INTRAPLATE DEFORMATIONAL HISTORY OF THE COLORADO PLATEAU TECTONIC PROVINCE

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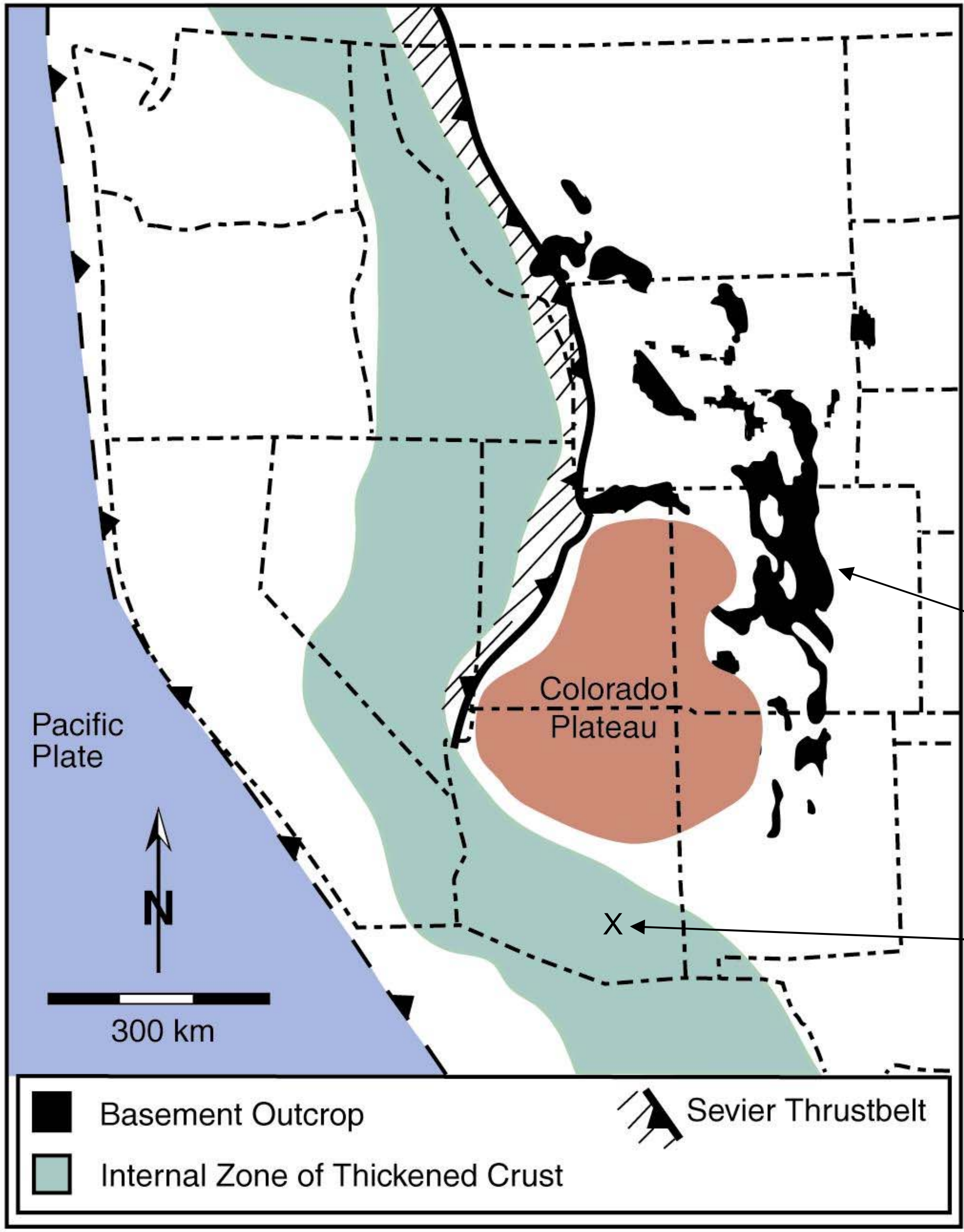
Presentation at National Central University, Taiwan

Friday, November 10, 2017



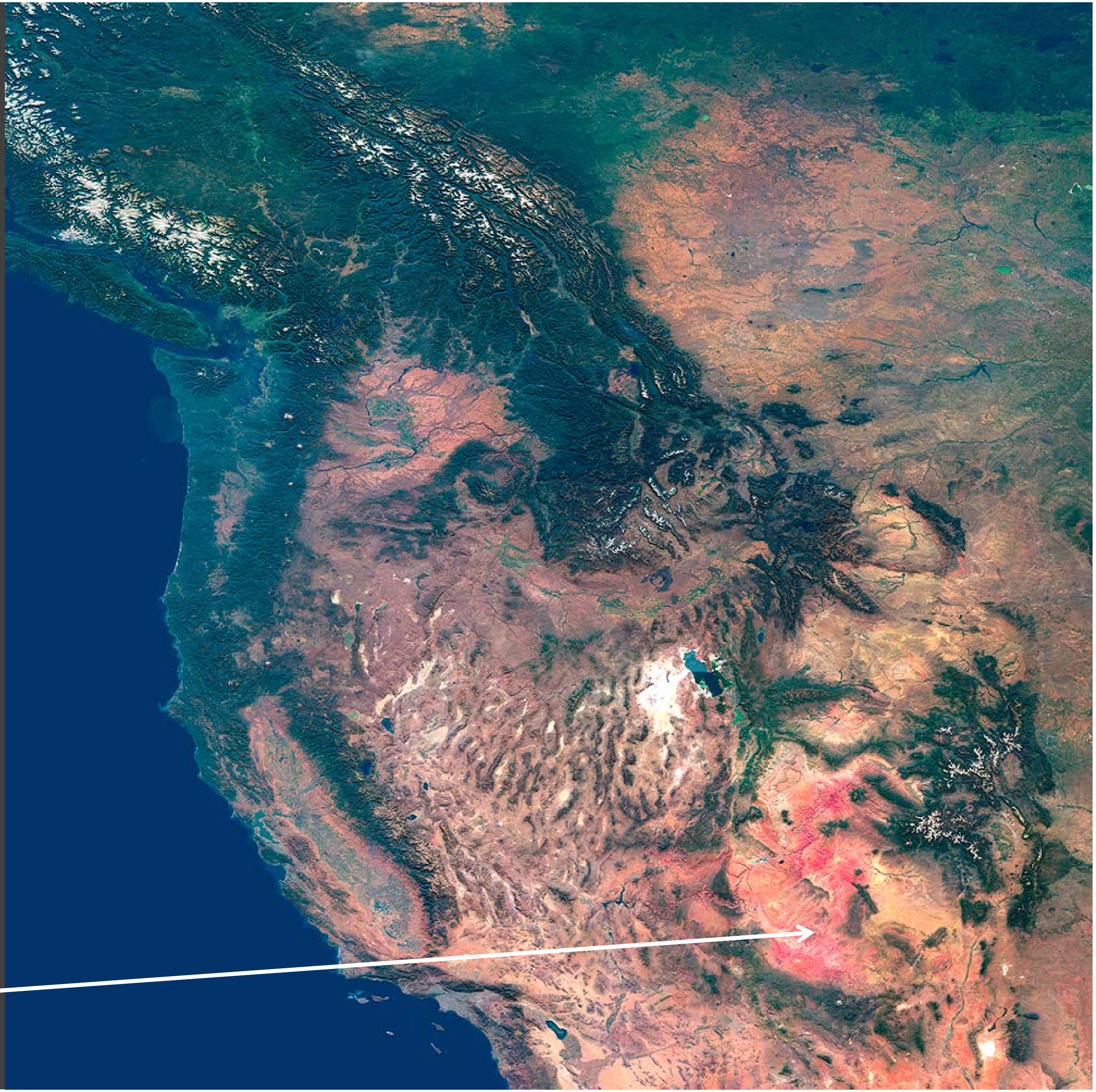
Location of the
Colorado Plateau within the
Western Cordillera

Black masses are
Rocky Mountain uplifts

Tucson, AZ

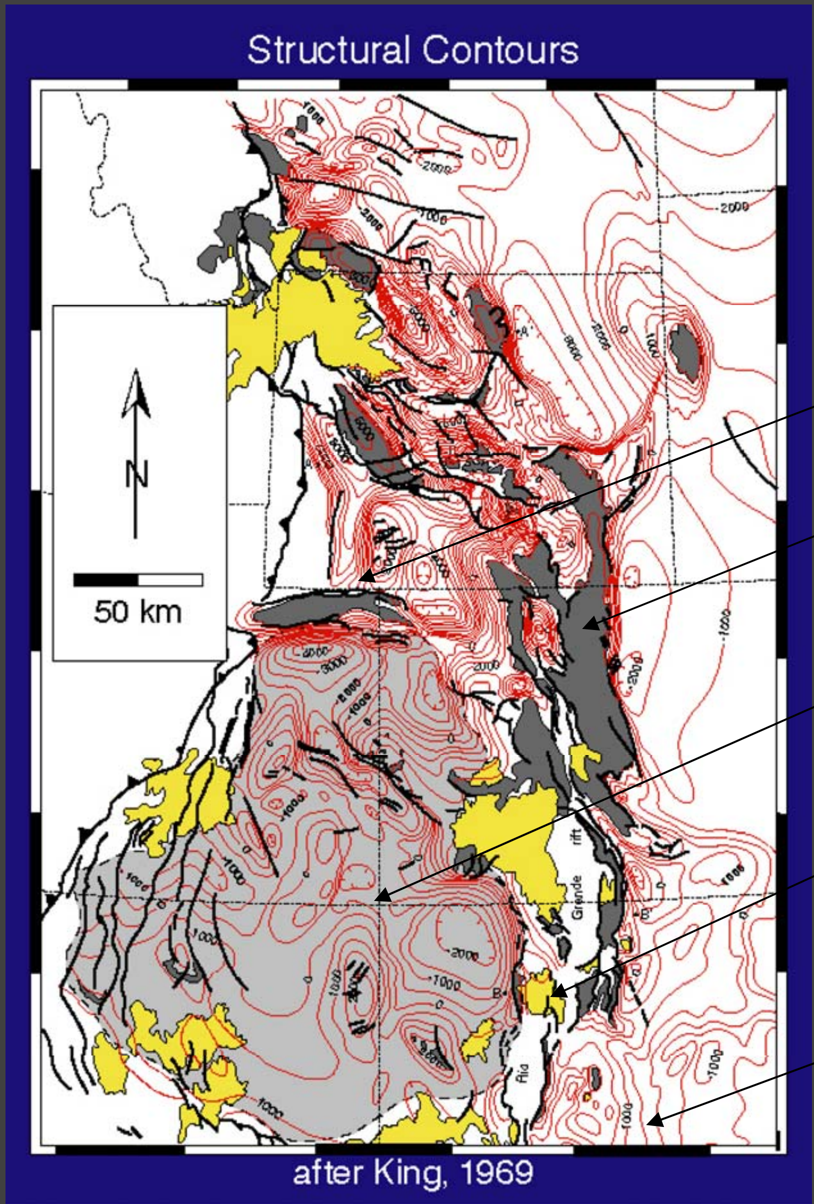
Davis and Bump, 2009

But here is what the Colorado Plateau really looks like, viewed in context of the Western Cordillera of North America.



Colorado Plateau

P.B. King's (1969) Tectonic Map of the Colorado Plateau and Rocky Mountains



"Wyoming Province"

Dark Gray: Precambrian Basement, the heart of Rocky Mountain Uplifts

Medium Gray: the Colorado Plateau

Yellow: Tertiary Volcanic Fields

Red Lines: Structure contours, interval ~ 150 m

SOME PRETTY PICTURES OF THE

COLORADO PLATEAU

Monument Valley

Canyonlands

Bryce Canyon

Capitol Reef

Raplee Anticline and San Juan River

San Francisco Peaks and S.P. Crater

Grand Canyon

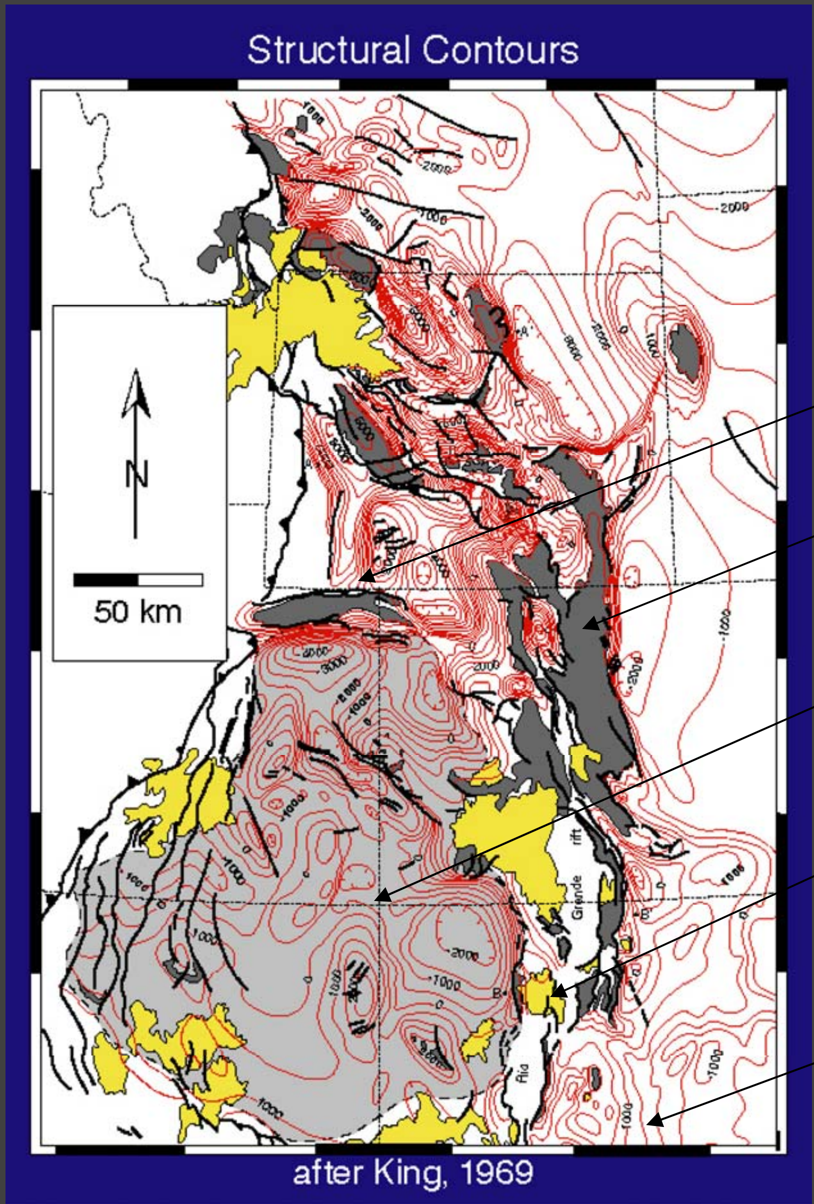
Zion Canyon

Arches

Comb Ridge Monocline

And almost everywhere there are geologic oddities, …

P.B. King’s (1969) Tectonic Map of the Colorado Plateau and Rocky Mountains



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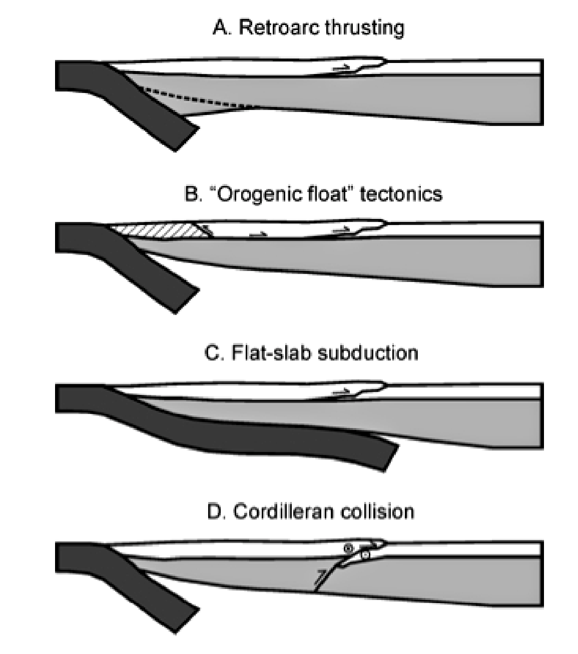


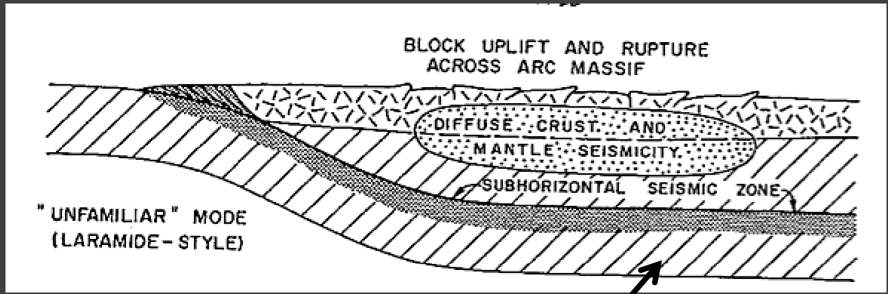
Stress transmitted across entire Cordillera

Foreland faults linked to margin by crustal basal detachment

Slab remains in contact with upper plate for 800 km inboard from trench

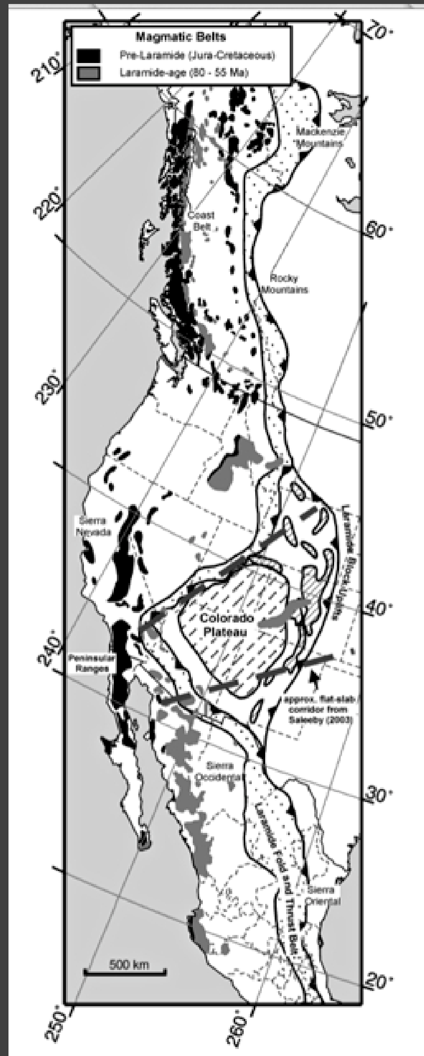
100-170 km of right lateral slip along N-striking Laramide faults

English & Johnson (2004) summarized 4 mechanism for producing the 'inboard deformation'.



Coney (1976, 1978) and Dickinson & Snyder (1978) proposed flat-slab dynamics responsible for Laramide.

Dickinson & Snyder (1978) used this model to explain magmatic lull, the source of tectonic loading so far from the trench, and the timing of most intense shortening.



Attractiveness of Flat-Slab Dynamics via subduction of oceanic plateau, producing Laramide.

*Relative buoyancy of thickened lithosphere creates buoyancy and shallow subduction.

*Arc magmatism is suppressed (70 to 40 Ma).

*Deformation primarily develops where subducting slab eventually steepens and descends into deep mantle.

*Non-collisional yet telescopes the foreland region.

*Oceanic plateau breadth is about same as breadth of Laramide foreland.

*Produces deformation 1000km+ inboard.

Humphrey's Interpretation of the Flat Slab Deformation

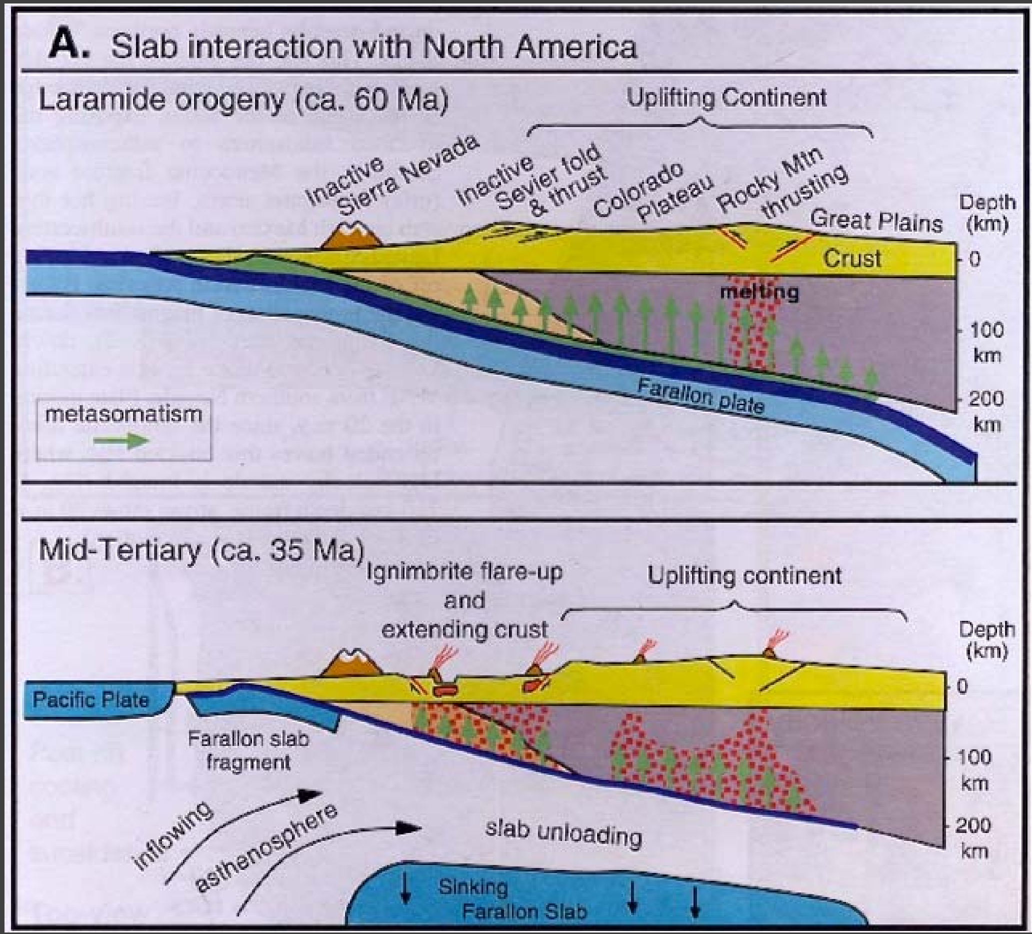
*__Pre-Laramide Sevier__: shallowing Farallon slab dip produced eastwad migration of arc magmatism (Nevada), thrust-thickening of crust, dynamic subsidence of continental interior. WNW-ESE shortening.

*__Laramide 75-45 Ma__: Slab contact with Colorado Plateau did not occur before Laramide. Driving force for uplifts was traction related to flat slab. NE-SW to ENE-WSW shortening.

*__Oligocene-Miocene Ignimbrite Flare-Up__: Removal of flat slab exposed thinned and hydrated lithosphere to infilling asthenosphere.

*__Basin and Range Exten__sion: Related to North American/Pacific plate motion.

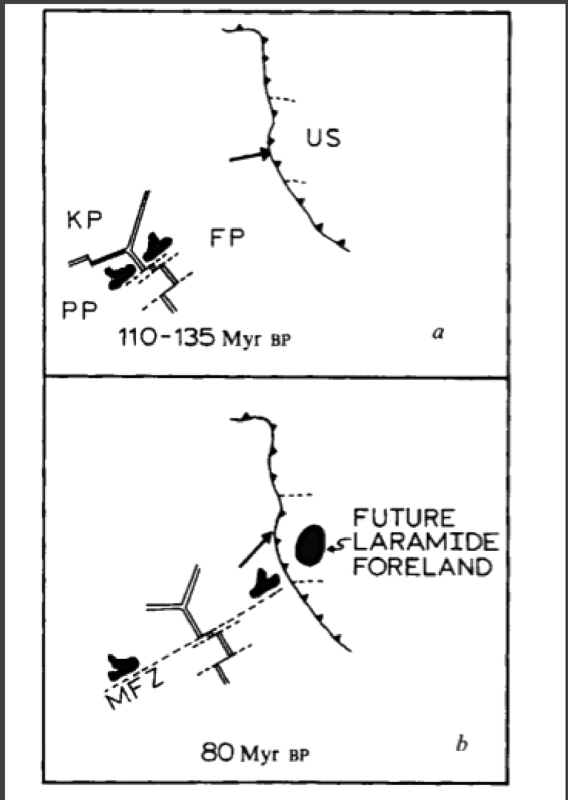
Cross-sections by Gene Humphreys, showing Flat-Slab Subduction followed by Collapse

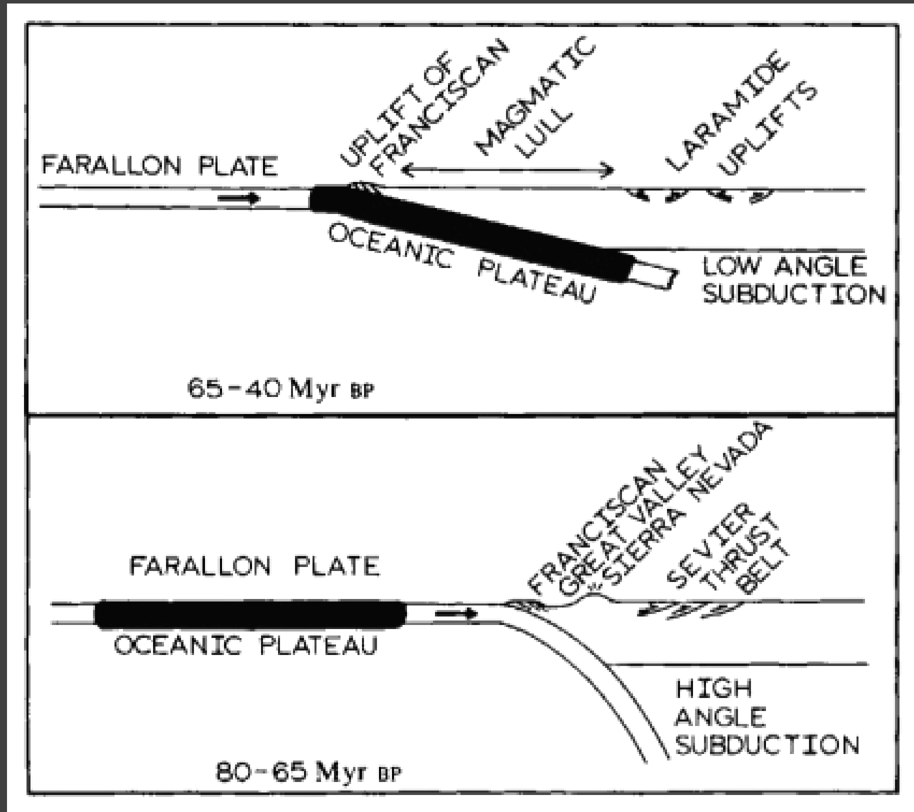


Livacarri, Burke, & Sengor (1981) proposed subduction of oceanic plateau, as did Henderson, Gordon, & Engebretson (1984).

Aseismic ridge of Late Jurassic and Early Cretaceous age on Farallon plate and subducted beneath the Western Cordillera during the “Laramide Orogeny.” The relative buyoncy of such an oceanic plateau would force shallow subduction, and would produce the 70 to 40 Ma magmatic lull. Creates uplift and faulting up to 1500 km from the trench.

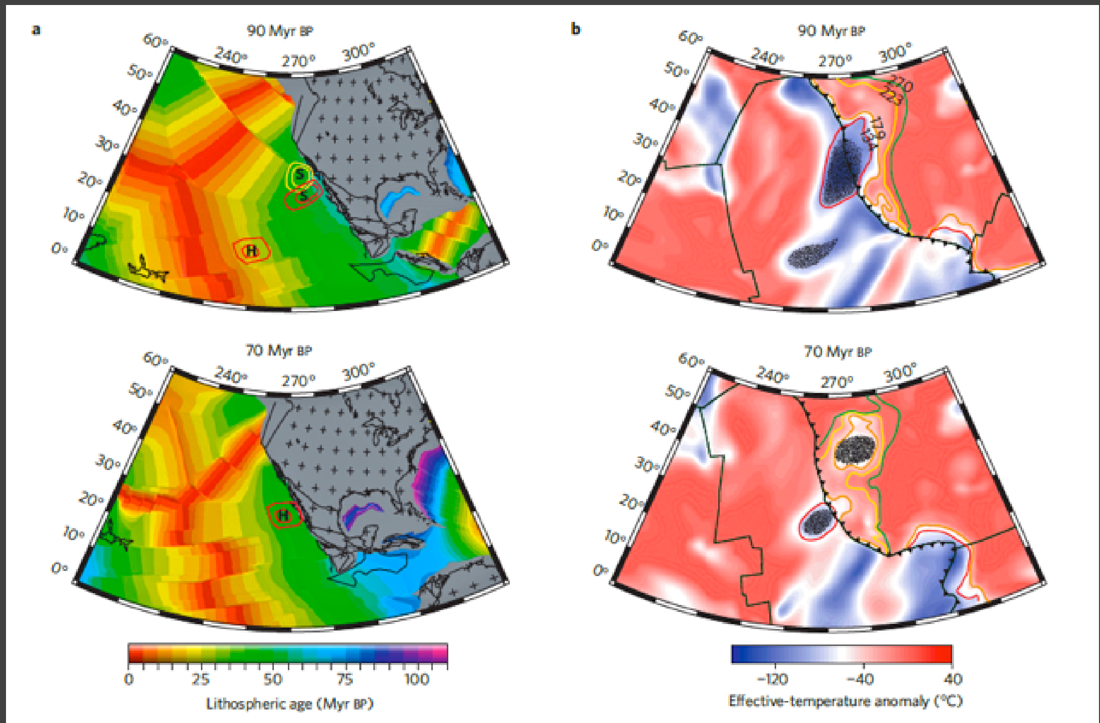
A large oceanic plateau would be anomalously thick and buoyant. The Shatsky plateau is approximately same dimension of the Laramide foreland.



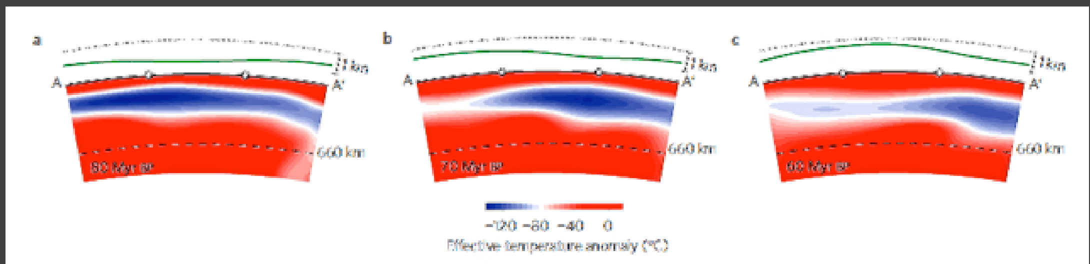


Livicarri, Burke, and Sengor (1981) thought that the Hess Rise ‘twin’ in the Farallon plate was the trigger for Laramide events. Uplift would be expected as fore-arc region rose to accommodate oceanic crust riding at relative high elevation. YET, ‘the authors felt that it cannot be directly proved that such an oceanic plateau region ever existed or was subducted beneath what is now the Colorado Plateau.”

