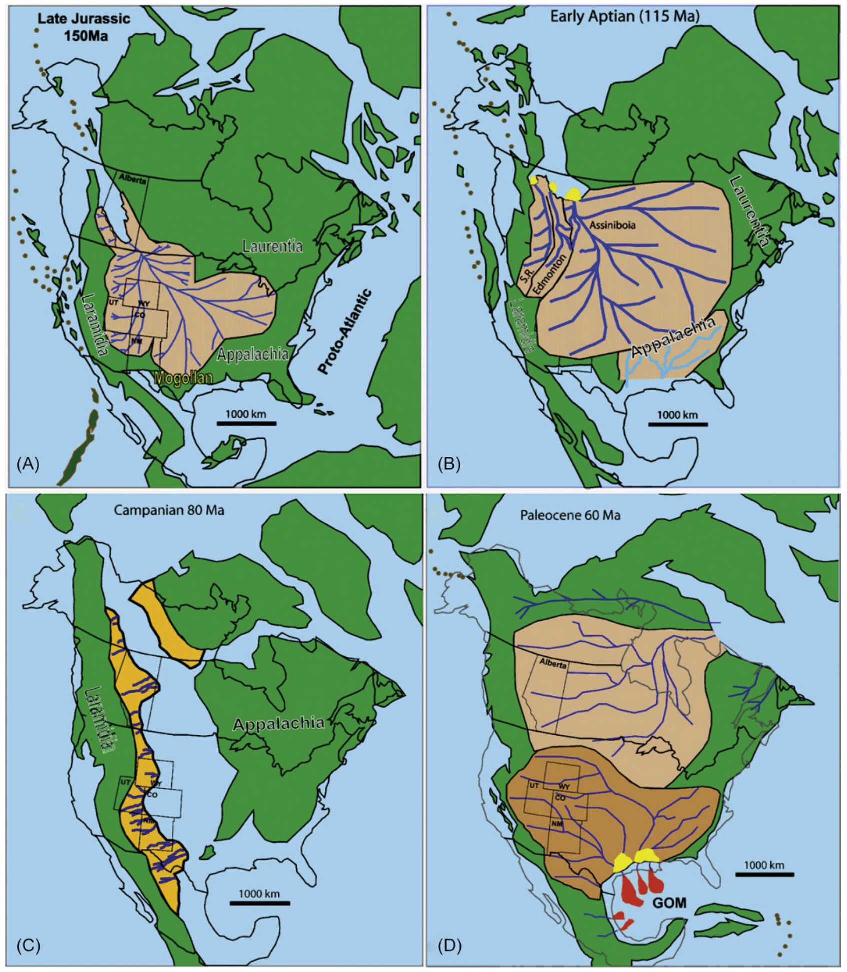
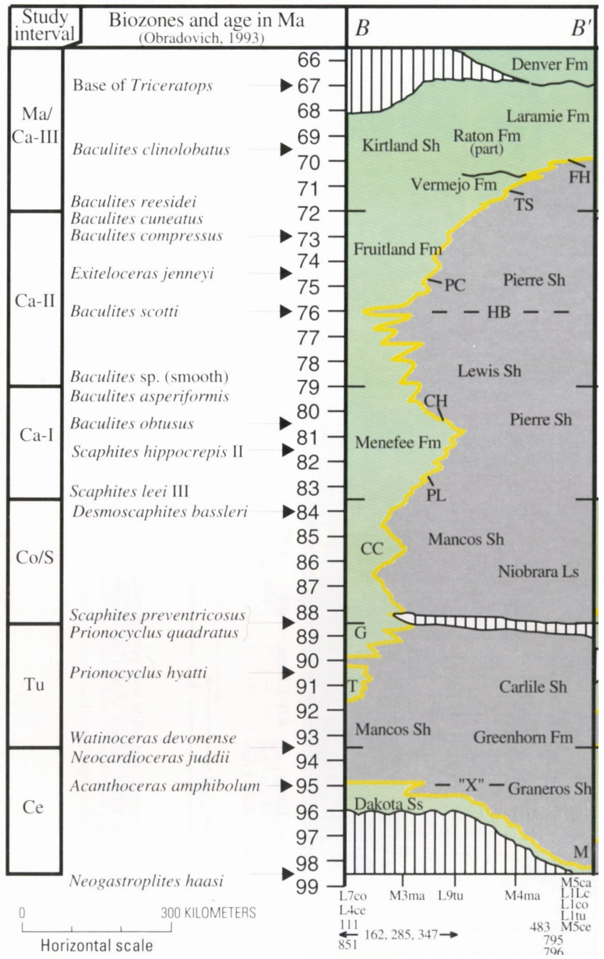
Dynamic Topography

and the Western Interior Seaway

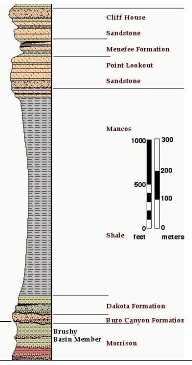


Maill & Catuneanu, in *Sed Basins US & Canada*, 2019

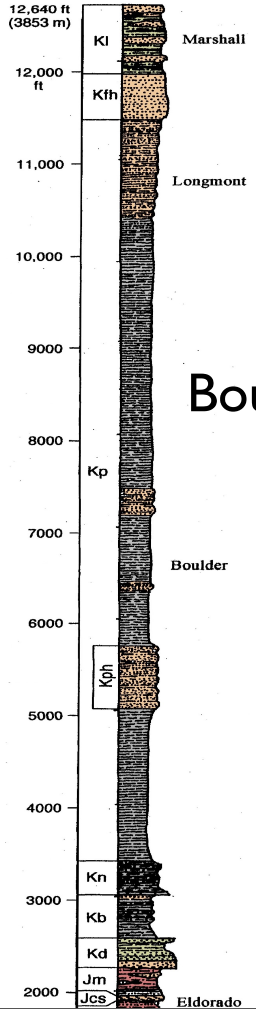


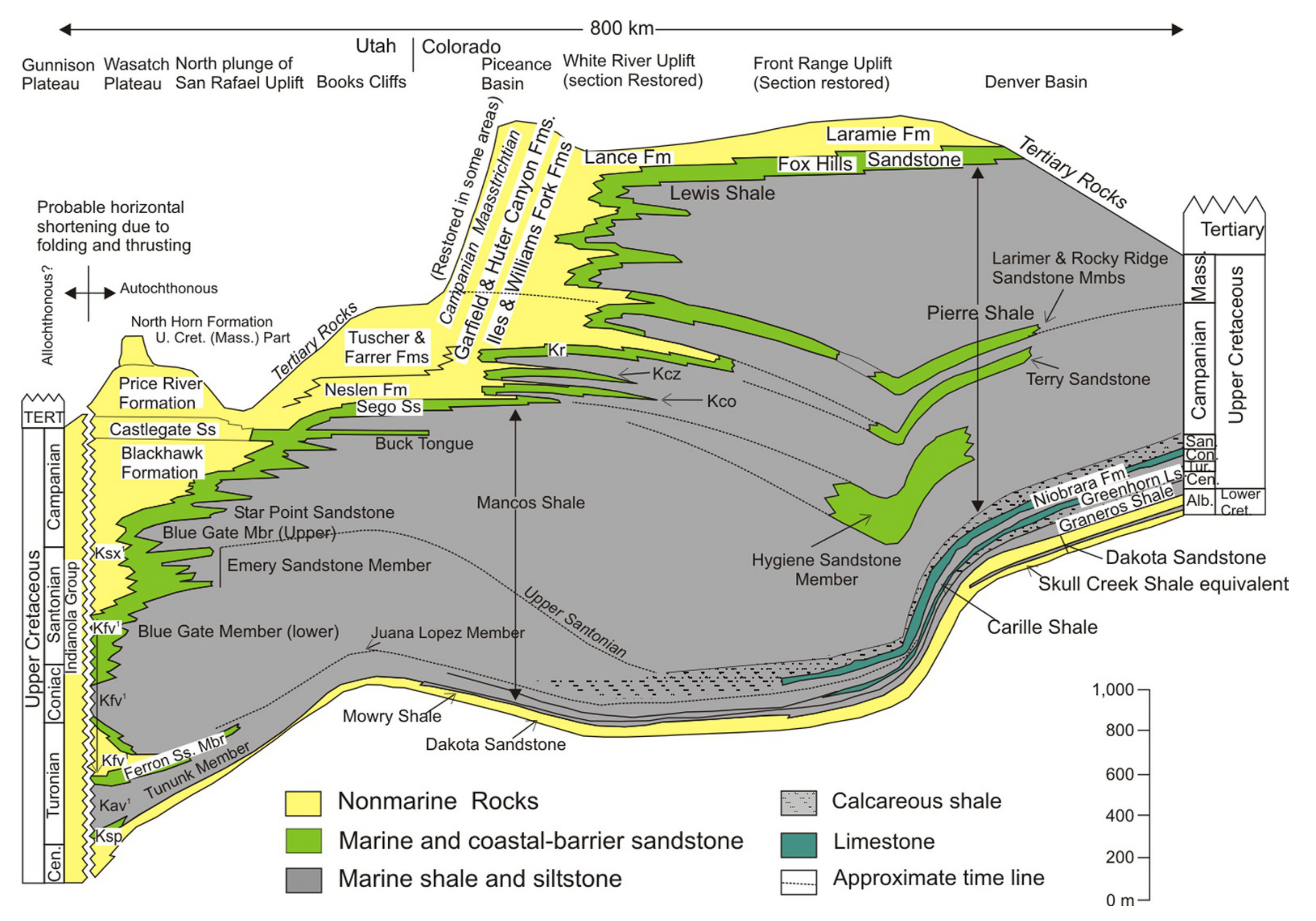
Roberts and Kirschbaum, USGS PP 1561

Durango



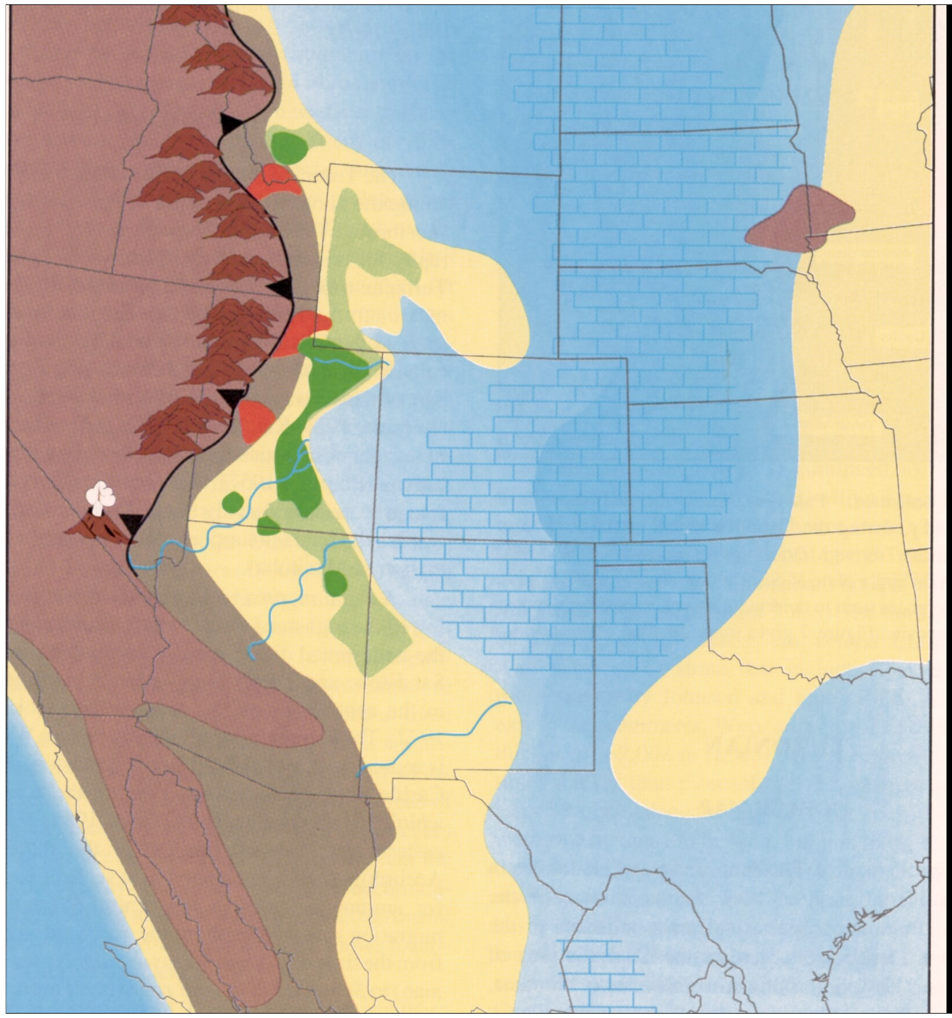
Boulder





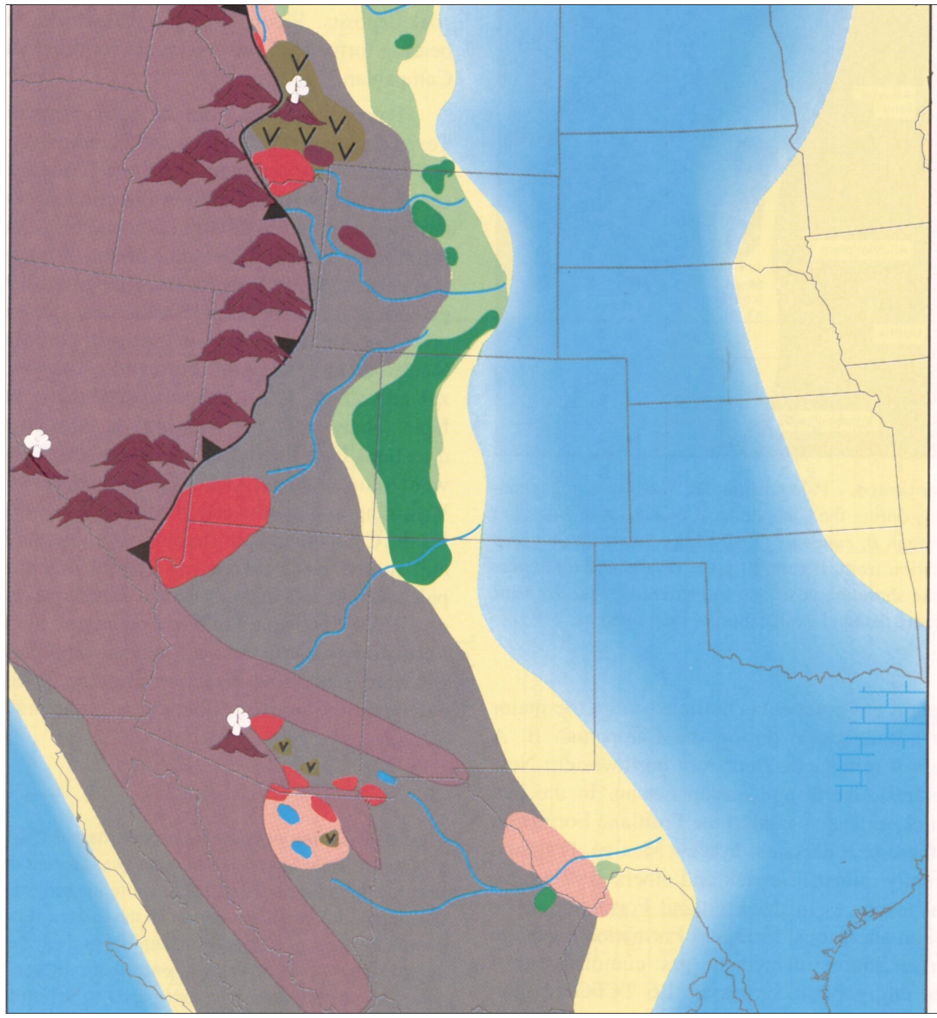
Maill & Catuneanu, in *Sed Basins US & Canada*, 2019

FIG. 7 Stratigraphic cross-section of Cretaceous rocks from central Utah to northeastern Colorado. Thicknesses are based on well and outcrop control. Vertical exaggeration approximately ×151. The Castlegate Sandstone has been interpreted as a product of "antitectonic" sedimentation (Yoshida et al., 1996). Colors were utilized in the paleogeographic maps. Abbreviations: Ksx, Sixmile Canyon Formation; Kfv, Funk Valley Formation; Kav, Allen Valley Formation; Ksp, Sanpete Formation; Kr, Rollins Sandstone Member; Kcz, Cozzette Sandstone Member; Kco, Corcoran Sandstone Member. (From Molenaar and Rice (1988).)

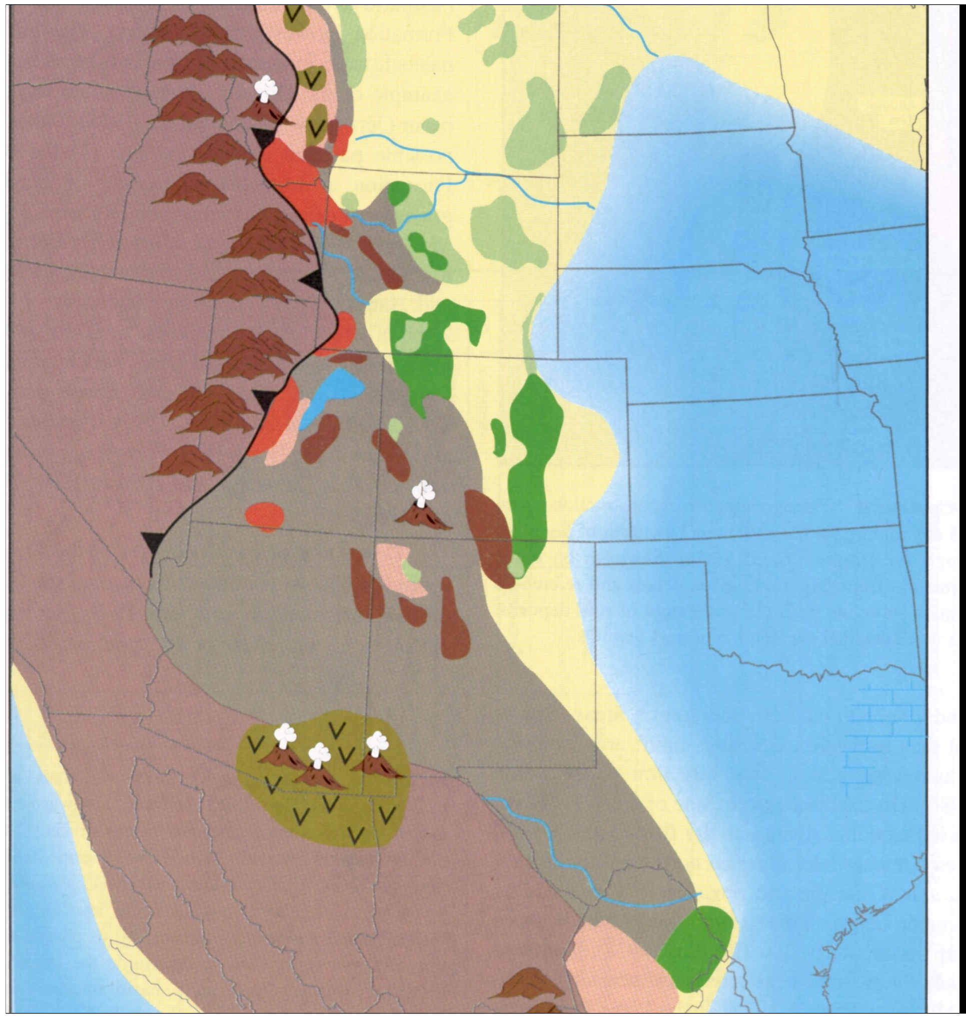


Turonian ~91 Ma

Explain what the colors are (greens are areas accumulating coals, bricks are carbonates). One initial question is, why a seaway? Classically, this was thought to largely be high stand of ocean



Campanian
~75 Ma



Maastrictian
~68 Ma

Seems like an orderly progradation of terrestrial facies out into the seaway…but look at sediment accumulation…

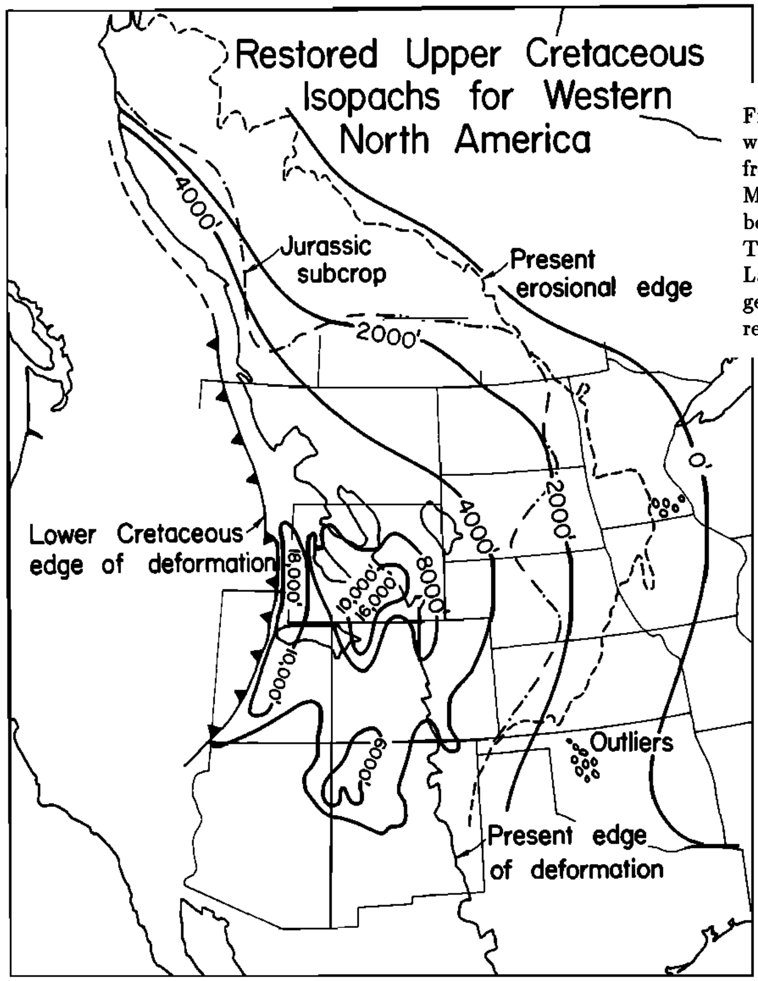


Fig. 1. Restored Upper Cretaceous isopach map for western North America. Data for the United States are from Cross and Pilger [1978b]. Data for Canada are from McCrossan and Glaister [1966]. Contours are given in feet because the original data are presented in this manner. The irregular pattern in Wyoming and Colorado is due to Laramide tilted block movements in the foreland. It is the general pattern and great width of the sedimentation that requires explanation.

Mitrovica et al., Tectonics, 1989

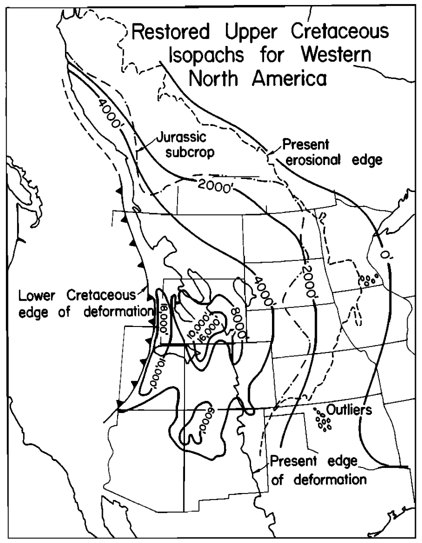
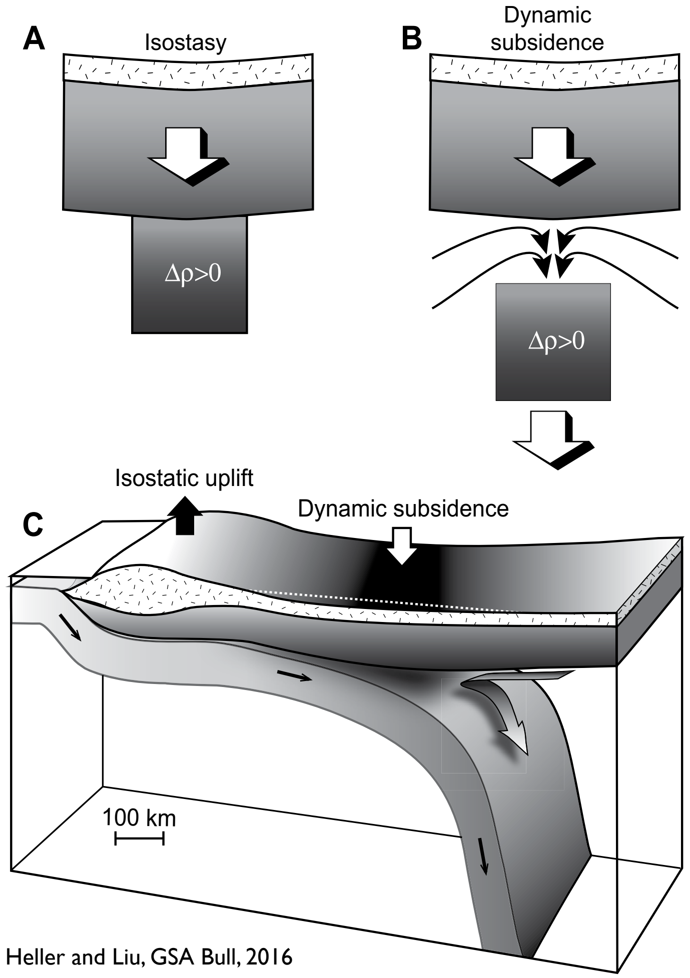


Fig. 1. Restored Upper Cretaceous isopach map for western North America. Data for the United States are from Cross and Pilger [1978b]. Data for Canada are from McCrossan and Glaister [1966]. Contours are given in feet because the original data are presented in this manner. The irregular pattern in Wyoming and Colorado is due to Laramide tilted block movements in the foreland. It is the general pattern and great width of the sedimentation that requires explanation.

