The Abdus Salam
International Centre
for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2464-6

Earthquake Tectonics and Hazards on the Continents

17 - 28 June 2013

Recognizing and characterizing thrust faults and earthquakes in the Himalaya

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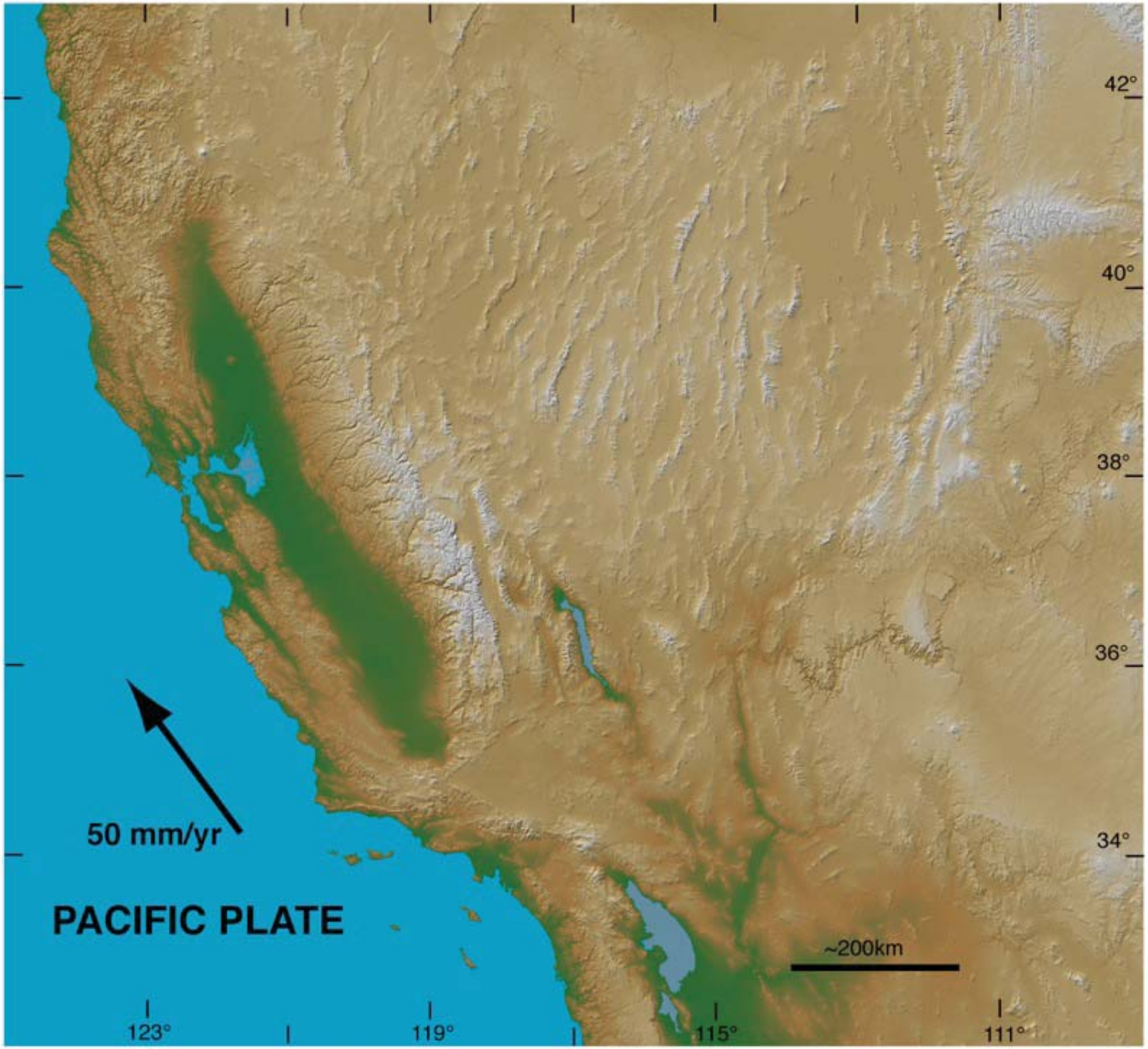
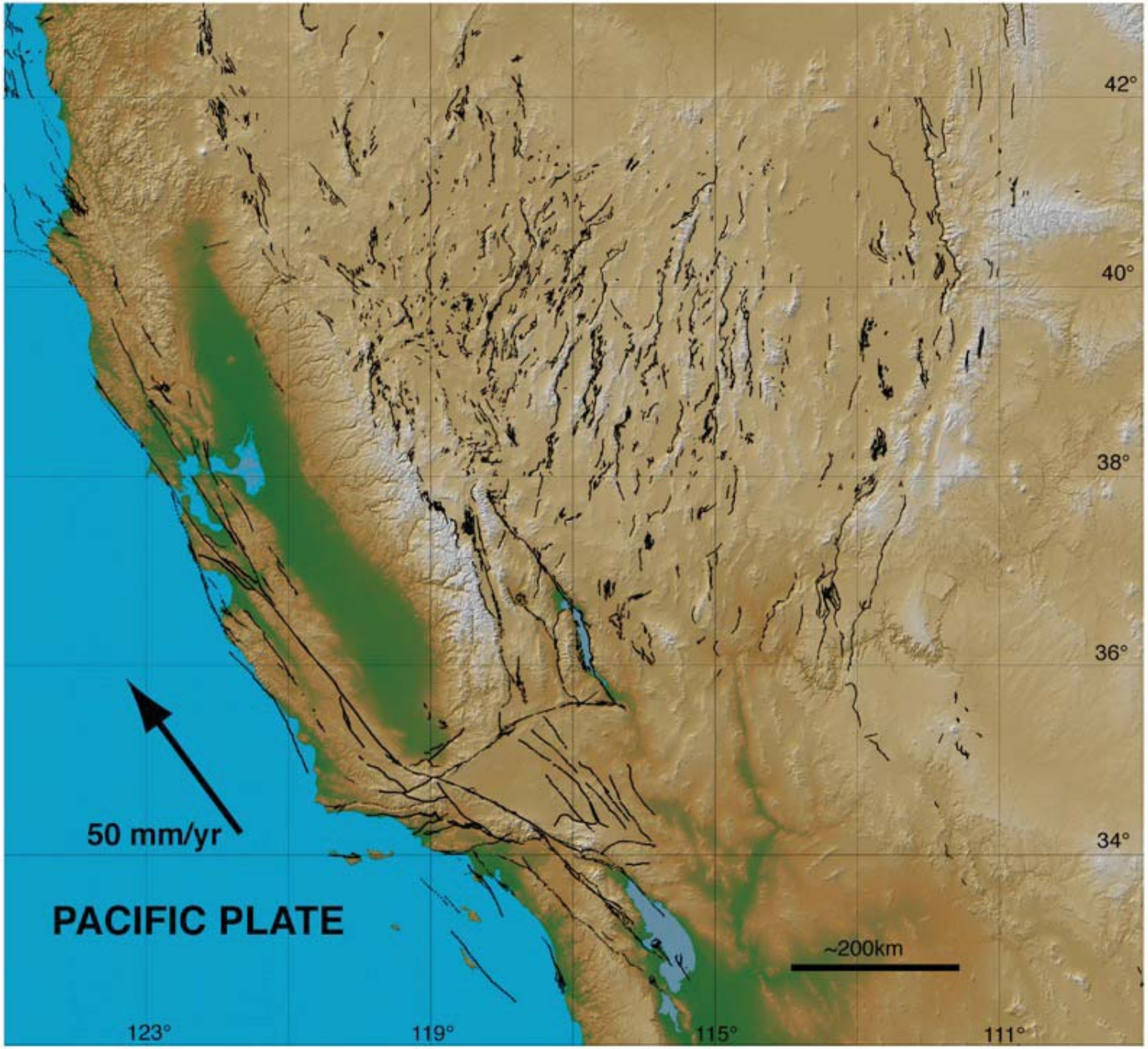
Extension and Transtension in the Basin and Range and the Walker Lane

Trieste 2013 Wesnousky


42°
40°
38°
36°
34°
50 mm/yr
PACIFIC PLATE
~200km
123°
119°
115°
111°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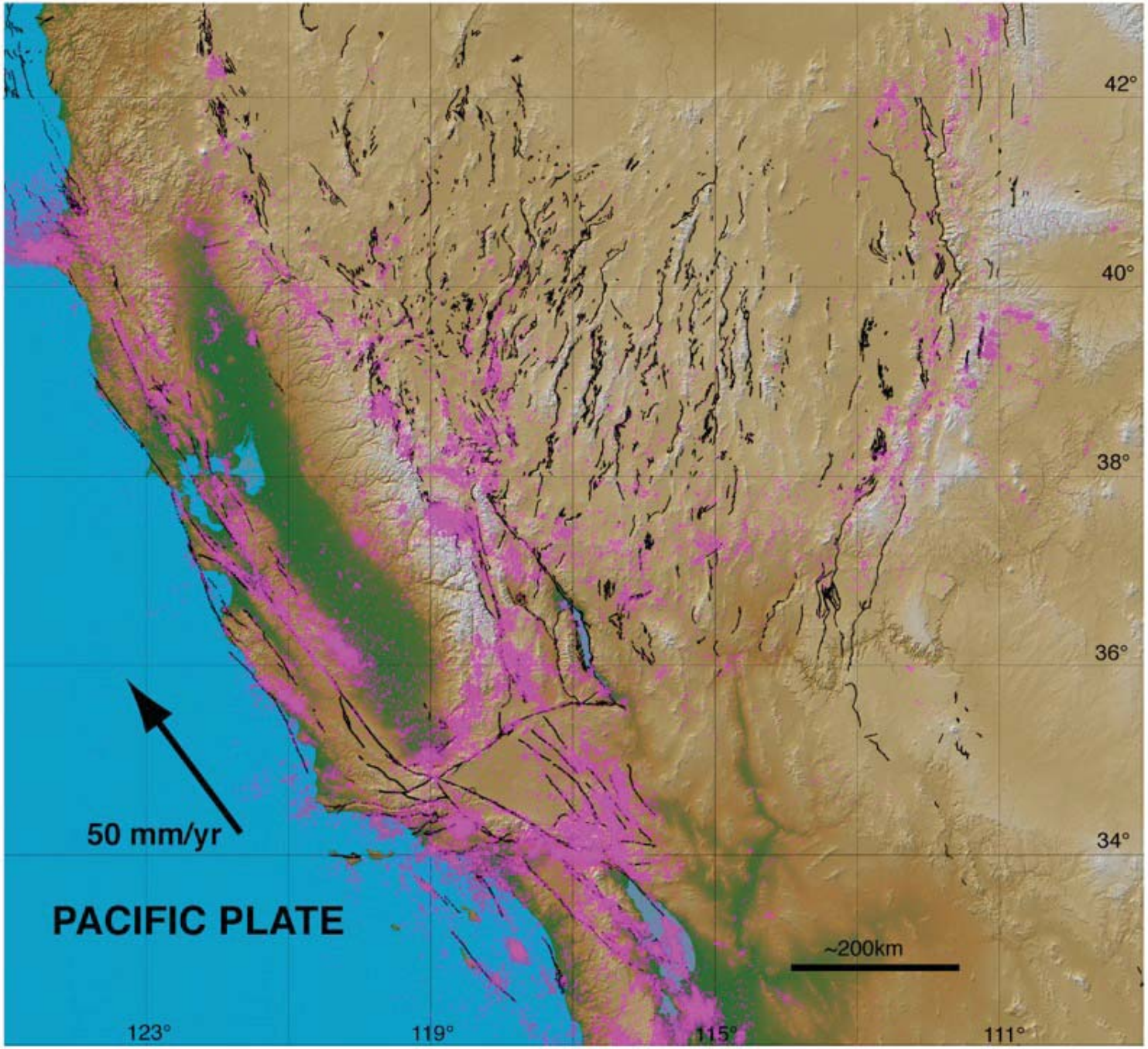
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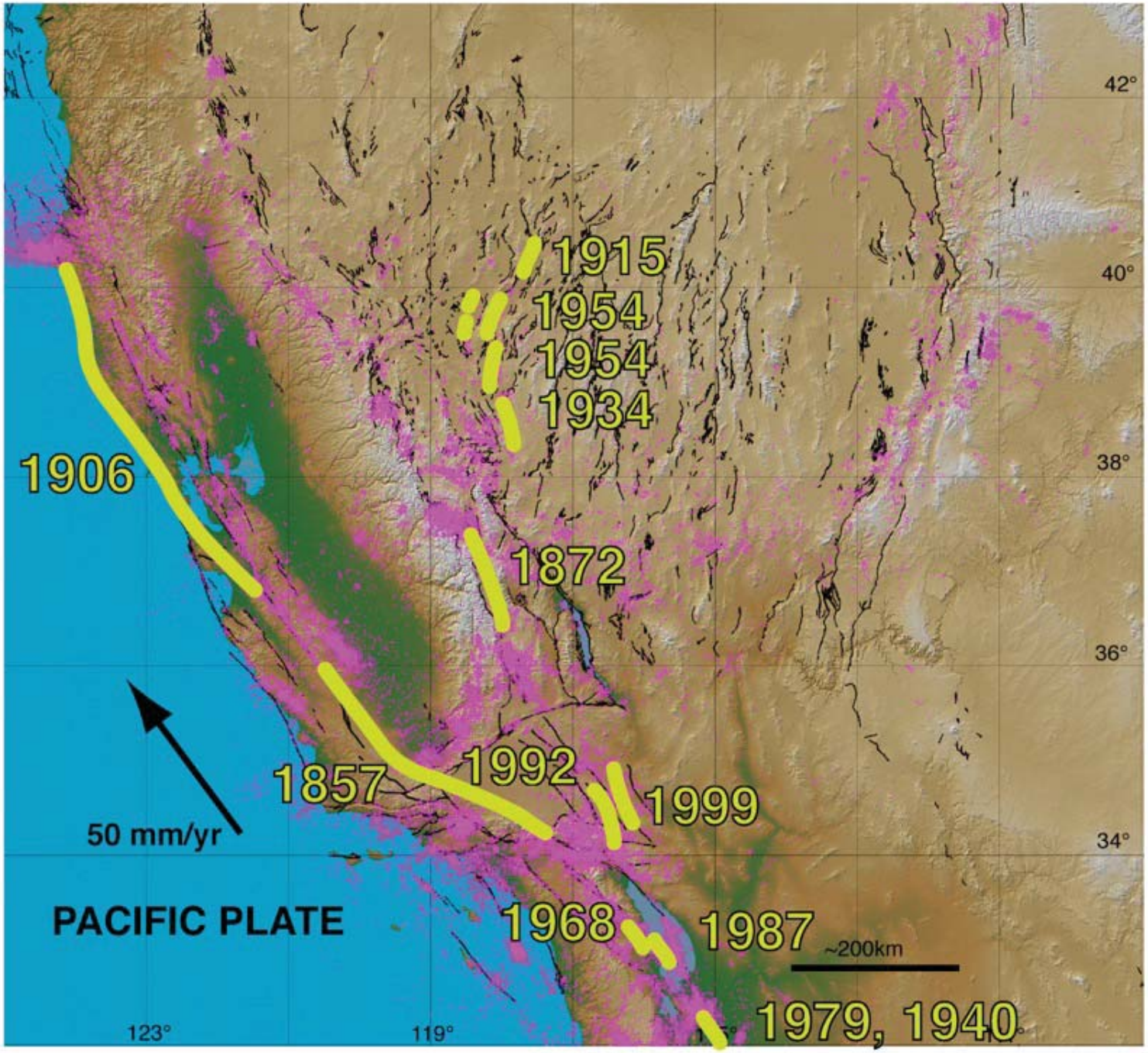
1915
1954
1954
1934
1906
1872
1857
1992
1999
1968
1987
1979, 1940
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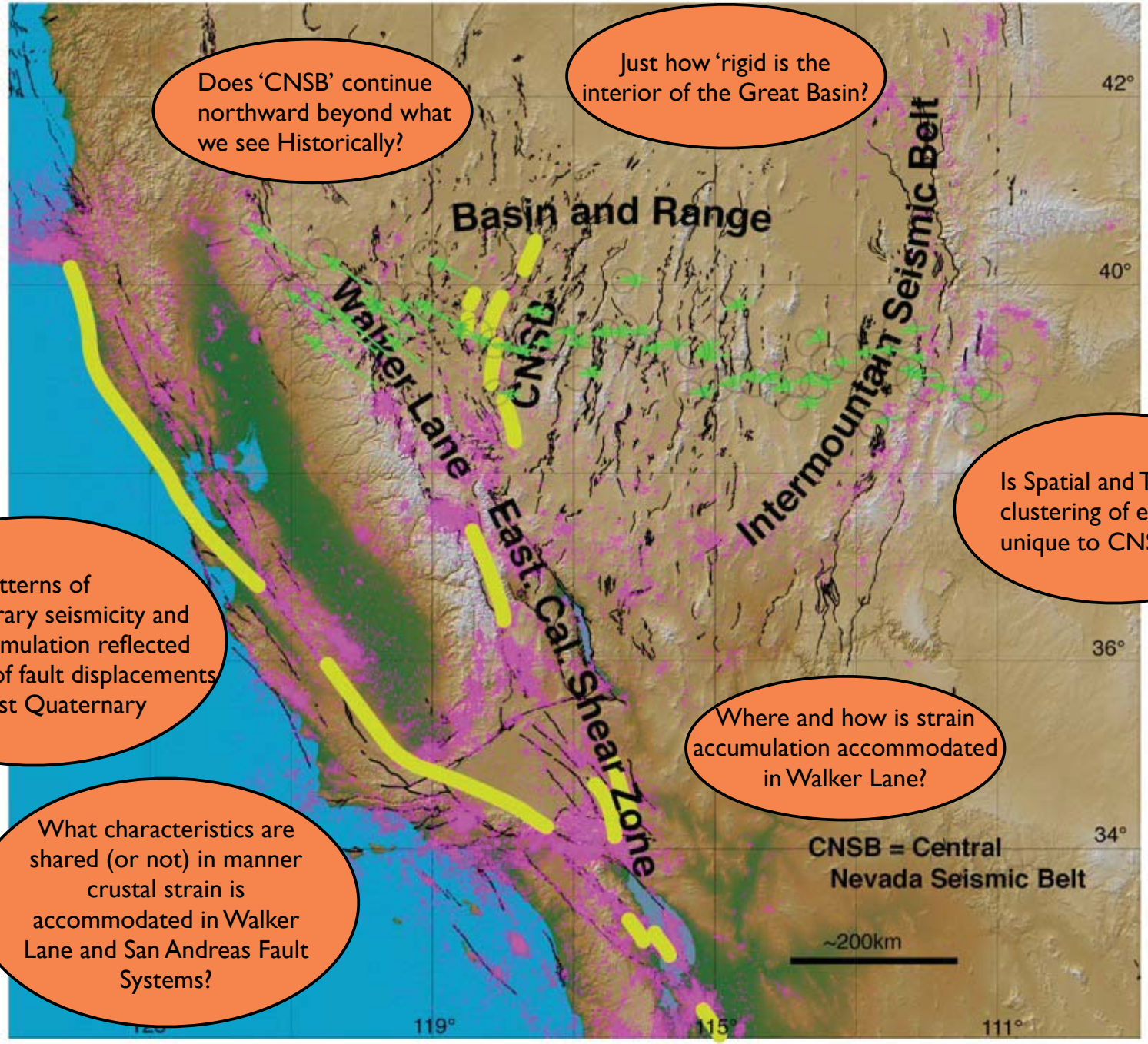
Does 'CNSB' continue northward beyond what we see Historically?
Just how 'rigid is the interior of the Great Basin?
Basin and Range
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42°
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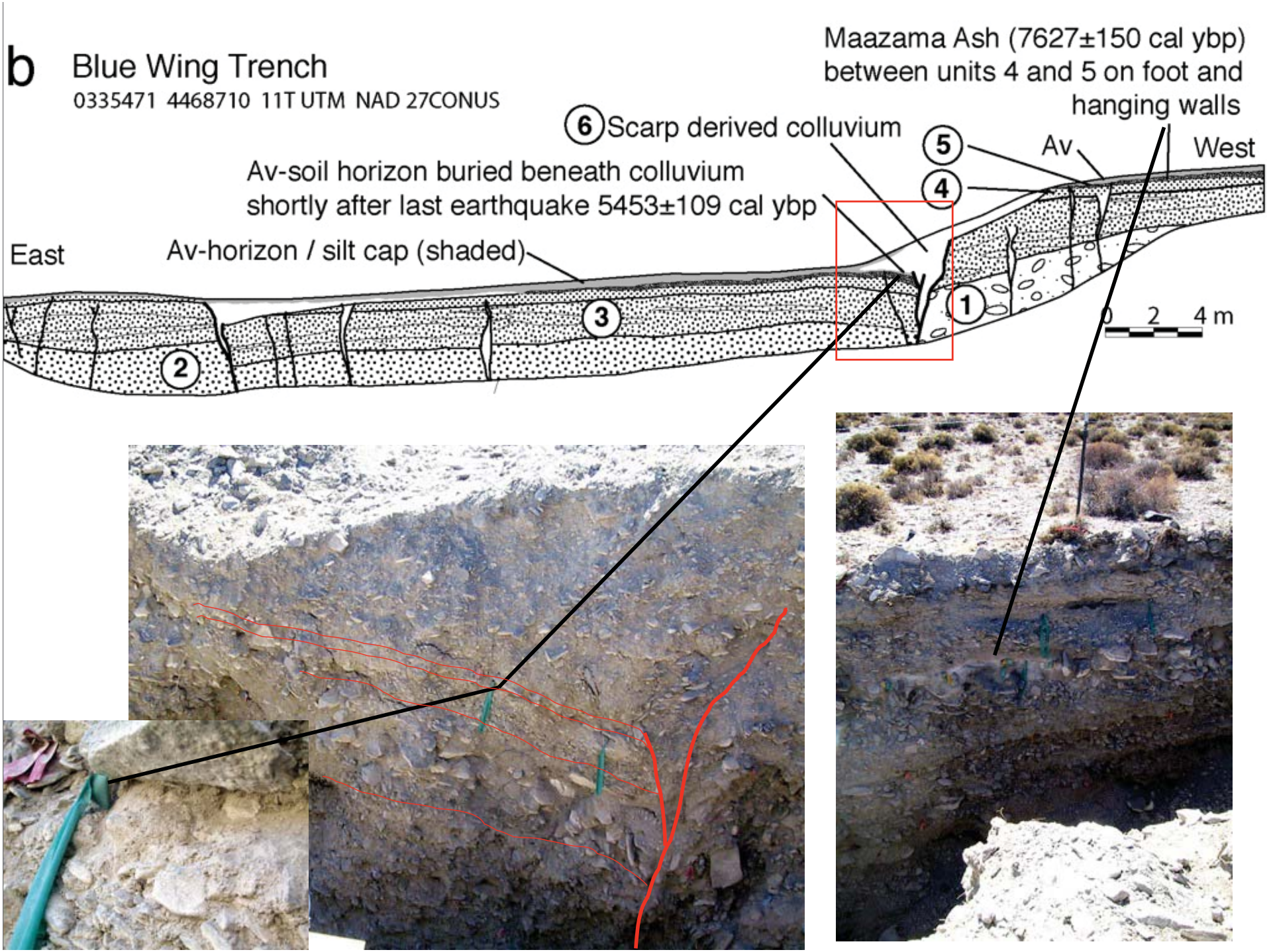
CASE


GMC


b Blue Wing Trench
0335471 4468710 11T UTM NAD 27CONUS
Maazama Ash (7627±150 cal ybp)
between units 4 and 5 on foot and
hanging walls
6 Scarp derived colluvium
5
4
Av
West
Av-soil horizon buried beneath colluvium
shortly after last earthquake 5453±109 cal ybp
East
Av-horizon / silt cap (shaded)
3
2
1
0 2 4 m

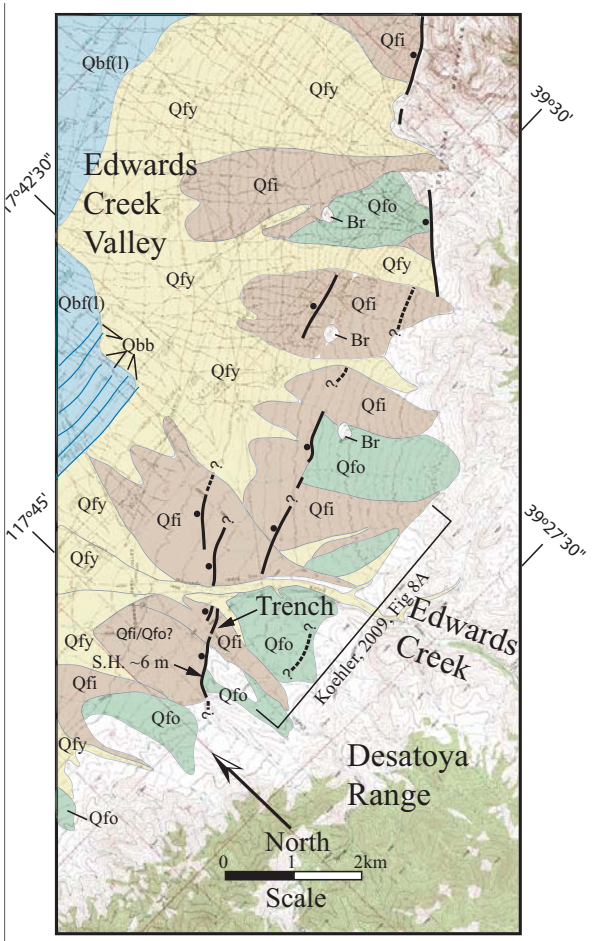


Figure 5.