Enter Liu, Gurnis, Seton, Saleeby, Muller, and Jackson (2010)

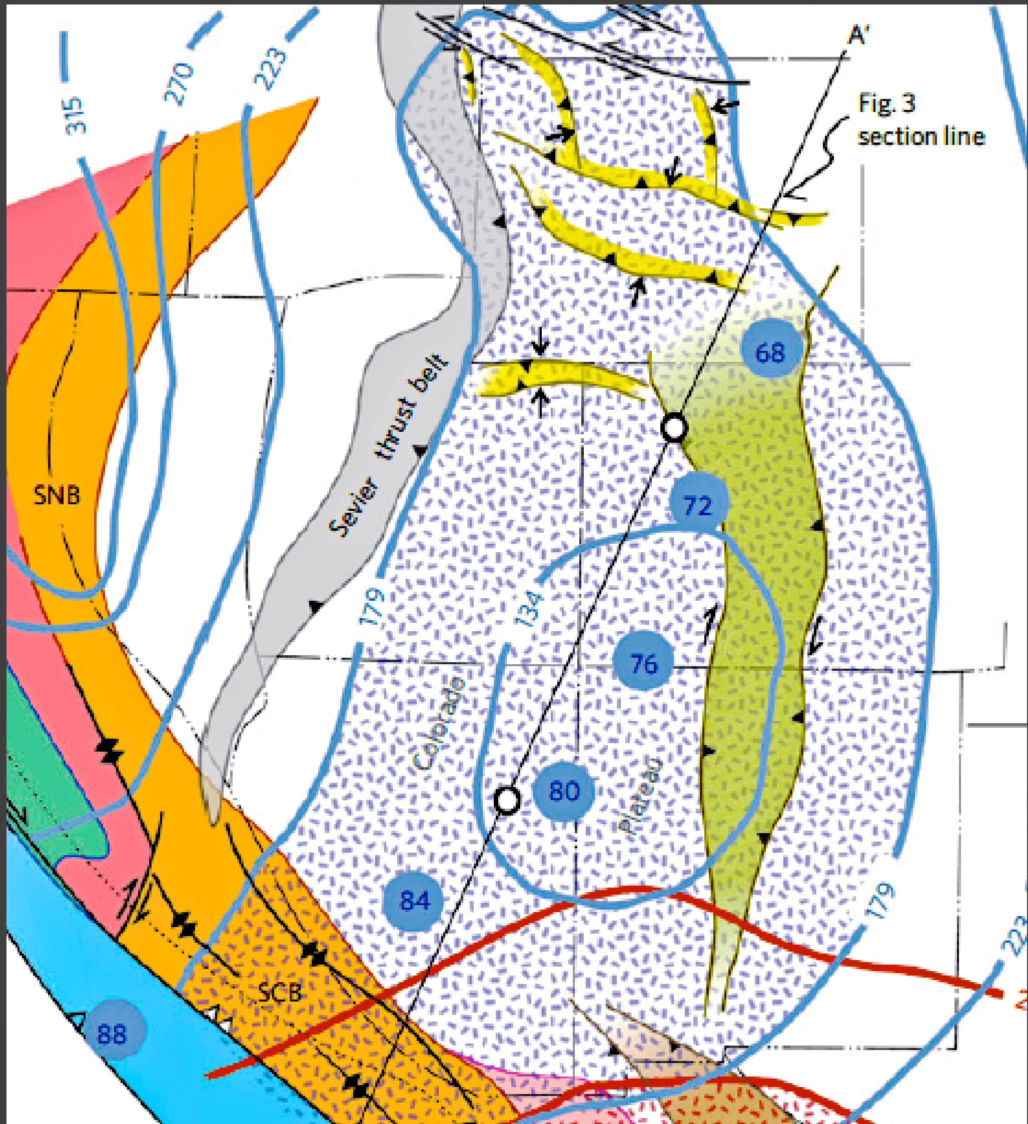


Combination of plate reconstructions and inverse convection models based on seismic tomography used to 'recover' locations of 'twins' of Shatsky and Hess oceanic plateaus. They predict that the distribtuion of Laramide crustal shortening events should coincide with the passage of the Shatsky plateau.



Laramide uplift resulted from removal, not emplacement, of the Shatsky oceanic plateau.

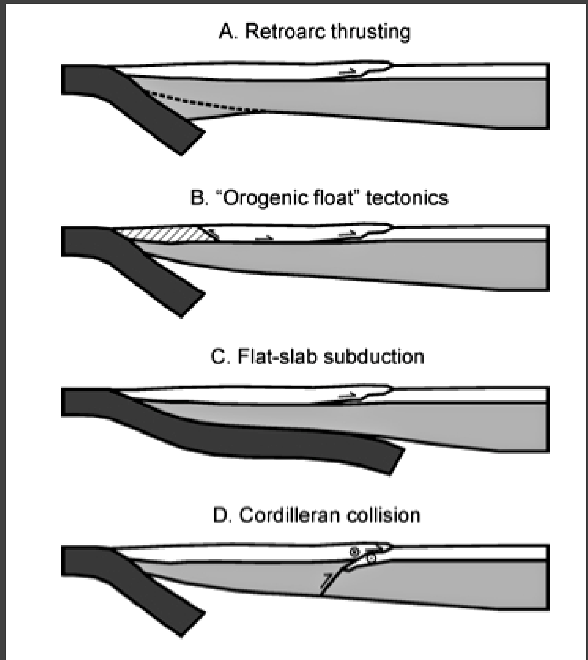
Big structures produced by flat-slab traction.

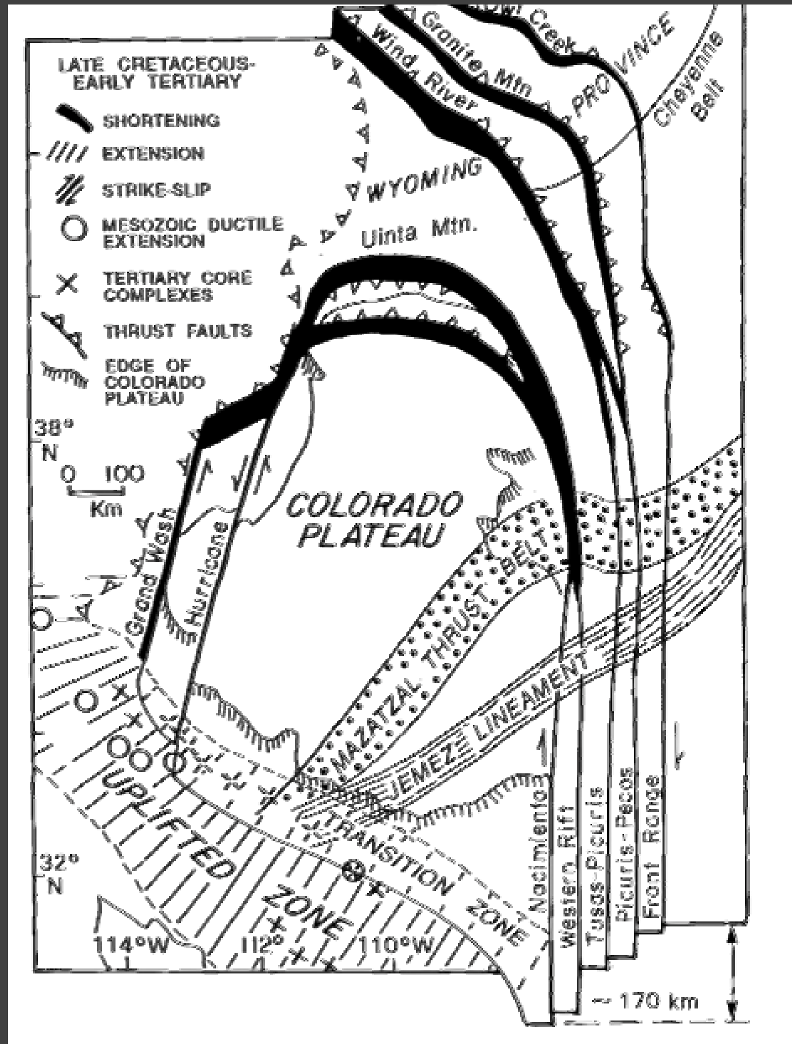


Liu et al. reconstruction of path of Shatsky oceanic plateau.

They argue that the distribution of Laramide crustal shortening events tracked the passage of the Shatsky conjugate beneath North America.

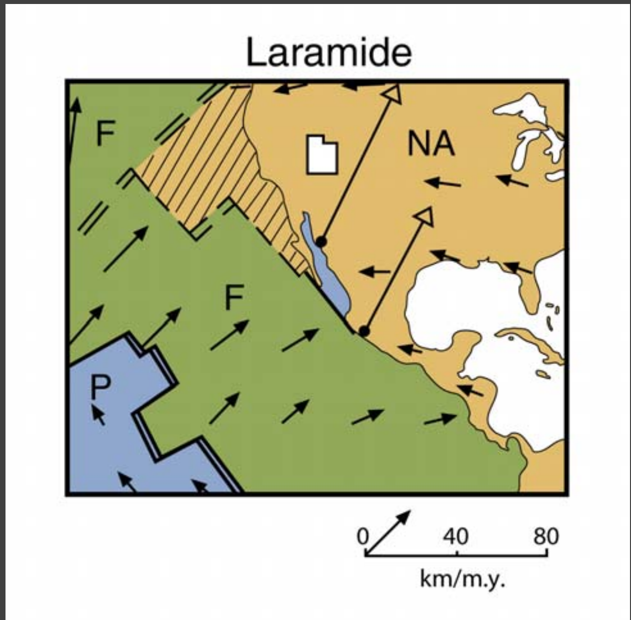
Removal of slab may have facilitated fault reactivation causing distribution of basement uplifts, "*although we do not yet understand the details of the process*."

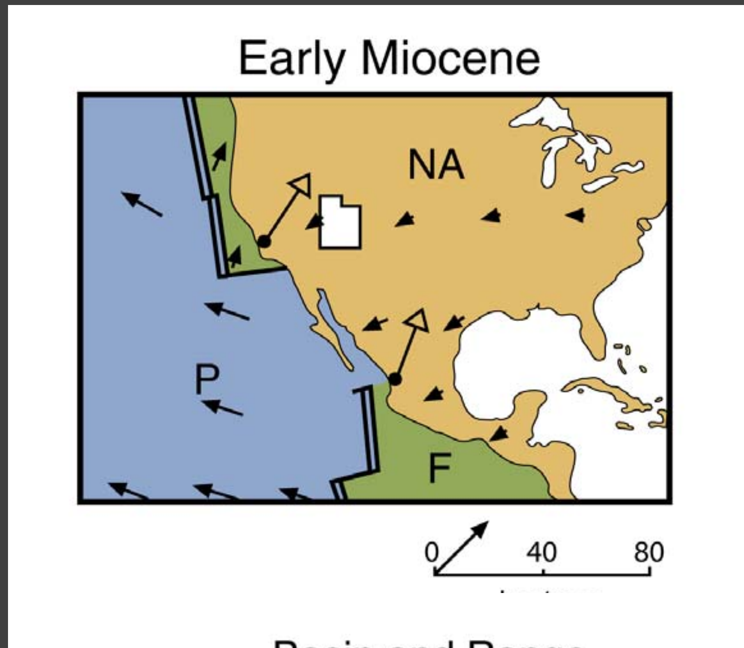


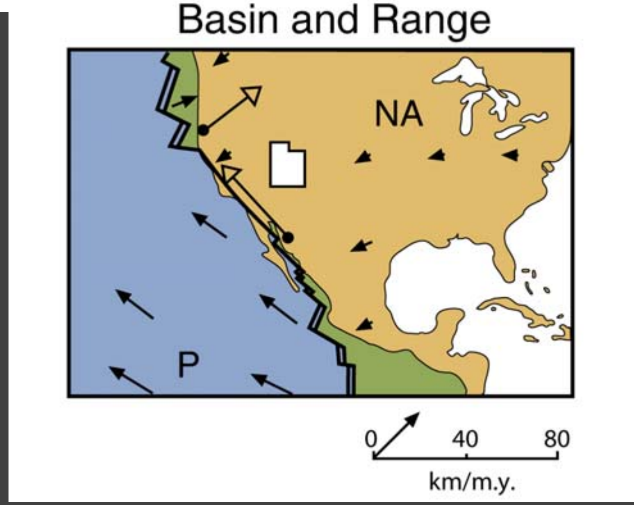


Karlstrom & Daniel (1993) advocated for Laramide as expression of giant dextral shear.

Plate Tectonic Framework of Colorado Plateau, during Late Cretaceous/Early Tertiary, Mid-Miocene, and Basin & Range Deformations



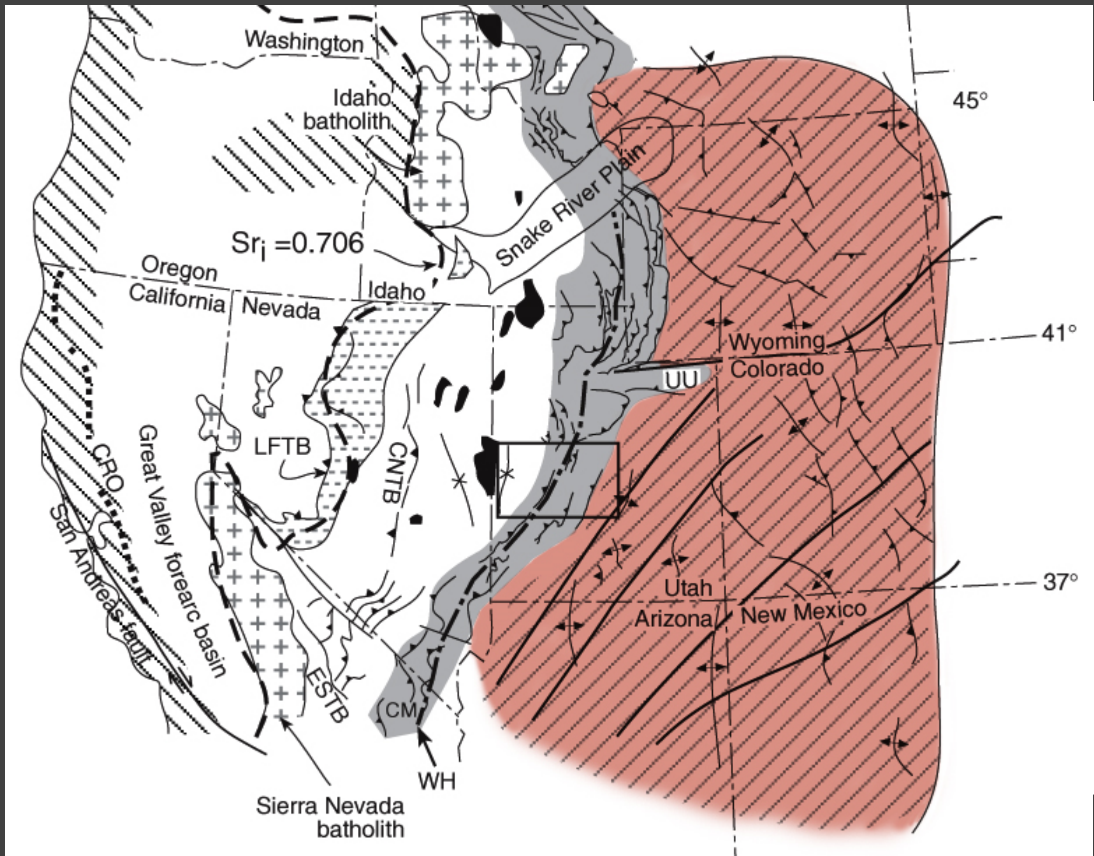


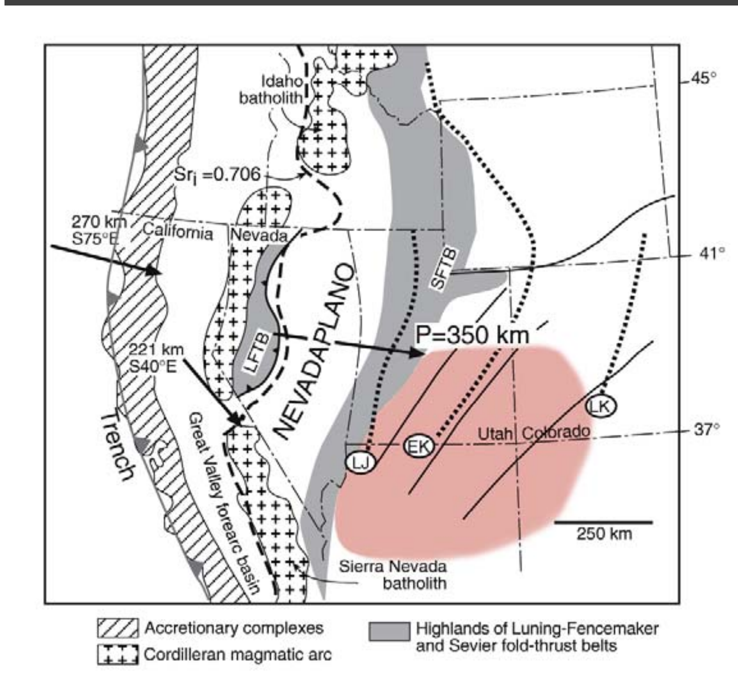


Main drift of Eurasia and NA occurred at 80 Ma; separation of ~5 cm/year. Dropped to 2 cm/yr at 53 Ma.

Engebretson et al., 1985

DeCelles and Coogan (2006):
“Sevier” Retro-arc thrusting, mid-Jurassic to late Cretaceous.
A picture just prior to the development of Colorado Plateau structures.



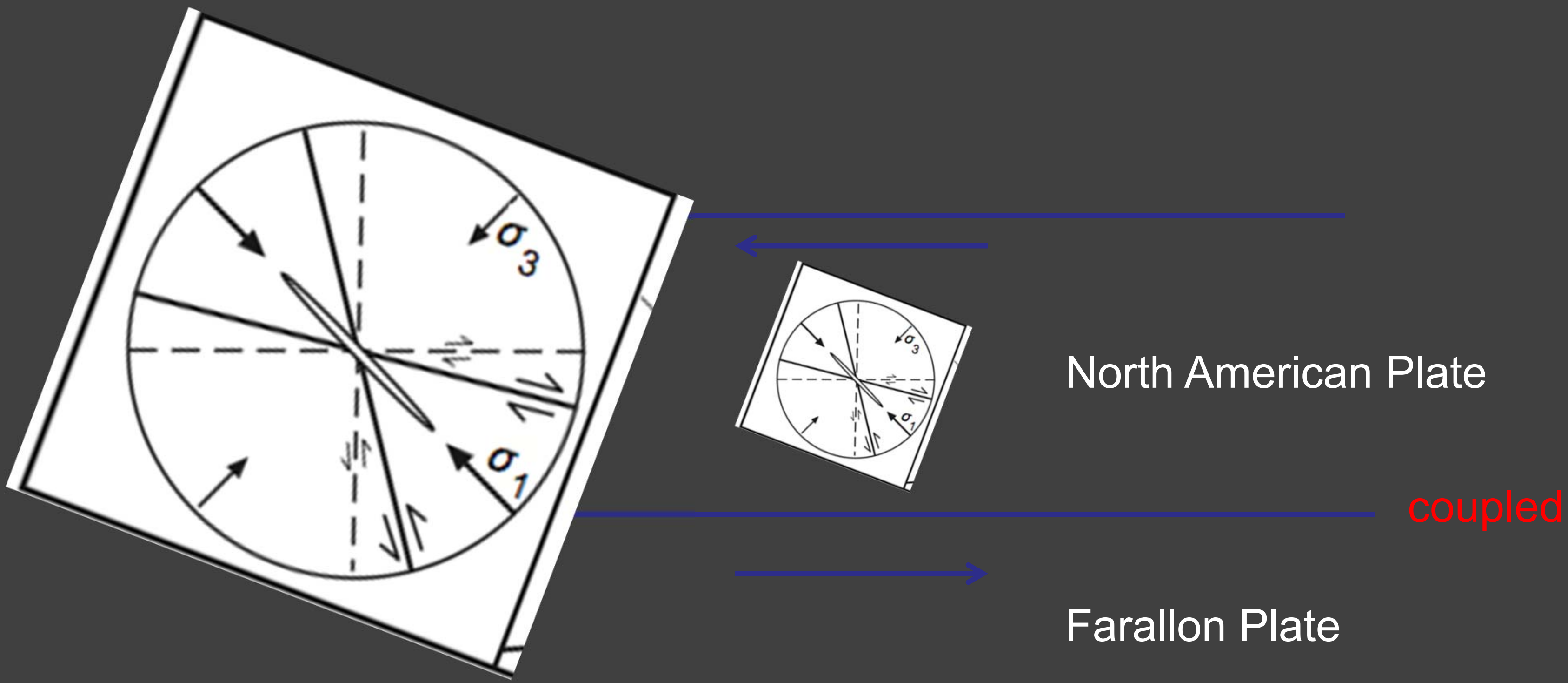


Overthickened Sevier belt triggers ENE-directed Edge Load to Colorado Plateau.

By Latest Cretaceous the Fold-Thrust Belt was Largely Formed

And Yet Shortening Continued into the Cenozoic.

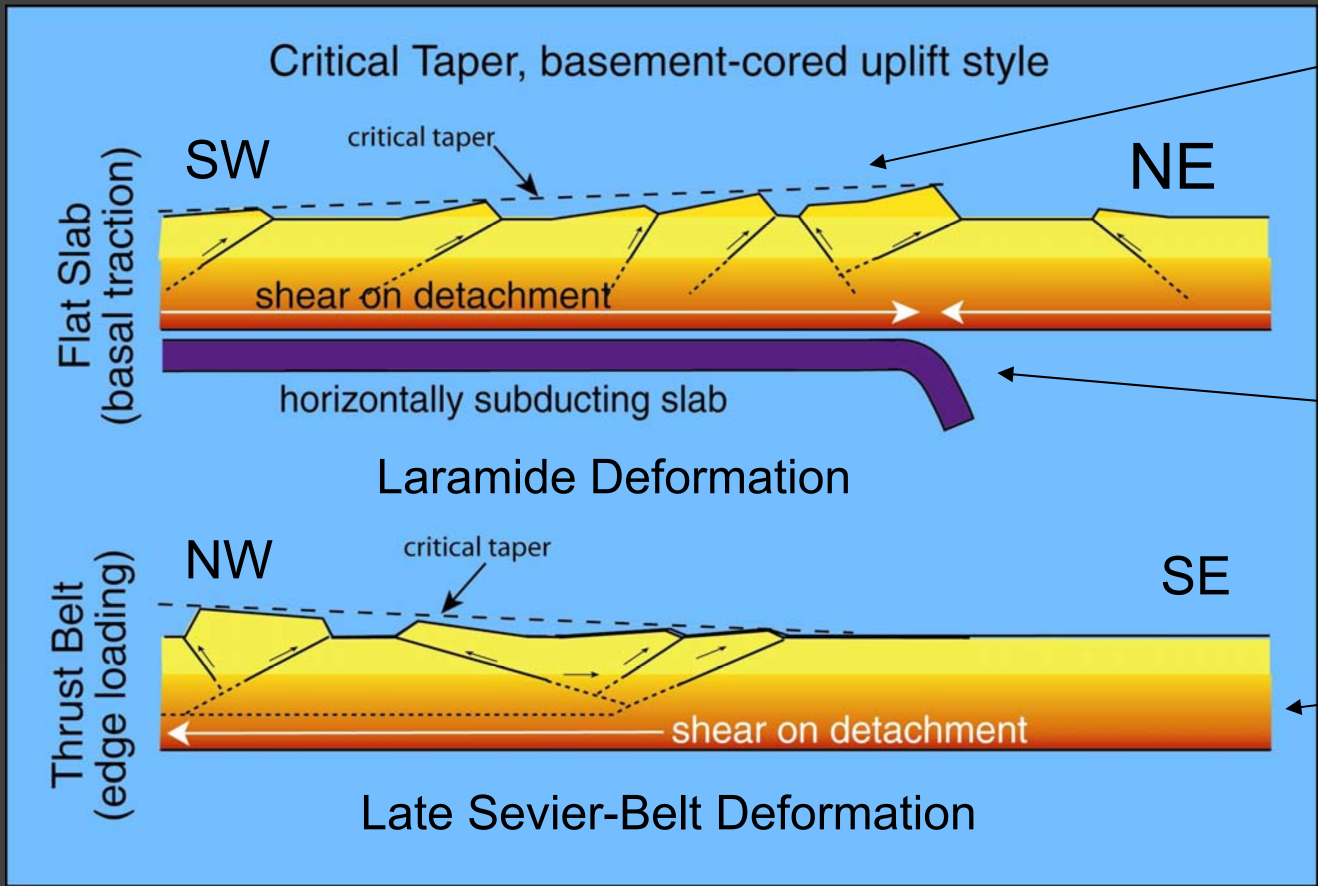
Dickinson and Snyder, 1978: “…***the Laramide problem reduces in gross outline to an analysis of the mechanical behavior of a surface slab of lithosphere subject to the influence of a subterranean slab sliding beneath it. Relative motion between the two plates was probably oriented*** **along a northeast-trending line.”**



Makes me focus on non-coaxial shear kinematics. Bird (1984) emphasized basement uplifts forming via drag-induced shear stress.

Basal traction associated with 'Flat Slab' might produce a kind of 'thick-skinned' critial taper, governed by distribution of gravitational loading, basal traction, internal friction, and sliding friction.

Not yet tested through modeling!



Concept of 'thick-skinned' critical taper suggested by Alex Bump

Flat slab of Humphreys (2009), creating basal traction.

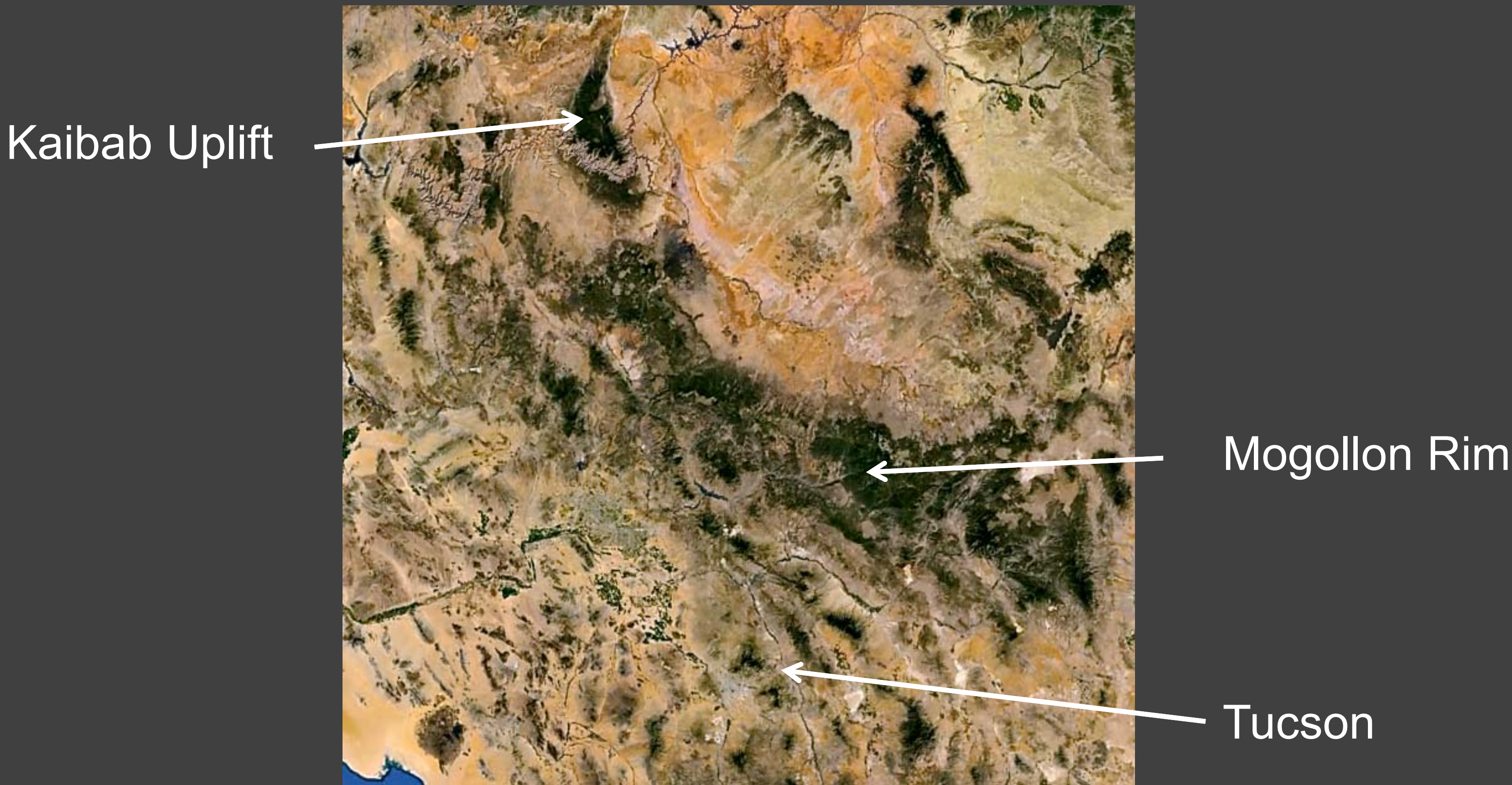
Edge loading by overthickened Sevier belt and development of more typical taper.

Moving now to the record of progressive deformation on the Colorado Plateau.

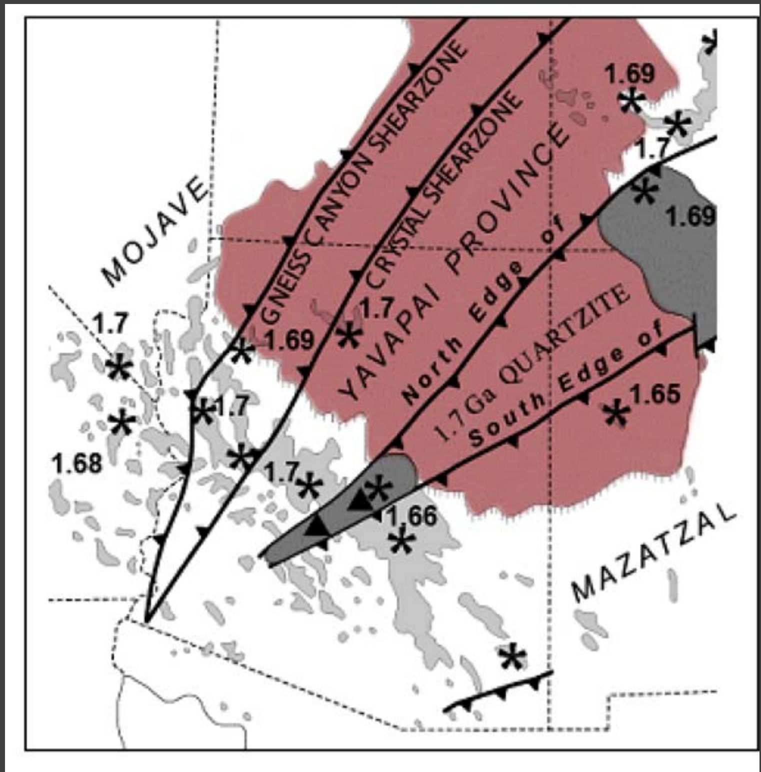
Very challenging to ‘invert’ the observed geological structures in ways that clarify the mechanics of a flat-slab subduction driver, including influence of underplating an oceanic plateau!!