Mitrovica et al., Tectonics, 1989



Heller and Liu, GSA Bull, 2016

We need something to pull crust down at least in some areas. What exactly can do this–what is “dynamic subsidence”

Viscous fluids

In a Newtonian fluid, if horizontal velocity is *u* and vertical is *v*, then the shear stress in the fluid is related to the gradient in velocity:

$$\tau_{zx} = \eta \frac{du}{dz}$$

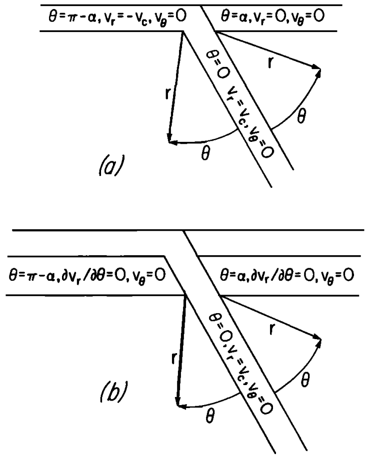
Applying continuity (conservation of fluid) and assuming equilibrium, can be shown that the dynamic pressure *P* is related to variations in fluid velocity *u* and *v* (horizontal and vertical):

$$\frac{\partial P}{\partial x} = \eta \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2} \right)$$

$$\frac{\partial P}{\partial z} = \rho g + \eta \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial z^2} \right)$$

$$P_{slabtop} = \frac{-8.558\eta U}{r} \text{ for dip=45°}$$

$$P_{slabbottom} = \frac{+0.462\eta U}{r} \text{ for dip=45°}$$



ıer flow models for (*a*) coupled lithosphere and (*b*) decoupled ıosphere.

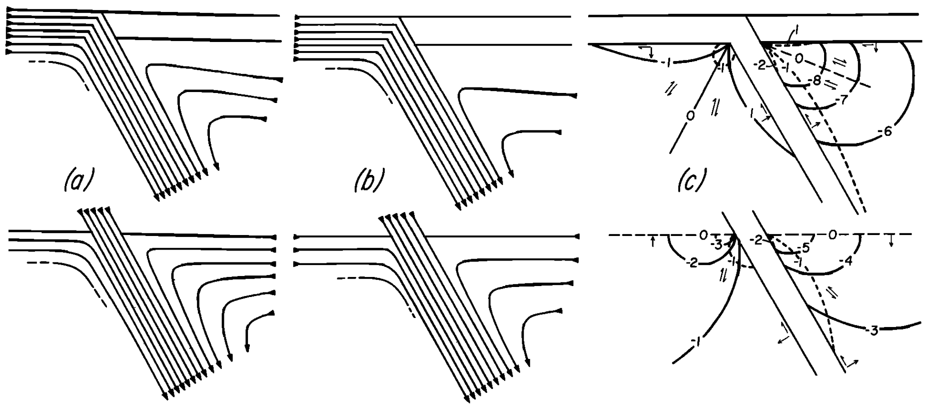


Fig. 2. Streamlines, isobars, and contours of constant shear stress for coupled lithosphere (upper row) and decoupled lithosphere (lower row) models with $\alpha = 60°$. Shown are (*a*) streamlines in a Newtonian fluid, (*b*) streamlines in a non-Newtonian fluid ($n = 3$), and (*c*) isobars (solid curves) and constant shear stress contours (dashed curves) for $n = 3$.

Tovish et al., JGR, 1978

Math from Turcotte and Schubert section 6.11. Torque is force x distance, so torque from tip of asthenospheric counterflow is constant downslab

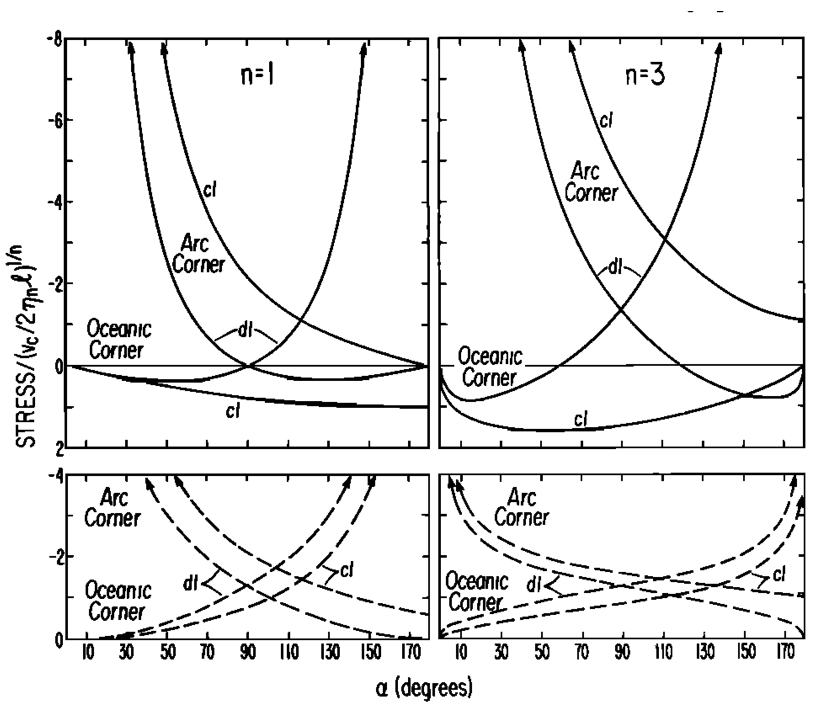


Fig. 4. Pressure (solid curves) and shear stress (dashed curves) on the top (arc corner) and bottom (oceanic corner) surfaces of the descending slab as functions of subduction angle α for (left) Newtonian and (right) non-Newtonian mantles in the coupled lithosphere (cl) model and the decoupled lithosphere (dl) model. Zero degrees corresponds to flat subduction, 90° to vertical subduction, and 180° to overturned subduction.

Tovish et al., JGR, 1978

OK, shows pressure on top ("arc corner") gets very negative [as this happens, presumably load on base of lithosphere above also become very negative--i.e., pulls down]--bottom side not so strong.

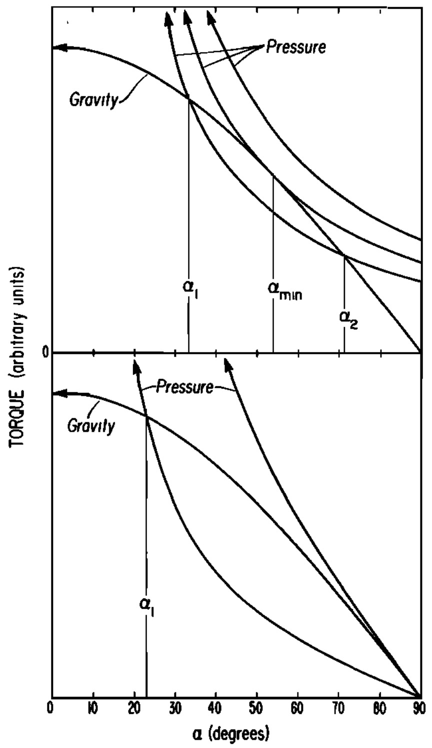


Fig. 6. The absolute values of the torques exerted on the slab by gravity and flow pressures ($n = 3$) as a function of slab dip α. Torques are equal and opposite at angles indicated by the subscripted α's. Several pressure curves are shown to indicate how variations in the relative magnitude of the gravity and pressure torques influence the number and types of equilibrium intersections. (Top) coupled lithosphere model and (bottom) decoupled lithosphere model.

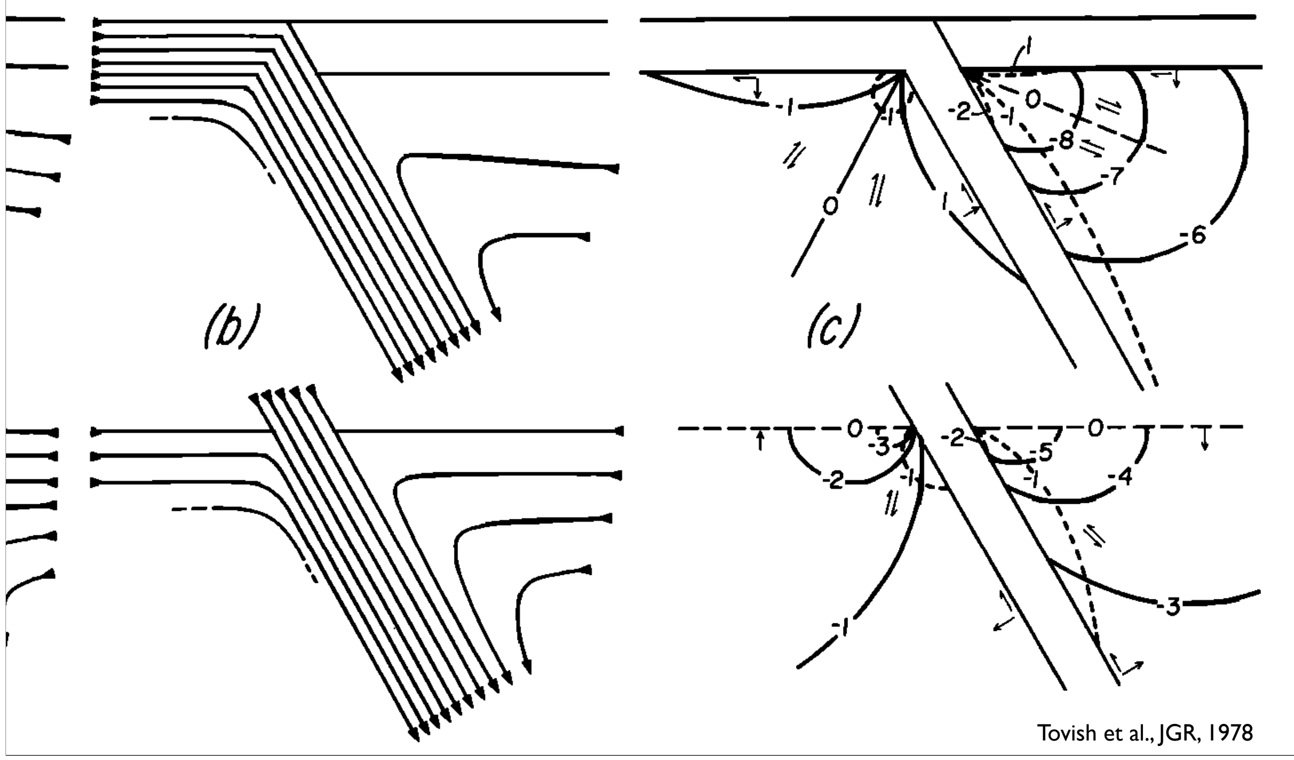
Tovish et al., JGR, 1978

Combining pressure from last slide with weight of slab and then calculating as a torque gives us this--the idea that there is a point where dip is unstable. However, this analysis ignores any deformation within the slab. Although this analysis is basis for Bird's inferences about subsidence, it is not the model preferred by most other mantle-flow modelers.

$$P_{slab\,top} = \frac{-8.558\eta U}{r} \text{ for dip=45°}$$

$$P_{slab\,bottom} = \frac{+0.462\eta U}{r} \text{ for dip=45°}$$

$$P_{upperplate} = \frac{-3.026\eta U}{x} \text{ for dip=45°}$$



Tovish et al., JGR, 1978

Similarly, we can estimate the force on the upper plate. Math from Turcotte and Schubert section 6.11. So subsidence should vary inversely to distance from the subduction zone. A major complication is that variations in rheology will allow for this to vary a lot.

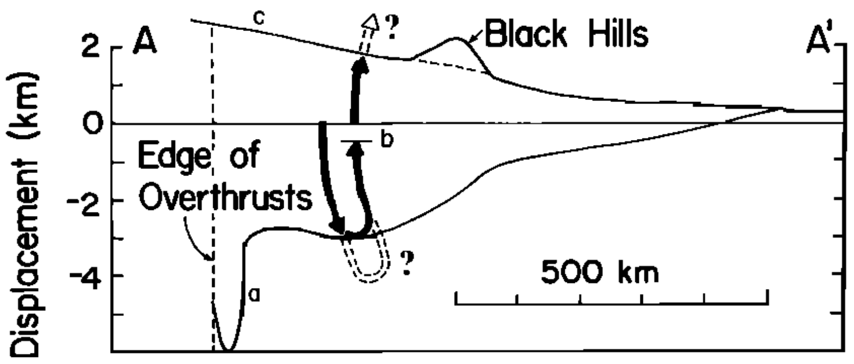


Fig. 5. Approximate estimate of the net effect of Late Cretaceous (including Late Maestrichtian) subsidence and Tertiary uplift for the cross section A-A′ given in Figures 3 and 4. The base of the sequence at the end of its deposition is shown by a. During subsequent uplift to b the surface has uplifted to c. The dashed arrows imply that the solid arrows probably underestimate the total subsidence and uplift.

Mitrovica et al., Tectonics, 1989

Prediction from this model is that if we remove post mid-K seds, things return to flat. Is this true? (certainly not in NE NM, maybe in some places to north).

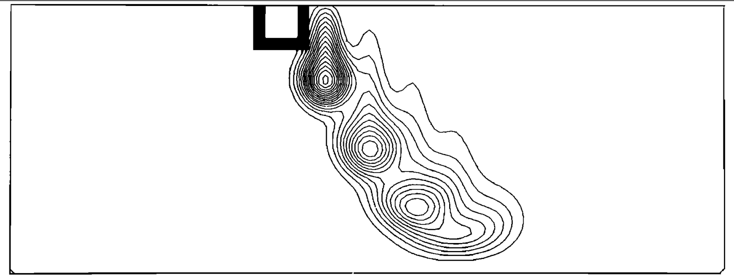


Fig. 10. The thermal field produced by superimposing the t = 0.0, 0.25, 0.50, 0.75, and 1.0 fields of the model of Figure 6 (Δt = 0.25, see text). Each field is horizontally shifted, with respect to the previous field, by an amount equal to the width of the initial block (116 km); only a portion of the cell is shown. The near-surface dip of the resulting subduction is approximately 45°.

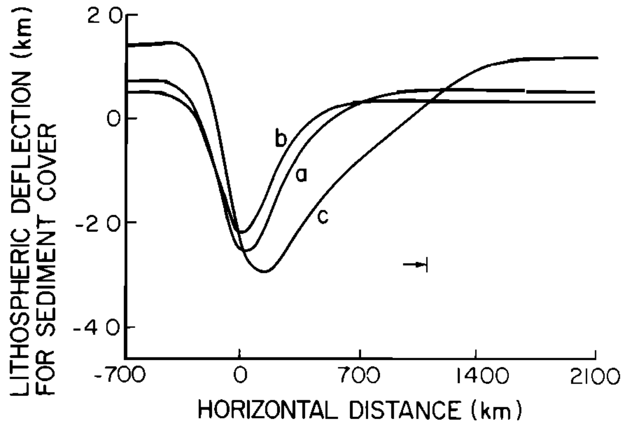
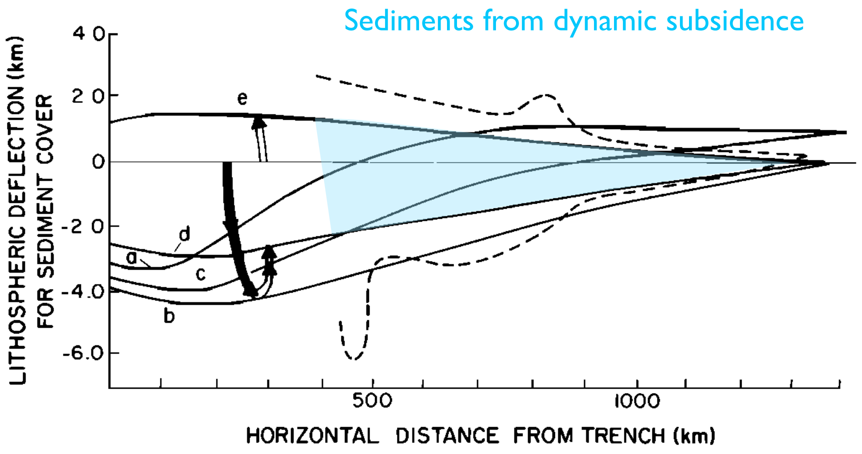


Fig. 11. The topographic profile corresponding to the field of Figure 10 (labeled a). Also shown are the deflections for the cases of near surface dips of 60° ($\Delta t = 0.33$, labeled b) and 30° ($\Delta t = 0.12$, labelled c). In all cases, $D = 5 \times 10^{23}$ Nm. The arrow gives the position of the right boundary of Figure 10.

Mitrovica et al., Tectonics, 1989

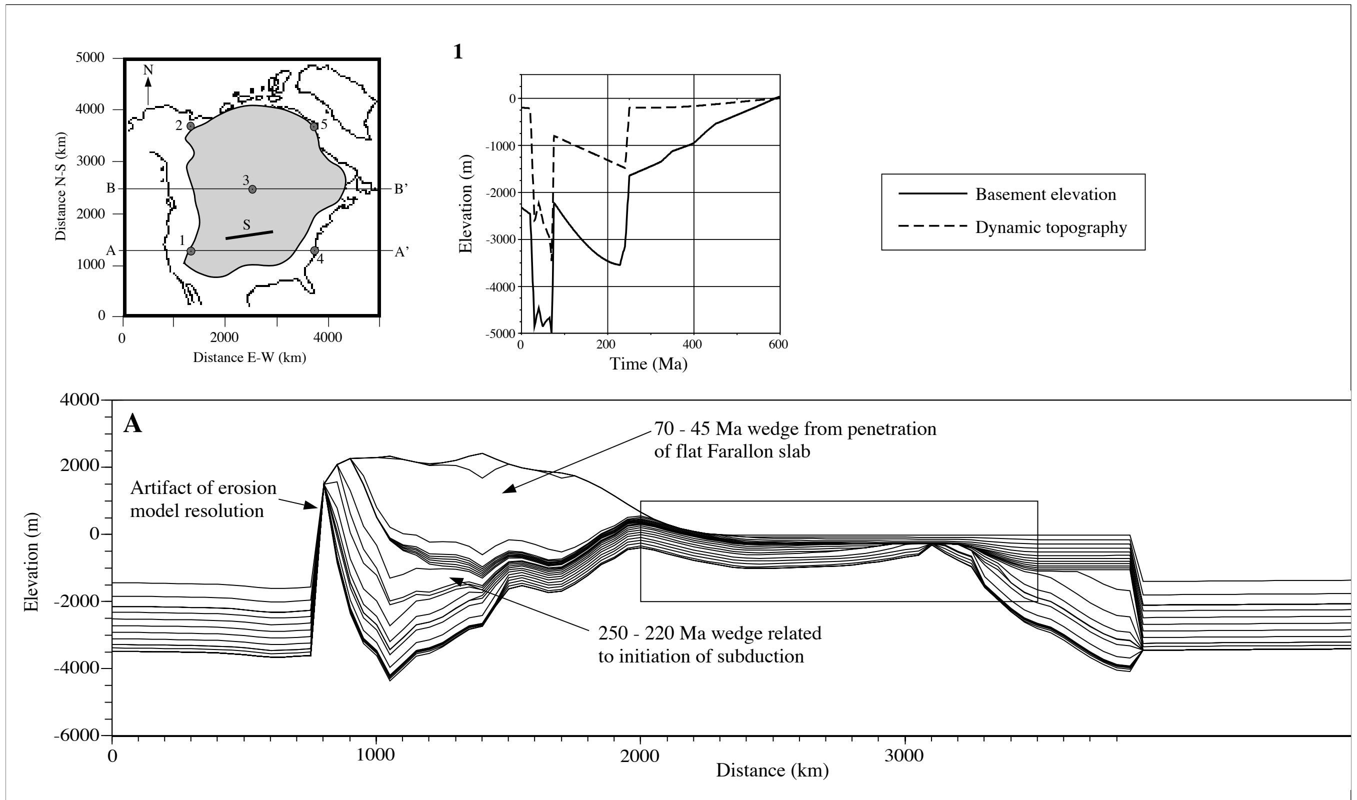


Sediments from dynamic subsidence

Fig. 16. Profile a, the lithospheric deflection profile corresponding to the subduction zone of Figure 15 except with a dip of 60°. The sequence a, b and c, shows the lithospheric deflection as the subduction geometry moves from 60° dip (a), to 25° dip (b), and back to a 60° dip (c). d gives the deflection 25 m.y. after subduction ceases at the surface. While the basement rebounds from b to d the surface uplifts to e. As in Figure 15, the topographic profiles are computed under the assumption that the sediment cover (of density 2.30×10^3 kg/m^3) remains intact subsequent to the onset of uplift.

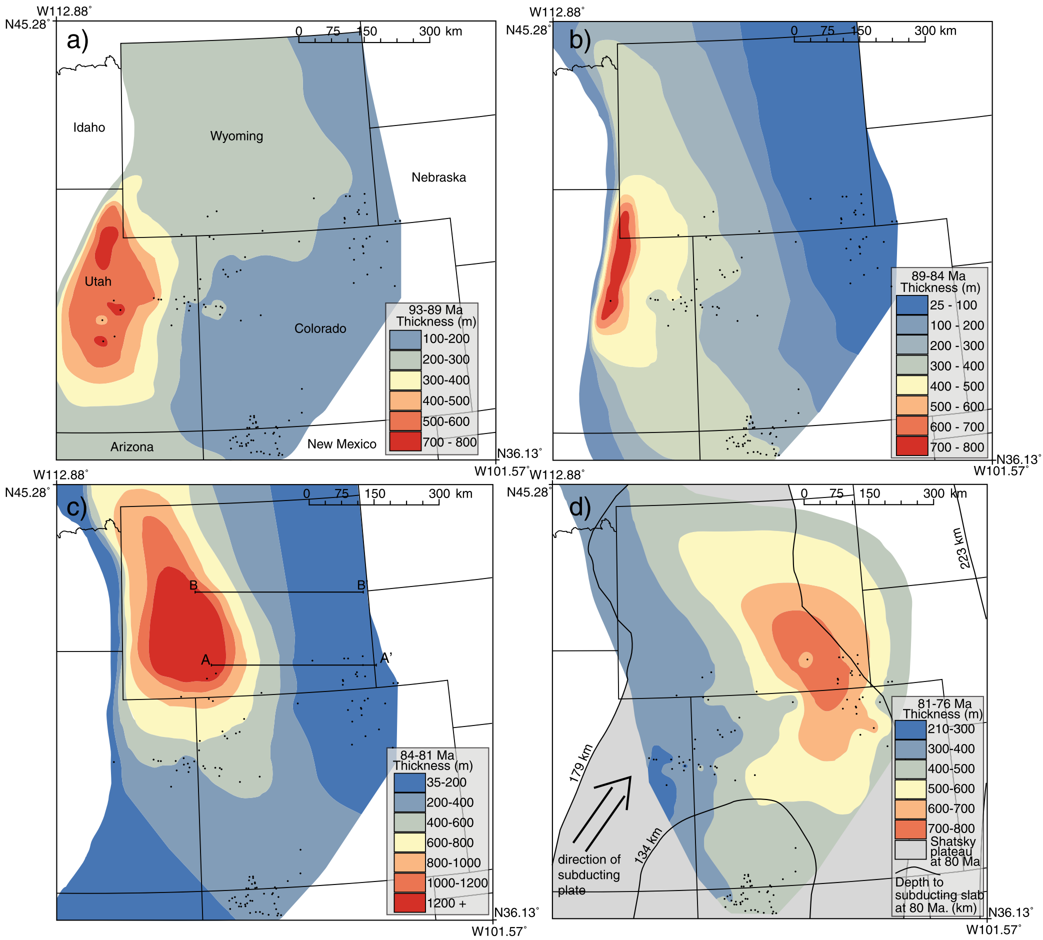
Mitrovica et al., Tectonics, 1989

This explicitly tested in Bogolub & Jones as well as Levandowski et al.