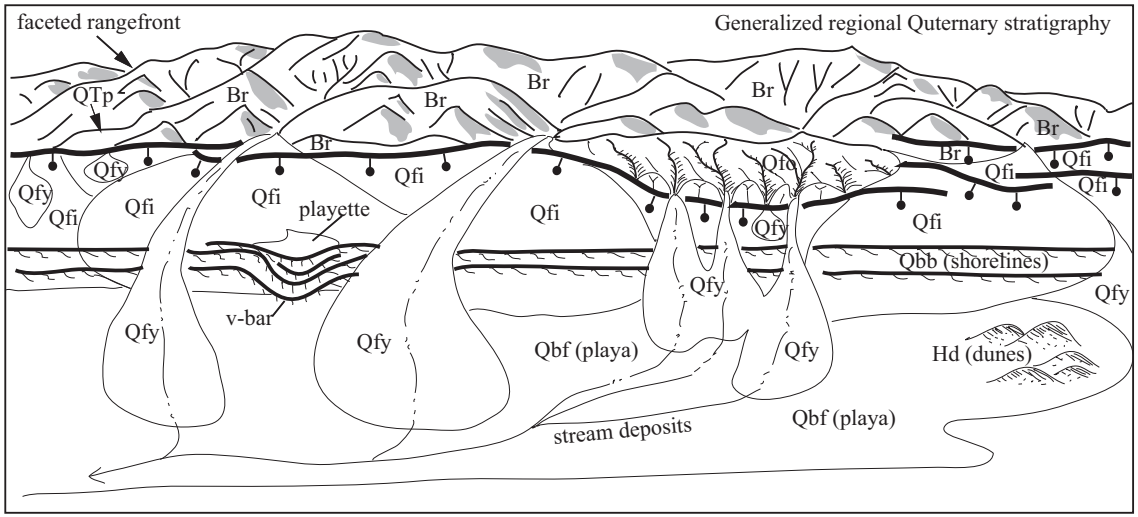


Figure 3.

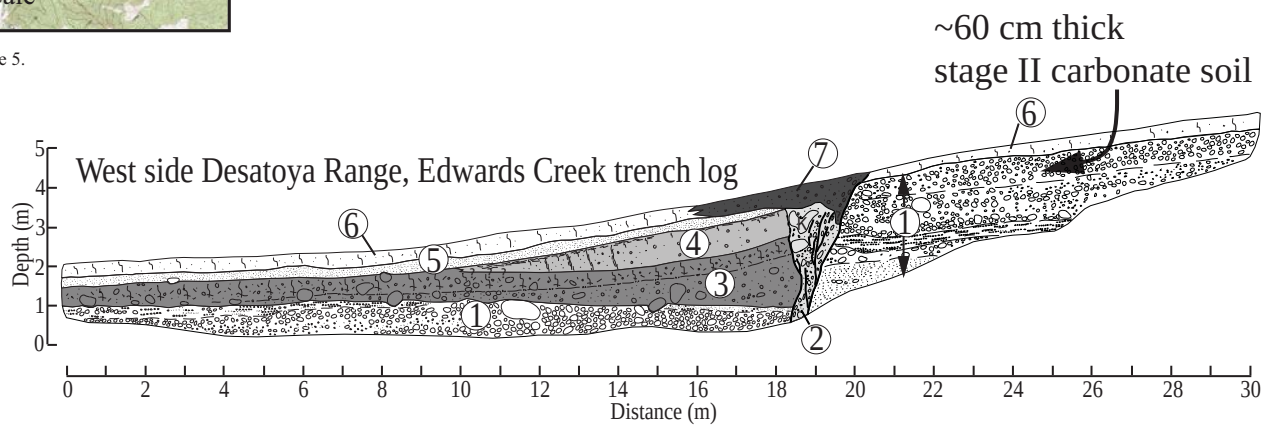


Figure 6.

time

Scarps degrade as function of time
Wallace (1977)

time

time

Diffusion-equation representation of scarp degradation

(Culling, 1970; Nash, 1980; Hanks&Wallace, 1985; Hanks&Andrews, 1989)

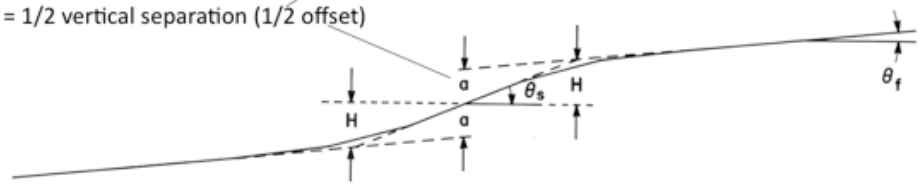
$$\frac{\delta u}{\delta t} - \kappa \frac{\delta^2 u}{\delta x^2} = 0$$

u = relative elevation of cross-strike scarp profile
t = time
κ = mass diffusivity (m^2/t)

slope of surfaces

$$u(x,t) = a\,\mathrm{erf}\left(\frac{x}{\kappa t}\right) + (\tan\Theta_f * x)$$

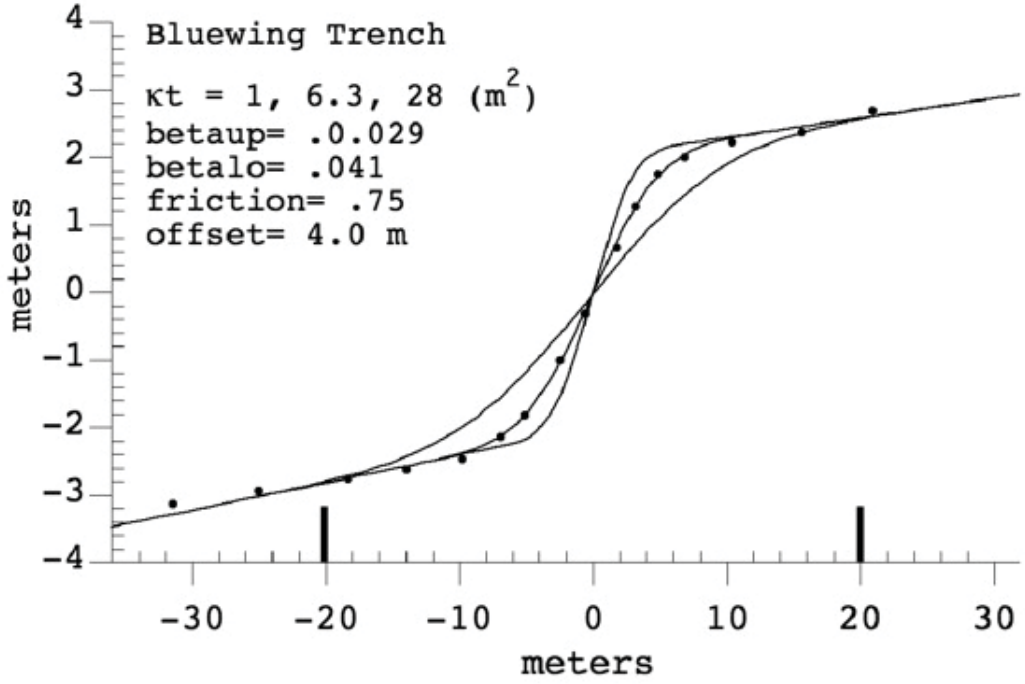
a = 1/2 vertical separation (1/2 offset)

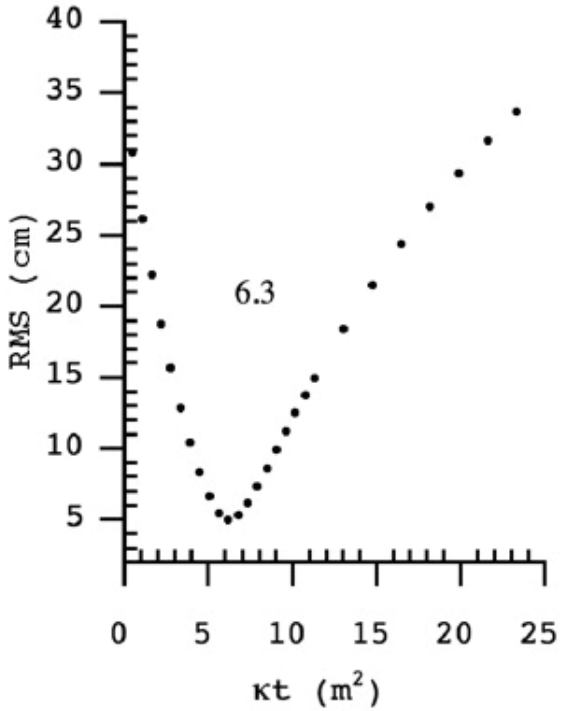


Assumptions:

1. Mass moves downhill at rate proportional to topographic gradient,.
2. Conservation of mass holds on a local scale.

Given that the slopes and offsets can be measured, the slope of the profile is a function of κt





If scarp age = 5500 years, then κ is about 1.2

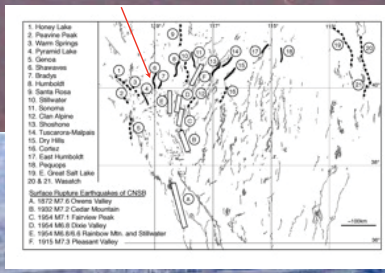
View northwest across Shawave Mountains

Lake Range

Nightingale Range

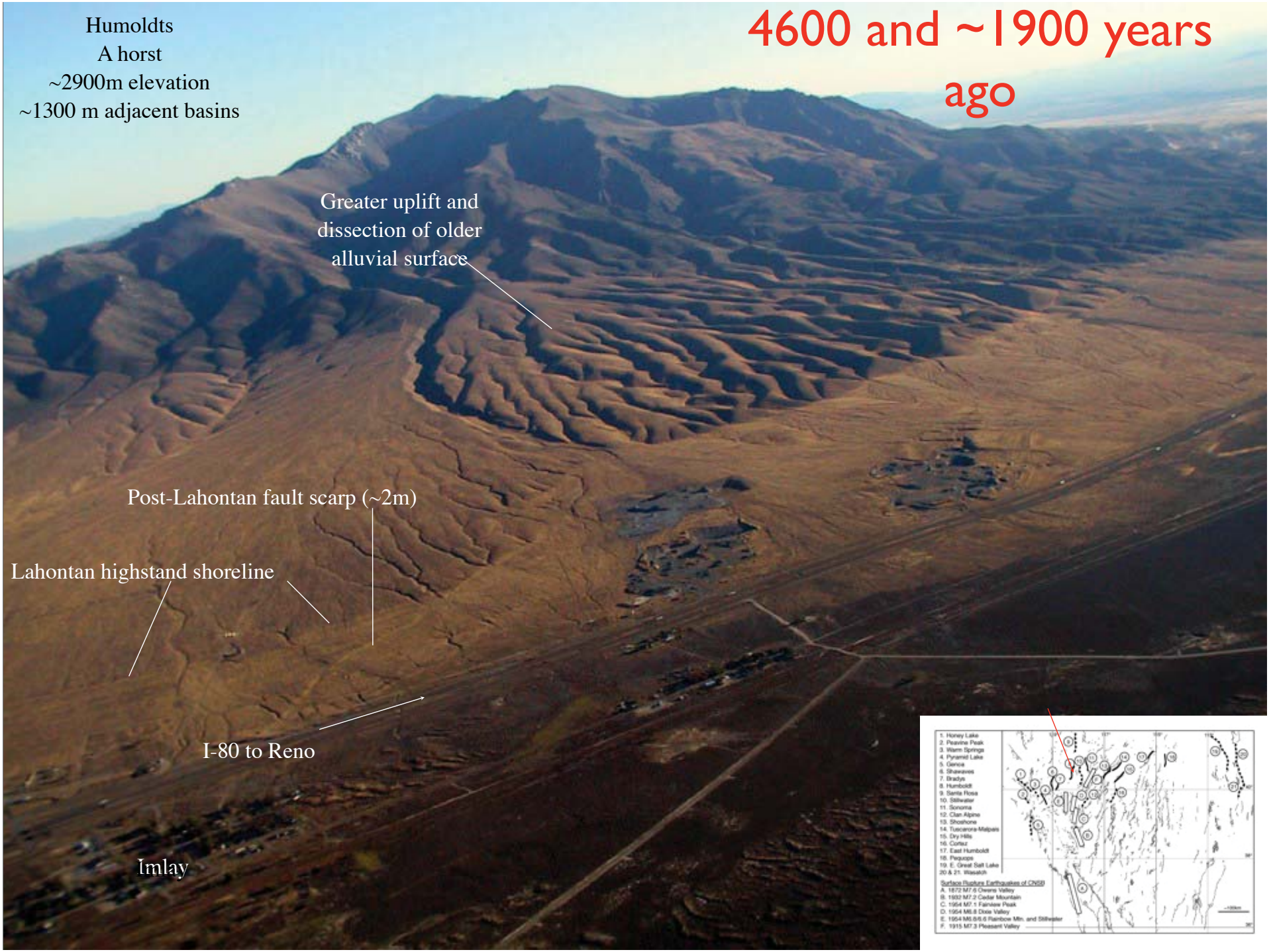
West-tilted fault block - ridgelines exceed 2100 m with adjacent flats ~1200 m

Selenite Range

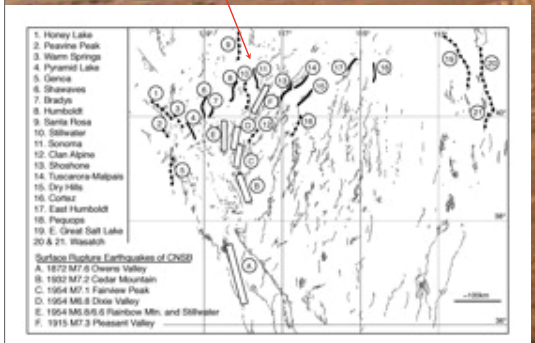


Trench

Trench


Humoldts
A horst
~2900m elevation
~1300 m adjacent basins
4600 and ~1900 years ago
Greater uplift and dissection of older alluvial surface
Post-Lahontan fault scarp (~2m)
Lahontan highstand shoreline
I-80 to Reno
Imlay