Circle Cliffs Uplift,
photograph by Kurt Constenius.

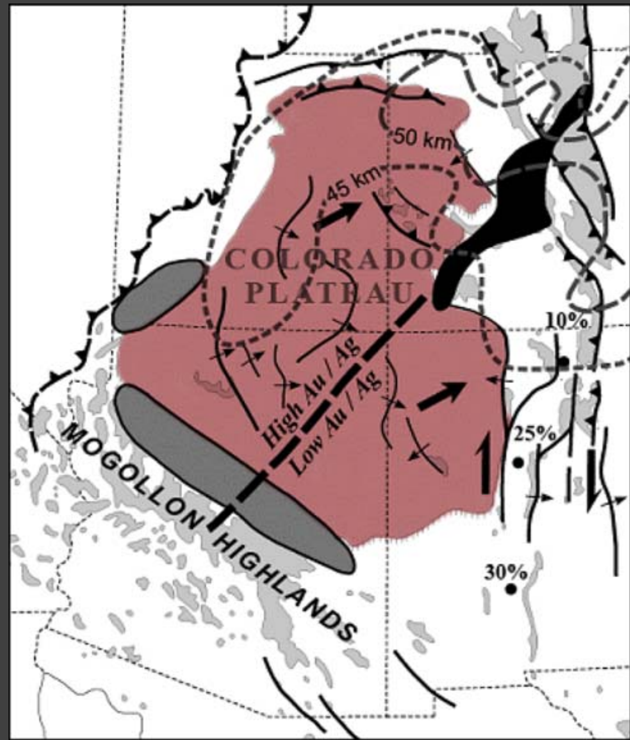
Though seldom utilized, the geology of the Mogollon Rim-Transition Zone of Arizona serves as a down-structure view of the Colorado Plateau basement/cover relationships.



Shear Zone Deformation Inferred Beneath Colorado Plateau



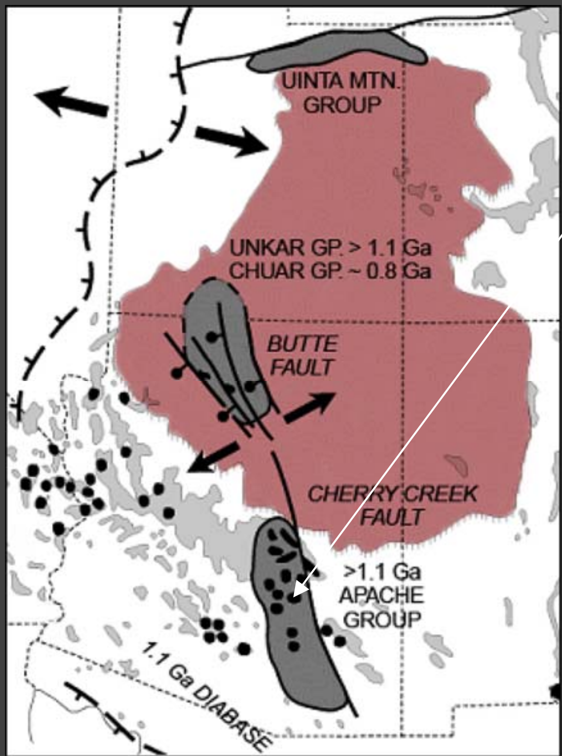
NE-trending Mesoproterozoic
Shear Zones



Late Cretaceous/Early Tertiary
Colorado Mineral Belt

Karlstrom and Humphreys, 1998

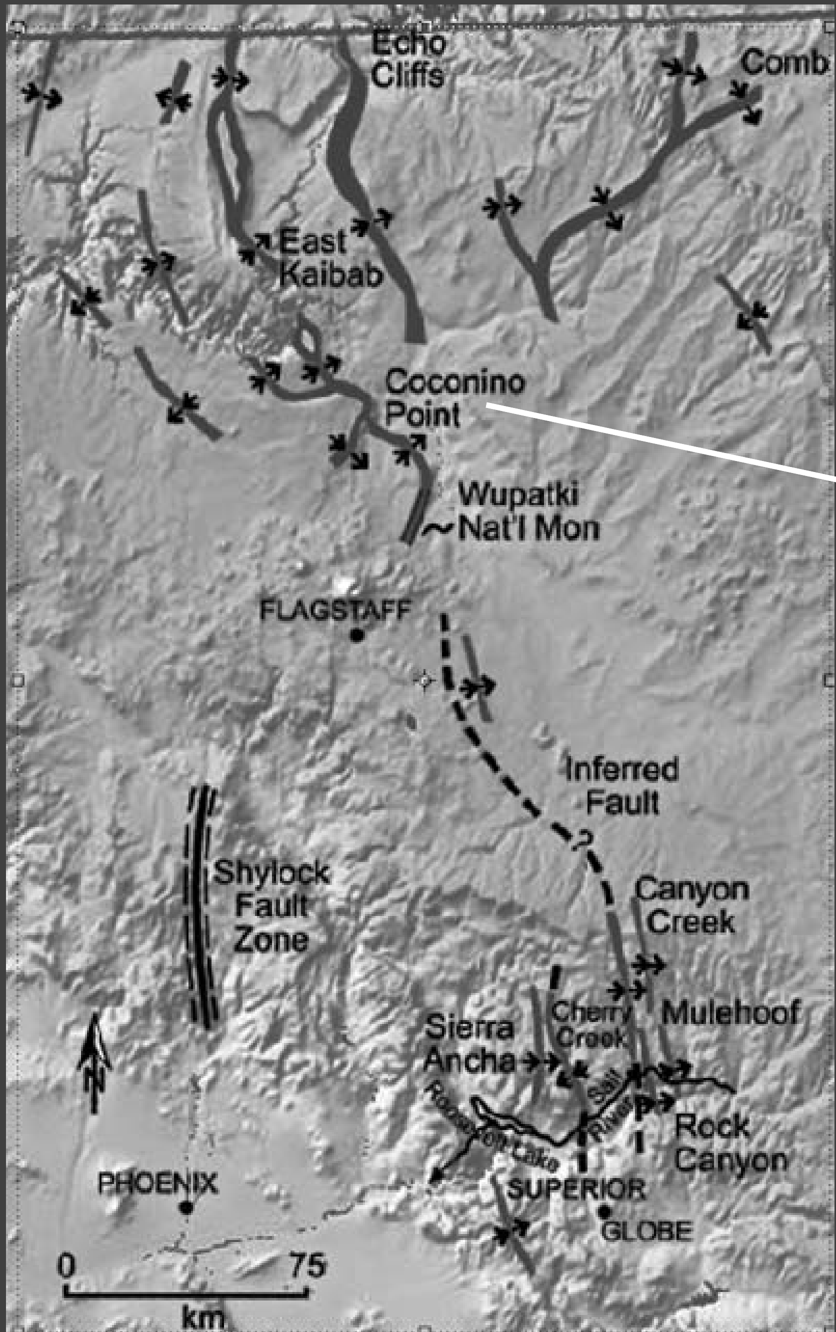
Transition Zone between Colorado Plateau and Basin and Range in Arizona contains important exposures of Reactivated Shear Zones.

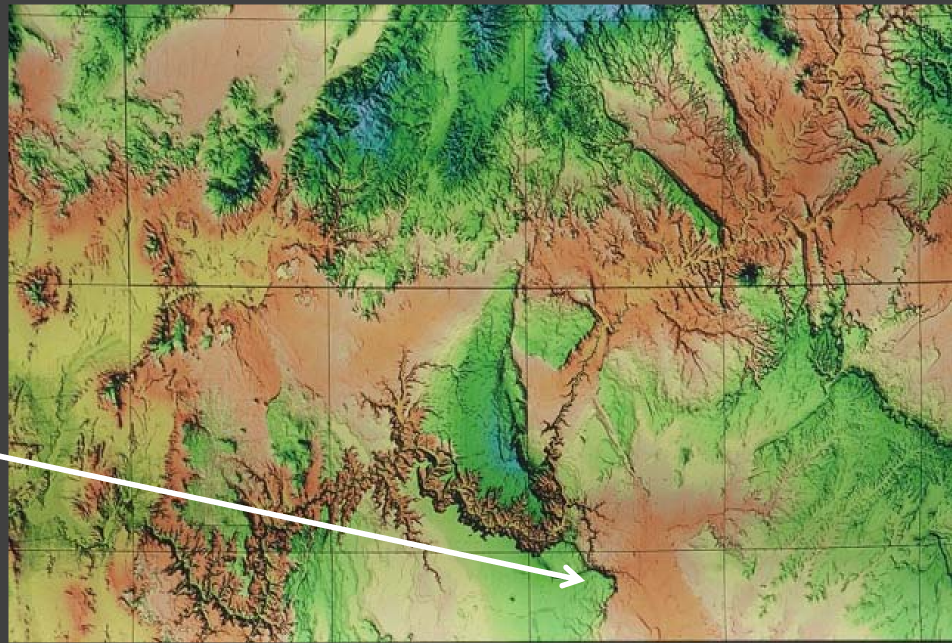


Karlstrom and Humphreys, 1998

The "Apache Uplift" (Davis et al, 1981) is a Colorado Plateu Uplift WITHOUT landscape expression. Boundary faults were Neoproterozoic extensional shear zones, positively inverted as Laramide reverse faults, and then negatively inverted as Basin and Range normal faults!!

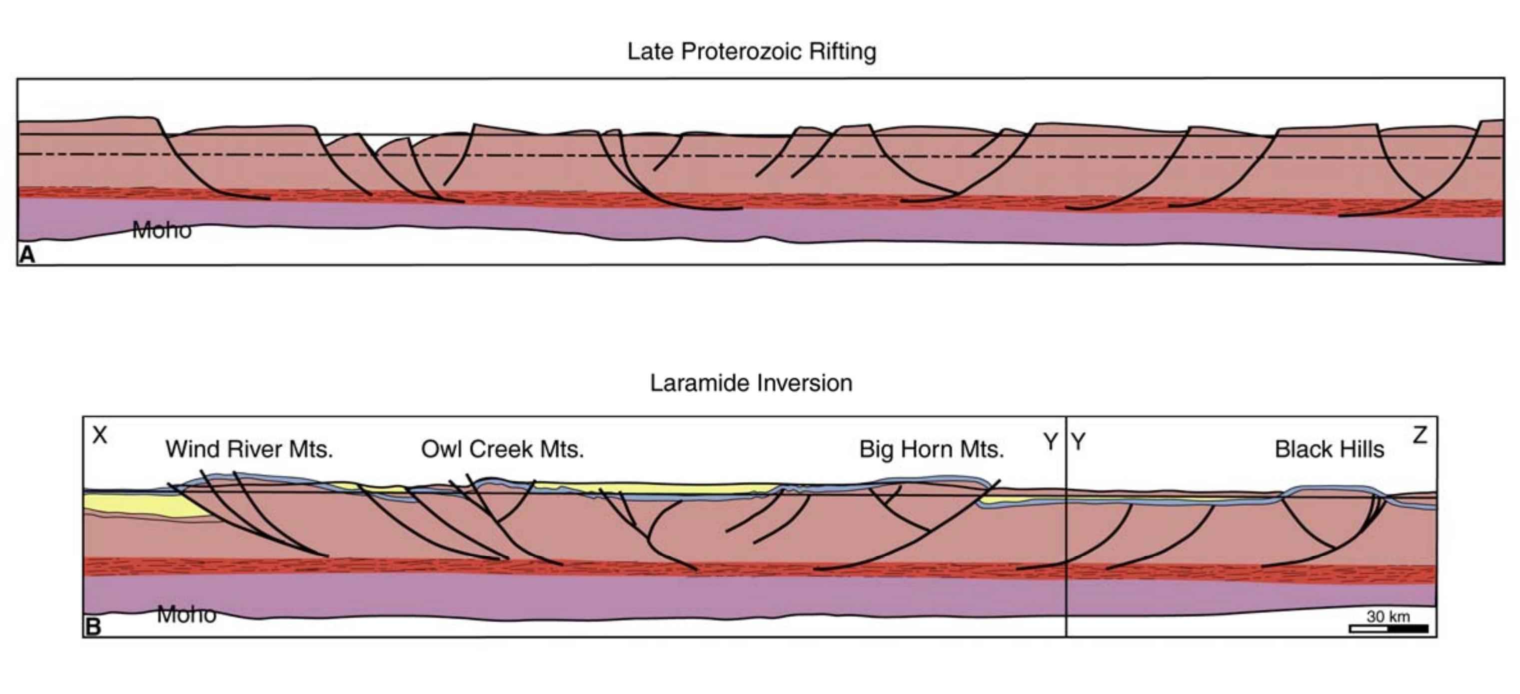
NW projection includes Butte Fault, exposed in the Grand Canyon.

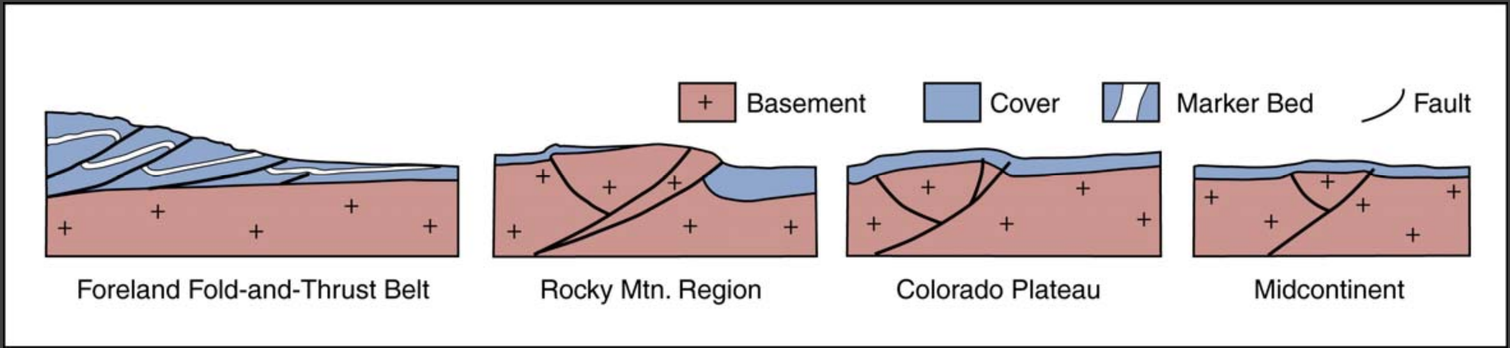




Location of Canyon Creek faulted monocline relative to 'classic' Colorado Plateau monoclines of Northern Arizona

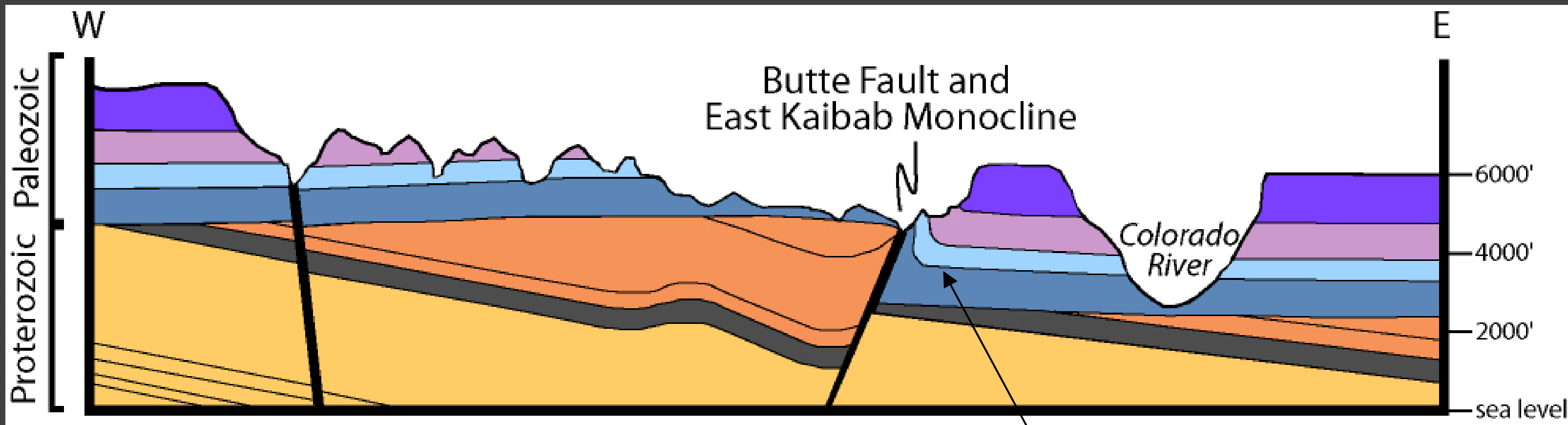
The Important Tectonic Inversion Story





From Marshak et al., 2000

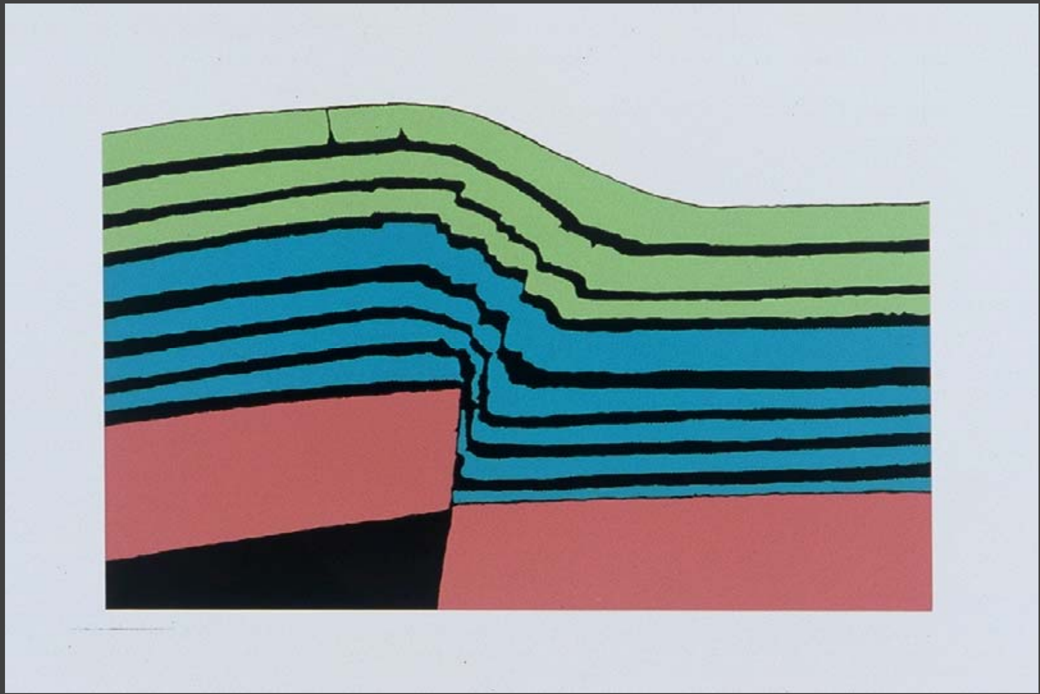
Classic Example of Tectonic Inversion, Grand Canyon

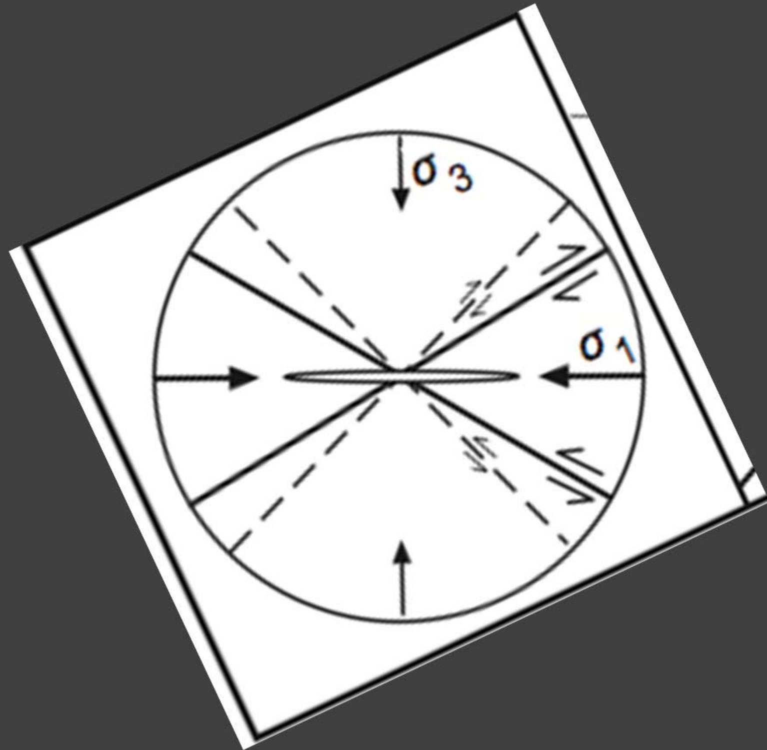


Tindall, 2000

Neoproterozoic strata in footwall of Butte fault

Important stress inversion work of Ze'ev Reches!

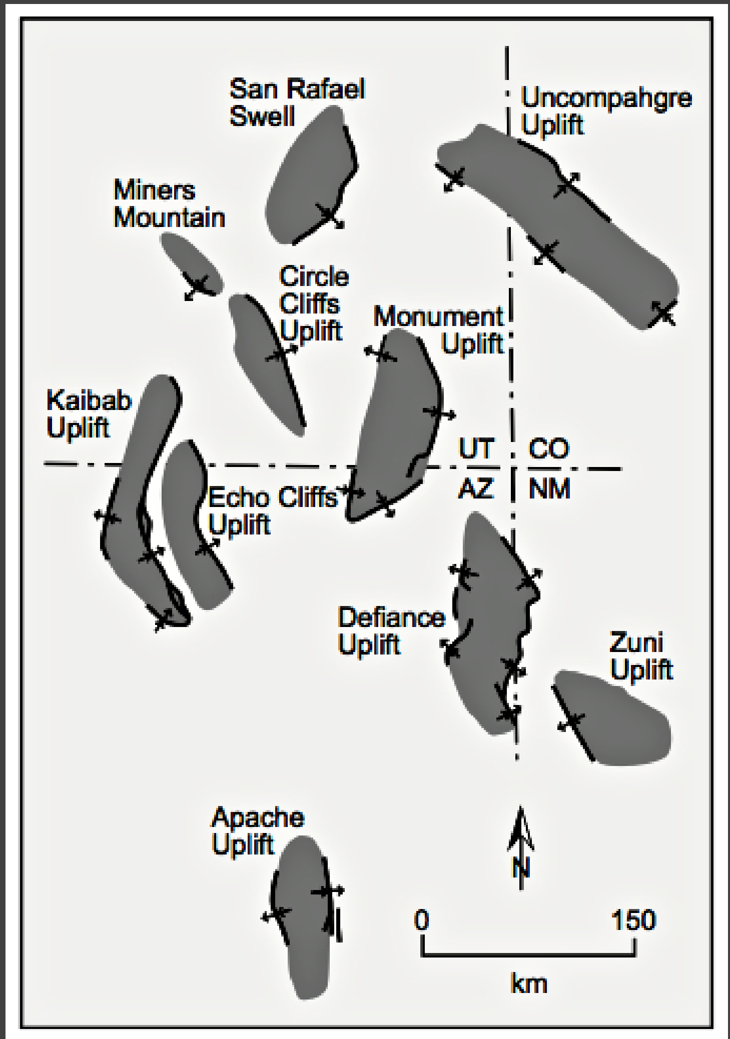




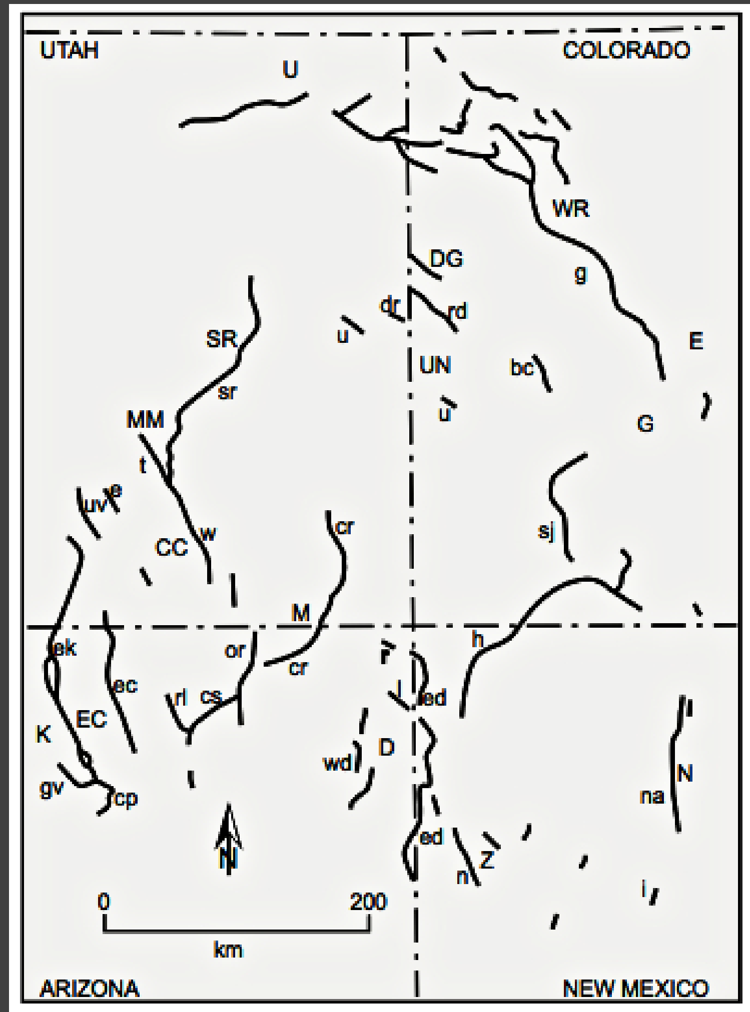
My crude physical modeling,
circa 1974.

Imagine the reality of 'forcing' slip on steep fault via horizontal tectonic loading!!

The Uplifts



The Monoclines



Davis, 1978, after Vince Kelley.

SOURCES OF DATA

EXPLANATION

Anticline

Syncline

Monocline

Monocline

Monocline

MAP LOCATION

SCALE

STRUCTURE MAP OF FOLDS IN PHANEROZOIC ROCKS COLORADO PLATEAU TECTONIC PROVINCE OF ARIZONA

by

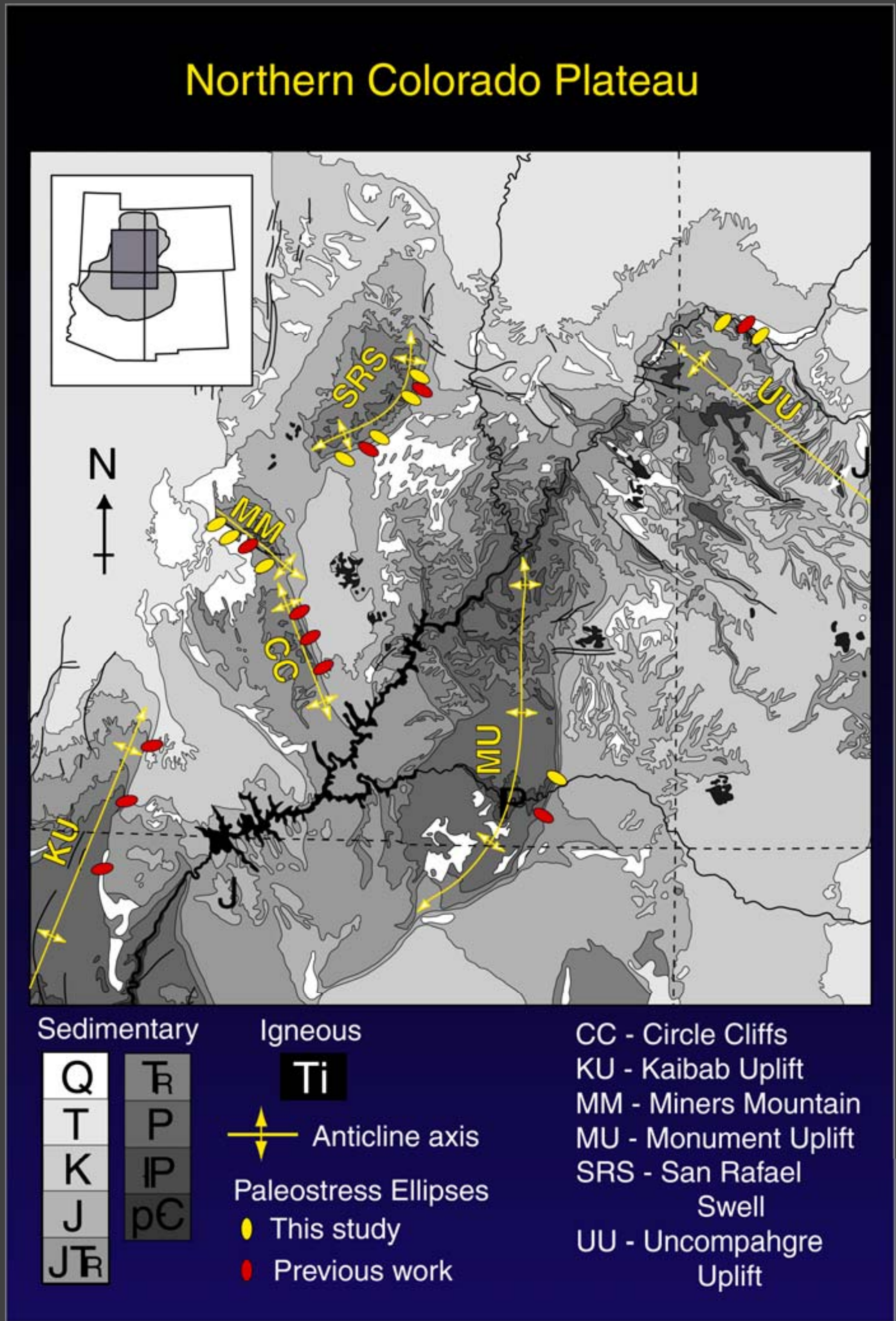
George H. Davis and Charles W. Kiven

1975

ACKNOWLEDGEMENT


WEST KAIBAB
KAIBAB
EAST KAIBAB
KAIBAB
VERMILLION
PARIA
Marble Canyon
ECHO CLIFFS
Cedar Ridge
ECHO
TUBA CITY
SMOKY MOUNTAIN
WAHWEAP
KAIBAB
EAST KAIBAB
KAIBAB

LAST CHANCE
COW SPRINGS
KAIBITO
RAINBOW
PIUTE
ROCK
ORGAN
ROCK
ORGAN ROCK
OLJETO
Kaibito
NAVAJO - HOPI
COW SPRINGS
JOINT
USE
AREA
RED LAKE
MALONEY
BIG MTN
PRESTON MESA
Tonalea PO

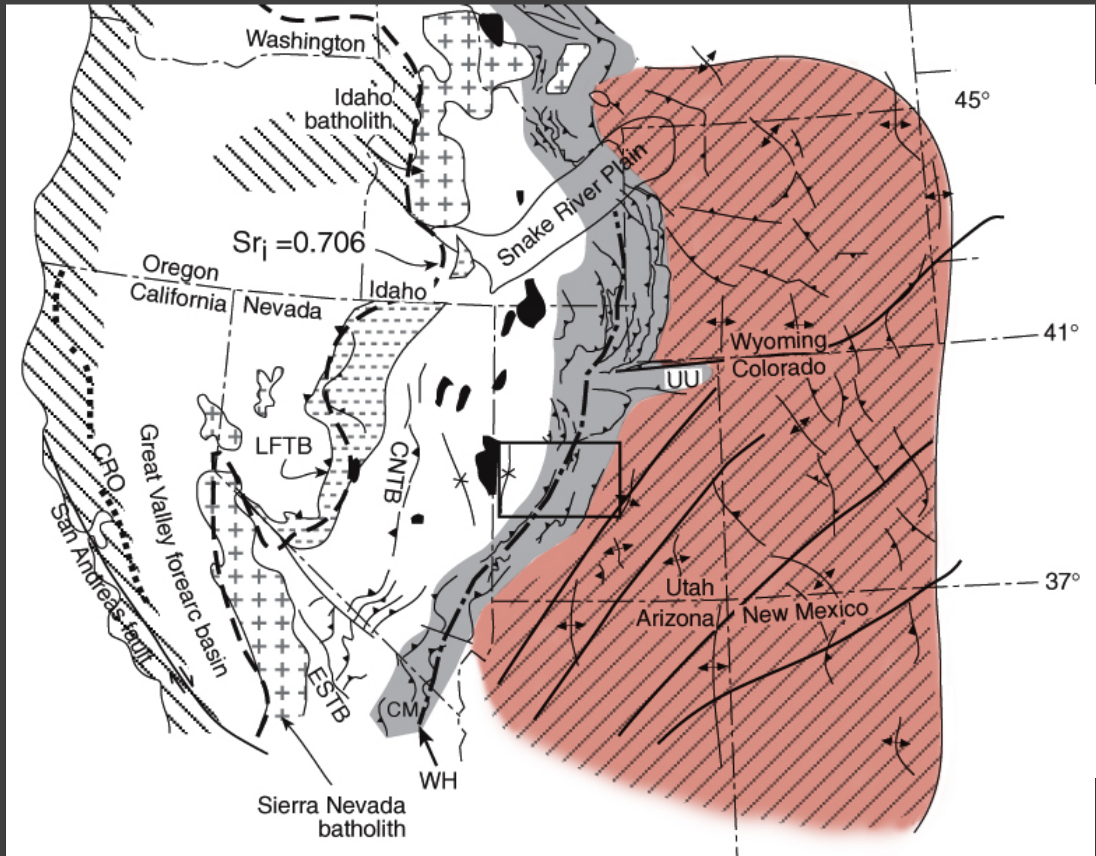


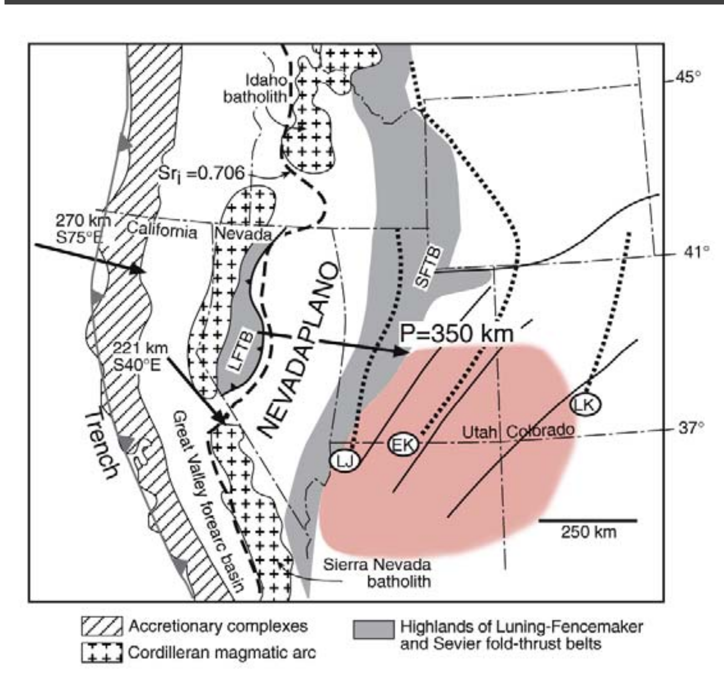
Origin of Variable Trends of the "Laramide-Style" Colorado Plateau Uplifts? Combination of:

* NE-trending uplifts may reflect Sevier edge loading.
* NW-trending uplifts may reflect Laramide flat-slab traction.

