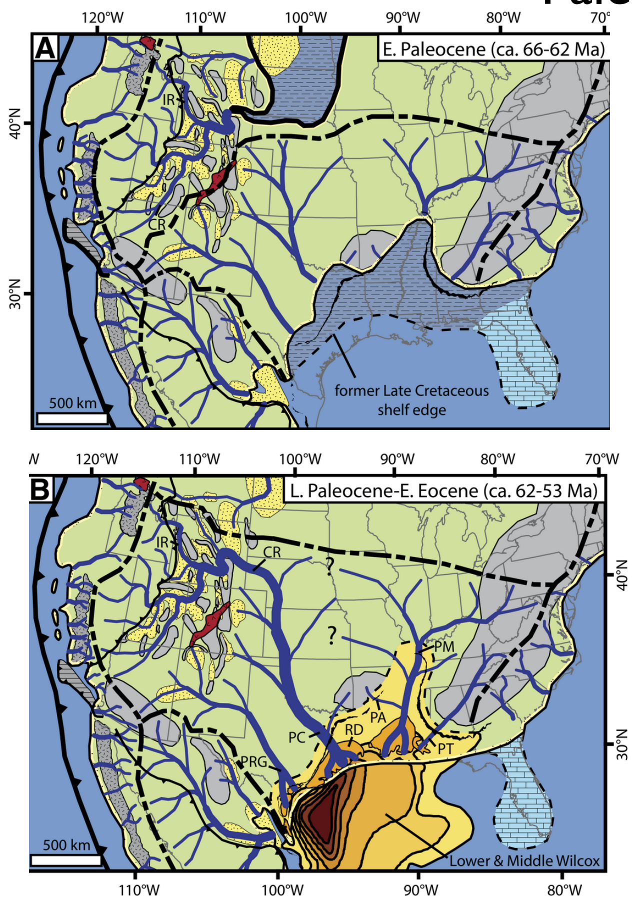
Figure 8.2 Along-strike trends in detrital zircon populations in Paleocene–Early Eocene Wilcox samples collected along an outcrop traverse extending from western Mississippi to south Texas. The plot shows spatial changes in percentage contributions of populations associated with different source terranes. Likely association to major fluvial axis is based on geographic correspondence of sample with mapped fluvial axes and inter-axial coastal plains. Modified from Blum *et al.* (2017).



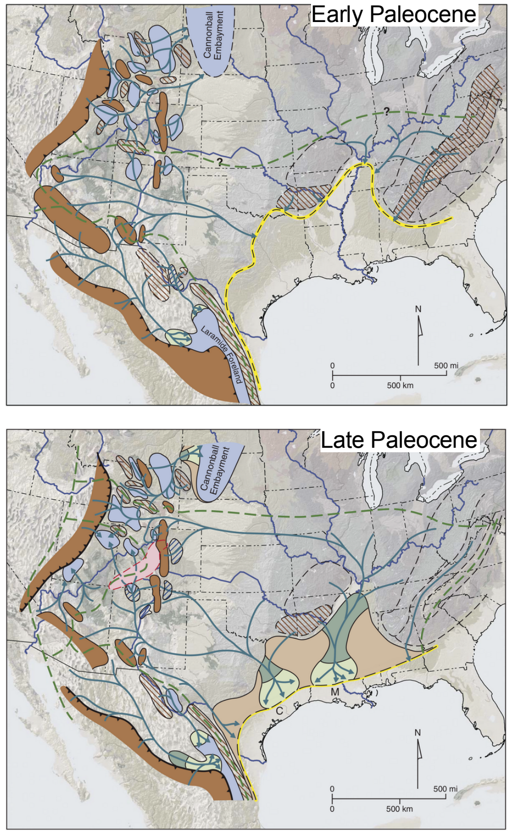
Snedden and Galloway et al., *Gulf of Mexico Sedimentary Bason, Ch. 8*, 2019

Contrasting tools. Detrital zircons deposited near the coast in the early Eocene (top) and classic petrographic ternary for interpreting sands.

Paleogene



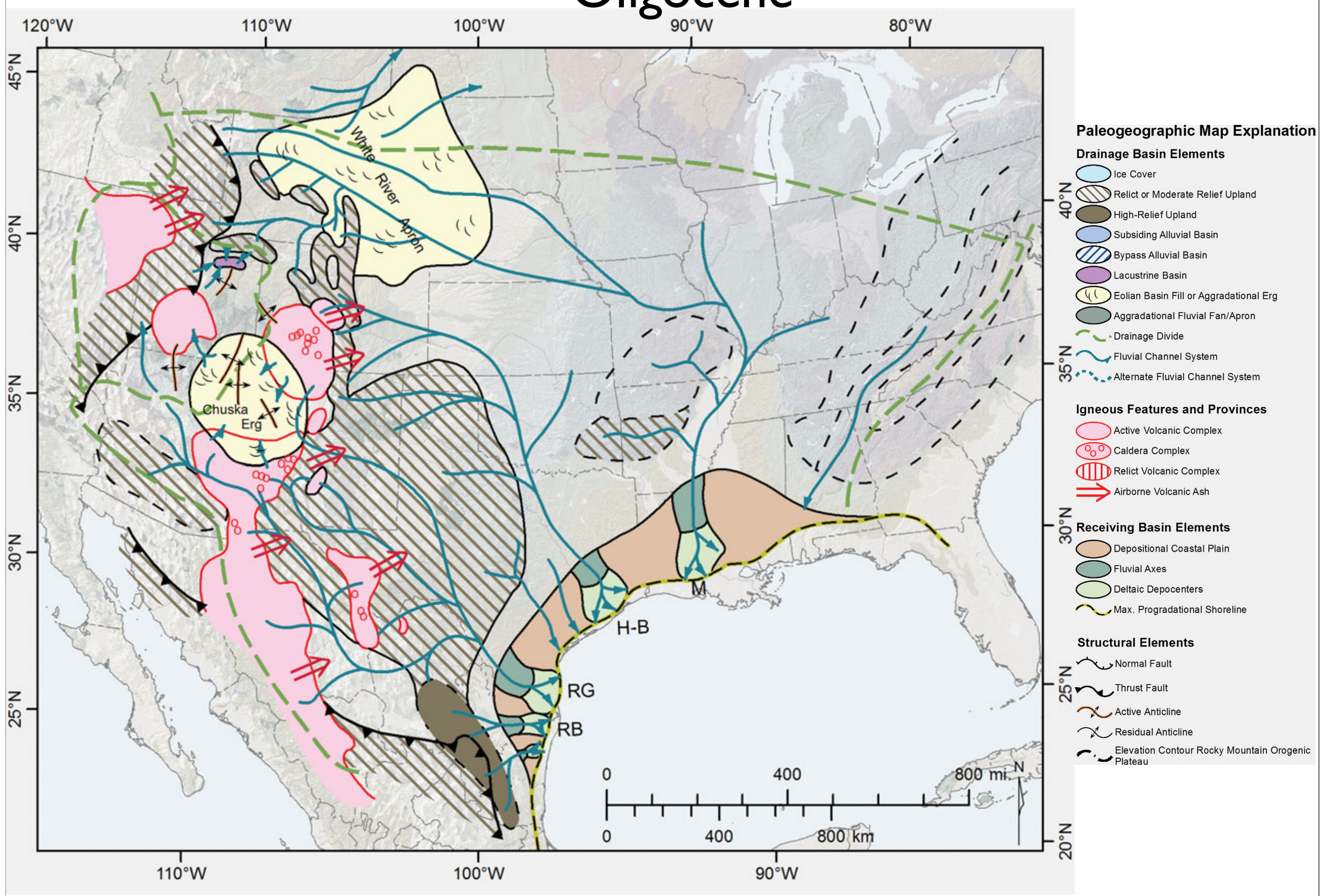
Sharman et al., *Geology*, 2017



Galloway et al., *Geosphere*, 2011

Surprisingly differences. Galloway 2011 was largely based on classic sedimentary petrography, Sharman et al. a lot of detrital zircons.

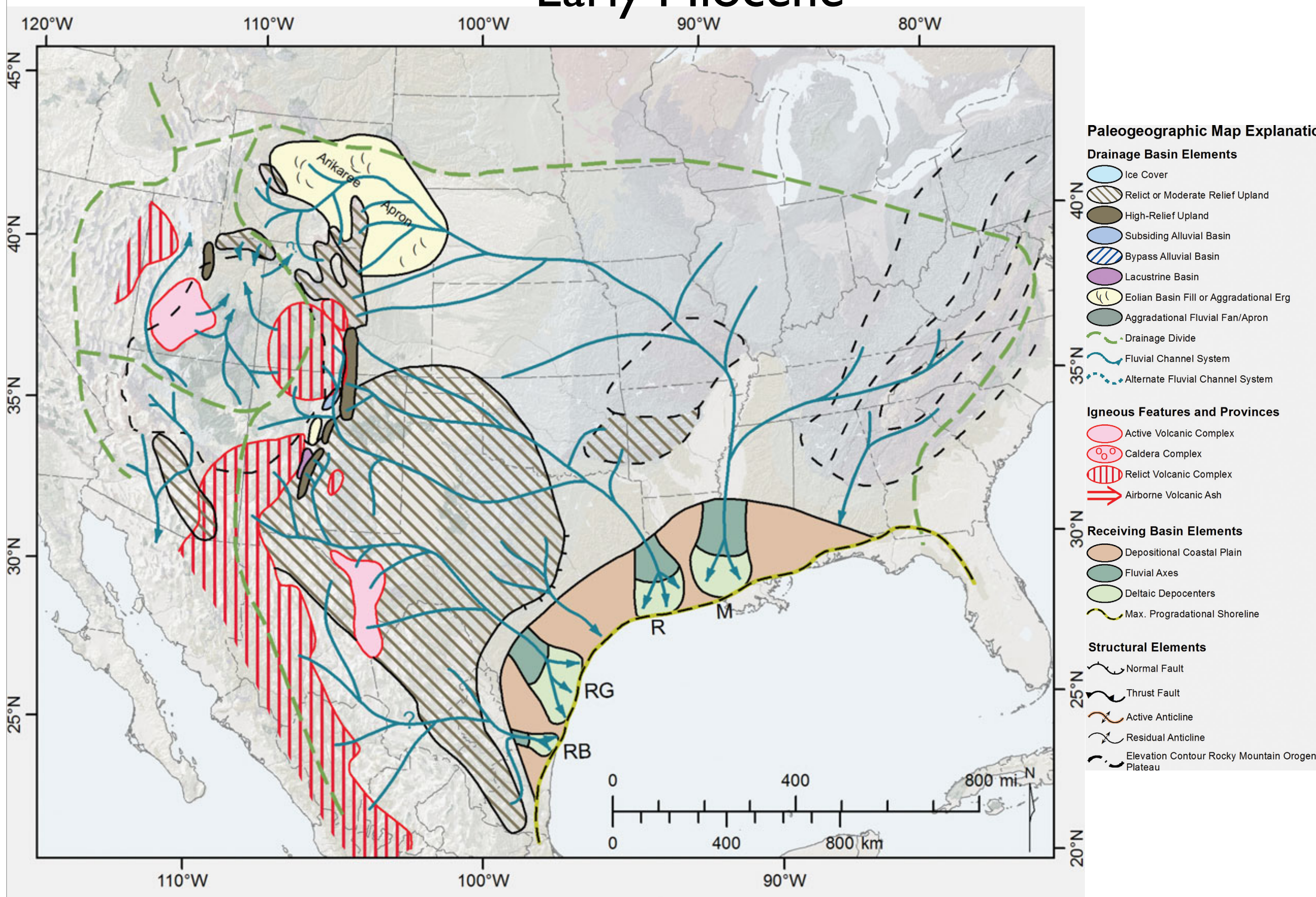
Oligocene



Snedden and Galloway et al., *Gulf of Mexico Sedimentary Bason, Ch. 8*, 2019

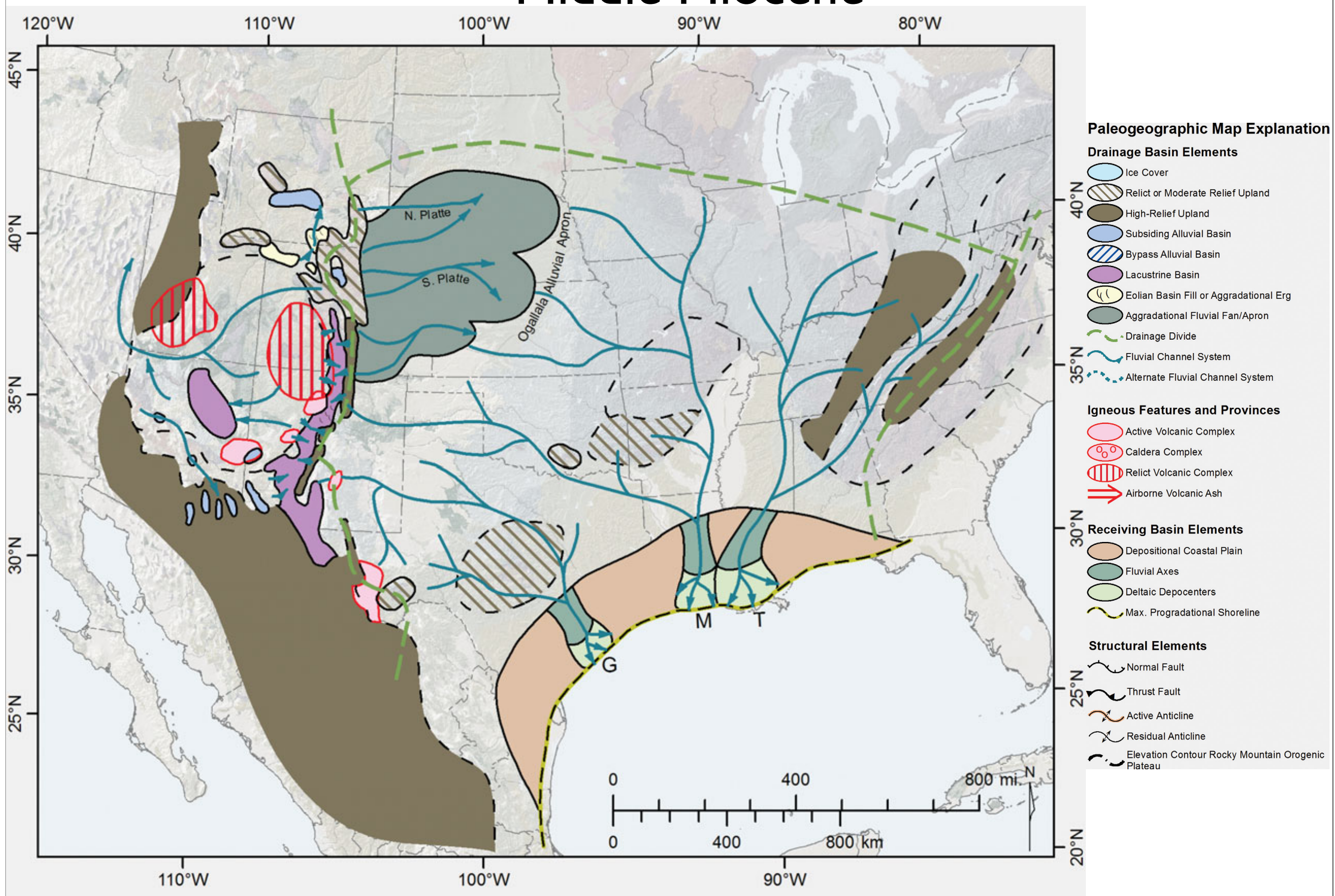
Interesting how they route the paleo-Salt River