Sonoma Range



Bacon Canyon Trench Site

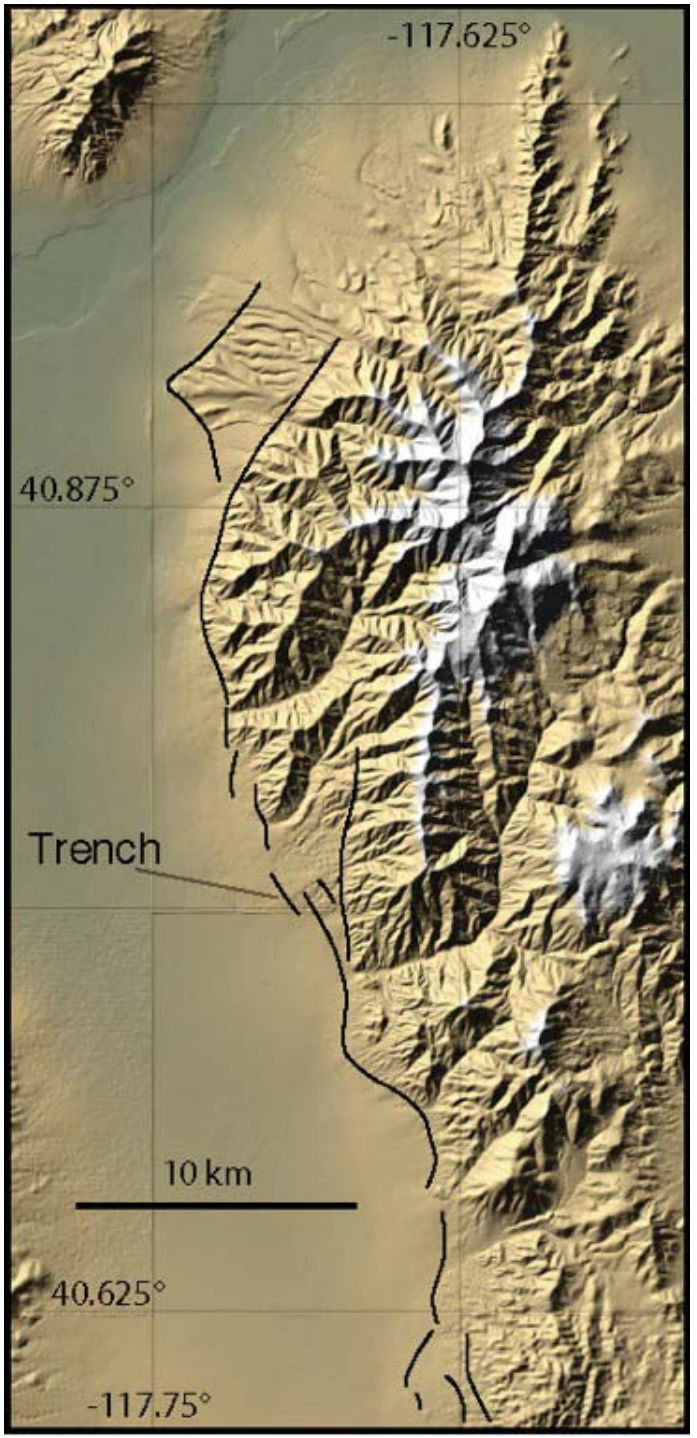
Scarp formed 20ka…

Sonoma Range

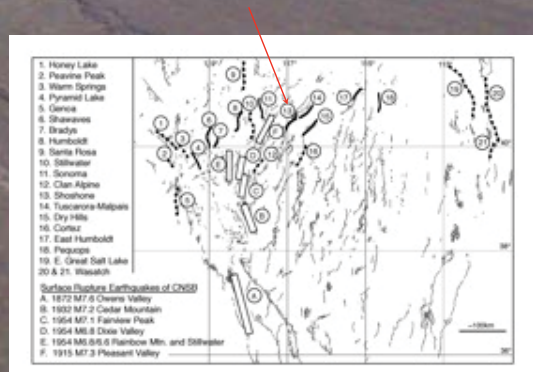
East-tilted fault block

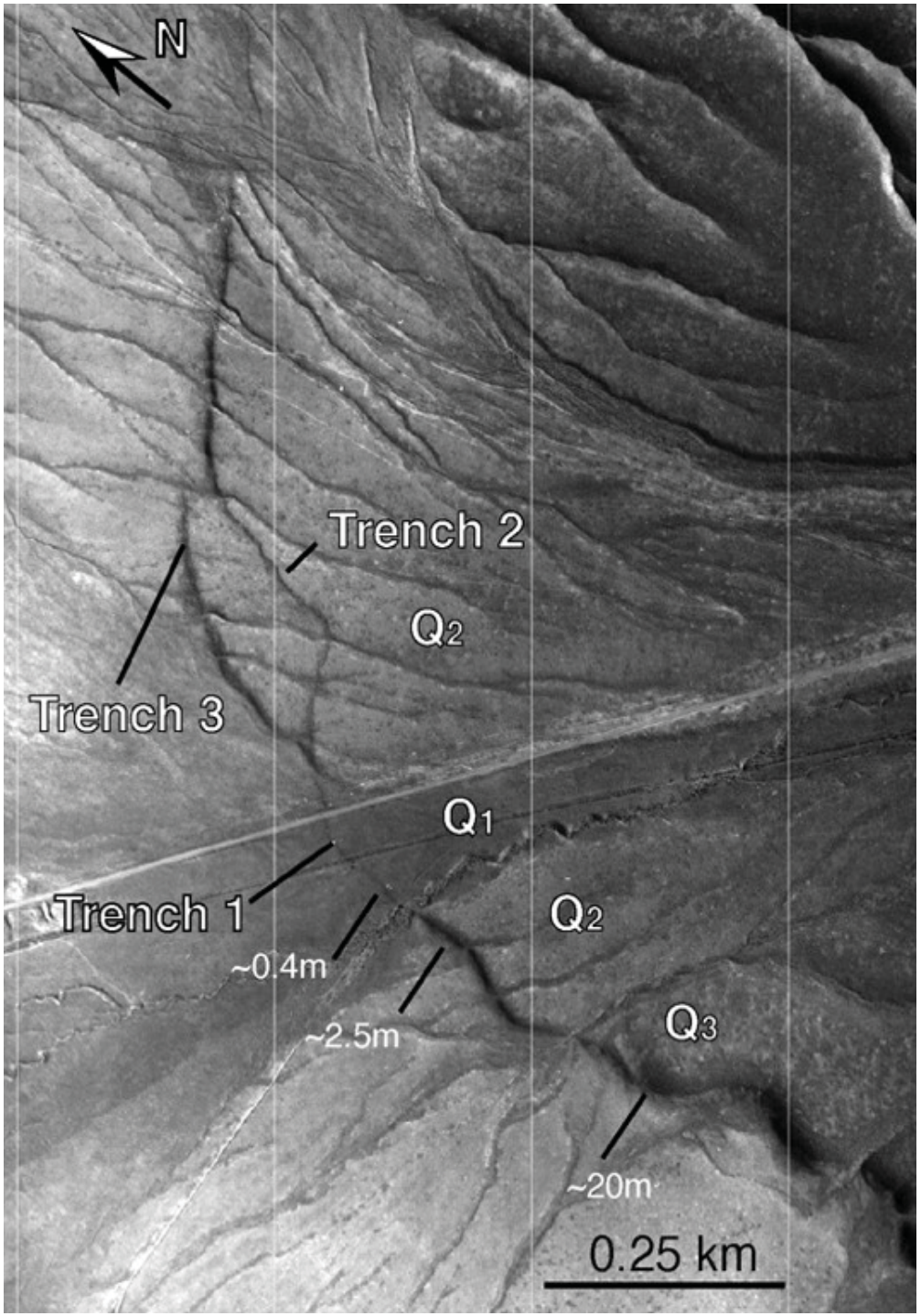
~1300 m vertical relief

Highest ridges ~2700 m



Shoshone Range - Lewis Canyon
Mt Lewis ~2800 m
adjacent valley fill ~1400 m



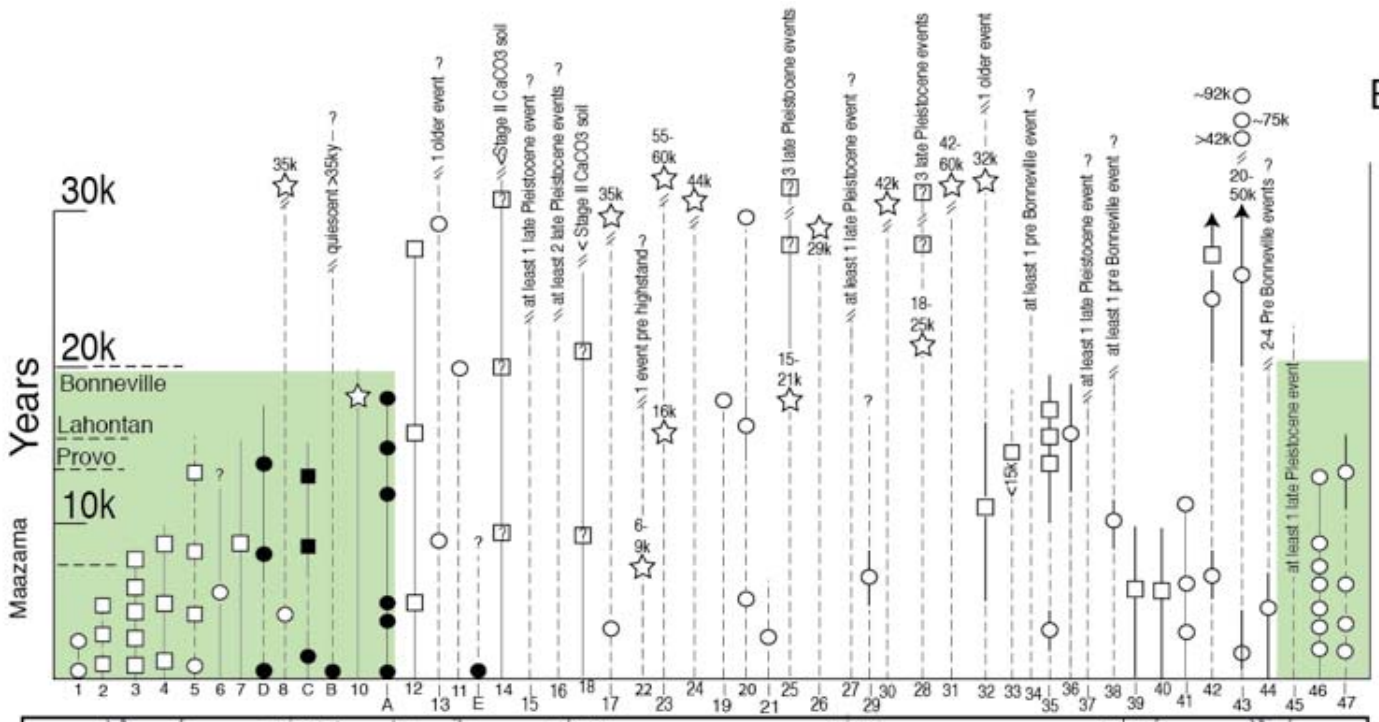


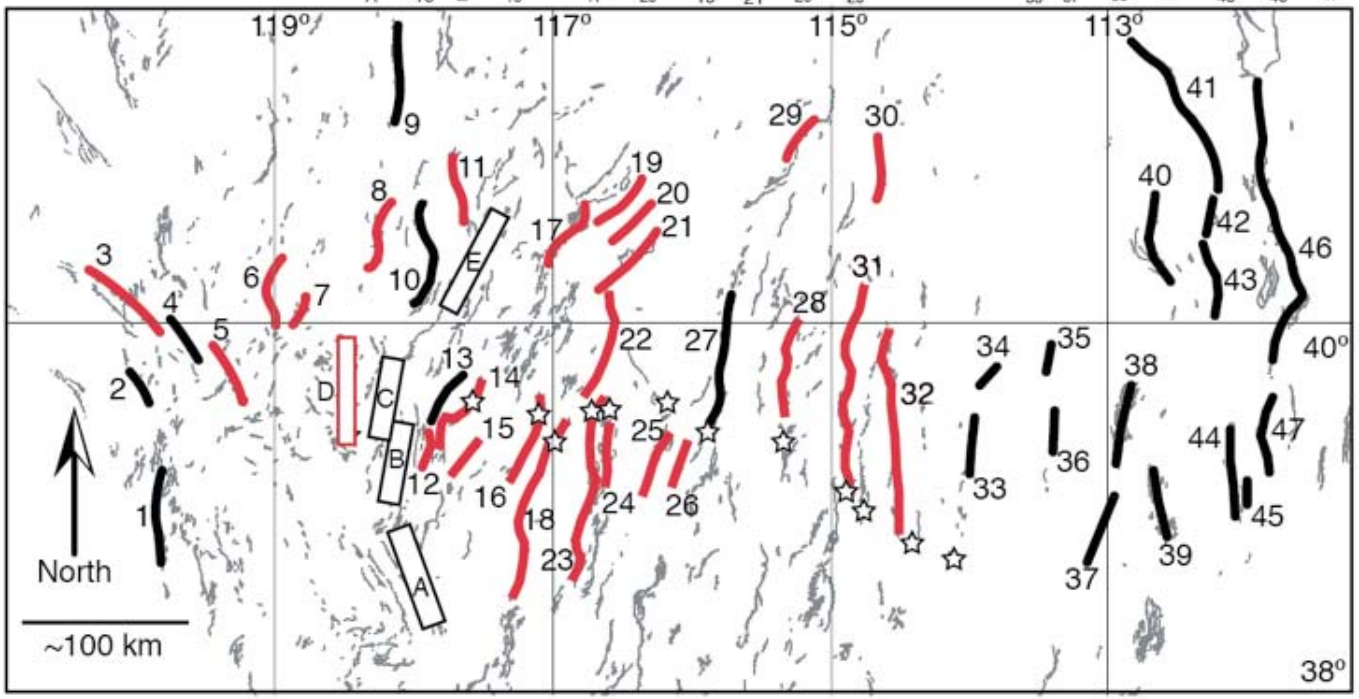
Progressive offset of fan surfaces -

most recent displacement ~3300 years ago

Proceeded by another ~40,000 years ago…

SPACE-TIME PLOT OF EARTHQUAKE RECURRENCE





DATED EARTHQUAKES

EARTHQUAKES SINCE PARTICULAR TIME

SCARP DIFFUSION ANALYSIS

CENTRAL NEVADA SEISMIC BELT

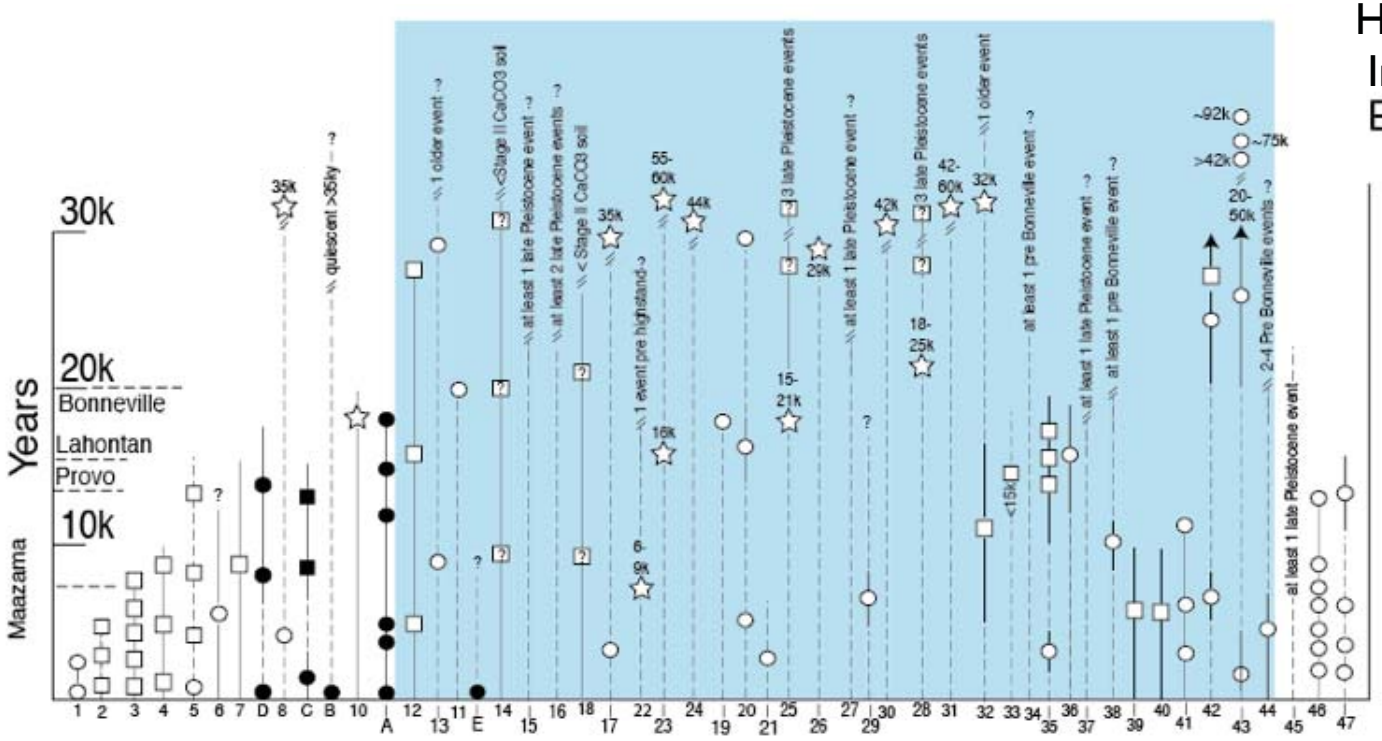
Center for Neotectonic Studies

USGS, NBMG, UGS (Utah)

Historical Ruptures of CNSB

Pts Along Hwy 50

Horizontal Extension Across Interior of Basin and Range
EARTHQUAKE RECURRENCE

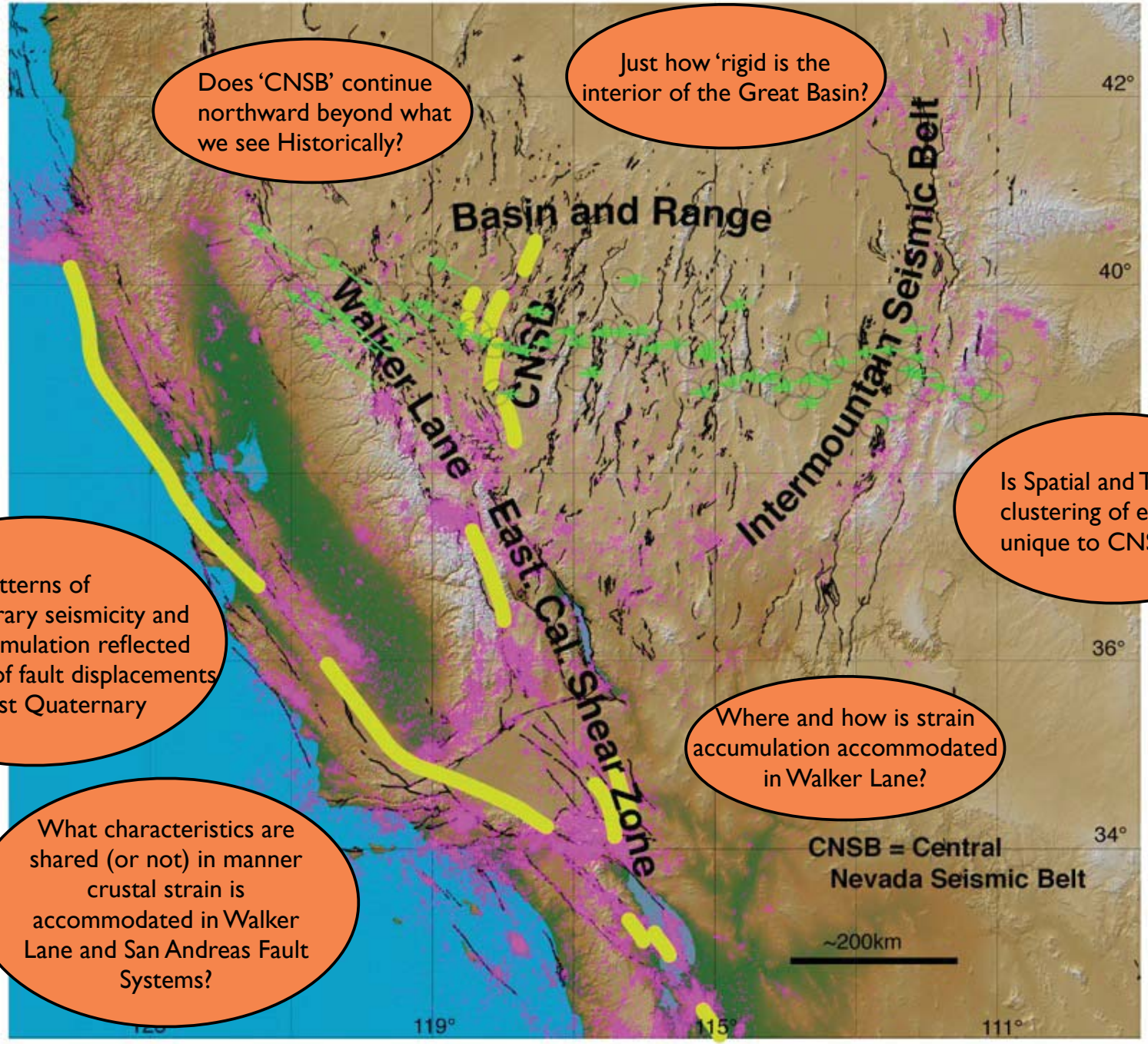


Fault	Vertical Separation (60 ky)	Extension	Strike	E-W Component of Extension
13. Clan Alpine	6 m	3.5 m	27°	3.1 m
.	.	.	.	.
.	.	.	.	.
SUM	91.3 m	58.5 m		48.4 m

48. 4 m / 60 ky = 0.8 mm/yr

Fault	Vertical Separation (20 ky)	Extension	Strike	E-W Component of Extension
13. Clan Alpine	1.2 m	0.7 m	27°	0.6 m
.	.	.	.	.
.	.	.	.	.
SUM	35.4 m	24.5 m		19.3 m

19.3 m / 60 ky = 1.0 mm/yr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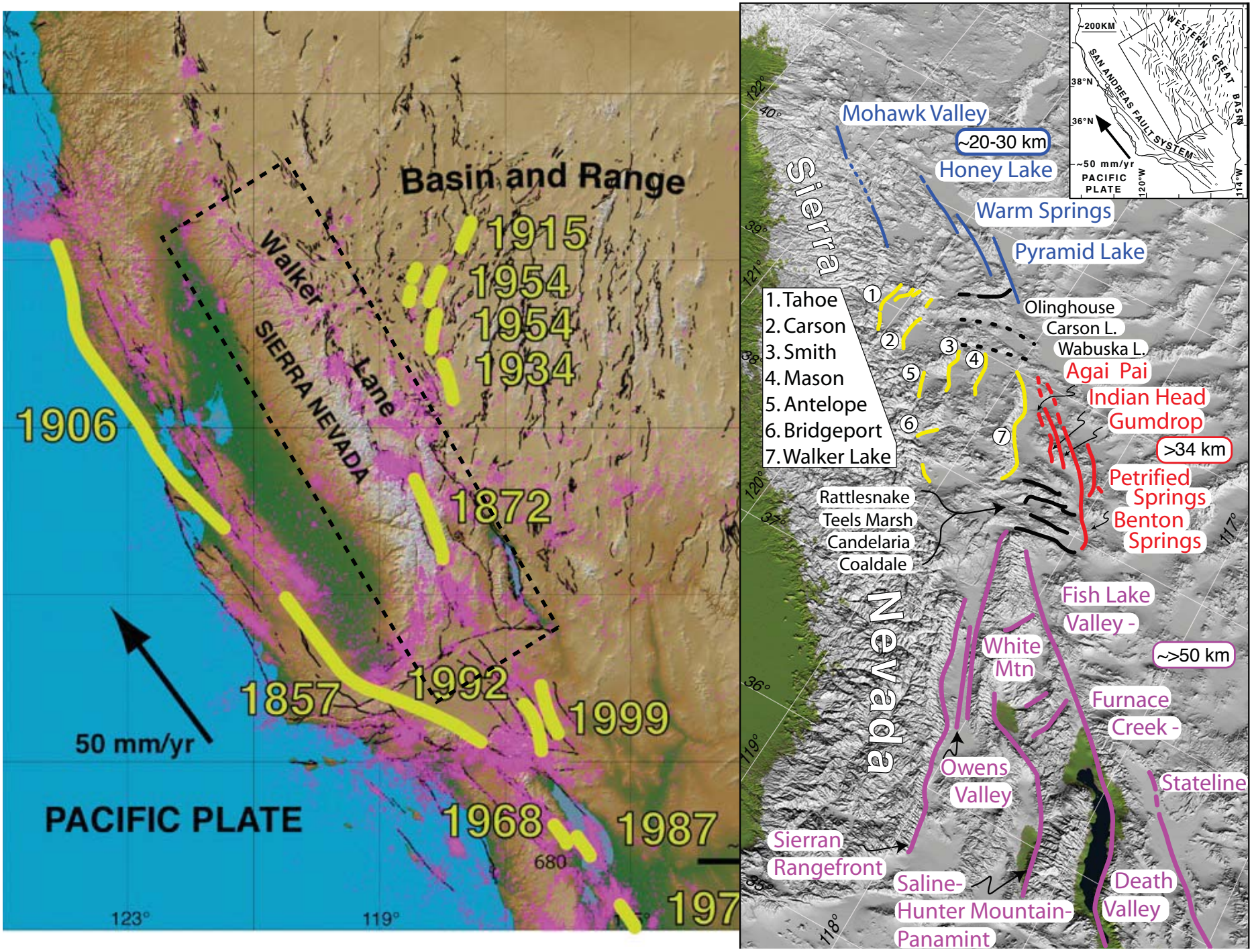
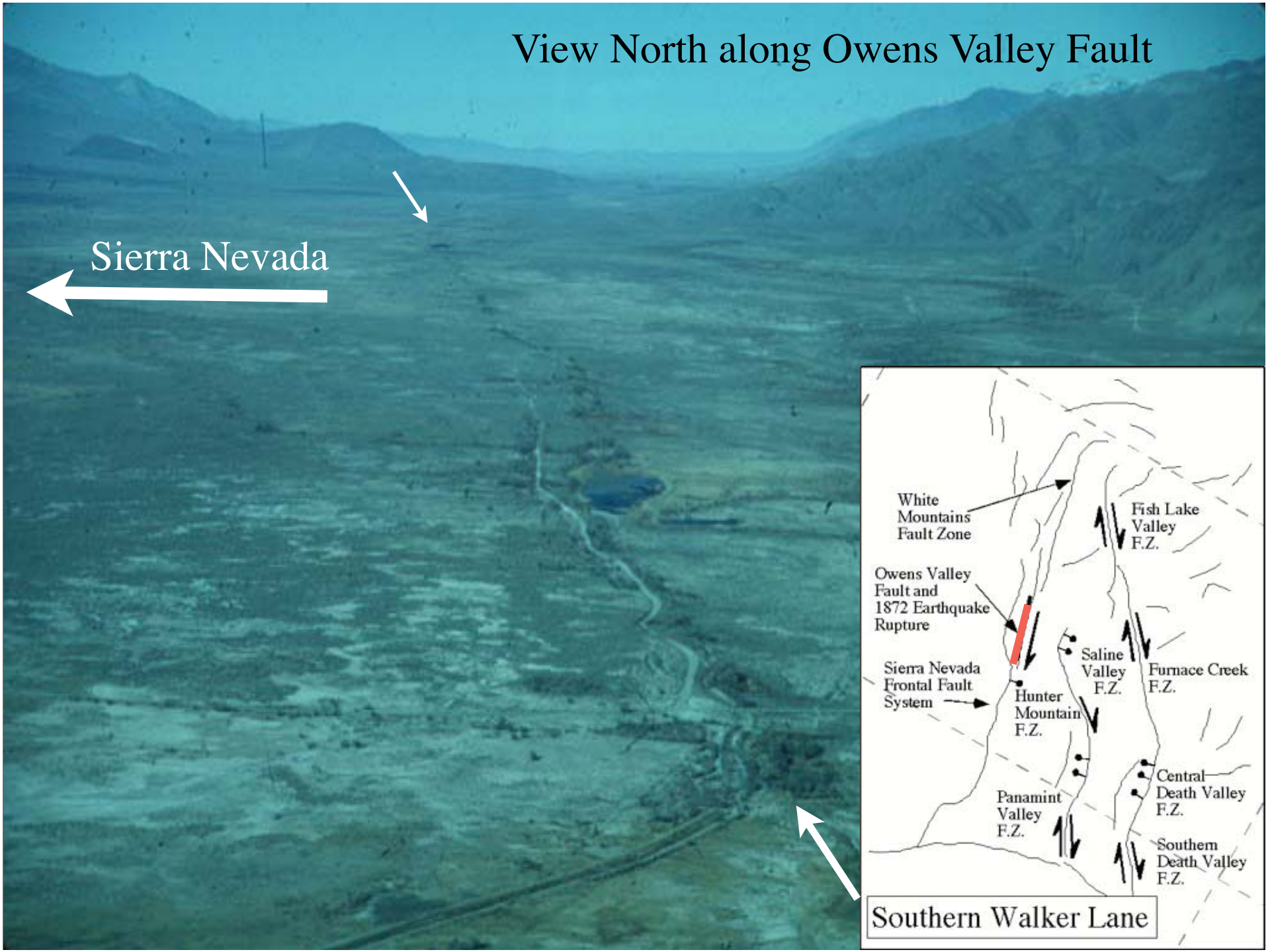
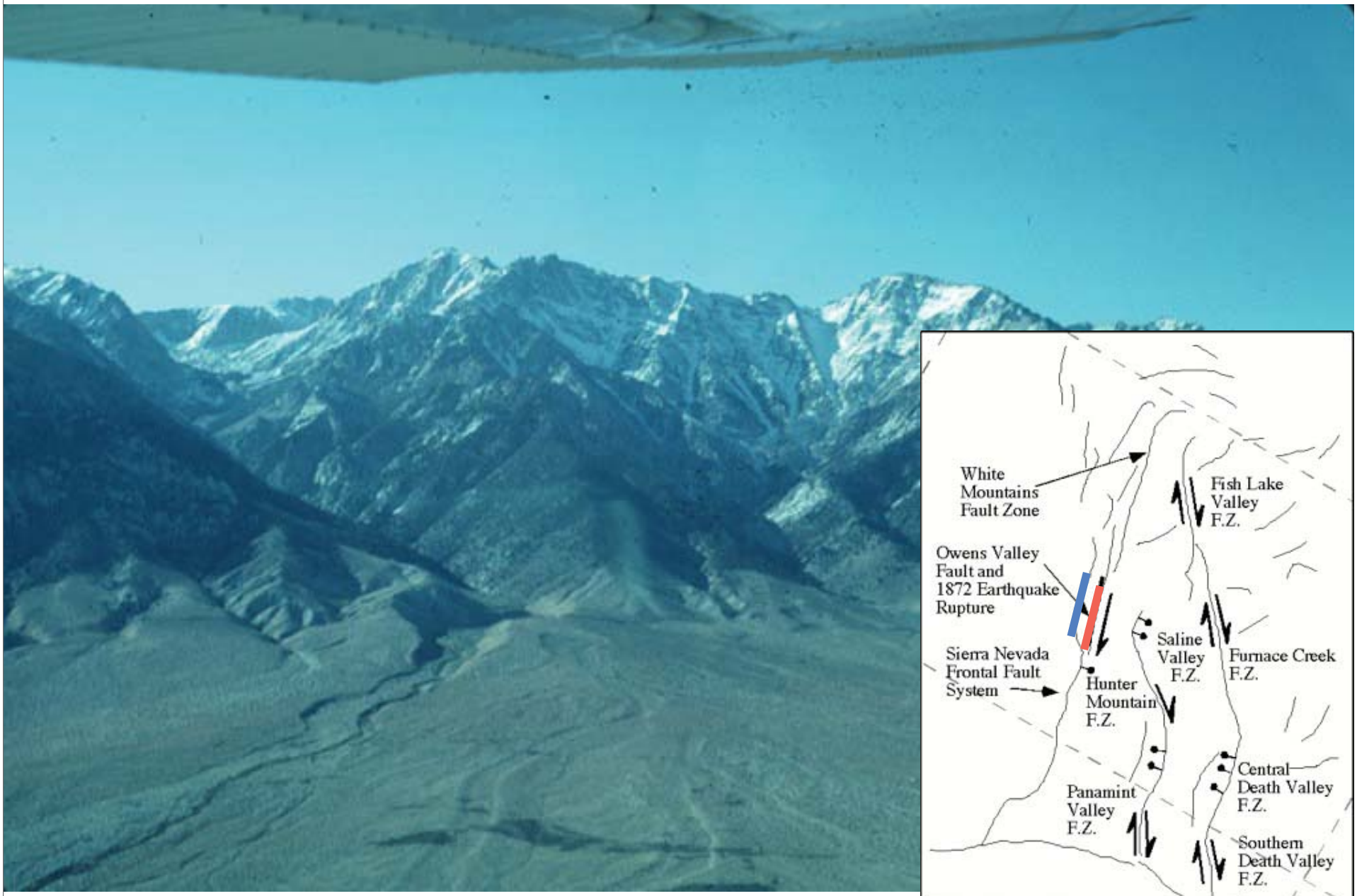
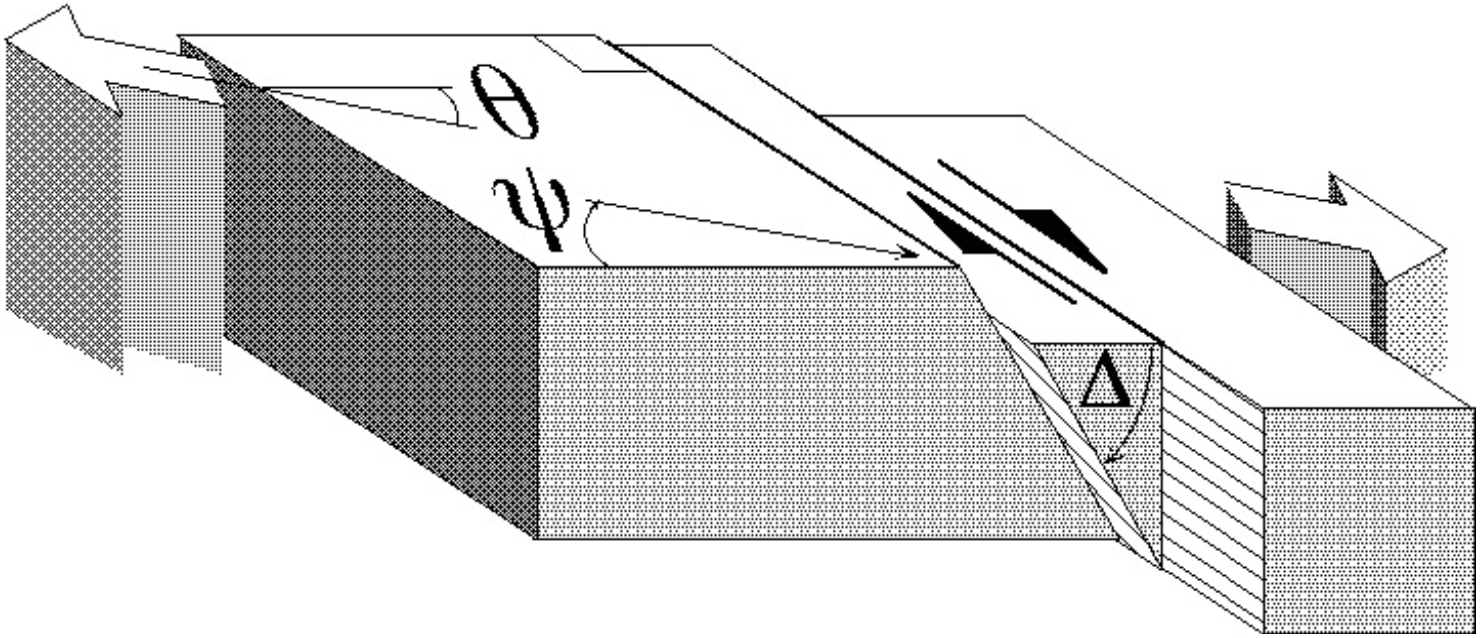