* Multiple trends may reflect Laramide reactivation of variably trending basement shear zones.

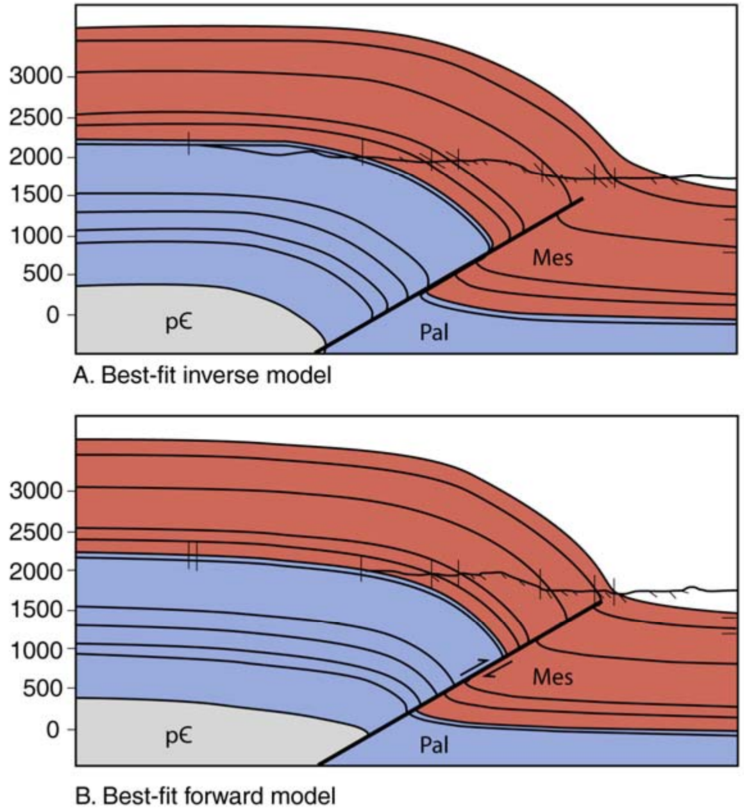
POSTSCRIPT on how faulting may contribute tectonically to the formation of a high plateau. Based on the antithesis of how faulting may operate during extension and collapse of a high plateau.





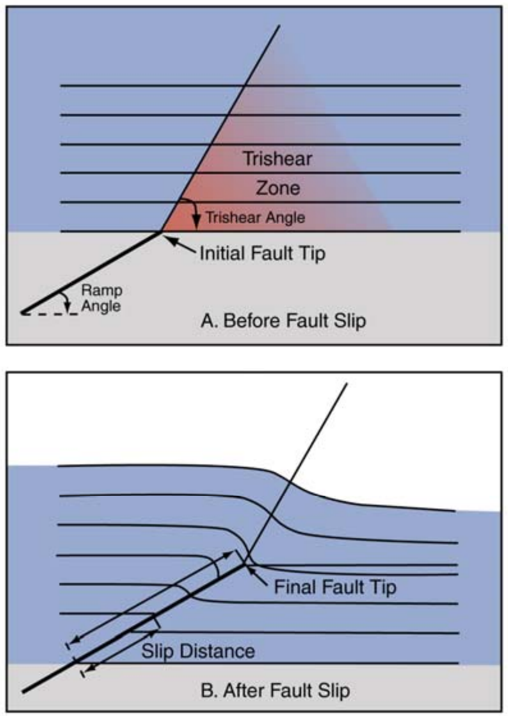
Consider the Nevadaplano as including the Colorado Plateau, at end of Paleocene.

Figures from DeCelles and Coogan, 2006



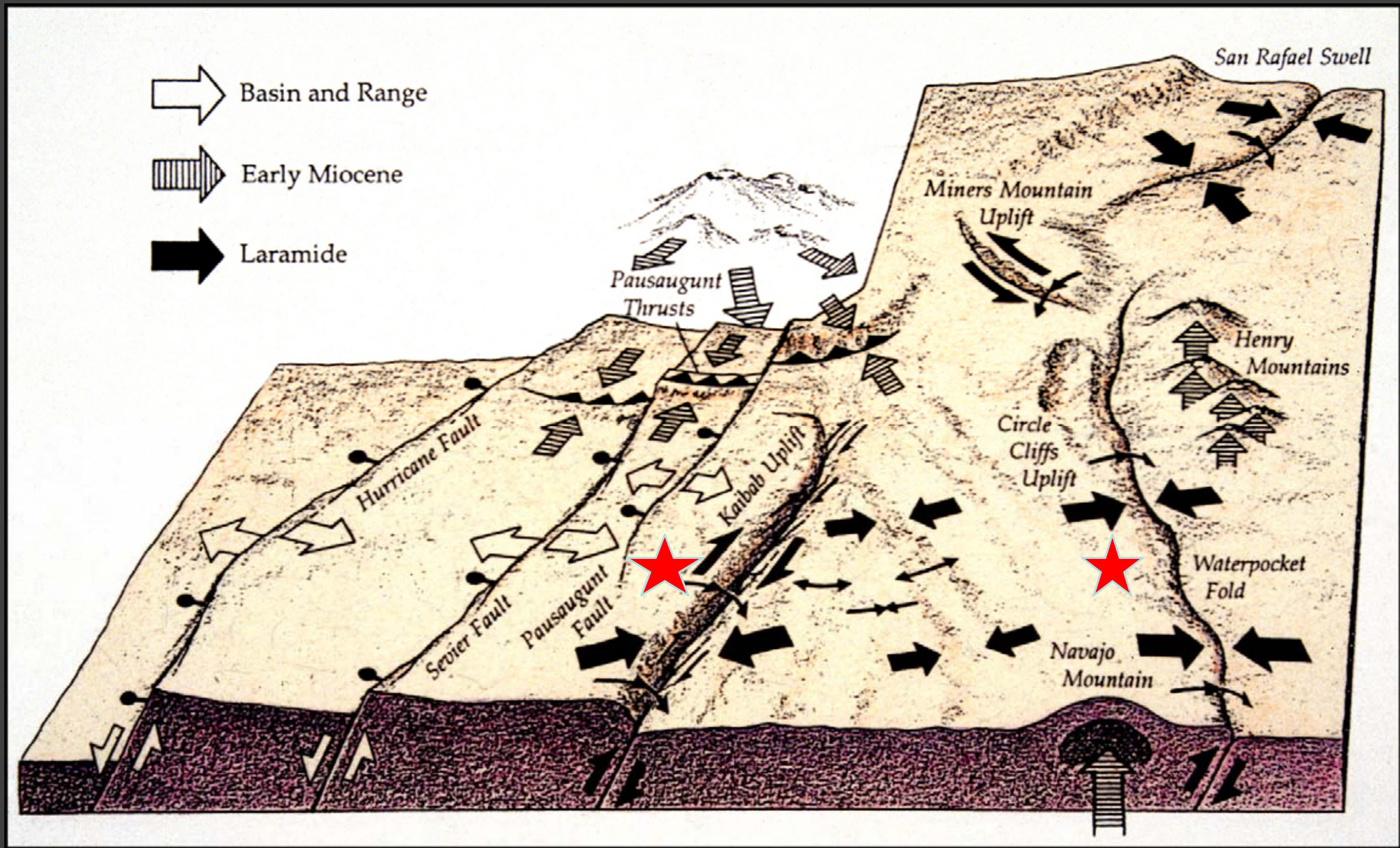
San Rafael Swell

Edge loading of the San Rafael Swell region may have produced the uplift and the monocline. Determining the blind-fault orientation at depth through tri-shear modeling, using Almendinger's freeware.



Figures from Bump and Davis, 2003

We'll take a closer look at the Kaibab and Circle Cliffs Uplifts



At the level of the Kaibab/Moenkopi, Paleozoic/Mesozoic contact.

At the level of the Navajo/Dakota, Jurassic/Cretaceous

The East Kaibab Monocline is the First Ever Described, by John Wesley Powell (1873)
In Paiute language, "*Kaibab*" = "*Mountain Lying on its Side*"

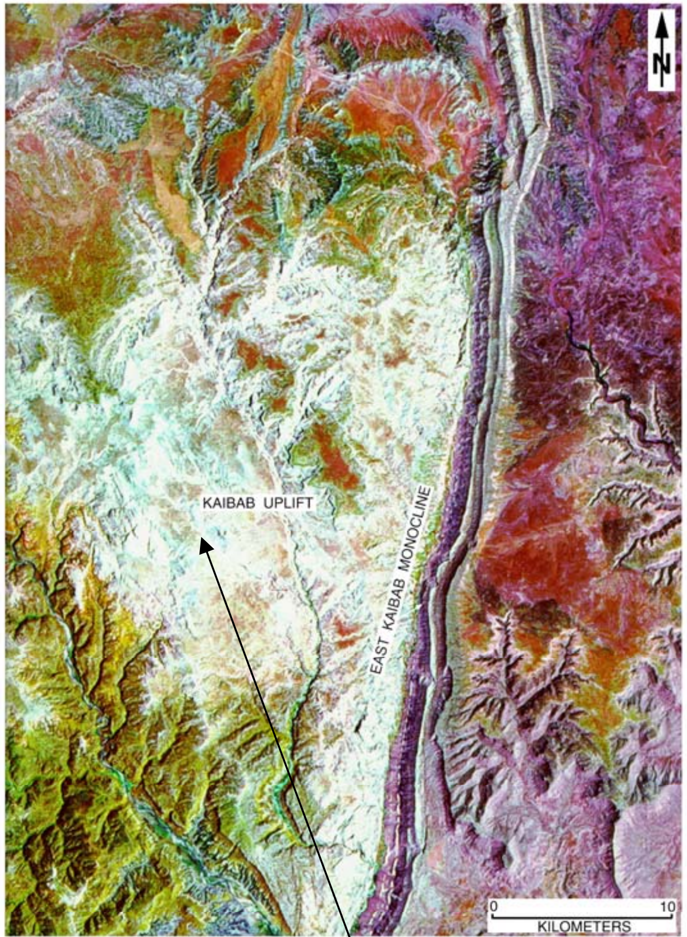
Jurassic Navajo Sandstone

Eocene Claron Formation (horizontal) rests in angular unconformity on inclined beds of the monocline.

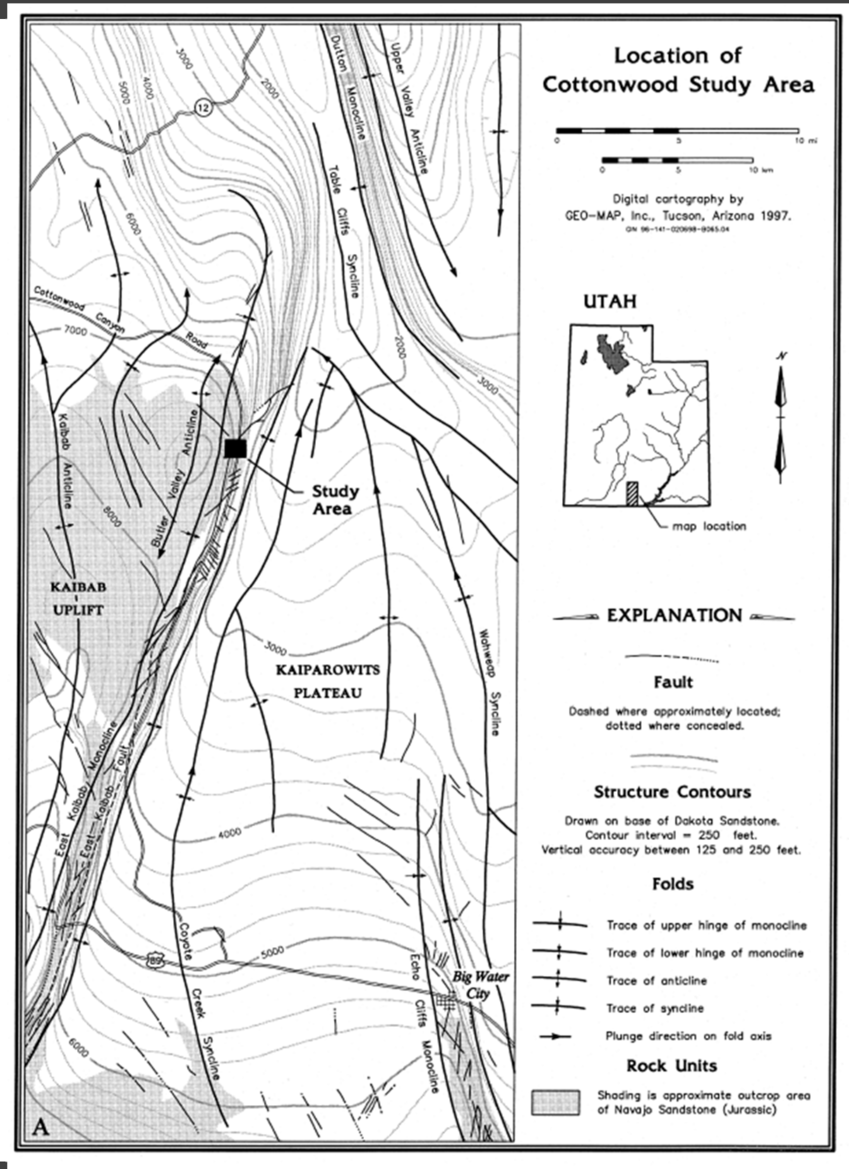
Lower Cretaceous Dakota Sandstone.

Lower Cretaceous black shale of the Tropic Formation.

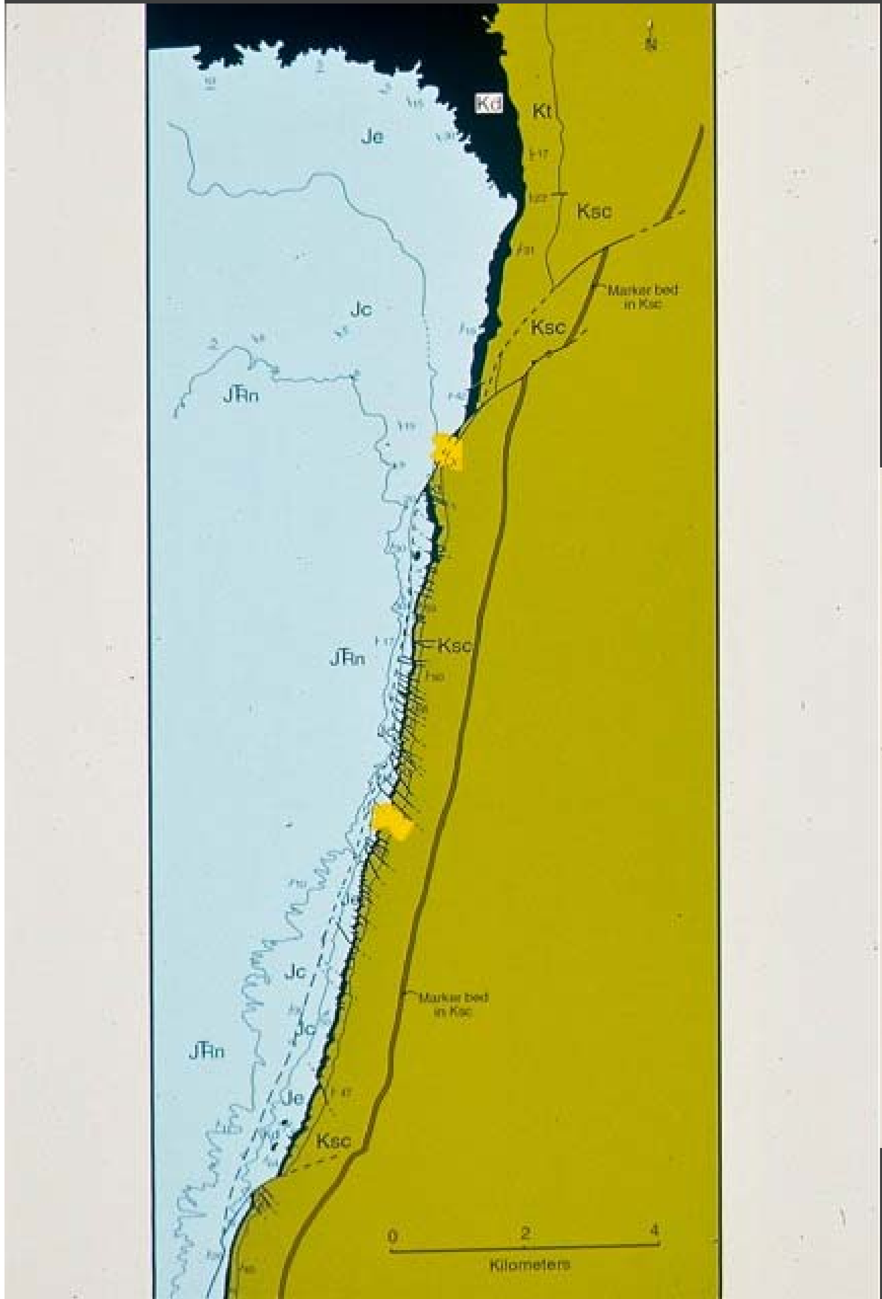
Overhead Views of the Kaibab Uplift and East Kaibab Monocline

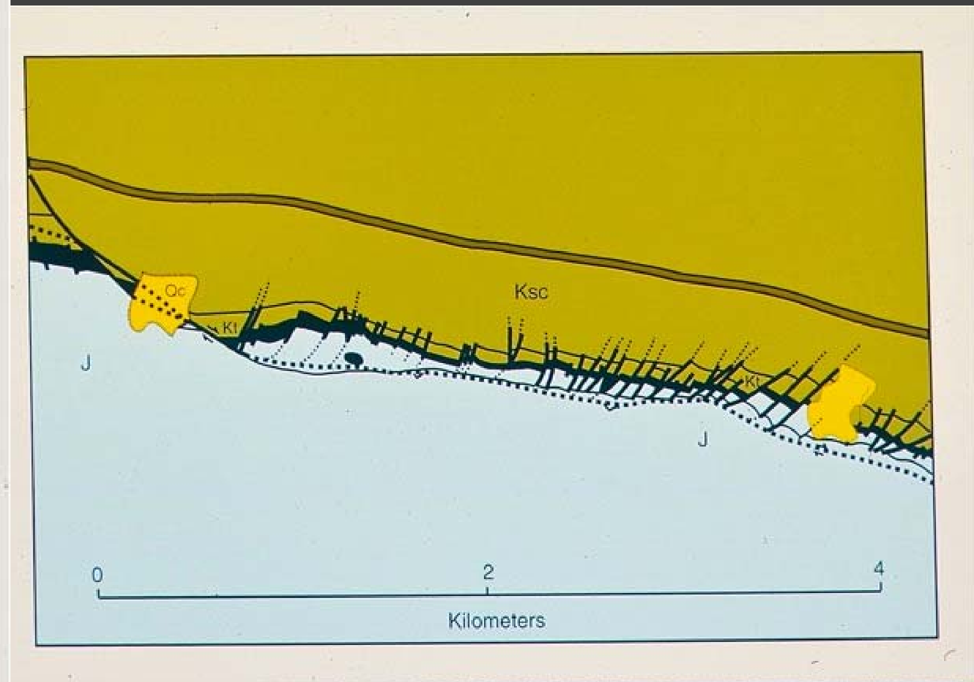


Kaibab Uplift

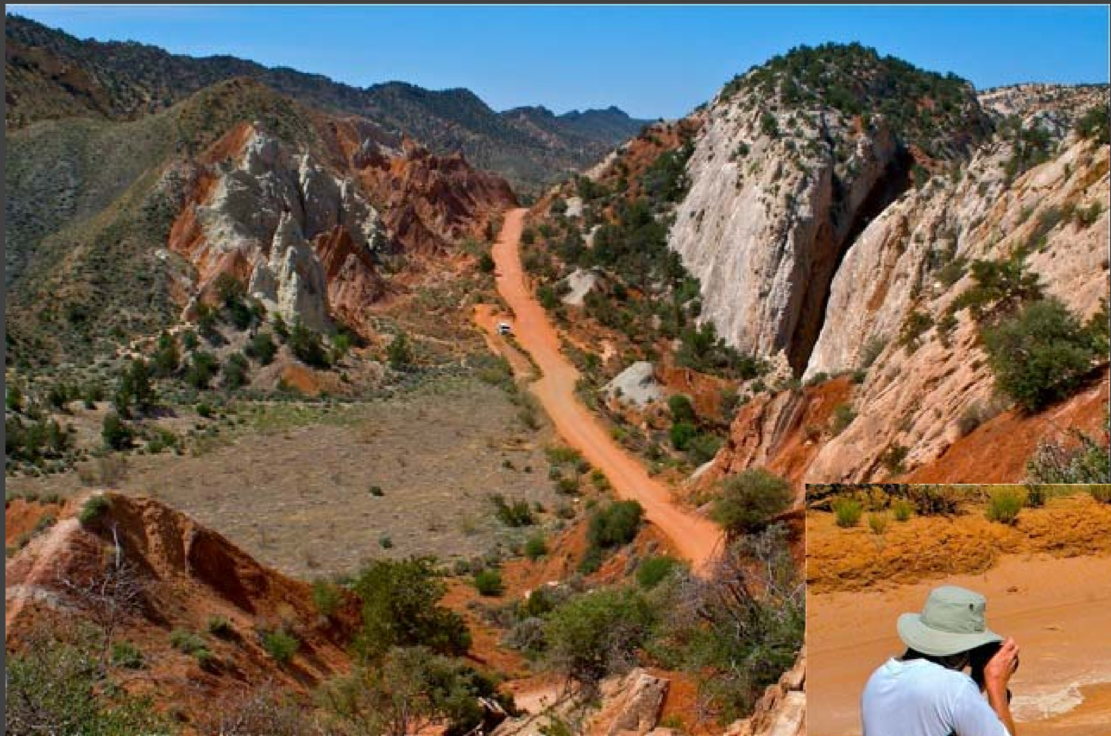


Mapping by Babenroth and Strahler (1945)



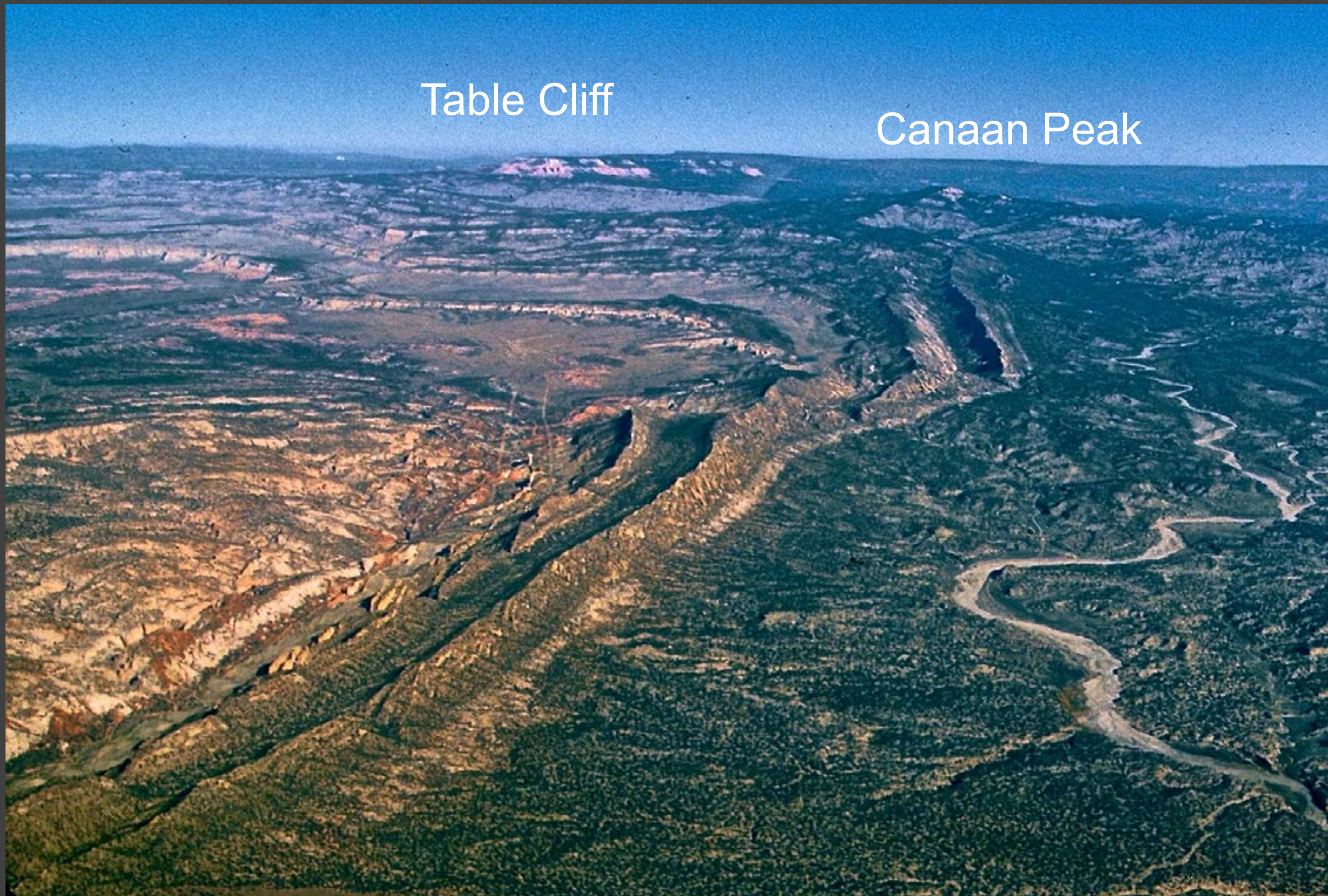


Freshly bladed Cottonwood Road reveals smallest-scale faulting



One of the left-handed faults

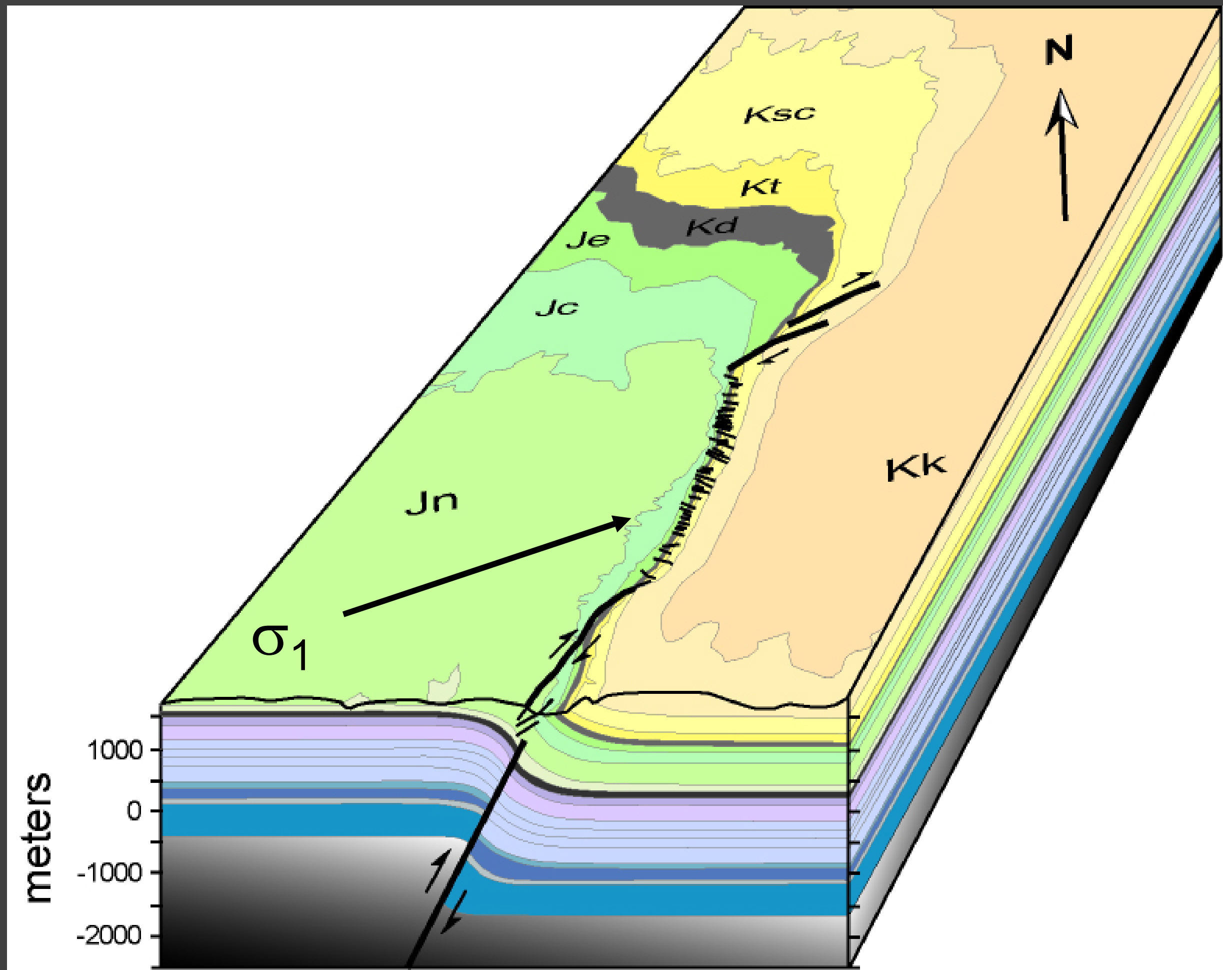
Laramide Structures Along the East Kaibab Monocline



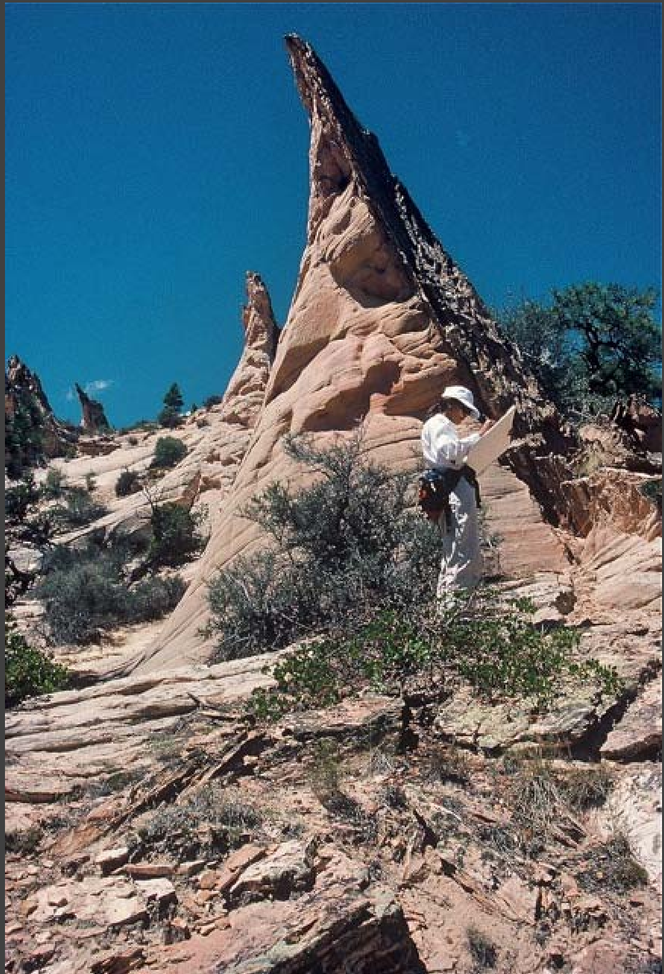
Northerly plunge ‘nose’ of the East Kaibab monocline and Kaibab Uplift.