Early Miocene



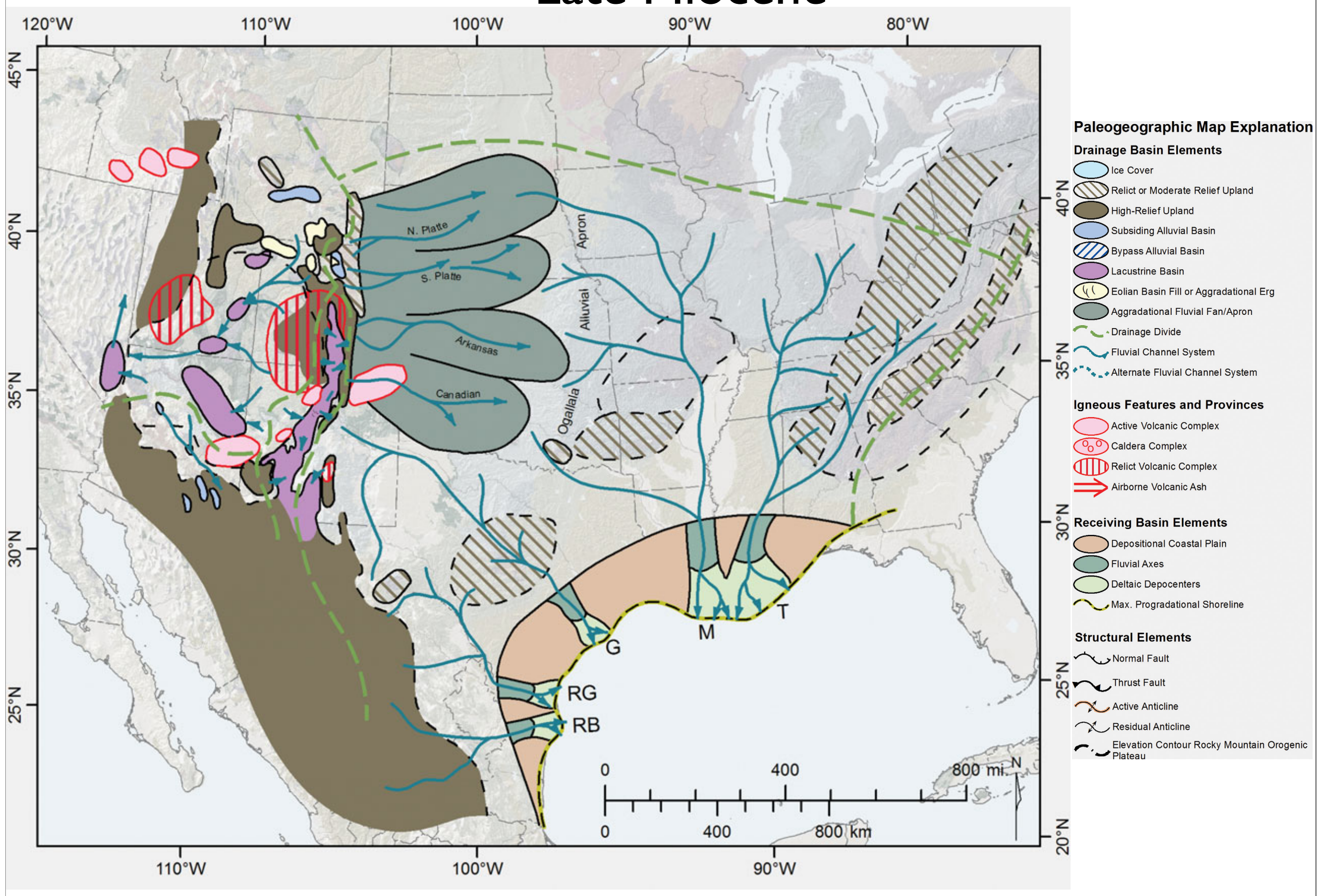
Snedden and Galloway et al., *Gulf of Mexico Sedimentary Bason, Ch. 8*, 2019

Middle Miocene



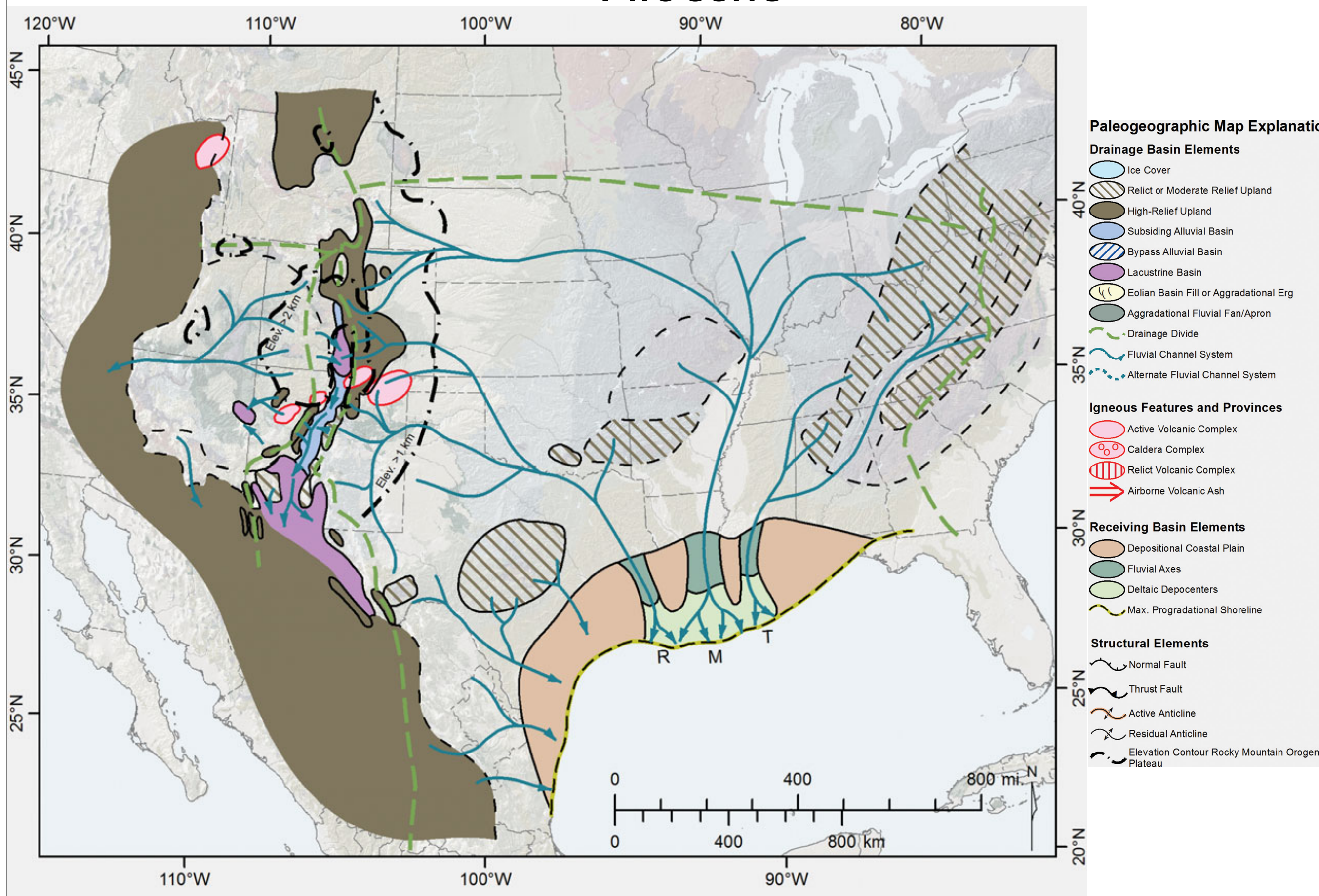
Snedden and Galloway et al., *Gulf of Mexico Sedimentary Bason, Ch. 8*, 2019

Late Miocene

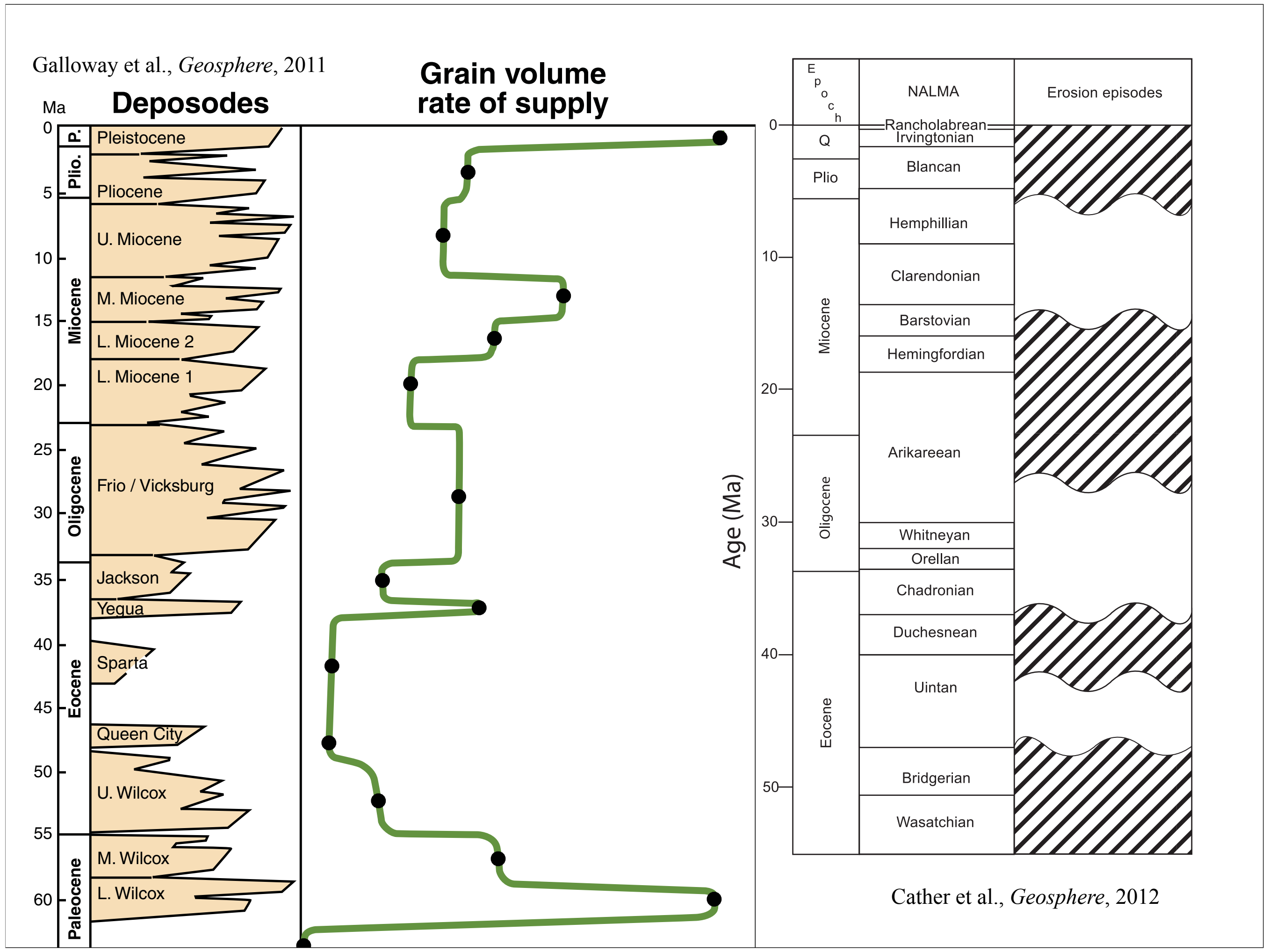


Snedden and Galloway et al., *Gulf of Mexico Sedimentary Bason, Ch. 8*, 2019

Pliocene

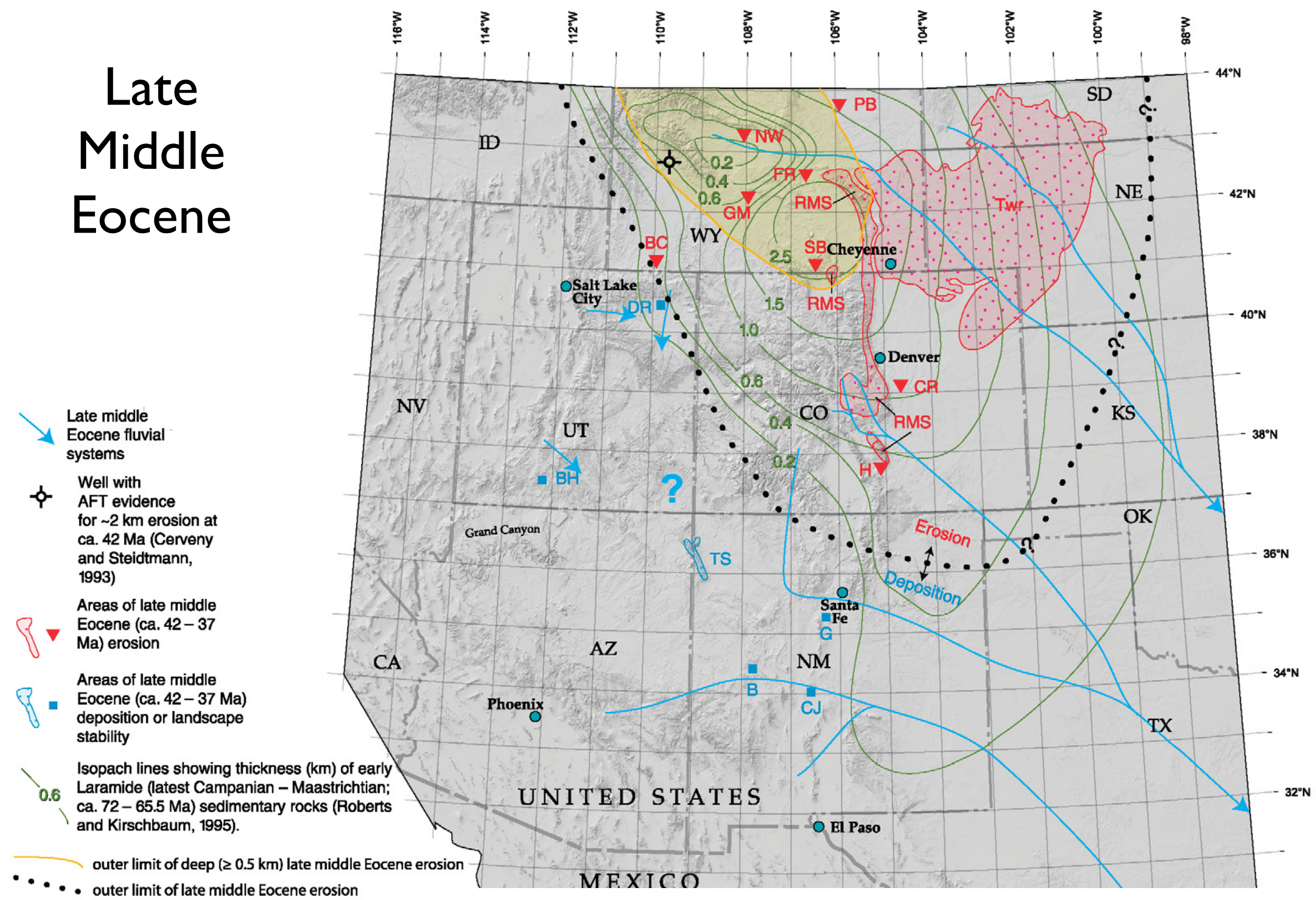


Snedden and Galloway et al., *Gulf of Mexico Sedimentary Bason, Ch. 8*, 2019



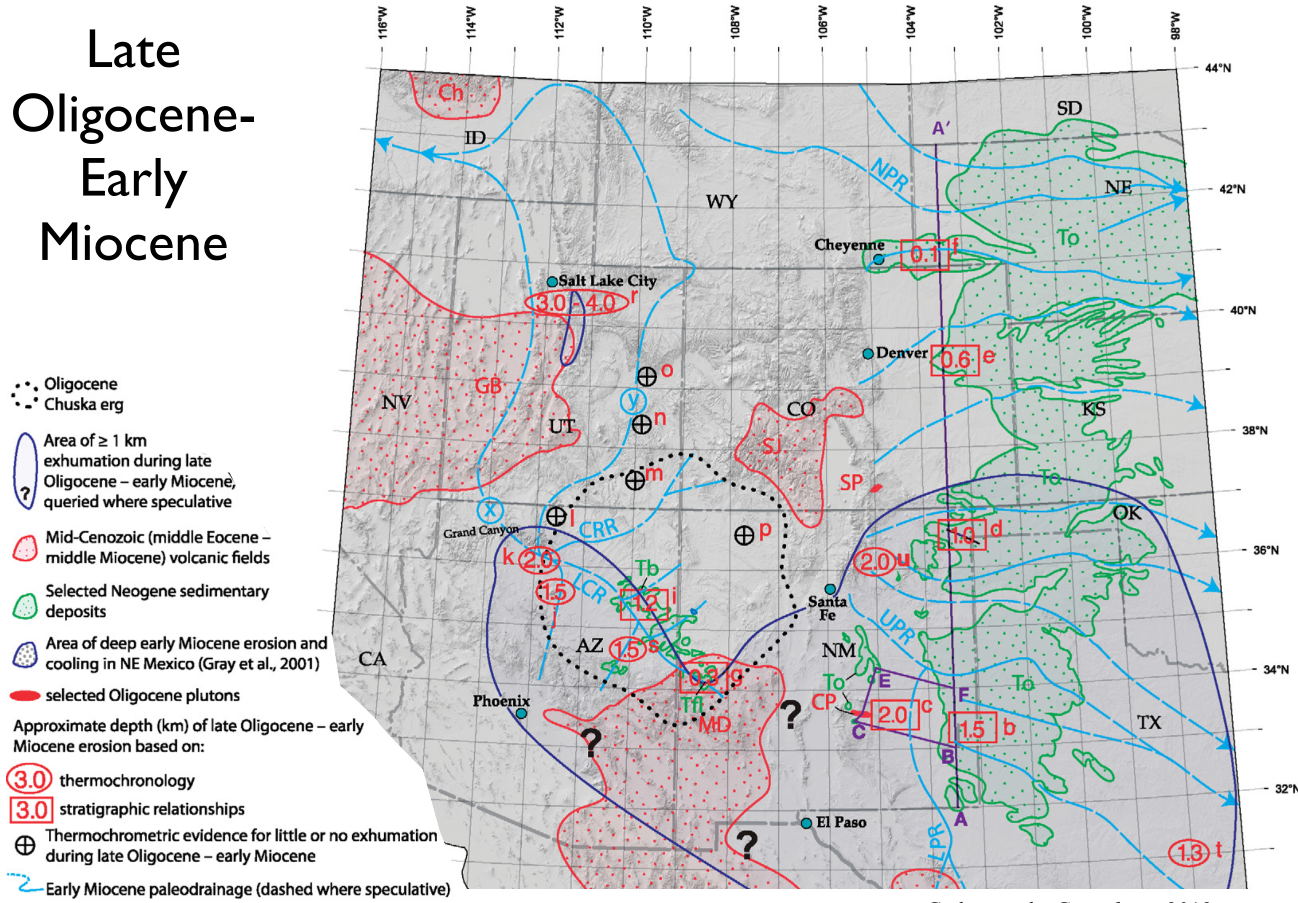
Erosional events in Rockies vs. sediment in Gulf--not exactly one to one...