Basin and Range
Walker Lane
SIERRA NEVADA
1915
1954
1954
1934
1906
1872
1857
1992
1999
1968
1987
197
50 mm/yr
PACIFIC PLATE
123°
119°
680
Sierra Nevada
Mohawk Valley
~20-30 km
Honey Lake
Warm Springs
Pyramid Lake
1. Tahoe
2. Carson
3. Smith
4. Mason
5. Antelope
6. Bridgeport
7. Walker Lake
Olinghouse
Carson L.
Wabuska L.
Agai Pai
Indian Head
Gumdrop
>34 km
Petrified Springs
Benton Springs
Rattlesnake
Teels Marsh
Candelaria
Coaldale
Fish Lake Valley -
~>50 km
White Mtn
Furnace Creek -
Owens Valley
Stateline
Sierran Rangefront
Saline-Hunter Mountain-Panamint
Death Valley
~200KM
WESTERN GREAT BASIN
SAN ANDREAS FAULT SYSTEM
38°N
36°N
~50 mm/yr
PACIFIC PLATE
120°W
122°
40°
39°
121°
38°
120°
37°
117°
36°
119°
35°
118°


View North along Owens Valley Fault
Sierra Nevada
White Mountains Fault Zone
Fish Lake Valley F.Z.
Owens Valley Fault and 1872 Earthquake Rupture
Saline Valley F.Z.
Furnace Creek F.Z.
Sierra Nevada Frontal Fault System
Hunter Mountain F.Z.
Central Death Valley F.Z.
Panamint Valley F.Z.
Southern Death Valley F.Z.
Southern Walker Lane



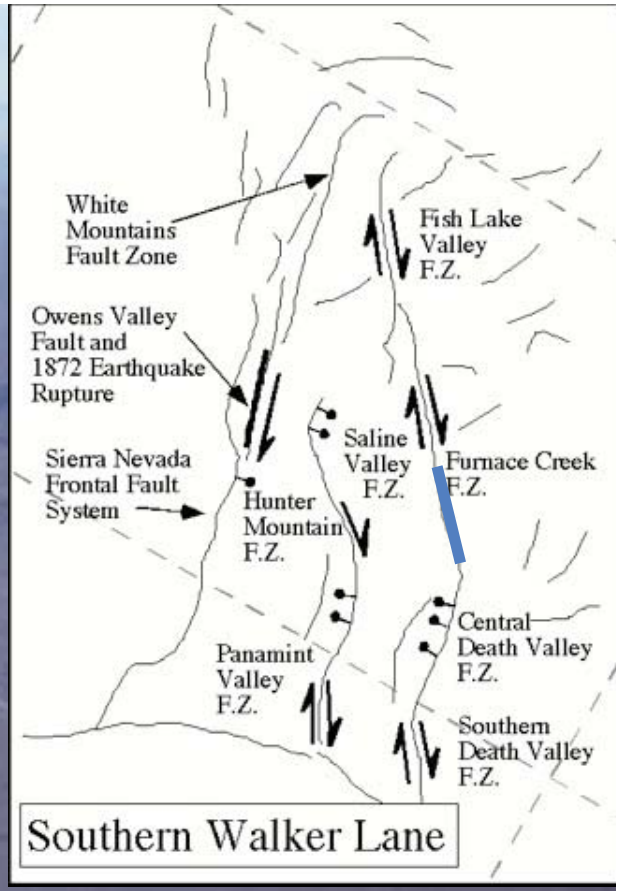
Shephard Creek - Sierra Rangefront

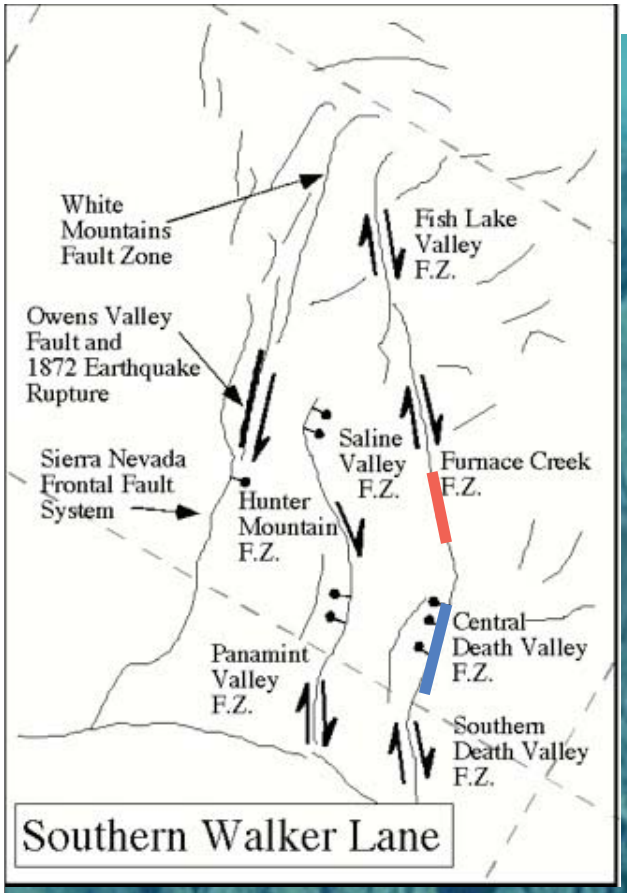
Oblique Extension



Partitioning of Oblique Slip between strike-slip and dip slip...

View South along Furnace Creek Strike-Slip toward Death Valley




White Mountains Fault Zone
Fish Lake Valley F.Z.
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Sierra Nevada Frontal Fault System
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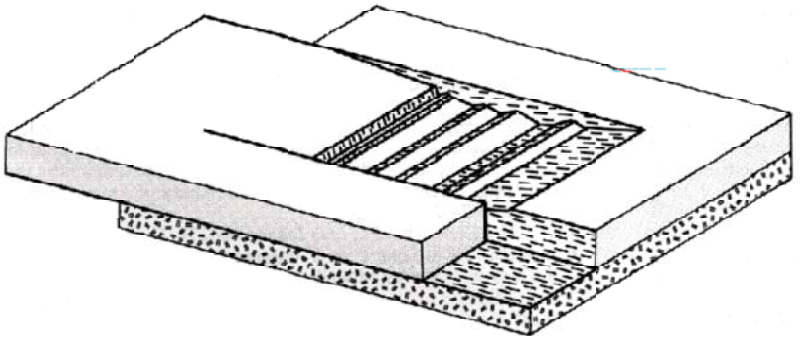
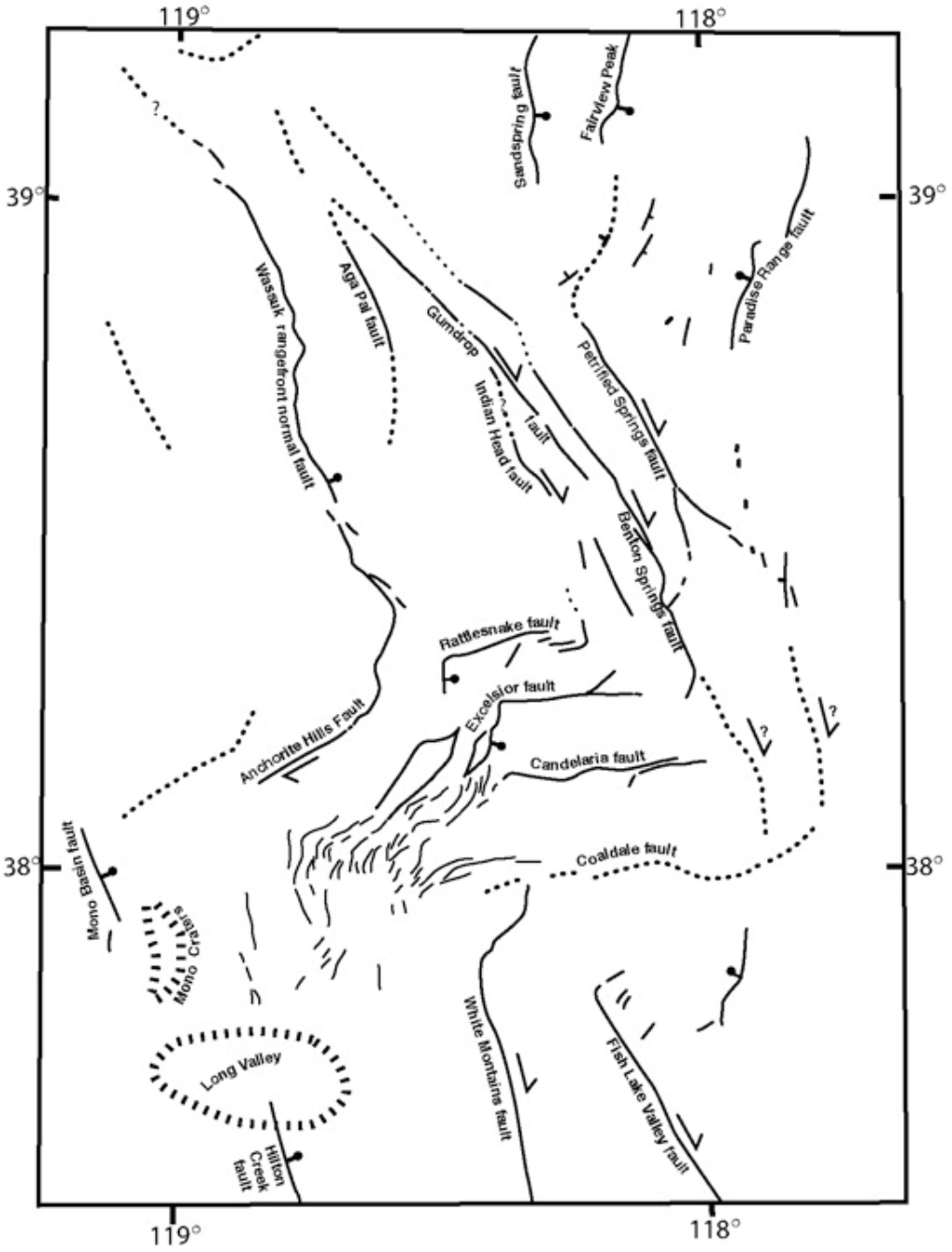
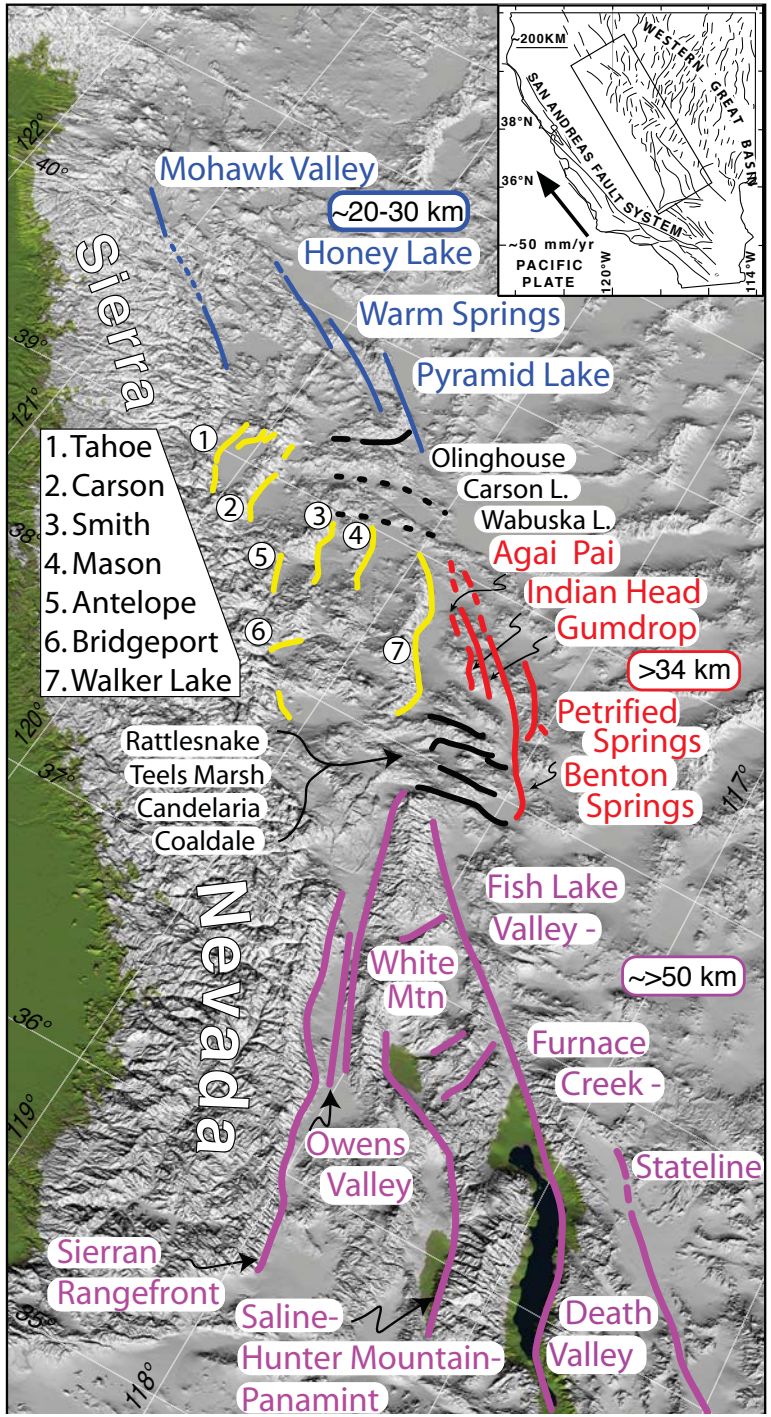
Panamint Valley F.Z.
Southern Death Valley F.Z.
Southern Walker Lane




119°
118°
39°
38°
Sandspring fault
Fairview Peak
Wassuk rangefront normal fault
Aga Pai fault
Gumdrop
Indian Head fault
fault
Petrified Springs fault
Paradise Range Fault
Benton Springs fault
Rattlesnake fault
Excelsior fault
Anchorite Hills Fault
Candelaria fault
Coaldale fault
Mono Basin fault
Mono Craters
Long Valley
Hilton Creek fault
White Mountains fault
Fish Lake Valley fault


~200KM
WESTERN GREAT BASIN
SAN ANDREAS FAULT SYSTEM
38°N
36°N
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PACIFIC PLATE
122°W
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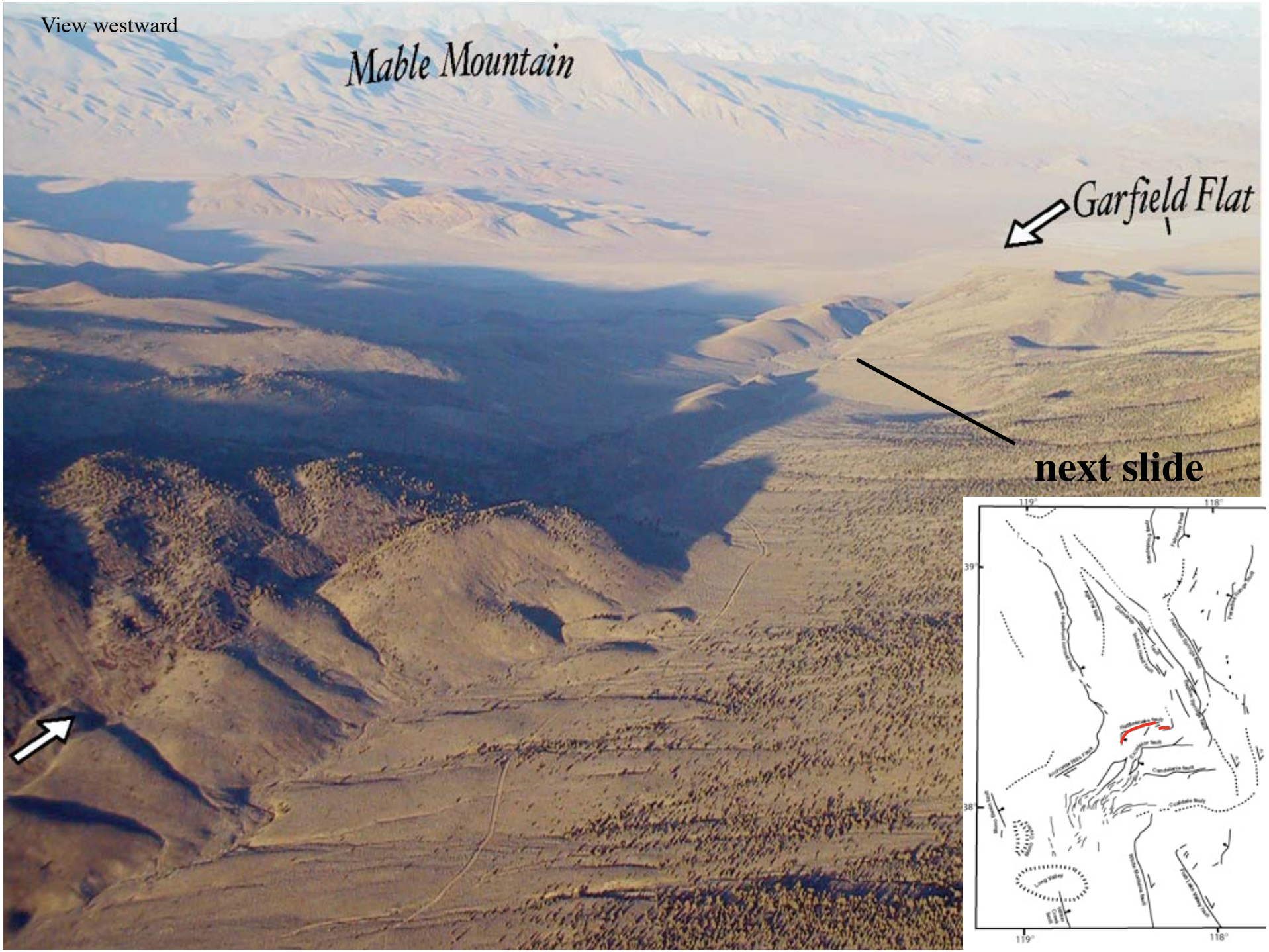
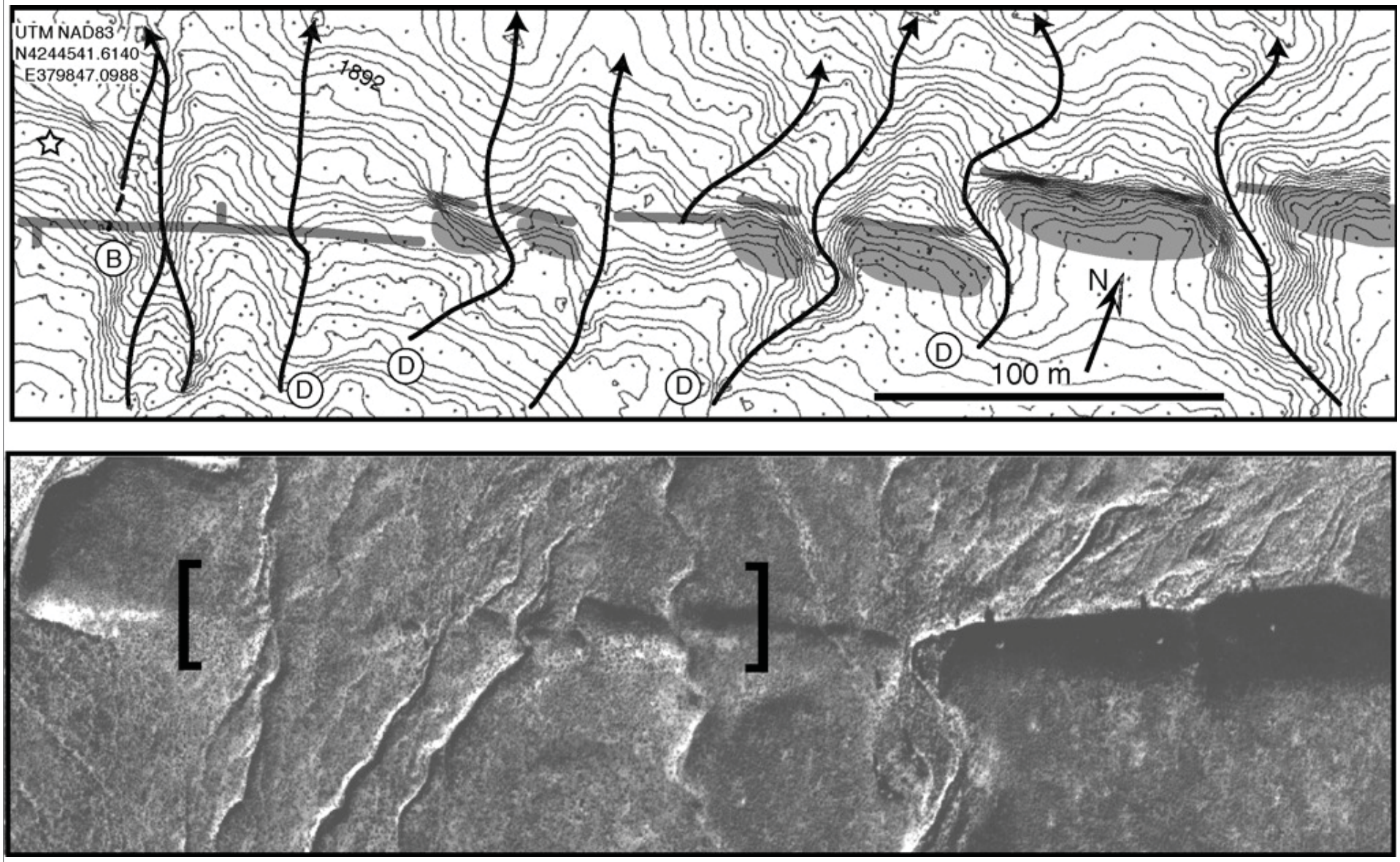
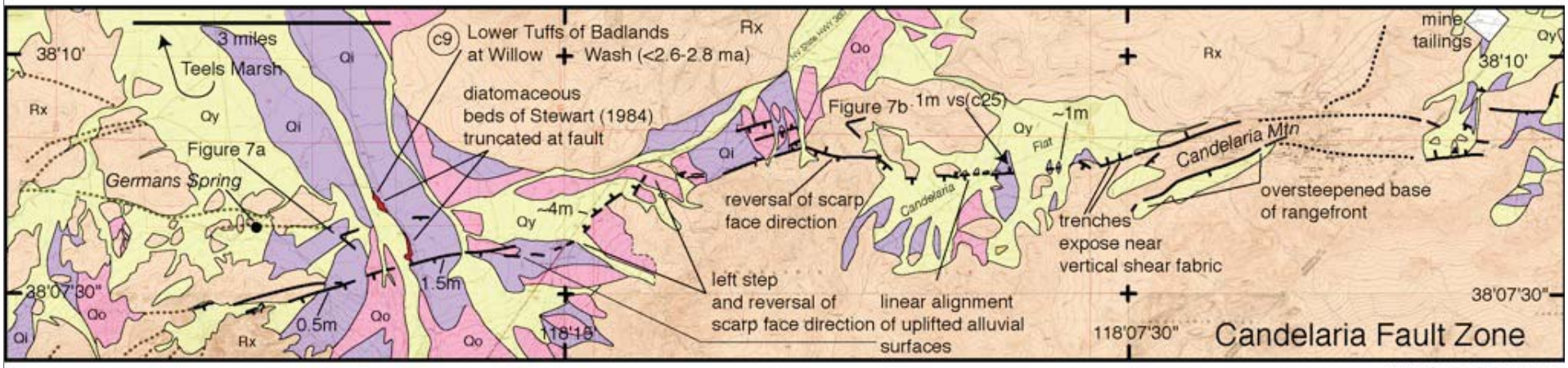
Nevada
Fish Lake Valley -
~>50 km
White Mtn
Furnace Creek -
Owens Valley
Stateline
Sierran Rangefront
Saline-Hunter Mountain-Panamint
Death Valley