It took a while, but I tracked down the main fault zone, which indeed is reverse right-handed, with 30º-plunging mullions and slickenlines. The Bingo Locality.

East Kaibab Monocline has formed in TRANSPRESSION, 'forced' by right-handed reverse faulting

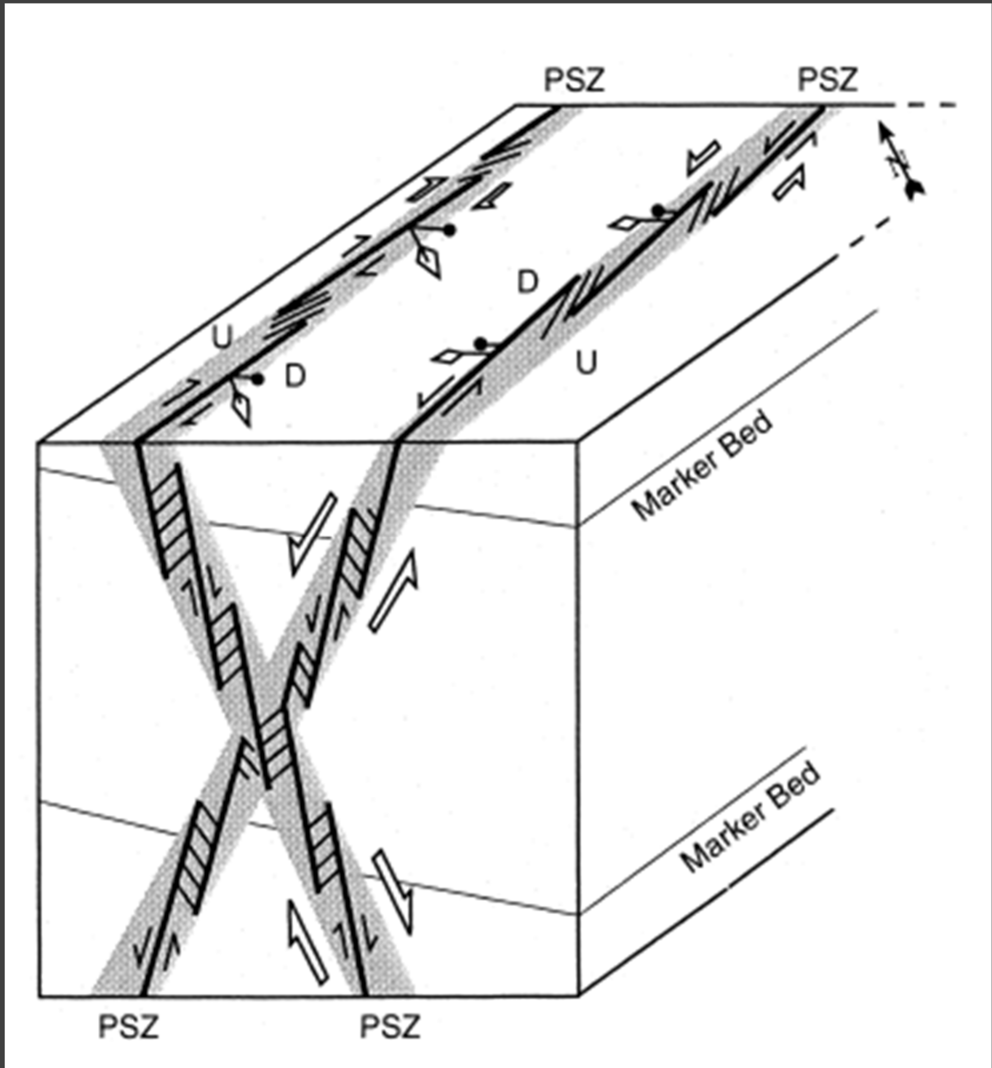


Tindall, 2000

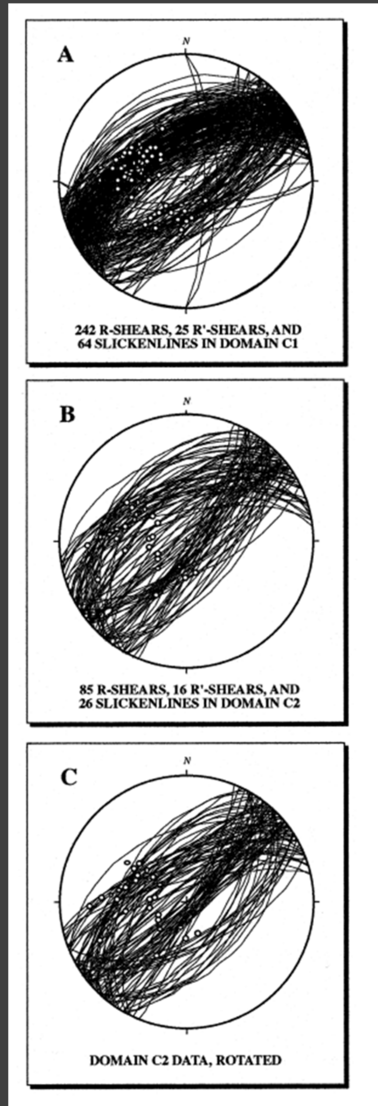


Deformation band shear zones in
Navajo Sandstone.

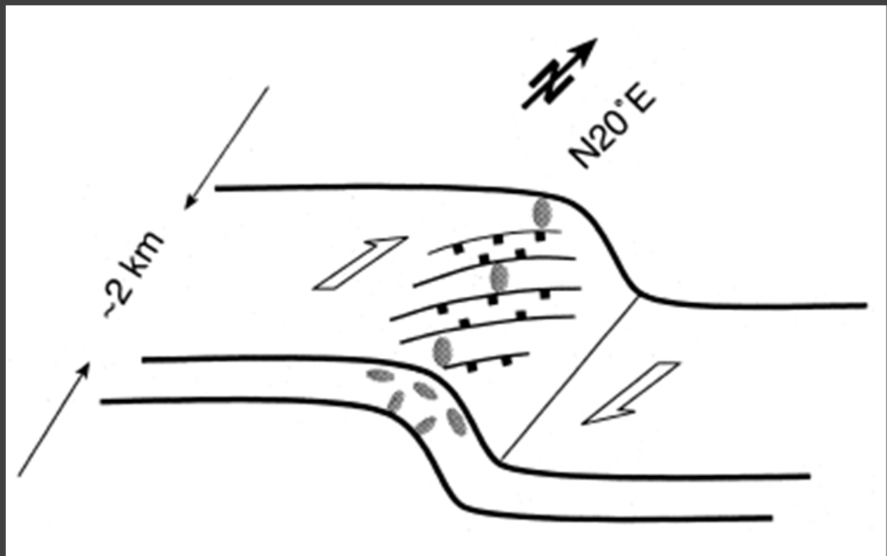
The deformation band shear zones along the East Kaibab Monocline are arranged as Conjugate Riedel Shears.



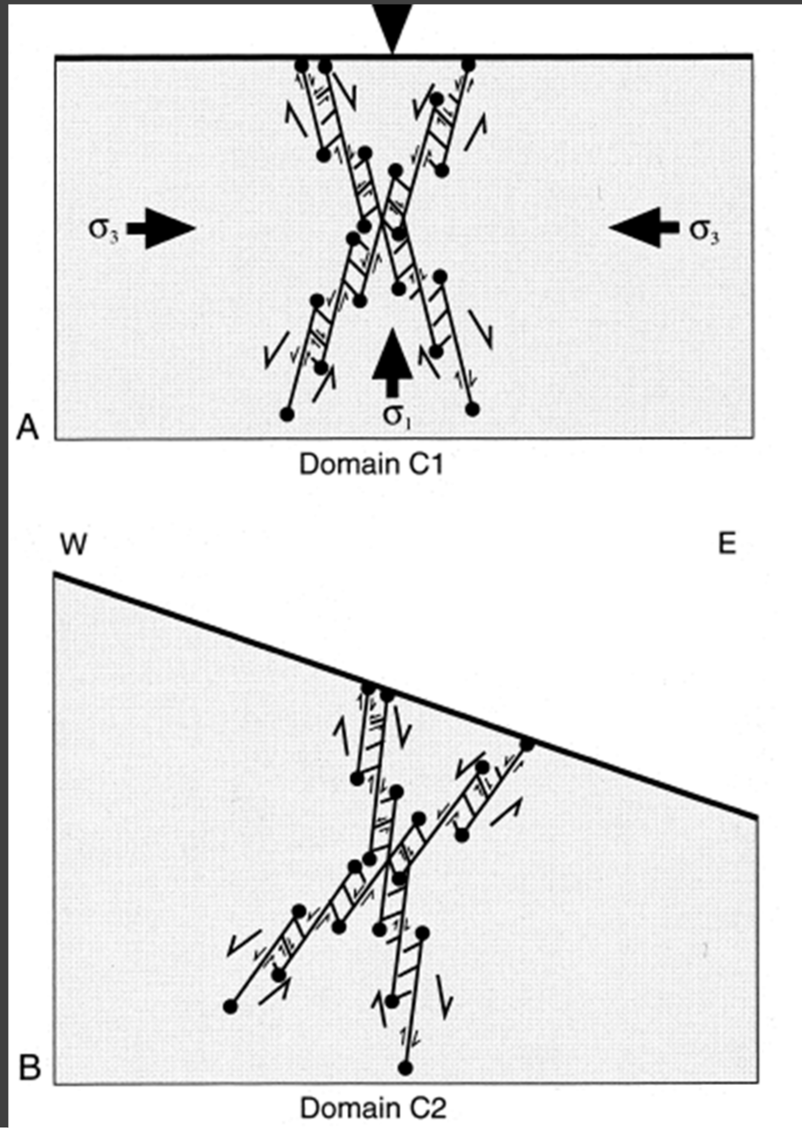
Davis, 1999



Relation of Deformation Bands to Transpressional Formation of East Kaibab Monocline



Davis, 1999



Learning from active plate setting.

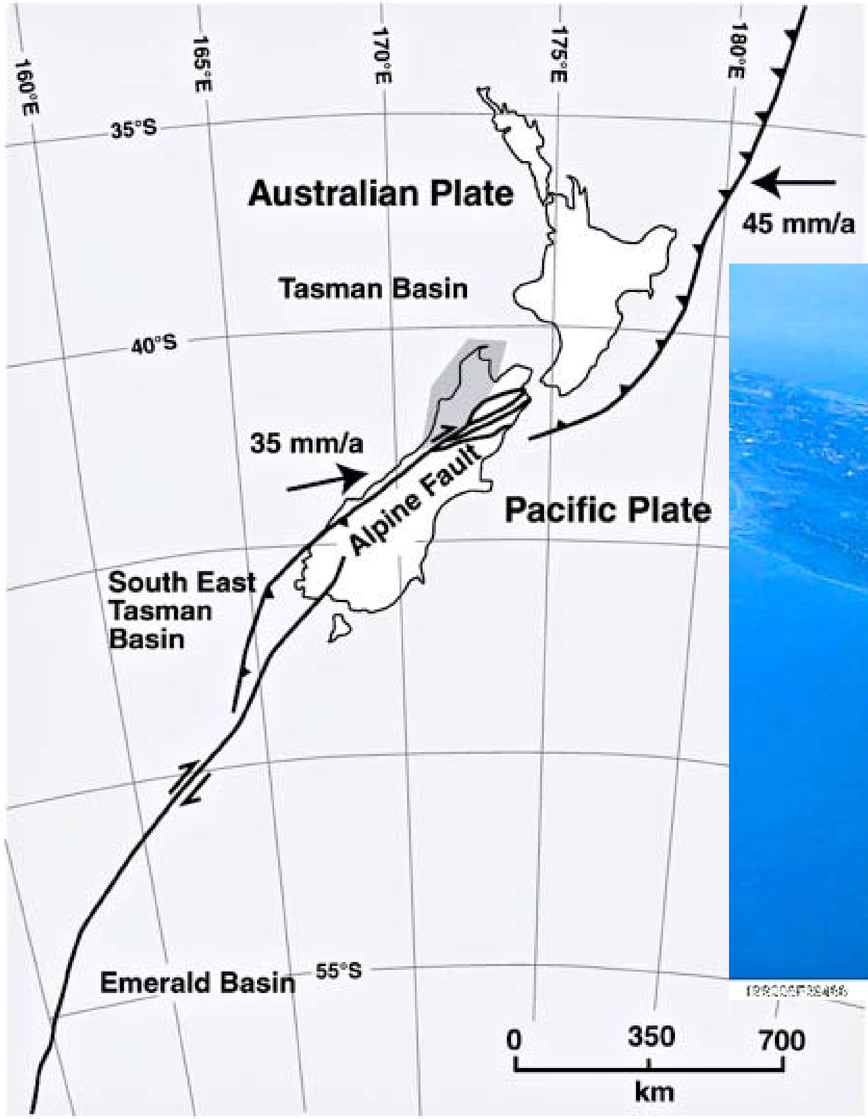
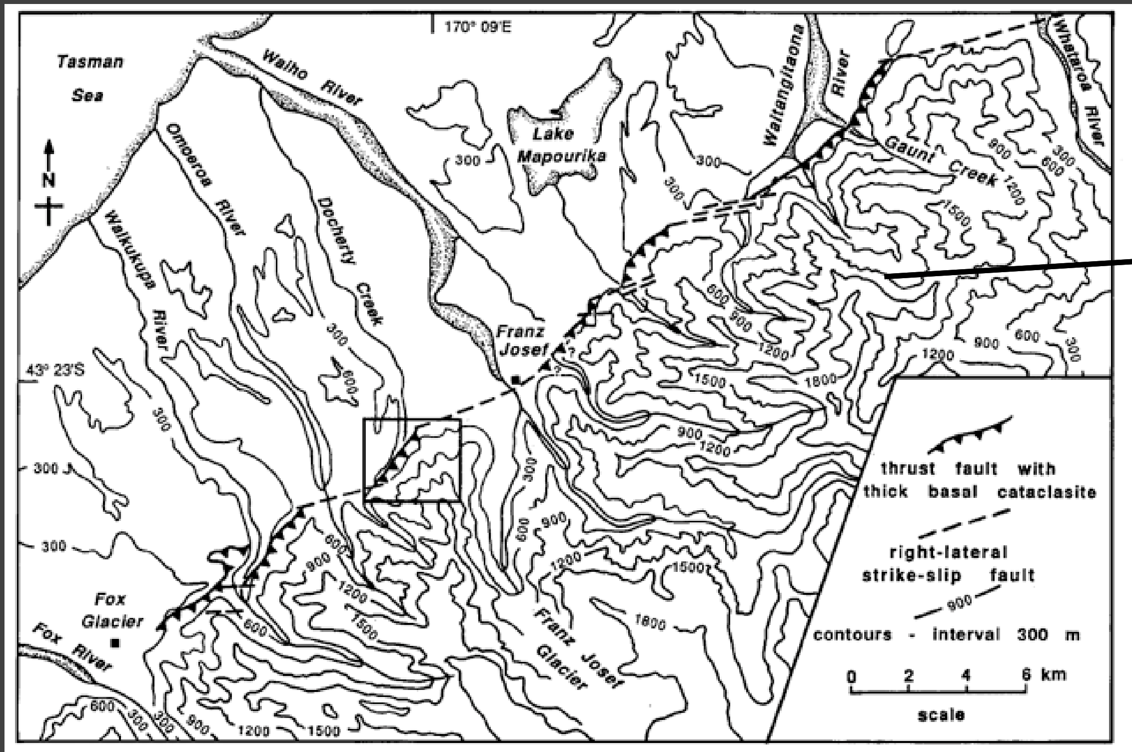


Figure 3.1
Reprinted from *Journal of Structural Geology*, v. 28, Ghisetti F. C. and Sibson R. H., Accommodation of compressional inversion in north-western South Island (New Zealand): Old faults versus new?, p. 1994–2010, © 2006, with permission from Elsevier.

Note Velocity Vector, ENE, west block of Alpine fault.

Along segments of the Alpine fault proper, beautiful partitioning of the oblique slip.



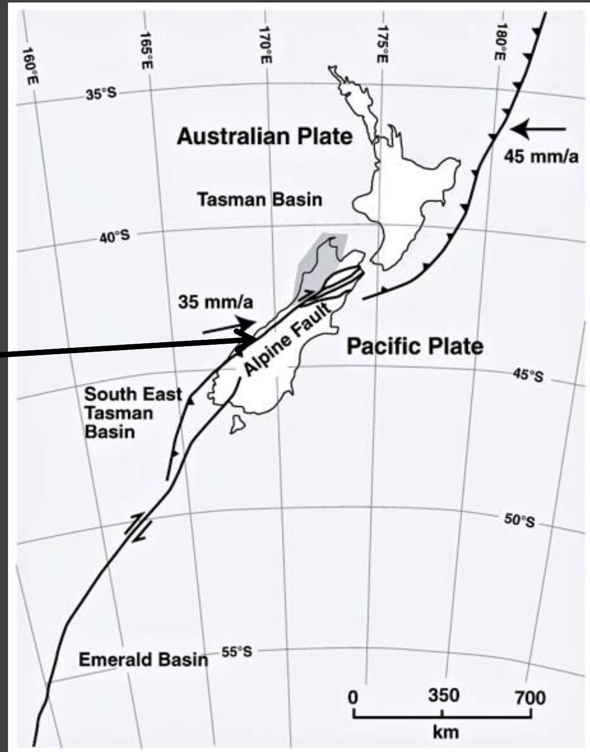
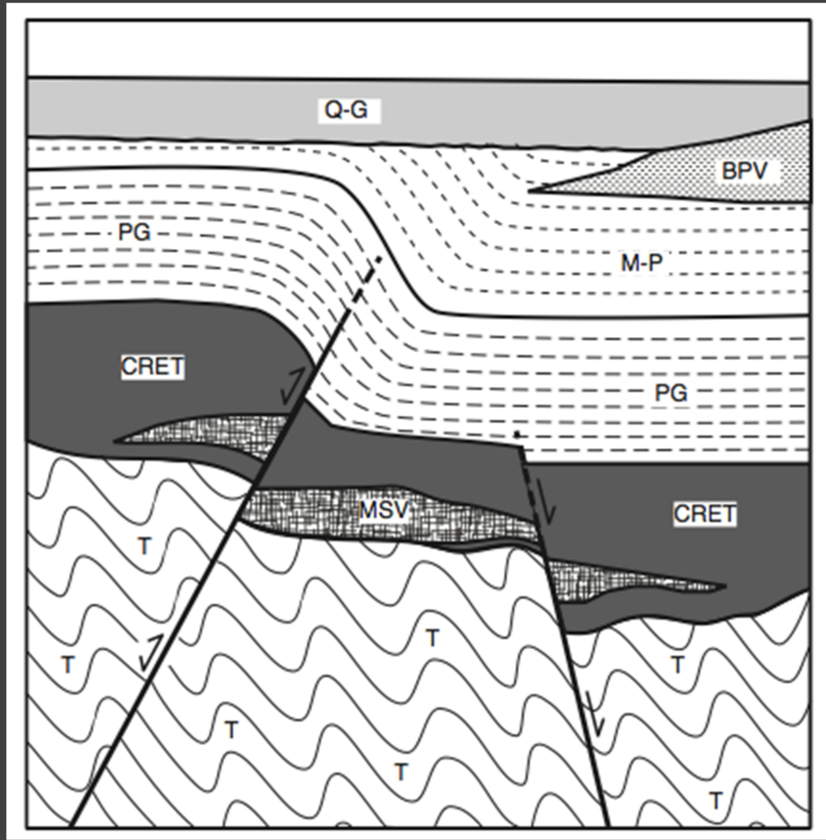


Figure 3.1
Reprinted from *Journal of Structural Geology*, v. 28, Ghisetti F. C. and Sibson R. H., Accommodation of compressional inversion in north-western South Island (New Zealand): Old faults versus new?, p. 1994–2010, © 2006, with permission from Elsevier.

But what about inboard from the transform boundary, in the region of Christchurch?

The subsurface setting (appropriately) includes Cretaceous normal faulting, and tectonic inversion.



Sibson, Ghisetti and Ristau, 2011, “Stress control of an evolving strike-slip system during the 2010-2011 Canterbury, New Zealand, Earthquake Sequence.

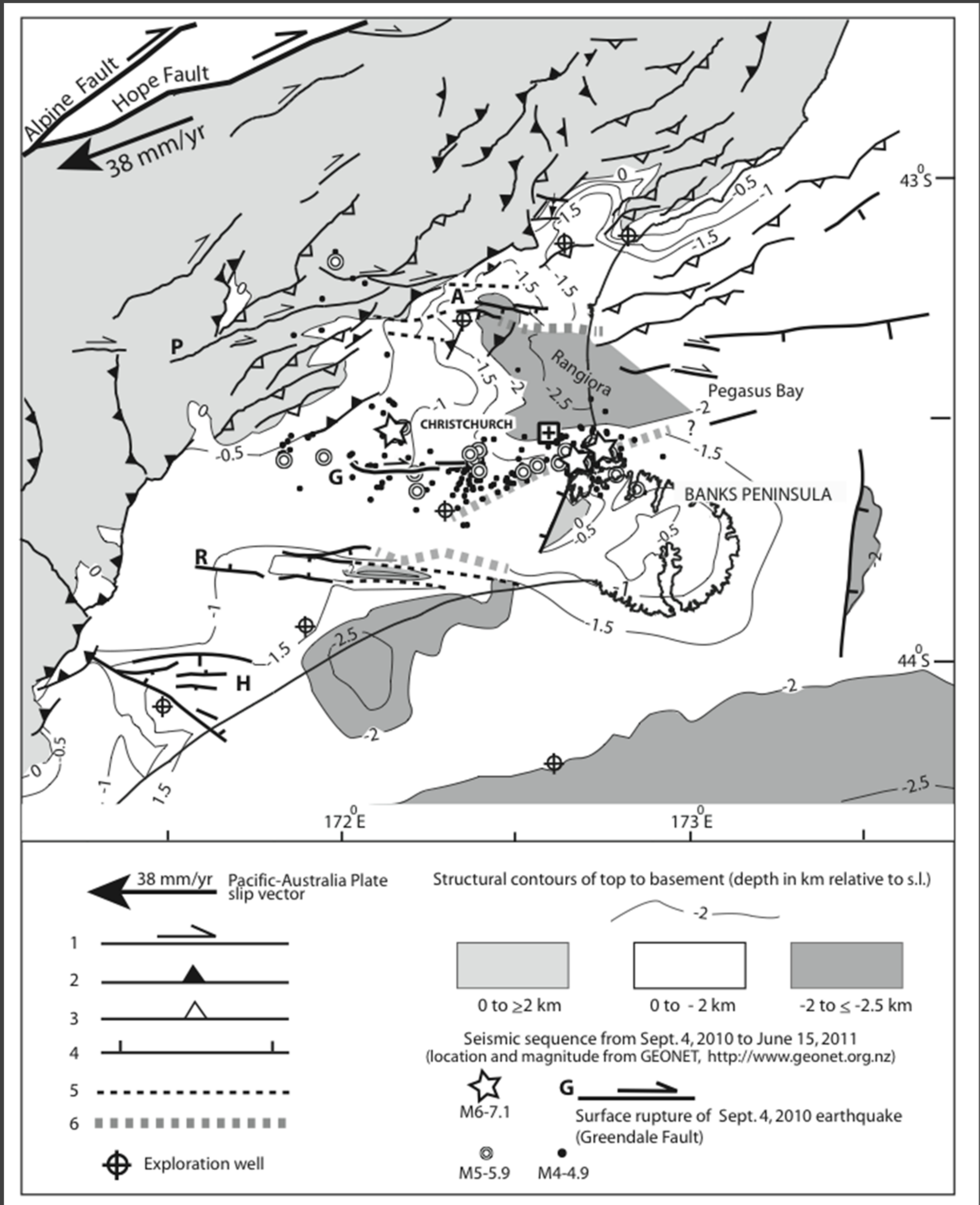
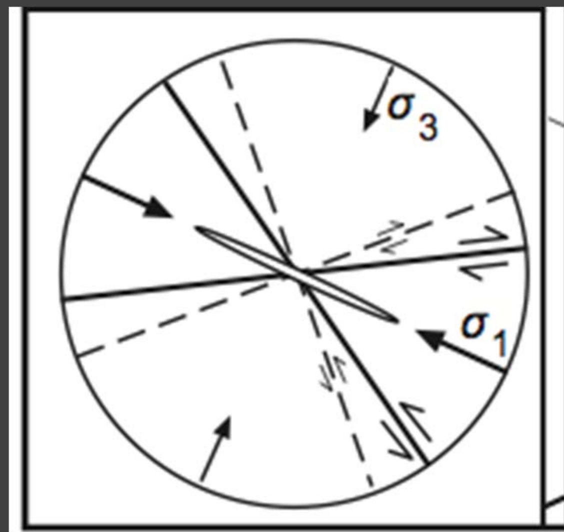
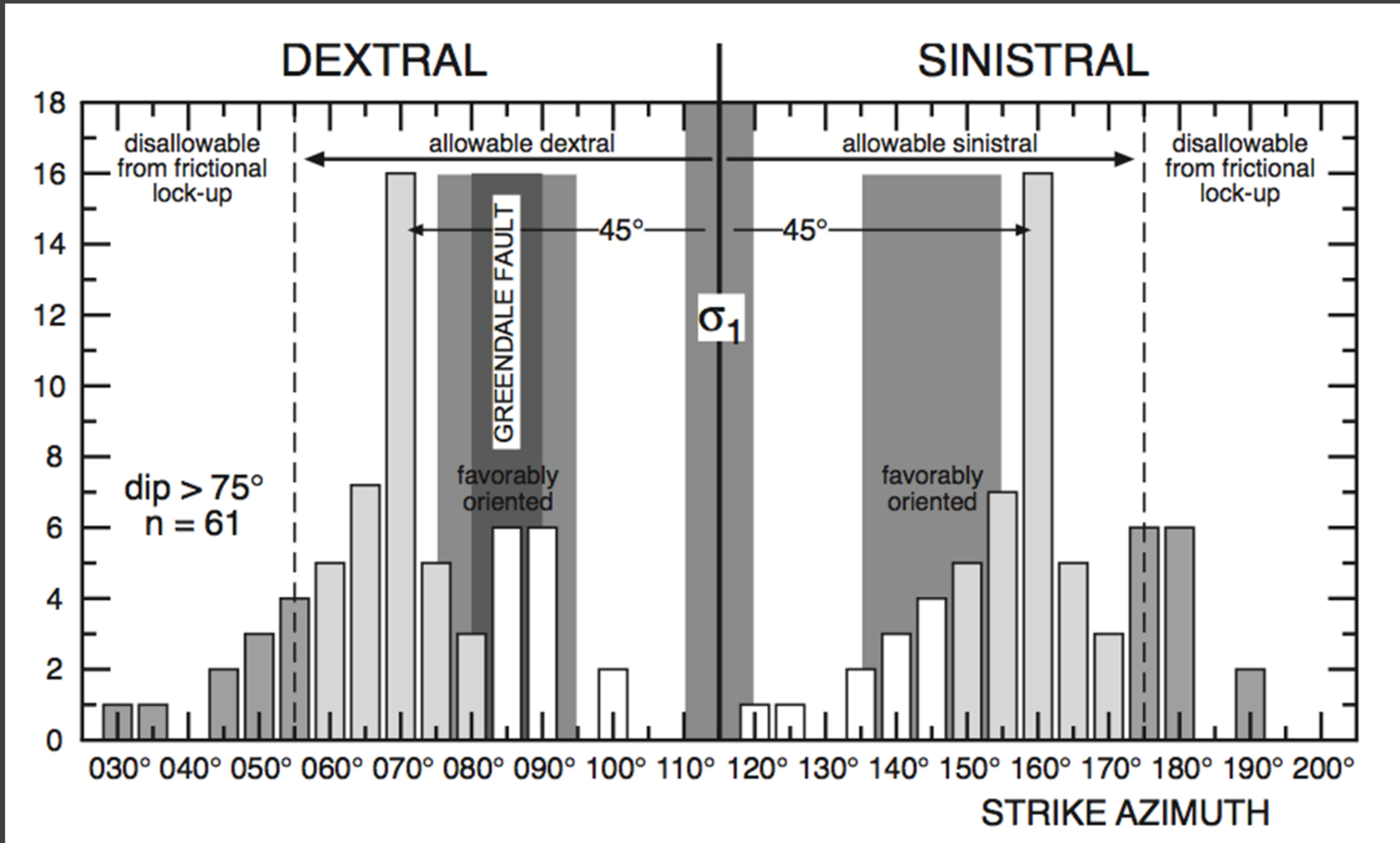


Figure 1 from Sibson et al.

