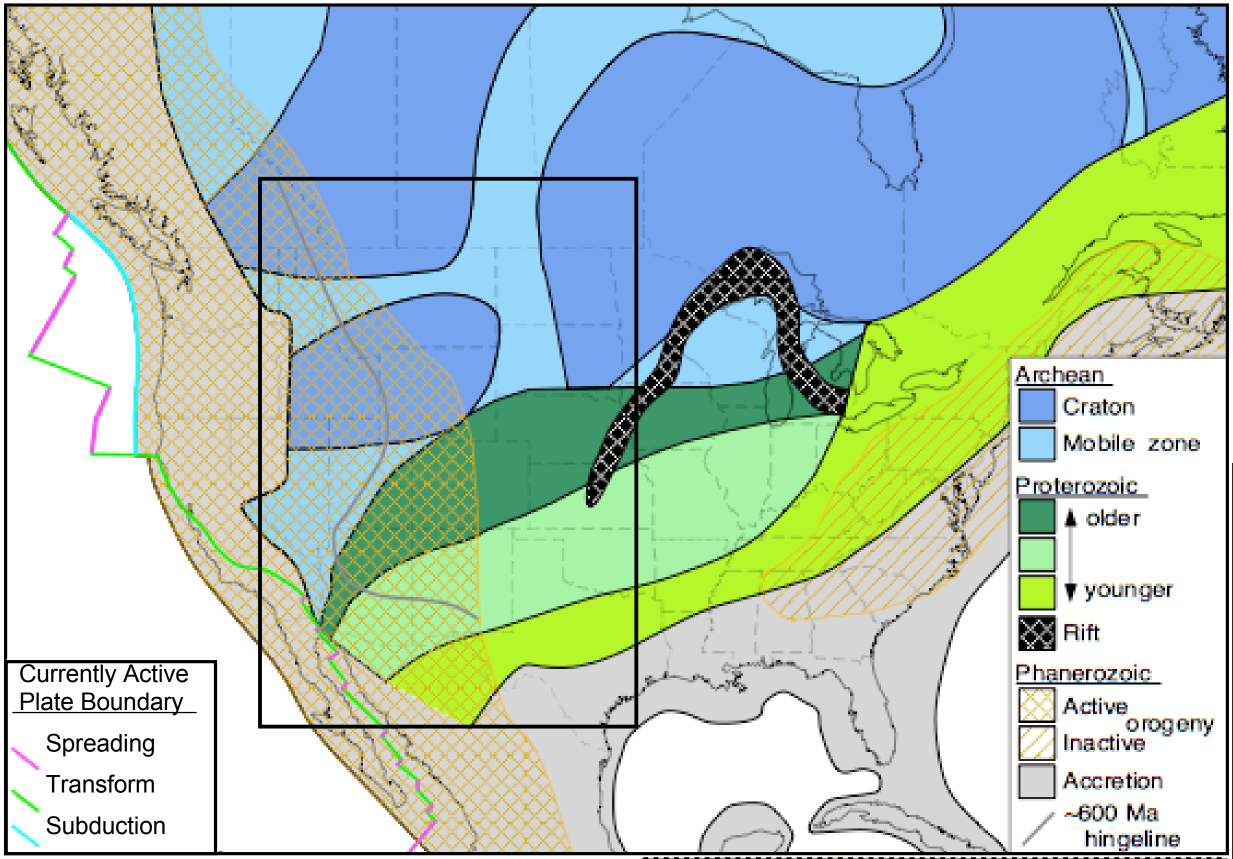
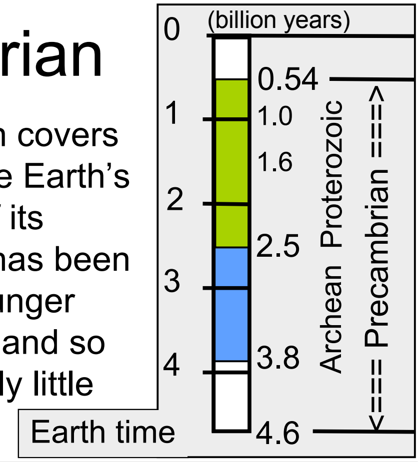
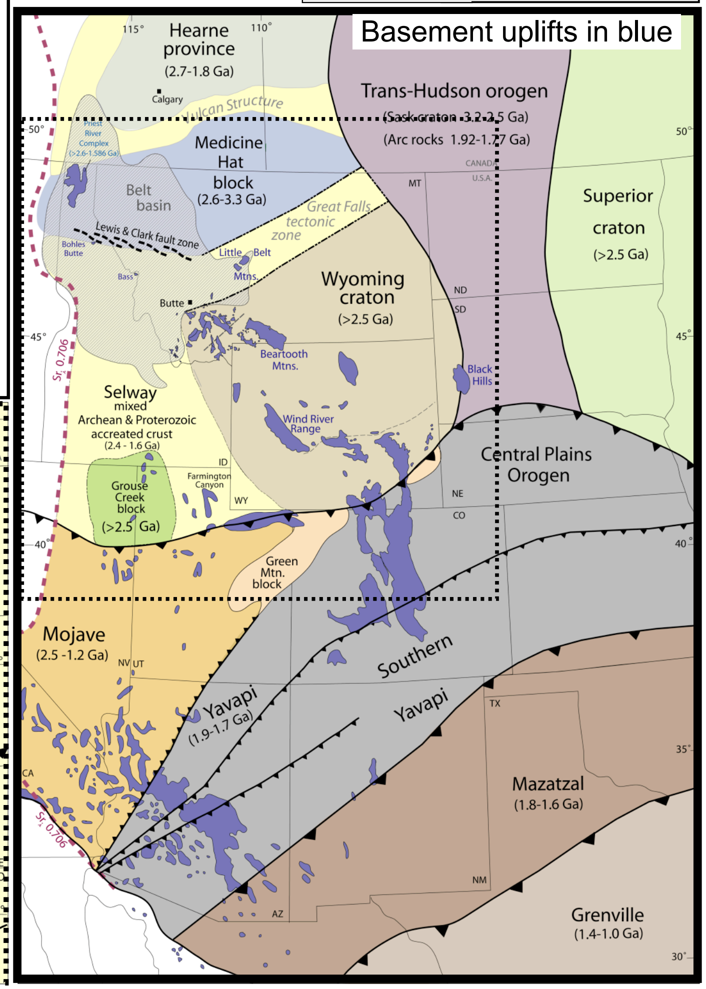


Precambrian

The Precambrian covers about 88% of the Earth's age, but much of its geologic record has been destroyed by younger geologic events, and so we know relatively little about it.



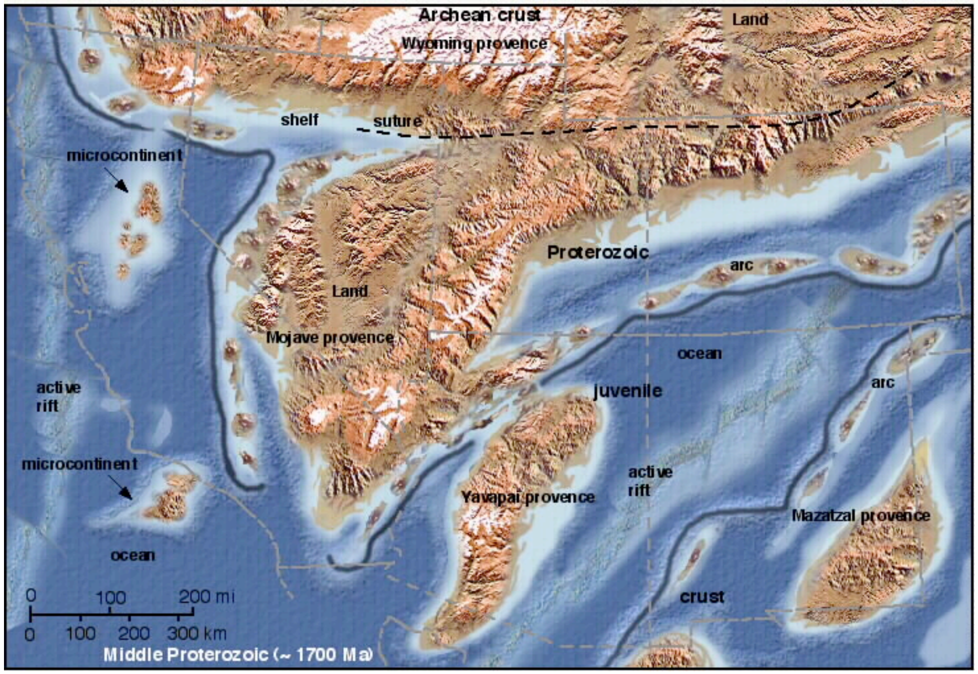


Archean (blue areas) is typified by blocks of craton (dark) and mobile belts (light), which are suture zones, where the craton blocks were joined, and often are old volcanic arcs.

These mobile belts remained weak, and were reactivated repeatedly through geologic time (even recently, as shown at right; thrust faults and crustal melting (purple) in mobile belt).

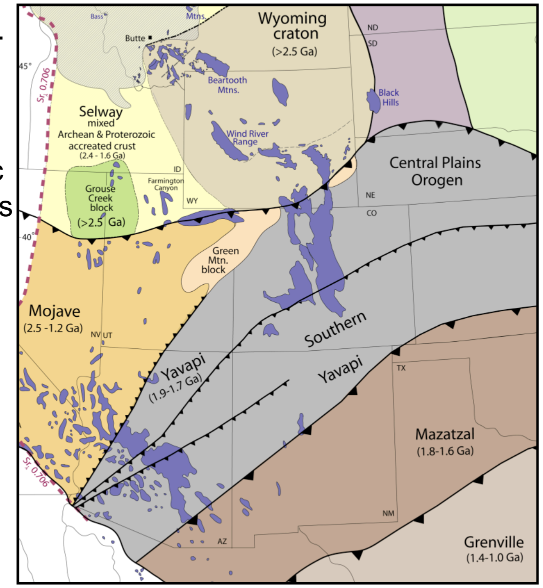
Proteozoic belts (green areas) were accreted to the southern continental margin. Most of these belts were volcanic arcs that accreted to the margin.

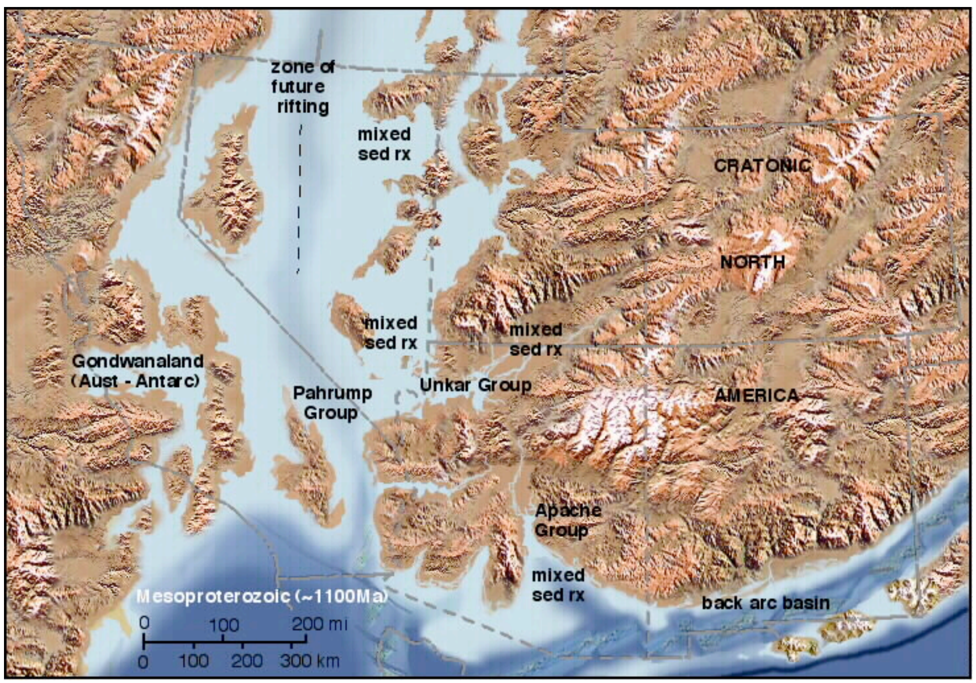
The continent then rifted along its western margin, truncating the Archean and Proterozoic structures.



Proterozoic (~1.7 Ga)

A speculative reconstruction. The Archean/Proterozoic Mojave province is accreted to the Archean Wyoming province, and the Proterozoic Yavapi and Mazatal provinces are about to be accreted as the ocean lithosphere is consumed
at the subduction zones
(the dark blue lines).