View westward



35cm contour interval





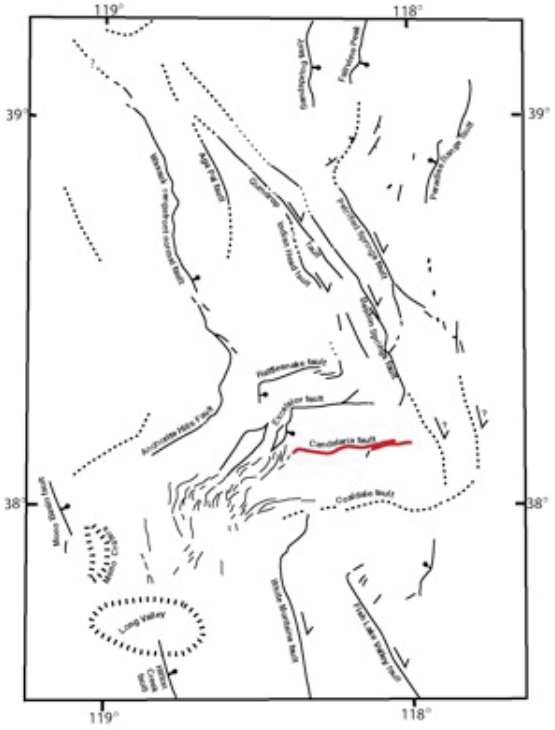
off fault geology adapted from Dohrenwend (82), Stewart (84)

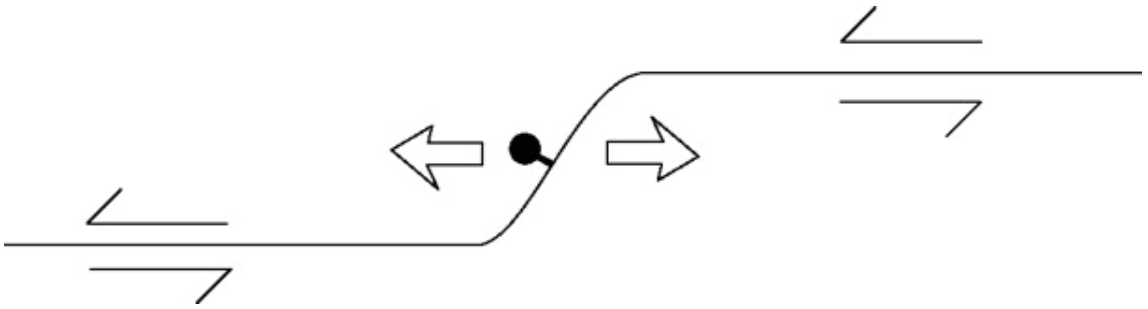
Youngest alluvial deposits and surfaces

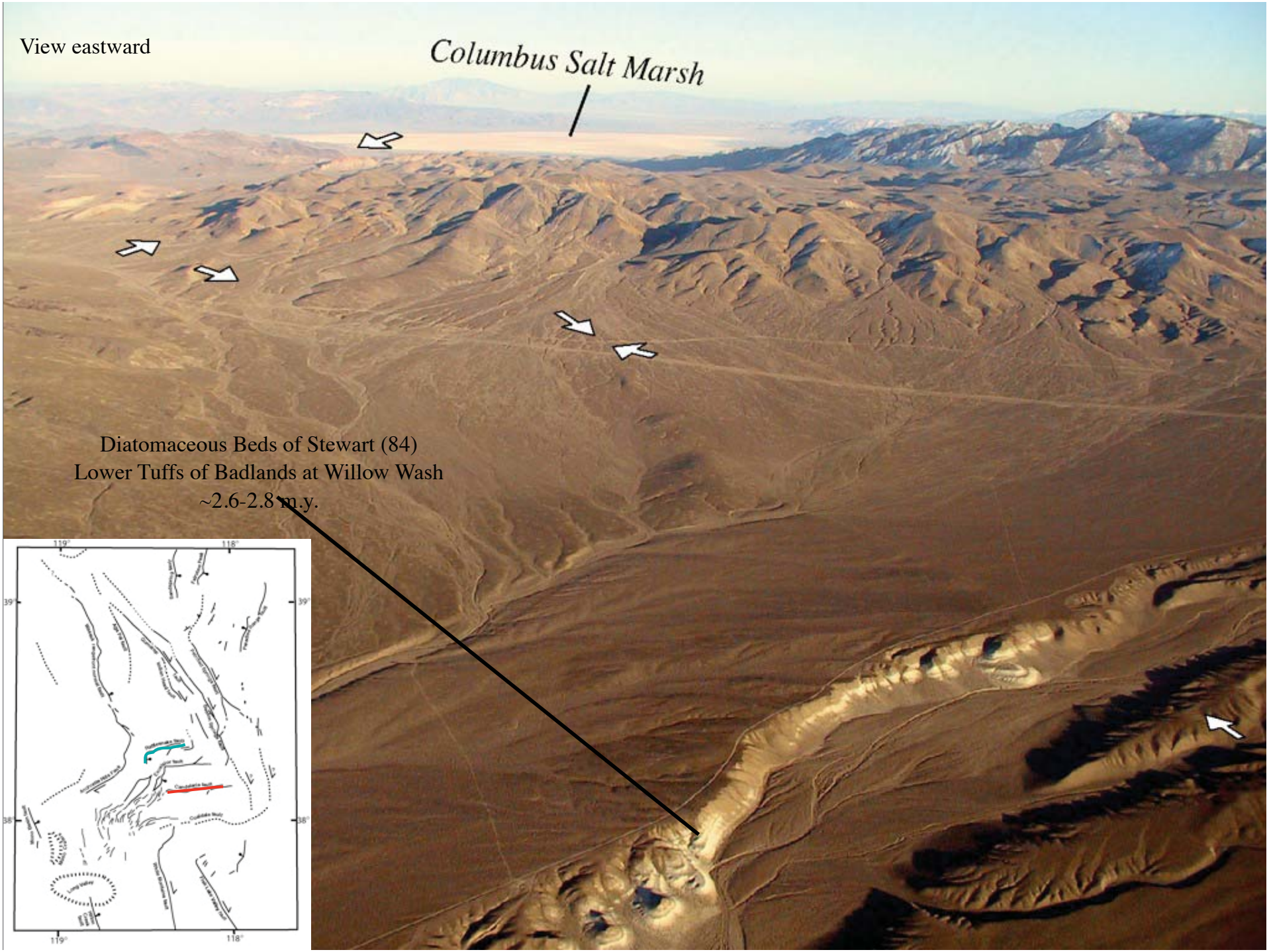
Intermediate age alluvial deposits and pediment surfaces

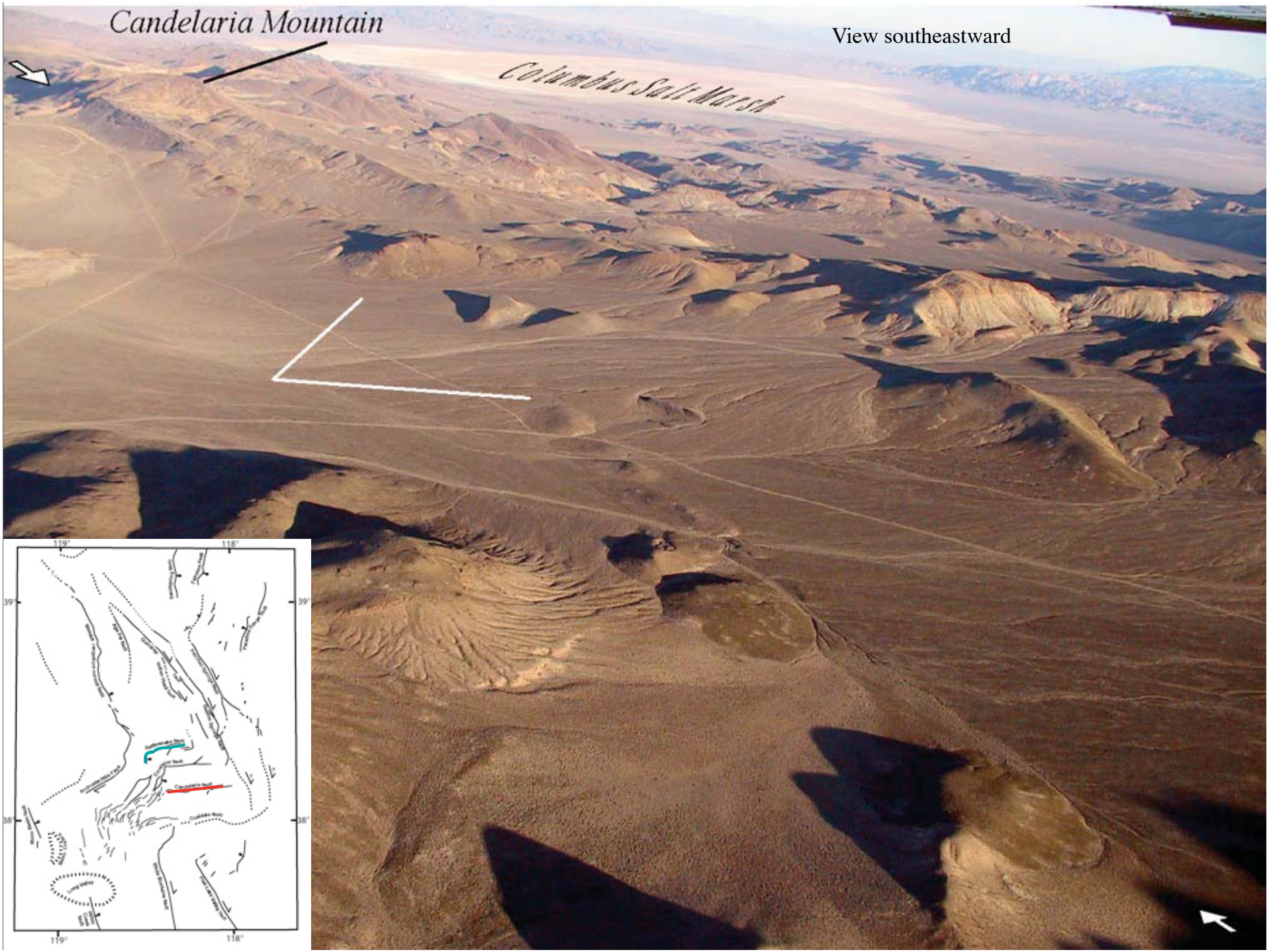
Oldest alluvial fan deposits and pediment surfaces

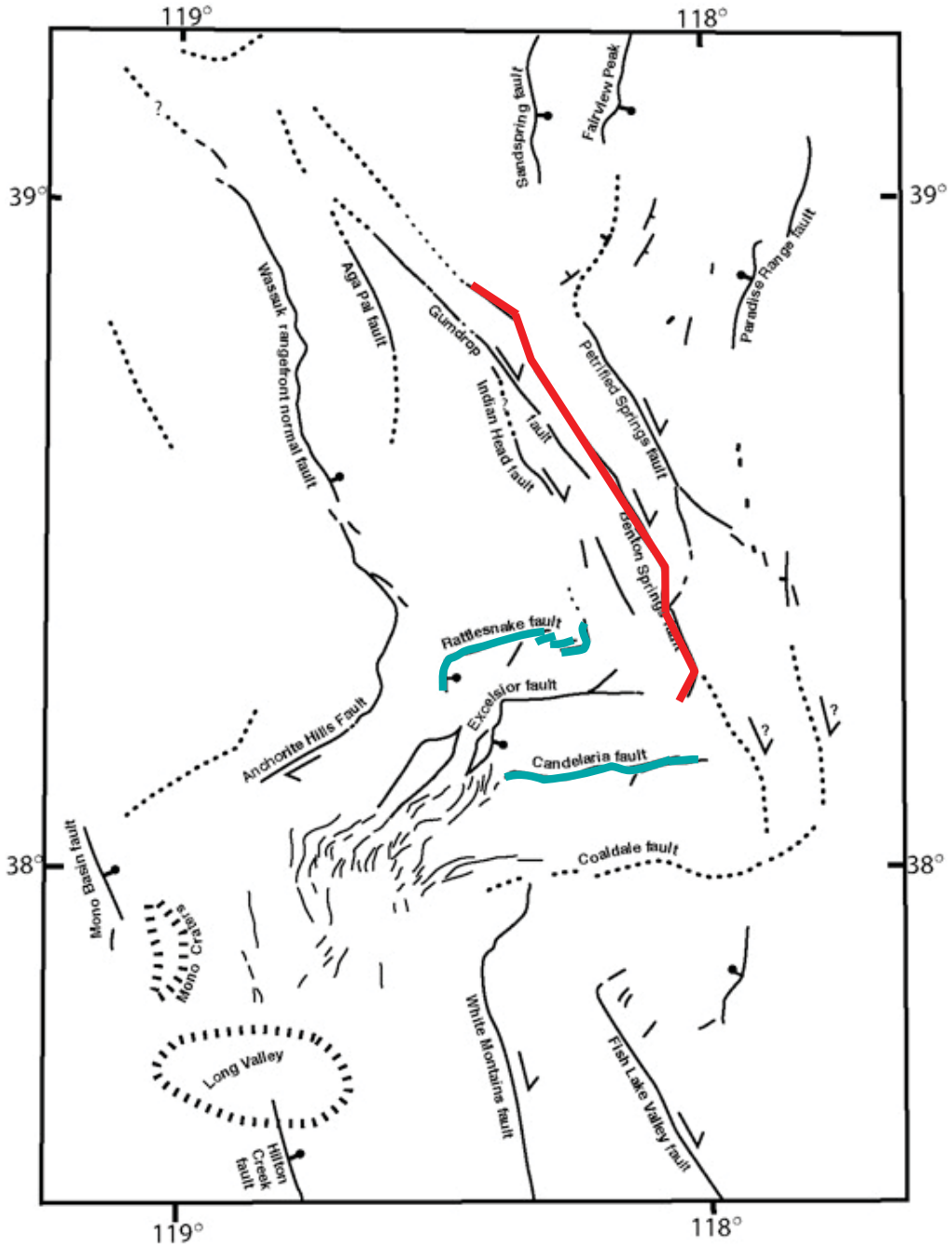
Undifferentiated, generally bedrock.

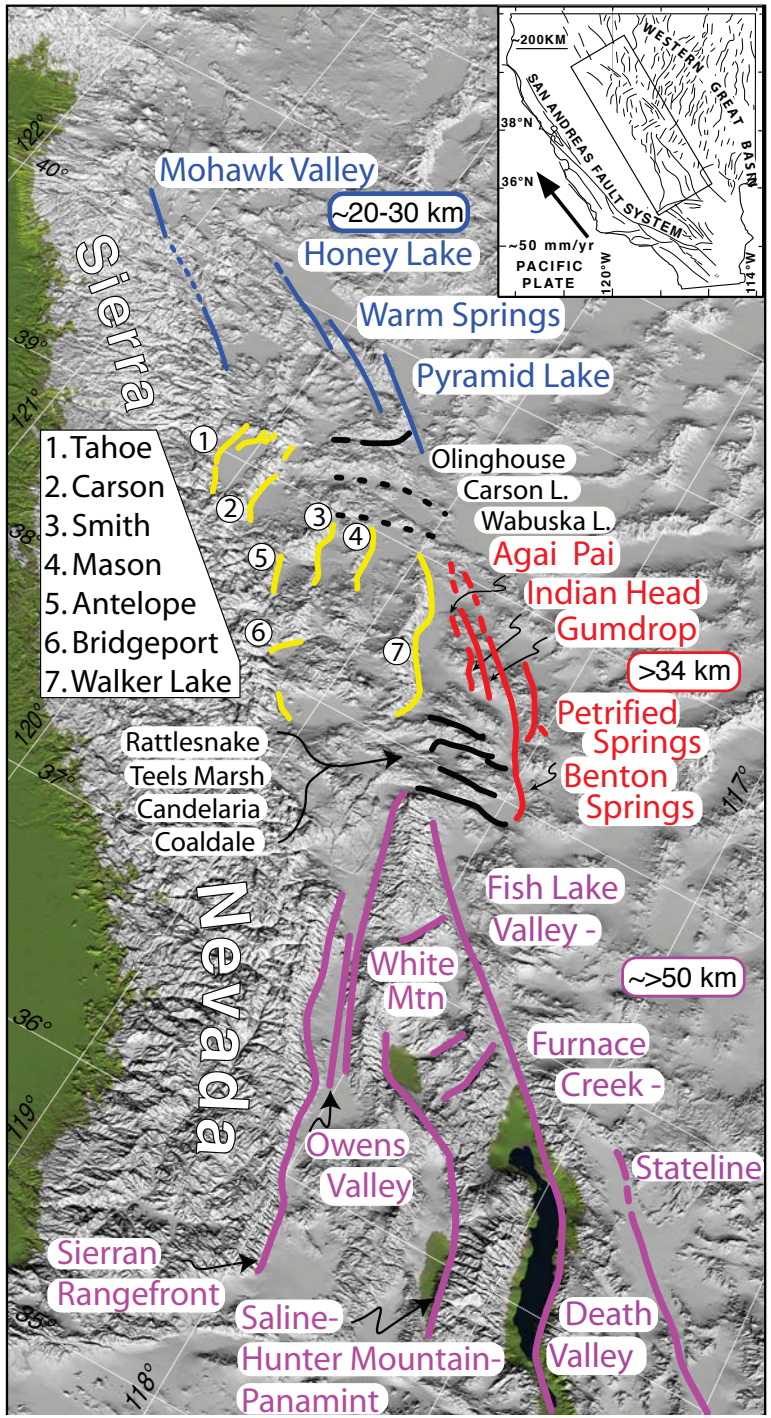




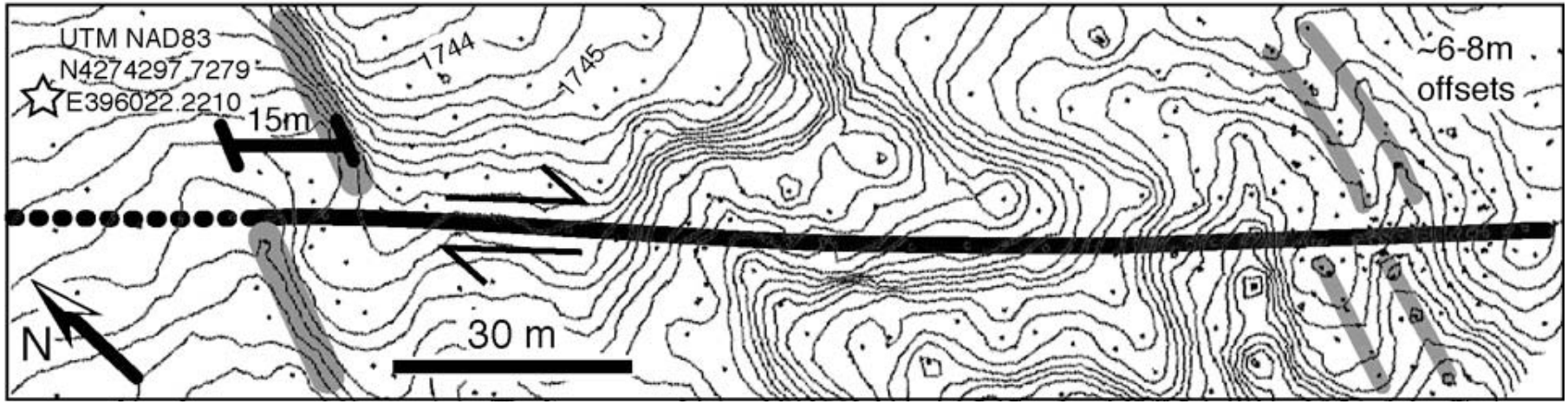

View eastward
Columbus Salt Marsh
Diatomaceous Beds of Stewart (84)
Lower Tuffs of Badlands at Willow Wash
~2.6-2.8 m.y.