Late Middle Eocene



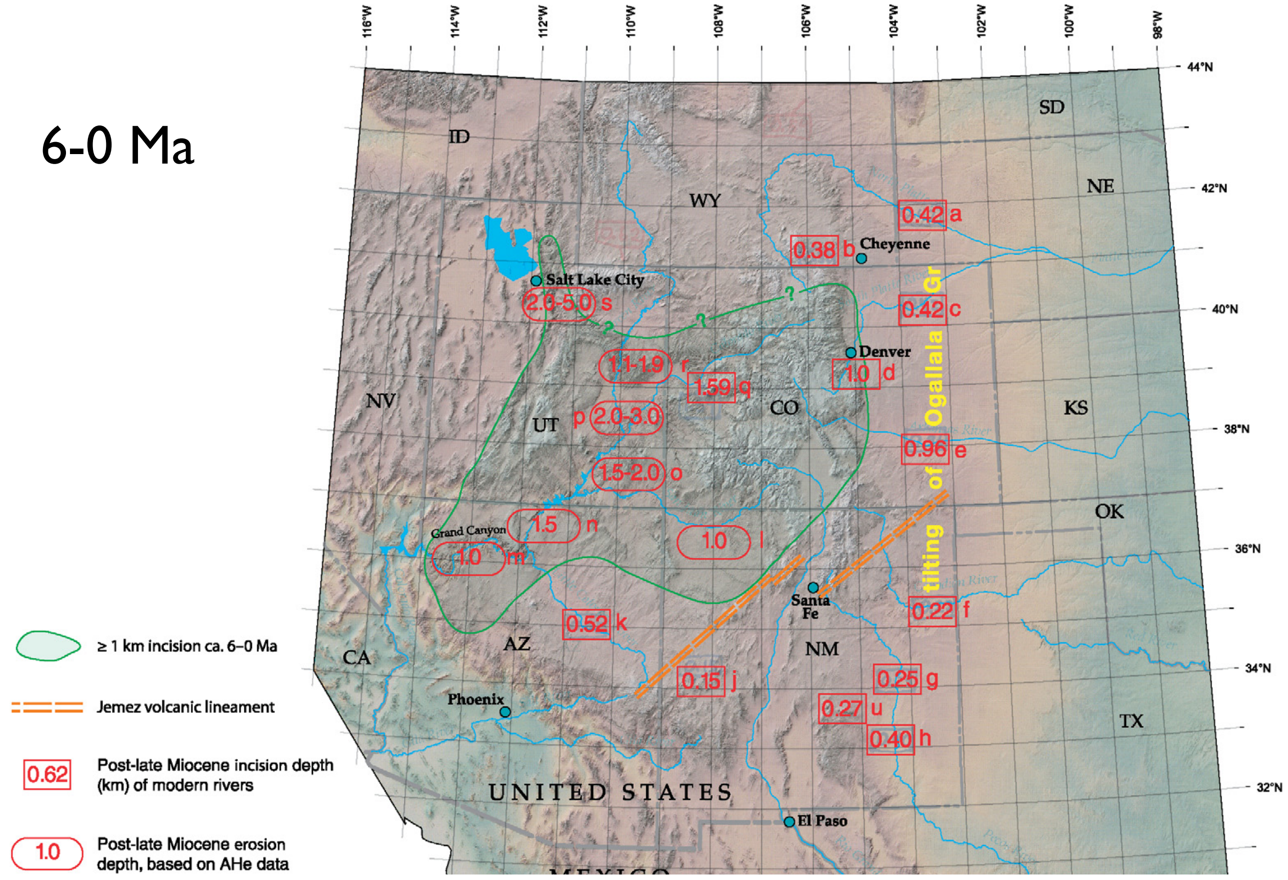
Cather et al., *Geosphere*, 2012

Late Oligocene-Early Miocene

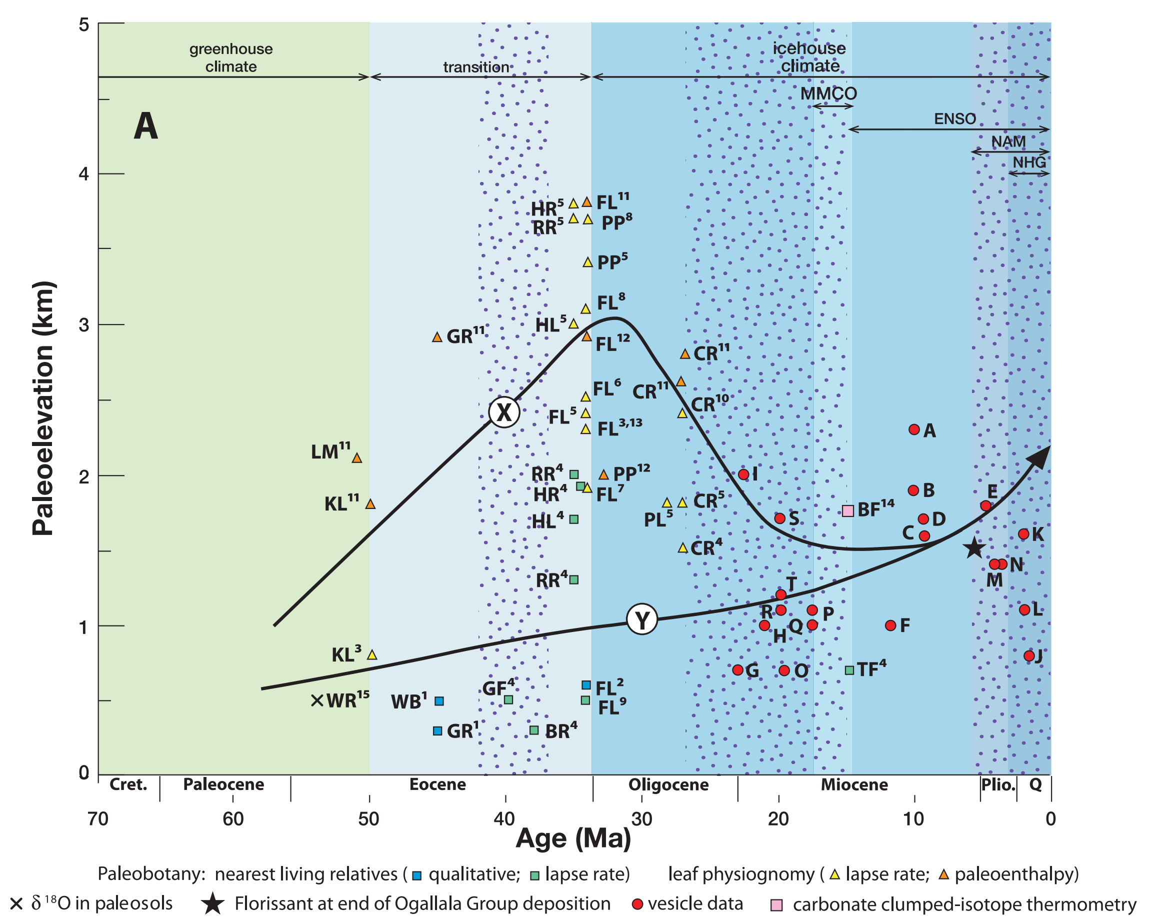


Cather et al., *Geosphere*, 2012

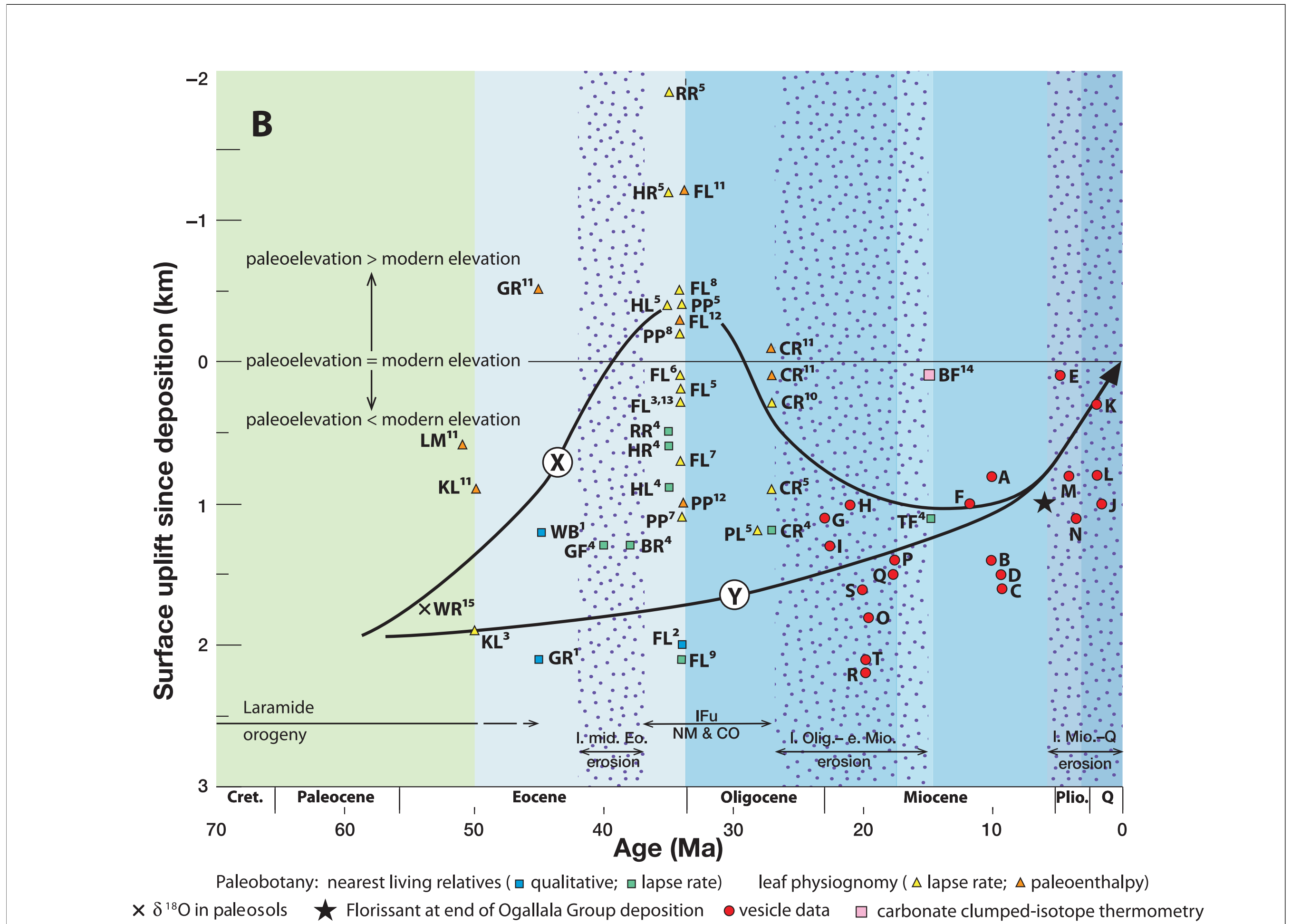
6-0 Ma



Cather et al., *Geosphere*, 2012

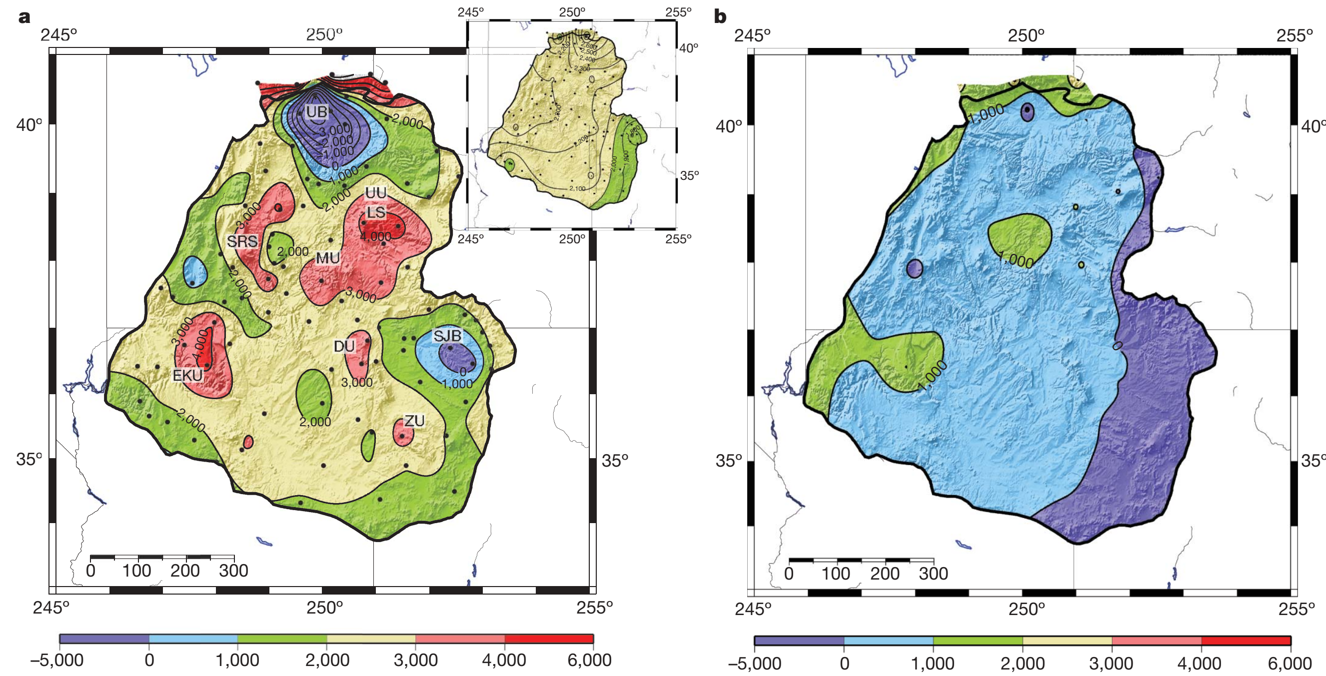


Cather et al., *Geosphere*, 2012



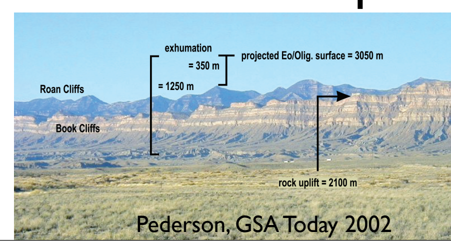
Cather et al., *Geosphere*, 2012

Note the BF at ~16 Ma is the clumped isotope work we saw before



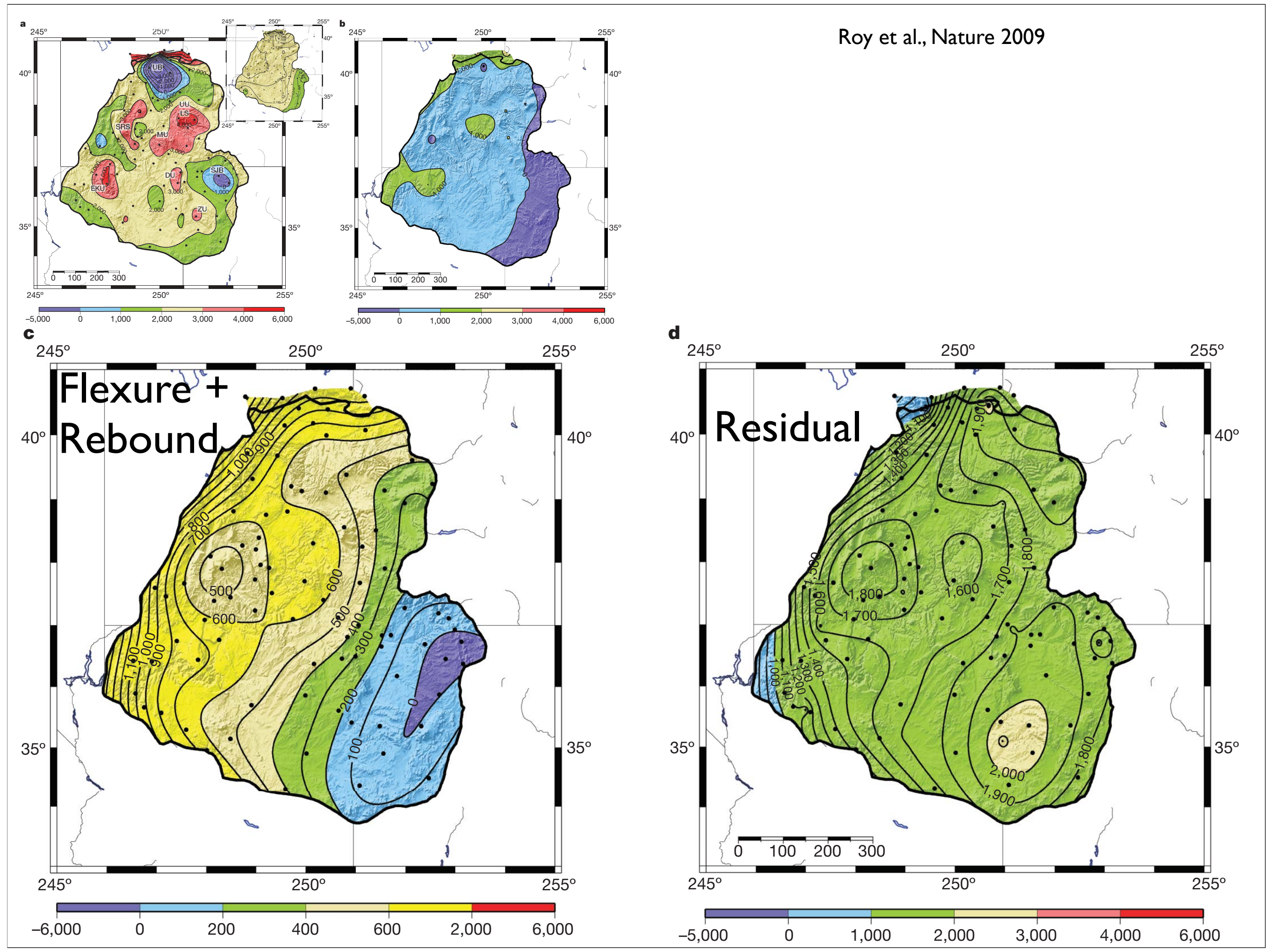
Cz Rock Uplift

Net Smoothed Erosion

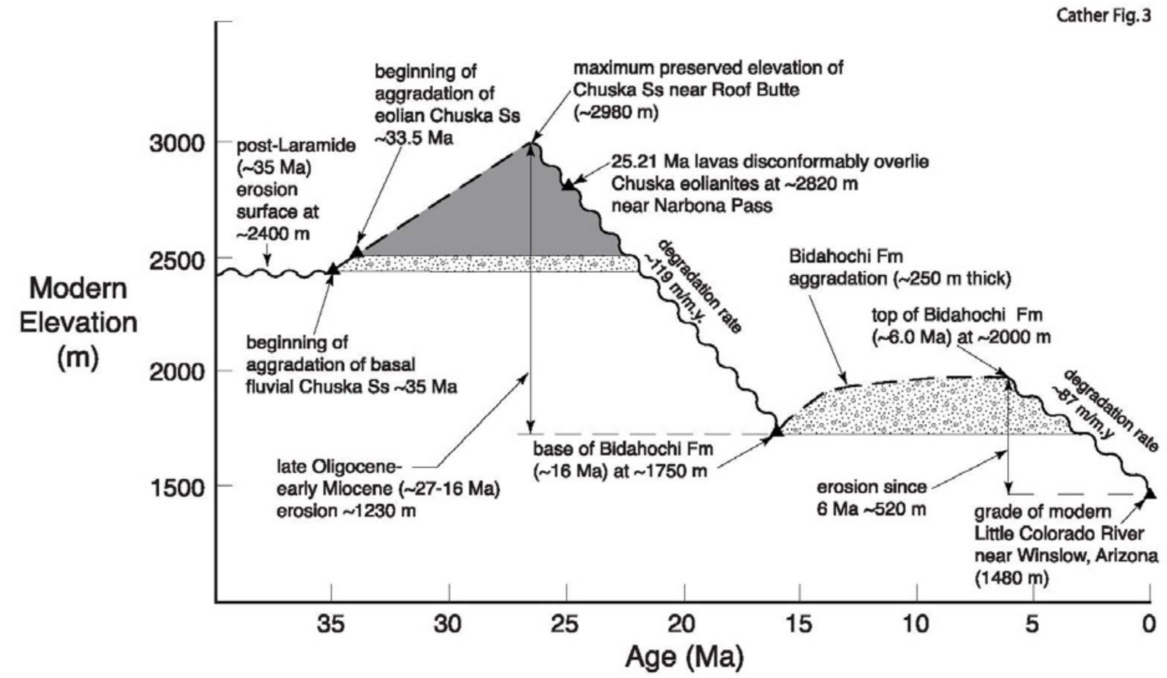


Roy et al., Nature 2009

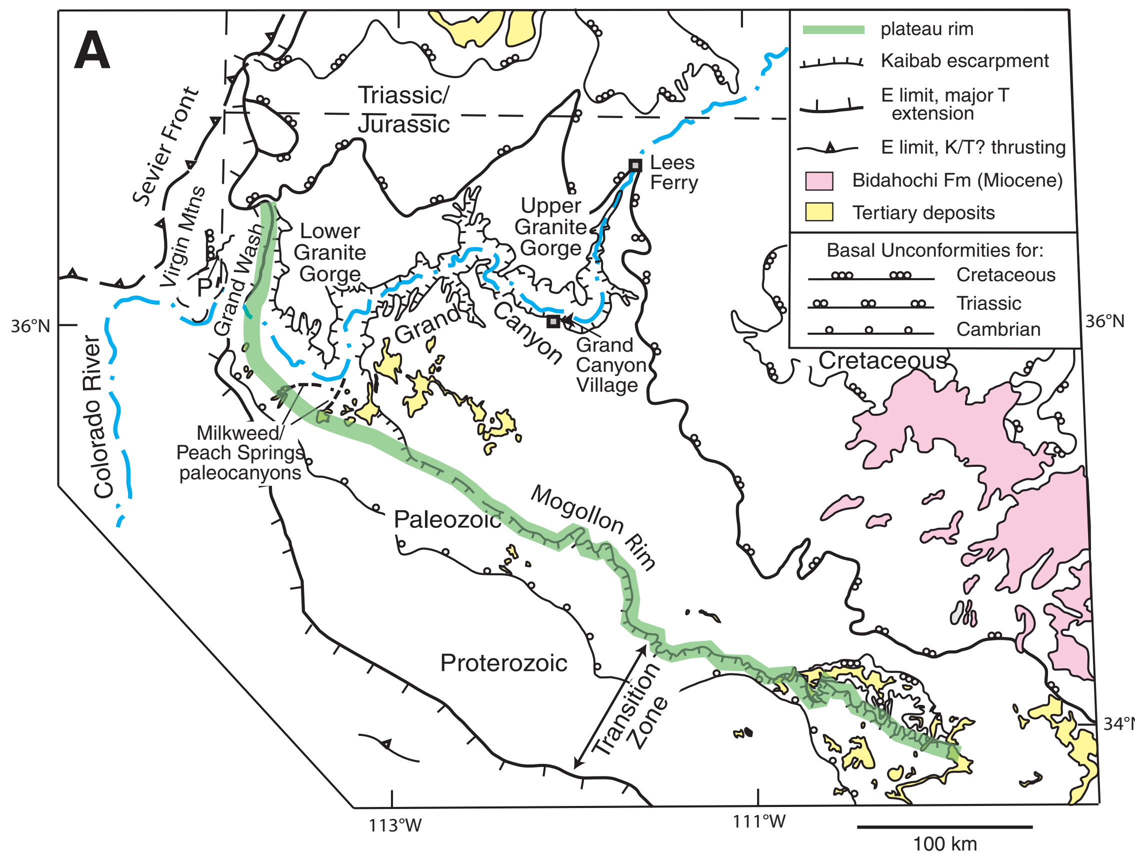