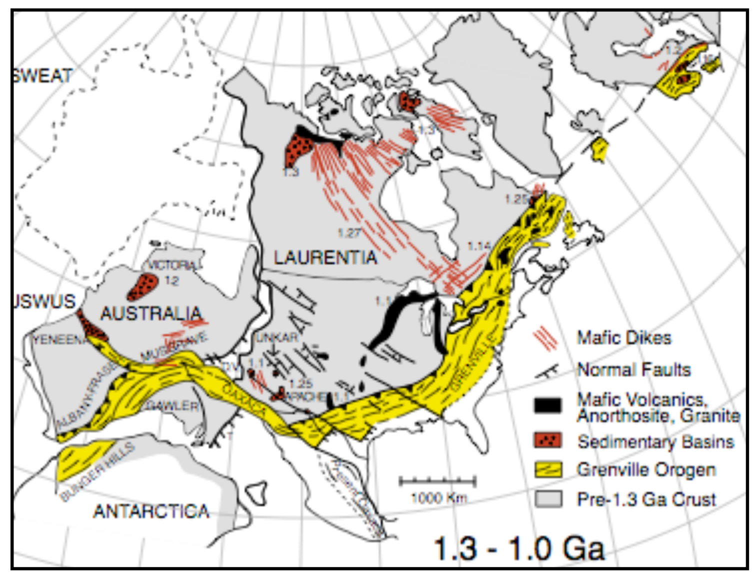


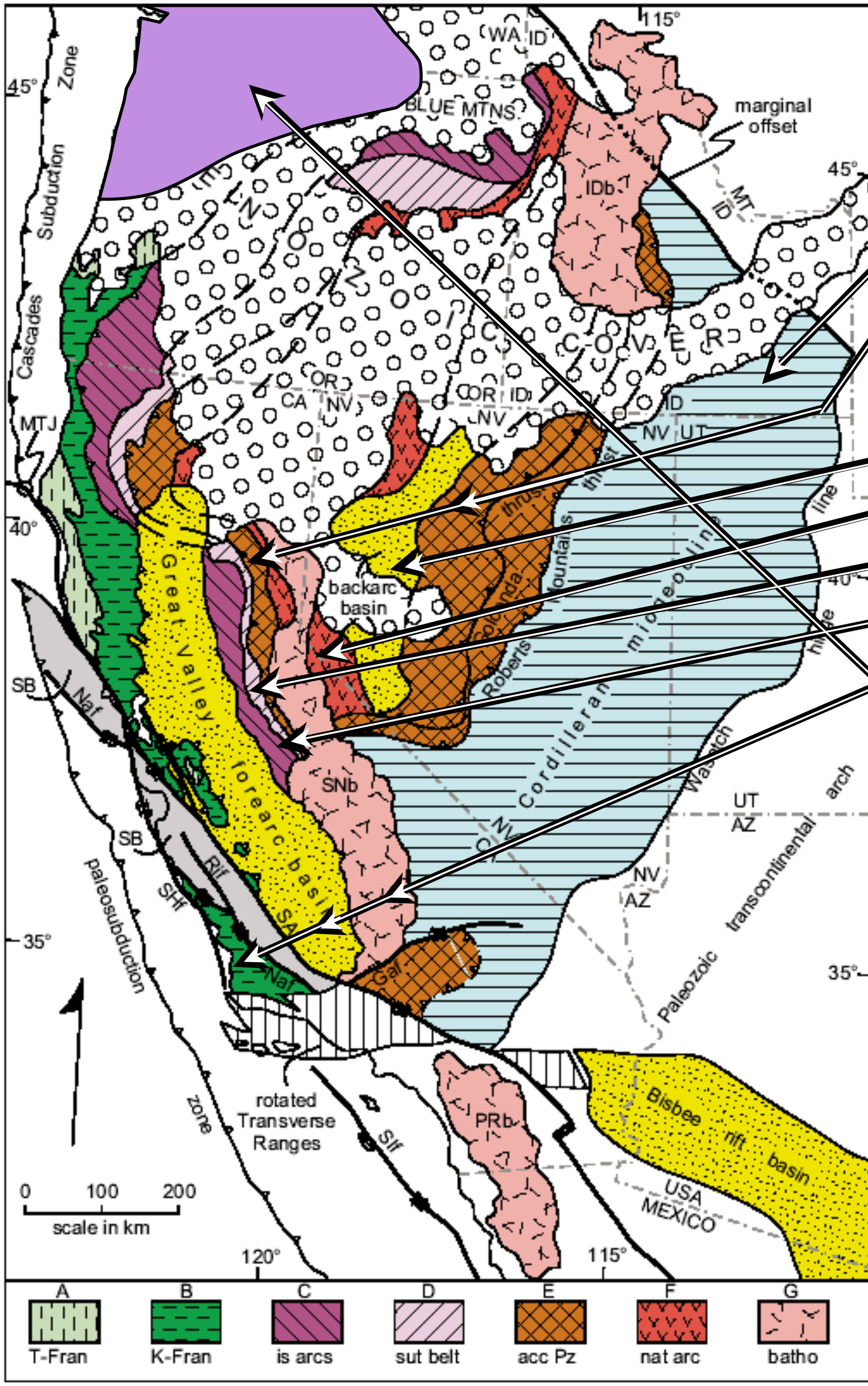


Proterozoic (~1.1 Ga)

North America was part of supercontinent Rodinia and possibly was adjacent to Australia. At left, Grenville accretion has not occurred yet.

Location of the future rifting (at 570 m.y. ago) is indicated.





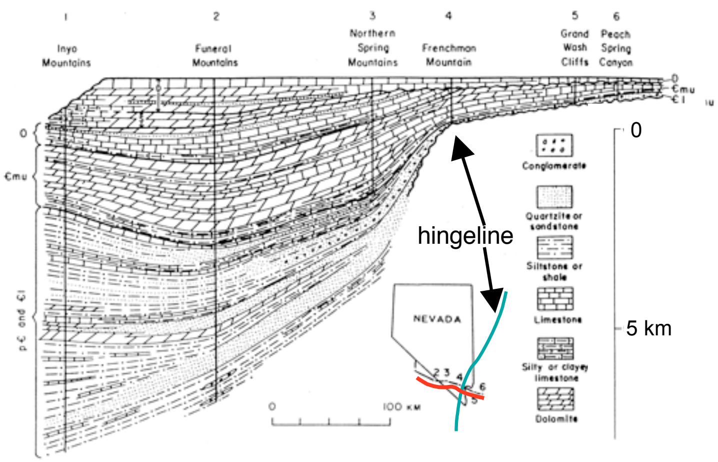
Modern setting of Phanerozoic Cordilleran terranes

East to West Transect

- Cordilleran Miogeocline
- Accreted Paleozoic. Roberts Mtn. and Golconda thrust sheets + arc fragments in Sierra Nevada and Klamath Mountains
- “Backarc Basin” - LFTB – Mudpile
- pre-Sierran “Native Arc”
- Suture Belt
- Accreted island arcs
- K-age batholiths/Great Valley/Franciscan
- Siletzia ocean lithosphere

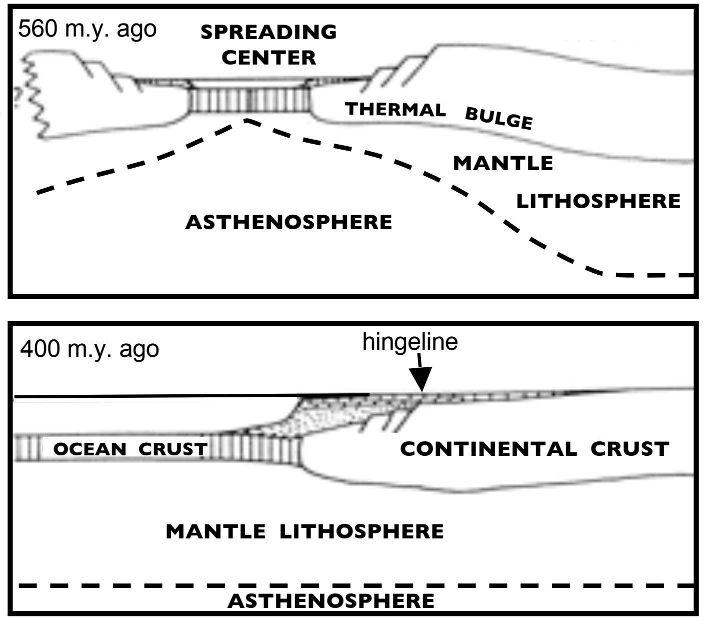
Dickinson (2008; Geosphere)

The Miogeocline (western U.S., 600-380 m.y. ago)



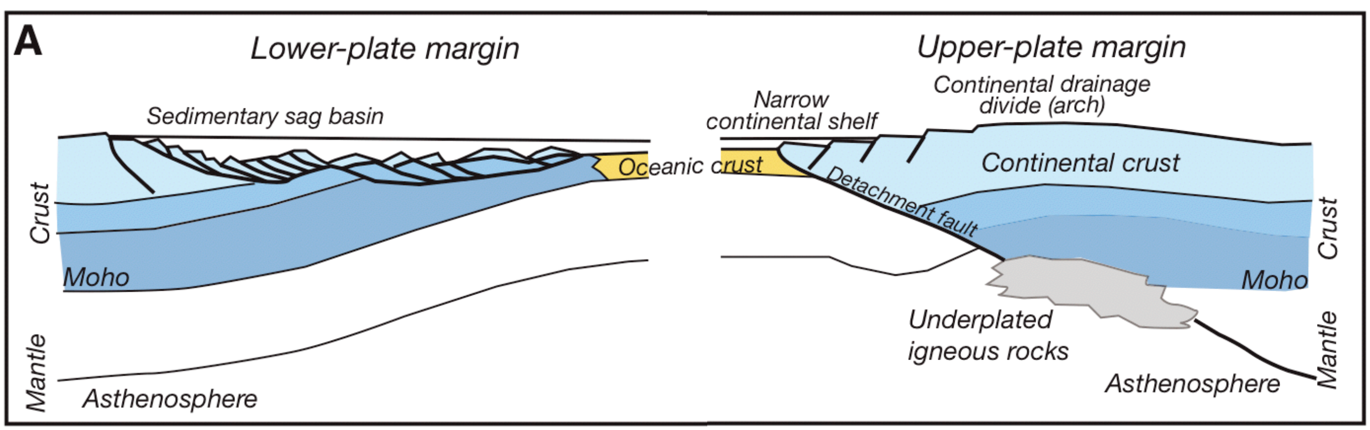
pC	Precambrian
Cl	lower Cambrian
Cmu	middle and upper Cambrian

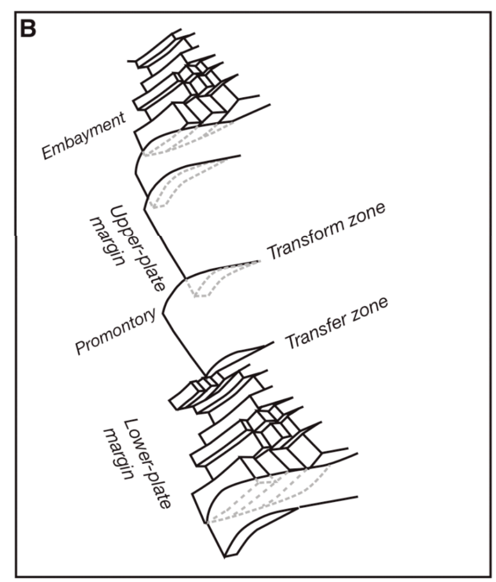
Cross section from the thin platform sediments east of the hingeline to the thick wedge of of sediment to the west.
Cross section follows the red line across the hingeline.



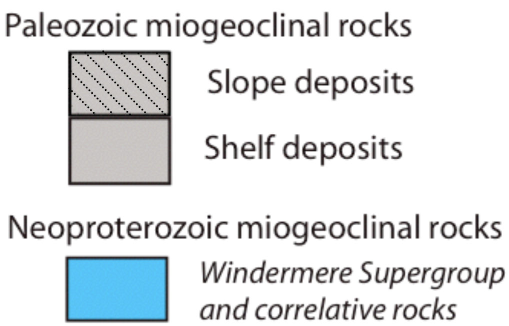
Creation of the Atlantic-type margin of the western U.S. in the youngest Precambrian and oldest Paleozoic.

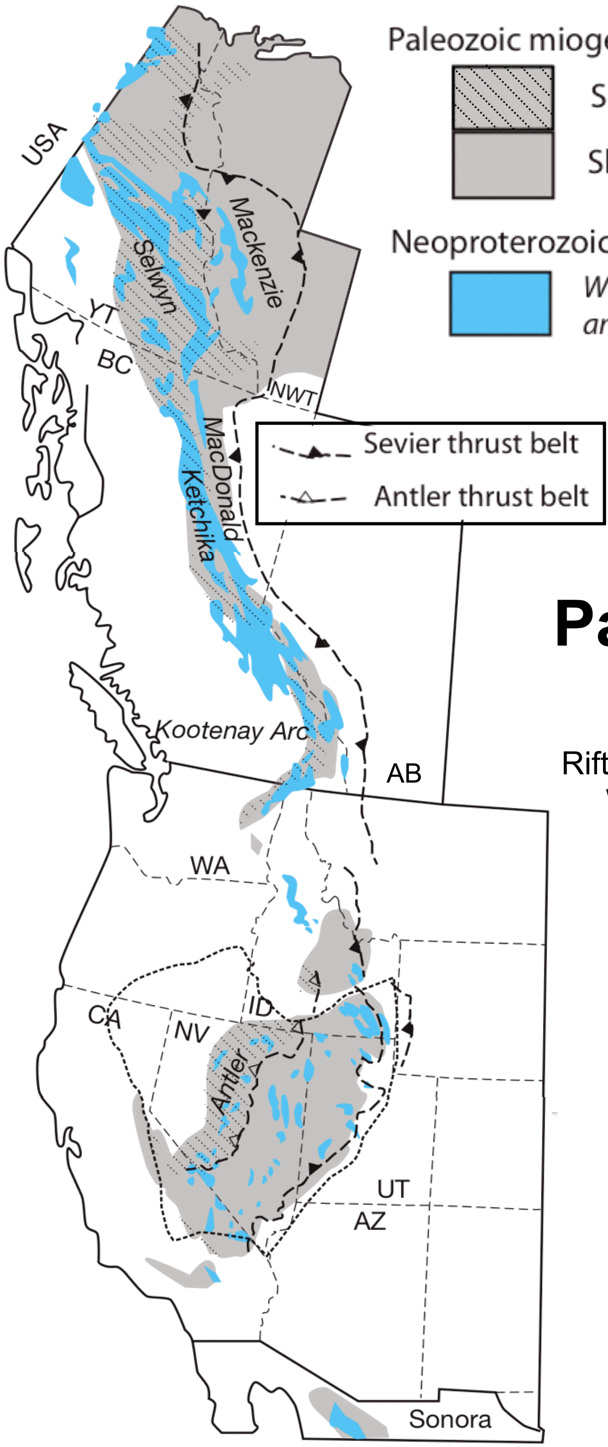
The 570 m.y. old rifting event created a passive "Atlantic-type" continental margin, characterized by the creation of the "wedge" of sediment (shown far left) that was deposited during the oldest part of the Paleozoic (until about 370 m.y. ago). This often is referred to in the literature as the miogeocline. The creation of the miogeocline is shown to the left, and was the subject of the 3/31 in-class exercise.