Candelaria Mountain
View southeastward
Columbus Salt Marsh
119°
118°
39°
38°

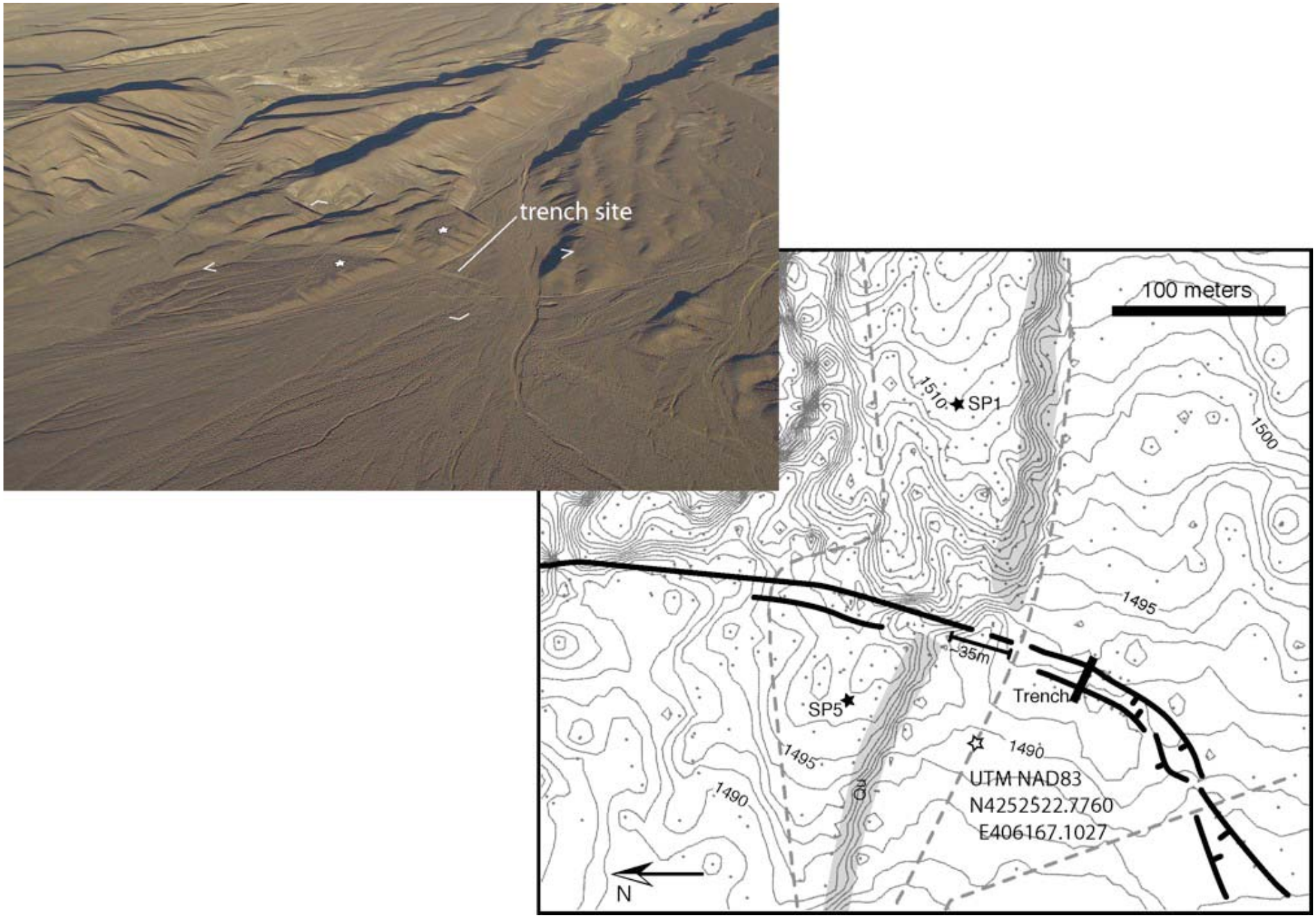

119°
118°
39°
38°
Wassuk rangefront normal fault
Aga Pai fault
Gumdrop
Indian Head fault
fault
Petrified Springs fault
Benton Springs fault
Paradise Range fault
Fairview Peak
Sandspring fault
Rattlesnake fault
Excelsior fault
Candelaria fault
Coaldale fault
Anchorite Hills Fault
Mono Basin fault
Mono Craters
Long Valley
Hilton Creek fault
White Mountains fault
Fish Lake Valley fault


Sierra
Nevada
Mohawk Valley
~20-30 km
Honey Lake
Warm Springs
Pyramid Lake
1. Tahoe
2. Carson
3. Smith
4. Mason
5. Antelope
6. Bridgeport
7. Walker Lake
Olinghouse
Carson L.
Wabuska L.
Agai Pai
Indian Head
Gumdrop
>34 km
Petrified Springs
Benton Springs
Rattlesnake
Teels Marsh
Candelaria
Coaldale
Fish Lake Valley -
~>50 km
White Mtn
Furnace Creek -
Owens Valley
Stateline
Sierran Rangefront
Saline-Hunter Mountain-Panamint
Death Valley
~200KM
WESTERN GREAT BASIN
SAN ANDREAS FAULT SYSTEM
38°N
36°N
~50 mm/yr
PACIFIC PLATE
122°
40°
39°
121°
38°
120°
37°
36°
119°
35°
118°
117°