A. Net Cenozoic (0–65 Myr ago) rock uplift across the Colorado Plateau, determined by stratigraphic constraints from field relations at the points marked (black dots). Laramide features: Uinta basin (UB), San Rafael swell (SRS), Uncompahgre uplift (UU), Monument uplift (MU), east Kaibab uplift (EKU), Defiance uplift (DU), San Juan basin (SJB), Zuni uplift (ZU), La Sal Mountains (LS). Inset, 2u-by-2u smoothed rock uplift function that effectively removes Laramide- related features. b, Net Cenozoic erosion function (smoothed rock uplift minus smoothed surface elevation; negative numbers denote burial)



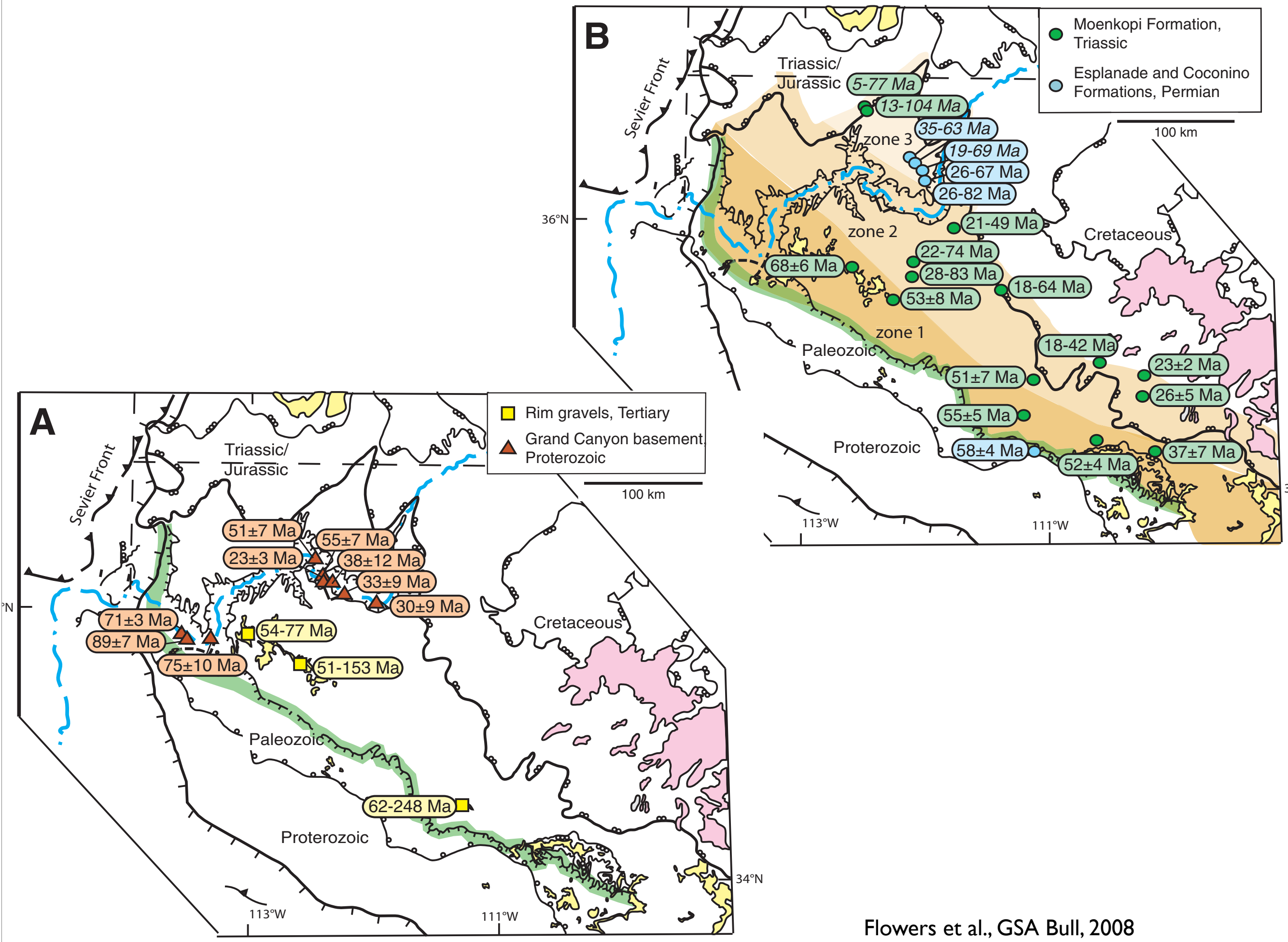
Flexure and rebound reflect Cz extension on margins and sediment/erosion loading. Residual then should be net uplift (in essence, tectonic uplift)