Continental rifting creates two kinds of rift margin, each with distinctive characteristics. Segments of plate margin typically are separated from each other by transform faults. The lower plate margin slid out from beneath the upper plate margin. The characteristics of these different types of plate margin are used by Lund (next page) to describe the western U.S. margin rifted 600 m.y. ago.

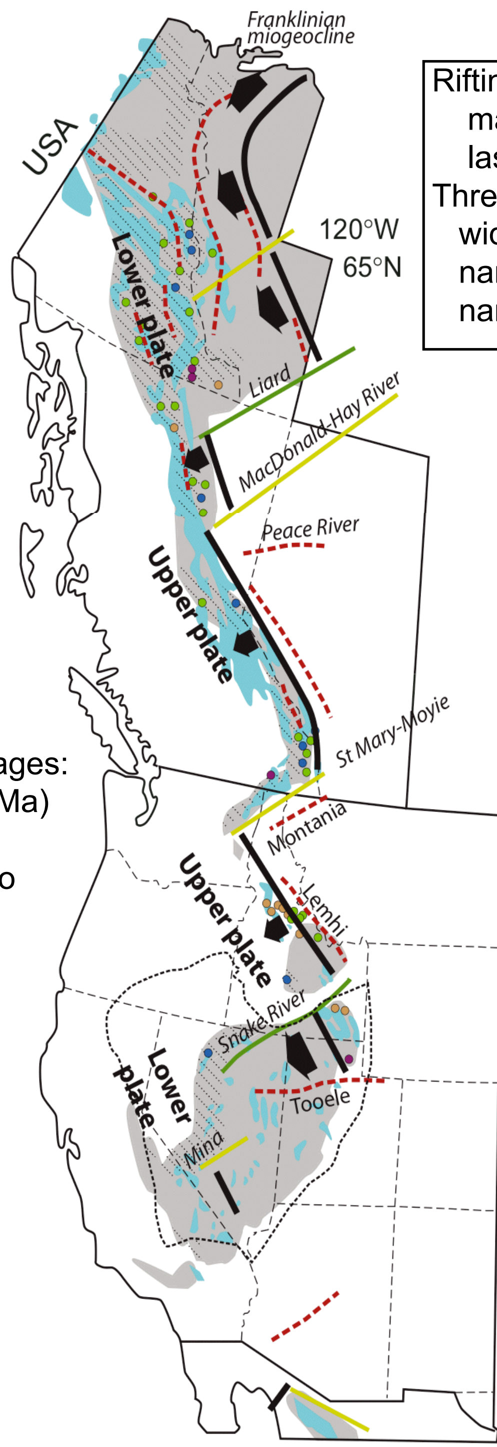




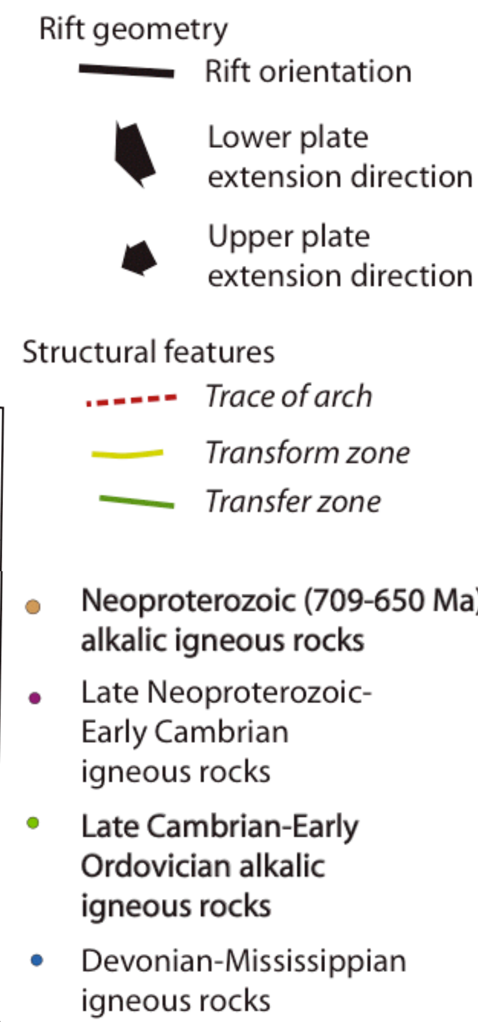
Paleozoic

Passive margin

Rifting occurred in two stages:
- Windemere (700-650 Ma)
  - Rifting formed large basins but did not go to completion.
- Main Rift (~570 Ma)
  - This completed rifting, and made ocean plate west of North America.

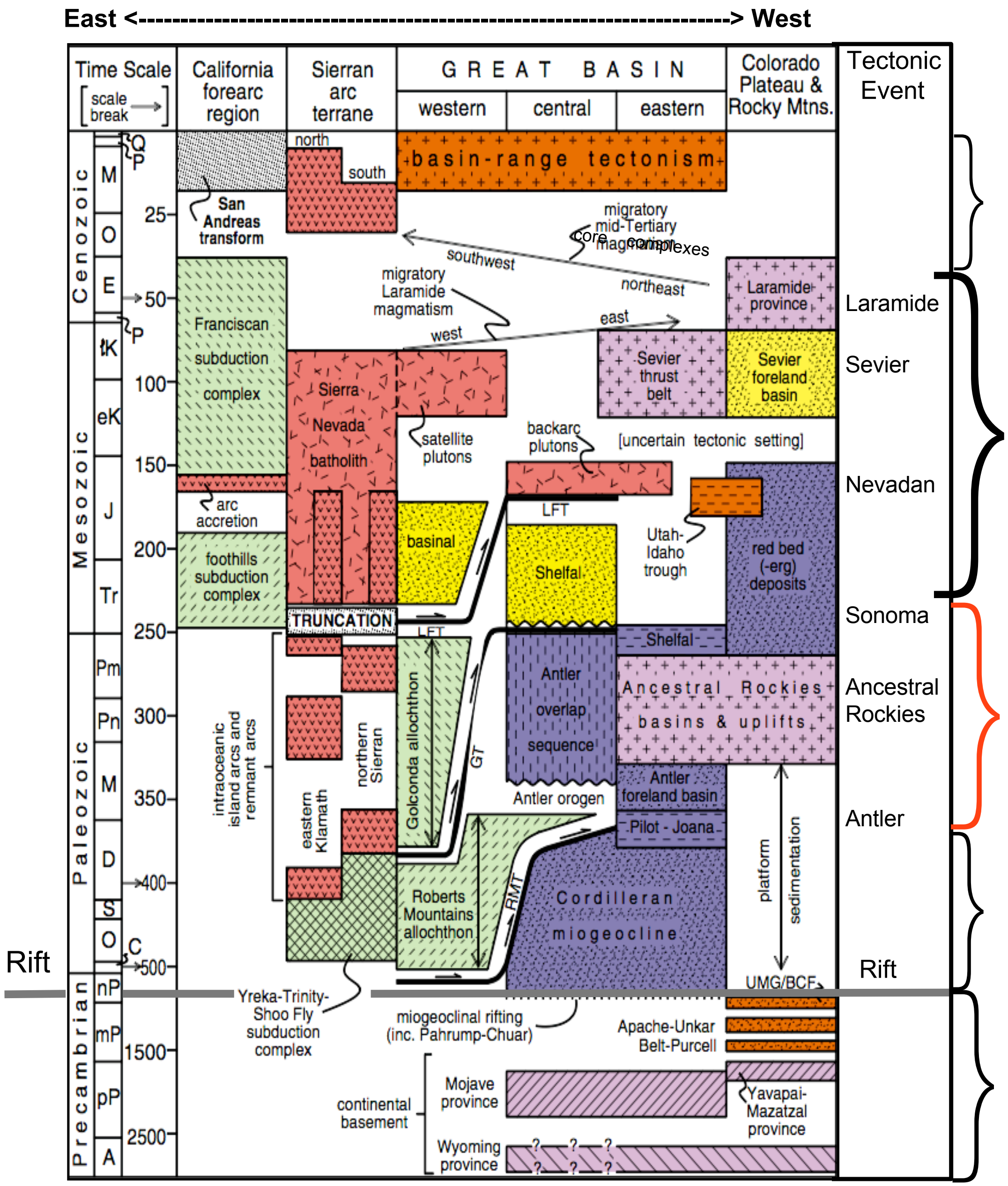


Rifting made a zig-zag continental margin that more-or-less has lasted to the present.
Three types of margin are created:
- wide lower plate margin
- narrow upper plate margin
- narrow transform/transfer zones.

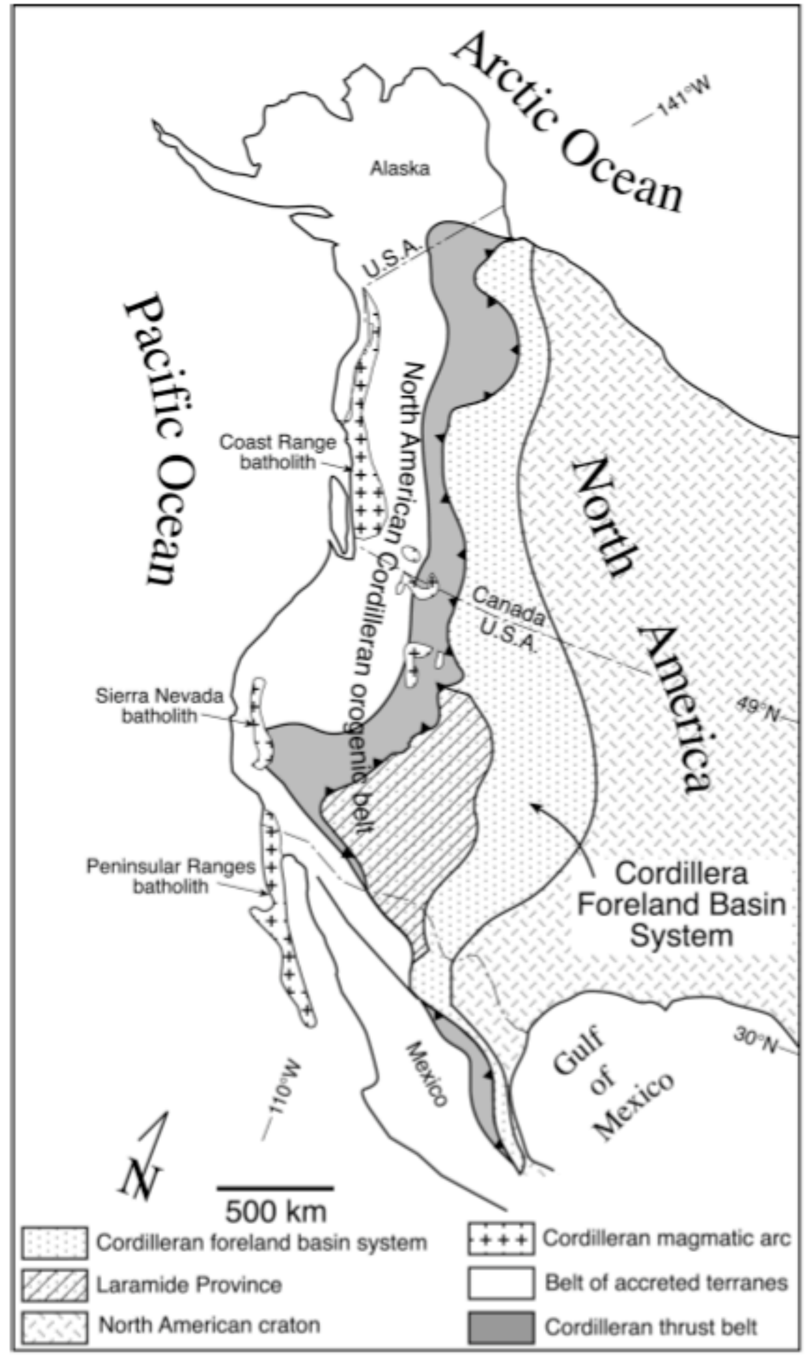


Post-rift rebuilding the western U.S.

Dickinson (2006)



Time-space diagram of lithic assemblages in the Great Basin and adjoining areas (note time-scale breaks at 50 Ma, 400 Ma, and 500 Ma). The rectangle labeled truncation denotes schematically the completion of continental truncation along the Permian-Triassic California-Coahuila transform and subsequent initiation of the Mesozoic-Cenozoic Cordilleran continental-margin magmatic arc. Key thrusts: GT—Golconda; LFT—Luning-Fencemaker; RMT—Roberts Mountains. UMG/BCF—Uinta Mountain Group and Big Cottonwood Formation.