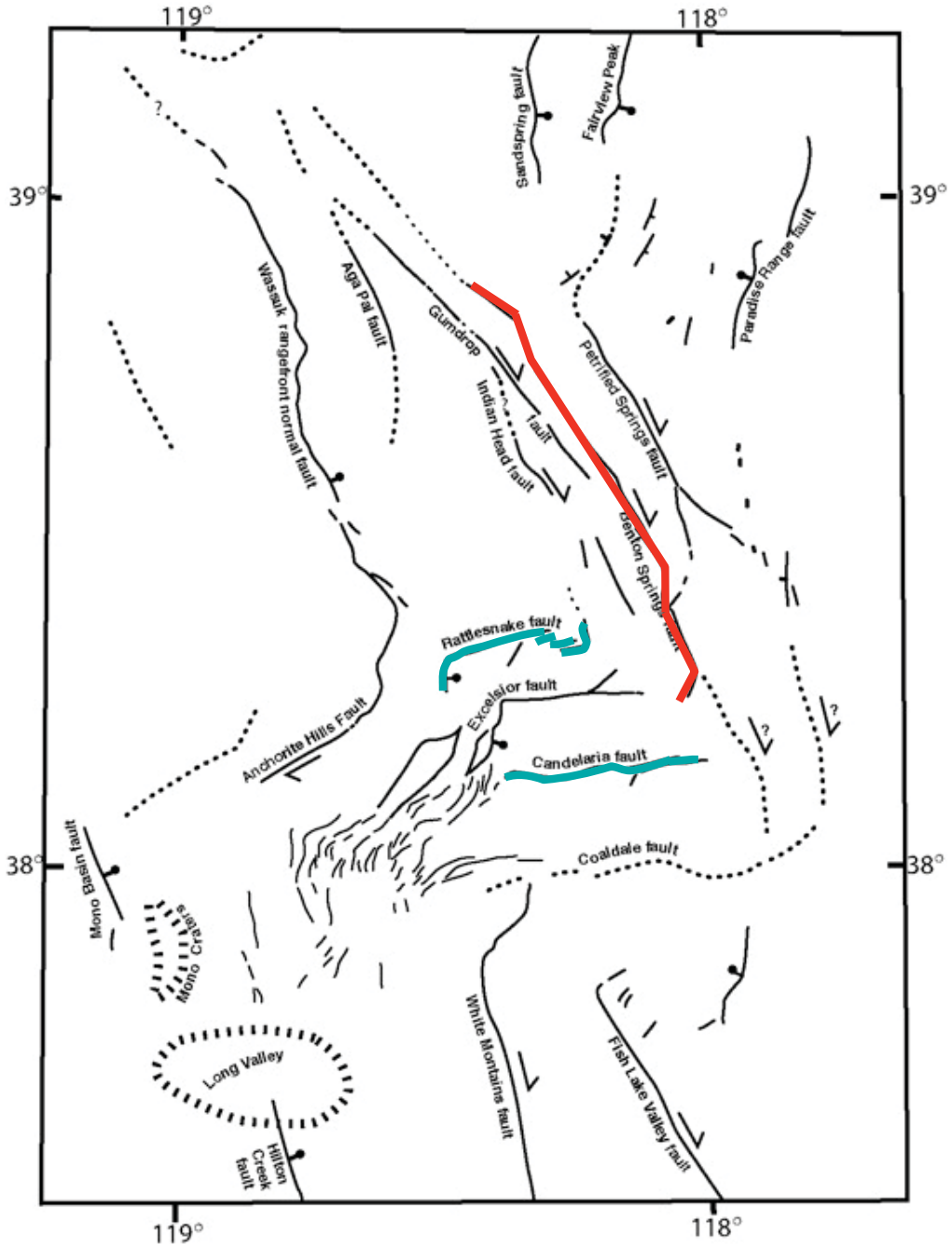

Pilot Mountains
Gabbs Valley Range
Bettles Wells Canyon
Soda Springs Valley

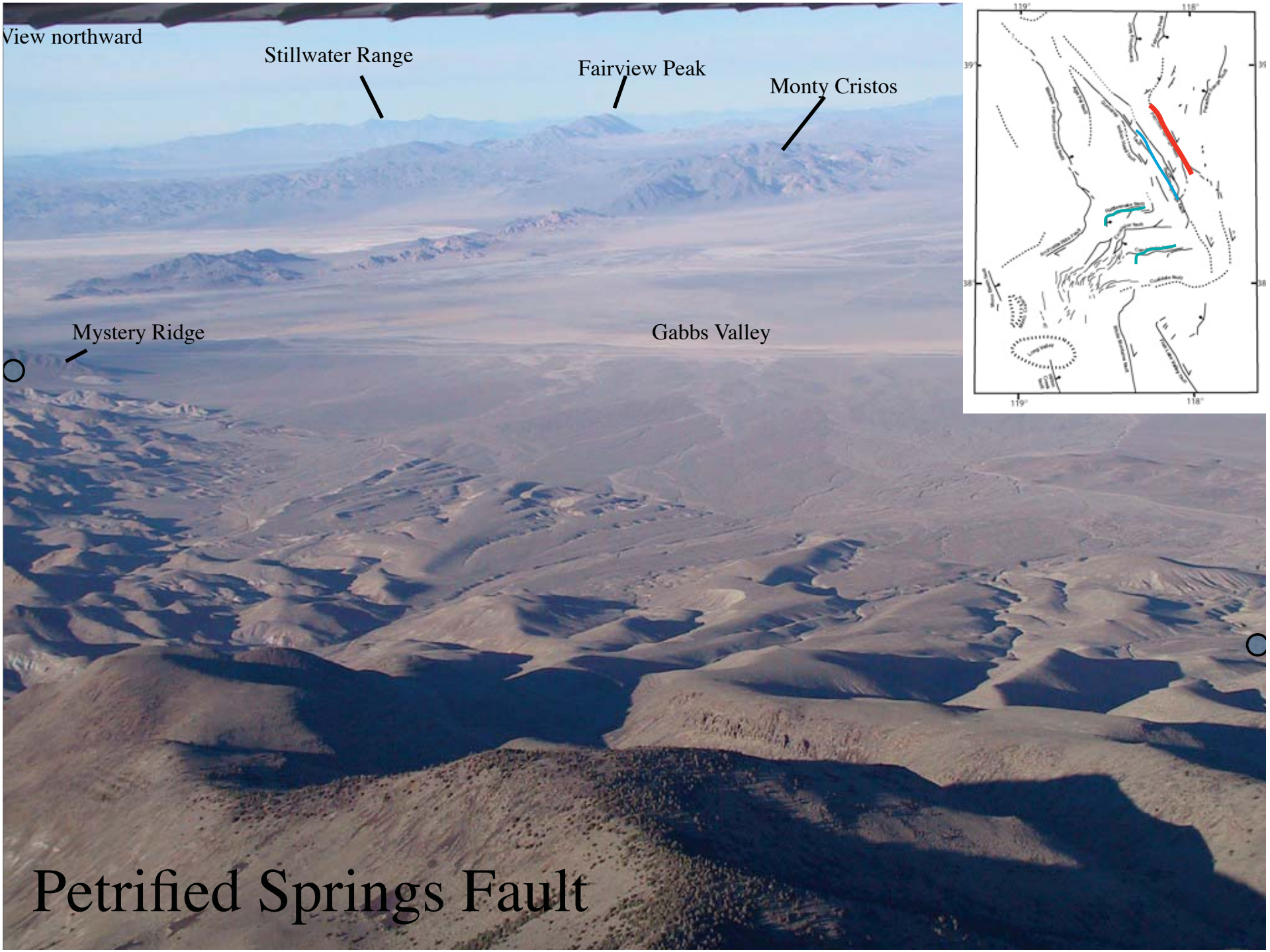


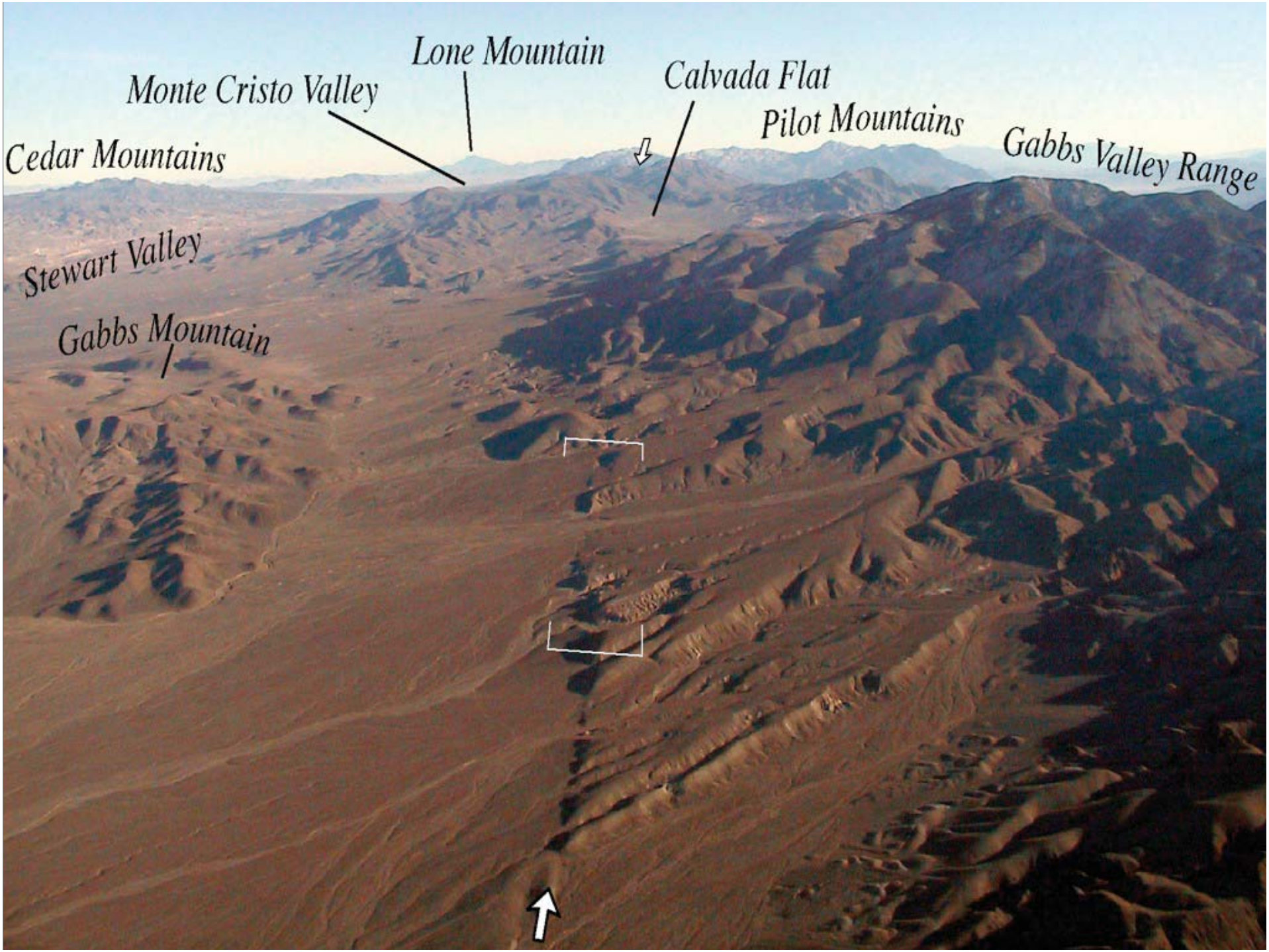
50cm contour interval

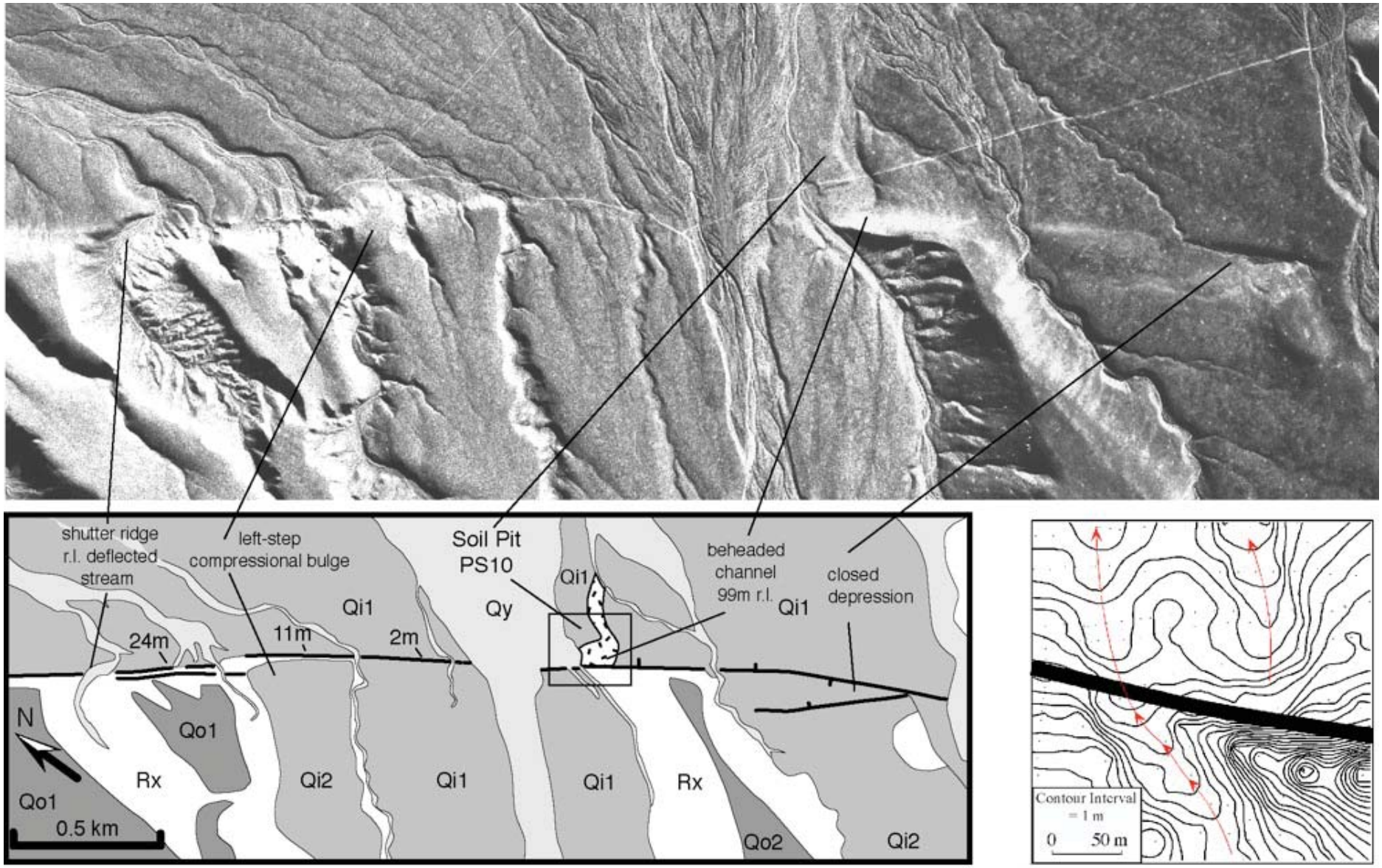


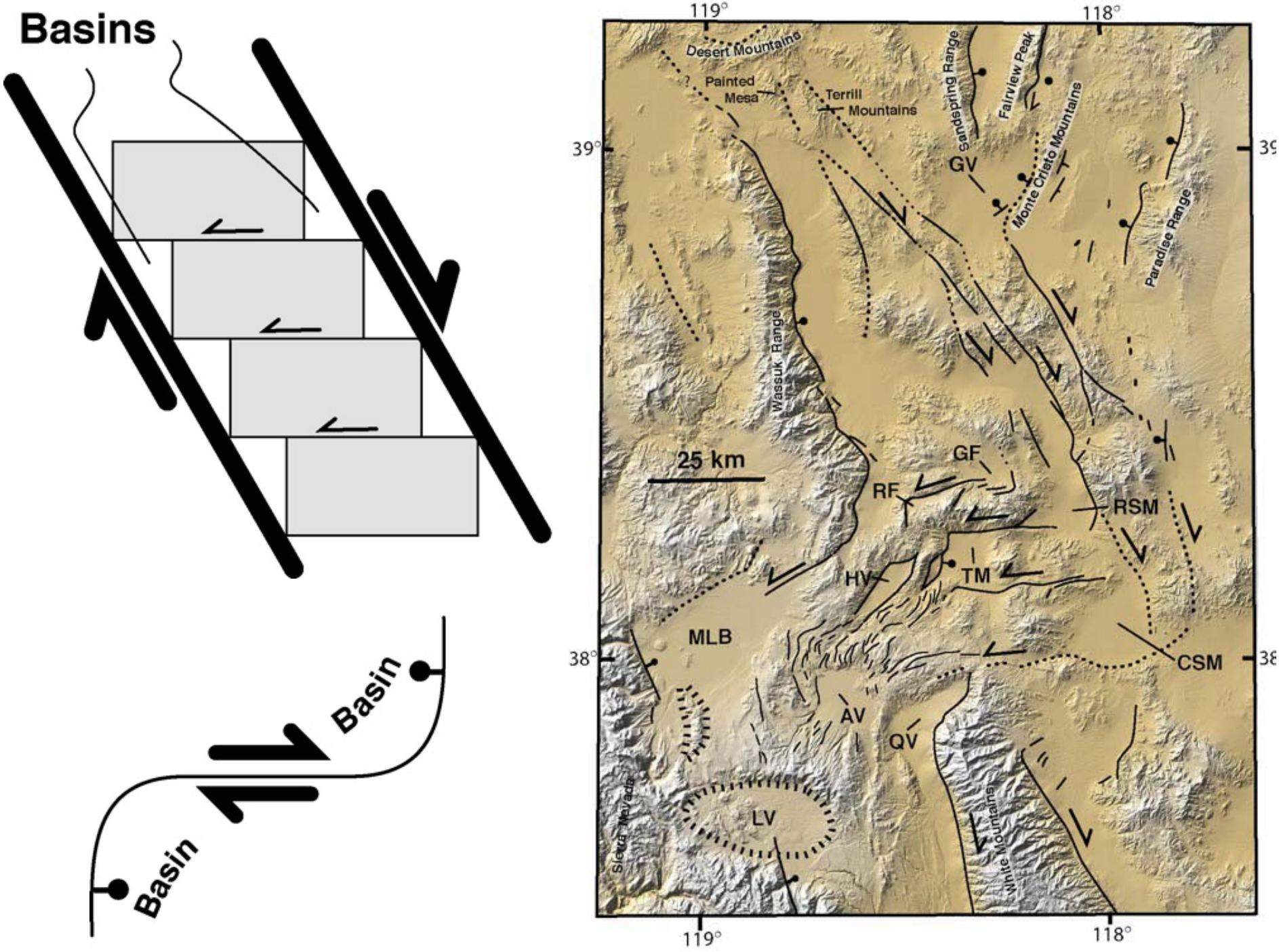
1 meter contour interval

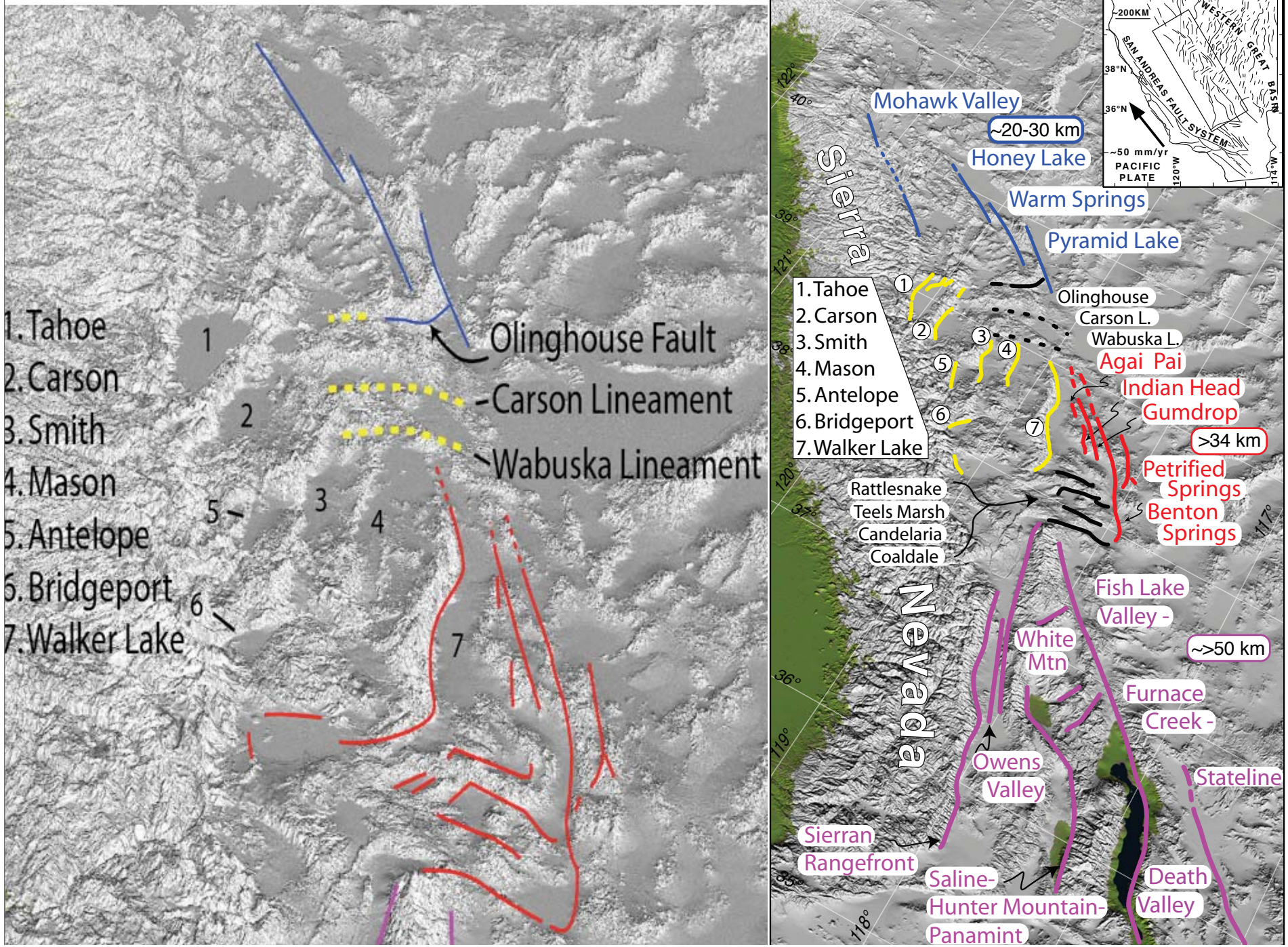

119°
118°
39°
38°
Sandspring fault
Fairview Peak
Paradise Range fault
Wassuk rangefront normal fault
Aga Pai fault
Gumdrop
Indian Head fault
fault
Petrified Springs fault
Benton Springs fault
Rattlesnake fault
Excelsior fault
Anchorite Hills Fault
Candelaria fault
Coaldale fault
Mono Basin fault
Mono Craters
Long Valley
Hilton Creek fault
White Mountains fault
Fish Lake Valley fault

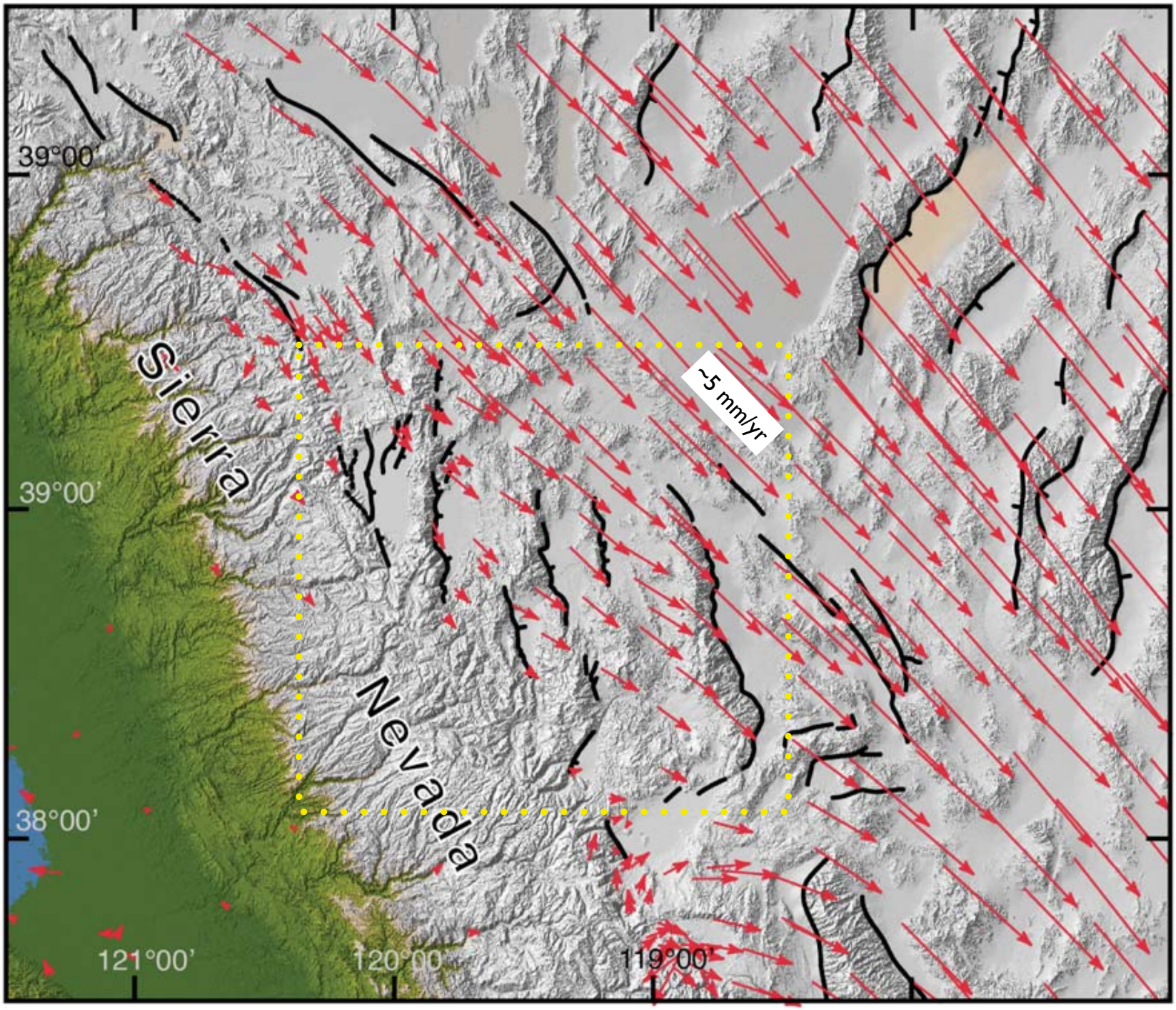

View northward
Stillwater Range
Fairview Peak
Monty Cristos
Mystery Ridge
Gabbs Valley
Petrified Springs Fault

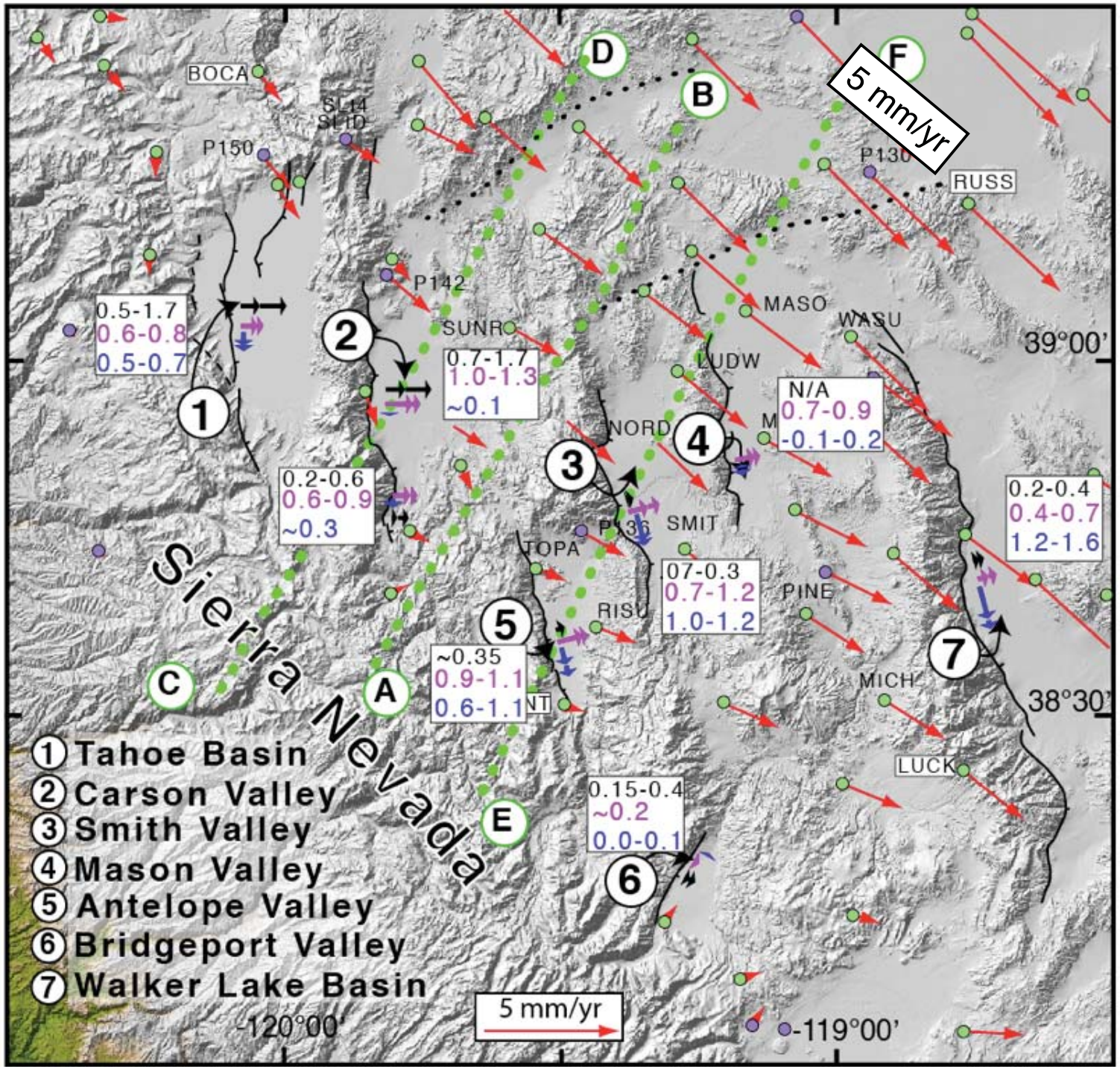

Lone Mountain
Monte Cristo Valley
Calvada Flat
Pilot Mountains
Gabbs Valley Range
Cedar Mountains
Stewart Valley
Gabbs Mountain


shutter ridge
r.l. deflected
stream
left-step
compressional bulge
Soil Pit
PS10
beheaded
channel
99m r.l.
closed
depression
Qi1
Qy
Qi1
Qi1
24m
11m
2m
N
Qo1
Rx
Qi2
Qi1
Qi1
Rx
Qo1
0.5 km
Qo2
Qi2
Contour Interval
= 1 m
0
50 m

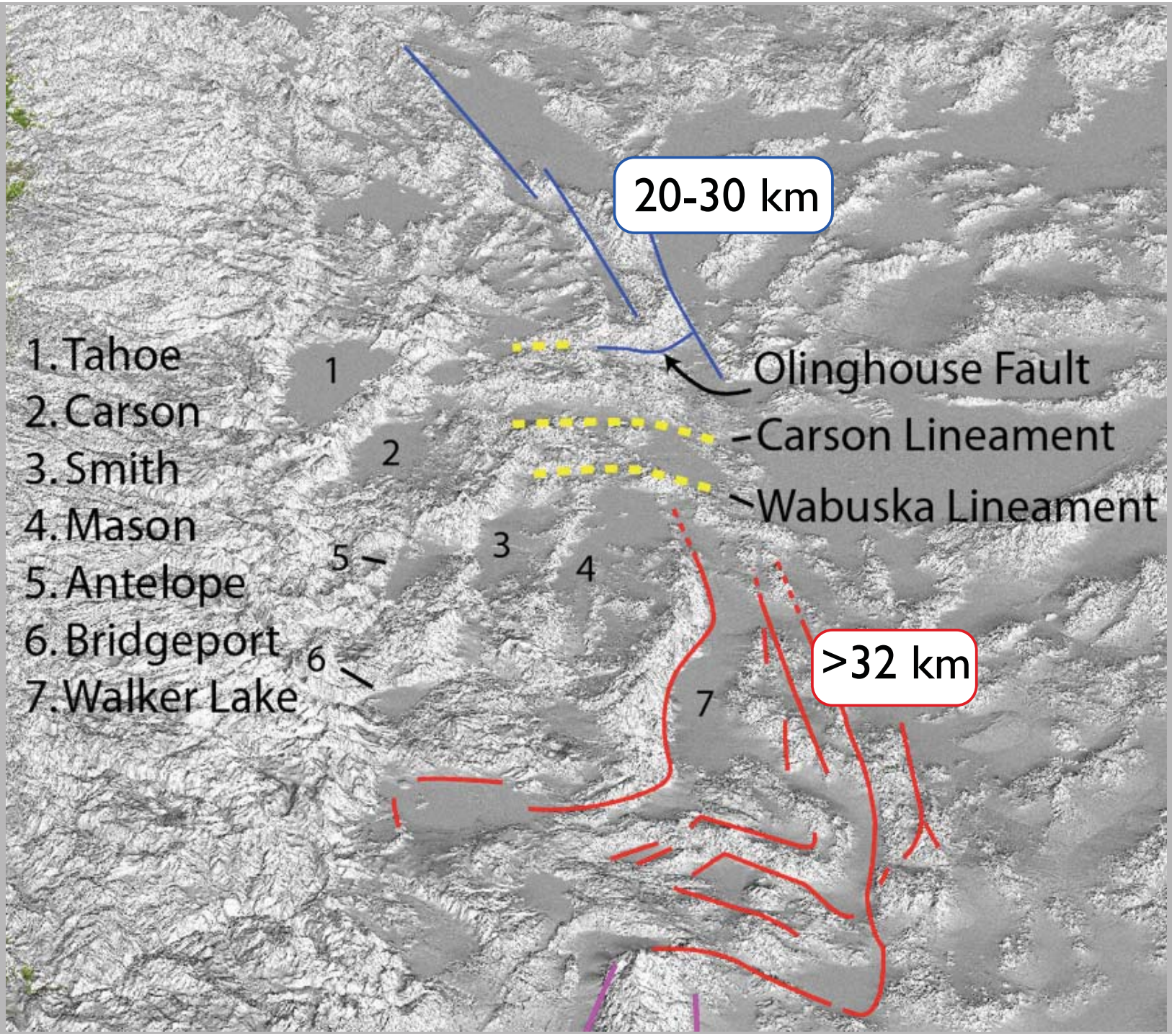

Basins
Basin
Basin
119°
118°
39°
38°
Desert Mountains
Painted Mesa
Terrill Mountains
Sandspring Range
Fairview Peak
Monte Cristo Mountains
Paradise Range
Wassuk Range
GV
GF
RF
RSM
HV
TM
MLB
CSM
AV
QV
LV
Sierra Nevada
White Mountains
25 km

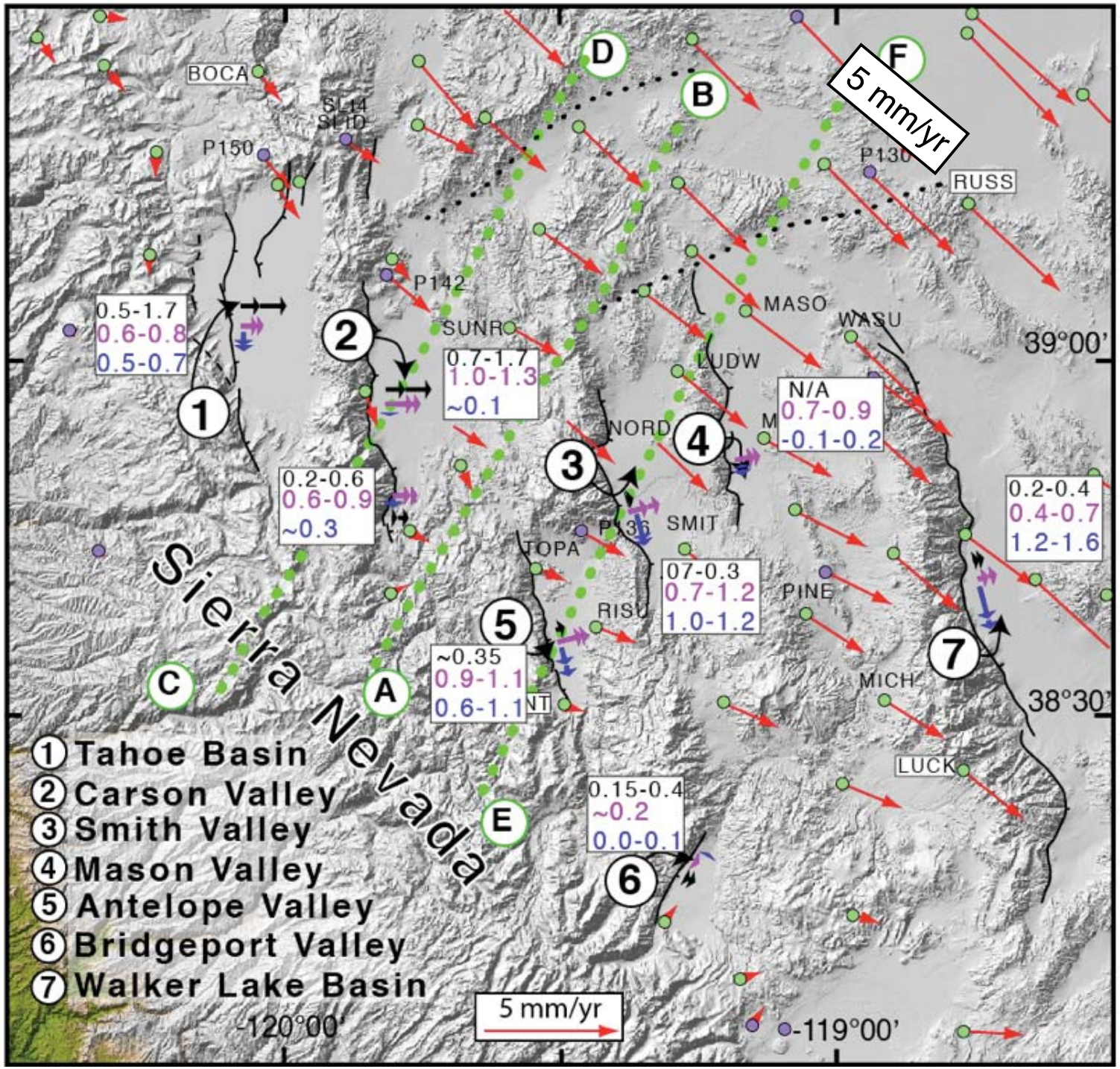

1. Tahoe
2. Carson
3. Smith
4. Mason
5. Antelope
6. Bridgeport
7. Walker Lake
Olinghouse Fault
Carson Lineament
Wabuska Lineament
Mohawk Valley
~20-30 km
Honey Lake
Warm Springs
Pyramid Lake
Olinghouse
Carson L.
Wabuska L.
Agai Pai
Indian Head
Gumdrop
>34 km
Petrified Springs
Benton Springs
Rattlesnake
Teels Marsh
Candelaria
Coaldale
Fish Lake Valley -
~>50 km
White Mtn
Furnace Creek -
Owens Valley
Stateline
Sierran Rangefront
Saline-Hunter Mountain-Panamint
Death Valley
Sierra
Nevada
~200KM
WESTERN GREAT BASIN
SAN ANDREAS FAULT SYSTEM
~50 mm/yr
PACIFIC PLATE