Cather, in *USGS OFR 2011-1210*, 2011

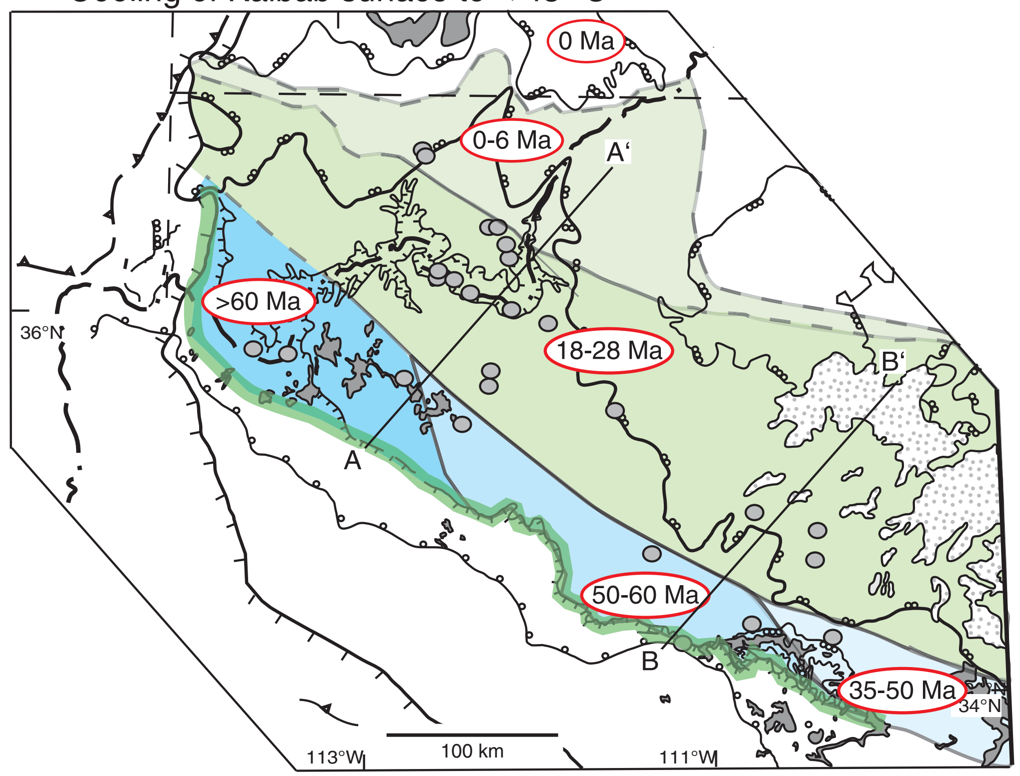


Flowers et al., GSA Bull, 2008



Flowers et al., GSA Bull, 2008

C Cooling of Kaibab surface to < 45 °C



Flowers et al., GSA Bull, 2008

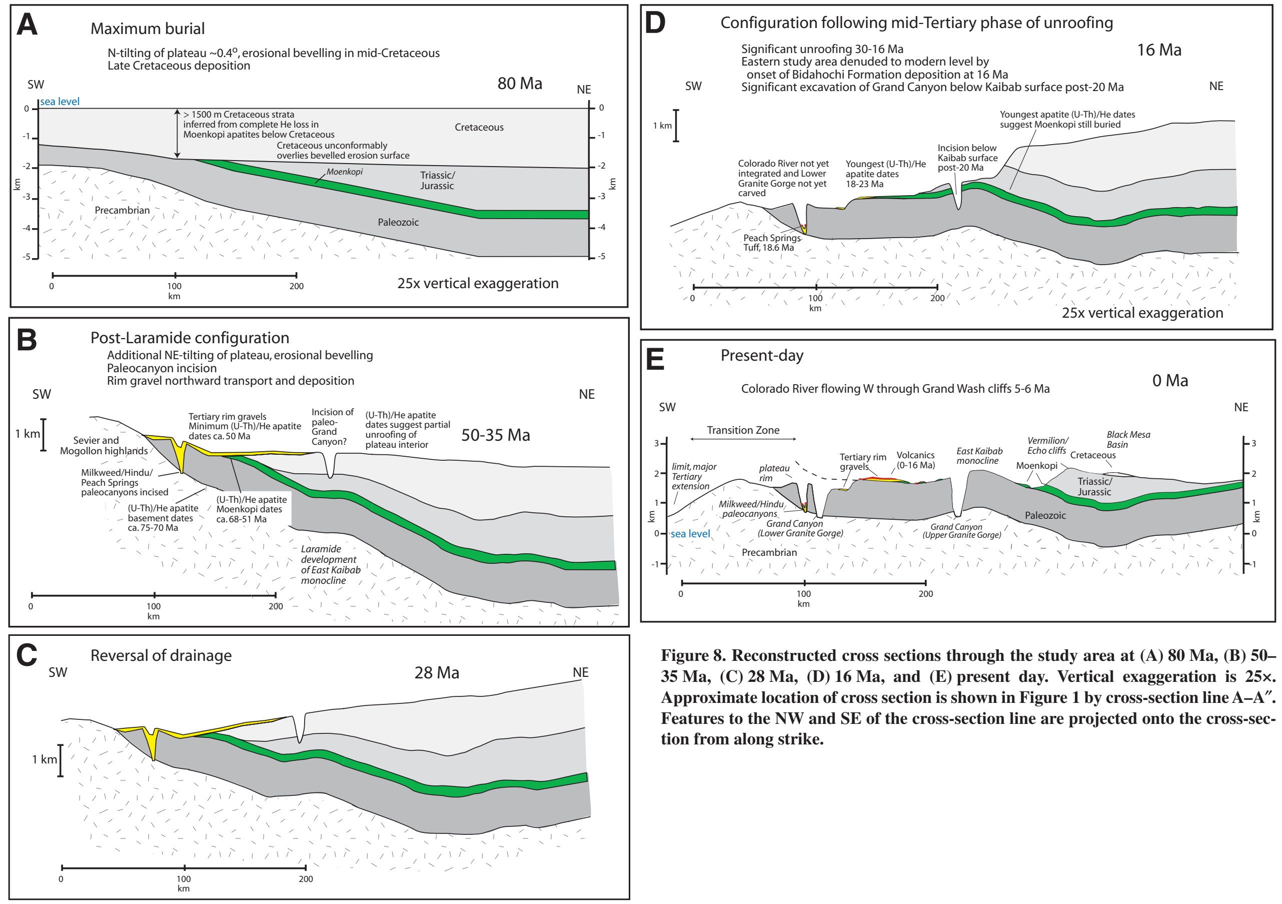


Figure 8. Reconstructed cross sections through the study area at (A) 80 Ma, (B) 50–35 Ma, (C) 28 Ma, (D) 16 Ma, and (E) present day. Vertical exaggeration is 25×. Approximate location of cross section is shown in Figure 1 by cross-section line A–A″. Features to the NW and SE of the cross-section line are projected onto the cross-section from along strike.

Flowers et al., GSA Bull, 2008

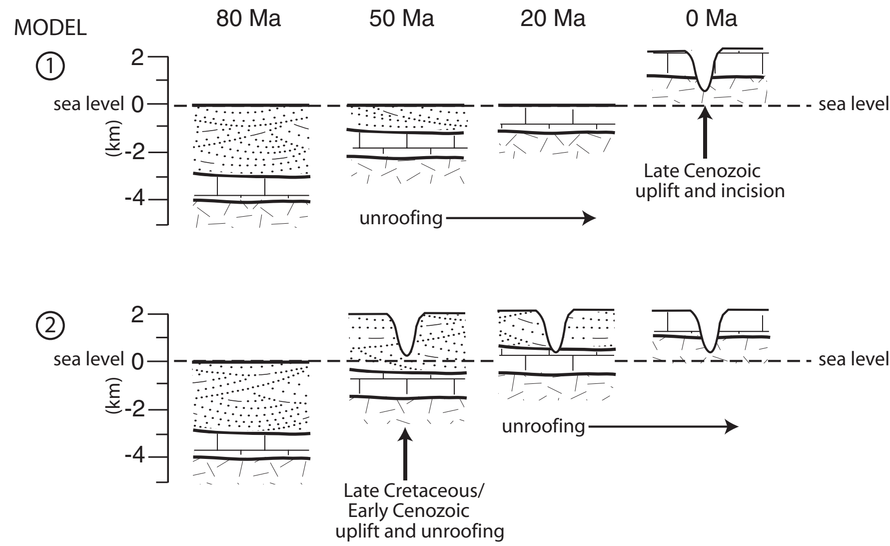
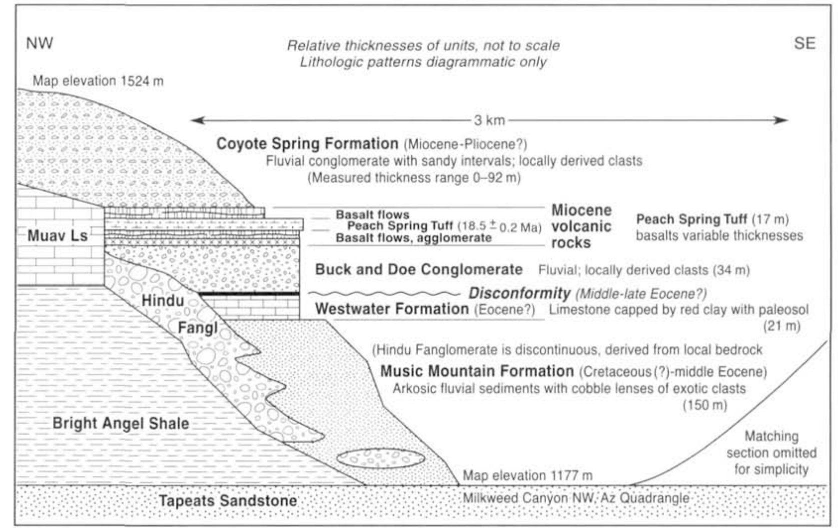


Figure 10. Endmember models for the uplift, incision, and unroofing history of the plateau interior in the Upper Granite Gorge region of the Grand Canyon.

Flowers et al., GSA Bull, 2008

Figure 2. Generalized cross section of Laramide paleochannel and formal geologic names (Young, 1999) at Milkweed Canyon type section on the Hualapai Plateau. Location of section is near west end of Milkweed-Hindu channel shown on Figure 1 at M. Disconformity marks boundary between old (Laramide) oxidized reddish arkosic sediments derived from distant sources and the younger, buff-to-tan, locally derived gravels of Oligocene or younger ages.



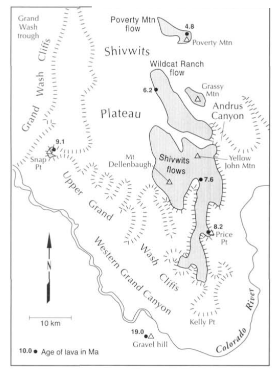
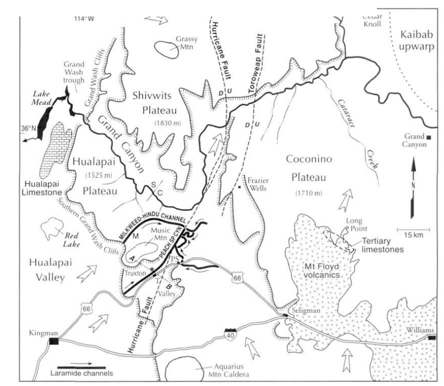
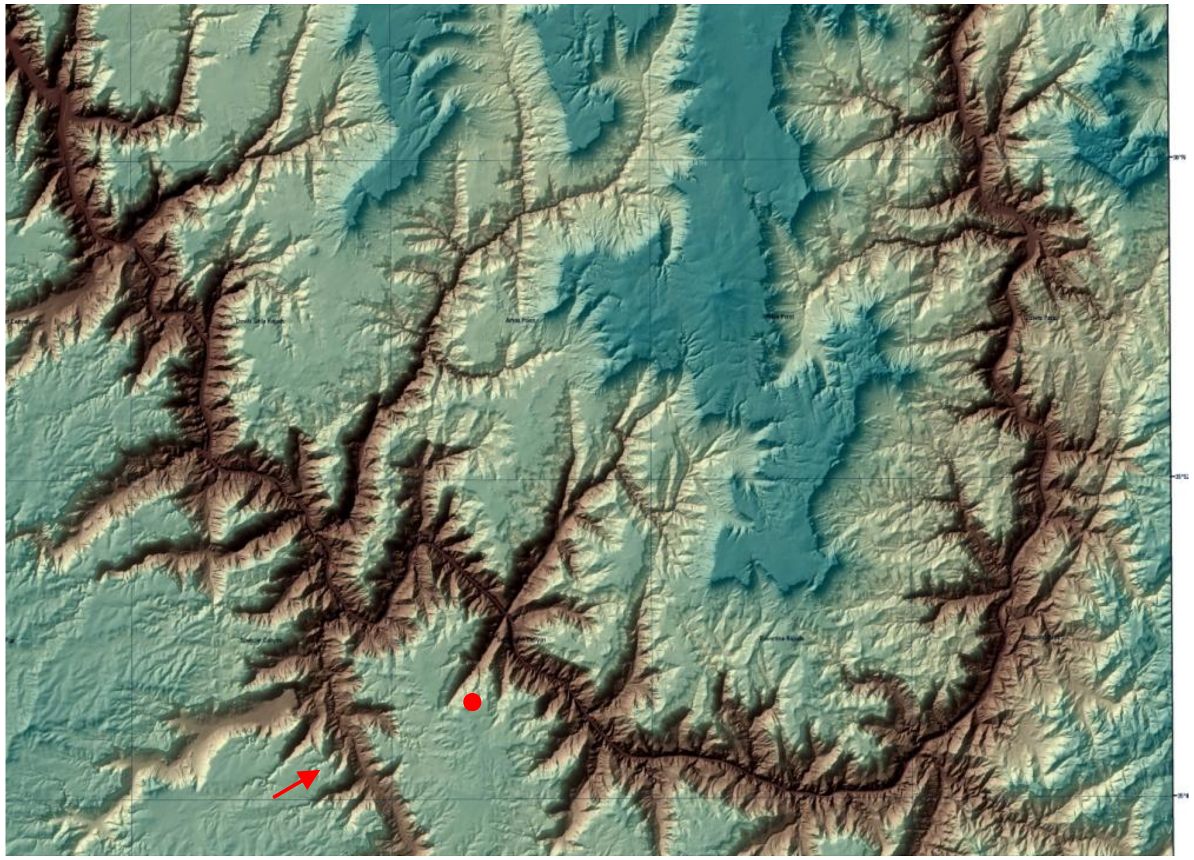


Figure 1. Location map showing basalt flows and their ages

Figure 1. General location map of Hualapai, Shivwits, and Coconino Plateaus in northwestern Arizona. Large open arrows are inferred directions of Laramide streams flowing onto plateau, as contrasted with actual mapped channels (solid black lines and small black arrows). SC = Separation Canyon; PS = Peach Springs; T = Truxton; line of section for Figure 8 = A-B. Star symbol is location of Bendix Corp. test well on Figure 8. M is location of section in Figure 2.