Antler orogeny (370 m.y. ago)

Paleozoic thrusting

Sonoma orogeny (250 m.y. ago) and **Transform truncation**

Ancestral Rockies (300 m.y. ago)

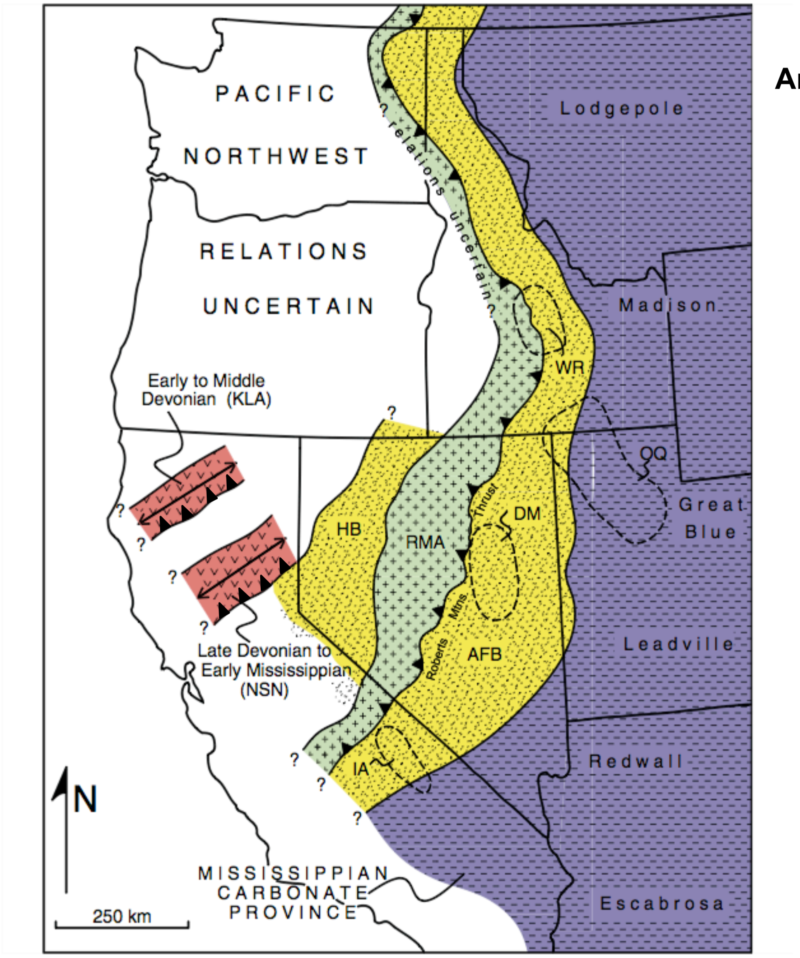


Figure 4. Syn-Antler (Devonian-Mississippian) and post-Antler but pre-Sonoma paleotectonic map of the Great Basin and adjacent areas. The relative positions of an intraoceanic frontal arc in the northern Sierra Nevada (NSN) and its paired remnant arc in the eastern Klamath Mountains (KLA) are uncertain. Double-headed arrows denote the NE-SW tectonic trends of Paleozoic island-arc elements oriented at a high angle to the Mesozoic-Cenozoic continental margin of California (Dickinson, 2000). Key tectonic elements in Nevada (west to east): HB—Havallah basin; RMA—Roberts Mountains allochthon (capped by the Antler overlap sequence); AFB—Antler foreland basin. Formational names indicate local components of the Mississippian carbonate province. Dashed outlines denote basins of the Ancestral Rocky Mountains province closest to the Antler thrust front: DM—Dry Mountain; I-A—Inyo-Argus; OQ—Oquirrh; WR—Wood River.

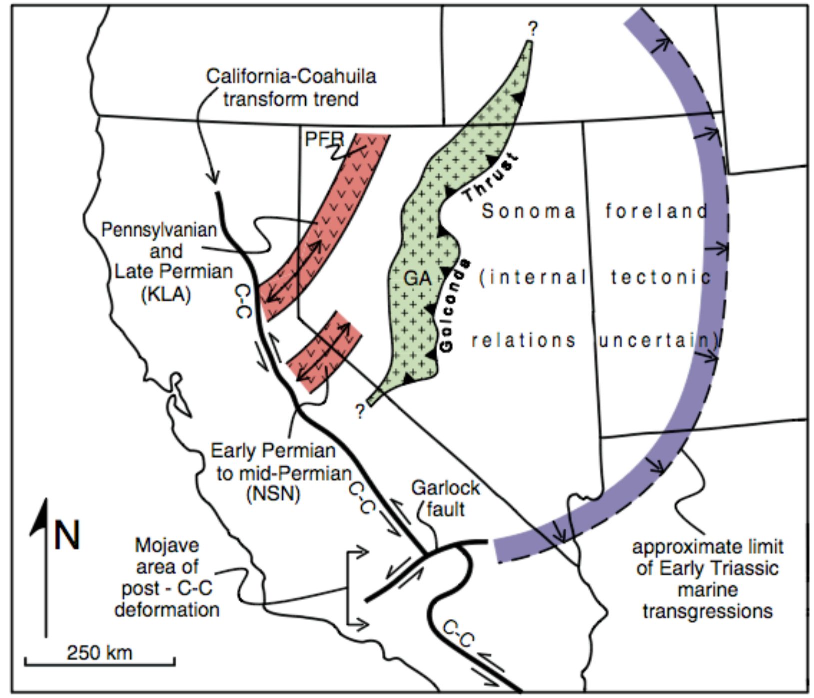


Figure 5. Syn-Sonoma (ca. 250 Ma) paleotectonic map of the Great Basin and adjacent areas (GA—Golconda allochthon) near the Permian-Triassic time boundary during oblique truncation of the Cordilleran continental margin by the California-Coahuila transform (C-C), which is contorted and offset by younger deformation in the Mojave region south of the Garlock fault. Eastern Klamath Mountains (KLA) and northern Sierra Nevada (NSN) arcs and remnant arcs (double-headed arrows denote NE-SW tectonic trends within the island-arc complex) are shifted SSE by 210 km to reverse Early Cretaceous dextral slip along the Mojave–Snow Lake fault, and the Klamath Mountains block is additionally shifted eastward to align with the Sierra Nevada block prior to Early Cretaceous forearc extension (Constenius et al., 2000) and later translation associated with Paleogene clockwise rotation of the Pacific Northwest (Oregon-Washington) Coast Range (see Fig. 8). PFR–Pine Forest Range.

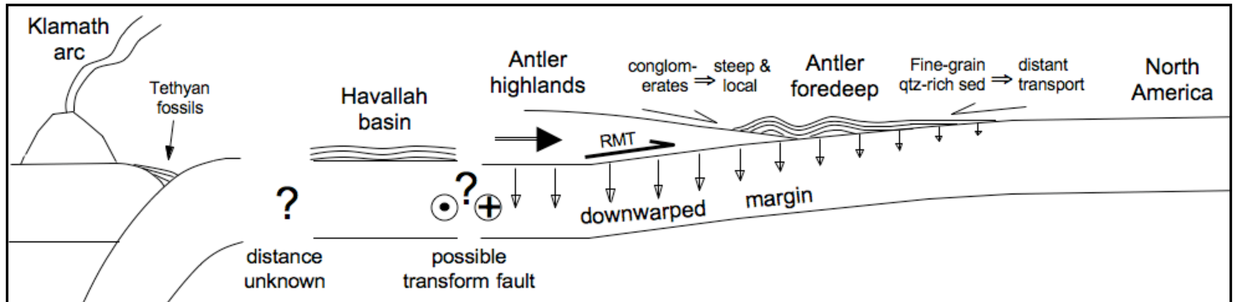
From Dickinson's 2006 summary of western U.S. tectonics, showing key elements of the Antler orogeny and the Sonona orogeny.

The Antler orogeny ended the passive times of of the Atlantic-type margin.
What was this orogeny?

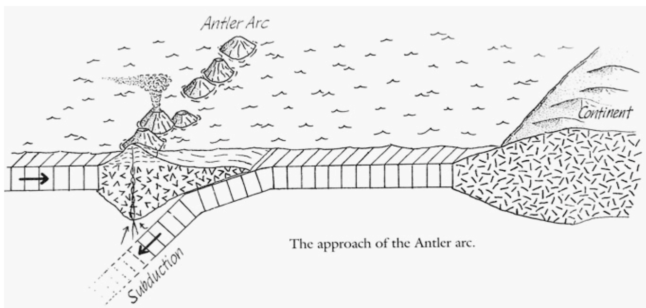
Paleozoic thrusting

The **Antler** orogeny (370 m.y. ago) ended the passive times of of the Atlantic-type margin, when the deep water sediments of the miogeocline were thrust over the shallow water sediments (on the Roberts Mountain thrust fault), and a volcanic arc arrived (fragments of which are found within the Klamath and Sierra Nevada Mountains). The main elements are shown to the right; with time, more information and context has come in.

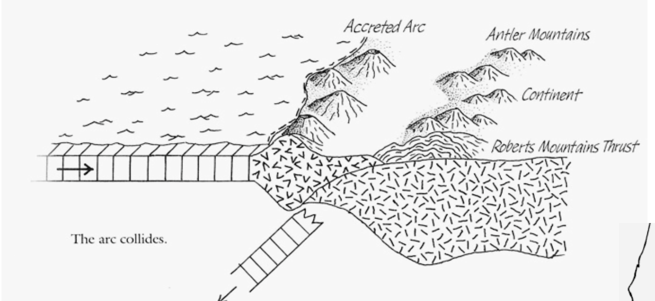
At each step, the available information has been used to propose a model for the Antler, which *tries to explain the data in the simplest manner* (Occam's Razor). Below is the classic story, which has a volcanic arc approaching from the west, which both closes the seaway between the arc and North America and causes volcanism in the arc. The docking of the arc drives thrusting. The Antler thrust sheet rides over the down-warped margin (foredeep) on the Roberts Mountain thrust (RMT above, in blue below).



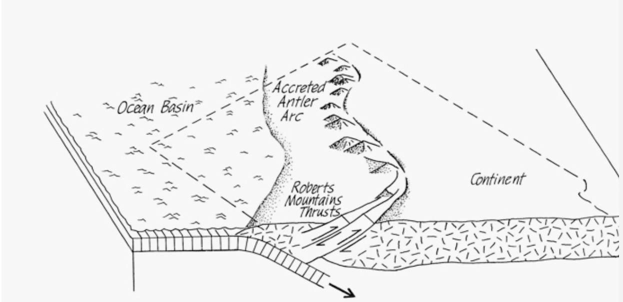
Antler orogeny. A ~370 Ma thrusting event (duration≈10 m.y.) that shoved deep-ocean sediment onto the North American margin. The Antler foredeep filled with sediment derived from both the west and the east… the first time any sediment came from the west. The Klamath arc is the same age, and the Antler orogeny probably represents its convergence onto North America. However, volcanic sediment is absent from the Havallah and Antler basins, suggesting that the Klamath arc was far away. Unlike the fossils in the Havallah and Antler basins (which indicate their proximity to North America) sediments in the Klamath arc accretionary prism have Tethyan fossils (suggesting a distant origin for the Kalamath arc). So, some mysteries.



The approach of the Antler arc.



The arc collides.

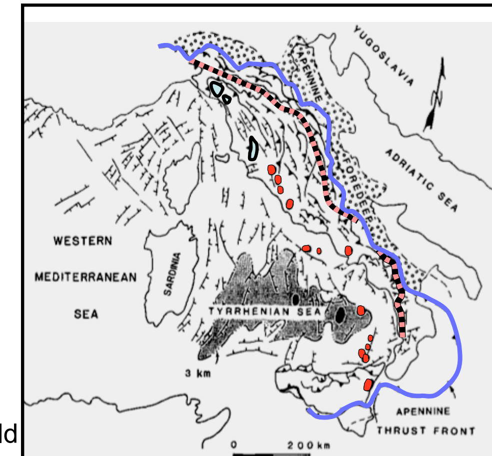


A problem with this model is the presence of the Havallah Basin between the thrust zone and the volcanic arc (that is supposed to be causing the thrusting). When a problem occurs with a model, we have two choices: throw away the old model and make a new one to account for the observations, or modify the existing model so as to accommodate the new observations (*this is common in Earth science-- simple models often fail because actual events are complicated and observations are quite incomplete*). Two suggested solutions to the Havallah basin problem are:

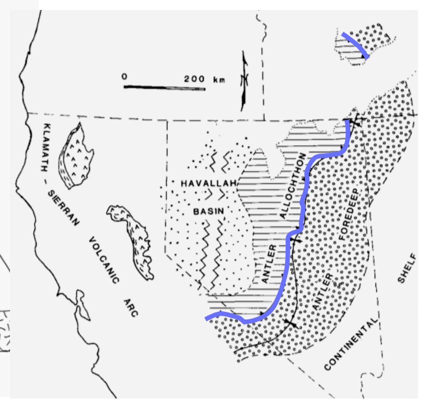
1) A transform fault juxtaposed unrelated elements at a later time (see above figure), and

2) The Antler orogeny was more like the Apennine orogeny currently active in Italy. This is the subject of the 3/31 in-class exercise; its suggestion is derived from working out processes that are currently active, which represents the application of knowledge about the Earth that wasn't available when the classic model was proposed.

(This doesn't mean it is correct, however.)



APENNINE OROGENY, ITALY



A tour of the diverse rocks associated with the Antler orogeny (this page and next)

Above: Sheared and folded deep water sediments of the distal (far west, deep sea) Antler marine basin thrust over and placed on top of the shallow water deposits of the continental margin.
Similar thrusting over the continental edge extended from southern California to Alaska.
We have a good idea that that these sediments were not transported much more than a few hundred kilometers as the sediments contain fossils of North American affinity but, they lack volcanic and arc materials.
To understand the story of what happened when, we rely on the sediments deposited during the orogeny.
The Antler foredeep (between the thrust front and the miogeocline) records the sediments derived from the mountain building event that occurred as the deep-water sediment overrode the shallow sediments.
In the foredeep, we see both sediments derived locally off the topographically high Antler thrust sheet and those from the long traveling continental rivers.
The Antler sediments, transported from the west are composed of conglomeratic deposits composed of cherts, shales and other low-grade metamorphic rocks. This is the first time we see sediments derived from the west-- a feature that indicates the first tectonic activity and mountain building in the west.
Transported from the east, we find finer-grained, quartz-rich sediments that have traveled great distances (during transport, other minerals are eroded away, weathered or deposited, leaving quartz grains preferentially carried over large distances).