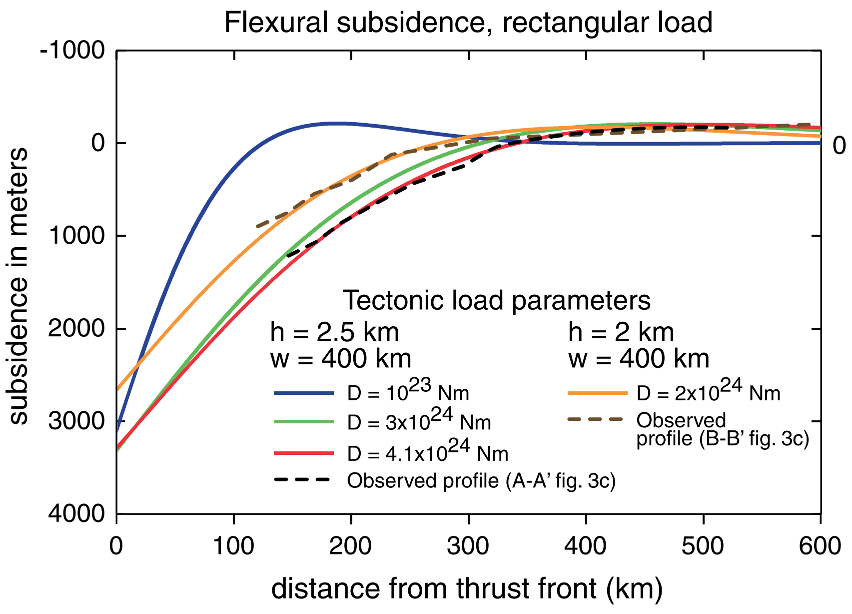


Burgess et al., GSA Bull 1997

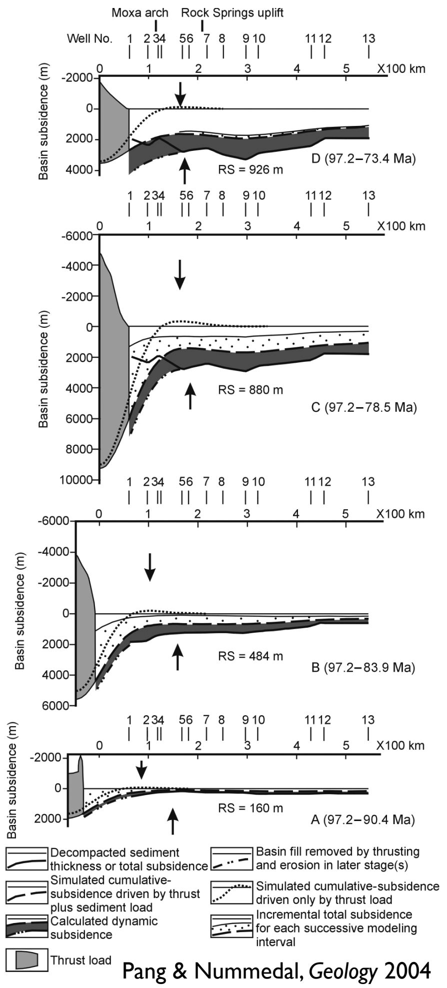
Note panel in upper right has oldest time at right. Suggesting western CP has jumped up as dynamic topo ended…



Painter & Carrapa, *GRL* 2013

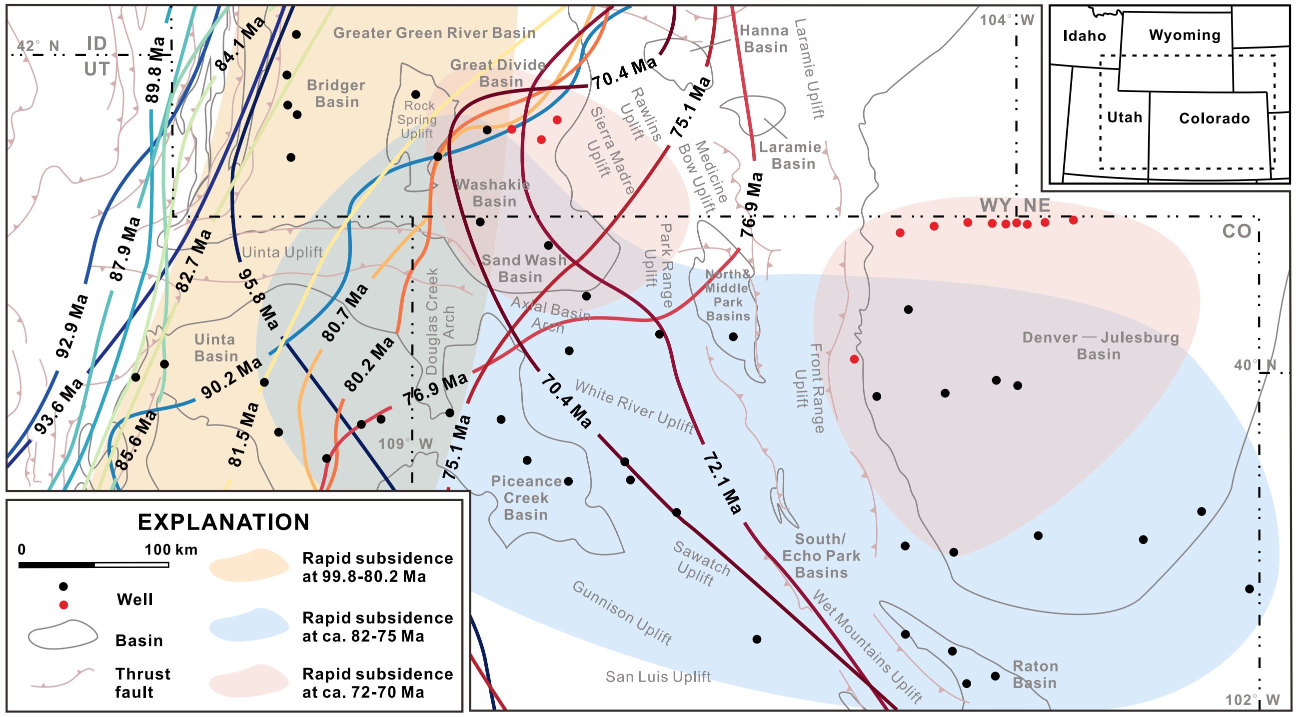


Painter & Carrapa, *GRL* 2013



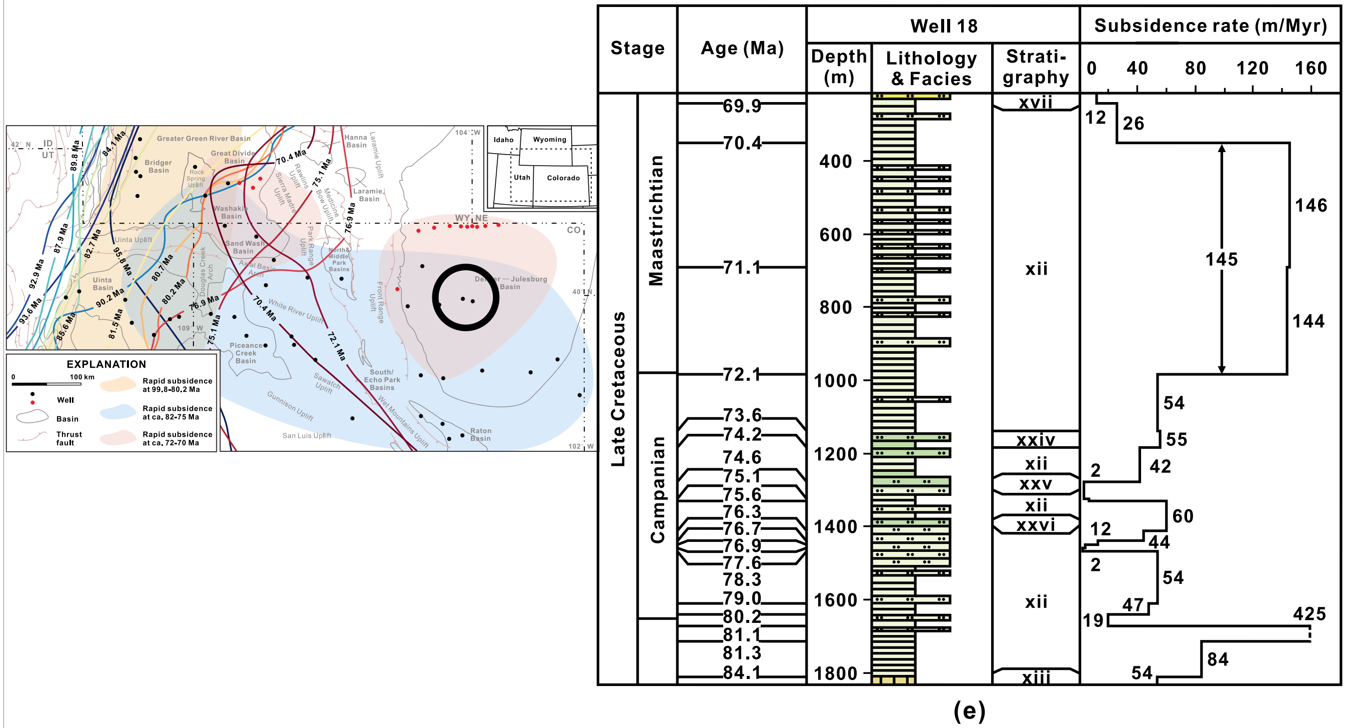
Pang & Nummedal, *Geology* 2004

Painter and Carrapa profiles EW in Wyoming pre-81 Ma; think dynamic effects then later. Pang and Nummedal inferred dynamic subsidence starting c 84 Ma and large by 79 Ma; could also be change in flexural rigidity?



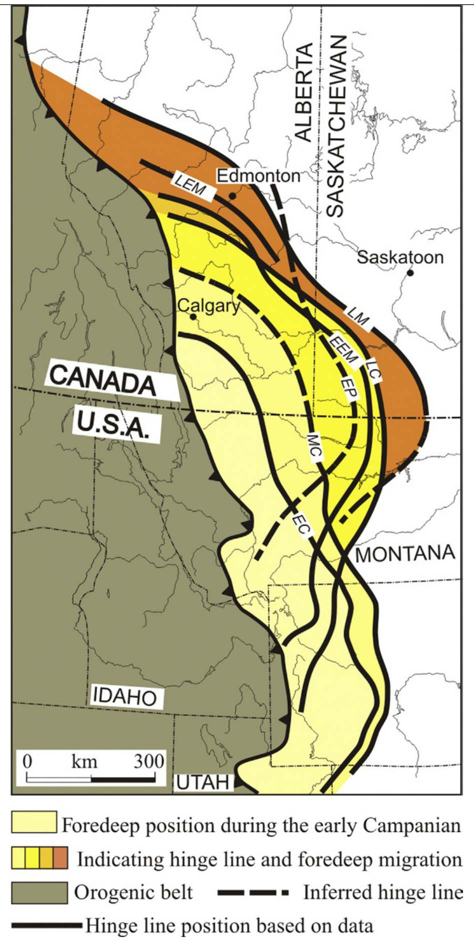
Zhou et al., *Tectonics*, 2024

More detailed sections help delineate major areas of subsidence. Pre-82 Ma foredeep, after that major migration east (not clear why Wyoming wasn’t included more—other work carries these subsidence areas northward). Colored lines are shorelines.

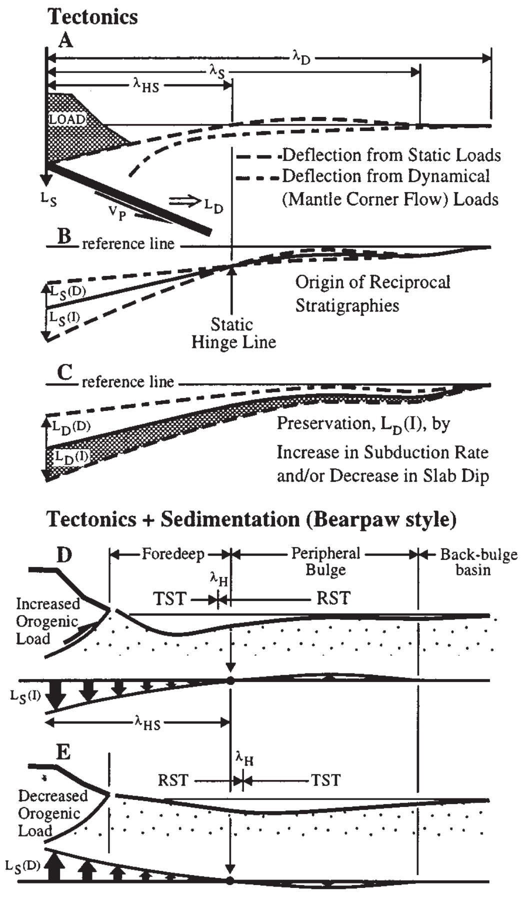


Zhou et al., *Tectonics*, 2024

Working with more detailed sections allows for calculation of subsidence rates. Note vertical scale is linear in depth (thickness) while age scale varies wildly. [I’m having real problems reconciling this plot with the tectonic subsidence plots; 145 m/Ma over 1.7 Ma should be maybe 250m subsidence, but over 600 m of section—is it really compacting that fast?]

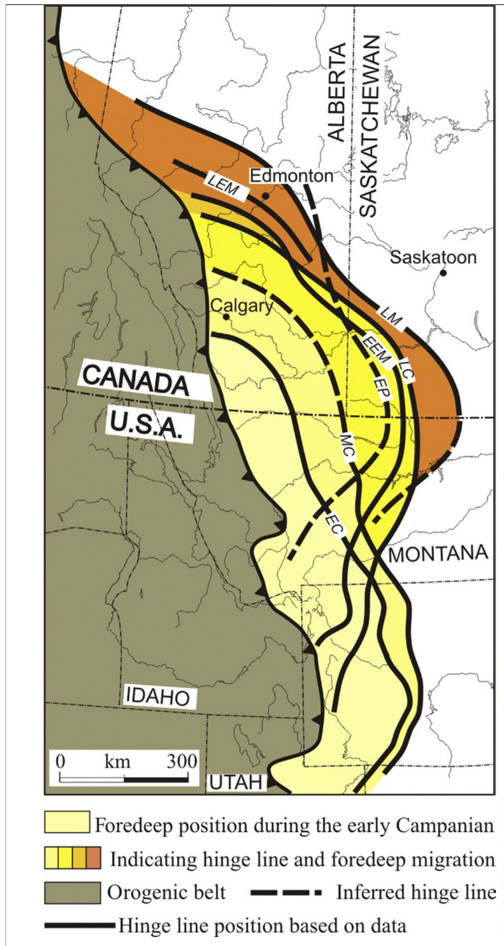


Maill & Catuneanu, in *Sed Basins US & Canada*, 2019,
after Catuneanu et al., *Sed. Geol.,* 2000

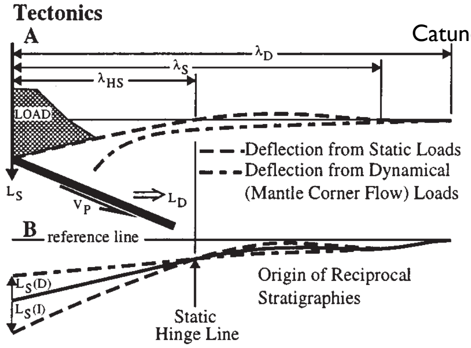


Catuneanu et al., *Geology* 1997

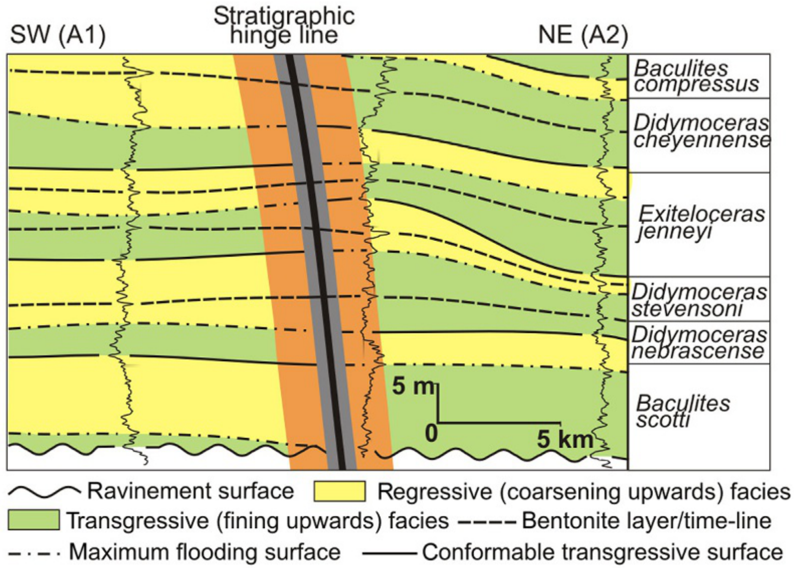
Location of the hingeline between the foredeep and the forebulge during the Campanian–Paleocene. The arcuate trend of the hingeline indicates the locus of greatest flexural load in the orogen—at the center of the arc. Abbreviations: C, M, P, Campanian, Maastrichtian, Paleocene; e, E, Early; l, L, Late. The location of maximum loading shifted progressively northward during the Late Cretaceous–Paleocene (Catuneanu et al., 1999, 2000).



Maill & Catuneanu, in *Sed Basins US & Canada*, 2019,
after Catuneanu et al., *Sed. Geol.,* 2000

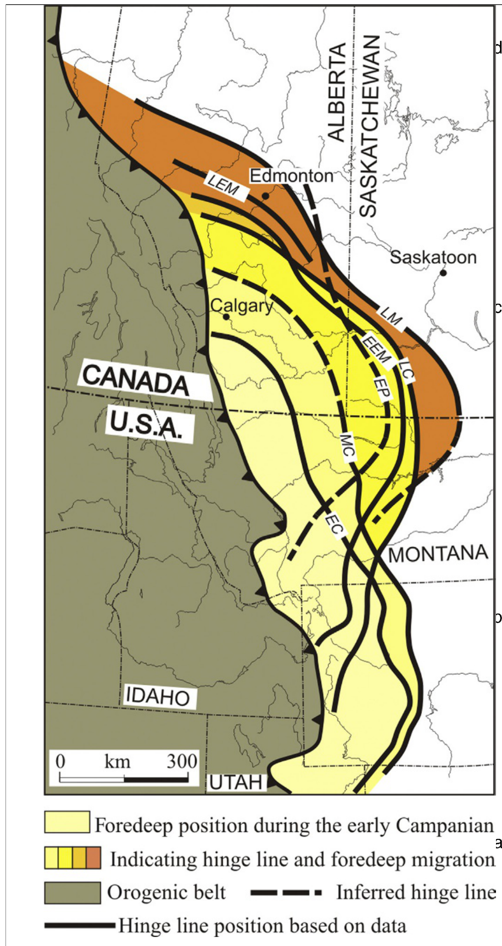


Catuneanu et al., *Geology* 1997



Maill & Catuneanu, in *Sed Basins US & Canada*, 2019

Lower right figure shows reciprocal stratigraphy with biozones and presence of airfall ashes from Alberta.



Maill & Catuneanu, in *Sed Basins US & Canada*, 2019, after Catuneanu et al., *Sed. Geol.*, 2000

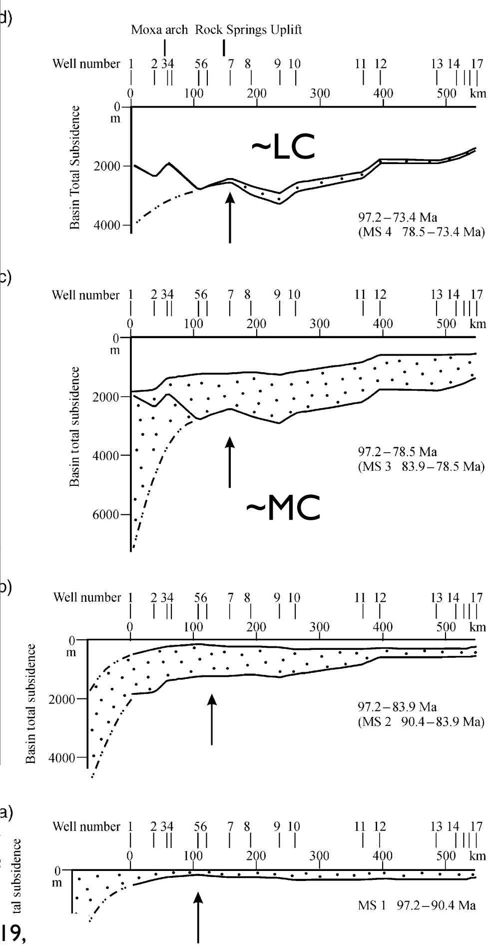


Fig. 7. Two-dimensional cumulative total subsidence history across Section II in Fig. 1 from 97.2 to 73.4 Ma (Liu & Nummedal, 2004). A series of sequentially restored and decompacted cross-sections were developed by setting the eastern ends of the sections as a reference point. The deformed deposition within the Sevier thrust belt was palinspastically restored, and the western extent of the deformed strata in the section was determined by balancing the deformation and shortening of the Hogsback, Absaroka and Crawford faults, respectively. The restored sediment thickness was shown in a dashed line with two dots. The foredeep strata deposited to the west of the ~180-km mark in the first three steps (A, B, and C) were mostly eroded or incorporated in the thrust belt in later stages. During the fourth step (from C to D) and afterward, the thrust belt and foredeep rebounded isostatically ~5000 m because of erosion during the tectonically quiescent phase. The dotted band represents incremental total subsidence for each successive megasequence interval. Arrows indicate forebulge position. Location of the section and Wells shown in Fig. 1.

Liu et al., Basin Res. 2005

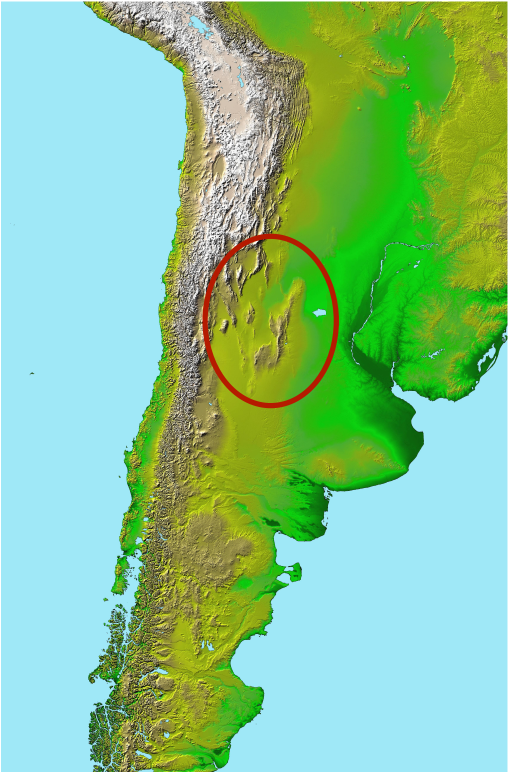
Left is map of hinges inferred by reciprocal strat, right is suggested forebulge position from Liu et al. EC=Early Campanian c. 80 Ma, MC c. 77 Ma, lC c. 73 Ma, EEM = early Early Maastrichtian, c. 71-72 Ma, LEM late Early Maas. c. 70 Ma, LM c. 67-68 Ma, EP = early Paleocene c. 63 Ma

Laramide Analogs

the present the key to the past?

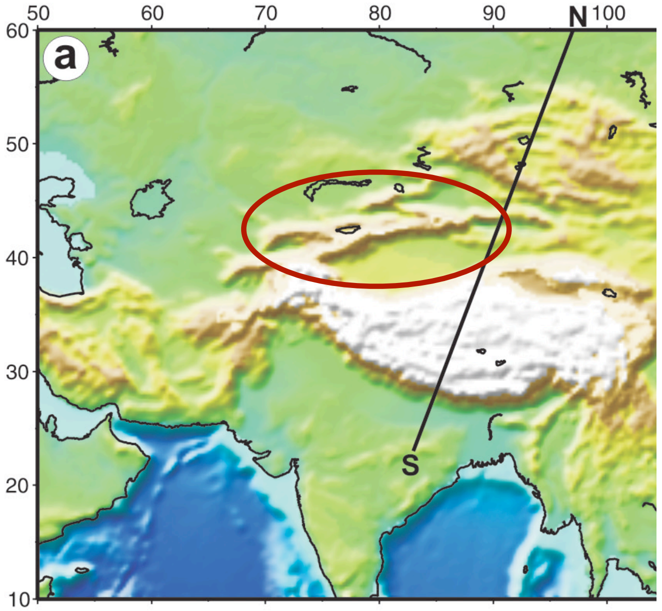
Laramide analogs

Sierras Pampeanas



"Flat slab" models

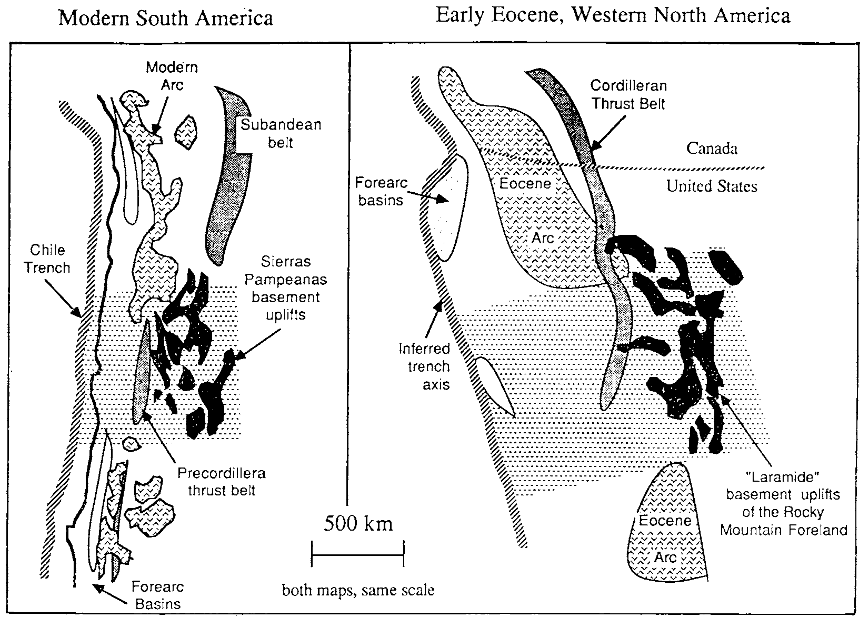
Tien Shan



Jiménez-Munt and Platt, Tectonics, 2006

Collision and "orogenic collapse" models

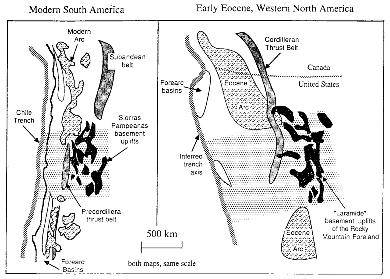
Sierra Pampeanas as an analog
Behind missing arc



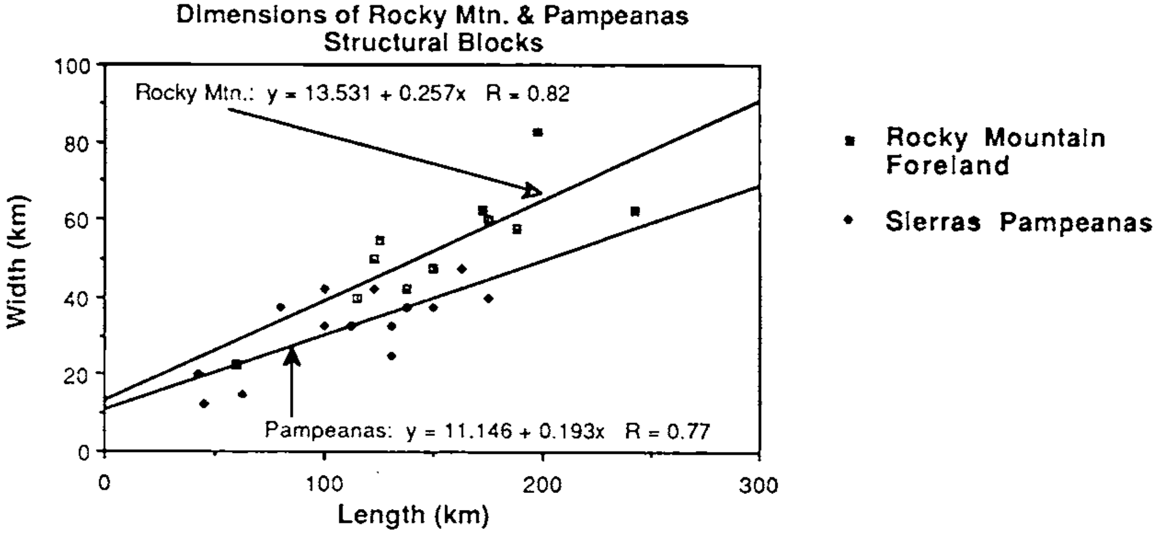
Jordan & Allmendinger, Am. J. Sci., 1986

So what of this analog? Style of deformation is similar, but is that reflective of driving force or simply the way that kind of crust shortens?