Inversion of focal mechanisms and fault slip result in determination that direction of greatest principal stress is 115°, i.e., ESE.

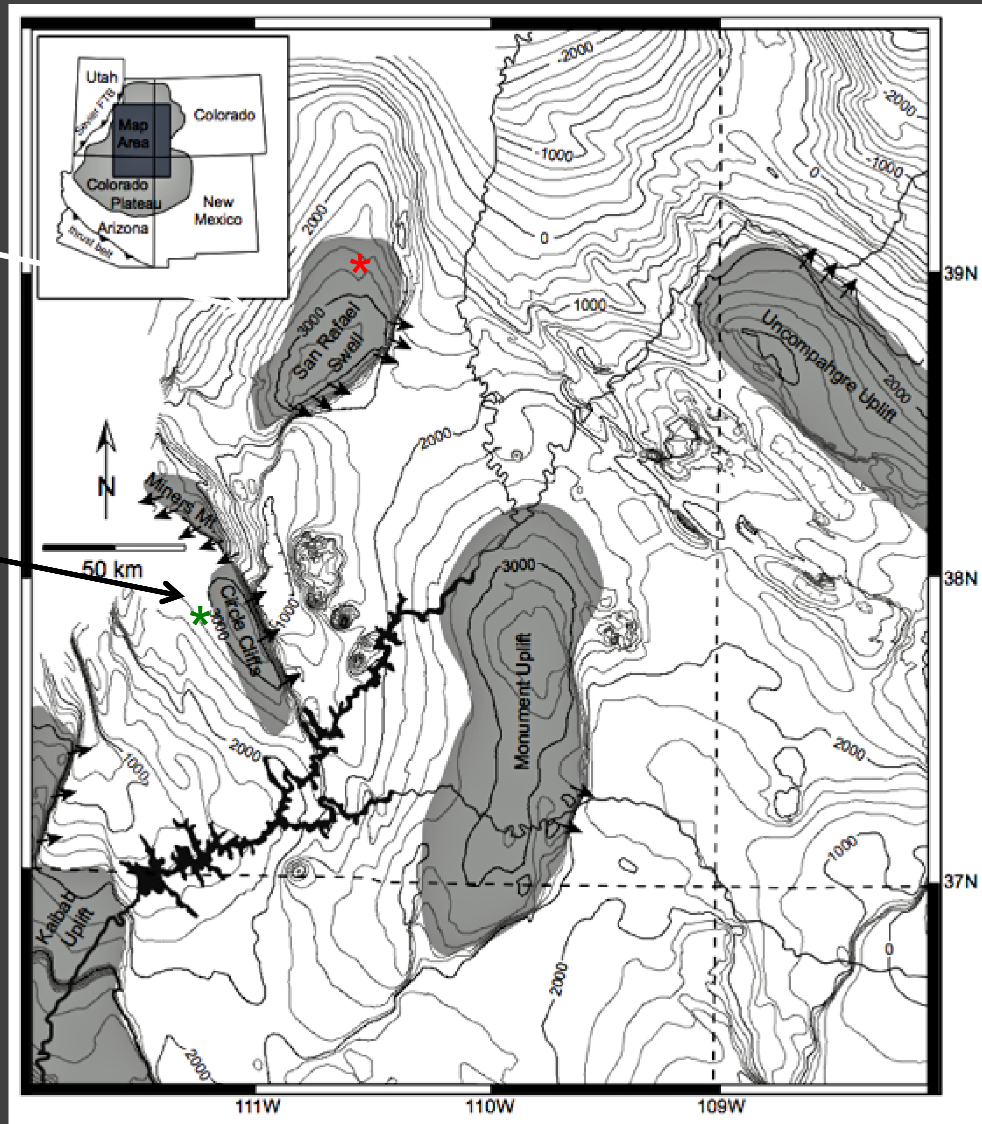




Exploration of potential reactivation of pre-existing fault surfaces. Frictional lockage occurs at 55° - 60° from σ_1.

*The San Rafael uplift may have been ‘forced’ by the thrust front of the Sevier belt.

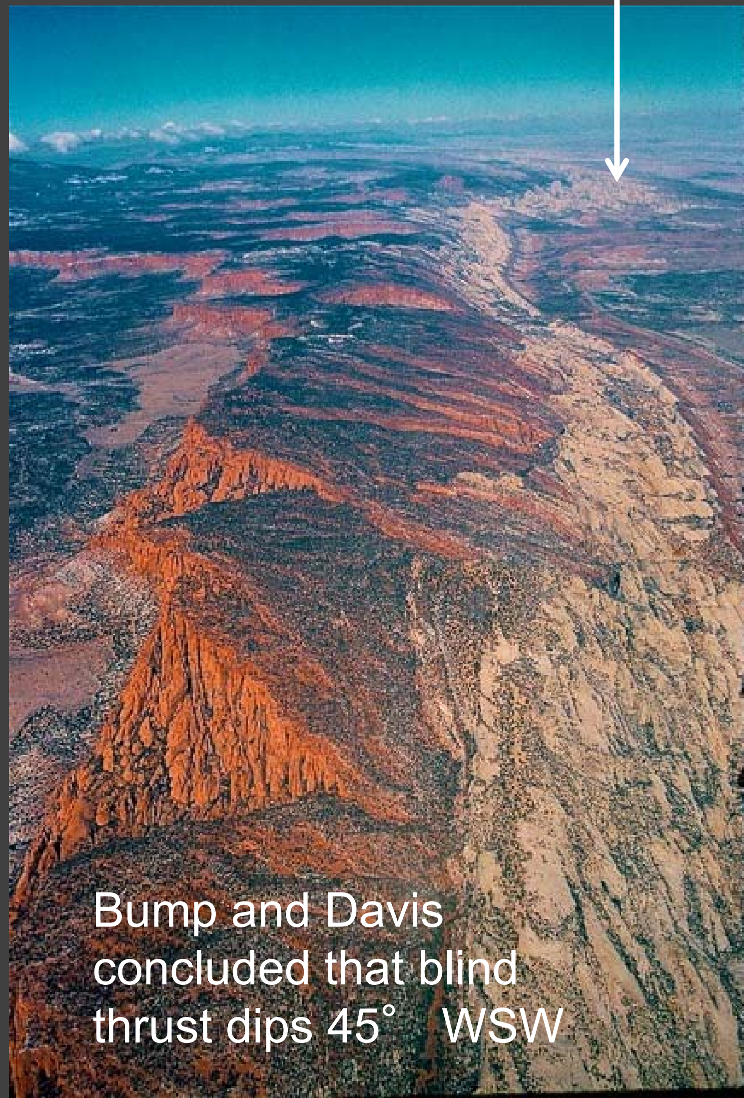
*Shifting now to the Circle Cliffs Uplift, which formed perpendicular to Laramide far-field greatest principal stress.



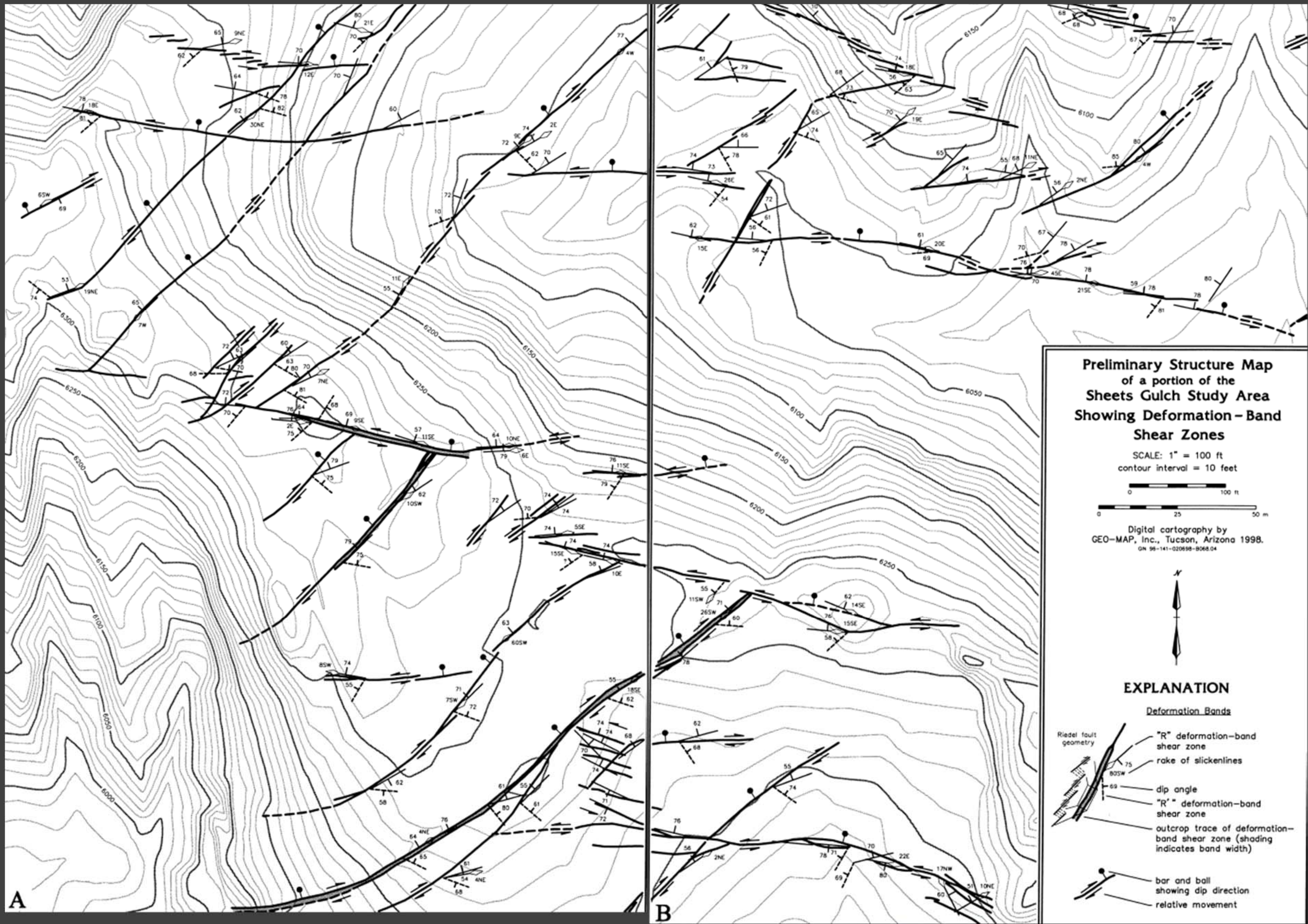
“Noise” along the Waterpocket Fold

Sheets Gulch

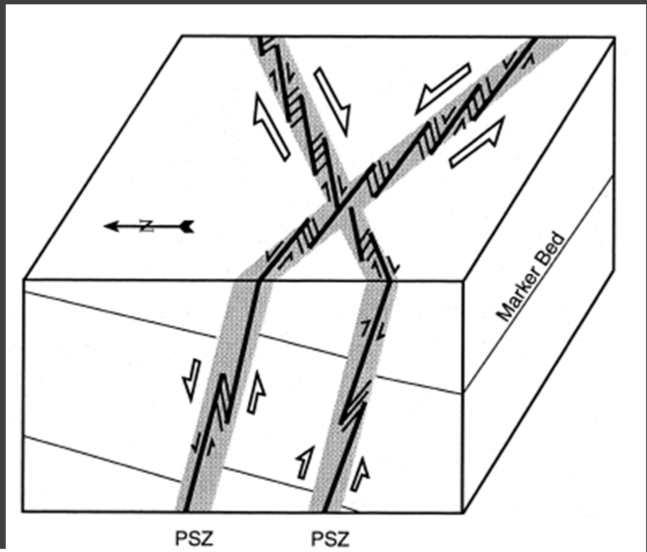
Sheets Gulch

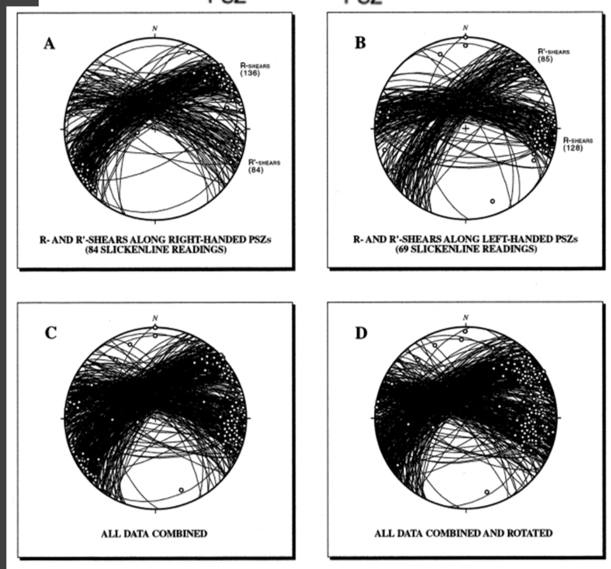


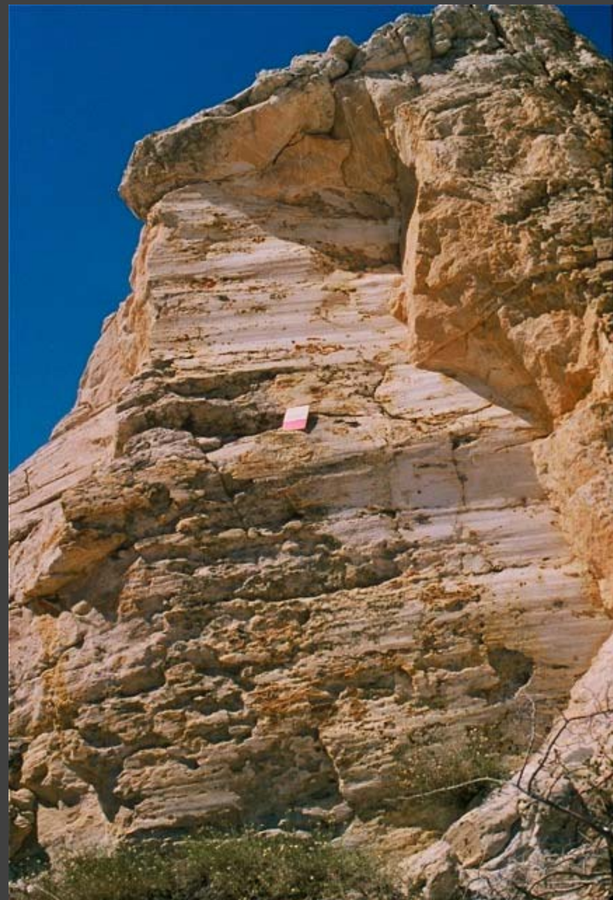
Davis' Detailed Mapping of Strike-Slip Deformation Band Shear Zones



The Deformation Band Shear Zones in the Sheets Gulch Area are Conjugate Strike-Slip Faults

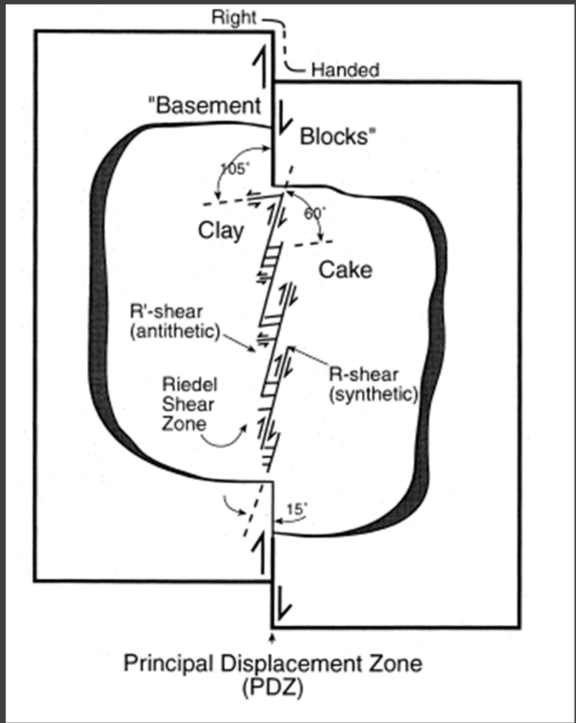


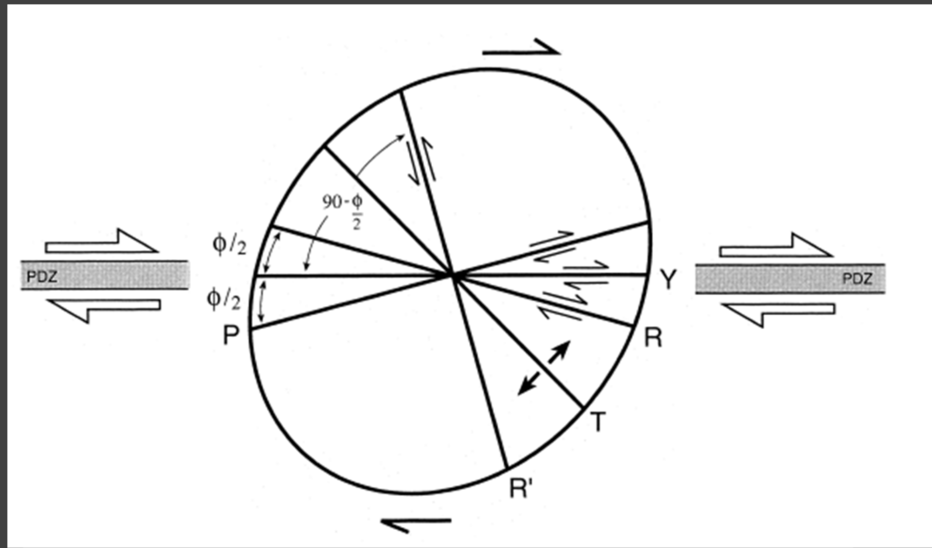


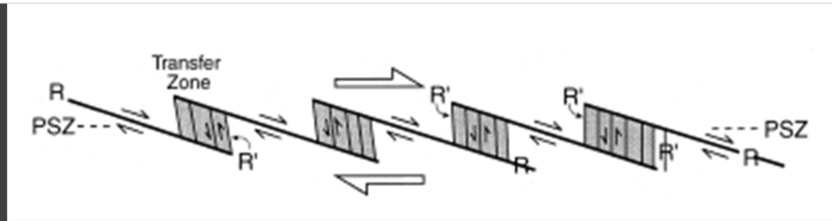


Nearly horizontal slickenlines

The deformation bands tend to array themselves in systems of Riedel Shears.

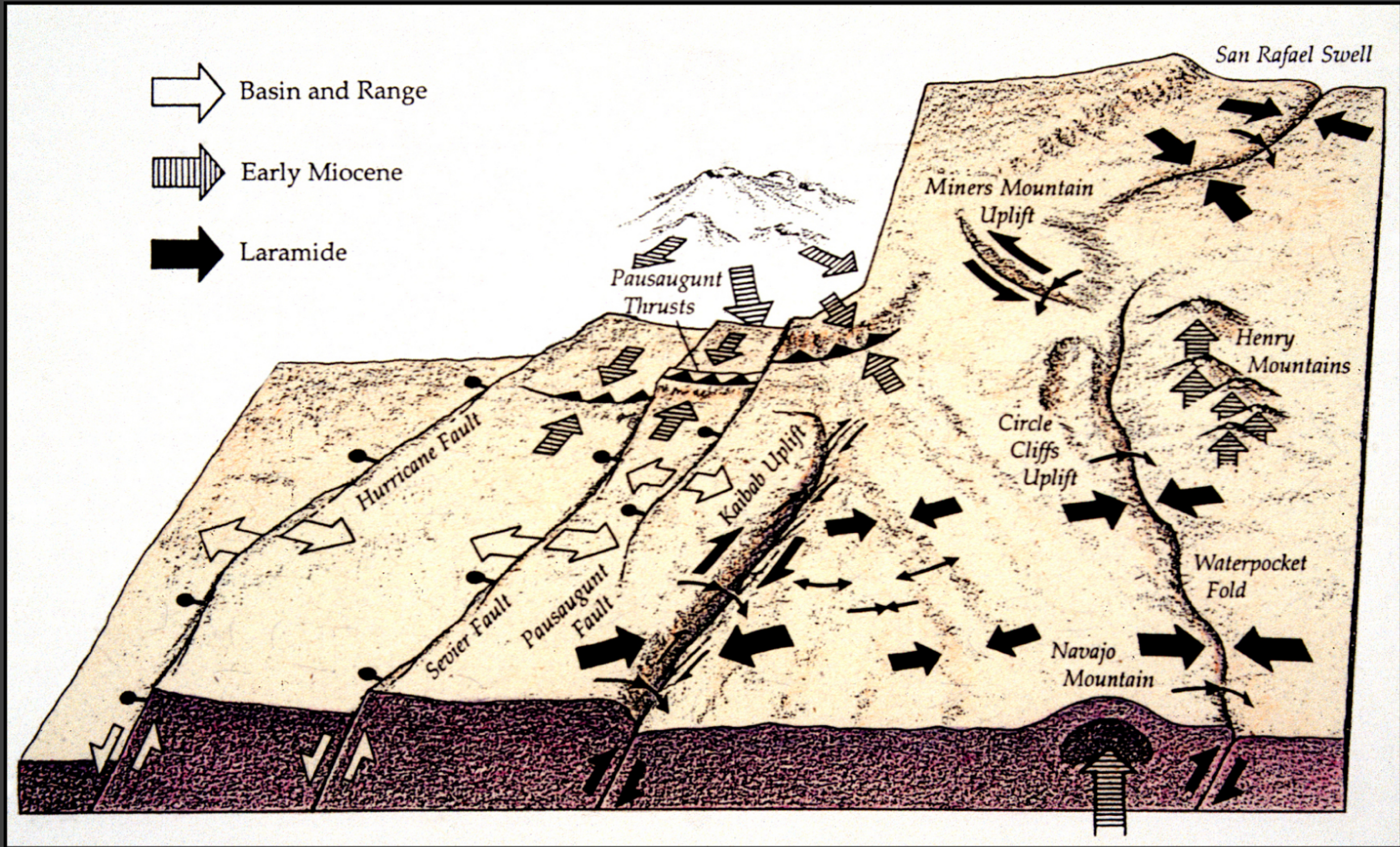


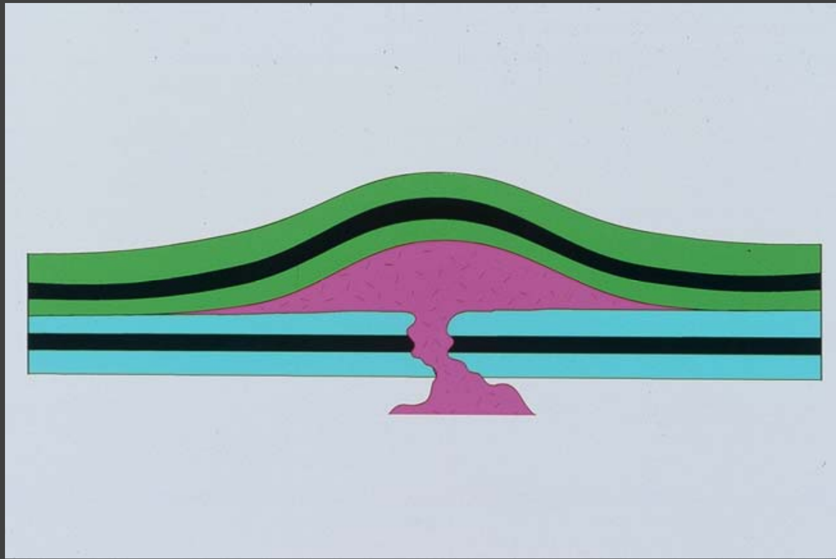




Davis et al, 1999

Post-Laramide Complications related to the ignimbrite flare-up and Basin and Range extension





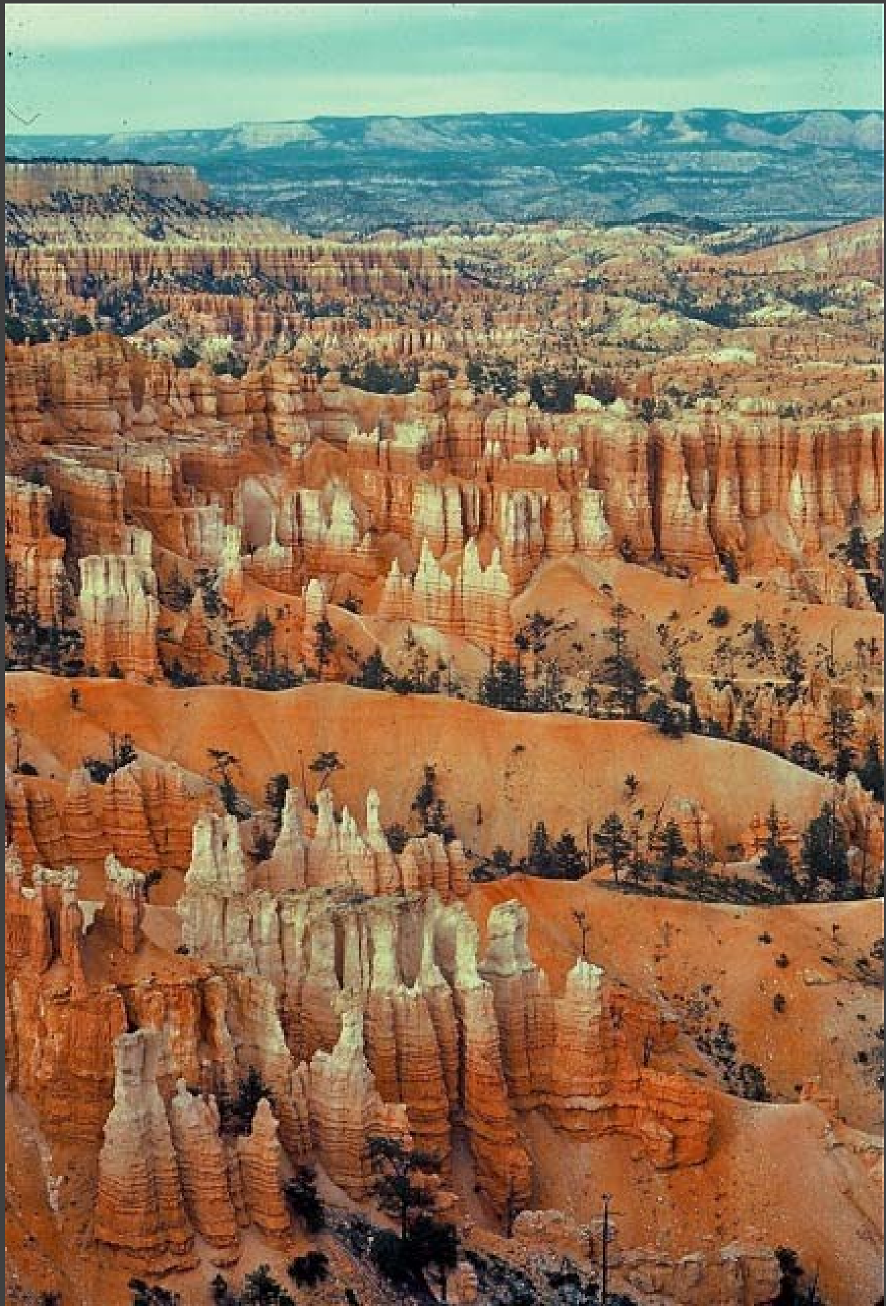
Henry Mountains
Laccoliths, of Miocene
age.

Here we see Entrada Formation (Jurassic redbeds) up-tilted along the flank of the Mt. Hillers Laccolith

Miocene ignimbritic volcanics, in background, overlying Claron Formation.

Miocene Deformation along the Paunsaugunt Thrust System

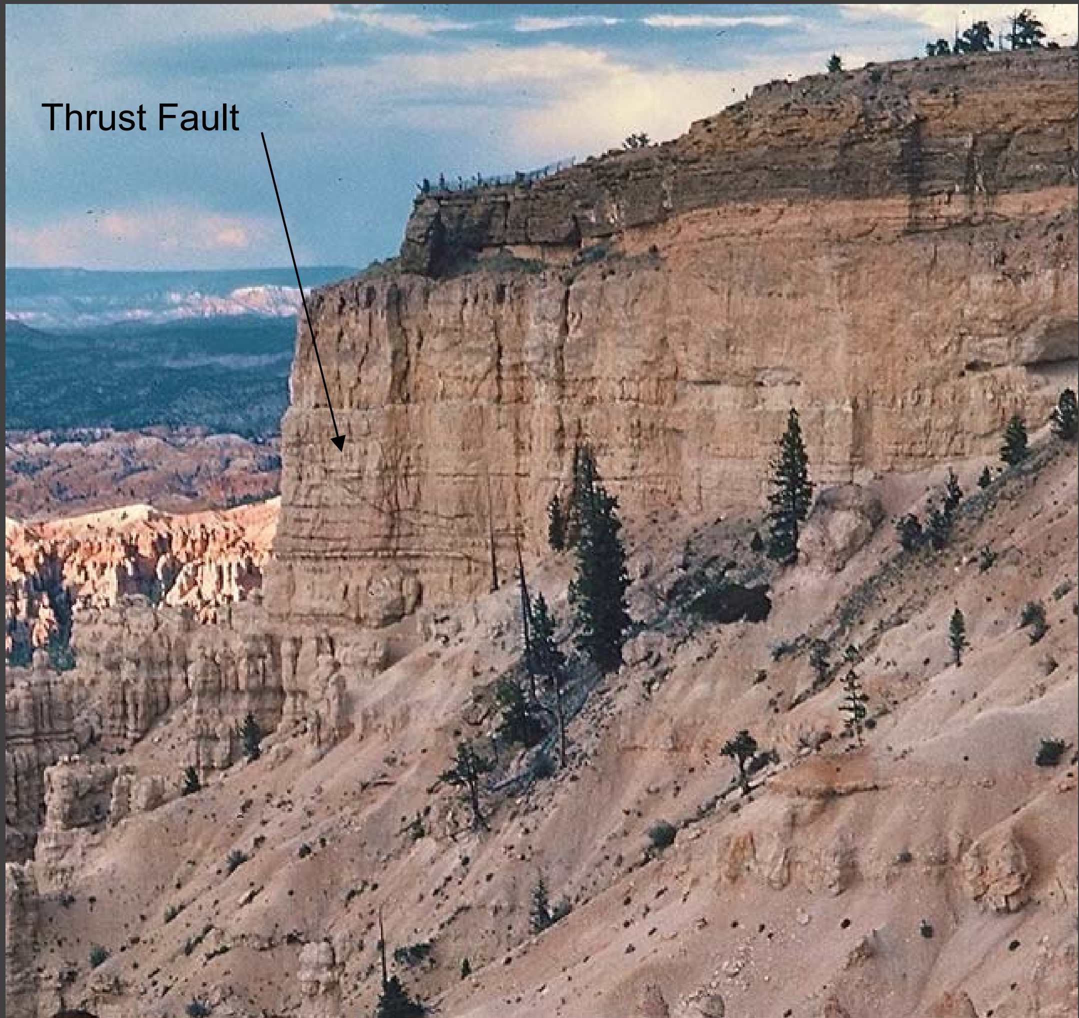
We would not expect *any* compressional deformation in the post-Laramide Claron Formation (Eocene). The Pink Cliffs exposures are flat-lying!