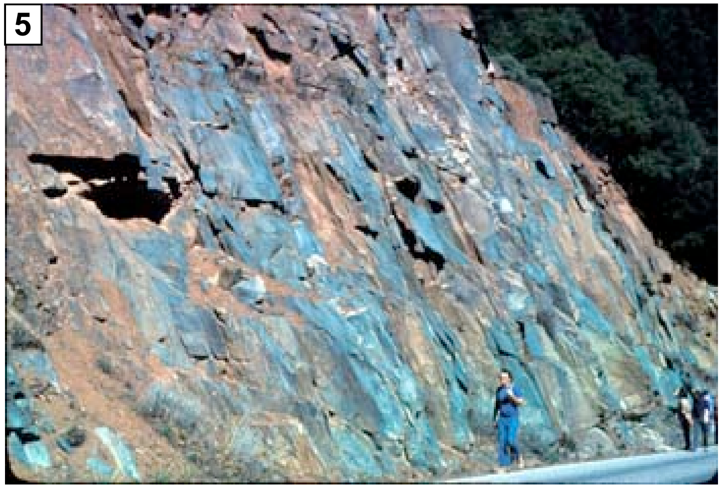
This is a view of the Robert's Mountain thrust contact up close. Above the contact we see the Early Missisppian conglomerates and below we see a thick band of sheared rocks.

To constrain the age of a thrust fault like this, you need to know the age of the youngest rocks in the footwall and the oldest age of the sediments produced by the deformation (the oldest age of the foredeep sediments). For the Roberts Mountain thrust, we know that the fault was active over roughly 10 million years.

If we move west from figure 3, we see the continental margin sediments sourced from the east inter-finger with the conglomerates sourced from the Antler Orogeny in the foredeep.
In the central part of the foredeep, the sediments are 5-6 km thick, but if you go east, out of the foredeep, toward the continentally derived sediments, you find for the same time period sediments that are 300-400m thick.

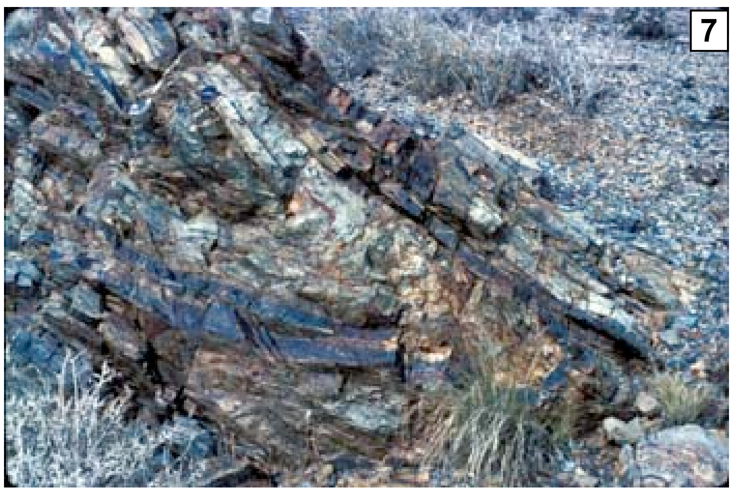
A thick section on the eastern edge of the foredeep where continental sediments and carbonates continued to do be deposited. Here there is no record of the Antler foredeep or orogeny.

This section stolen from: http://ocw.mit.edu/ans7870/12/12.114/f05/gallery/lec3final/pages/lec3photo1.html



An arc of the same age as the Antler orogeny, now found in the Klamath Mountains, was active somewhere west of North America. This image shows ashes and sediments related to this arc.
Although these volcanically derived deposits were created at the same time as the Antler, there are no evidence of ashes or volcanic fragments in the Antler-related sediments, suggesting that the Arcs were still far away from the edge of North America during Antler time.

Student contemplating the rocks further west of the Klamath arc. This is the ocean floor upon which the Arc was deposited. The structurally lowest rocks we find are tectonically layered dunite (olivine-rich) and peridotite (olivine-pyroxene) mantle rocks from below the ocean crust.



Folded carbonates that were deposited in the Havallah basin west of the Antler Orogeny at the time that deformation was occurring. This suggests that there was no major continental or island arc collision that created the Antler Orogeny.

Early Pennsylvanian sediments deposited over the eroded mountains of the Antler Orogeny, suggesting that Antler topography eroded to low relief, and the Antler Orogeny was complete by early Pennsylvanian.

Timing of depositional events around the time of the Antler Orogeny (dates are approximate).
Arc Volcanism continued throughout the time oft the Antler.
Sediment found in the Antler Allochthon experienced active deposition until ~360 Ma.
The filling of the foredeep then starts ~355 Ma, suggesting that the material had been thrust over the sinking continental margin.
By ~350 Ma, we find sediments overlapping the Antler Orogeny, suggesting that it had been significantly eroded.
Note that deposition continues in the Havallah basin east of the arc and west of the developing Antler Mountain belt, suggesting there was no arc collision during Antler time.

Now back to the scientific adjustments that result by obtaining new information. Next comes big changes resulting from what seems like scant data derived from **zircon** crystals.

Zircons

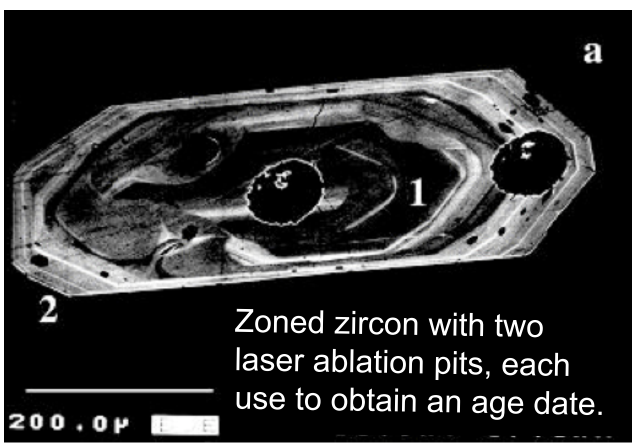
Zircon ($ZrSiO_4$) is created by igneous and metamorphic processes. Zircon incorporates uranium, but not lead, into its crustal structure. This makes it a good mineral to use for uranium-lead dating. Furthermore, it is hard and resists resorbsion when recycled through a magma chamber. Hence, zircons can last just about forever.

As products of erosion they are found as grains in sedimentary rocks, and as such they get recycled into magma chambers where they often develop overgrowth layers. This creates zoned zircons, such as those shown along the bottom. Because uranium and lead almost don't diffuse in zircon, each layer carries information on the age when the layer was created.

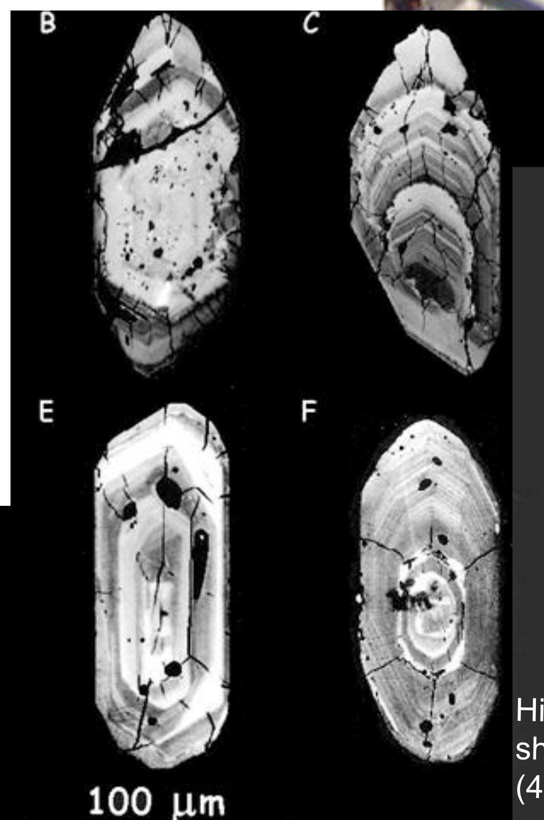
So zircons are durable little time vessels. They can carry a record of old ages when everything else looks young. Indeed, in many locations every rock is made of recycled material and is young, while a zircon speaks of a much earlier history.

When many age dates are obtained from zircons in a sedimentary rock, the age distribution represents an average of the source region that contributed sediment to that rock and can typify that region.

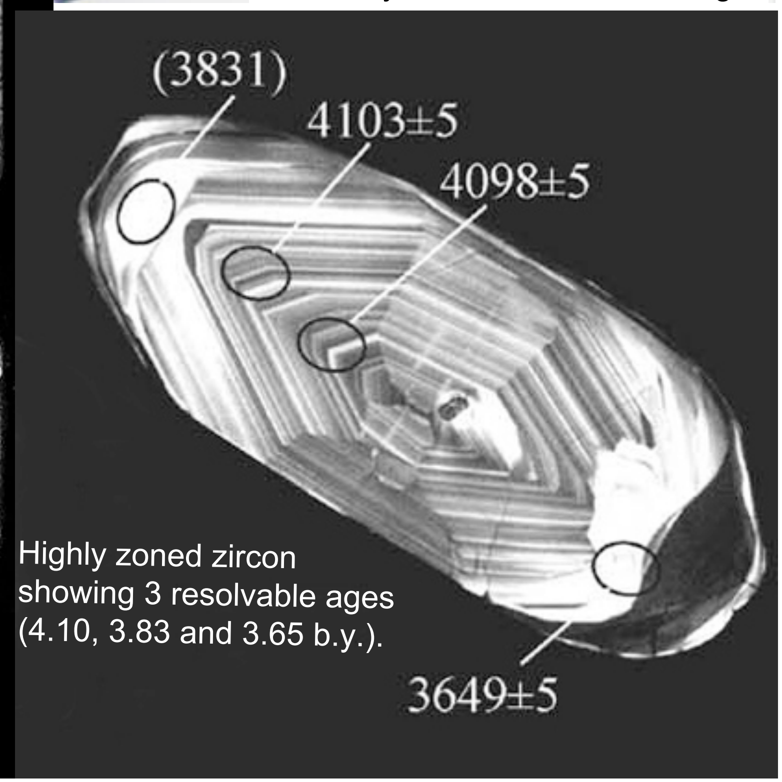
Zircon crystals, seen in normal light



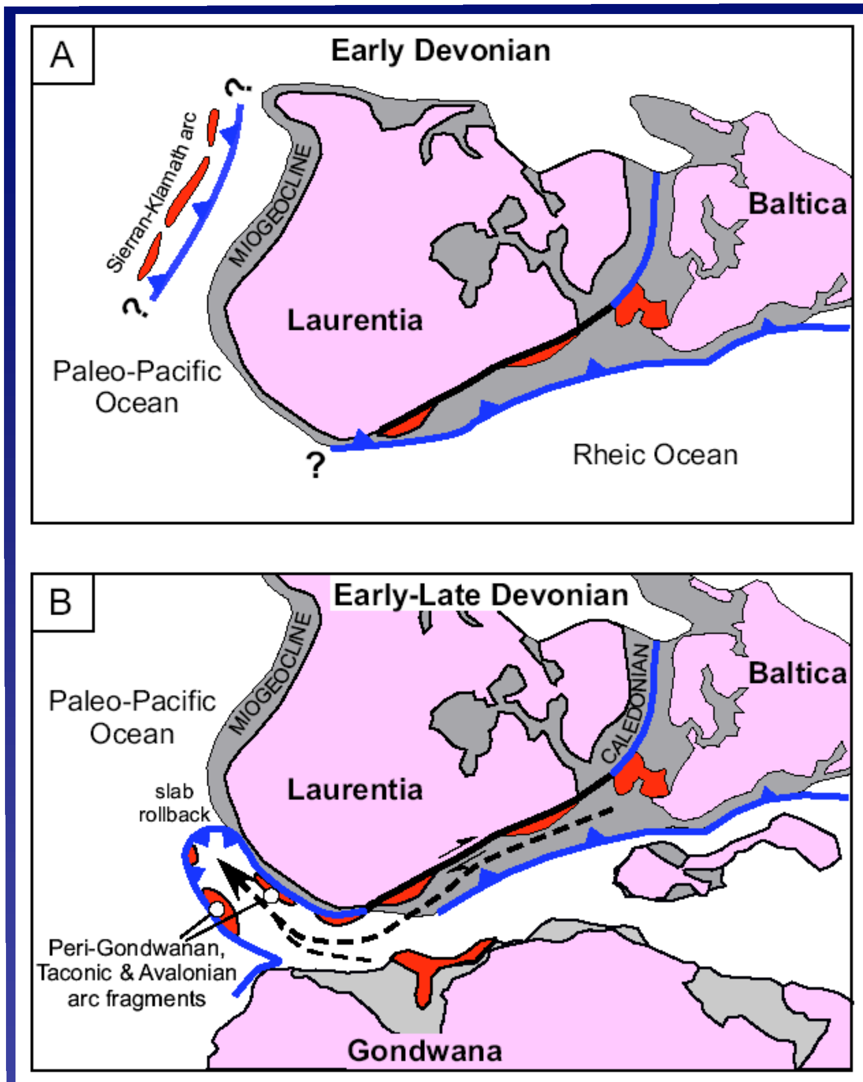
Zoned zircon with two laser ablation pits, each use to obtain an age date.