Sierra Pampeanas as an analog



Similar structural style



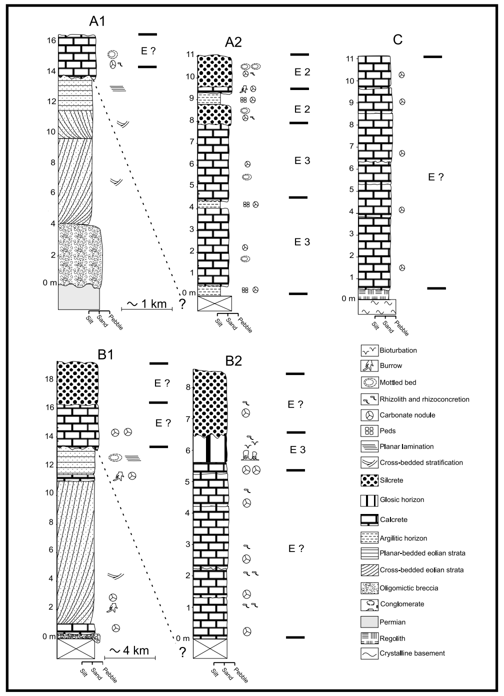
B.

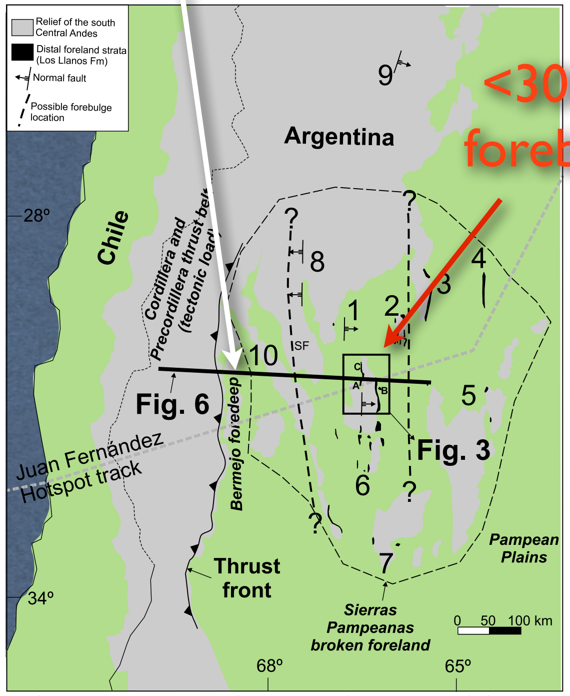
Jordan & Allmendinger, Am. J. Sci., 1986

Sierra Pampeanas differences

Miocene sediments

10 km foredeep



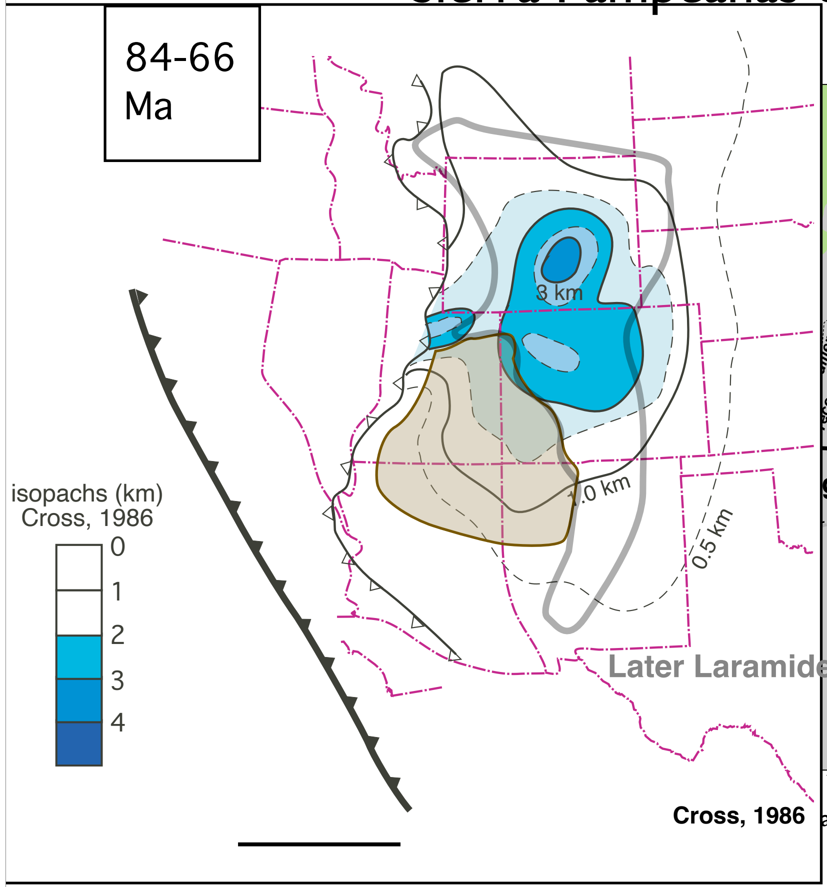


<300 m forebulge

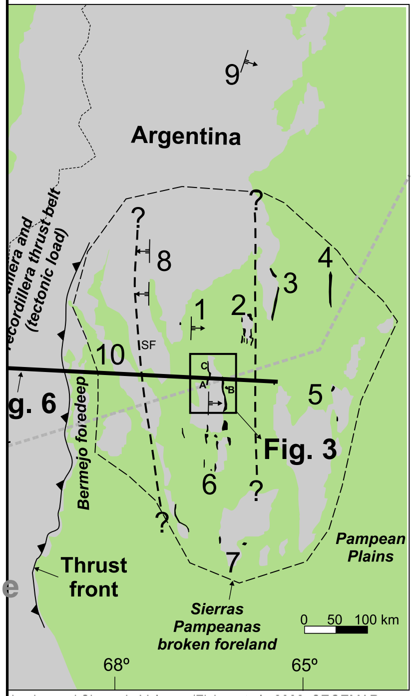
Dávila et al., Tectonics, 2007

What of pre-shortening sedimentation? In Pampeanas, most sections only a few 10s of meters; up to maybe 300m in some wells. There is a ~10km deep foredeep to the west...

Sierra Pampeanas differences



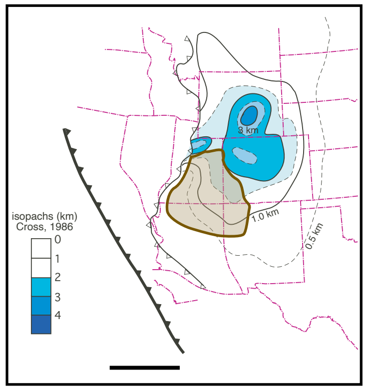
Cross, 1986

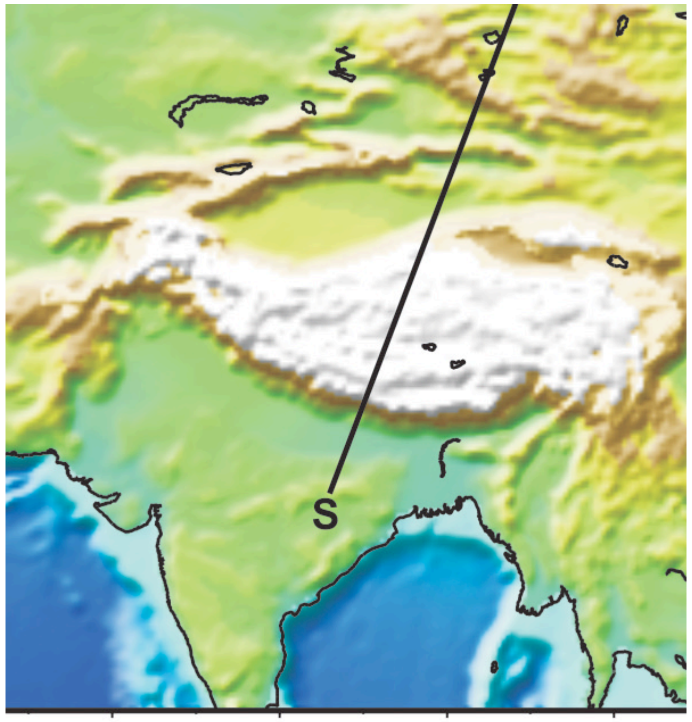


a et al., 2007

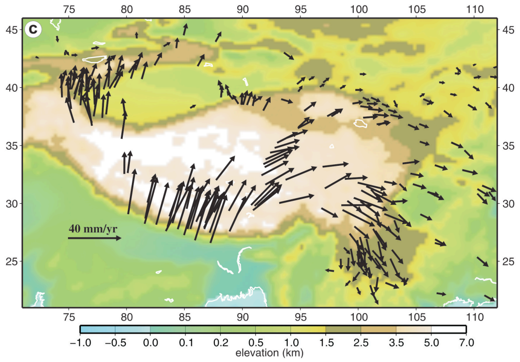
Rockies has kilometers of section. Also has undeformed Colorado Plateau between foreland and thin-skinned deformation--larger than entire Pampean orogen!

Tien Shan as analog



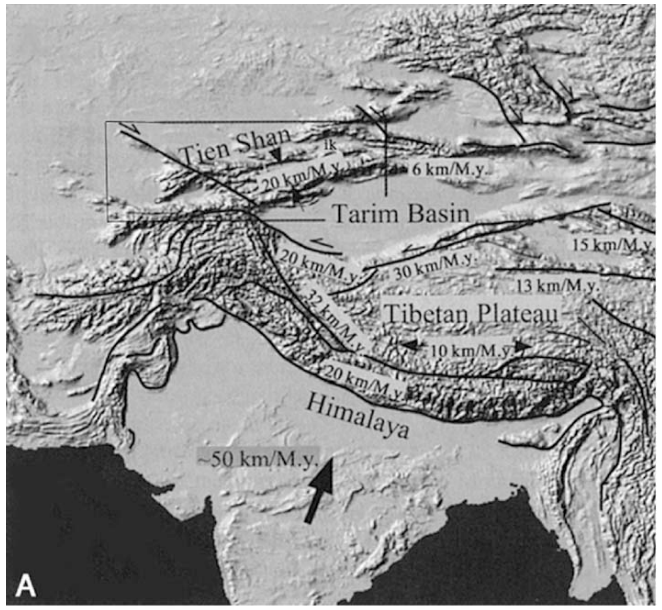


Tien Shan differences



Jiménez-Munt and Platt, Tectonics, 2006

Is there an "India"?
Active shortening between collider and foreland mountains?
Colorado Plateau as rigid as Tarim Basin?
Subsidence pre-shortening?



Dickerson, Tectonophysics, 2003

Laramide Models

what are we looking to recreate?

Bird, P., 1984, Laramide crustal thickening event in the Rocky Mountain foreland and Great Plains: *Tectonics*, v. 3, no. 7, p. 741-758, doi: 10.1029/TC003i007p00741.

What was the main criterion Bird focused on as representing the essence of the Laramide orogeny?

Bird, P., 1984, Laramide crustal thickening event in the Rocky Mountain foreland and Great Plains: *Tectonics*, v. 3, no. 7, p. 741-758, doi: 10.1029/TC003i007p00741.

What was the main criterion Bird focused on as representing the essence of the Laramide orogeny?

I'd say it was an increase in crustal thickness

Elements of Bird’s 1984 analysis:
Posits that the main Laramide event is thickening of crust by average of 9 km.
Was the cause:

- sediments
- intrusion
- shortening
- crustal flow
- shear of lower crust

Elements of Bird’s 1984 analysis:
Posits that the main Laramide event is thickening of crust by average of 9 km.
Was the cause:

- ~~sediments -~~ only averages to 200m thickness
- intrusion
- shortening
- crustal flow
- shear of lower crust

Elements of Bird's 1984 analysis:
Posits that the main Laramide event is thickening of crust by average of 9 km.
Was the cause:

- ~~sediments -~~ only averages to 200m thickness
- ~~intrusion~~ - small volume and no thermal anomaly
- shortening
- crustal flow
- shear of lower crust

Elements of Bird's 1984 analysis:
Posits that the main Laramide event is thickening of crust by average of 9 km.
Was the cause:

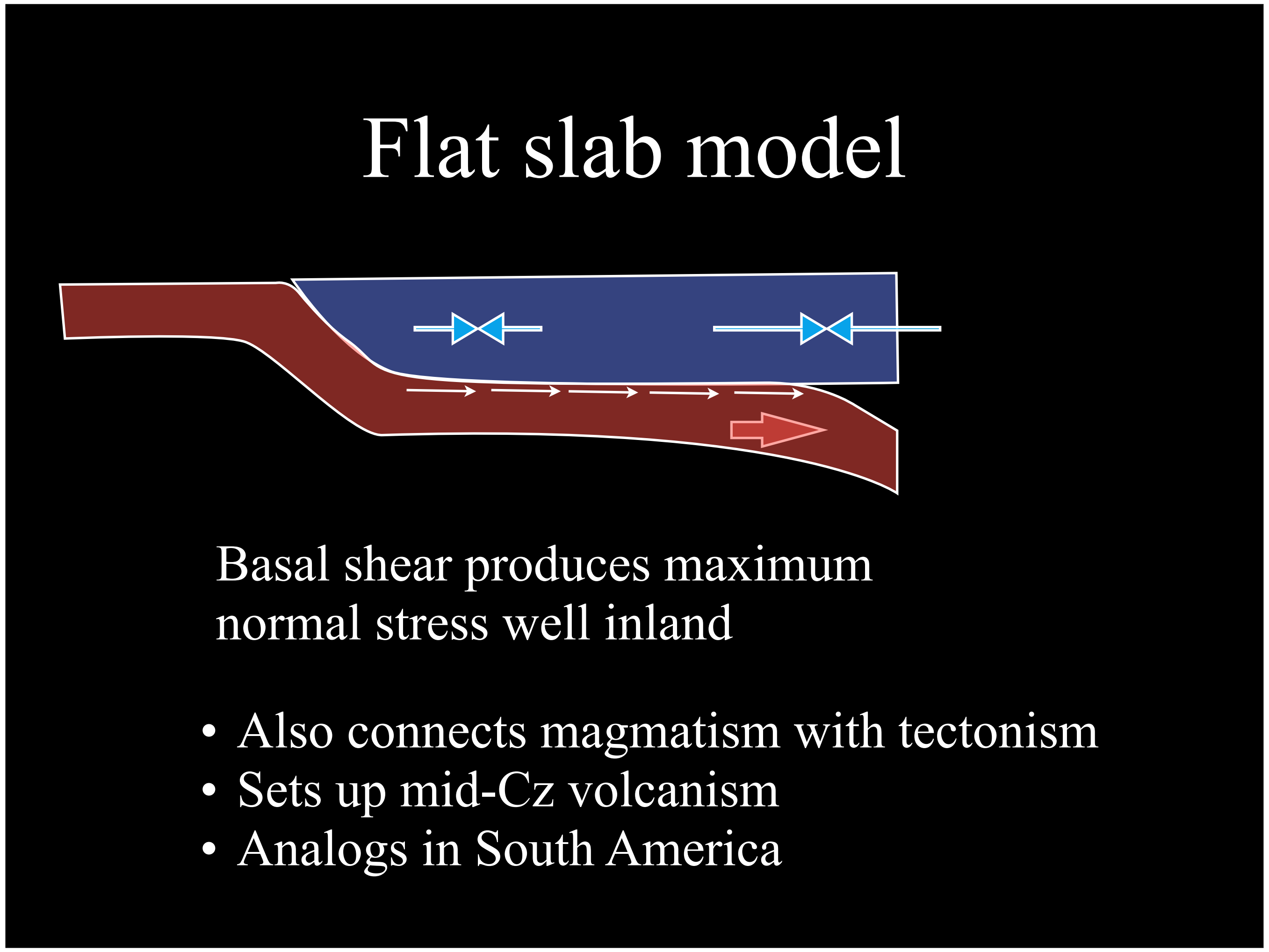
- ~~sediments -~~ only averages to 200m thickness
- ~~intrusion~~ - small volume and no thermal anomaly
- ~~shortening-~~only 13% and not in Great Plains
- crustal flow
- shear of lower crust

Others had higher estimates of shortening than Bird; 25% in Wyoming would thicken 35 km crust to about 44 km. Still shy of Bird's targets…

Elements of Bird’s 1984 analysis:
Posits that the main Laramide event is thickening of crust by average of 9 km.
Was the cause:

- ~~sediments -~~ only averages to 200m thickness
- ~~intrusion -~~- small volume and no thermal anomaly
- ~~shortening-~~only 13% and not in Great Plains
- ~~crustal flow~~-can’t move crust far enough
- shear of lower crust

(Not considered: phase changes at the Moho)



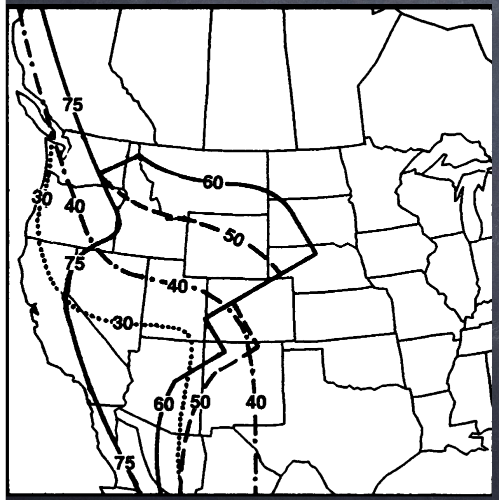
Flat slab model

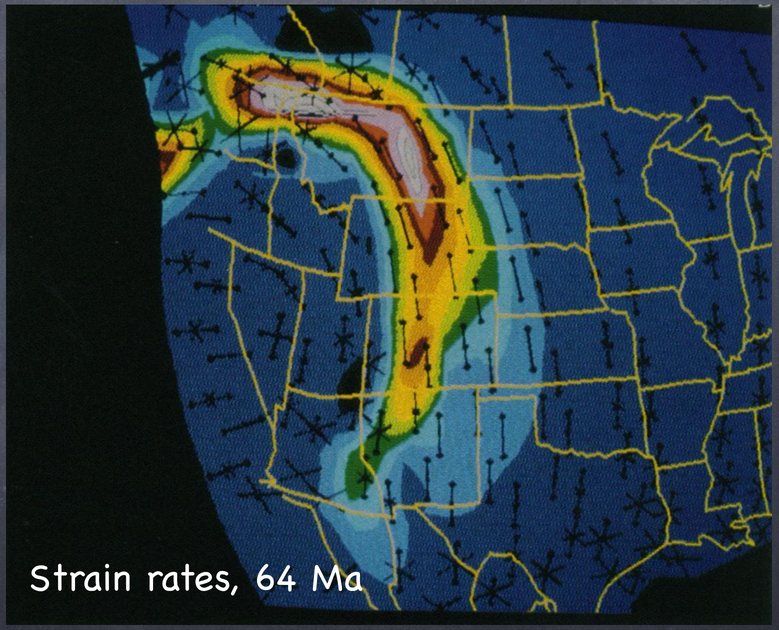
Basal shear produces maximum normal stress well inland

- Also connects magmatism with tectonism
- Sets up mid-Cz volcanism
- Analogs in South America

Although flat slab originally from volcanic variations, basic physics, goes back to Dickinson & Snyder (1978) and esp. Bird (1984, 1988).

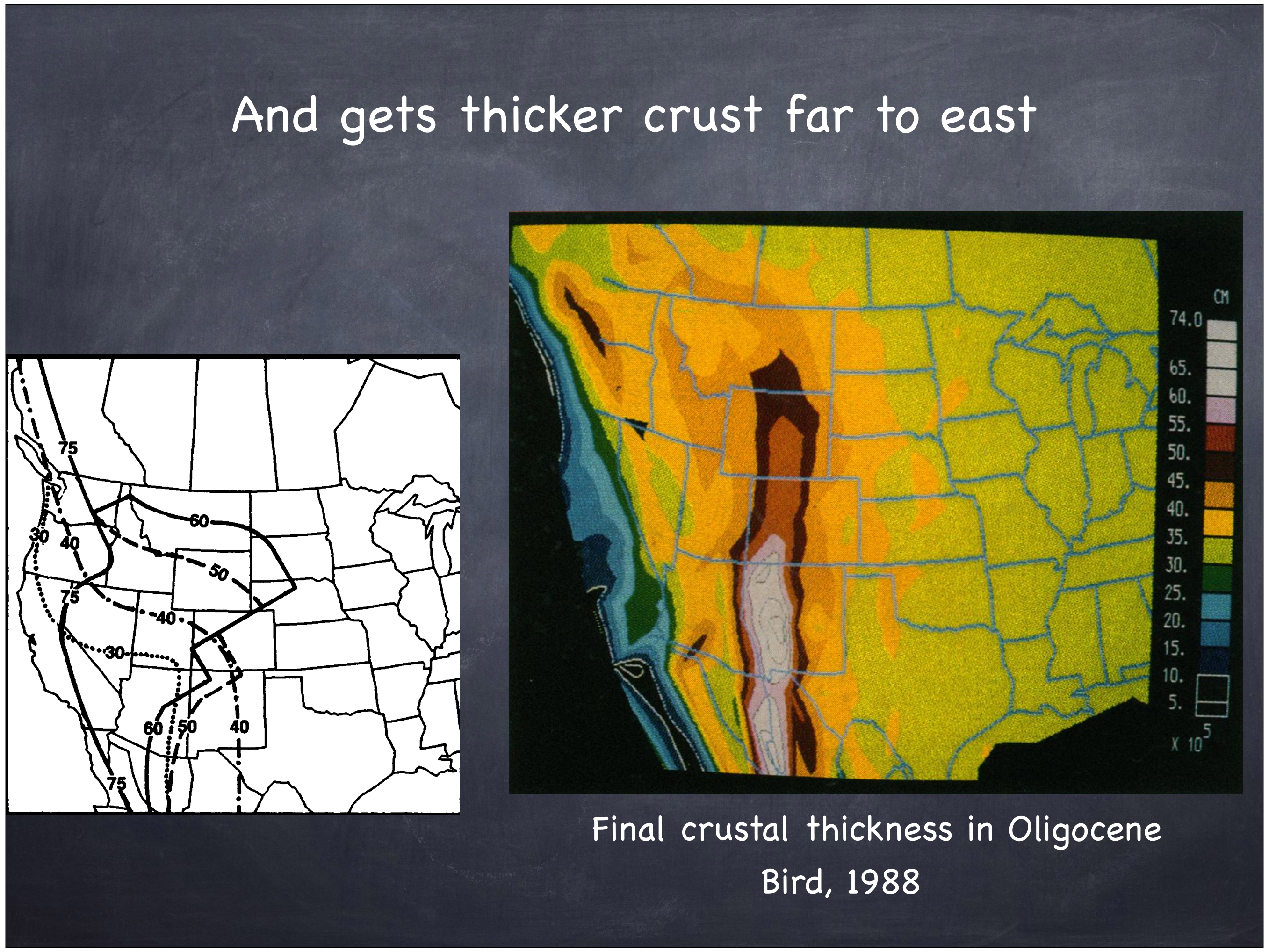
Can produce deformation in about the right places





Strain rates, 64 Ma

Bird, 1988

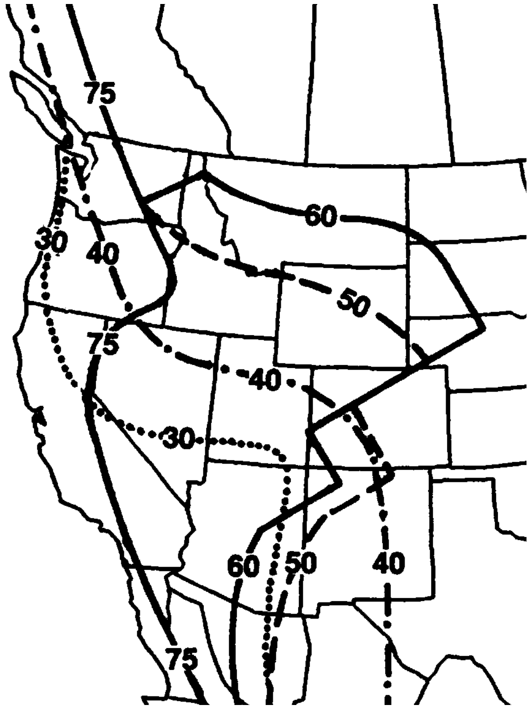


And gets thicker crust far to east

Final crustal thickness in Oligocene
Bird, 1988

Also seems to wipe out Nevadaplano…and destroys California

…but has other issues



Bird, Science, 1988

1) Removal of lithosphere

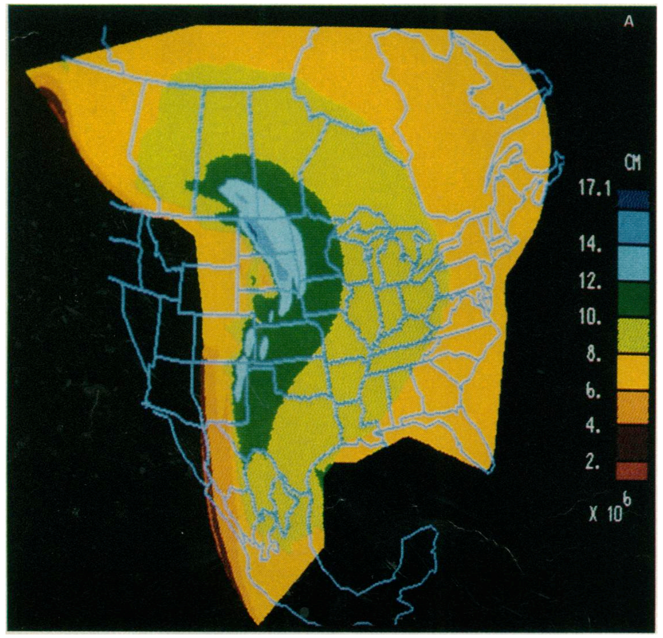


Fig. 3. (**A**) Final (middle Oligocene) displacement and thickness of the mantle layer of North America lithosphere. Thickness is contoured in 20-km intervals.