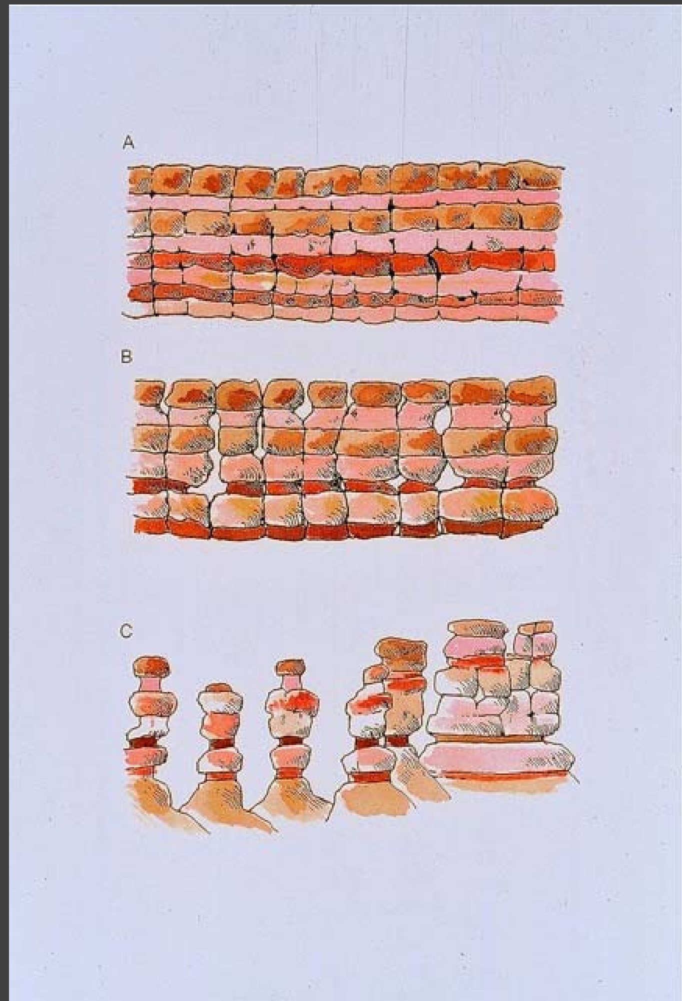
Claron Formation (Eocene) was thought to be everywhere flat-lying and undeformed. “Hoodoos” were/are viewed as forming via interplay of bedding and jointing.

Bryce Canyon National Park

Yet, I discovered (in 1984) that Claron Formation is cut by thrusts. The flanks of hoodoos not uncommonly are marked by strike-slip slickenlines.

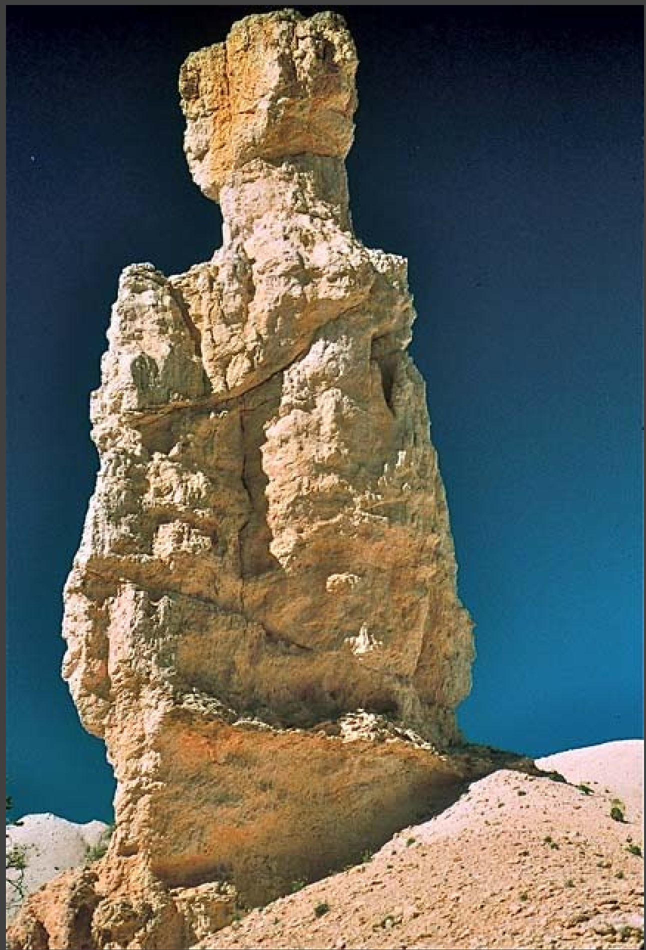


Bryce Point Observation Point

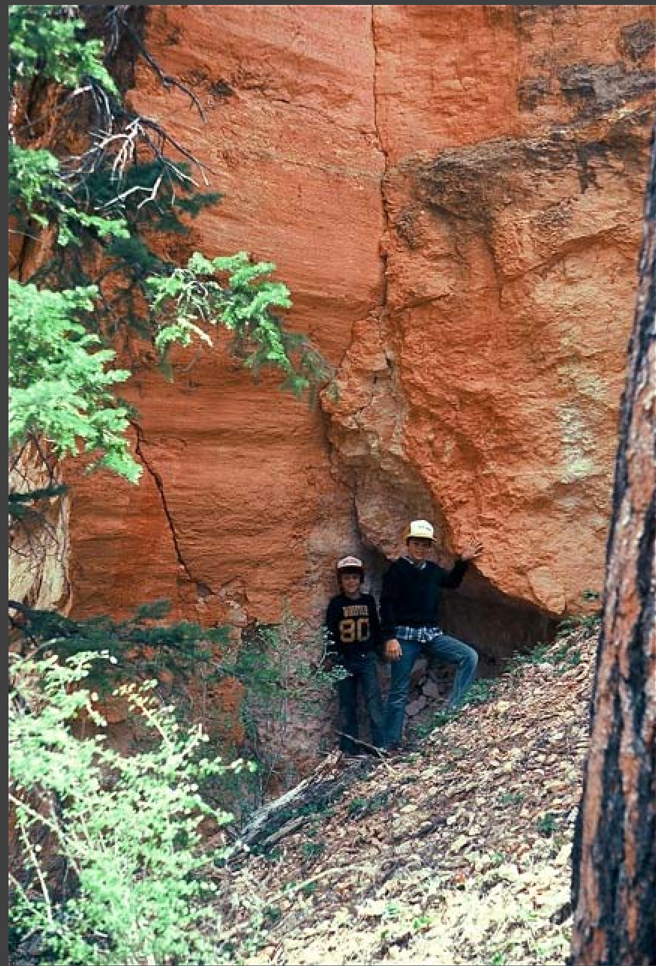


“Proper” Behavior of Claron

Hoodoos contain abundant evidence of faulting and shearing

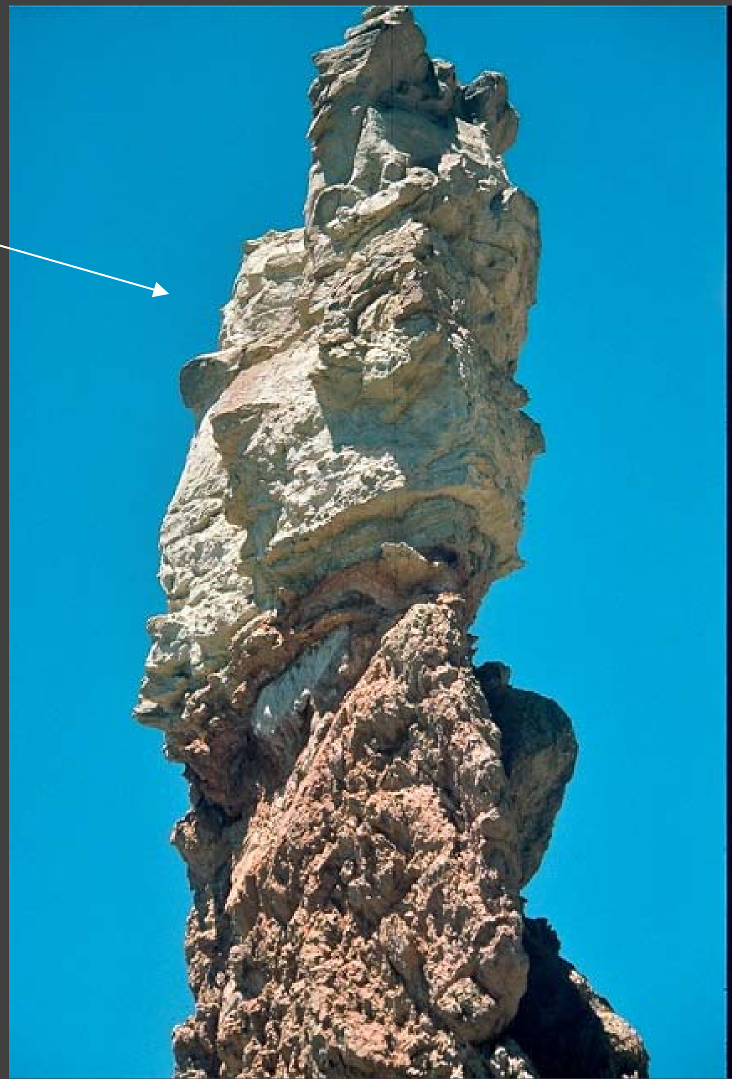


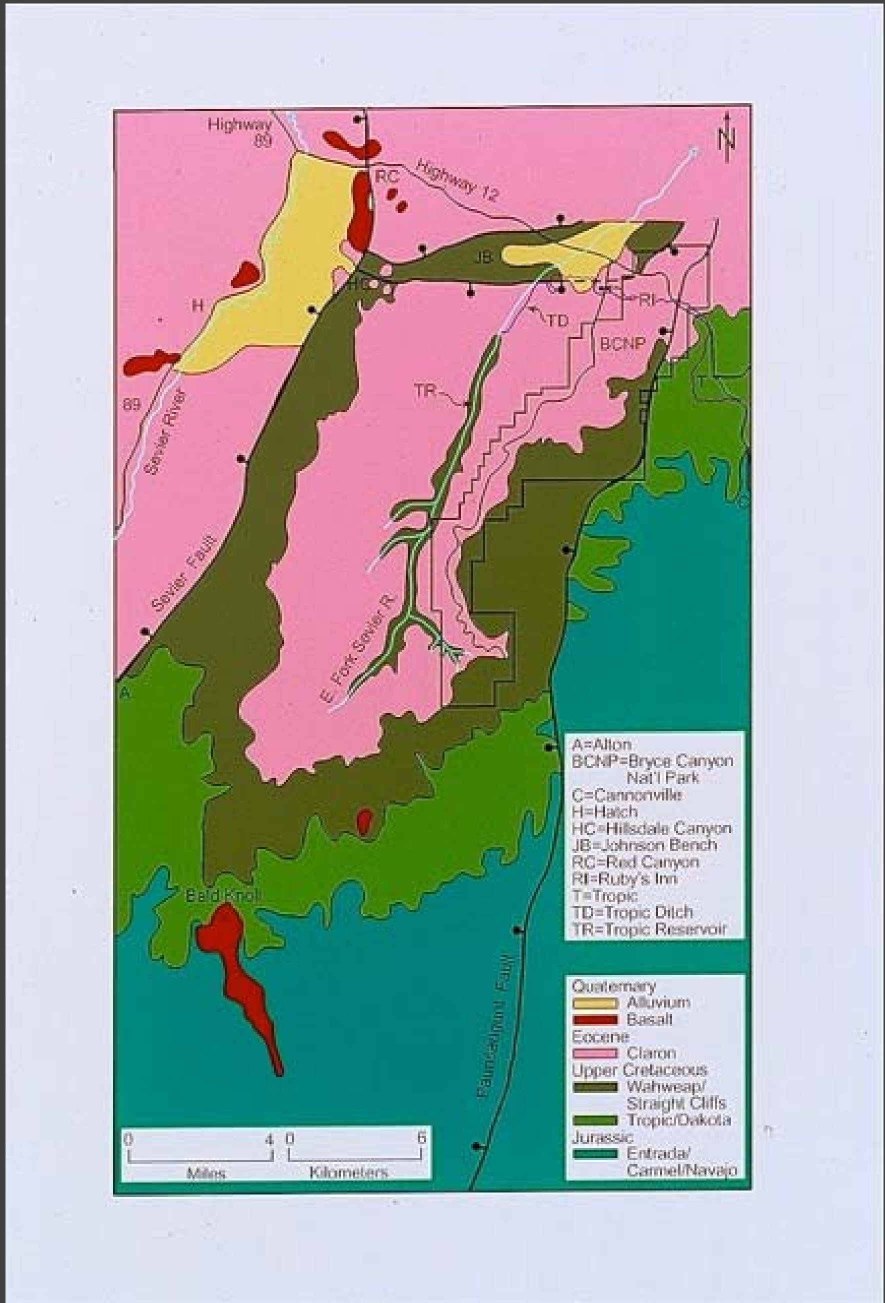
Thrusts



Horizontal Slickenlines

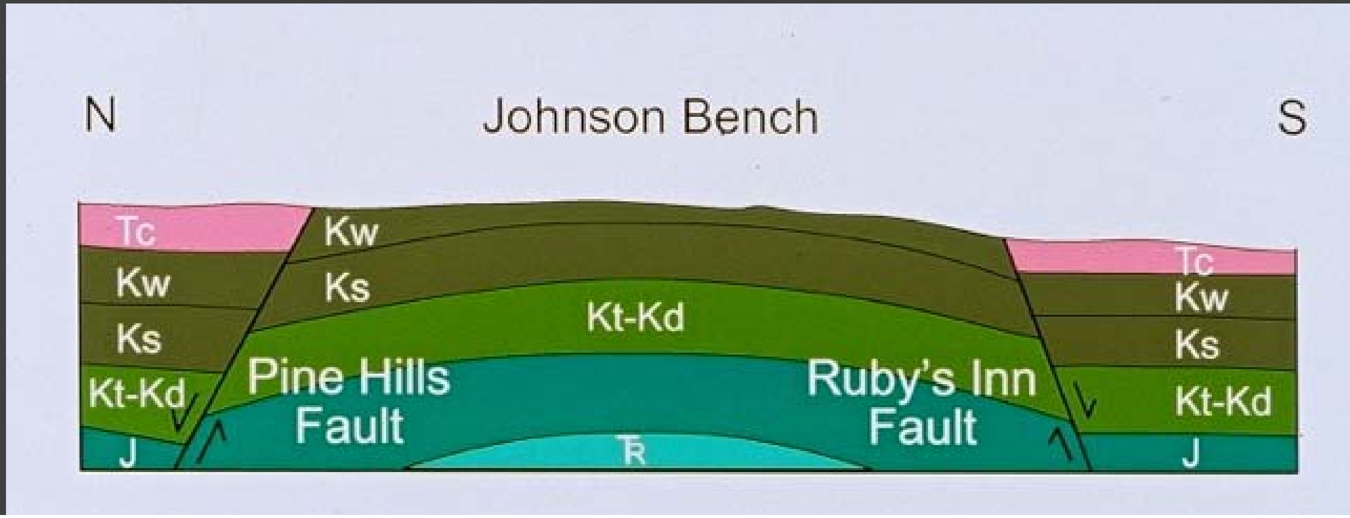
Monumental "*Hoodoo*" Fault Exposure of Cretaceous on Eocene

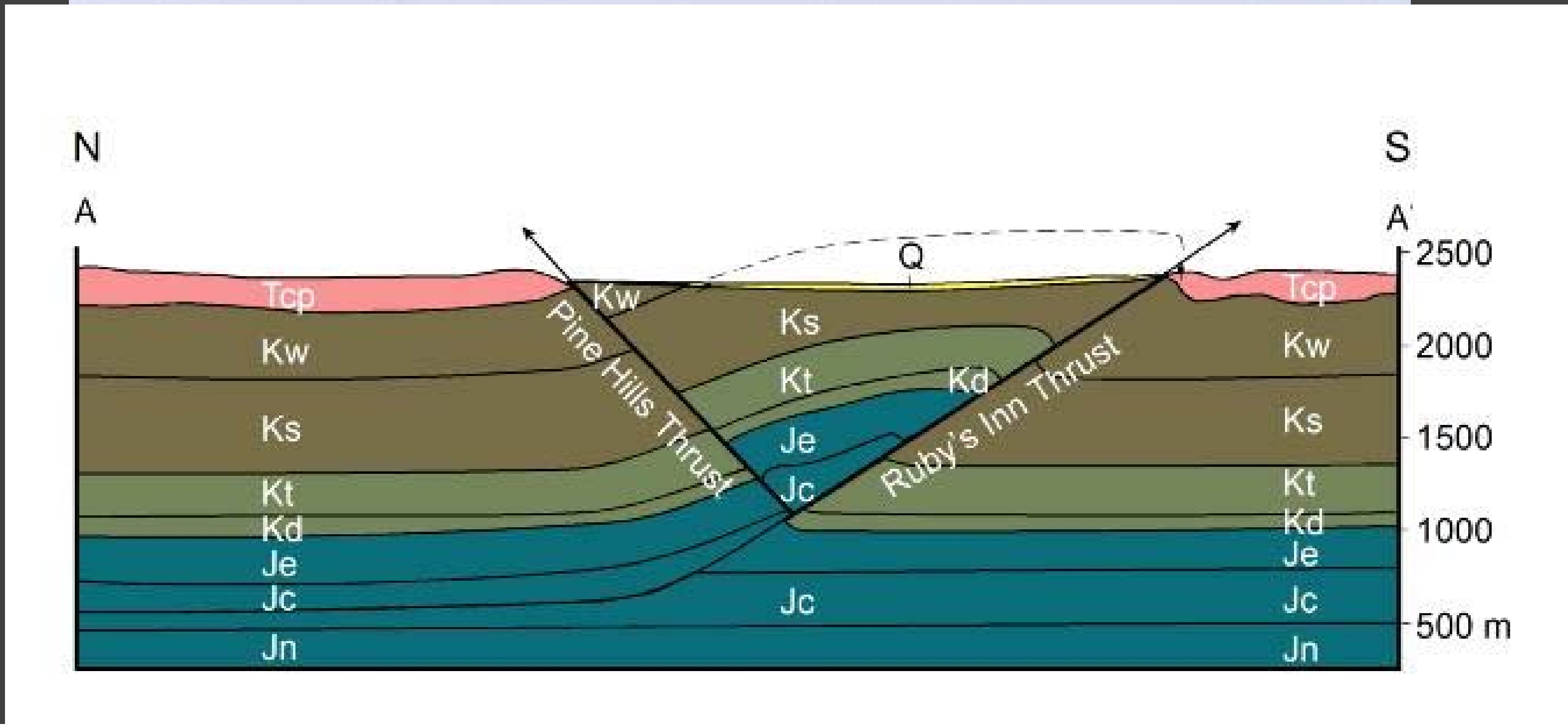



Highway 89
Highway 12
N
RC
JB
HC
H
TD
RI
BCNP
TR
T
89
Sevier River
Sevier Fault
E. Fork Sevier R.
A
Bald Knoll
Paunsaugunt Fault
A=Alton
BCNP=Bryce Canyon Nat'l Park
C=Cannonville
H=Hatch
HC=Hillsdale Canyon
JB=Johnson Bench
RC=Red Canyon
RI=Ruby's Inn
T=Tropic
TD=Tropic Ditch
TR=Tropic Reservoir
Quaternary
Alluvium
Basalt
Eocene
Claron
Upper Cretaceous
Wahweap/ Straight Cliffs
Tropic/Dakota
Jurassic
Entrada/ Carmel/Navajo
0 4
Miles
0 6
Kilometers

Eric Lundin

Rediscovery of Miocene Thrust Faults in Bryce Region Subsurface.

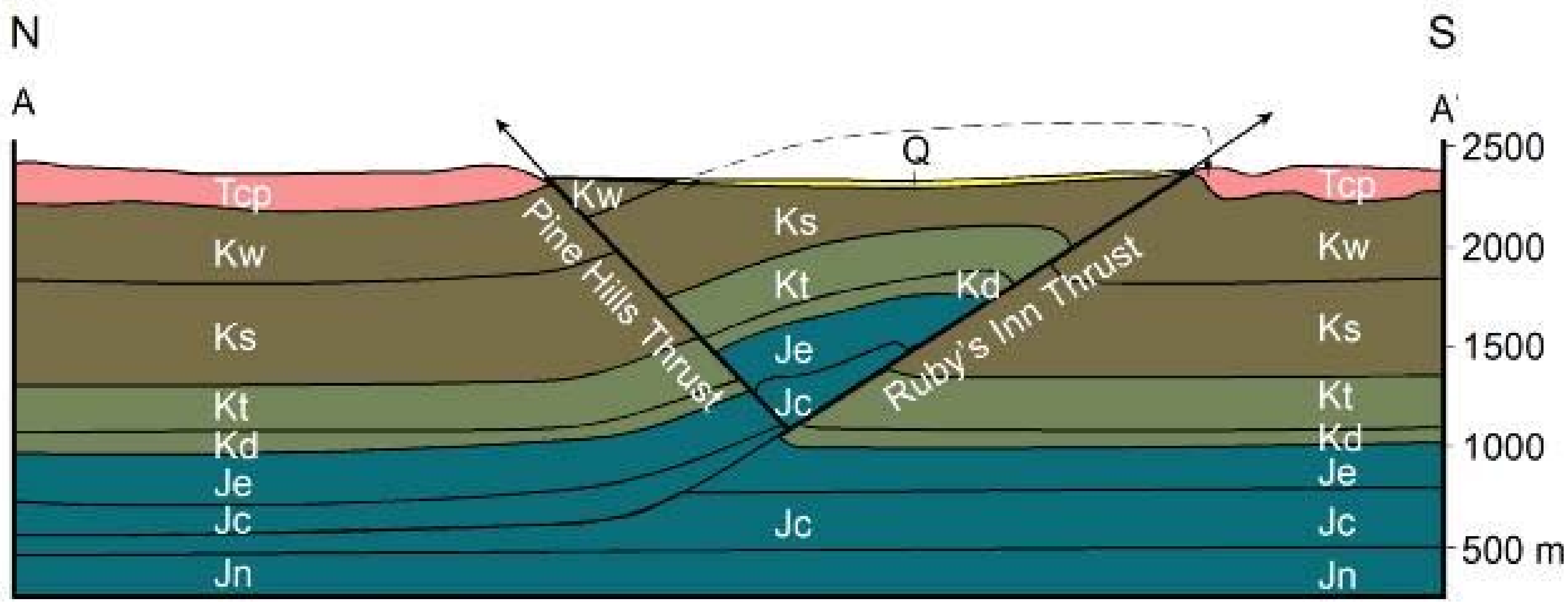




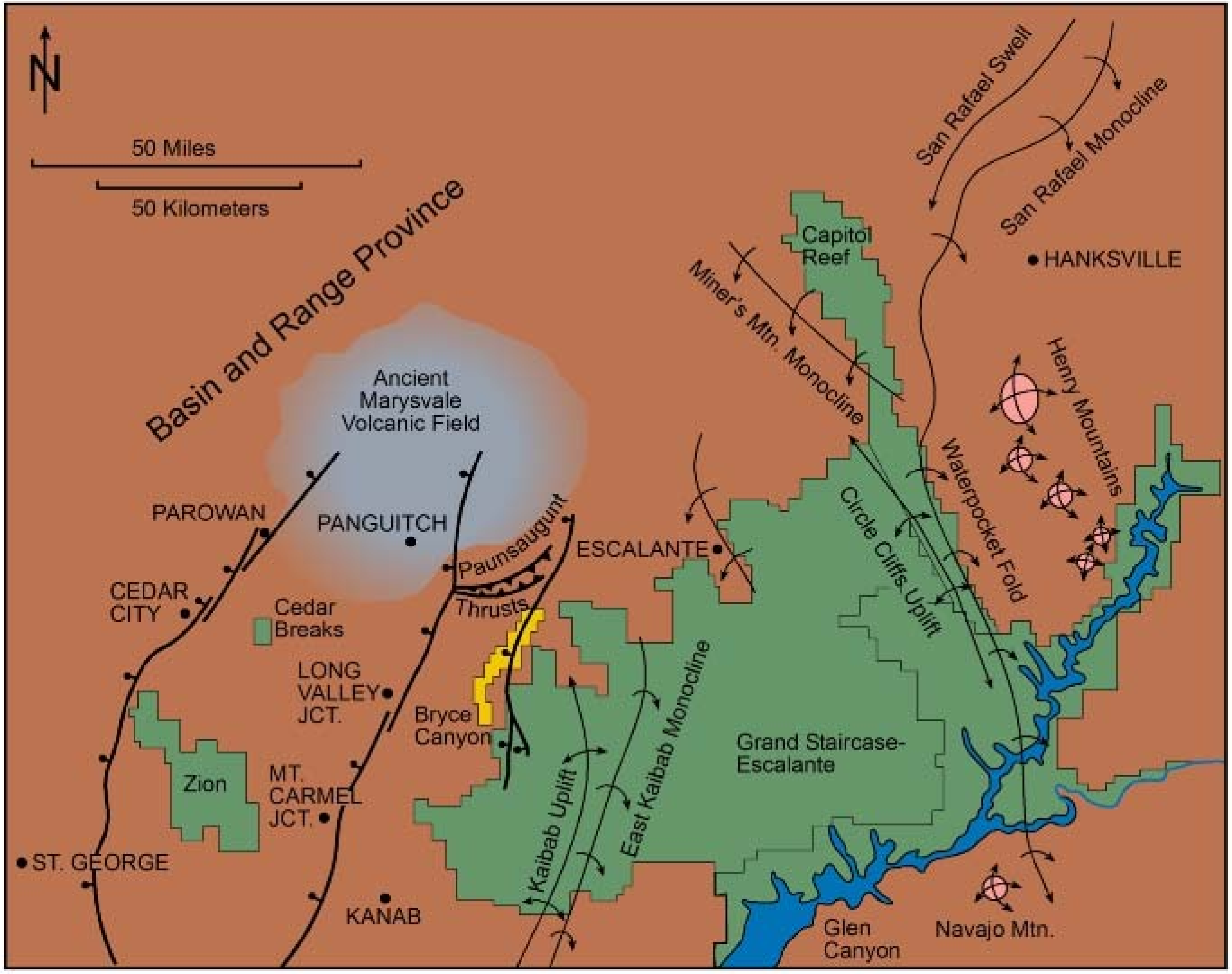
Ahlstrom Hollow Exposure of Fault


Hi George!
How 'bout this
crazy fault!

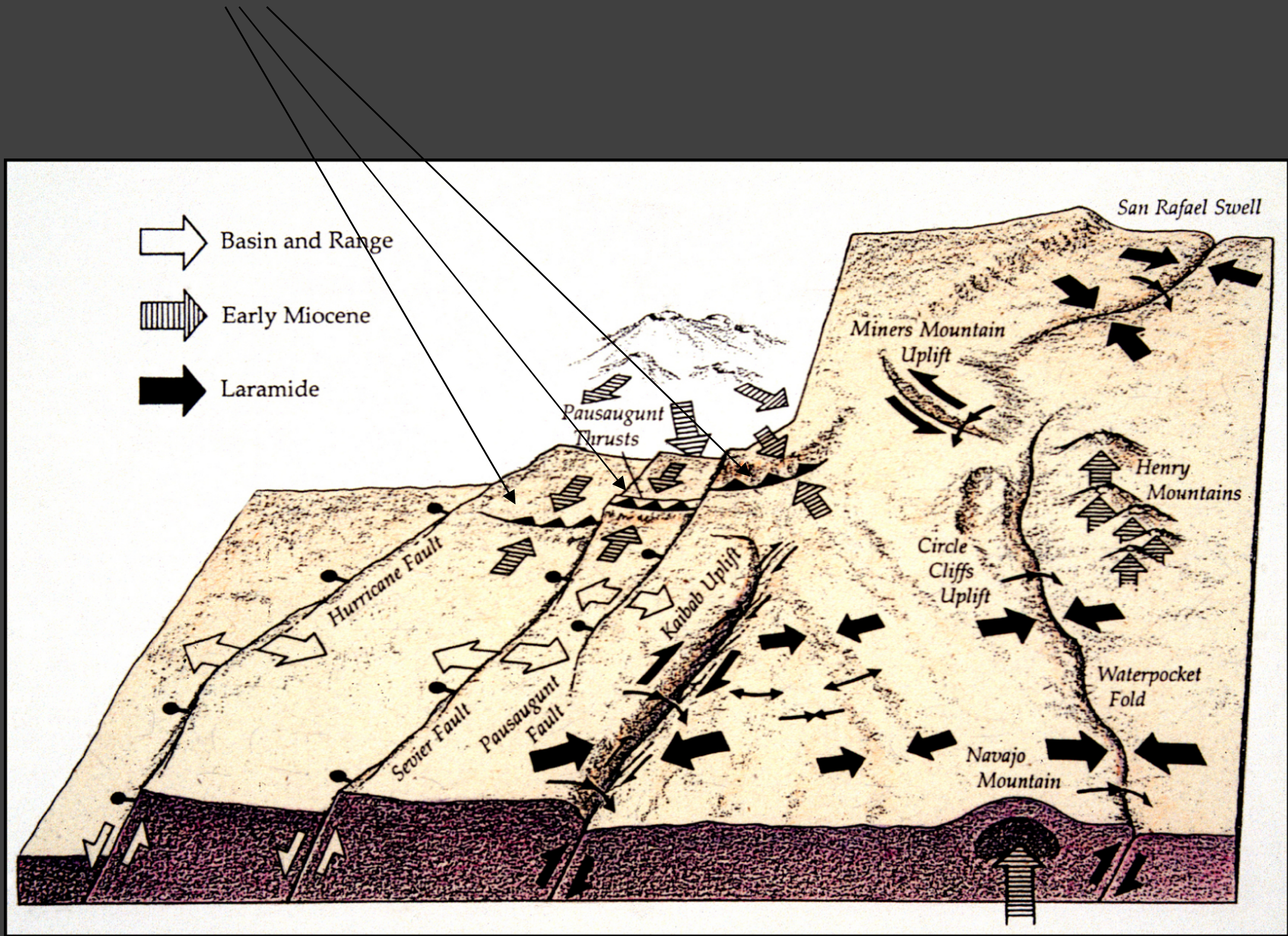
Chevron drilled into this fault in the 1960's!!