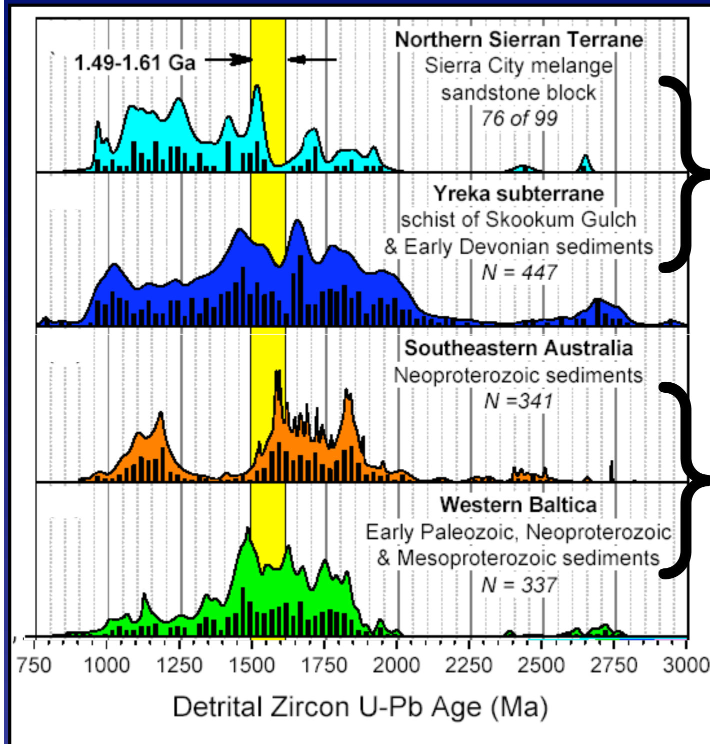


Zircon crystals, imaged with a scanning electron microprobe.



Highly zoned zircon showing 3 resolvable ages (4.10, 3.83 and 3.65 b.y.).





Note: Klamath sediments are ~400 m.y. old, but are derived from material of Precambrian origin

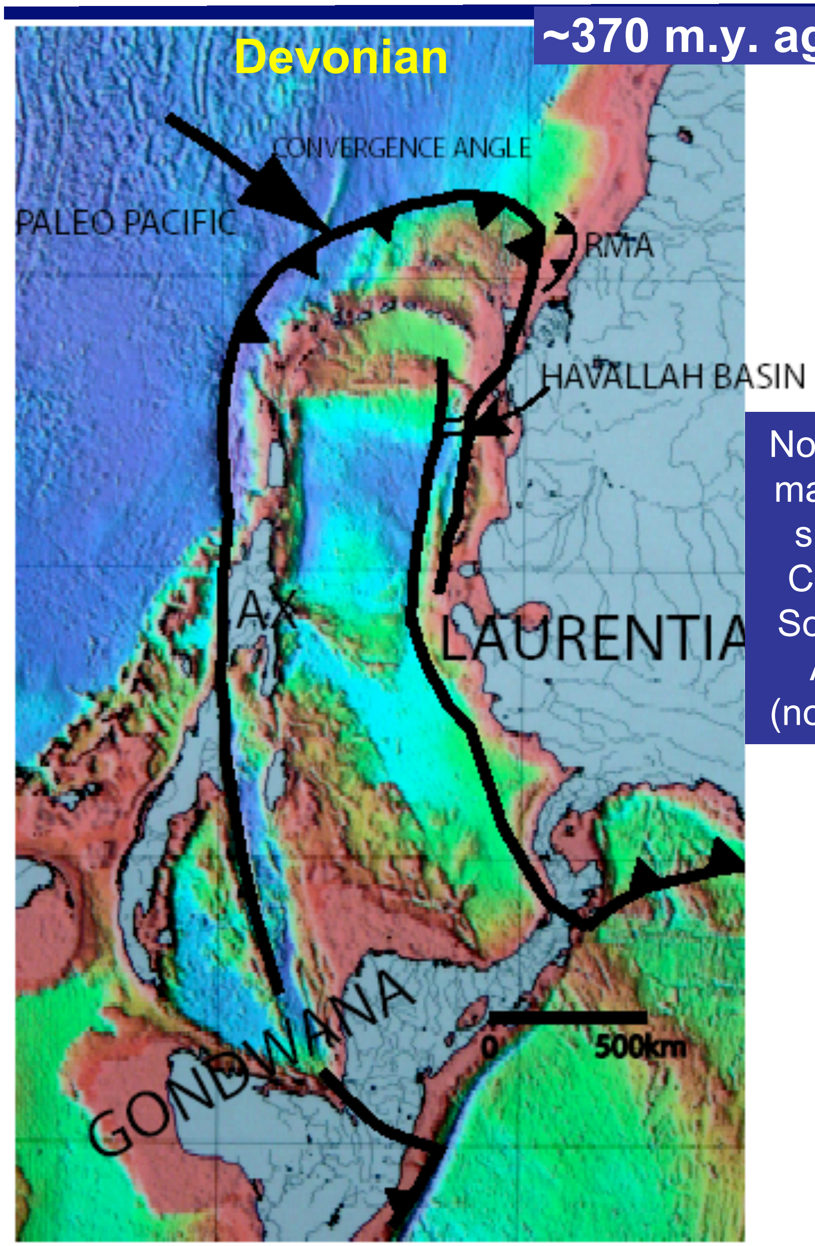
Klamath sediments are more similar to Baltica sediments than to Austrailian sediments.

Grove et al., 2008;
GSA Sp. Pap. 438

The Antler-age portions of the Sierran-Klamath arc originated
(1) near a craton with Archean source material (and not option A above), and
(2) has a zircon age distribution most similar to the Baltica region.
To get an arc transported from Baltic, it is hypothesized that this evolved as a carribean-style arc.

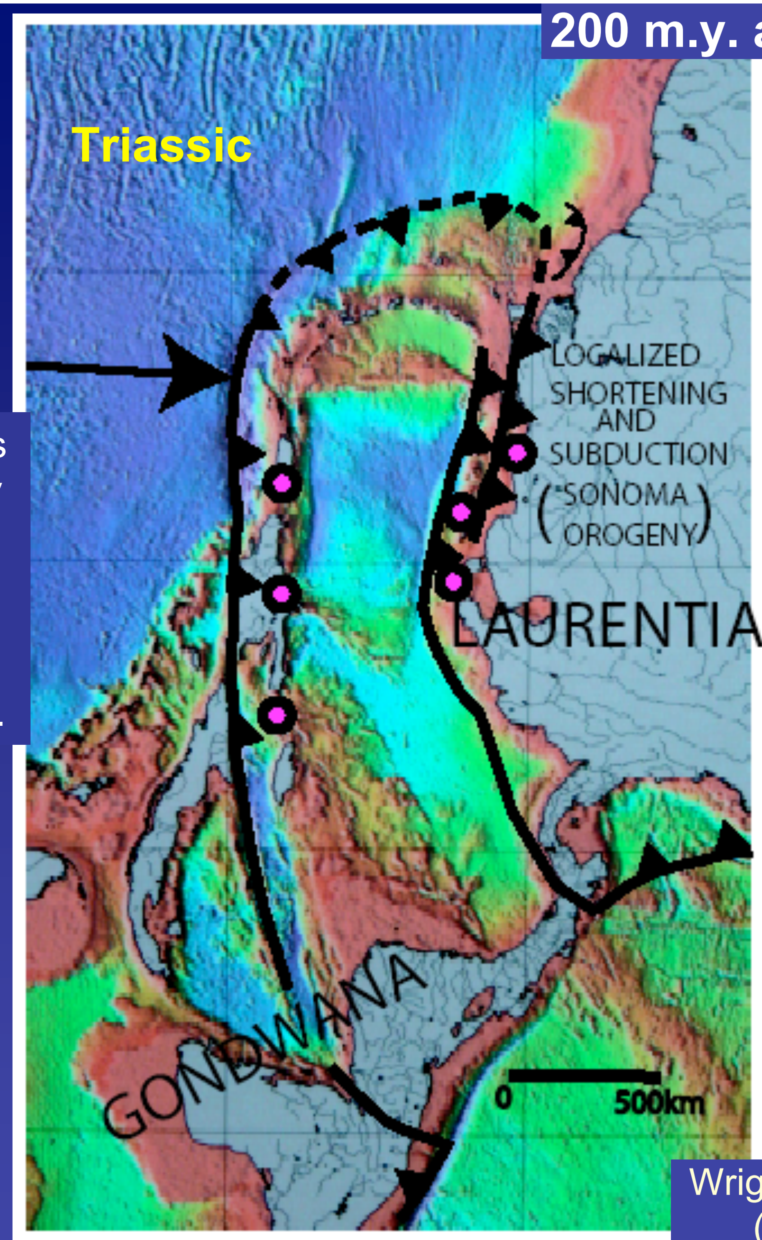
In thinking about the scientific evolution of thought on the Antler orogeny, it is interesting to see how much more complicate the models have become as the variety of old and new information is considered.   One thing that concerns me about this model is, I don't see how this makes an Antler orgeny at ~370 m.y. ago along entire miogeocline.

~370 m.y. ago



Note that this map actually shows the Caribbean, South & mid America (north is left).

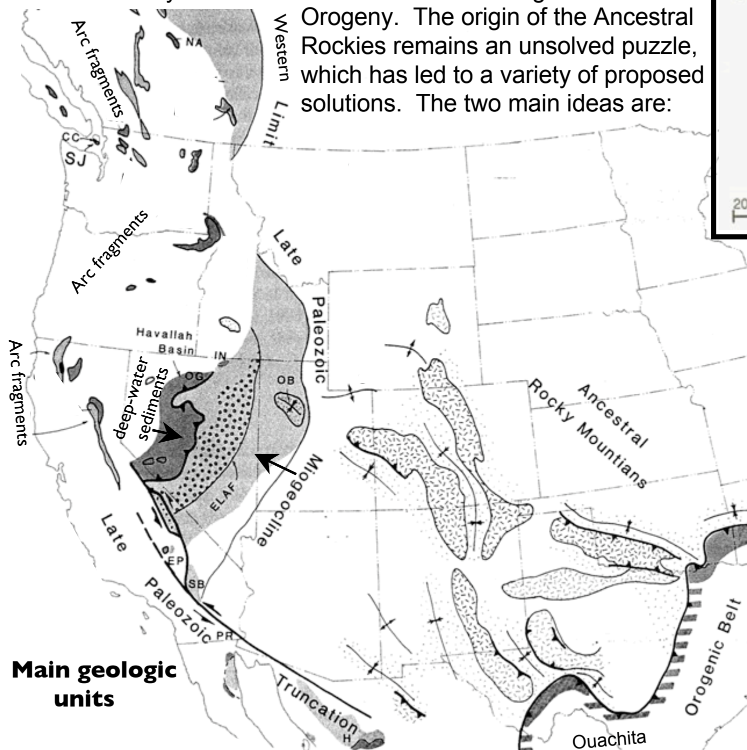
200 m.y. ago

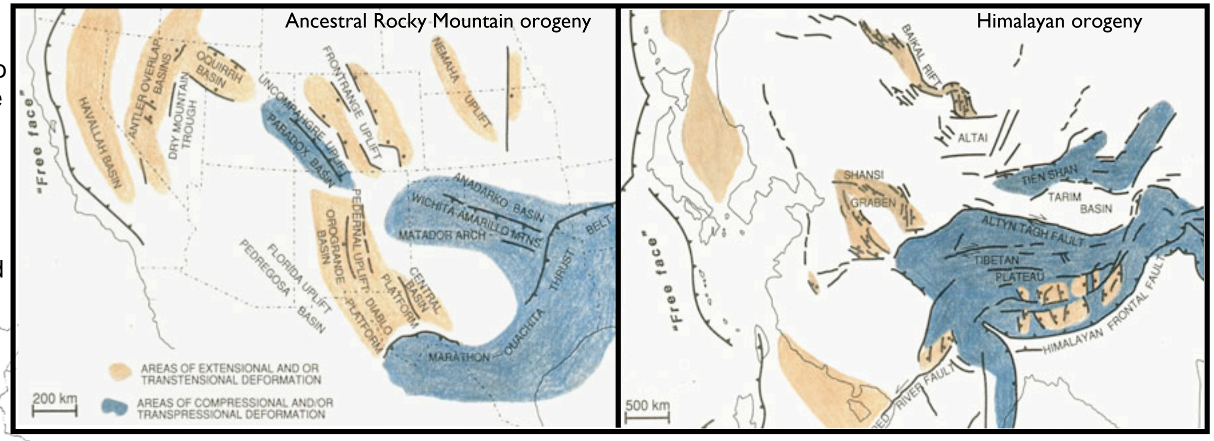


Wright & Wyld (2006)

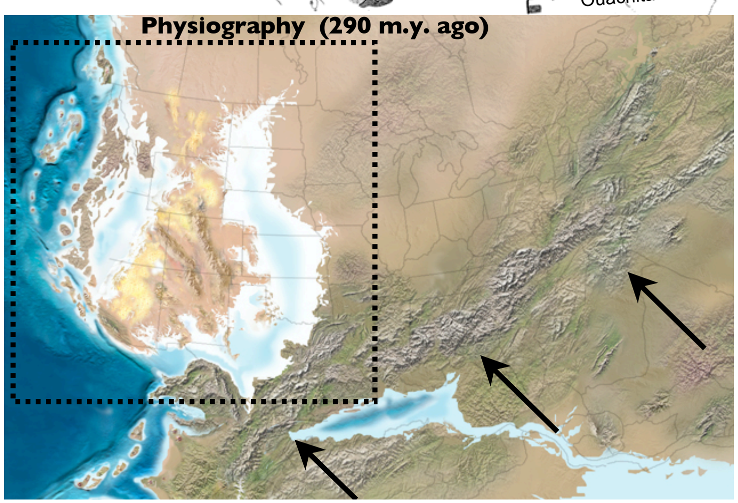
The Caribbean analogy. Roberts Mtn allochthon, developed far from the western U.S. and was transported to western U.S. during the Devonian. It wasn't simply the deep-water sediments west of the miogeocline that were thrust onto the shelf. Also, Havallah basin is a separate basin to the south that was emplaced in **Triassic**… there was no Sonoma orogeny in the Paleozoic.