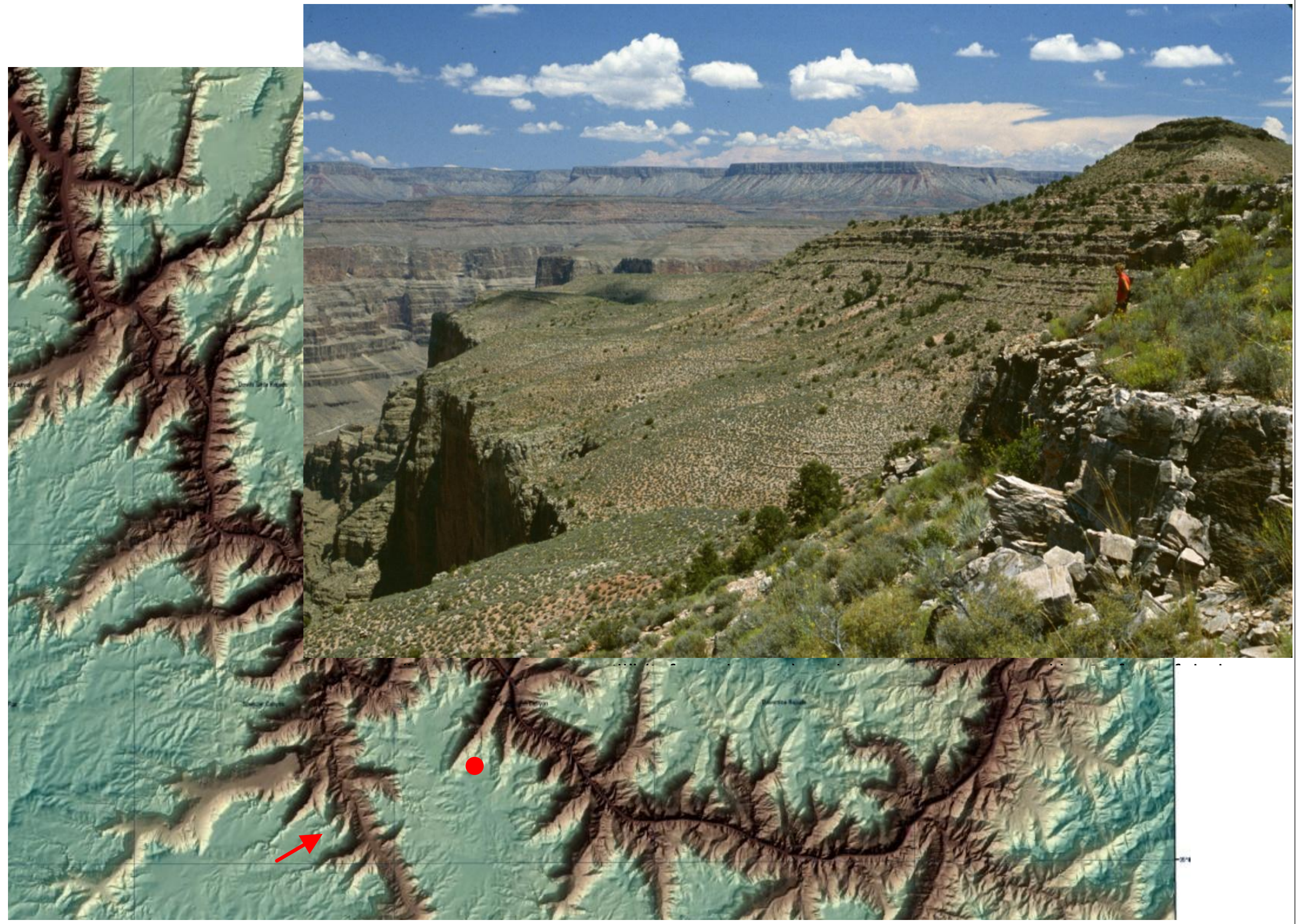


Young, in Colorado River: Origin and Evolution, 2001



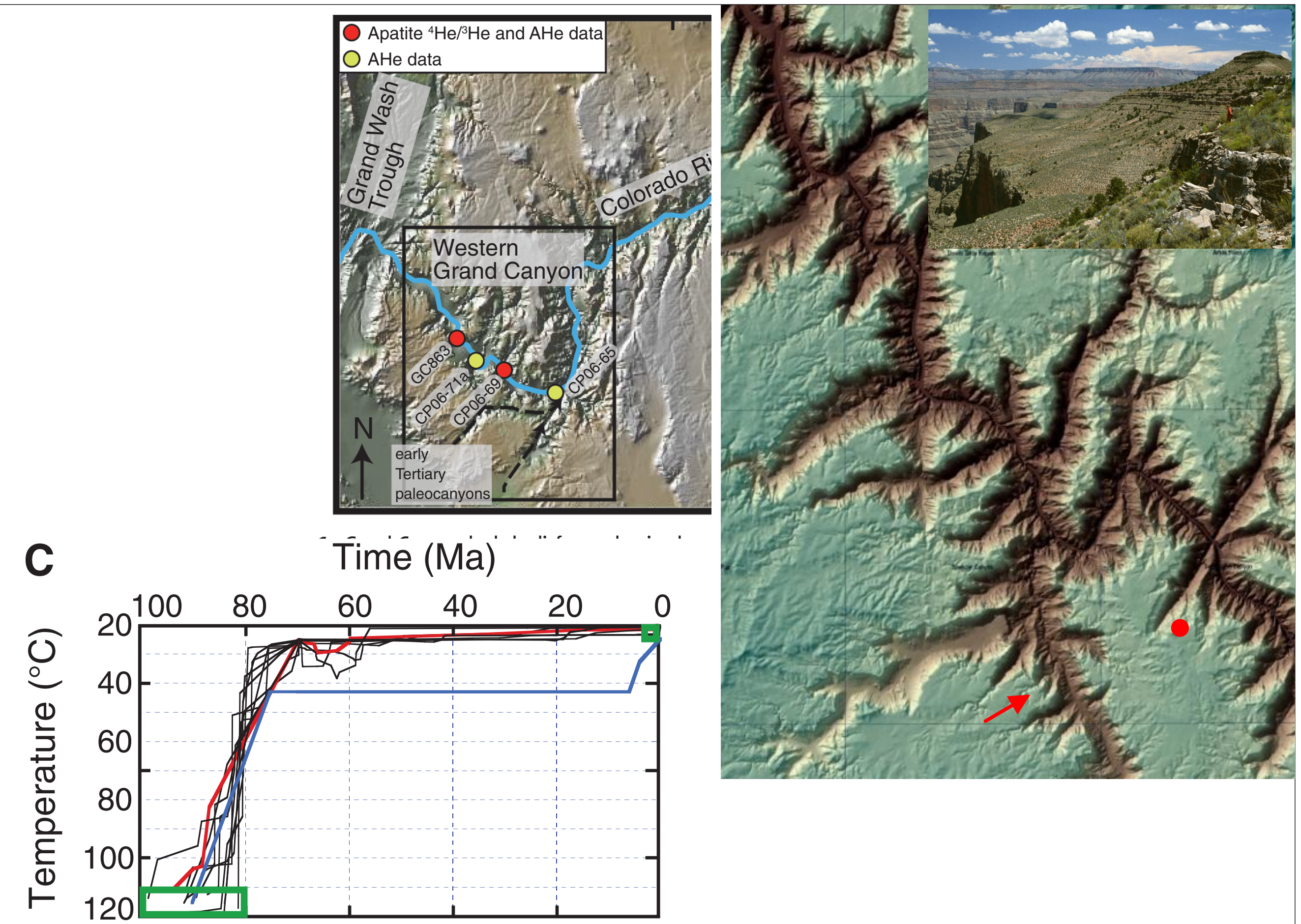
Young, *Az Contrib GeolSurv Rept., CR-11-O*, 2011

Red dot is “Separation Canyon Hill” butte (Figure 28); Red arrow is source of basalt shown on Figures 28 and 29. Large canyon between arrow and red dot is Spencer Canyon.



Young, *Az Contrib GeolSurv Rept., CR-11-O*, 2011

Photo caption: Figure 29. “Separation Canyon Hill” (informal name) at the upper right, capped by 30 feet of dark Miocene basalt (19 Ma; Wenrich et al. 1995) over a similar thickness of lighter-colored Buck and Doe Conglomerate (Milkweed member), sits directly on the south rim of Grand Canyon adjacent to “south Separation Canyon” in left foreground (not formally named on published maps). Same butte as in Figure 28. The Shivwits Plateau is on the horizon and Grand Canyon is partially visible at left center. South Separation Canyon is a small, fault-controlled canyon in direct structural alignment with the better- known Separation Canyon (of J.W. Powell fame) located on the opposite side of the Colorado River. Note that even minor erosion to begin the formation of south Separation Canyon would have provided a lower, more logical route for the thin, fluid basalt flows to follow as they flowed to this location from their southerly source vent (Red arrow, Figure 1b). The logical inference is that neither Grand Canyon nor its modern tributaries could have existed, even in a less incised state, when streams carried Buck and Doe gravels to this location. The subsequent basalt flows, whose source is nearly 5 miles distant, would also have followed the lowest available elevation. Therefore, if any precursor to south Separation Canyon had existed at that time, the fluid basalt would have been diverted along such a lower route and would have flowed into any older canyon that might be postulated to have existed. Figure shows scale.



Young, *Az Contrib GeolSurv Rept., CR-11-O*, 2011

CP06-69 is very close to the red dot in map on right

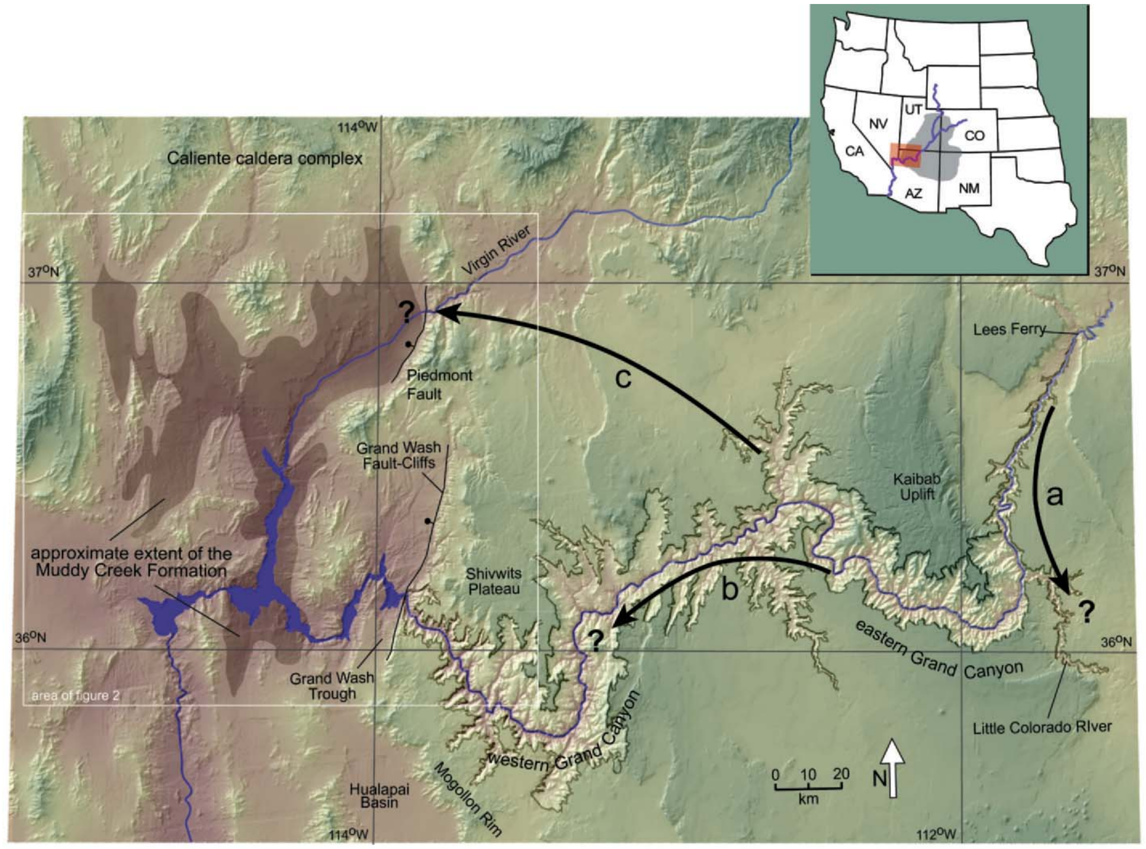


Figure 1. Regional geography and topography of Grand Canyon and Lake Mead region along the Colorado River at the edge of the Colorado Plateau (gray area of inset), southwestern United States. Large arrows indicate hypothetical paths of late Miocene upper Colorado River before major incision of Grand Canyon, with letters matching the hypotheses as reviewed in the text.

Pederson, GSA Today, 2008

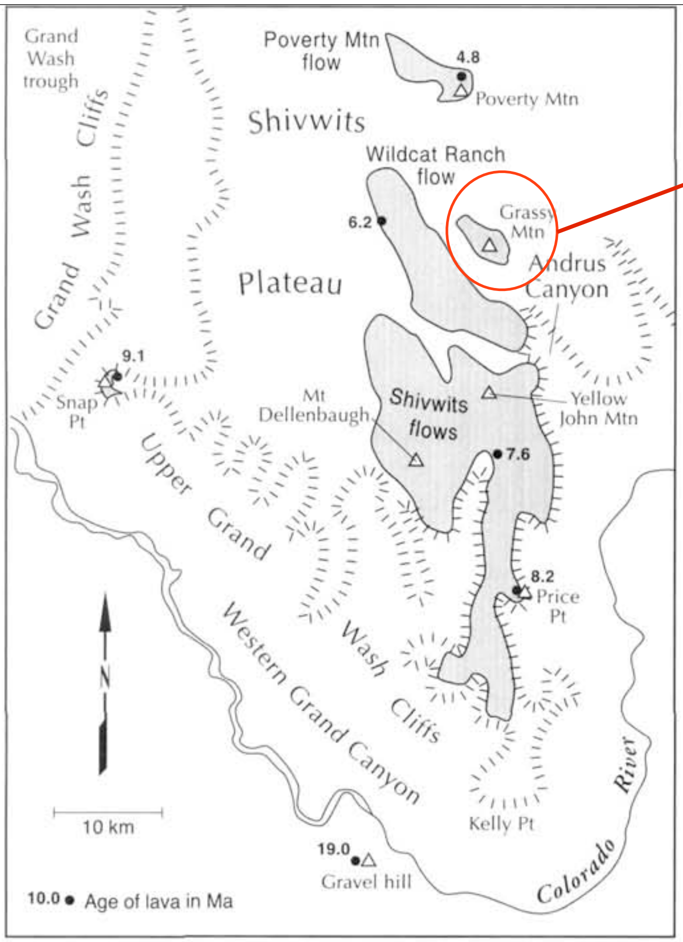


Figure 1. Location map showing basalt flows and their ages

Sub-lava clasts from off Plateau

Absence of cascades into canyon (but cascades preserved over Grand Wash Cliffs)

Lucchitta & Jeanne, in Colorado River: Origin and Evolution, 2001

Figure 1. General location map of Hualapai, Shivwits, and Coconino Plateaus in northwestern Arizona. Large open arrows are inferred directions of Laramide streams flowing onto plateau, as contrasted with actual mapped channels (solid black lines and small black arrows). SC = Separation Canyon; PS = Peach Springs; T = Truxton; line of section for Figure 8 = A-B. Star symbol is location of Bendix Corp. test well on Figure 8. M is location of section in Figure 2.

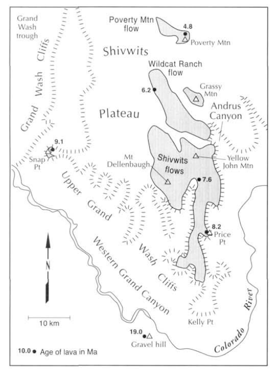
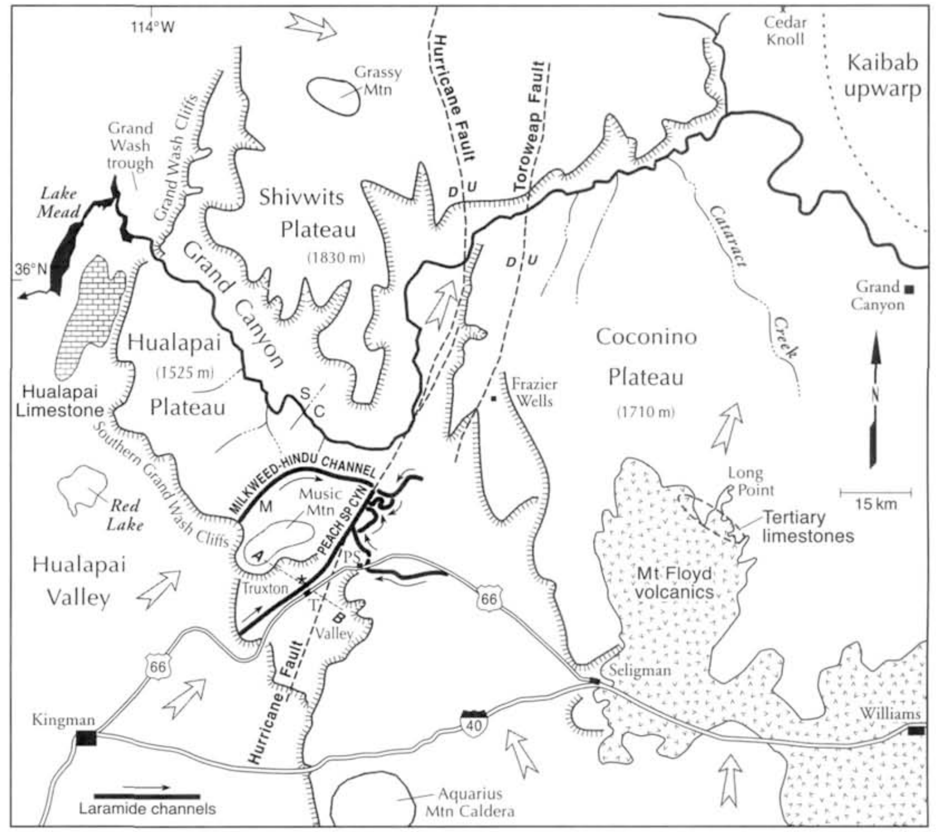
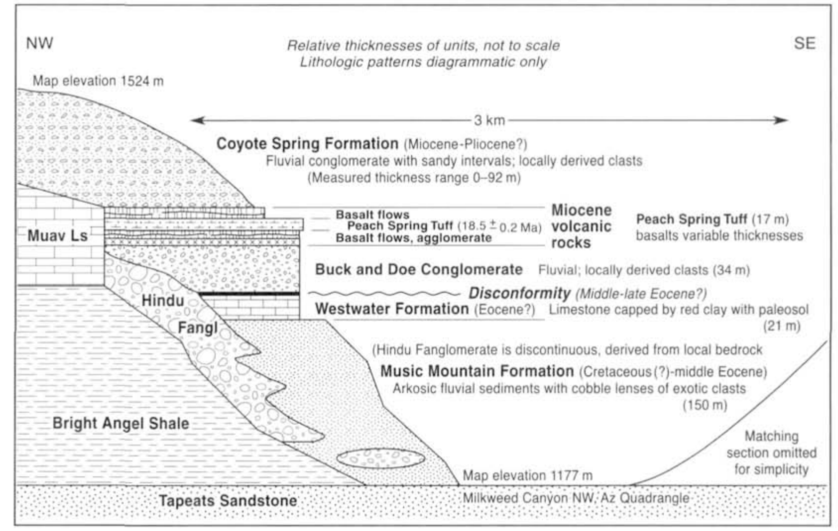


Figure 1. Location map showing basalt flows and their ages



Young, in Colorado River: Origin and Evolution, 2001

Figure 2. Generalized cross section of Laramide paleochannel and formal geologic names (Young, 1999) at Milkweed Canyon type section on the Hualapai Plateau. Location of section is near west end of Milkweed-Hindu channel shown on Figure 1 at M. Disconformity marks boundary between old (Laramide) oxidized reddish arkosic sediments derived from distant sources and the younger, buff-to-tan, locally derived gravels of Oligocene or younger ages.



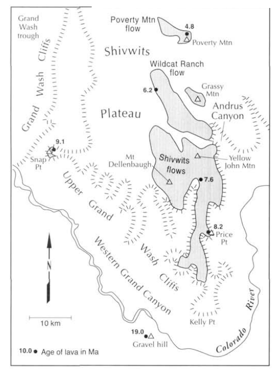
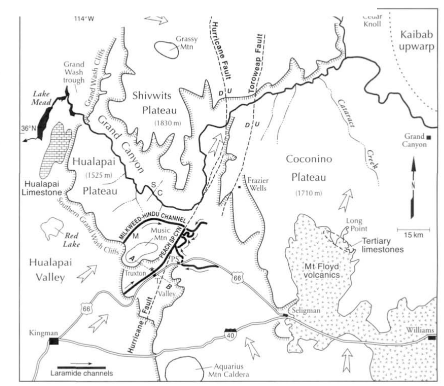


Figure 1. Location map showing basalt flows and their ages

Figure 1. General location map of Hualapai, Shivwits, and Coconino Plateaus in northwestern Arizona. Large open arrows are inferred directions of Laramide streams flowing onto plateau, as contrasted with actual mapped channels (solid black lines and small black arrows). SC = Separation Canyon; PS = Peach Springs; T = Truxton; line of section for Figure 8 = A-B. Star symbol is location of Bendix Corp. test well on Figure 8. M is location of section in Figure 2.