Flat slab predictions

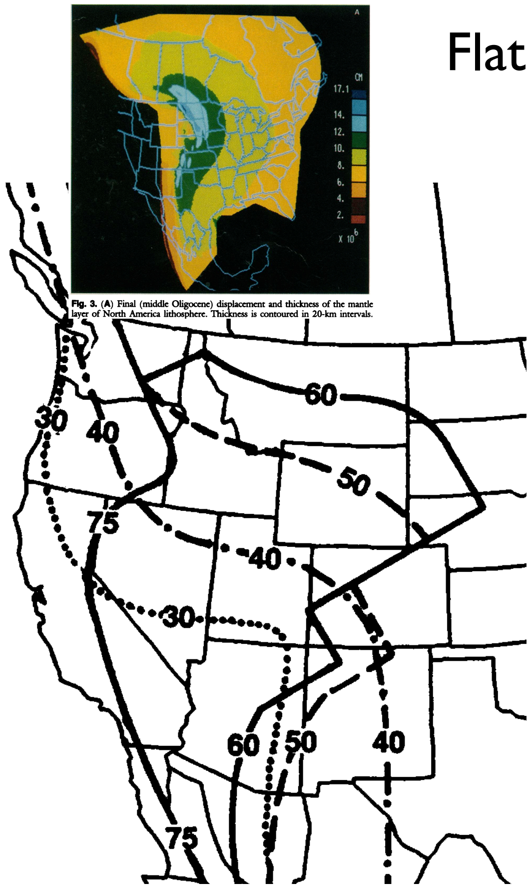
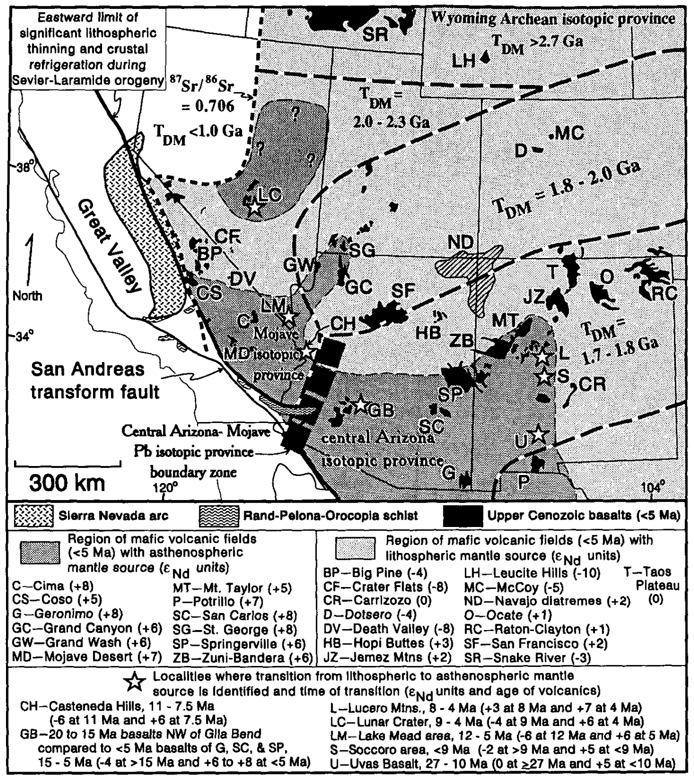


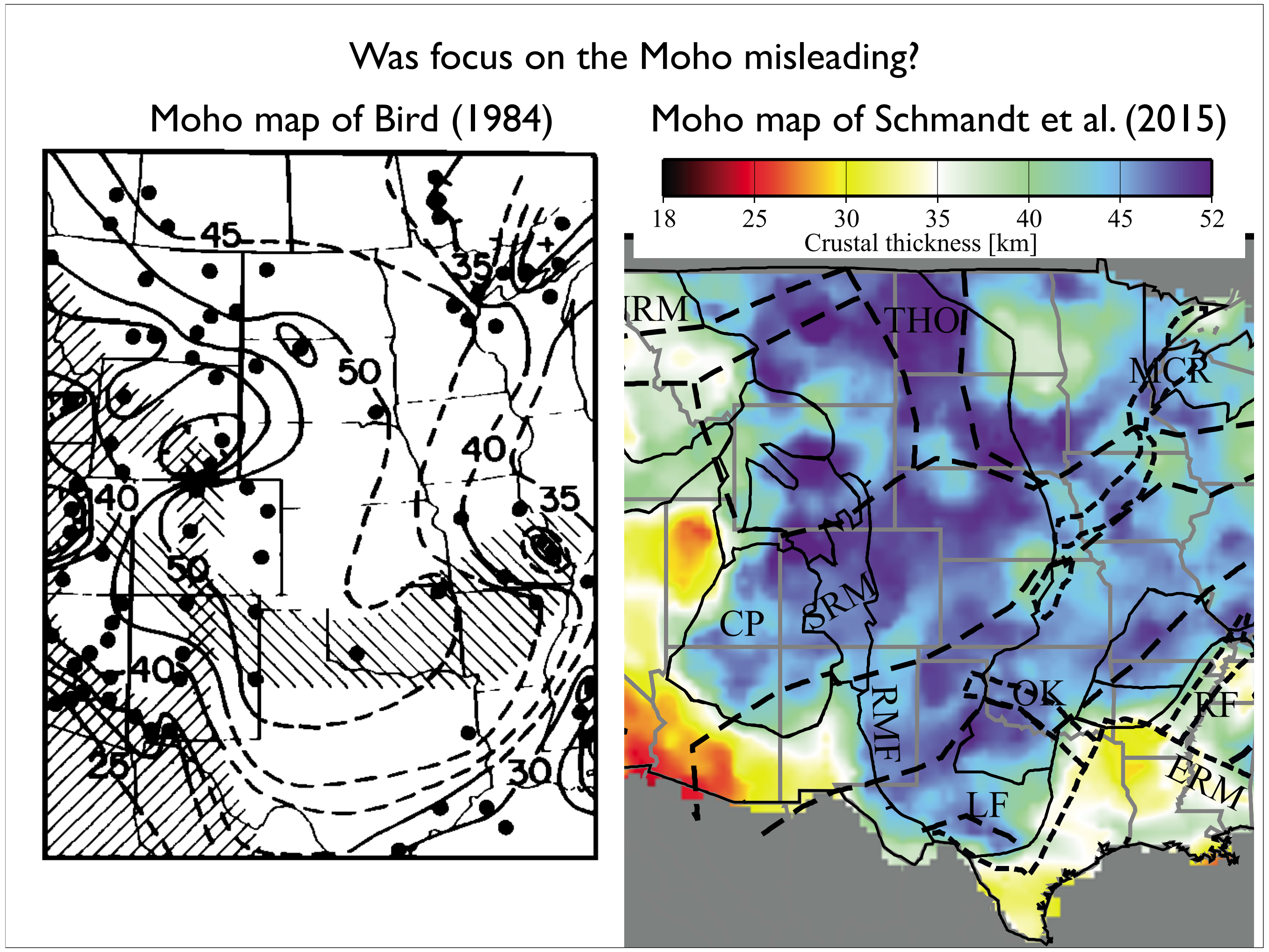
Fig. 3. (**A**) Final (middle Oligocene) displacement and thickness of the mantle layer of North America lithosphere. Thickness is contoured in 20-km intervals.

Bird, Science, 1988

Livaccari and Perry, Geology, 1993



So just how fatal should this be? Is it a trivial modification of Bird's model? Or does this create a bigger problem? Is the focus on crustal thickness misplaced? Could it be younger and sourced in the mantle?

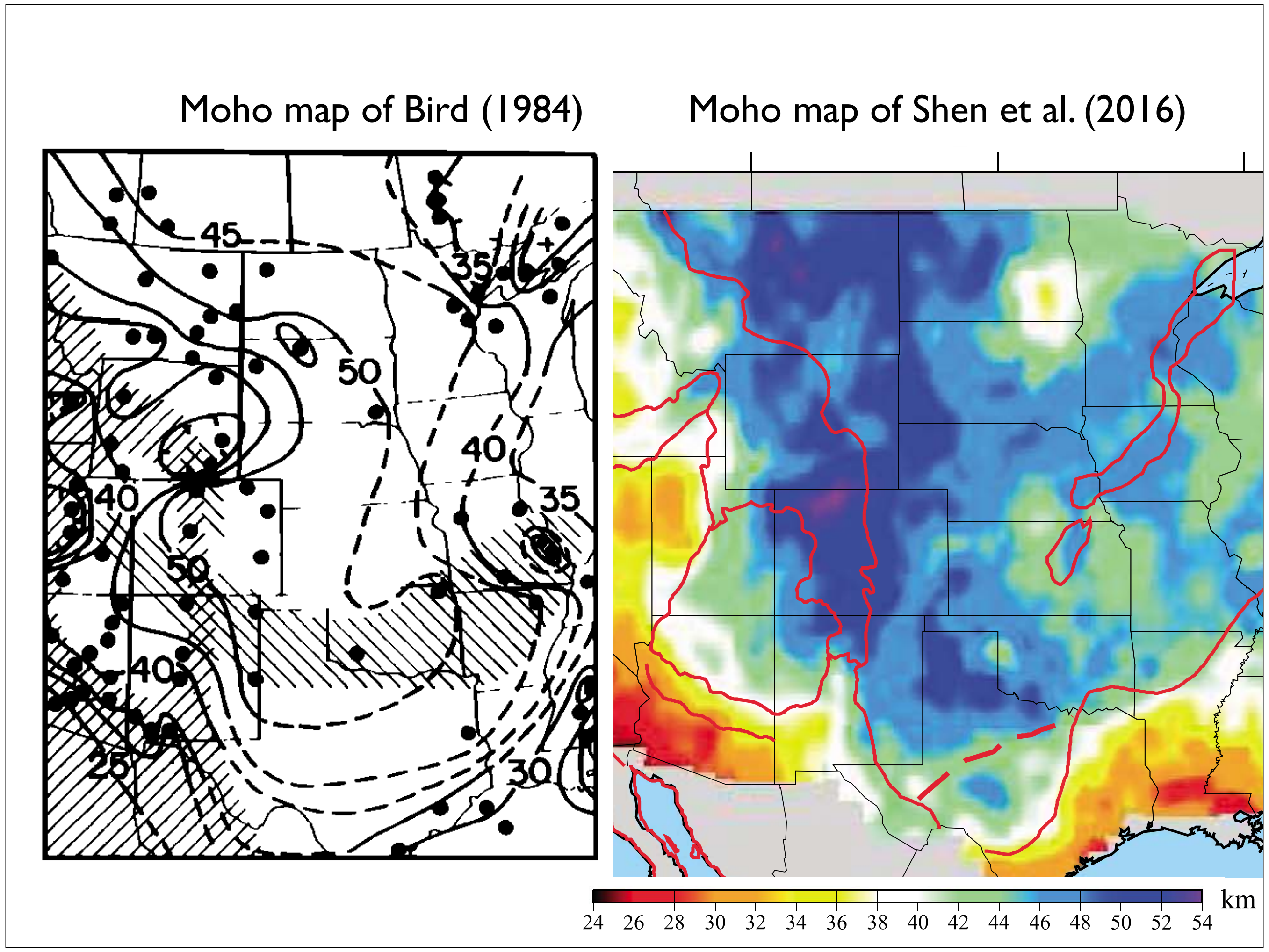


Was focus on the Moho misleading?

Moho map of Bird (1984)

Moho map of Schmandt et al. (2015)

Schmandt map doesn’t show obvious Rockies thickening…

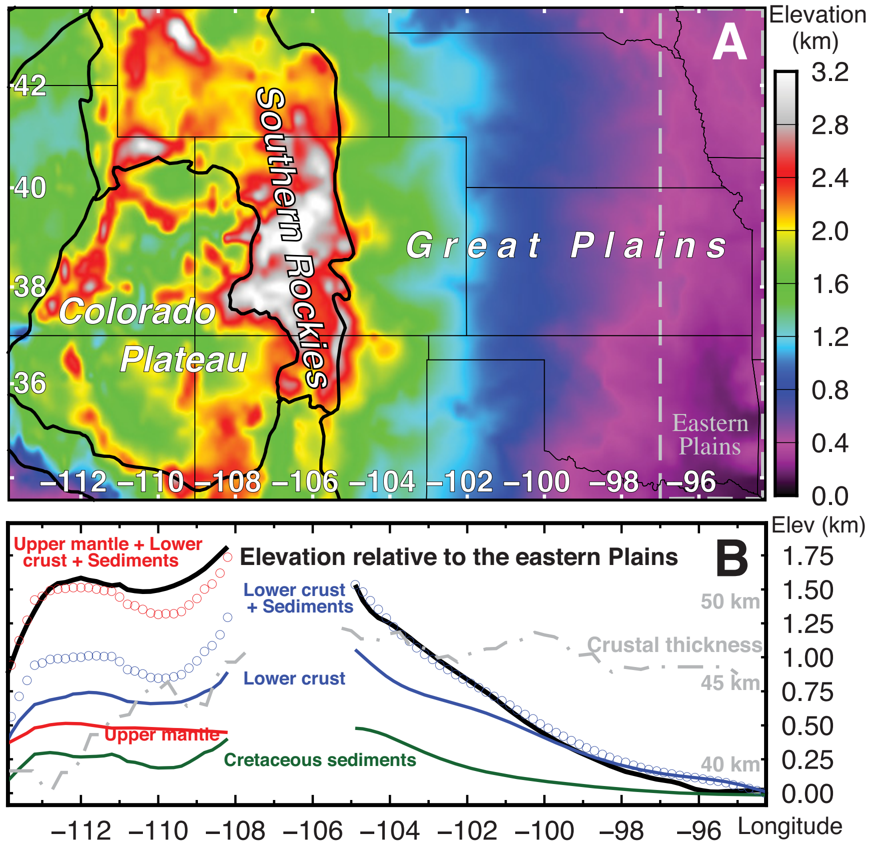


Moho map of Bird (1984)

Moho map of Shen et al. (2016)

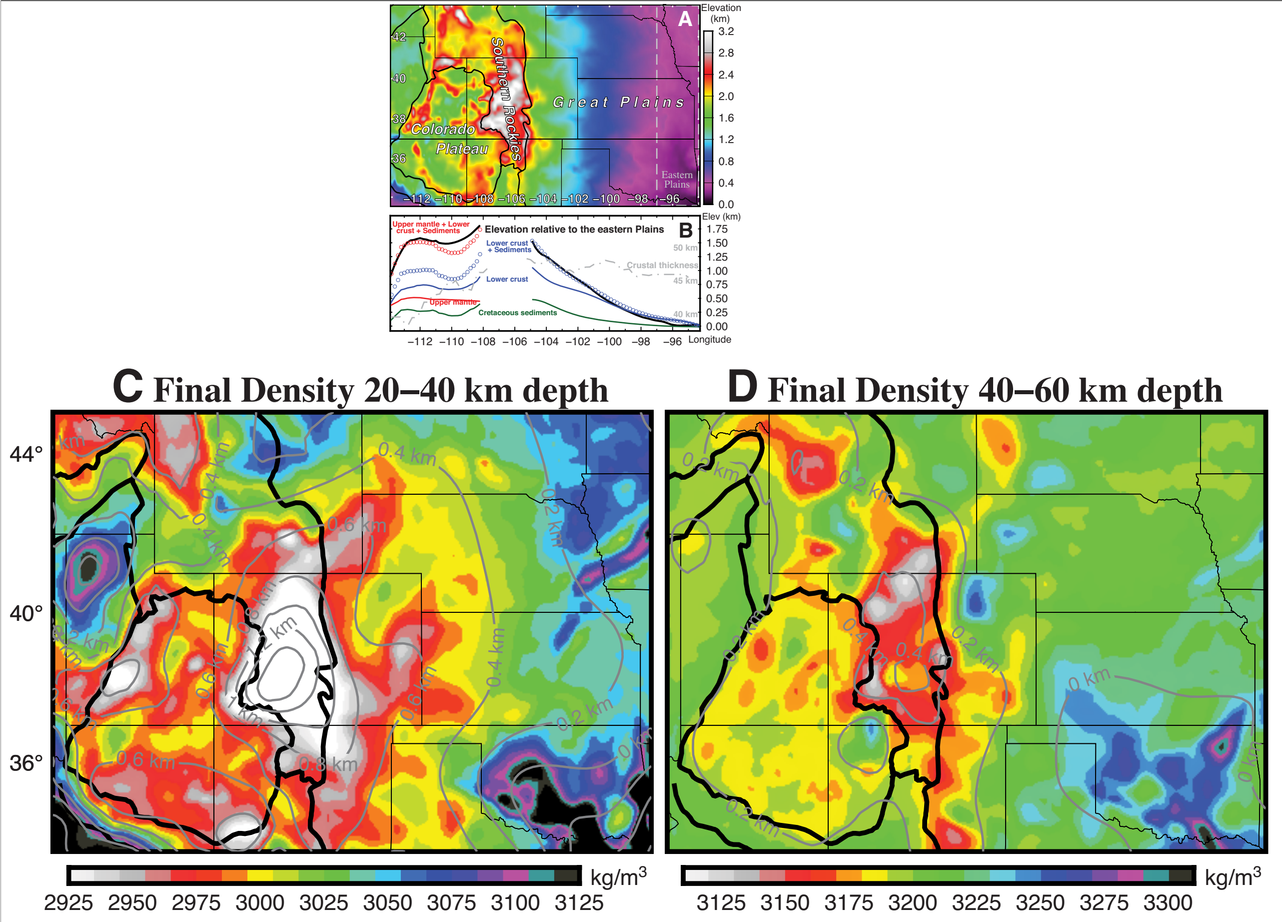
but Shen map does seem to show it.

Is there intracrustal variation of importance?



Levandowski et al., *Geosphere*, 2018

Maybe Moho isn’t as important as structure of the crust—note crustal thickness not well correlated with contribution to topography from lower crust. Solid black line is smoothed topography.



C Final Density 20–40 km depth

D Final Density 40–60 km depth

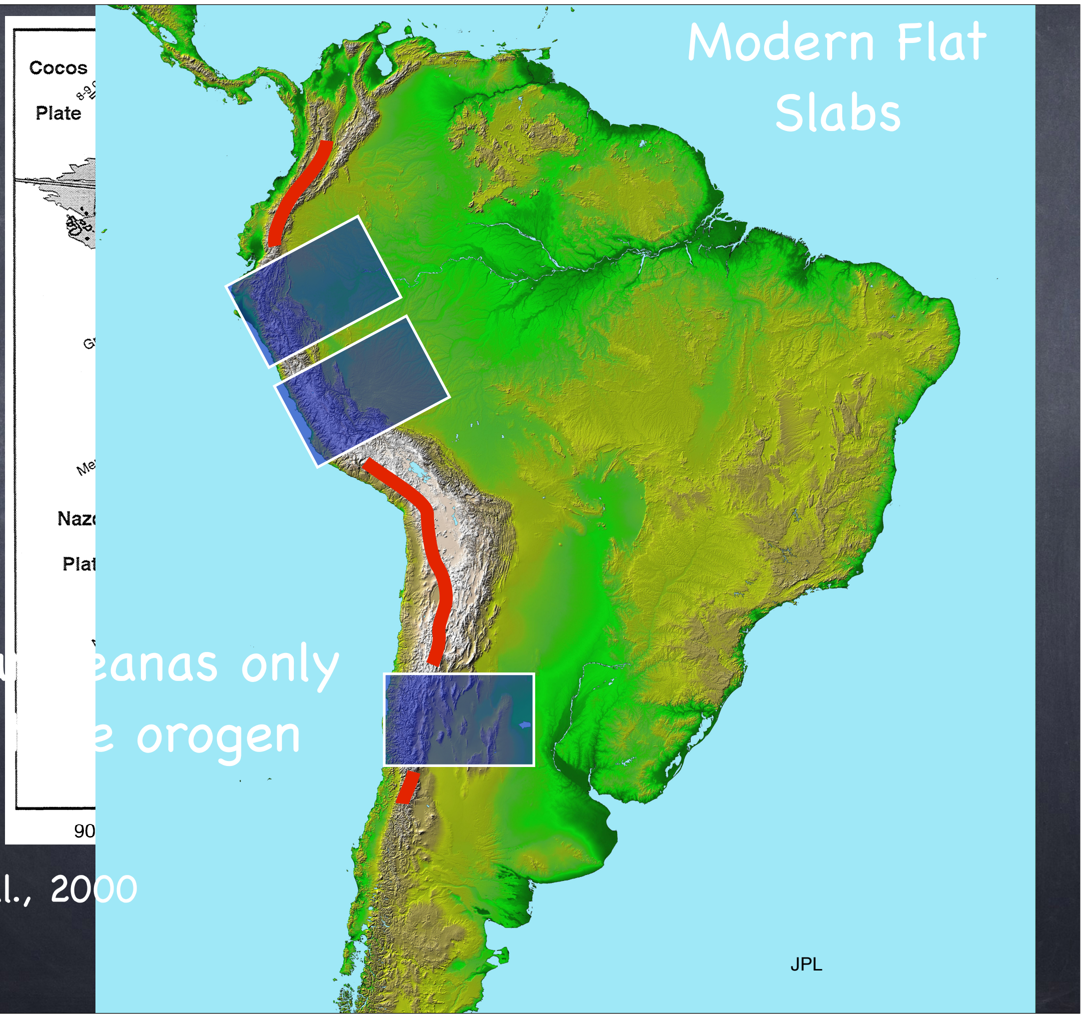
Levandowski et al., *Geosphere*, 2018

Mid-lower crust has large density variations absent at greater depths in mantle except in the RGR/southern Rockies…so *Plains* don't seem to have deeper support. Light gray contours show contribution to elevation…

Flat slabs elsewhere

rather than look for Laramide ranges elsewhere,
what about flat slabs elsewhere?

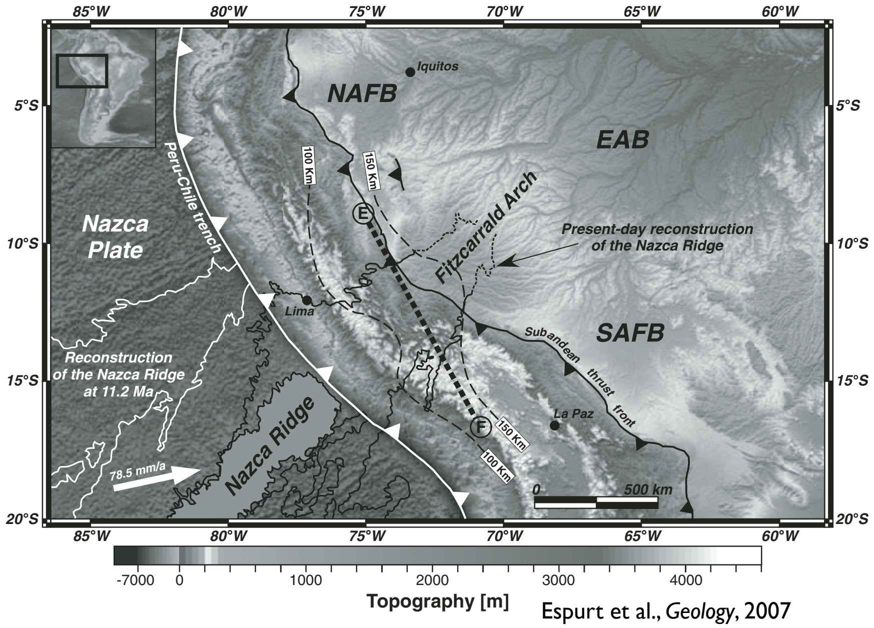
Modern Flat Slabs



Sierras Pa eanas only
Rockies- e orogen

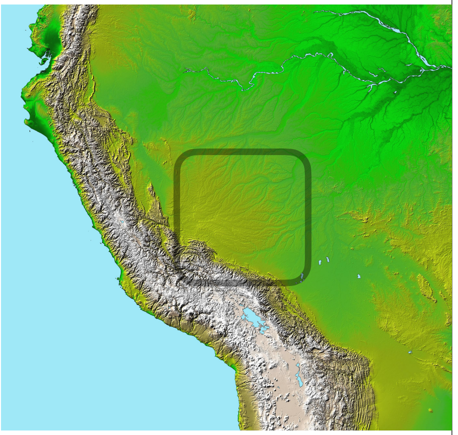
Gutschler et al., 2000

What do flat slabs do?

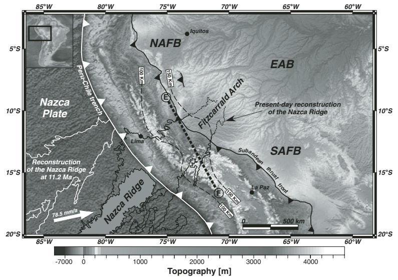


Espurt et al., *Geology*, 2007

Make things go up?

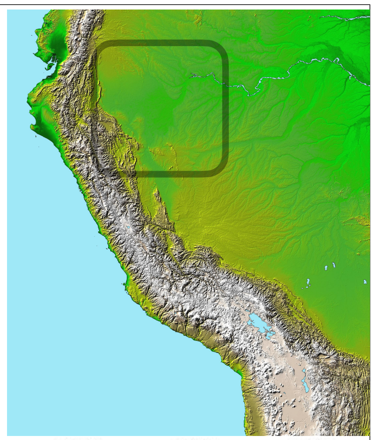


What do flat slabs do?