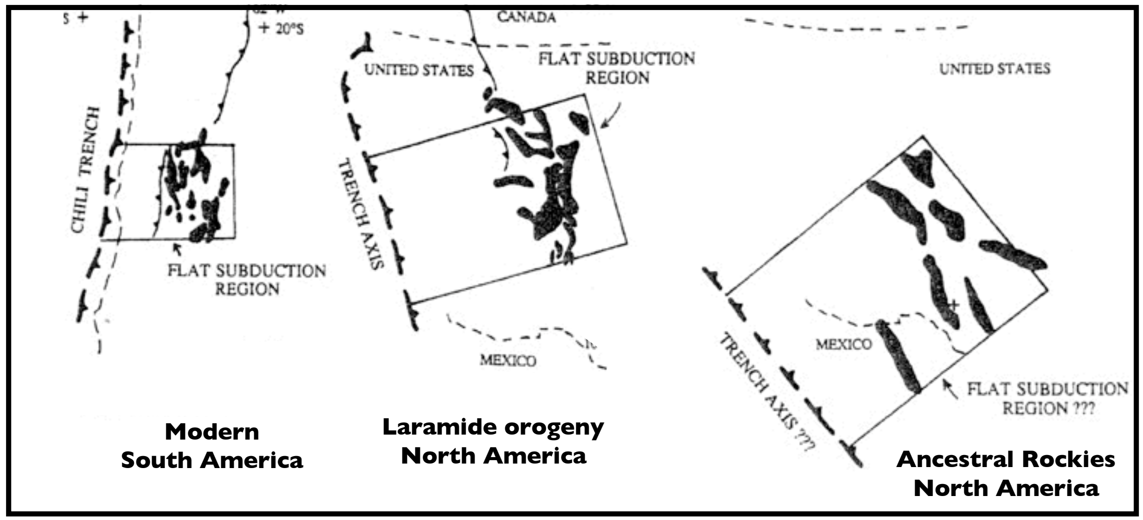
The **Ancestral Rockies** are a series of thrust-related basement uplifts and associated basins created by an intense orogeny 320-270 m.y. ago that spanned across the Proterozoic continent (up to 1500 km from a plate margin!). These mountains have long since eroded away, but their former presence is inferred from basin stratigraphy and offsets of the basin-bounding faults. Many Ancestral Rocky structures were reactivated during the Laramide Orogeny. The origin of the Ancestral Rockies remains an unsolved puzzle, which has led to a variety of proposed solutions. The two main ideas are:





Ouachita-Marathon Orogeny: Suturing of North America with South America and Africa occurred simultaneously with the Ancestral Rockies, and often is cited as their cause (e.g., Kluth and Coney, 1981). The direction of collision would have applied NNW-oriented compressional stress, and the trick is to explain how the shortening in the Ancestral Rockies was perpendicular to this direction. Analogy with the Himalayan orogeny (figure above, with east and west reversed) demonstrates that orogeny similar in scale and orientation of structures can occur.





NE-directed subduction beneath Mexico: Igneous rocks in NE Mexico suggest a late Paleozoic volcanic arc SW of the Ancestral Rockies (e.g., Ye et al, 1996). Recognition of highly compressive "flat slab" subduction events currently occurring in South America and recently occurring in North America during the Laramide orogeny (80-50 m.y. ago), suggests that such an even may have caused the Ancestral Rockies, and NE-directed compression would be a natural consequence.

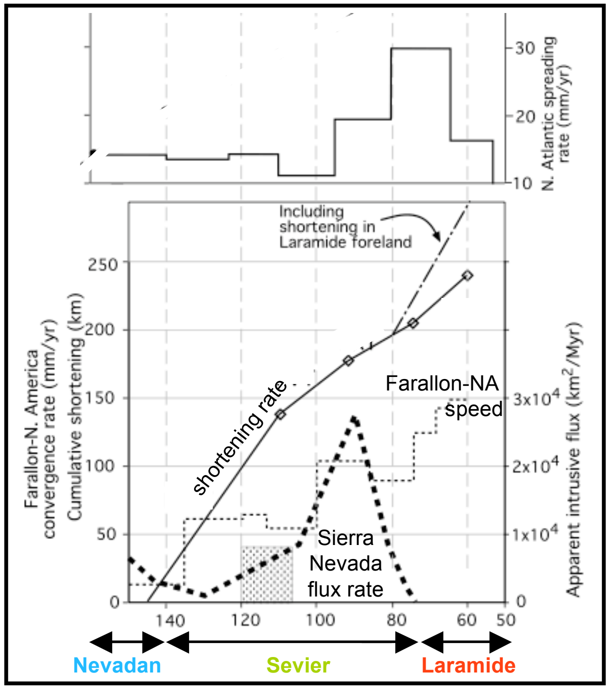
Of course, these two explanations are not mutually exclusive

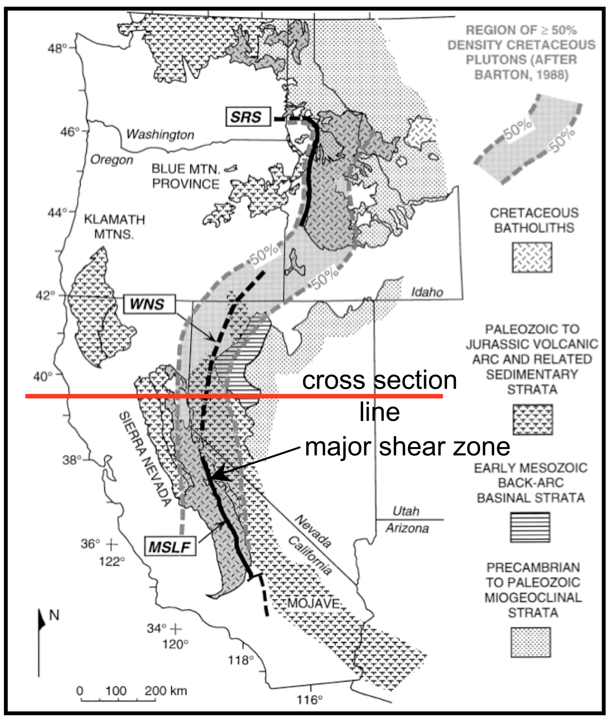
Figures and discussion modified from: www.colorado.edu/GeolSci/Resources/WUSTectonics/AncestralRockies

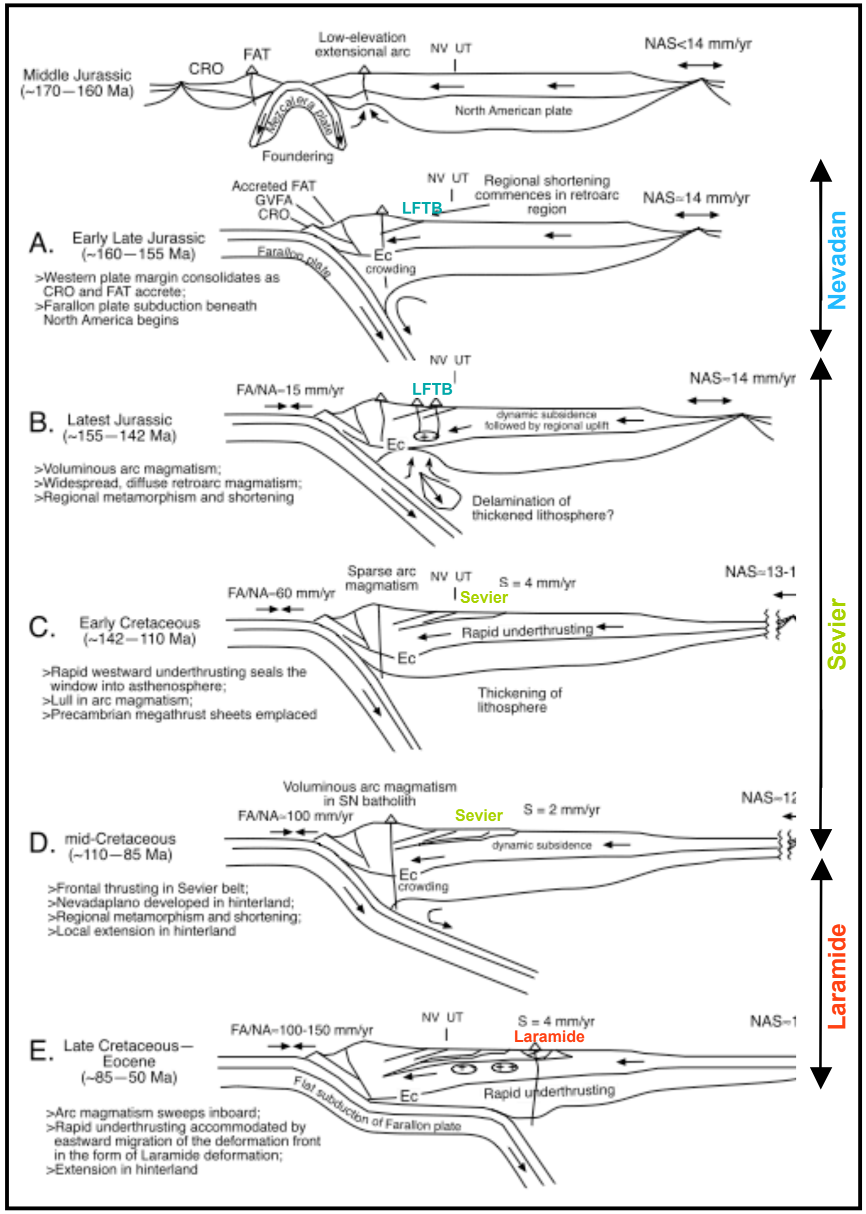
Mesozoic subduction

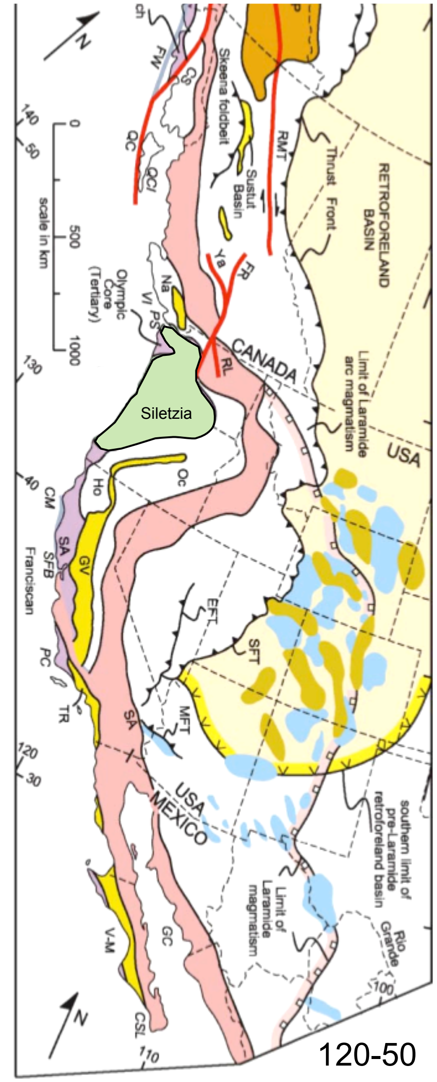
Arc accretion
Backarc thrusting
Arc flareup and quiescence