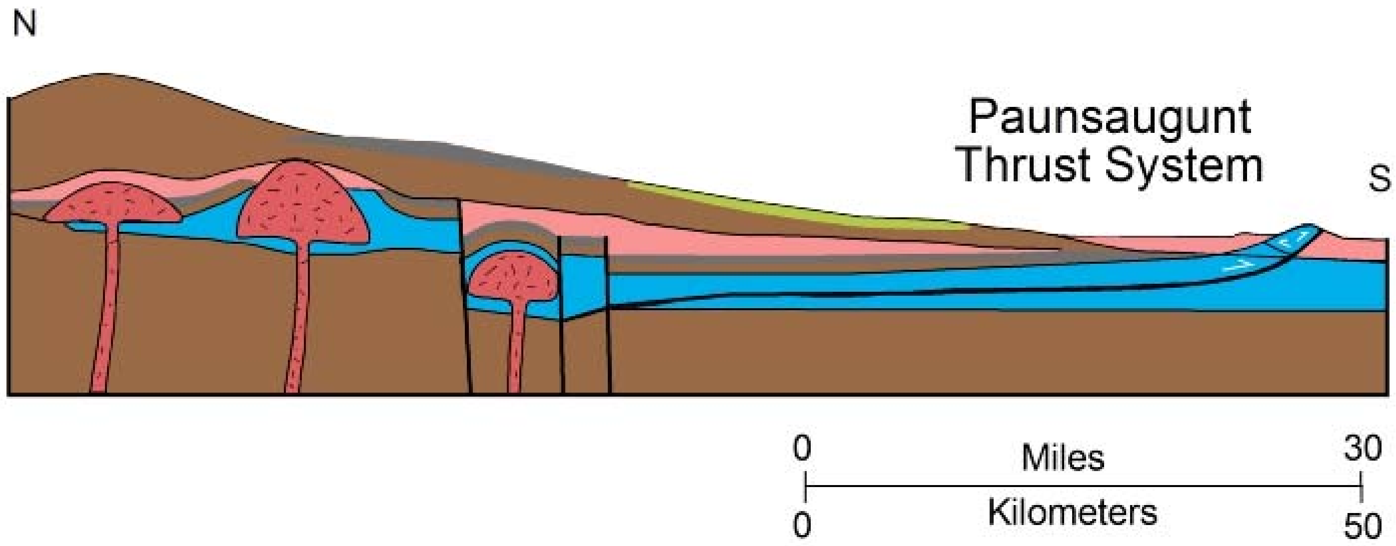
Volcano Collapse and Spreading, …Etna-like.



Mapping Out of the Thrust System Revealed Arcuate Belt

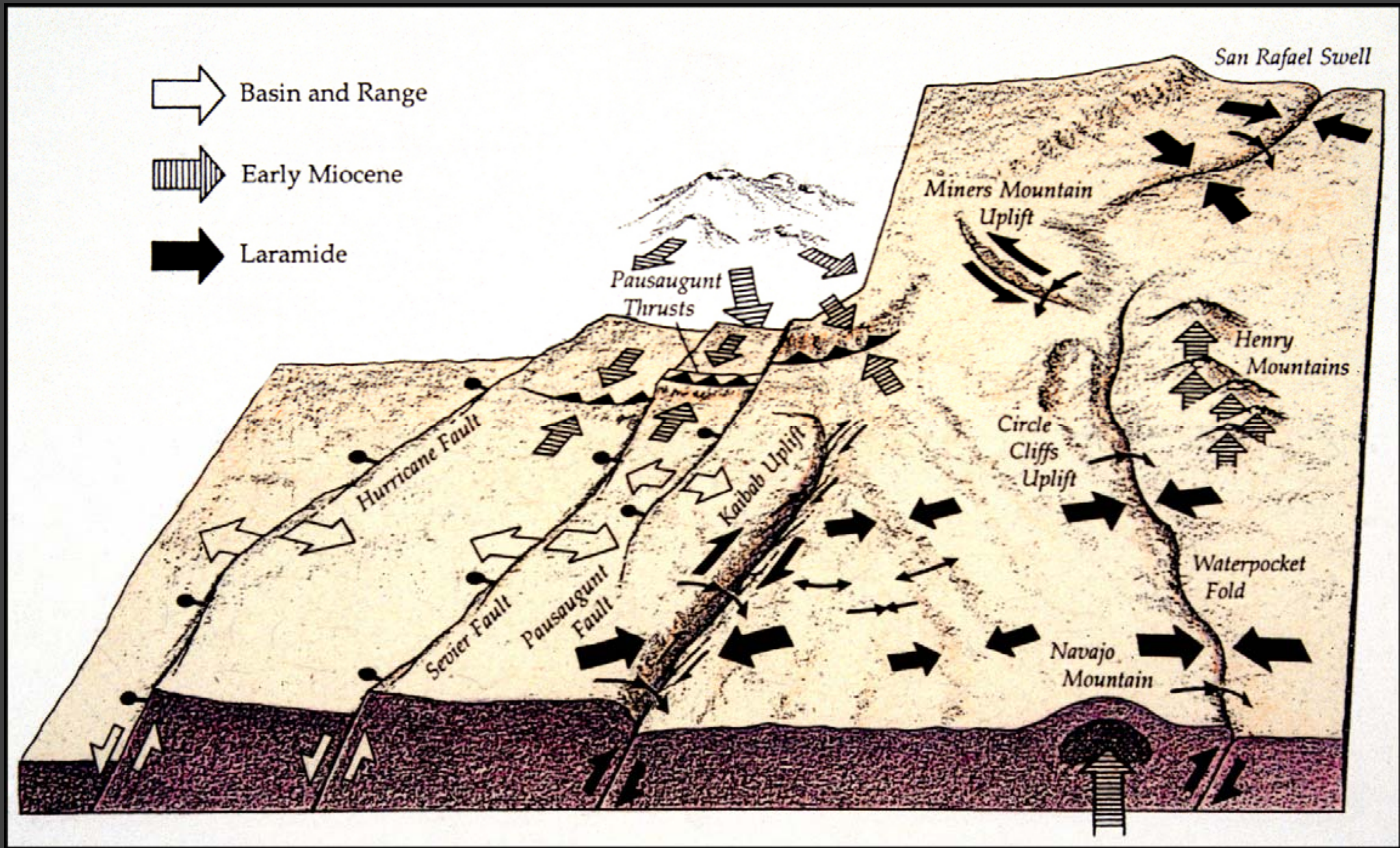


My Interpretation of Paunsagunt Thrust System as a response to Gravitational Spreading of the Marysvale Igneous Complex



Modern counterpart is Mt. Etna

Basin & Range Deformation: Three Major Normal Faults of the Western High Plateaus: Hurricane, Sevier, and Paunsaugunt.



Tell-Tale Expression of Basin and Range Extension in the Western High Plateaus of Utah.

The Paunsagunt Fault, a high-angle Basin & Range fault, the easternmost such fault in the Colorado Plateau

Pink rock is Eocene Claron Formation

Gray rock is Upper Cretaceous Sandstone

Now <u>THIS</u> is a Fault Exposure!

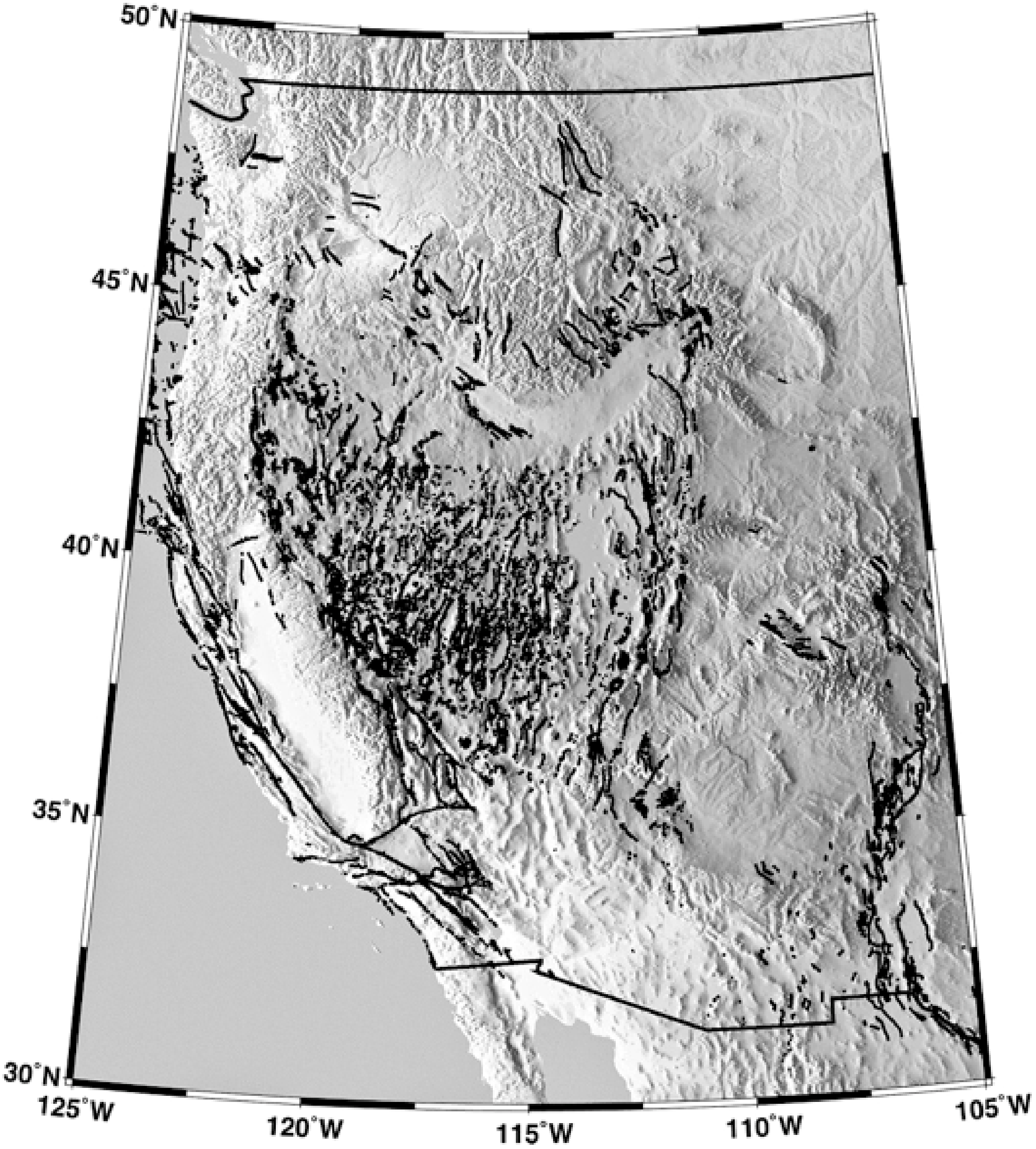


Figure 11.98b
Previously unpublished. Prepared specifically for this chapter by Rick Bennett and Joshua Spinler, Department of Geosciences, The University of Arizona.

Map of Active Faults in the western U.S.

Courtesy of Rick Bennett and Joshua Spinler.

MAGIC of system of normal faulting exposed in a quarry in Naxos, Greece (pegmatite encased in marble).

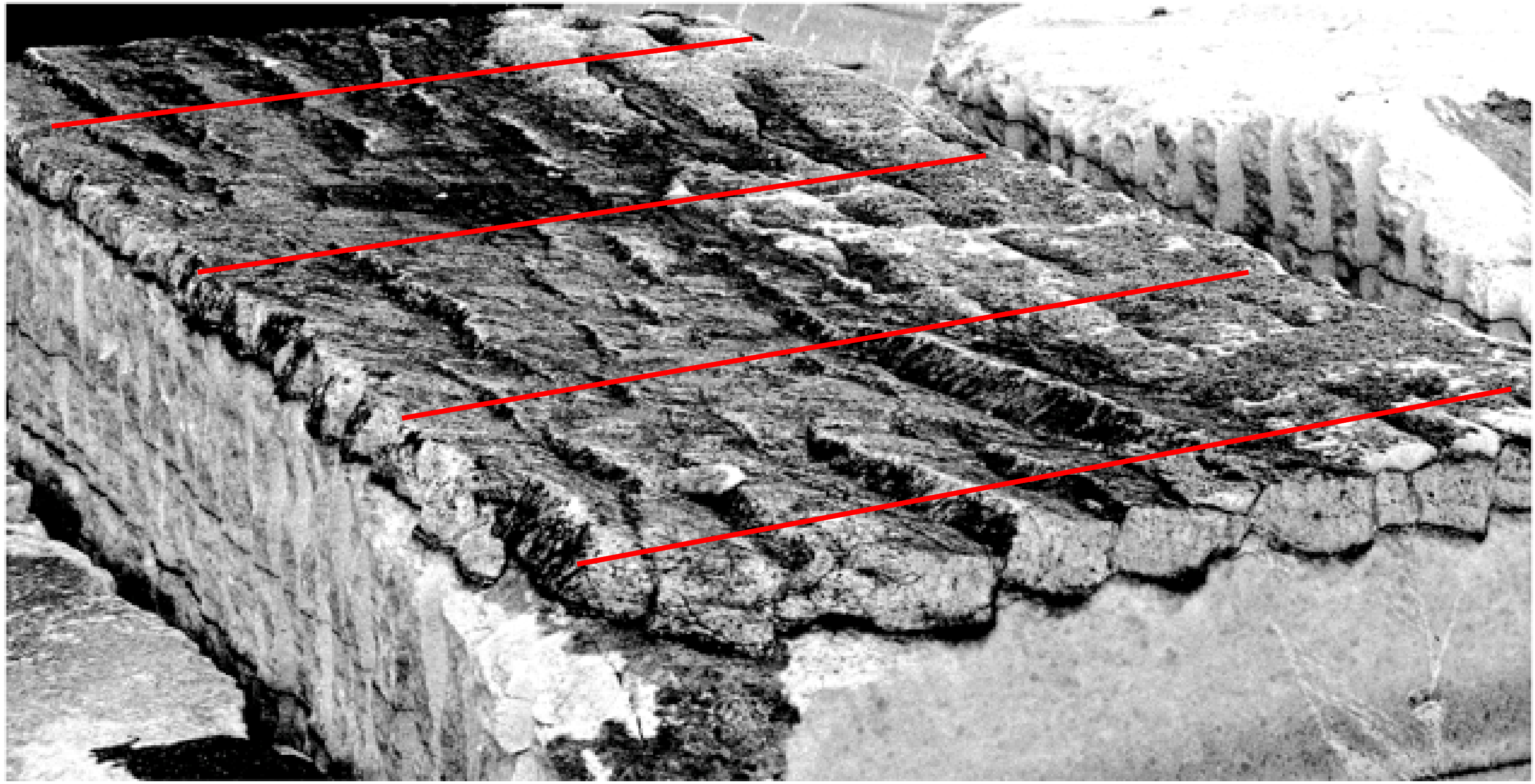


Figure 6.61
Reprinted from *Journal of Structural Geology*, v. 30, Urai, J. L., Schenk, O., van der Zee, W., and Blumenthal, M., Photograph of the month, p. 1201, © 2008, with permission from Elsevier.

From Urai and others, 2008)

Faults 'talk' to one another.
Progressive normal faulting within Taupo Rift, New Zealand.

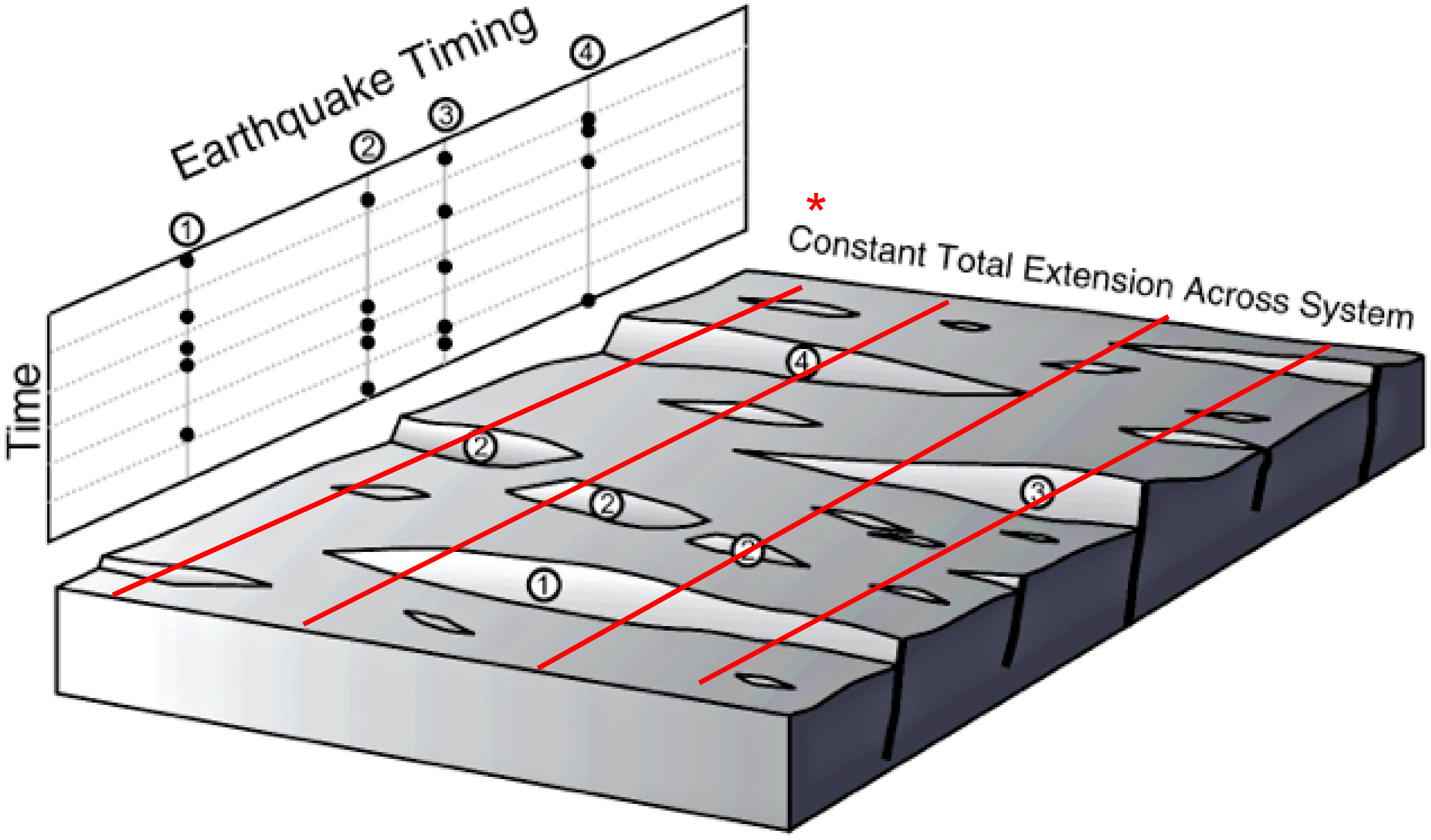


Figure 6.62
Reprinted from *Journal of Structural Geology*, v. 32, Nicol, A., Walsh, J. J., Villamor, P., Seebeck, H., and Berryman, K. R., Normal fault interactions, paleoearthquakes and growth in an active rift, p. 1101-1113, © 2010, with permission from Elsevier.

From Nicol and others, 2010)

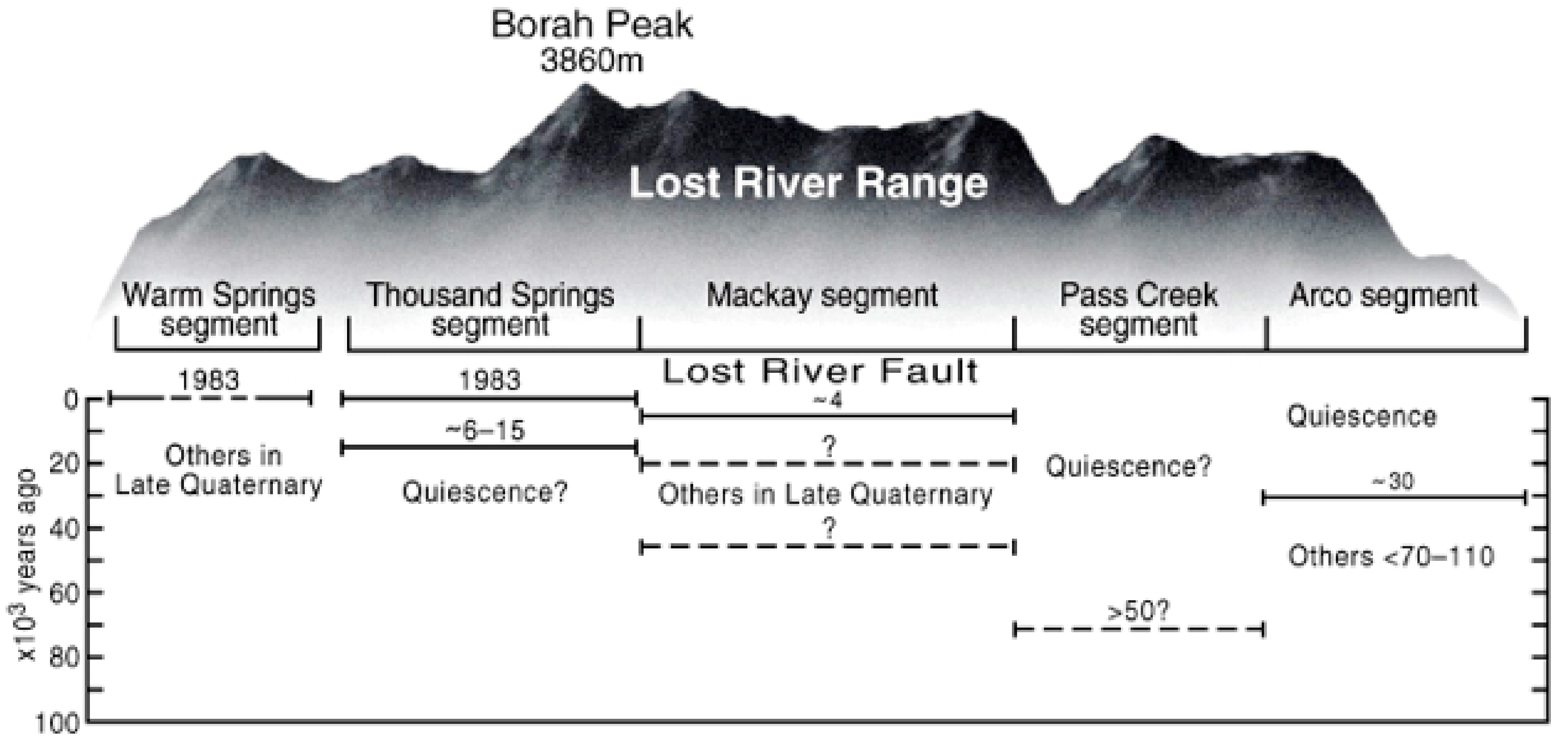


Figure 11.77
From Wallace, 1987, Figure 1, p. 869. Mountain artwork by David A. Fischer.

Robert Wallace's (1987) concept of Fault Grouping (along individual faults) and Fault Migration (from one subprovince to another). The fault slip bounces around along a major fault system, but produces a 'REGULAR' slip gradient from tips inward.

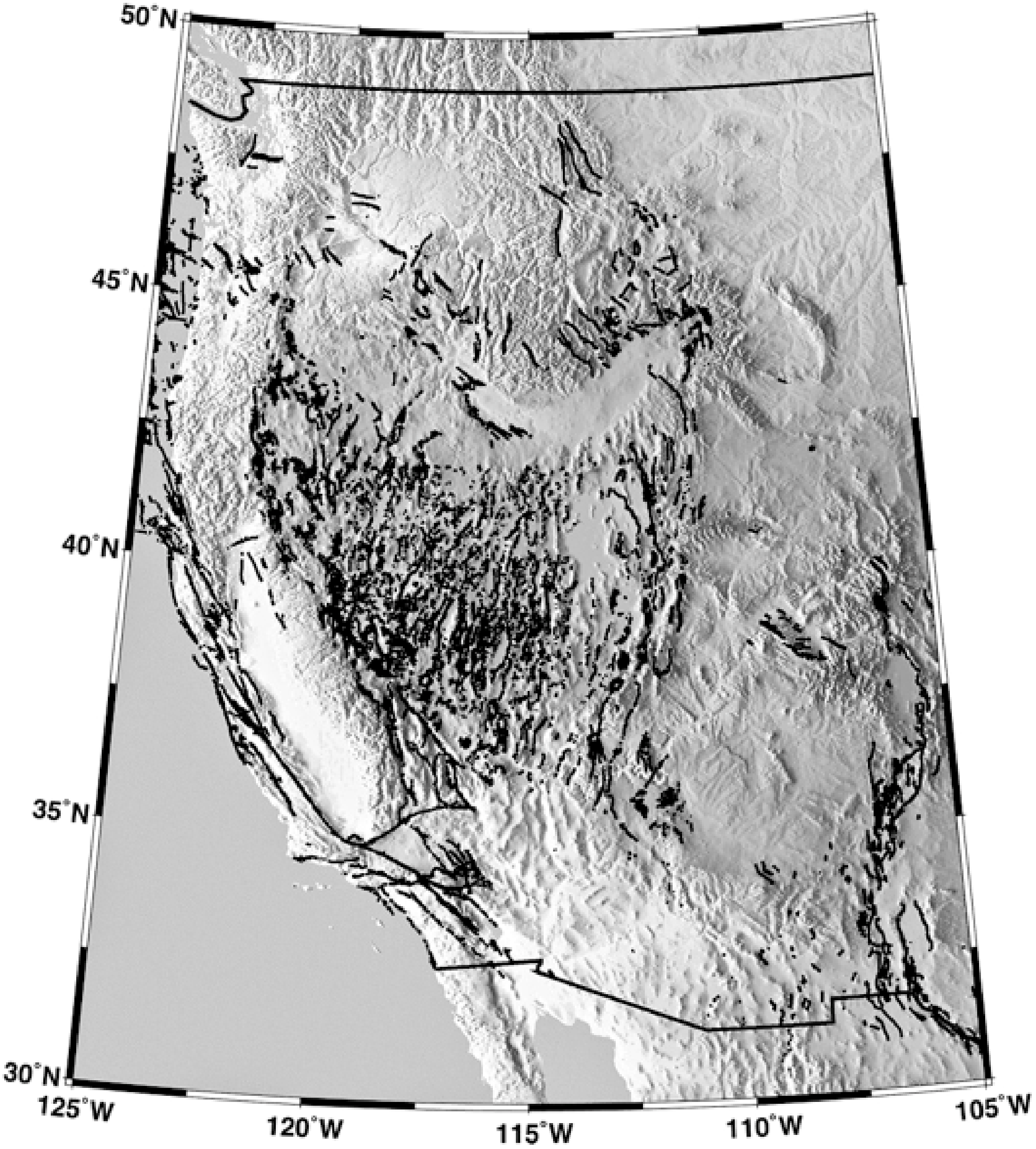
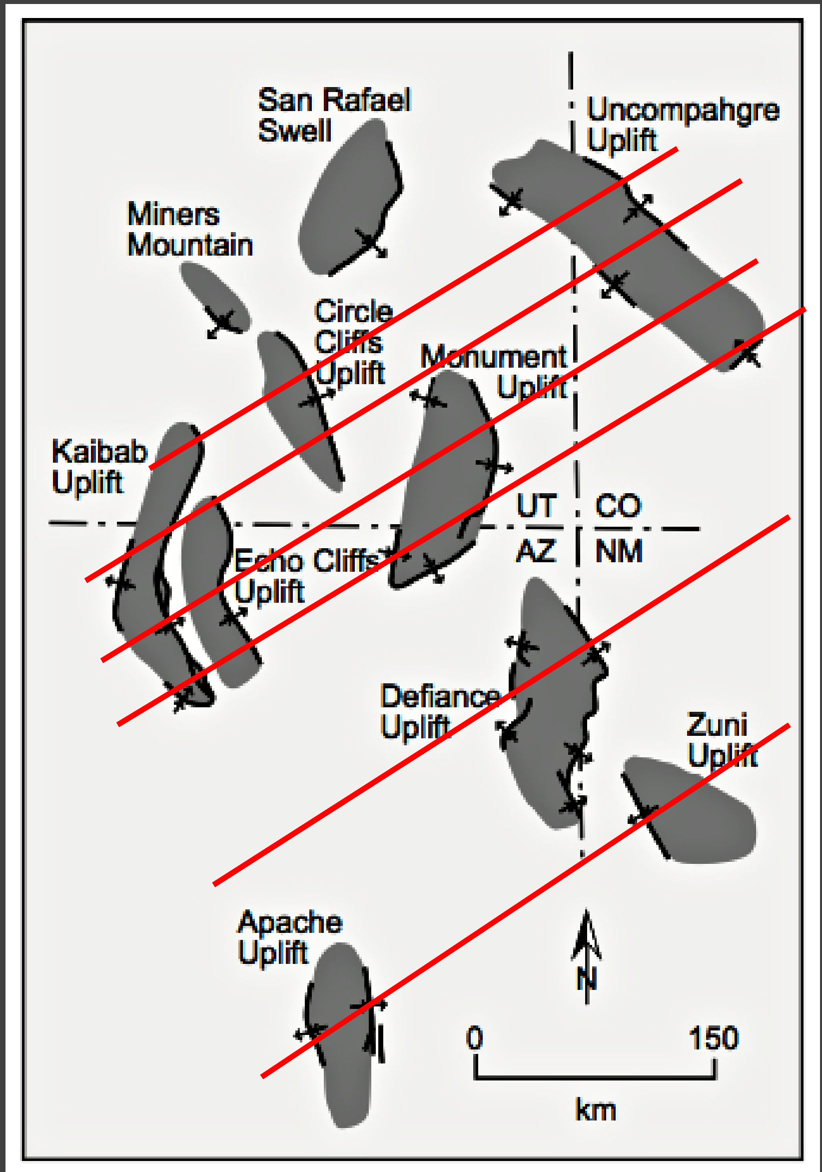


Figure 11.98b
Previously unpublished. Prepared specifically for this chapter by Rick Bennett and Joshua Spinler, Department of Geosciences, The University of Arizona.

The Nevadaplano has collapsed by a time/space dynamic of fault grouping and fault migration.



Did the Colorado Plateau 'uniformly' build and rise in the same fashion, i.e., through fault slip grouping and fault slip migration?

Will we find that the % of shortening along each of these traverses is near-identical, or systematically interrelated within a regular gradient of strain?

What will we learn about the detailed timing of formation of each uplift?

Will the history of progressive deformation reveal how flat-slab underplating generates basement-cored uplifts high above?

Sheets
Gulch Area

Mapping and detailed structural analysis will be essential, but not sufficient. Timing, as always, really matters!

…and glimpses of
the past.

Slickrock hiking, …and the unanticipated wildlife...Can you see the Bighorn Sheep for scale?