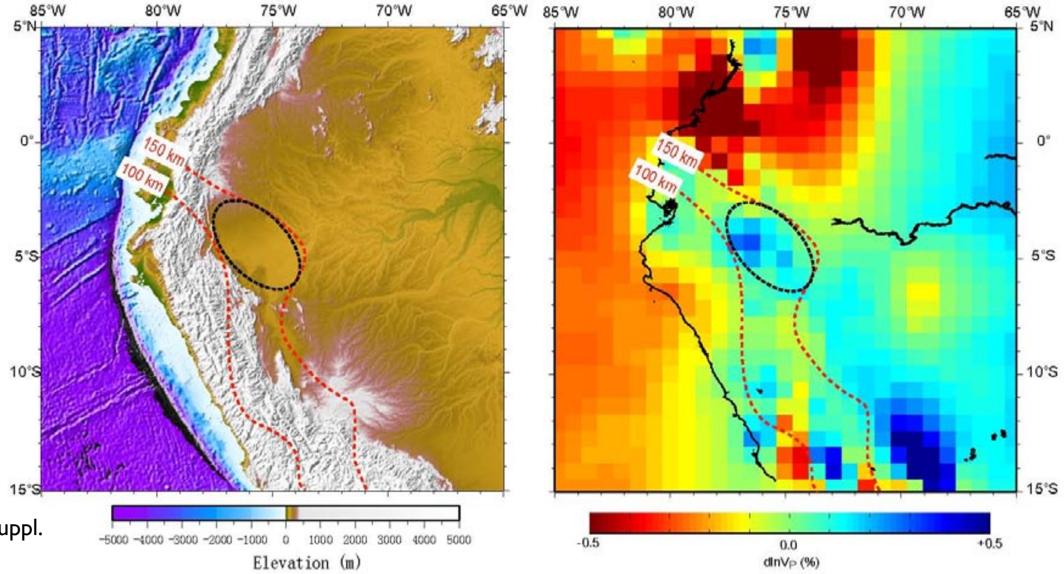


Make things go up?

Espurt et al., *Geology*, 2007



Make things go down?



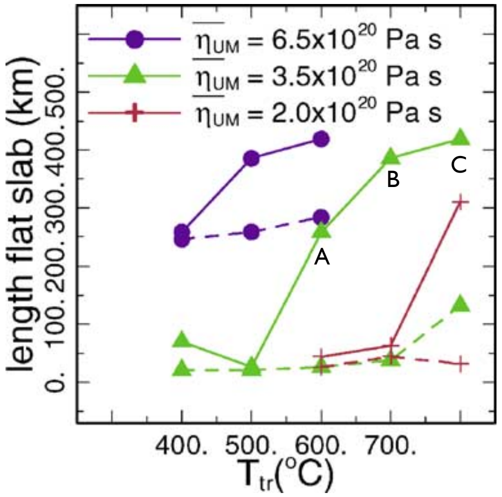
Liu et al., *Nature Geosci*, Suppl. Mat., 2010

As an aside, the Skinner et al. 2013 paper argues that due to asymmetry in spreading in Pacific, Inca Plateau is 600 km farther east than shown here

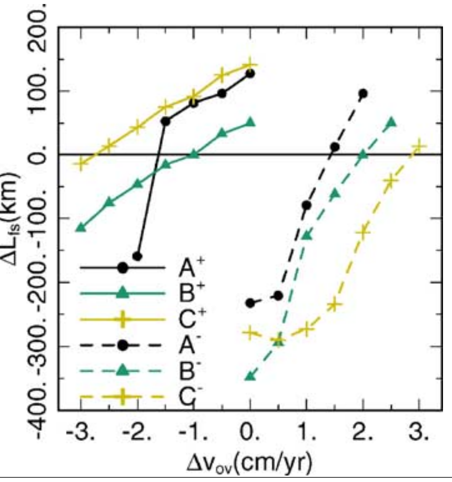
What makes slabs go flat?

Oceanic plateau under some circumstances

(Models with plateau solid lines, without dashed)
van Hunen et al., PEPI, 2004



Metastable basalt



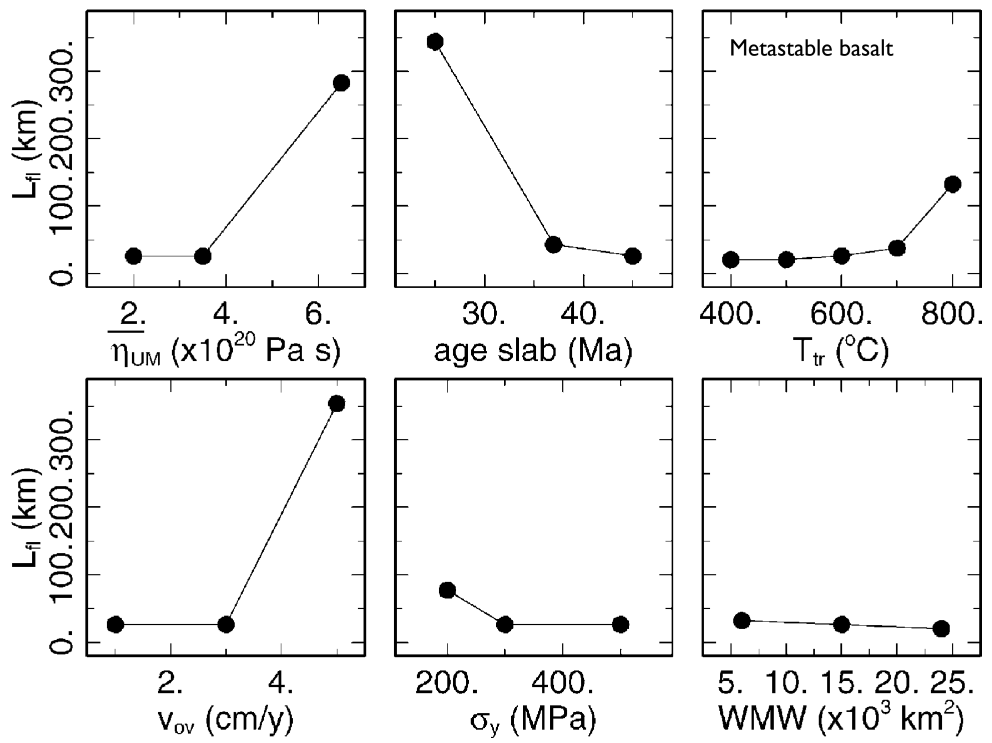
Rapidly moving upper plate under some circumstances

(Models with doubly thick plateau solid lines, no plateau dashed)
van Hunen et al., PEPI, 2004

Top: Fig. 4. Length of the flat slab segment at model time t = 14.4 Ma for several values of the transition temperature Ttr and average upper mantle viscosity η¯ UM . Solid lines represent situations with a plateau, dashed lines without. Only the Ttr = 600 and 700 ○ C cal- culations with intermediate mantle strength, and the Ttr = 800 ○ C with the weakest mantle show the observed characteristics at Peru, i.e. flat subduction with a plateau, and steep without.

Bottom Fig. 5. Relative importance of the overriding plate motion and plateau subduction for modified versions of models A–C at model time t = 15 Ma. Lengths of the flat slab are for models with a 'twice-as-thick' plateau (solid lines) and without a plateau (dashed lines) for several overriding plate motion adjustments (with respect to the default overriding plate motion of 3cm per year at Peru). Flat slab length differences Lfs are measured with respect to the lengths obtained in model A–C.

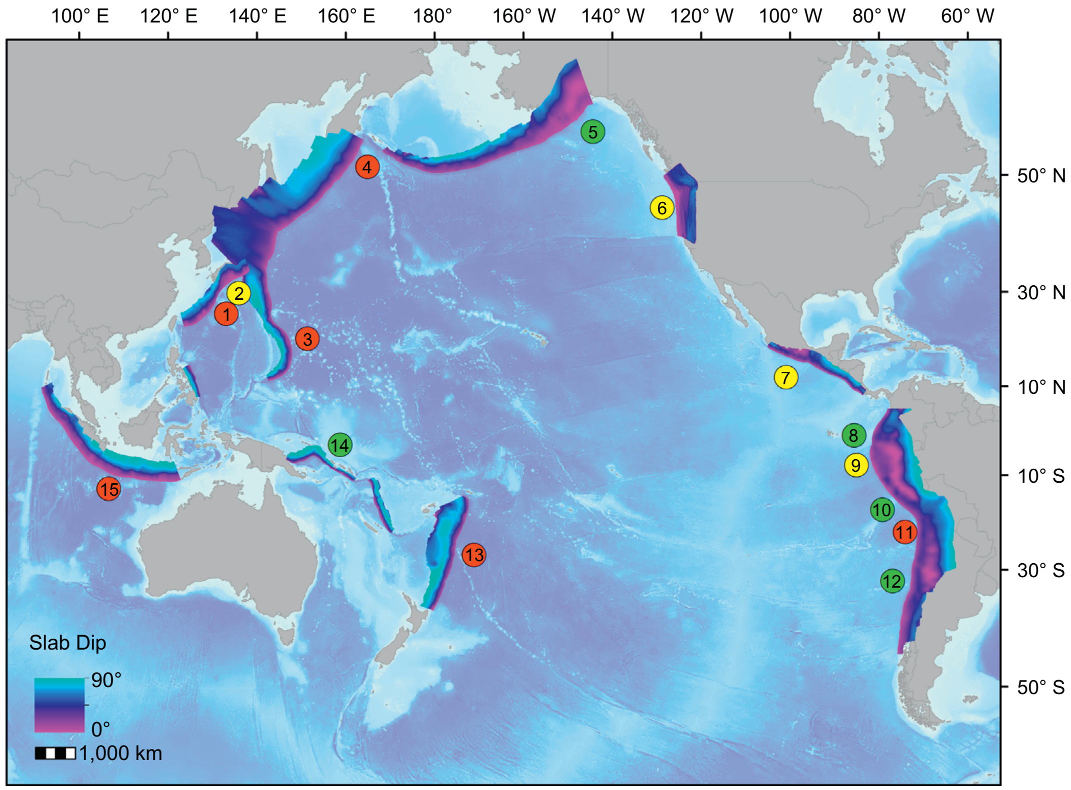
Some other effects that can shallow subduction



van Hunen et al., PEPI, 2004

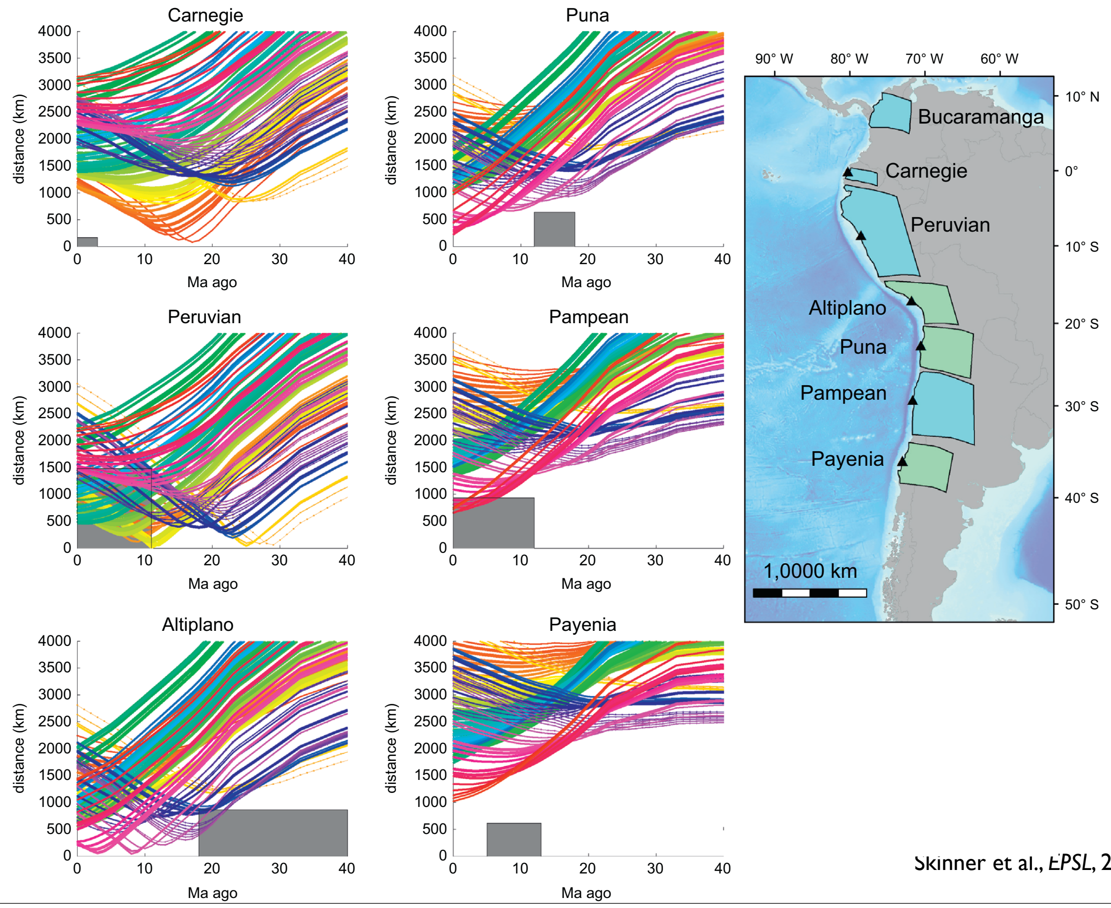
Fig. 6. Compilations of model calculations without an oceanic plateau. Several important model parameters are varied around the values from Peru model A. Most important parameters are the average upper mantle viscosity η¯UM, age of the slab, and overriding plate velocity vov, while eclogitisation kinetics (varied through variation in Ttr), slab yield stress τy and size of the weak mantle wedge seem to be of minor importance.

Observed effect of subducting a plateau?



Skinner et al., *EPSL*, 2013

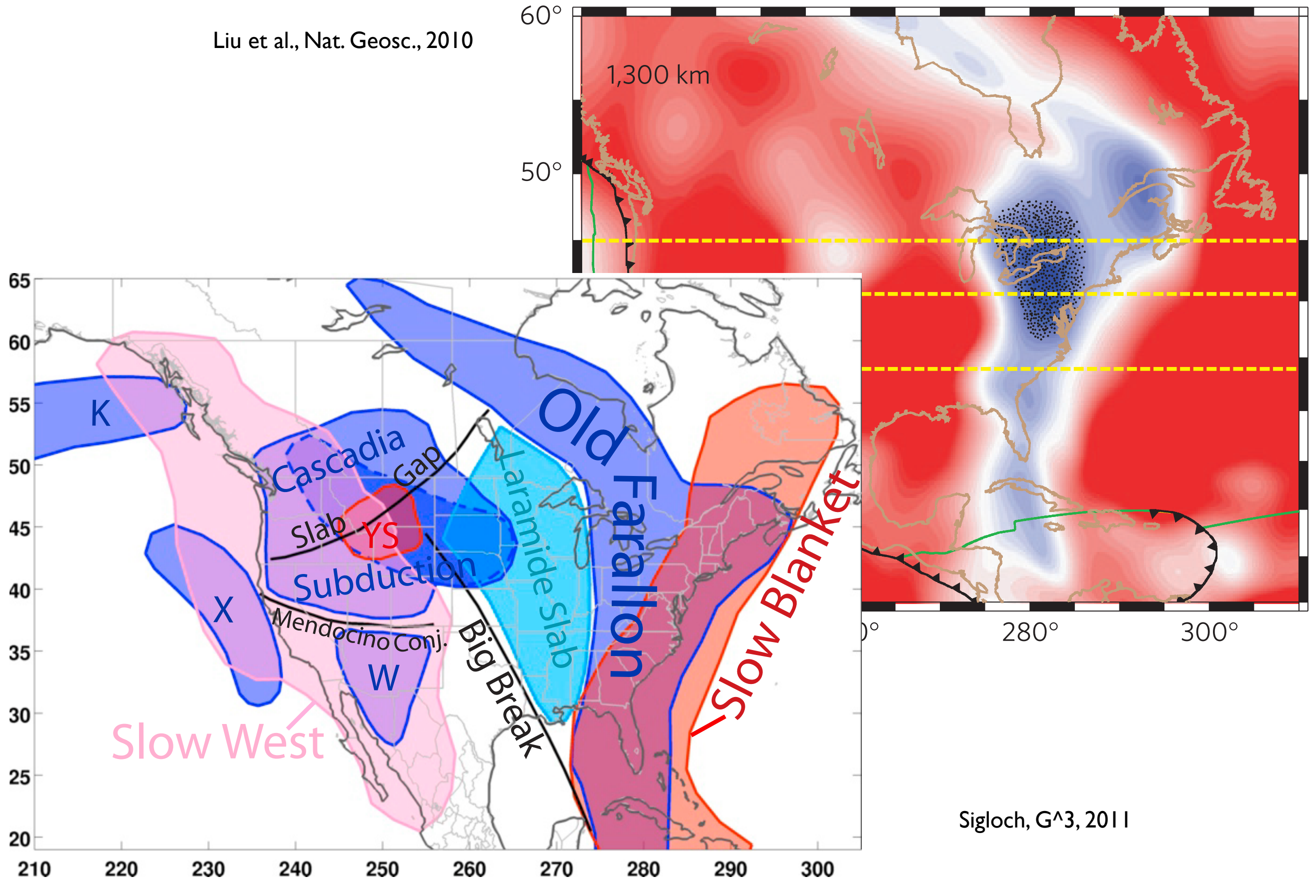
Observed effect of subducting a plateau?



Skinner et al., *EPSL*, 2013

Fig. 3. Location of Pacific–Farallon/Nazca conjugate features relative to a given flat slab. We have placed points along Pacific plate bathymetric highs, and created conjugate features using standard plate reconstruction techniques and the rotation model of Müller et al. (2008). A plot for each flat slab shows the proximity of a reconstructed point on the bathymetric anomaly to that flat slab, plotted as a function of time. The thickness of the line scales with the crustal volume in a 100 km 200 km box around the Pacific plate conjugate point. The grey box represents the spatial and temporal extent of the flat slab from Ramos and Folguera (2009). We expect impactors to pass through this target zone if the buoyancy hypothesis is the cause of the flat slab. The map shows the location of the flat slabs along the South American margin (Ramos and Folguera, 2009). The black triangles are the point from which our distances are calculated. See Supplementary Table 3 for information about the conjugate points.

Where is flat slab today?

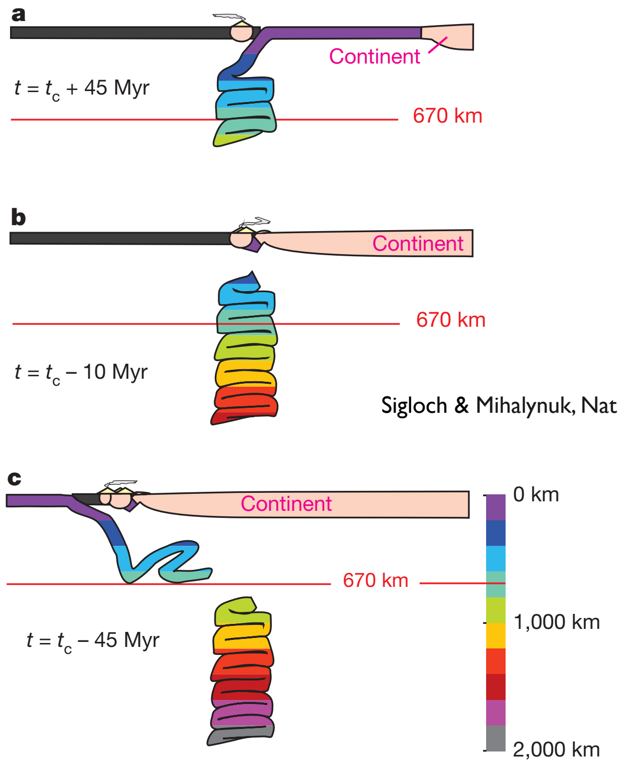


Liu et al., Nat. Geosc., 2010

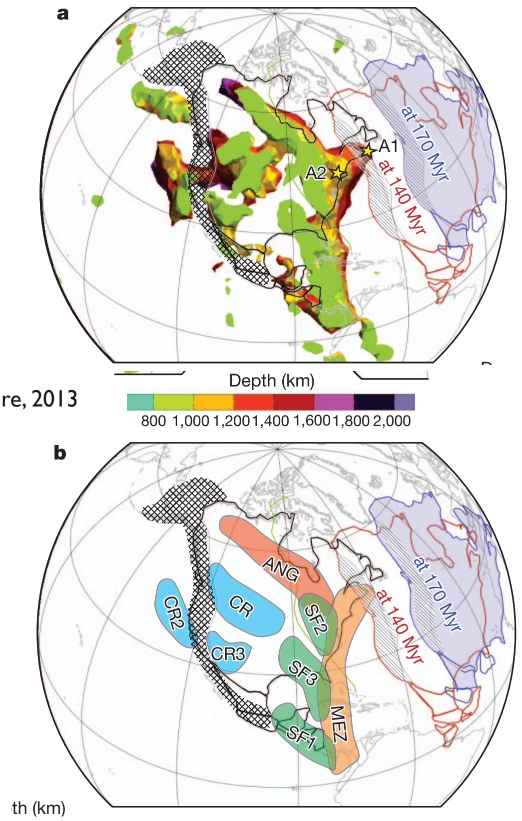
Sigloch, G^3, 2011

“Old Farallon” is basically ~1300km depth shown as pre-Laramide Farallon plate in this image (it is Mescalara in later papers , which is Jurassic). Black dots in Liu image are “tracers" in their mantle flow model tracking the Shatsky conjugate [but there is some circularity here]

...or is it even Farallon?

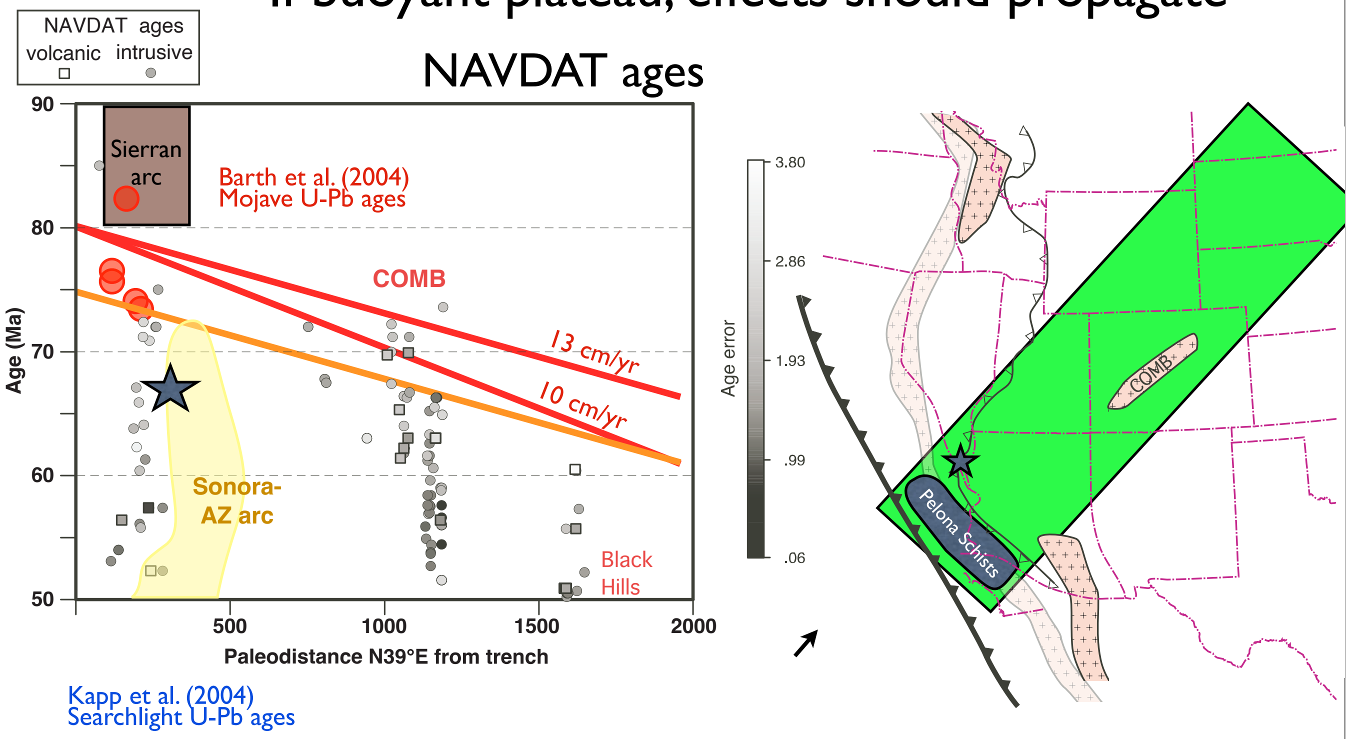


Sigloch & Mihalynuk, Nature, 2013



Flat slab predictions

If buoyant plateau, effects should propagate



NAVDAT ages

For Laramide, are there timing problems anyways? (Recall some of the subsidence stuff we looked at)

Other ideas

are we just not imaginative enough?

Collision predictions

South-to-north movement of igneous gap
(and emplacement of schists)

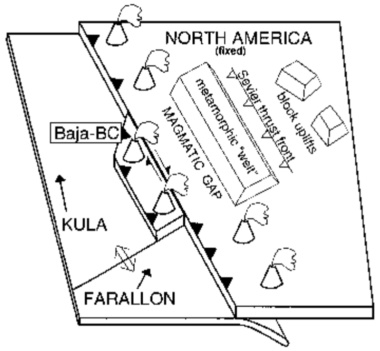
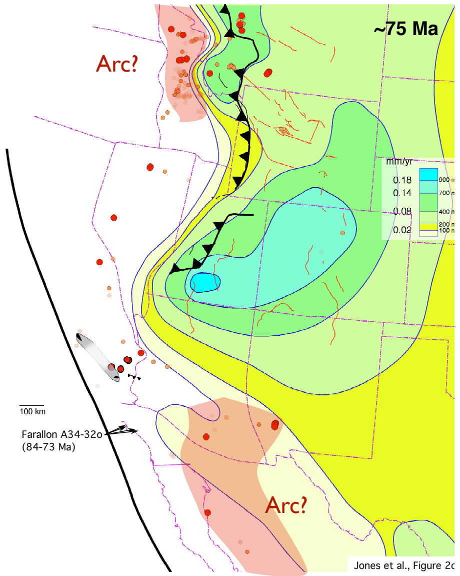
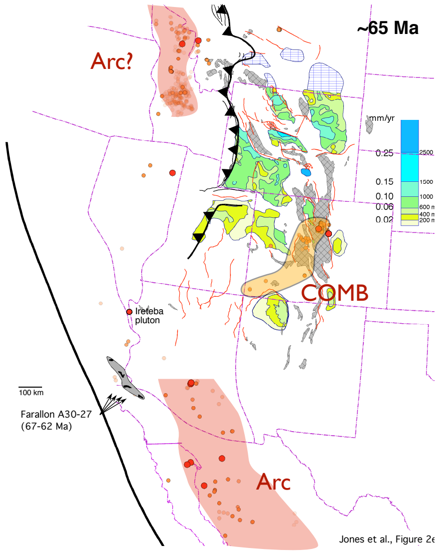


Figure 2. Paleogeographic configuration of dextral transpressional collision ("run") of Baja BC microplate and North America, resulting in the Laramide orogeny. Baja BC is inferred to have had an east-dipping subduction zone beneath its western edge and dextral, transpressional fault system on its eastern edge, which shut off subduction-related arc magmatism on adjacent North America during its northward movement.