DeCelles—Late Jurassic to Eocene evolution of the Cordilleran thrust







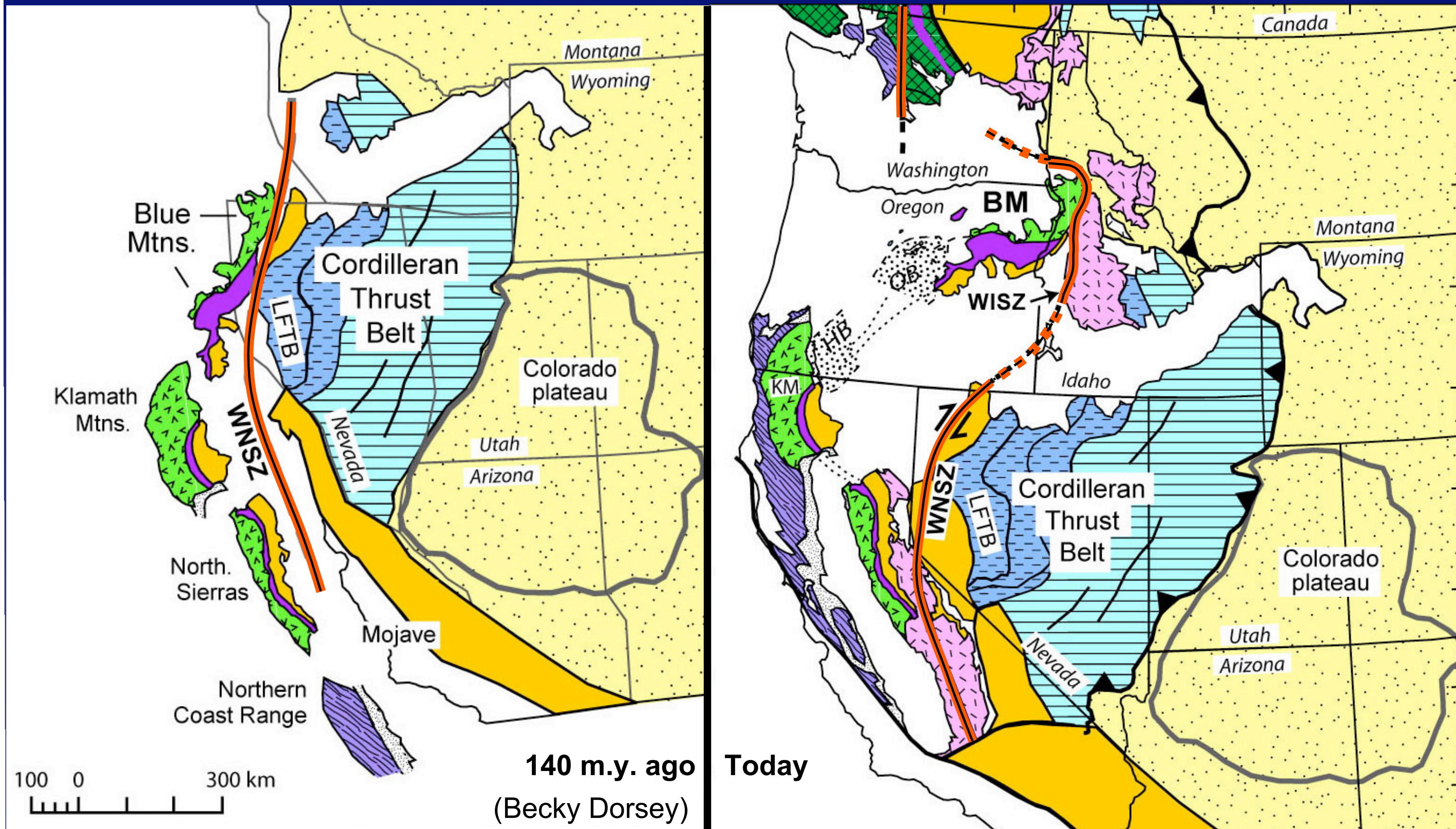


120-50 m.y. ago

Laramide & pre-Laramide features

- Subduction complex
- Forearc basin
- Magmatic arc
- Laramide uplift
- Basin

The shearing of western North America



Parts of the Sevier/Laramide Orogeny

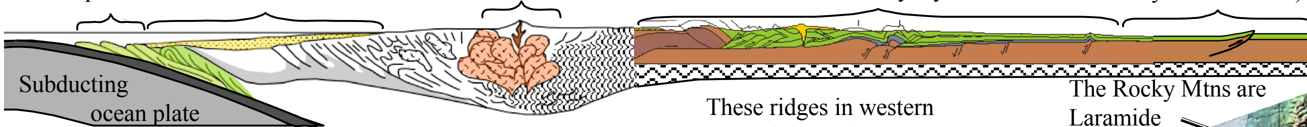
A Accretionary Prism
Sediment scraped off of subducting plate

B Forearc Basin
Sediment derived from the volcanic arc

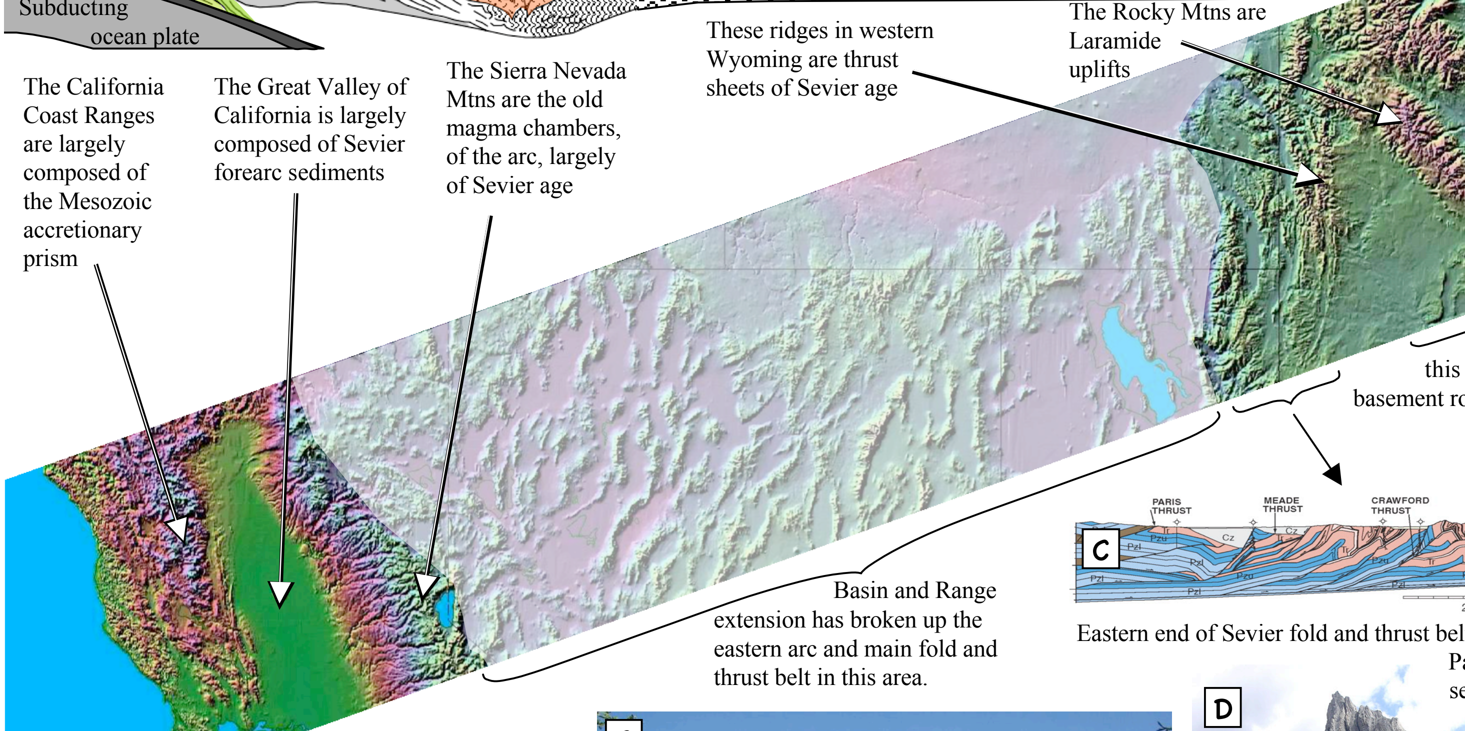
C Volcanic Arc
Magmatic intrusion into the crust

D Fold and Thrust Belt
Thin-sheet thrusting within the sedimentary layers

E Basement-cored uplifts
Thrusting through upper crust (sediment layer is thin here)



Basement-cored Laramide uplift.



The California Coast Ranges are largely composed of the Mesozoic accretionary prism

The Great Valley of California is largely composed of Sevier forearc sediments

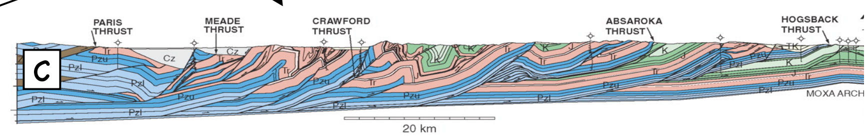
The Sierra Nevada Mtns are the old magma chambers, of the arc, largely of Sevier age

These ridges in western Wyoming are thrust sheets of Sevier age

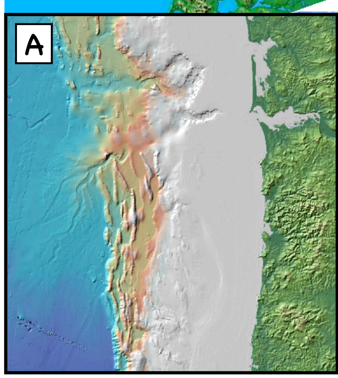
The Rocky Mtns are Laramide uplifts

The Laramide is the last 30 m.y. of this orogeny. It involved up-thrusting of basement rocks very far east of the subduction zone.

Basin and Range extension has broken up the eastern arc and main fold and thrust belt in this area.



Eastern end of Sevier fold and thrust belt, where it is preserved in western Wyoming. Paleozoic (blue) and lower Mesozoic (pink) sediments were folded in this Cretaceous event.



The boring Great Valley

Oregon's active accretionary prism

The Sevier-age mid-crustal granitic magma chamber, now exposed in Yosemite

Spectacular folds in layers of sedimentary rock within fold and thrust belts

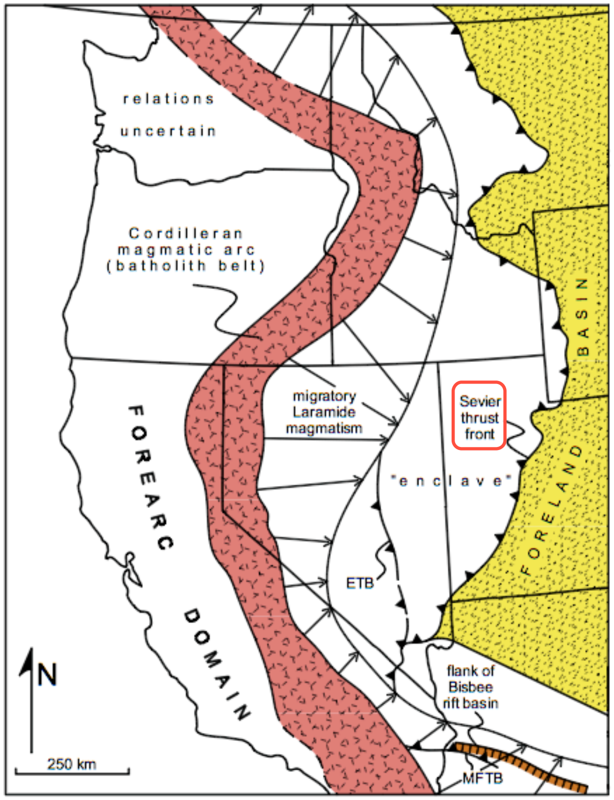


Figure 7. Cretaceous-Paleogene paleotectonic map of the Great Basin and adjacent areas. Migratory Laramide magmatism is modified after Dickinson and Snyder (1978). Flank of Bisbee rift basin is after Dickinson and Lawton (2001b). Subordinate retroarc structures: ETB—Eureka thrust belt; MFTB—Maria fold-and-thrust belt.

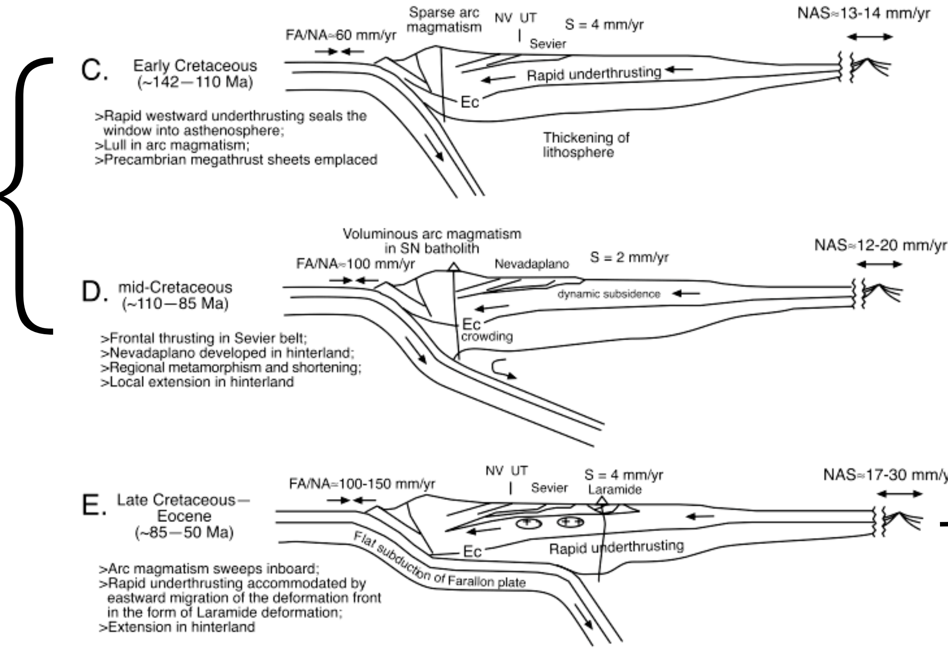
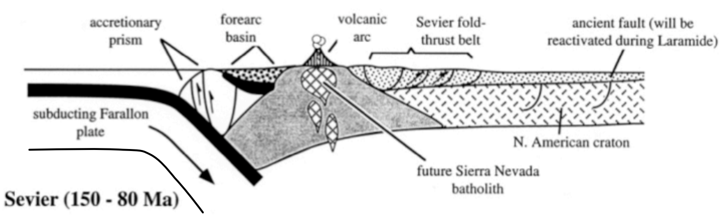


Fig. 19. Sequential plate-scale kinematic reconstruction for the Cordilleran orogenic belt at the latitude of Utah and Nevada. See text for discussion. Abbreviations as follows: CRO, Coast Range ophiolite; FAT, Foothills arc terrane; GVFA, Great Valley forearc basin; SN, Sierra Nevada; Ec, eclogitized lower crust and lithosphere; NAS, North Atlantic spreading rate; S, shortening rate; FA/NA, rate of convergence between Farallon and North American plates; NV|UT, Nevada-Utah border. Although the Middle Jurassic panel incorporates the Mezcalera plate of Dickinson and Lawton (2001b), other models involving marginal oceanic basins and offshore arcs are also viable (for example, Harper and Wright, 1984; Dickinson and others, 1996).

Sevier orogeny



- Beginning of Cordilleran mountain building
- Typical Andean-Type subduction
- 165 Ma, Subduction of Farallon Plate begins

Laramide orogeny

- Beginning about 80 Ma
- Unusual mountain building far inland; magmatism stops.
- Caused by flat-slab subduction.
- Ends about 50 Ma with a profound transition to extensional tectonics and vigorous magmatism.