Young, in Colorado River: Origin and Evolution, 2001

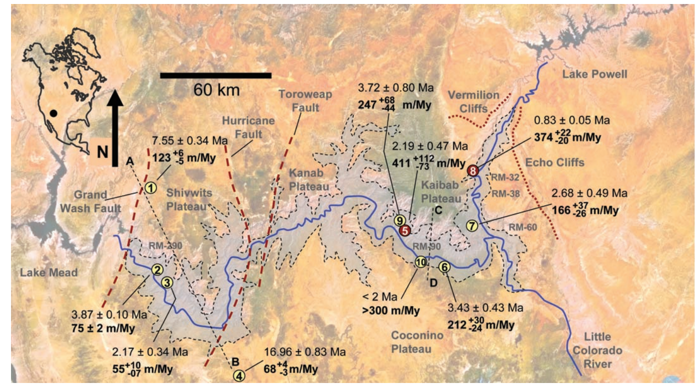


Fig. 2. Map showing locations and U-Pb ages of cave mammillary samples and their apparent incision rates. Site numbers (in circles) are those referred to in Table 1 and the text; those in brown circles represent surface-exposed mammillary calcite. Washout satellite image was taken from the NASA World Wind Web site, with darker regions representing higher elevations. Gray area is the canyon corridor. Two cross sections, A-B and C-D (fig. S3), show generalized pertinent stratigraphy. RM denotes the river-mile location. Incision rate errors assume $\delta^{234}U_{initial}$ values = 3100‰ for sites 1, 2, 4, 6, and 9; see Fig. 3C for expanded uncertainties for these sites.

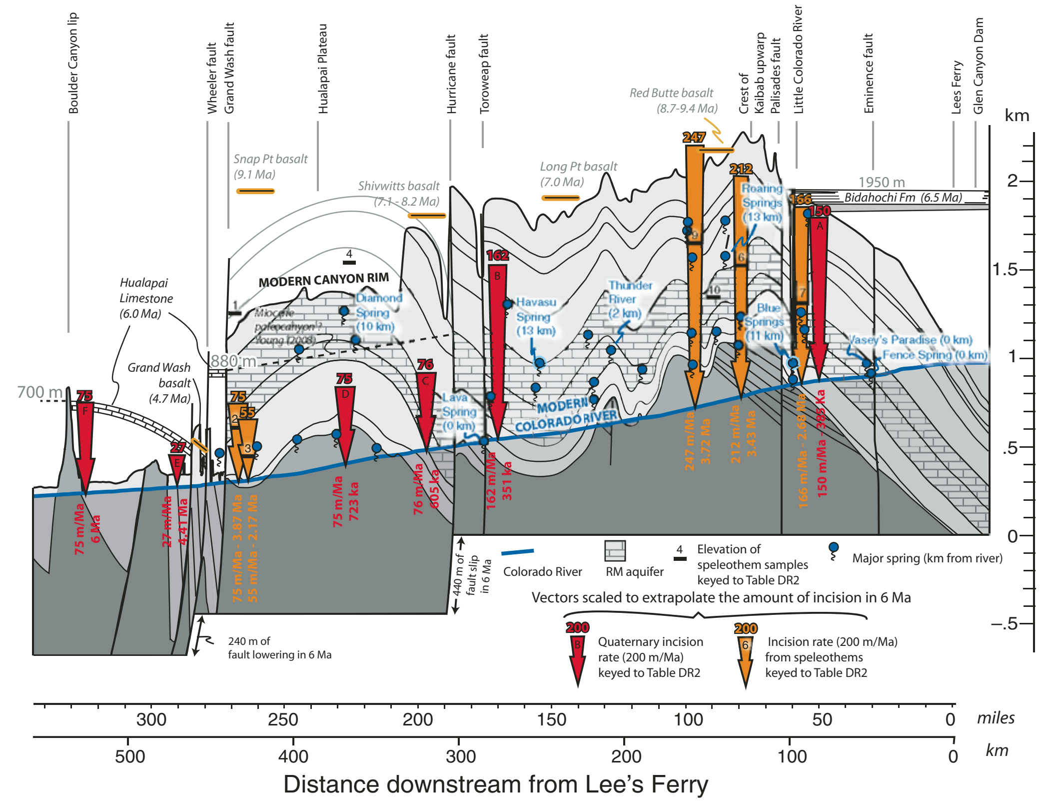
Table 1. U-Pb ages and incision rates from cave mammillaries. RM, river mile; IR, incision rate. Mother Cave mammillary age is estimated from $\delta^{234}U_{measured}$ of 17 ± 3‰ with $\delta^{234}U_{initial}$ of 3000 ± 2500‰. For sites with $\delta^{234}U_{measured}$ = 0‰, $\delta^{234}U_{initial}$ is assumed to be 3100‰. Extended 2σ absolute errors on the incision rates assume a large uncertainty of the $\delta^{234}U_{initial}$ = 3100 ± 2500‰.

Site	Region	$^{238}U/^{206}Pb$ age (Ma)	$^{235}U/^{207}Pb$ age (Ma)	Concordia-constrained linear 3D age (Ma)	Dist. above river (m)	Dist. from river (km)	RM	IR (m/My)	2σ error	Abs. error	Extended 2σ error	Extended Abs. error
1	Grand Wash Cliffs	7.53 ± 0.42	7.1 ± 1.4	7.55 ± 0.34	930	38.6	277	123	+6	–5	+24	–18
2	Cave B	3.8 ± 0.32	4.3 ± 0.5	3.87 ± 0.10	290	0.5	266	75	+2	–2	+35	–15
3	Dry Canyon	2.17 ± 0.42	8.1 ± 9.9	2.17 ± 0.34	120	1.6	265	55	+10	–7		
4	Grand Canyon Caverns	17.3 ± 1.60	29.0 ± 14.0	16.96 ± 0.83	1160	28.9	190	68	+4	–3	+4	–3
5	Gavain Abyss	2.39 ± 0.77	6.2 ± 5.9	2.19 ± 0.47	900	5.5	93	411	+112	–73		
6	Tsean Bida	3.37 ± 0.50	1.0 ± 16.0	3.43 ± 0.43	726	4.6	80	212	+30	–24	+134	–59
7	Butte Fault Cave	2.73 ± 0.63	3.7 ± 7.9	2.68 ± 0.49	445	2.6	57	166	+37	–26		
8	Bedrock Canyon	0.8 ± 0.12	0.7 ± 0.3	0.83 ± 0.05	310	2.1	32	374	+22	–20		
9	Shinumo Creek Cave	3.5 ± 1.30	–1.0 ± 5.2	3.72 ± 0.80	920	6.6	94	247	+68	–44	+208	–78
10	Mother Cave	^{234}U age = 1.6 ± 0.5			605	2.2	90	>300				

Polyak et al, Science, 2008

Using cave speleothems to estimate river level.

Figure 2. Longitudinal river profile, modern canyon rim, stratigraphic units, spring elevations (Table DR1; see footnote 1), and incision points (Table DR2).



Karlstrom et al., Geology 2008

Note that the actual ages involved are smaller (sometimes by a lot) than the arrows' scales would suggest. But in general idea of more recent incision of eastern canyon seems to be agreed by workers—dispute in west continues…

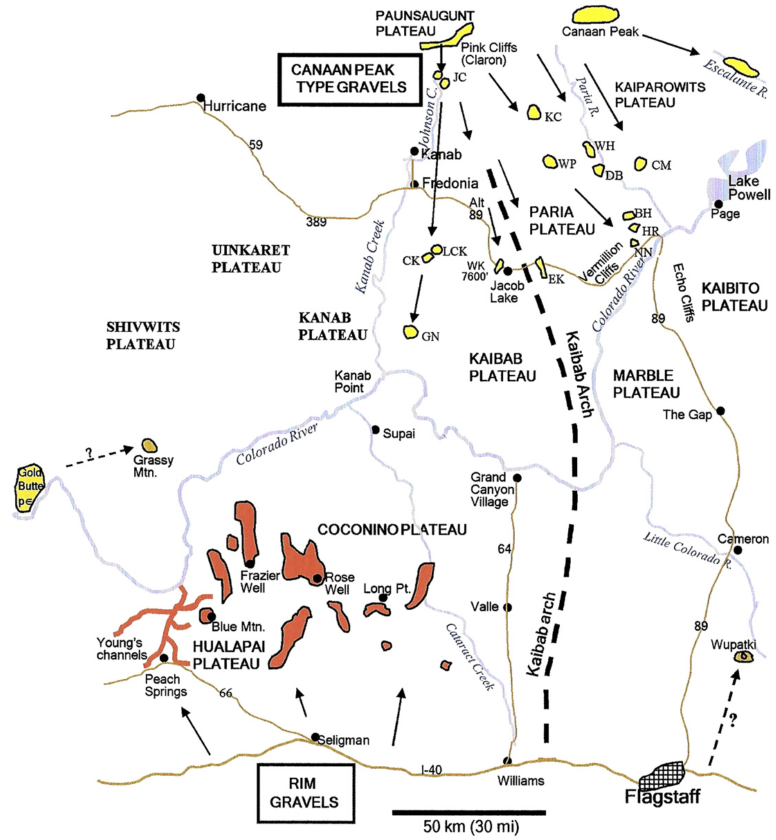


Fig. 3. Schematic drawing showing geographic features and place names relative to the location of South Rim and North Rim gravel remnants. The solid red areas denote the "rim gravels" of Koons (1964) and Scarborough et al. (2007). "Young's channels" are those of Young (2001) denoting rim gravels exposed along Milkweed and Hindu Canyons, Peach Springs Canyon, and other smaller canyons to the east. The solid yellow areas denote "Canaan Peak-type" gravels coming down from the north. The arrows point in the presumed direction of transport of these gravels. Note that no South Rim rim gravels (red) have been found north of the Colorado River and no Canaan Peak-type gravels (yellow) have been found south or east of the Colorado River. JC=Johnson Creek, CK=Cedar Knoll, LCK=Little Cedar Knoll, GN=Goosenecks, WK=West Kaibab arch, EK=East Kaibab arch, KC=Kitchen Corral, WP=Wire Pass, WH=White House, DB=Dive Butte, CM=Cedar Mountain, BH=Bushhead Knoll, HR=Horse Ridge, NN=No-Name Knoll. The Grassy Mountain and Wupatki gravels are of problematic origin and are discussed in the text.

Hill & Ranney, Geomorph. 2008

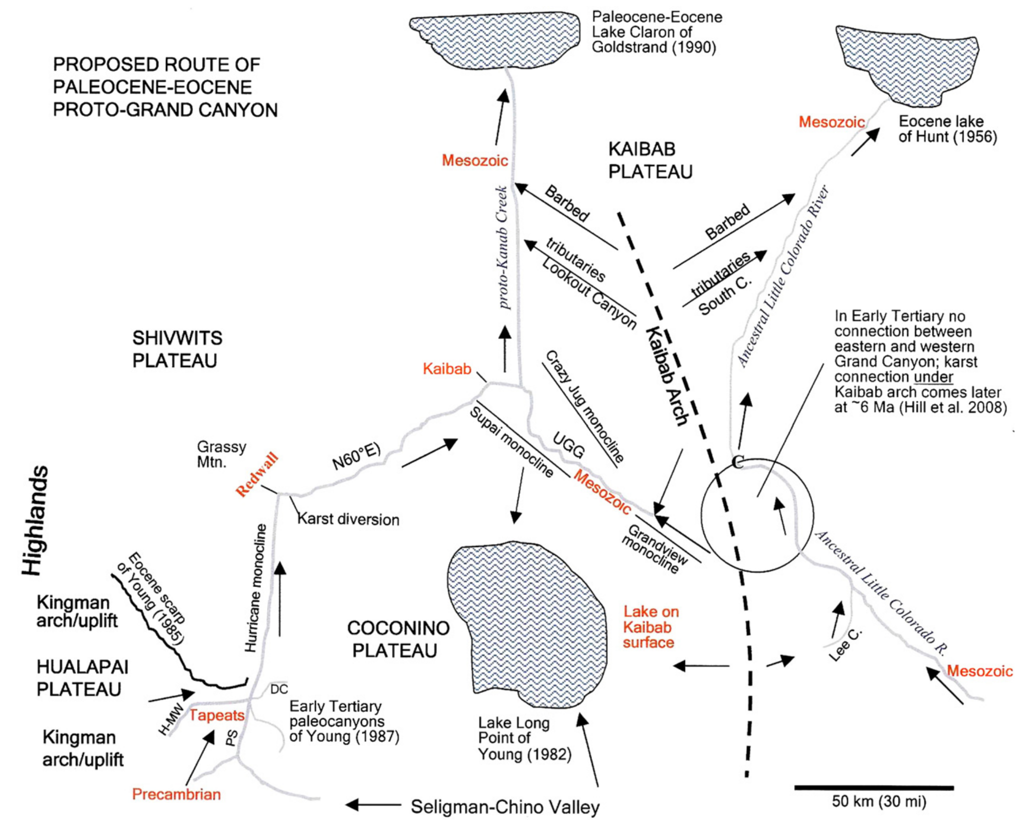


Fig. 5. Schematic drawing showing the route of the proposed proto-Grand Canyon in Laramide time. Black arrows show the direction of proposed flow. Red words denote the level to which this paleocanyon incised. The "barbed tributaries" are those off both the east and west sides of the Kaibab arch that are obtuse to the direction of today's drainage. UGG = Upper Granite Gorge, H-MW = Hindu-Milkweed Canyon, PS = Peach Springs Canyon, DC = Diamond Creek. Monoclines after Huntoon et al. (1996).

Hill & Ranney, Geomorph. 2008

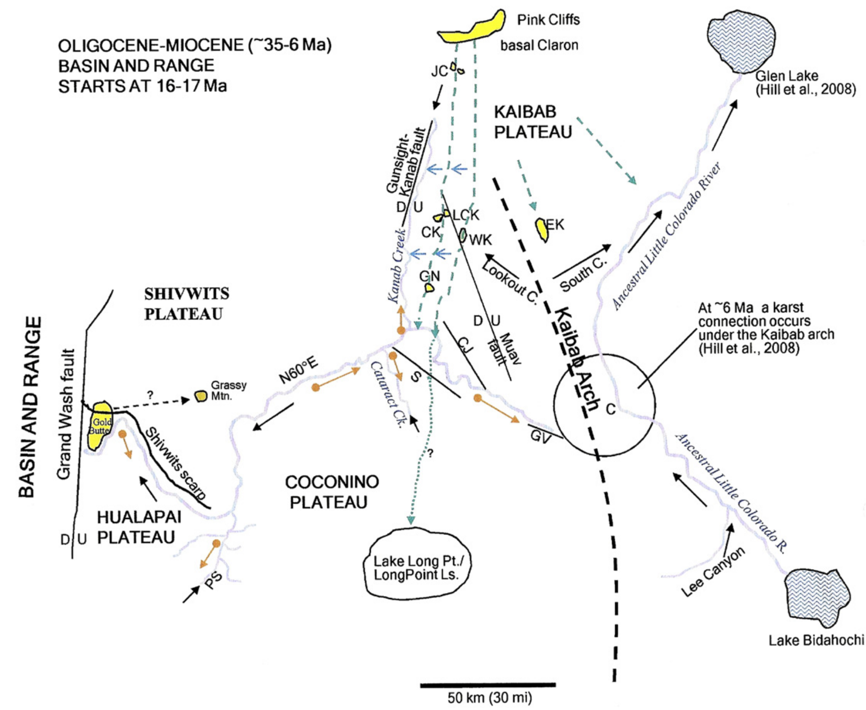
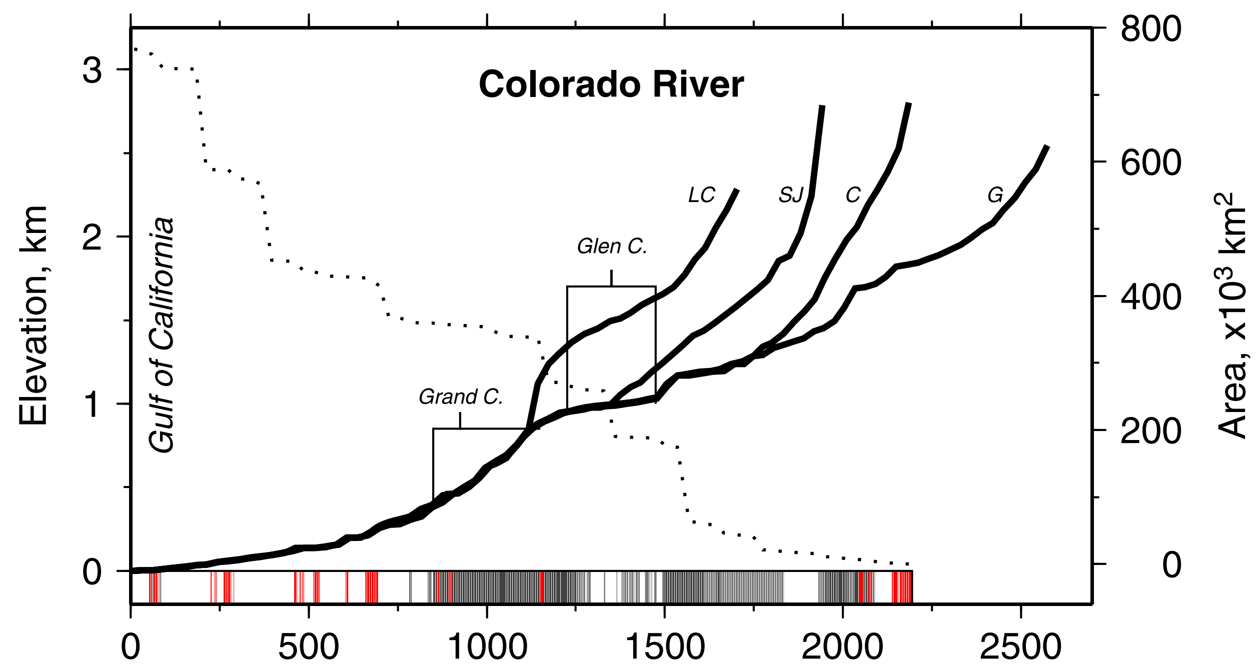