Maxson & Tikoff, Geology 1996



Jones et al., Figure 2c



Jones et al., Figure 2e

Collision and collapse predictions

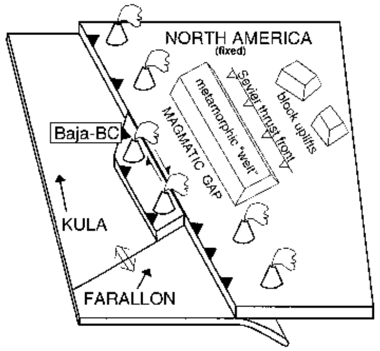
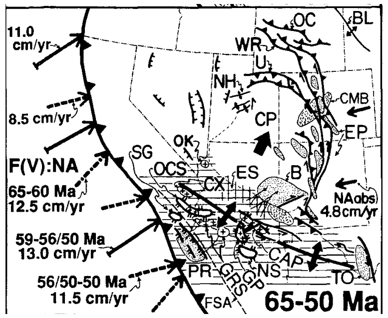
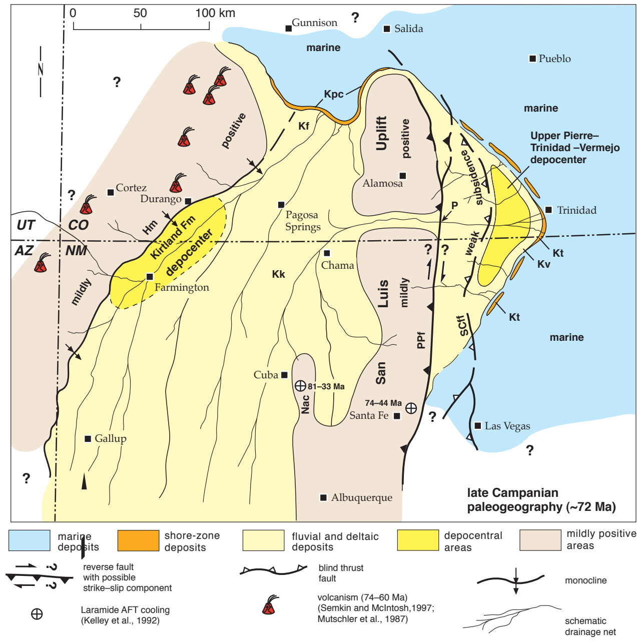


Figure 2. Paleogeographic configuration of dextral transpressional collision ("run") of Baja BC microplate and North America, resulting in the Laramide orogeny. Baja BC is inferred to have had an east-dipping subduction zone beneath its western edge and dextral, transpressional fault system on its eastern edge, which shut off subduction-related arc magmatism on adjacent North America during its northward movement.



Rigidity of Colorado Plateau



Cather, 2003

Cather (2003) estimates 1/2 to 3/4 of structural throw on Hogback Monocline could be during deposition of Kirtland Frm, 74-67 Ma

Collision and collapse difficulties

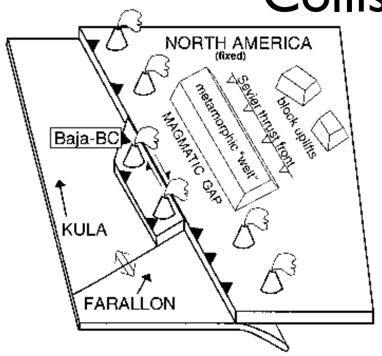
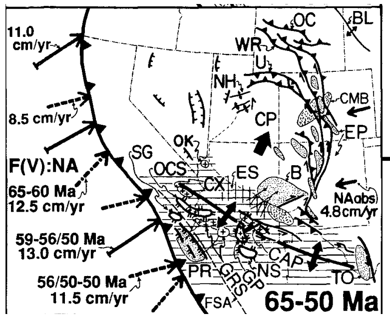


Figure 2. Paleogeographic configuration of dextral transpressional collision ("run") of Baja BC microplate and North America, resulting in the Laramide orogeny. Baja BC is inferred to have had an east-dipping subduction zone beneath its western edge and dextral, transpressional fault system on its eastern edge, which shut off subduction-related arc magmatism on adjacent North America during its northward movement.

Where is collisional deformation near margin?

Why would Sevier belt shutdown?



Why was igneous activity temporally tied to Laramide?

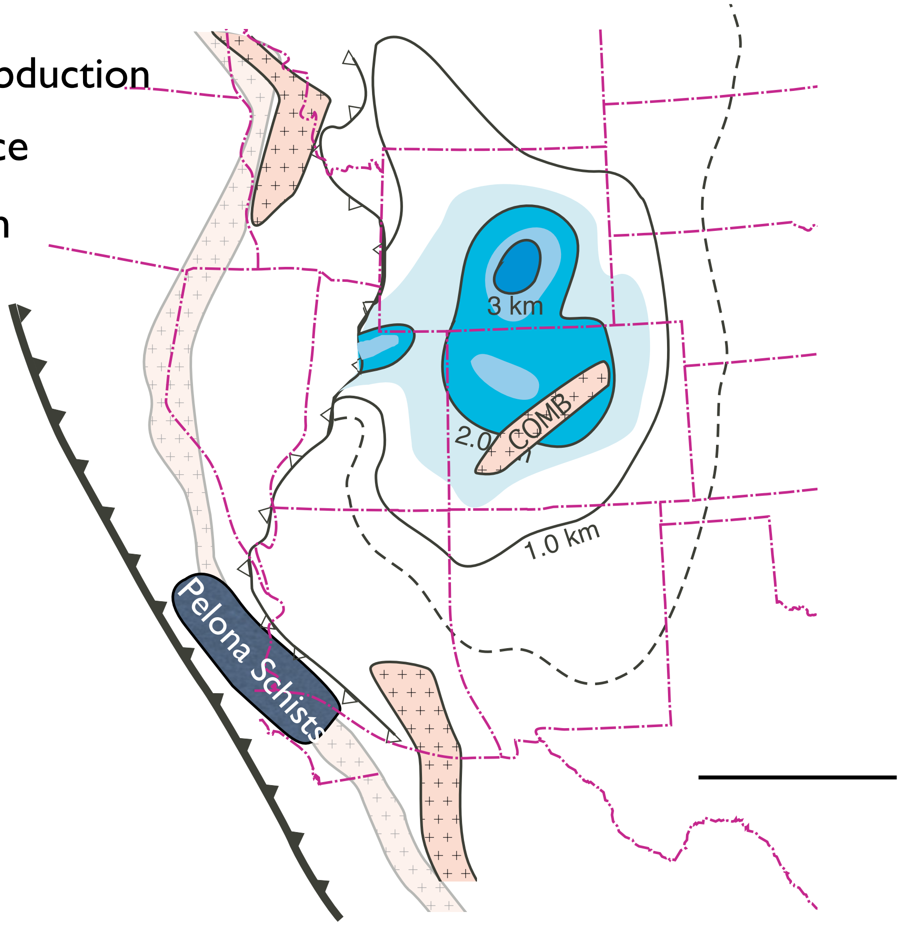
Underexplained Laramide elements

Limited shallow subduction

Latest K subsidence

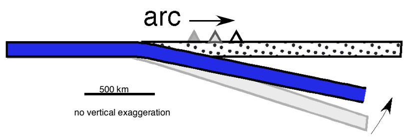
COMB orientation and timing

Duration

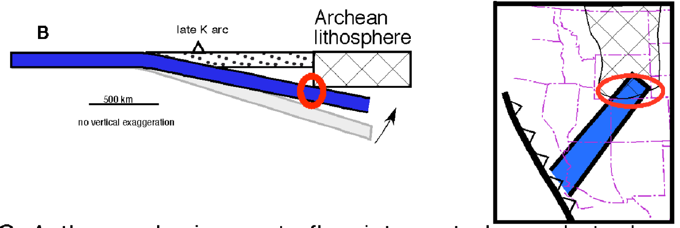


So we have some contradictions. Also note Colorado Plateau, extent of arc shutdown. UNclear if schists record true flat slab

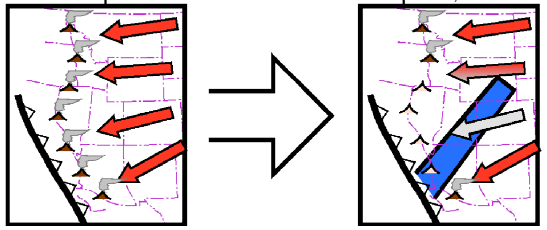
A. Shallowing subduction as North America moves westward



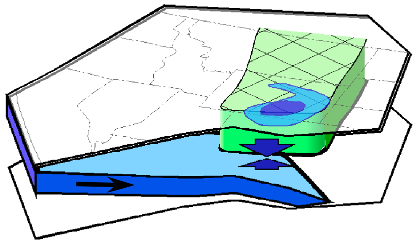
B. Shallowing slab locally interacts with thick lithosphere



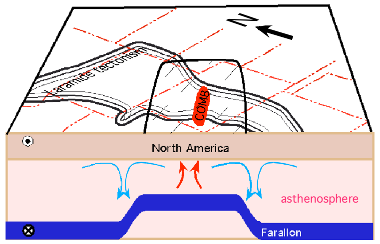
C. Asthenospheric counterflow interrupted, arc shuts down



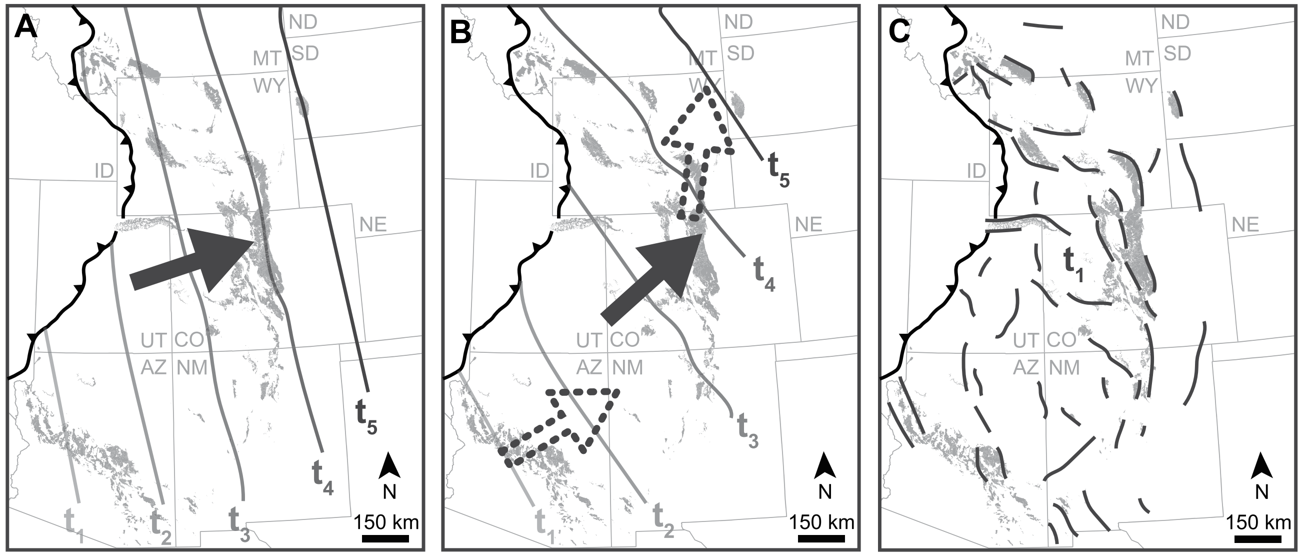
D. Suction on lithosphere drives subsidence, stresses



E. Secondary convection in asthenosphere
localizes Colorado Mineral Belt



Another examination of time transgression



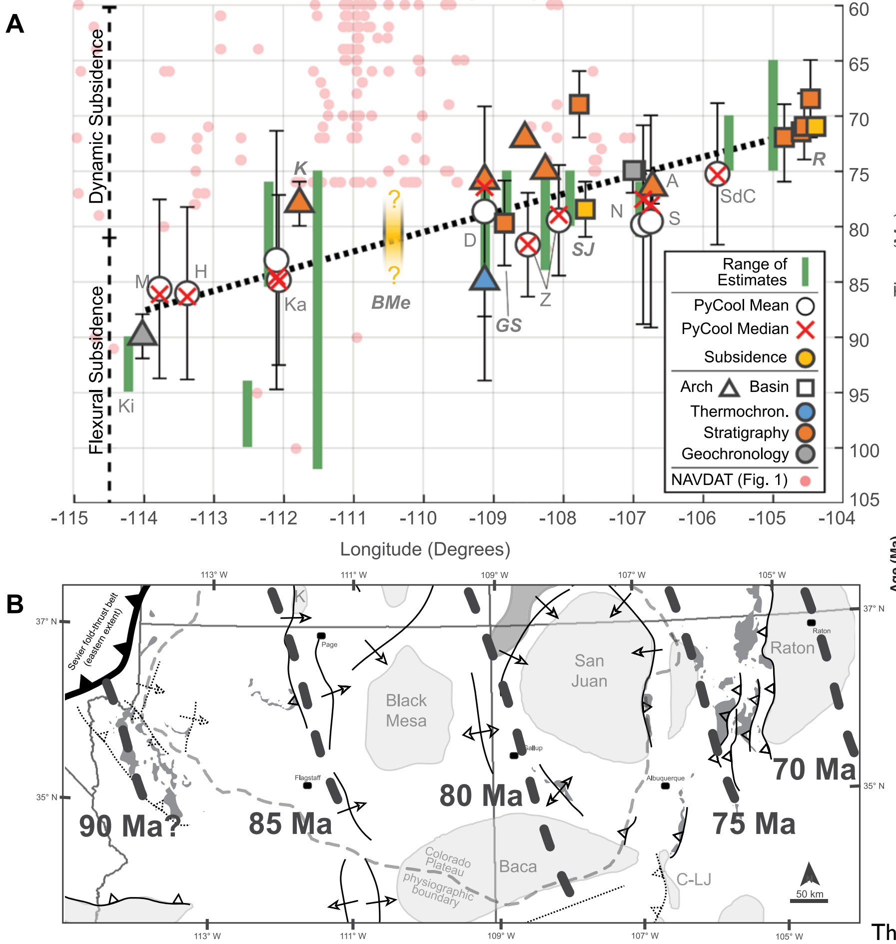
Easterly-Directed Onset of Deformation

Northeast-Directed Onset of Deformation (and two-phase NE to N trajectory)

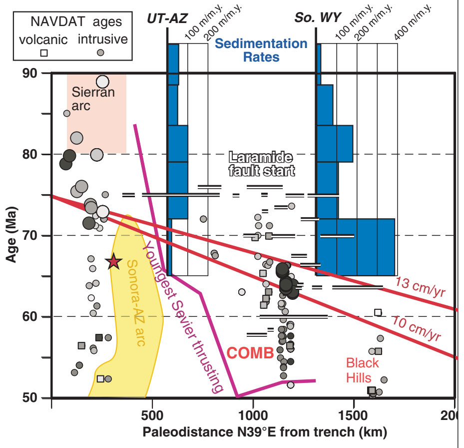
Regionally Synchronous (Coeval) Onset of Deformation

Thacker et al., *GSAB* 2023

Use cooling ages



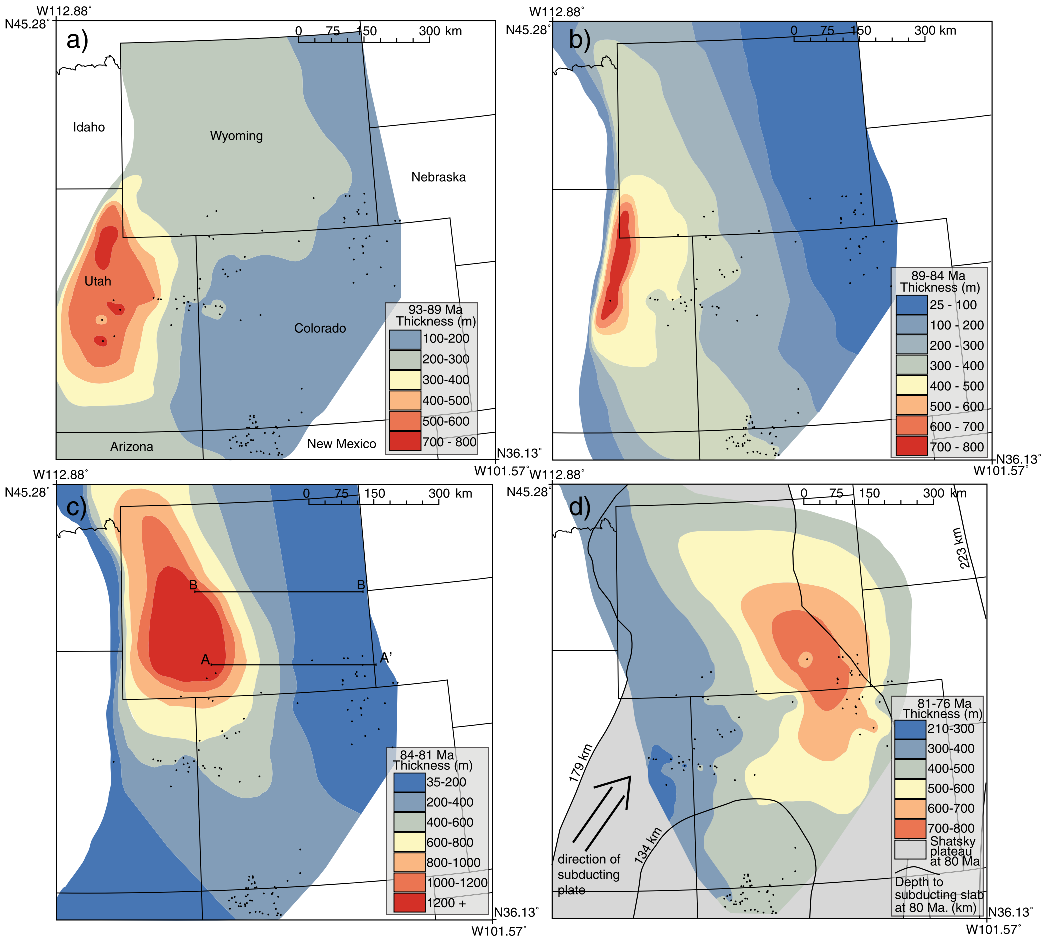
Thacker et al., *GSAB* 2023



Jones et al., *Geosphere* 2011

So maybe there is time-transgression? This is using cooling ages…and uncertainties are kind of high. Is this really reflecting deformation or just erosion (tilting of Plateau?)

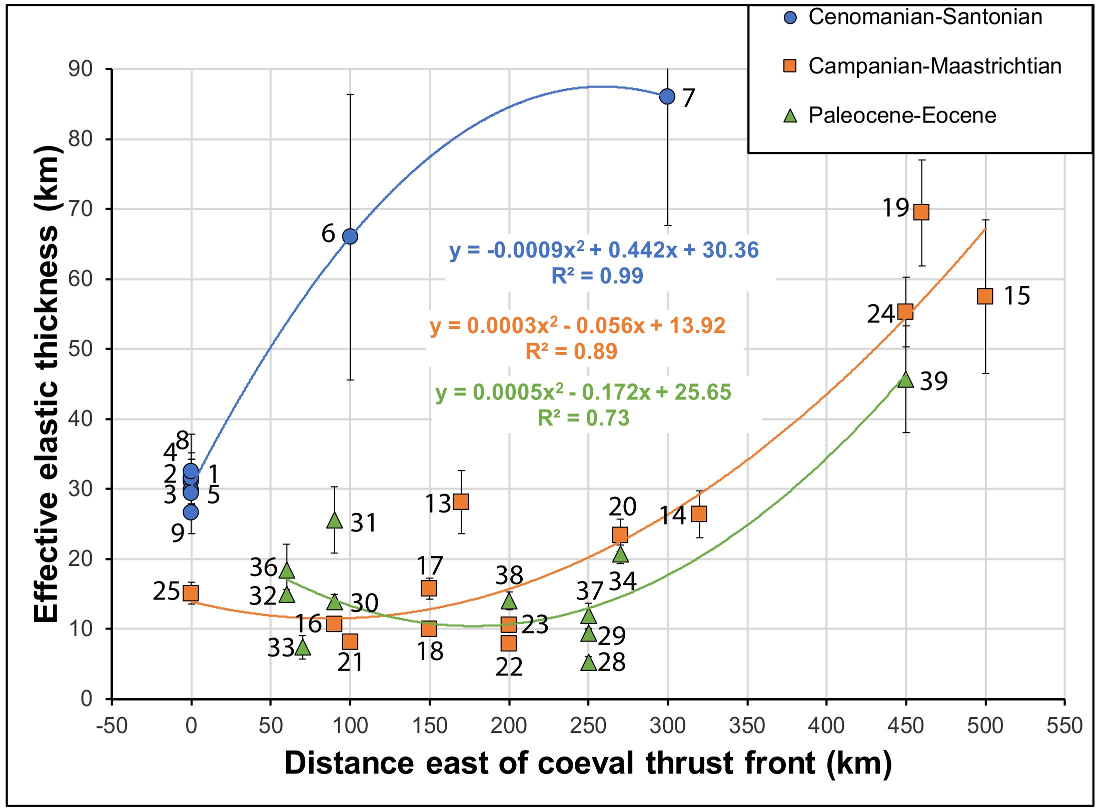
NAVDAT ages are mostly south or far north; many of these are K-Ar or Ar-Ar ages, so wouldn't want to go very far with that. Note that these ages are older than intrusives to west…



Painter & Carrapa, *GRL* 2013

Recall this…they estimates flexural strength

Flexural estimate of lithospheric strength

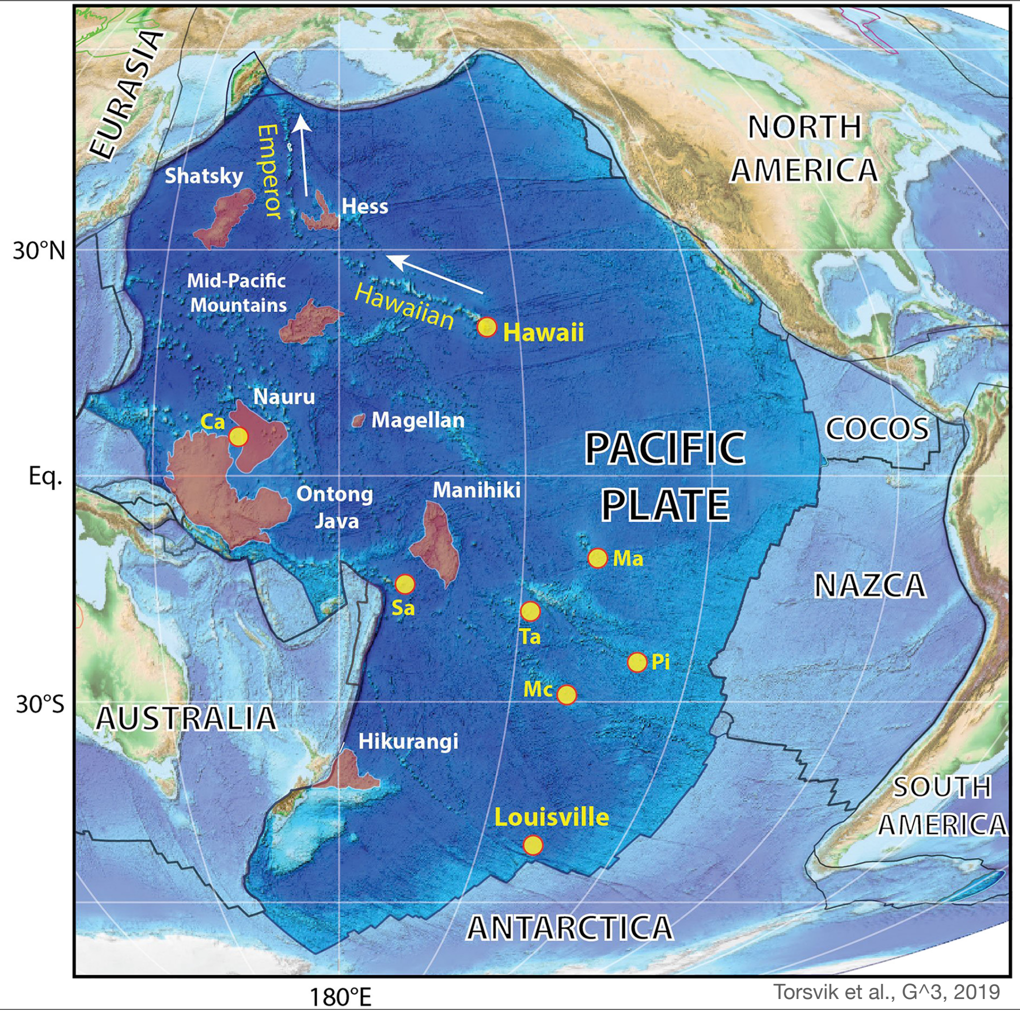


Saylor et al., JGR, 2020

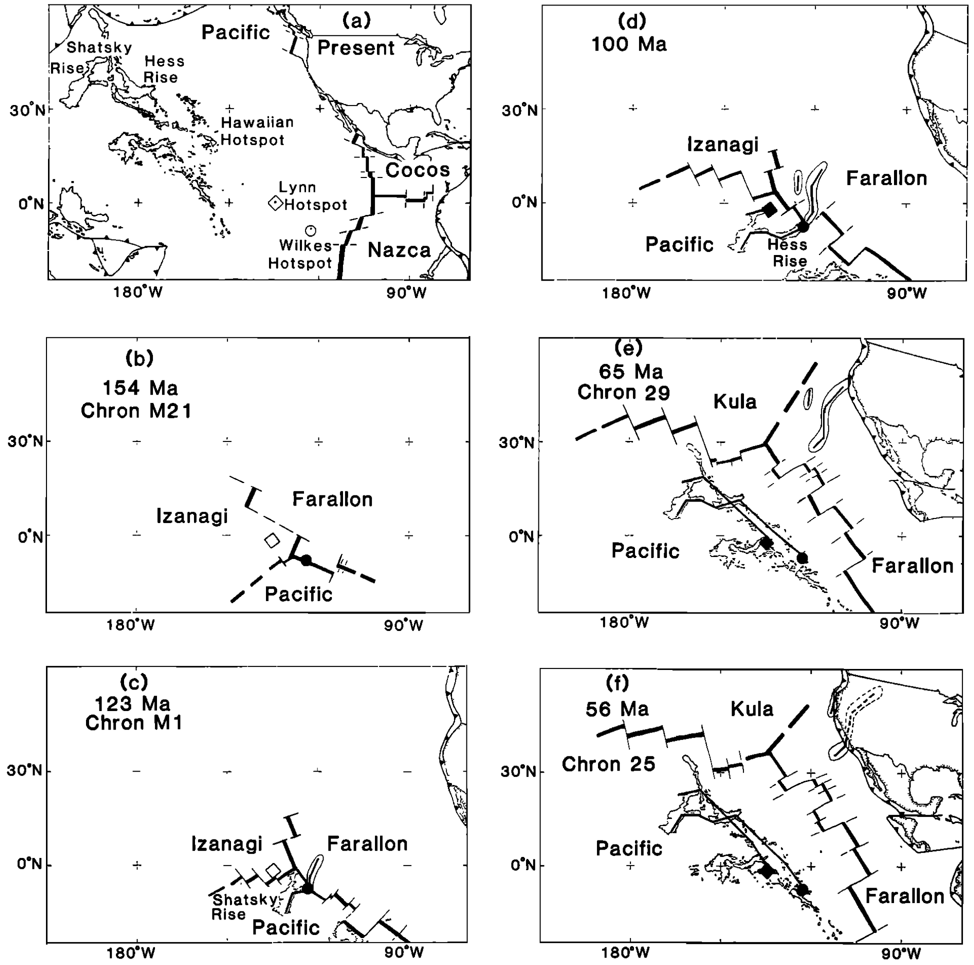
Is there a material change to the lithosphere from shallow subduction?
Attempts to measure flexural rigidity at different times—often in different places at different times. Argues that the change from Cenomanian to Campanian is due to a change in lithospheric strength. Clearly points 6 & 7—with huge error bars—are crucial to this—eastern Green River Basin and Wind River Basin.

Plateau subduction

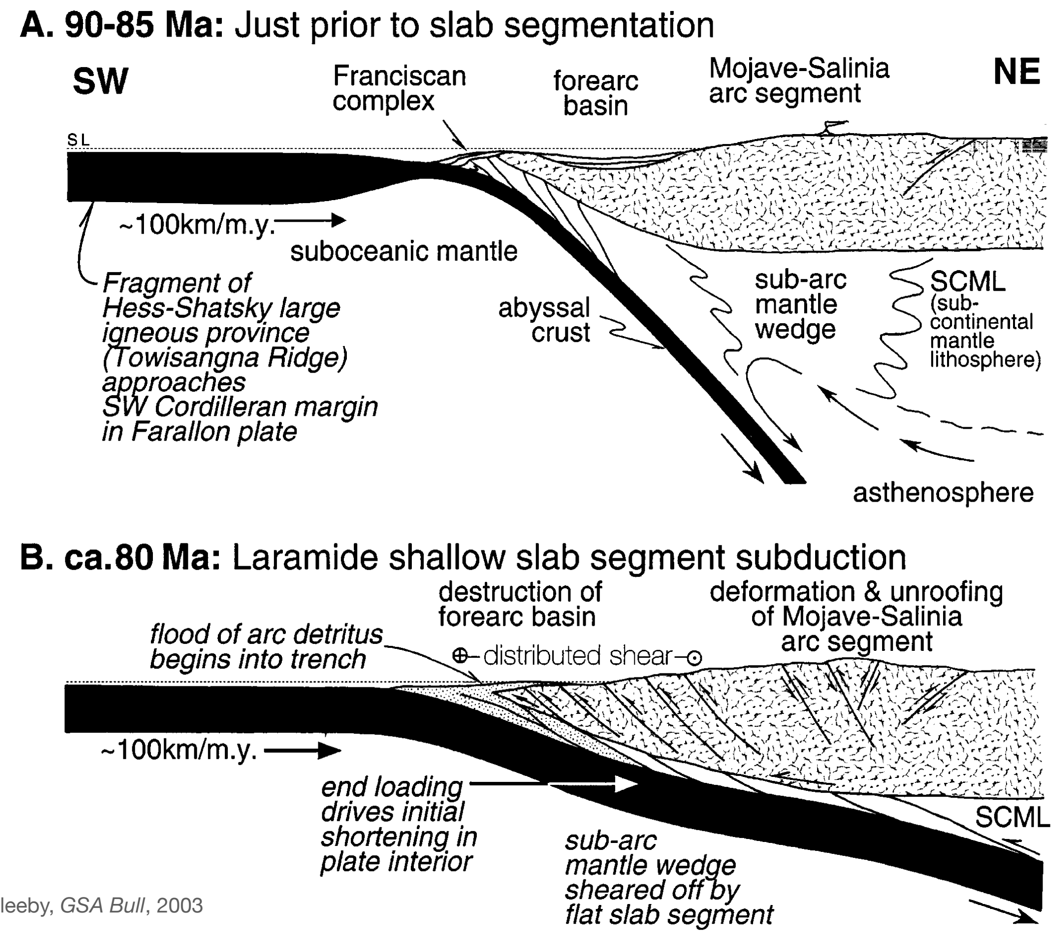
attractive possibility in some other ways?



Torsvik et al., G^3, 2019

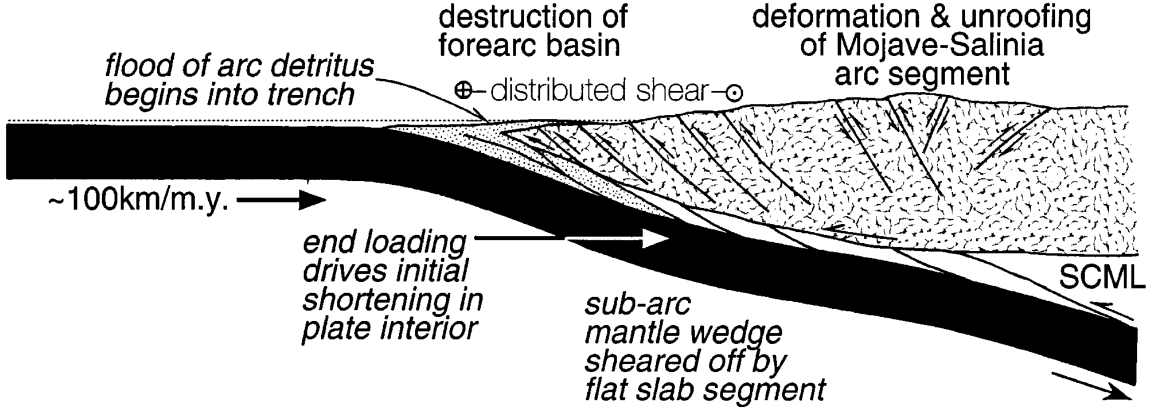


Henderson et al., *Tectonics*, 1984



Saleeby, *GSA Bull*, 2003

B. ca.80 Ma: Laramide shallow slab segment subduction


destruction of forearc basin

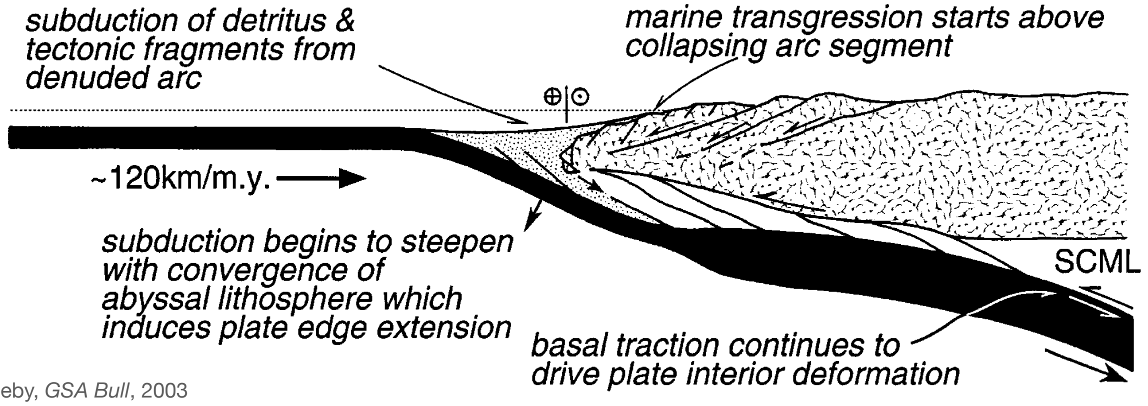
deformation & unroofing of Mojave-Salinia arc segment

flood of arc detritus begins into trench

end loading drives initial shortening in plate interior

sub-arc mantle wedge sheared off by flat slab segment

C. ca.70 Ma: Extensional collapse starts in wake of shallow slab segment

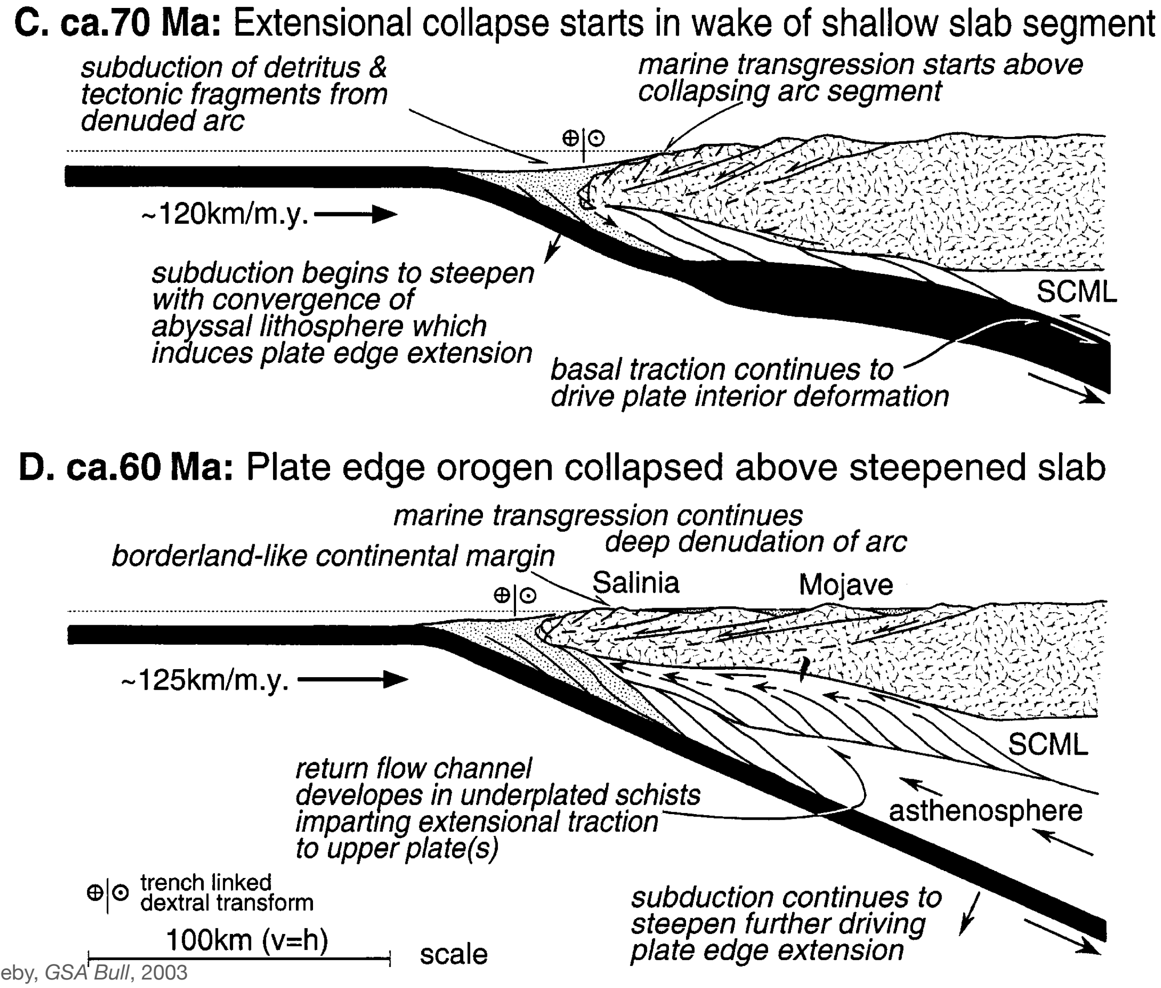

subduction of detritus & tectonic fragments from denuded arc

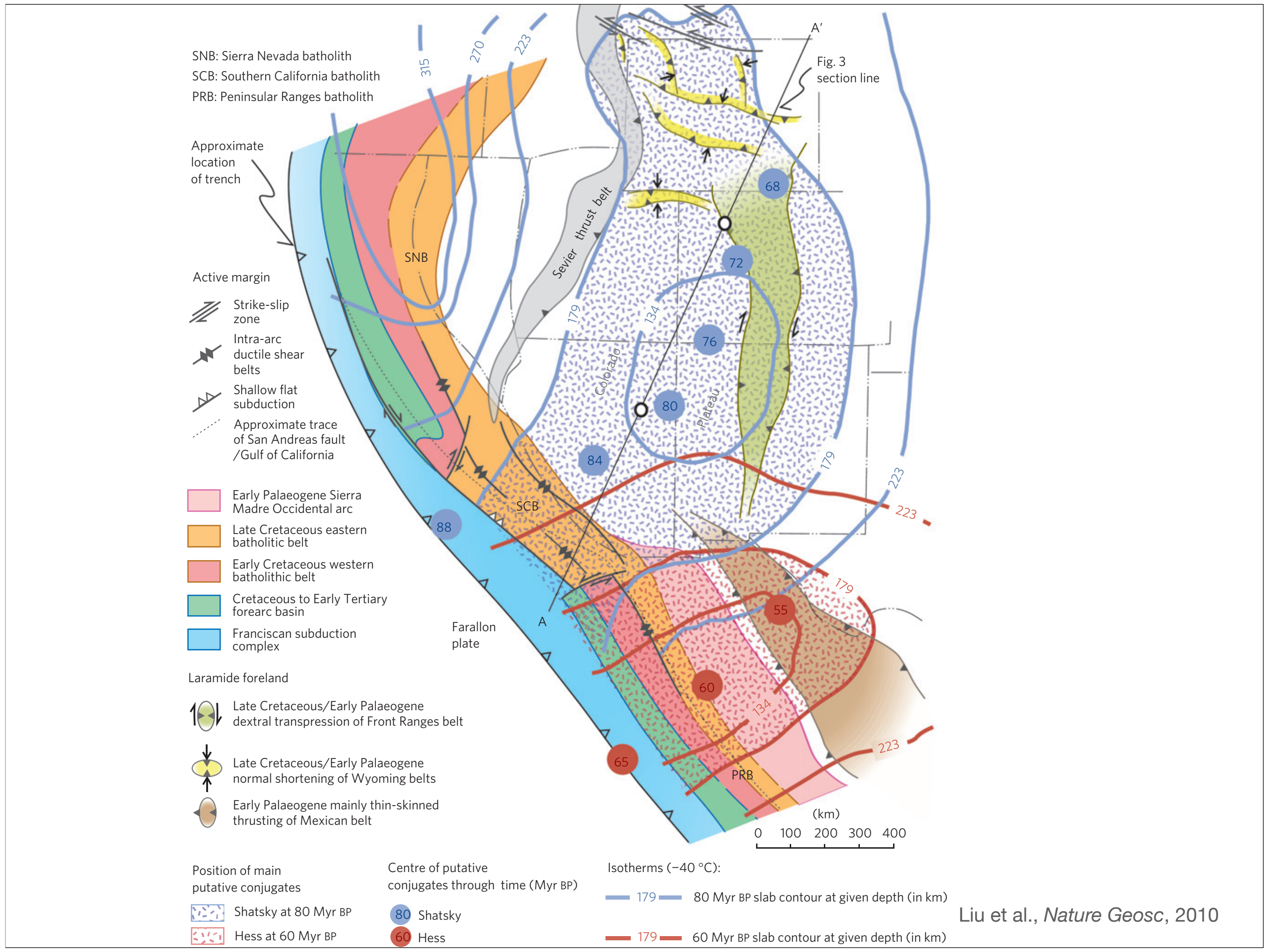
marine transgression starts above collapsing arc segment

subduction begins to steepen with convergence of abyssal lithosphere which induces plate edge extension

basal traction continues to drive plate interior deformation

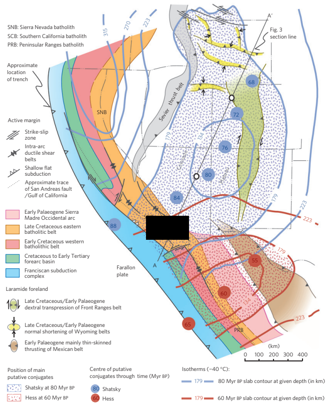
Saleeby, *GSA Bull*, 2003



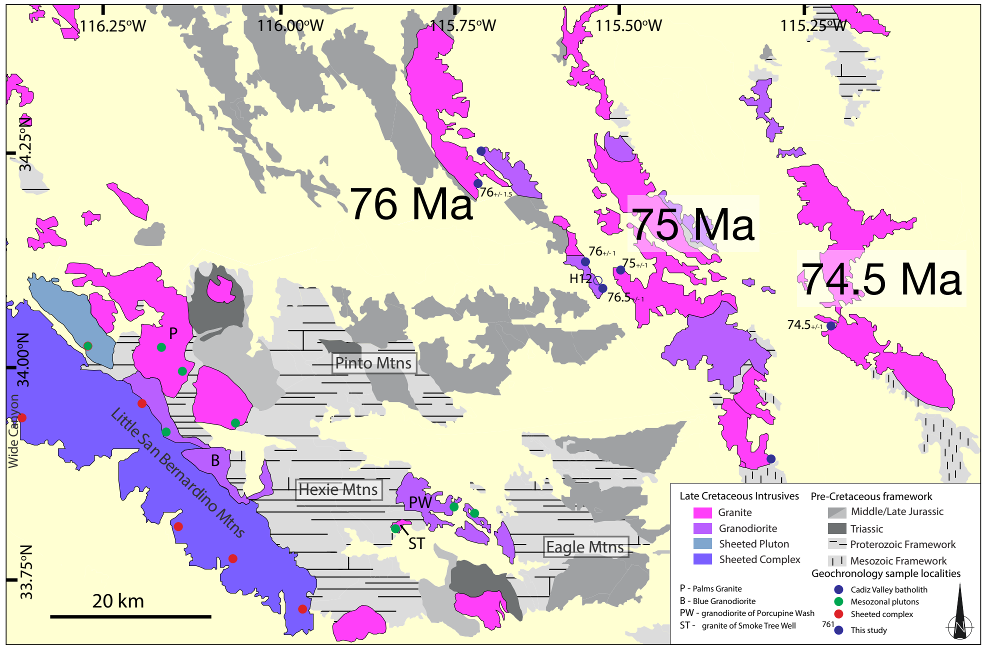


Liu et al., *Nature Geosc*, 2010

Keep in mind timing problems…

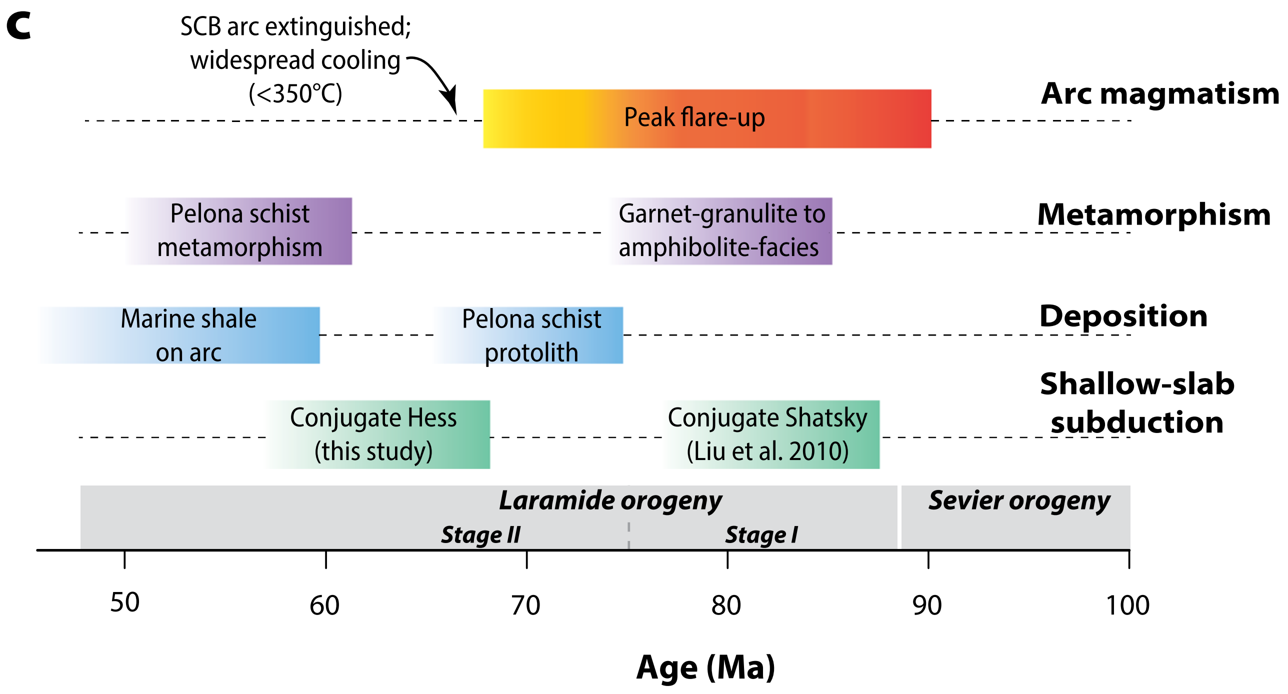


Liu et al., *Nature Geosc*, 2010



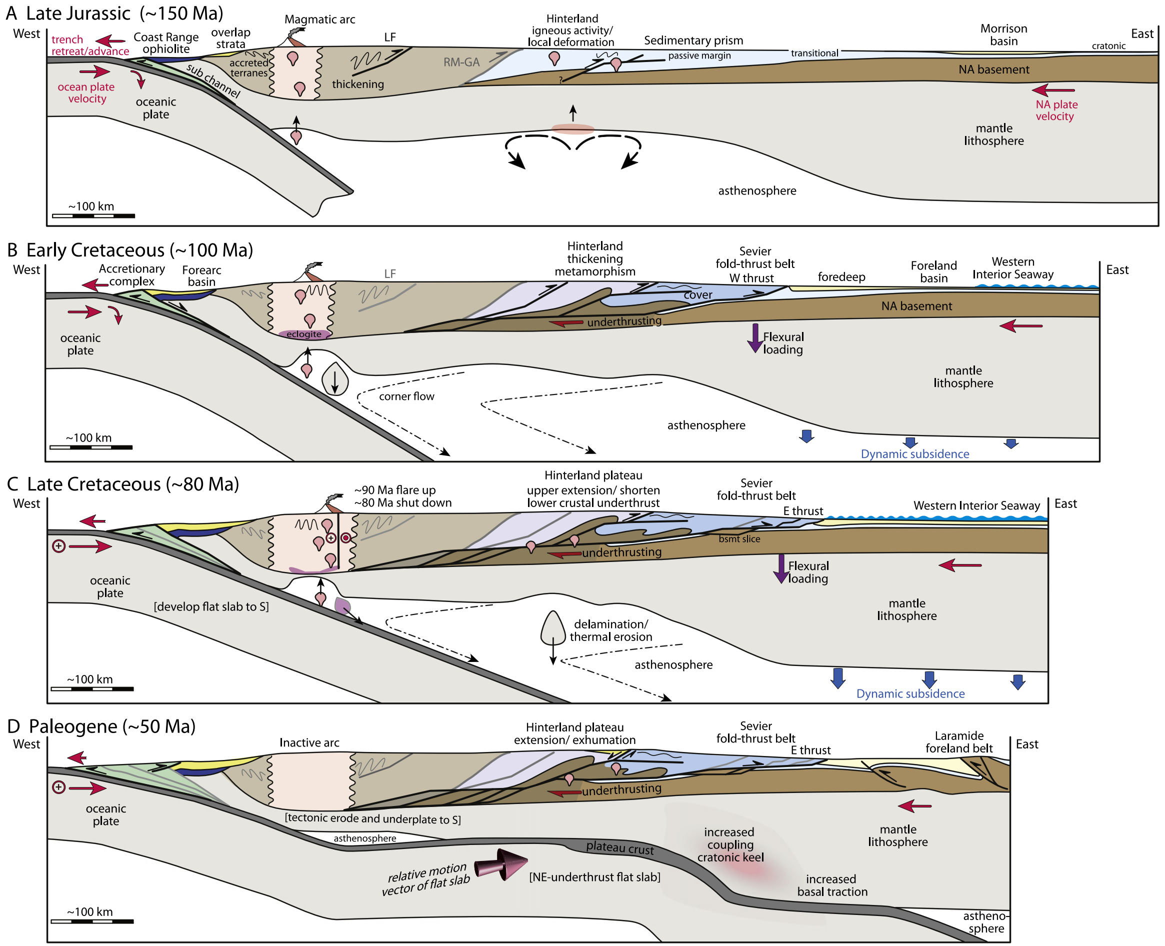
Economos et al., *Geosphere*. 2021

Keep in mind timing problems…



Schwartz et al., *Nat. Comm.*. 2023

SCB = Southern California Batholith (Mojave and pieces on west of SAF)



Yonkee & Weil, *Earth Sci Rev*, 2015