Fig. 10. The evolution of Grand Canyon from the time of a drainage reversal (~35 Ma?) to the time of an integrated Colorado River through the canyon at ~6 Ma. Black arrows = direction of water flow. Orange-balled arrows = direction of headward erosion. Green dashed arrows = direction of transport of Canaan Peak-type gravels southward and southeastward from the Bryce Canyon area. Blue open arrows = direction along which southward drainage "slid" westward from its original high position along the west side of the Kaibab arch (WK), to its intermediate position along Johnson Creek/Cedar Knoll–Little Cedar Knoll/Goosenecks, to its final position along Kanab Creek. Dotted green arrow = hypothetical drainage route down a south-dipping Supai monocline and into a still-existent Oligocene Lake Long Point. After this time the lake dried up and the Long Point Limestone was progressively reduced in size by erosion. Yellow areas = remnant Canaan Peak-type gravels still present today along both sides of the Kaibab arch (other remnant gravels east of the Kaibab arch are shown in Fig. 3). The Shivwits scarp is shown cutting across the Gold Butte area, with the northernmost part of the block supplying material eastward to Grassy Mountain. C = Confluence, EK = East Kaibab arch, WK = West Kaibab arch, JC = Johnson Creek, LCK = Little Cedar Knoll, CK = Cedar Knoll, GN = Goosenecks, GV = Grandview monocline, CJ = Crazy Jug monocline, S = Supai monocline, PS = Peach Springs.

Hill & Ranney, Geomorph. 2008

Analyses extend to whole river systems

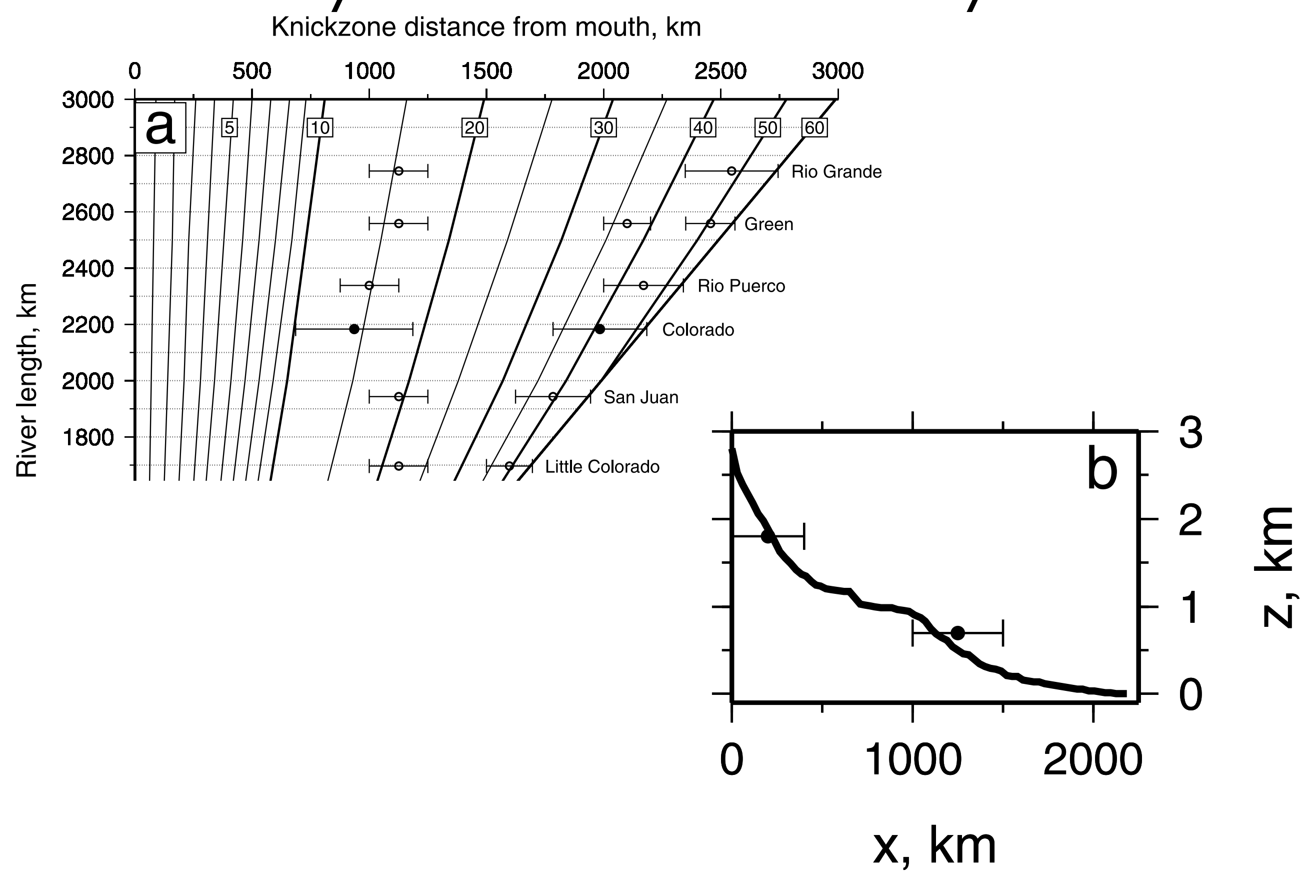


Roberts et al., *Tectonics,* 2012

So the idea of a river system out of equilibrium is that there will be a knick zone that migrates up a river—stretches that are anomalously steep…

Longitudinal river profiles and their upstream drainage areas from Colorado River and Rio Grande catchments (see Figure 5 for locations). Solid lines = Colorado (C), Green (G), Little Colorado (LC), San Juan (SJ), Rio Grande (RG) and Rio Puerco (RP) river profiles; man-made dams were removed. Dotted lines = upstream drainage area of Colorado River and Rio Grande only. Horizontal bars along base = lithology along river bed : black bar = Precambrian/Paleozoic rocks, gray bar = Mesozoic rocks, white bar = Cenozoic rocks, red bar = igneous rocks [from Choubert and Faure-Muret, 1990]

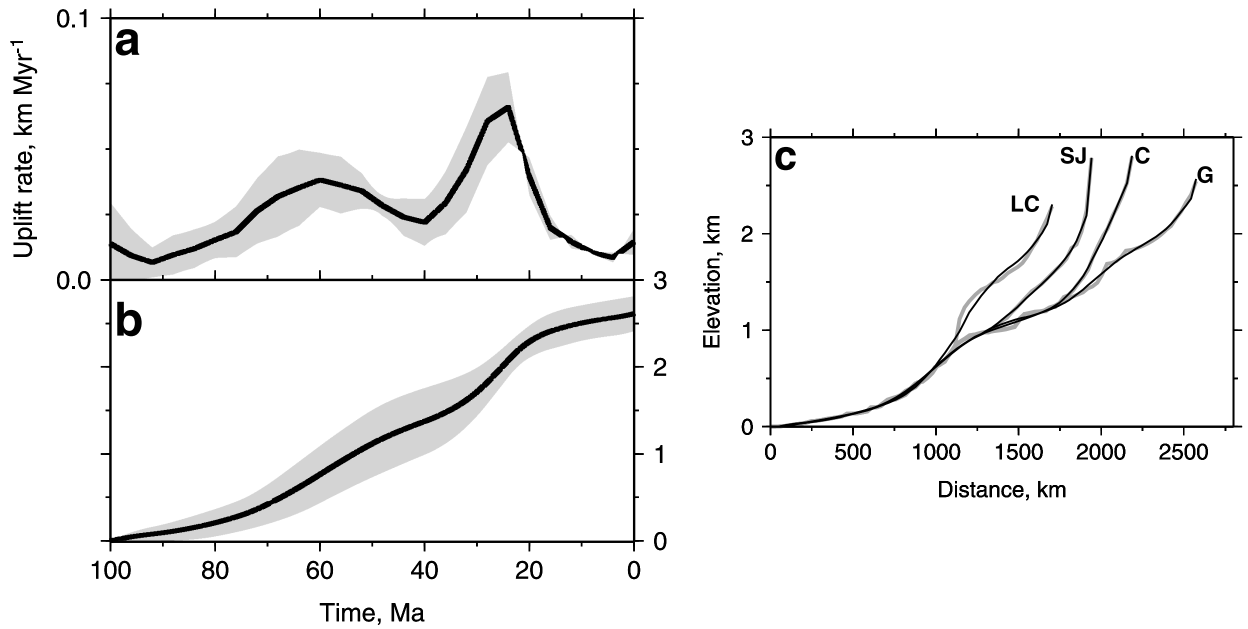
Analyses extend to whole river systems



Roberts et al., *Tectonics*, 2012

So as interpreted here, knicks farther upstream are from older events. Is this really valid? (Little diagram is the Colorado River)

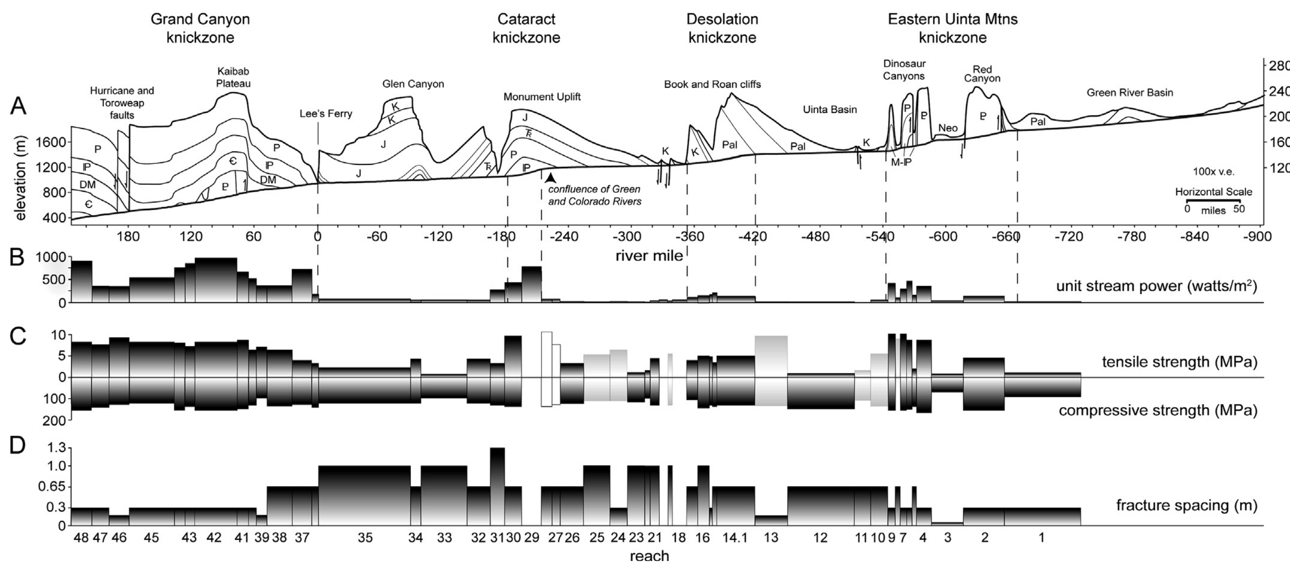
Can fit the whole Colorado River system with a uniform uplift history



Roberts et al., *Tectonics*, 2012

So as interpreted here, knicks farther upstream are from older events. Is this really valid?

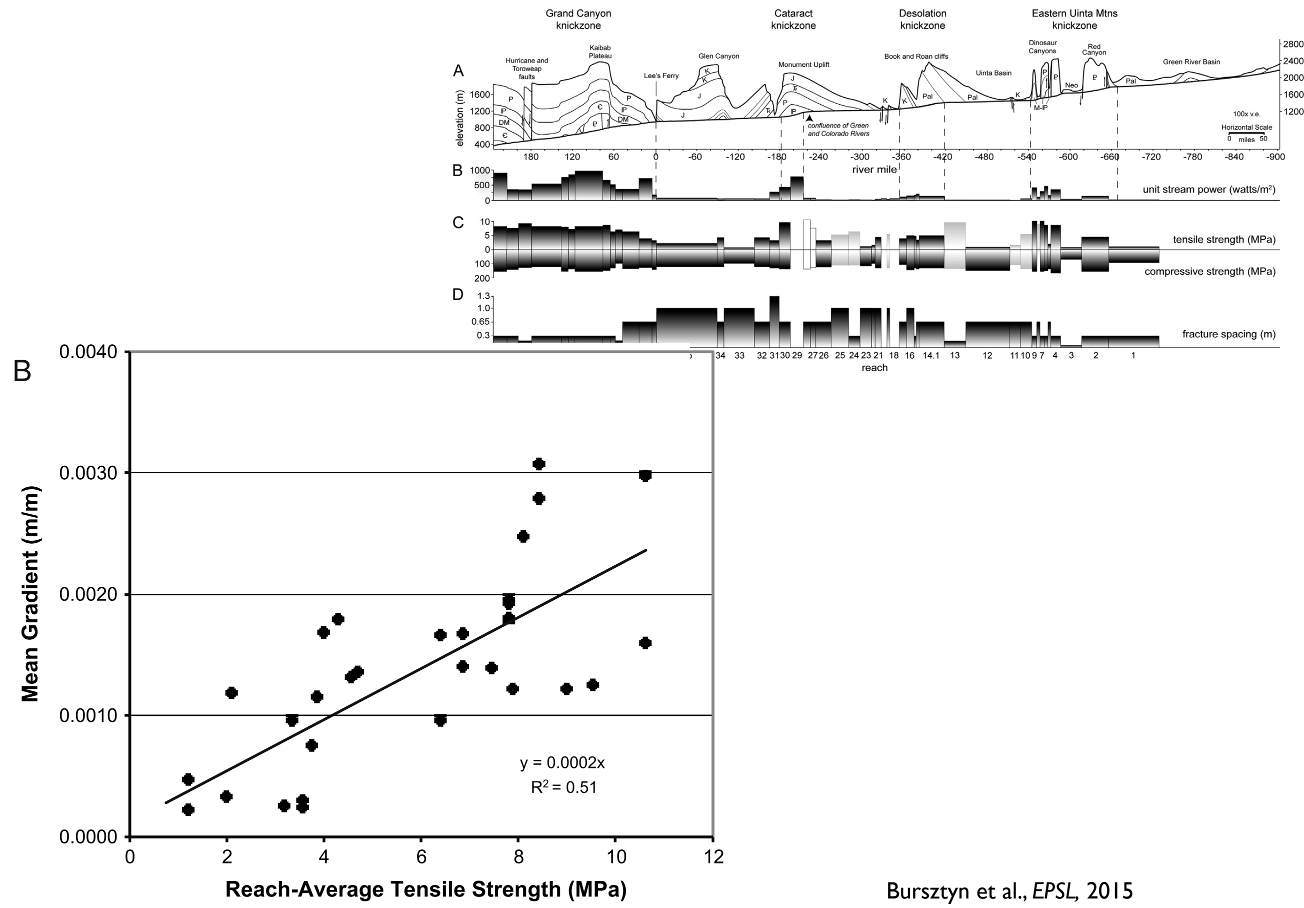
But how much is other factors?



Bursztyn et al., *EPSL,* 2015

Others have argued that much of the change in gradient of the Colorado is from strength of the rock…

But how much is other factors?



Bursztyn et al., *EPSL*, 2015

So there is more complexity in this paper, but basically see good correlation with rock strength except in Desolation Canyon.