39°00'
39°00'
38°00'
121°00'
120°00
119°00'
Sierra
Nevada
~5 mm/yr

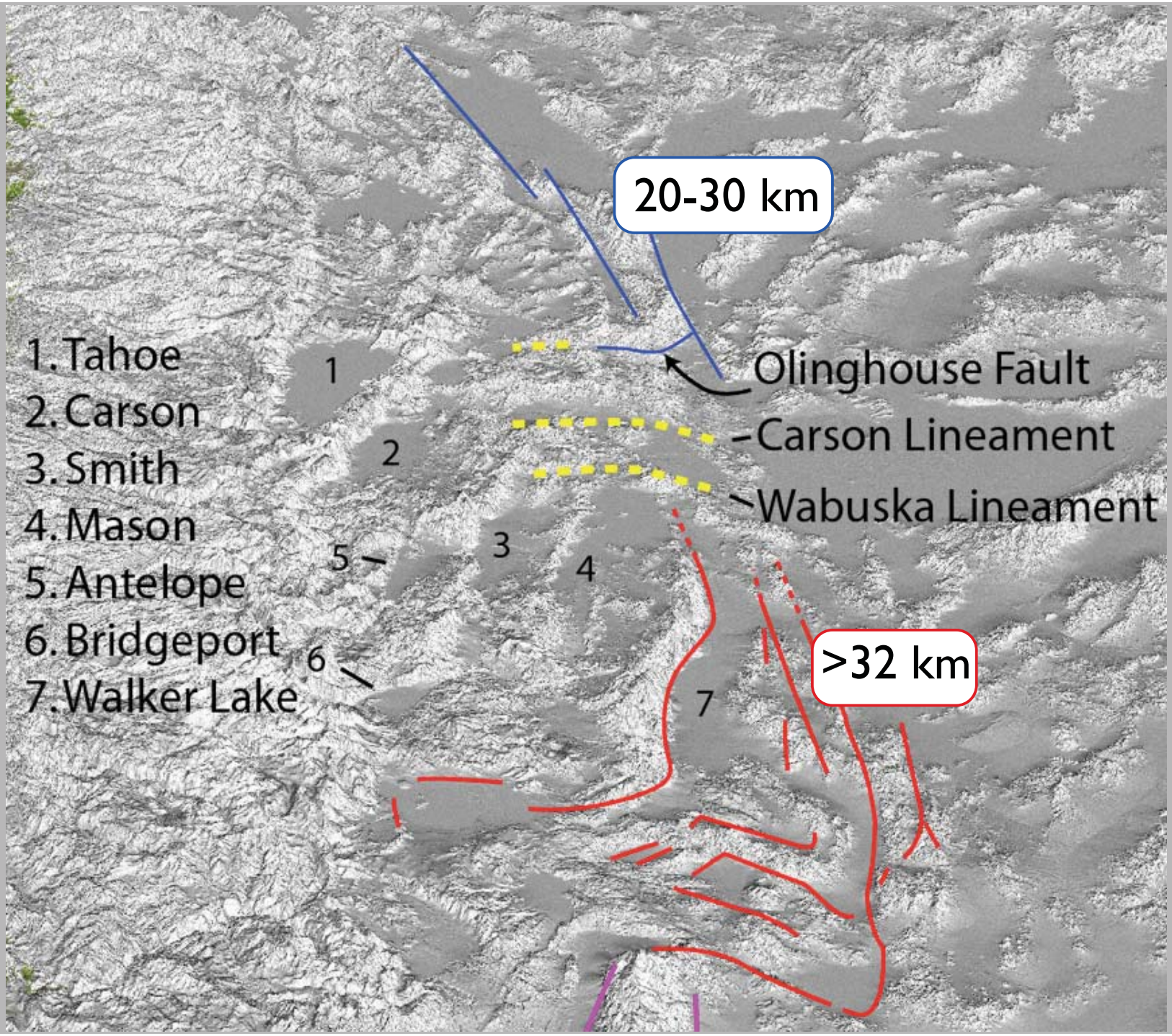

BOCA
SL14
SLID
P150
P142
SUNR
P130
RUSS
MASO
WASU
LUDW
NORD
SMIT
TOPA
P136
RISU
PINE
MICH
LUCK
39°00'
38°30'
-120°00'
-119°00'
5 mm/yr
5 mm/yr
0.5-1.7
0.6-0.8
0.5-0.7
0.7-1.7
1.0-1.3
~0.1
N/A
0.7-0.9
-0.1-0.2
0.2-0.6
0.6-0.9
~0.3
0.2-0.4
0.4-0.7
1.2-1.6
07-0.3
0.7-1.2
1.0-1.2
~0.35
0.9-1.1
0.6-1.1
0.15-0.4
~0.2
0.0-0.1
Sierra Nevada
A
B
C
D
E
F
1
2
3
4
5
6
7
1 Tahoe Basin
2 Carson Valley
3 Smith Valley
4 Mason Valley
5 Antelope Valley
6 Bridgeport Valley
7 Walker Lake Basin

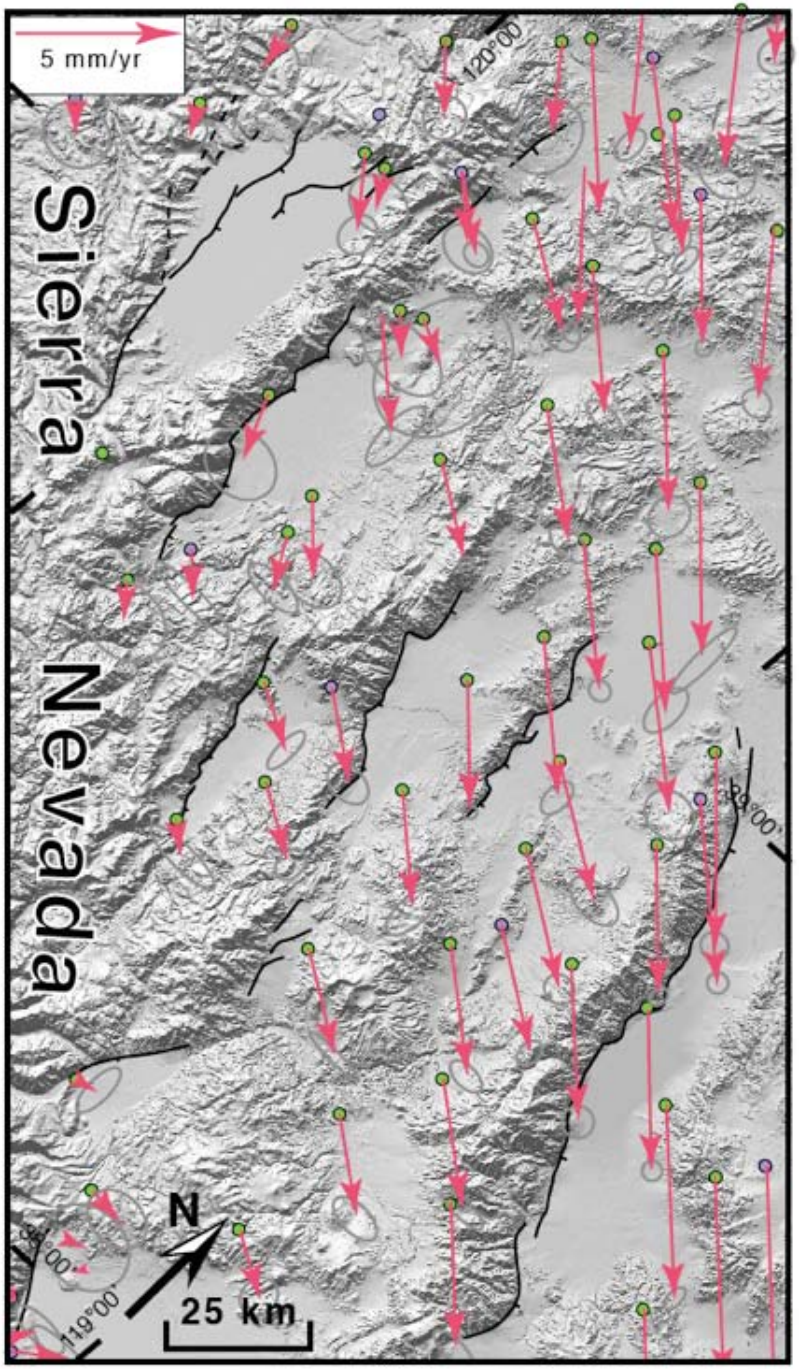
oblique
view

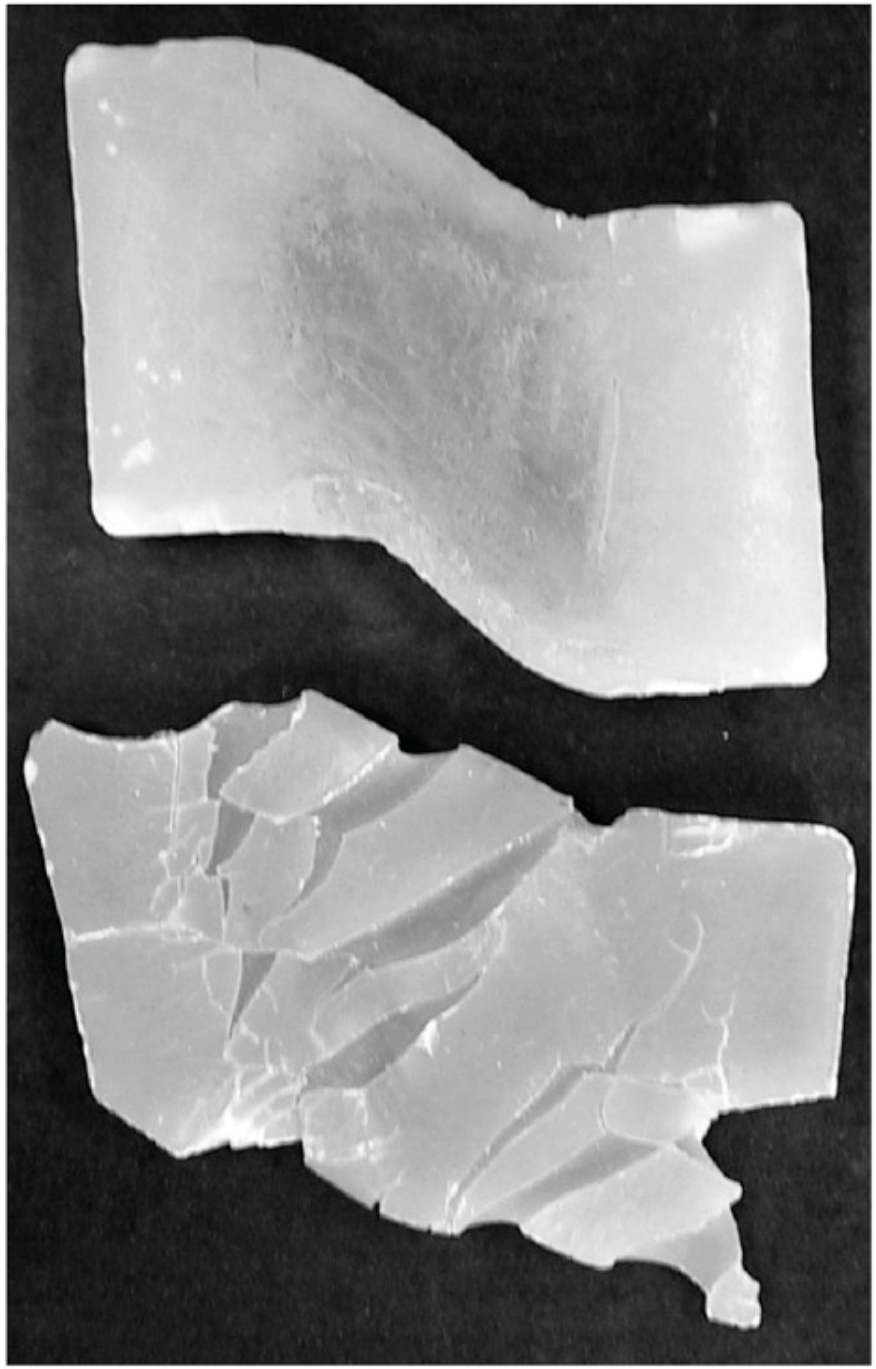


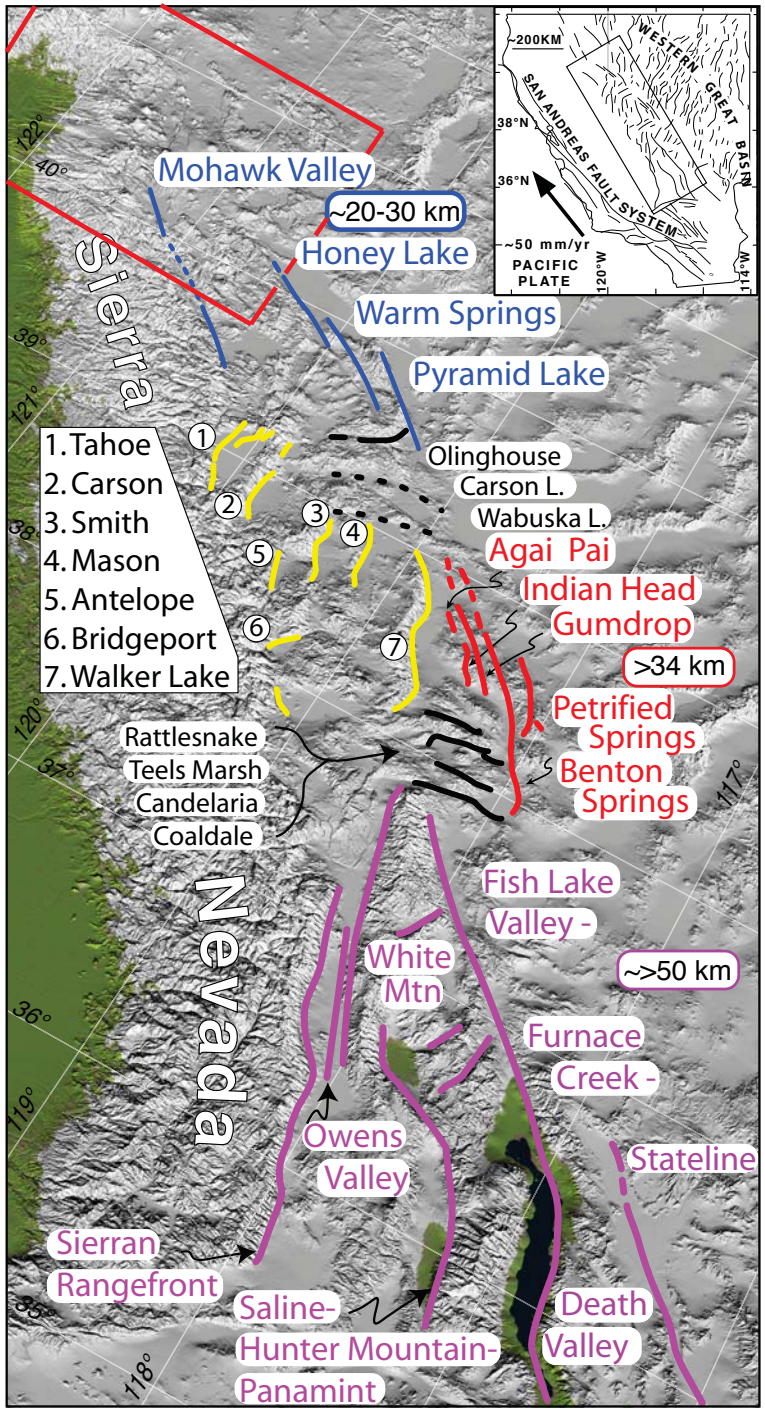

BOCA
SL14
SLID
P150
P142
SUNR
P130
RUSS
MASO
WASU
LUDW
NORD
SMIT
TOPA
P136
RISU
PINE
MICH
LUCK
39°00'
38°30'
-120°00'
-119°00'
5 mm/yr
5 mm/yr
0.5-1.7
0.6-0.8
0.5-0.7
0.7-1.7
1.0-1.3
~0.1
N/A
0.7-0.9
-0.1-0.2
0.2-0.6
0.6-0.9
~0.3
0.2-0.4
0.4-0.7
1.2-1.6
07-0.3
0.7-1.2
1.0-1.2
~0.35
0.9-1.1
0.6-1.1
0.15-0.4
~0.2
0.0-0.1
Sierra Nevada
A
B
C
D
E
F
1
2
3
4
5
6
7
1 Tahoe Basin
2 Carson Valley
3 Smith Valley
4 Mason Valley
5 Antelope Valley
6 Bridgeport Valley
7 Walker Lake Basin

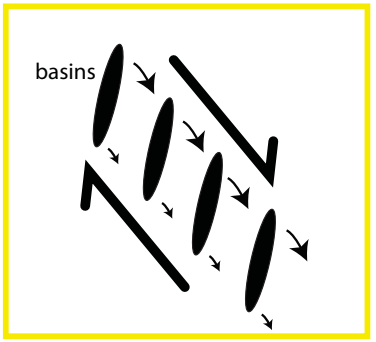
oblique
view

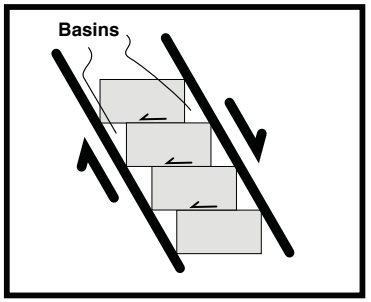


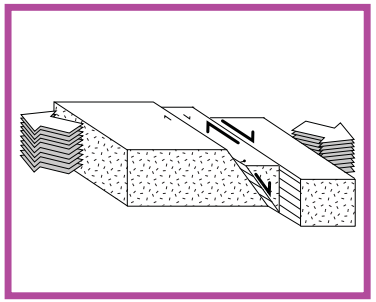

5 mm/yr
Sierra Nevada
120°00'
39°00'
38°00'
119°00'
N
25 km

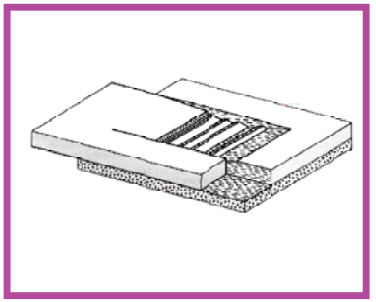








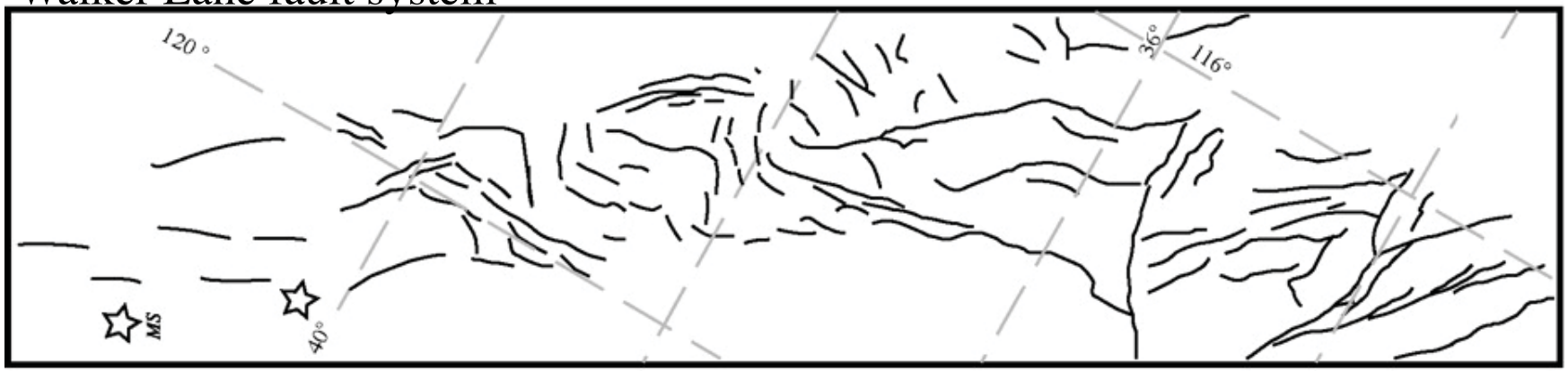




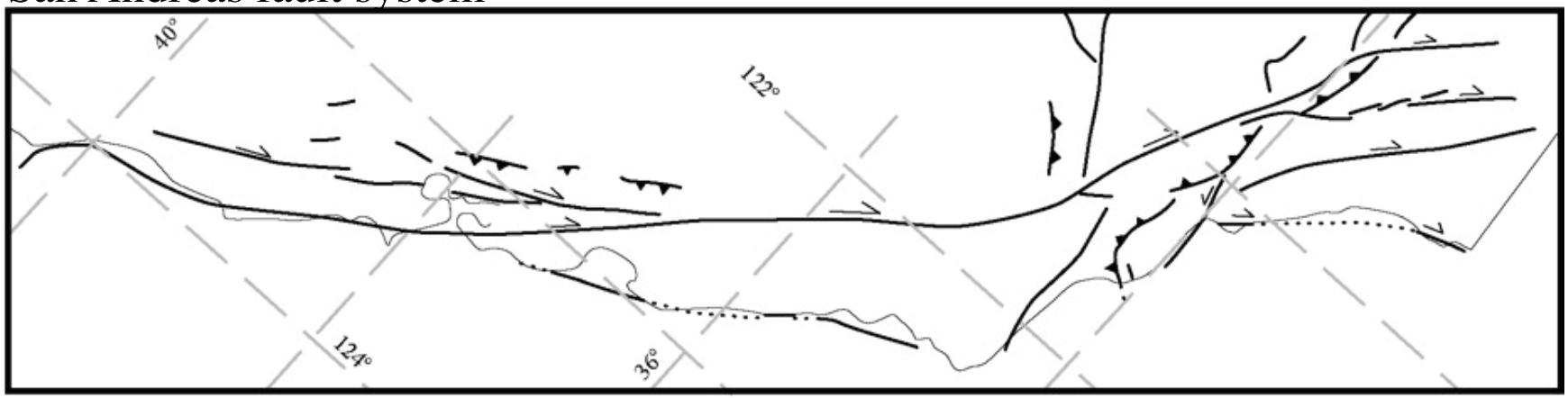
The modes of deformation are many and complex

somewhat more so than the San Andreas...

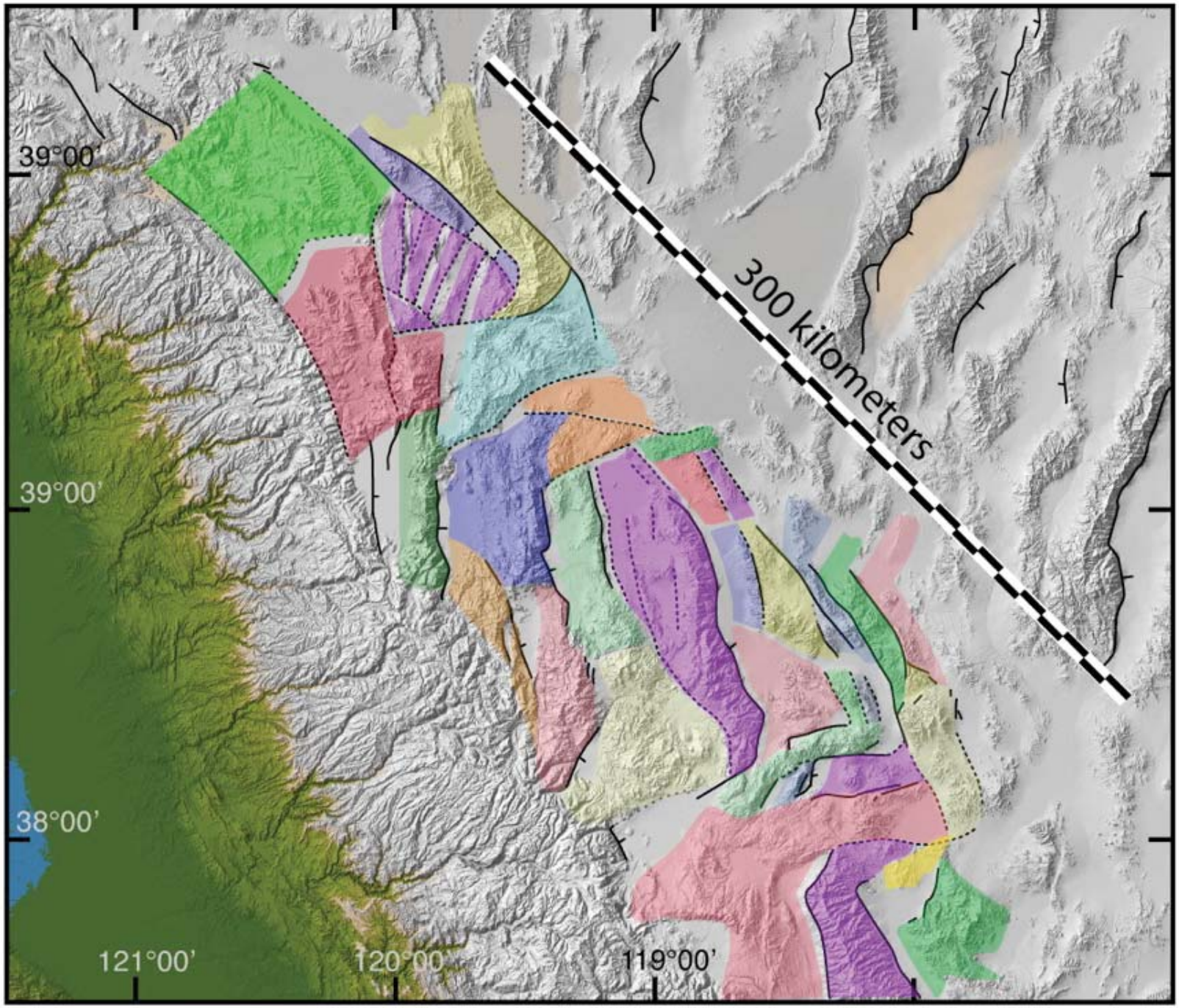
Walker Lane fault system

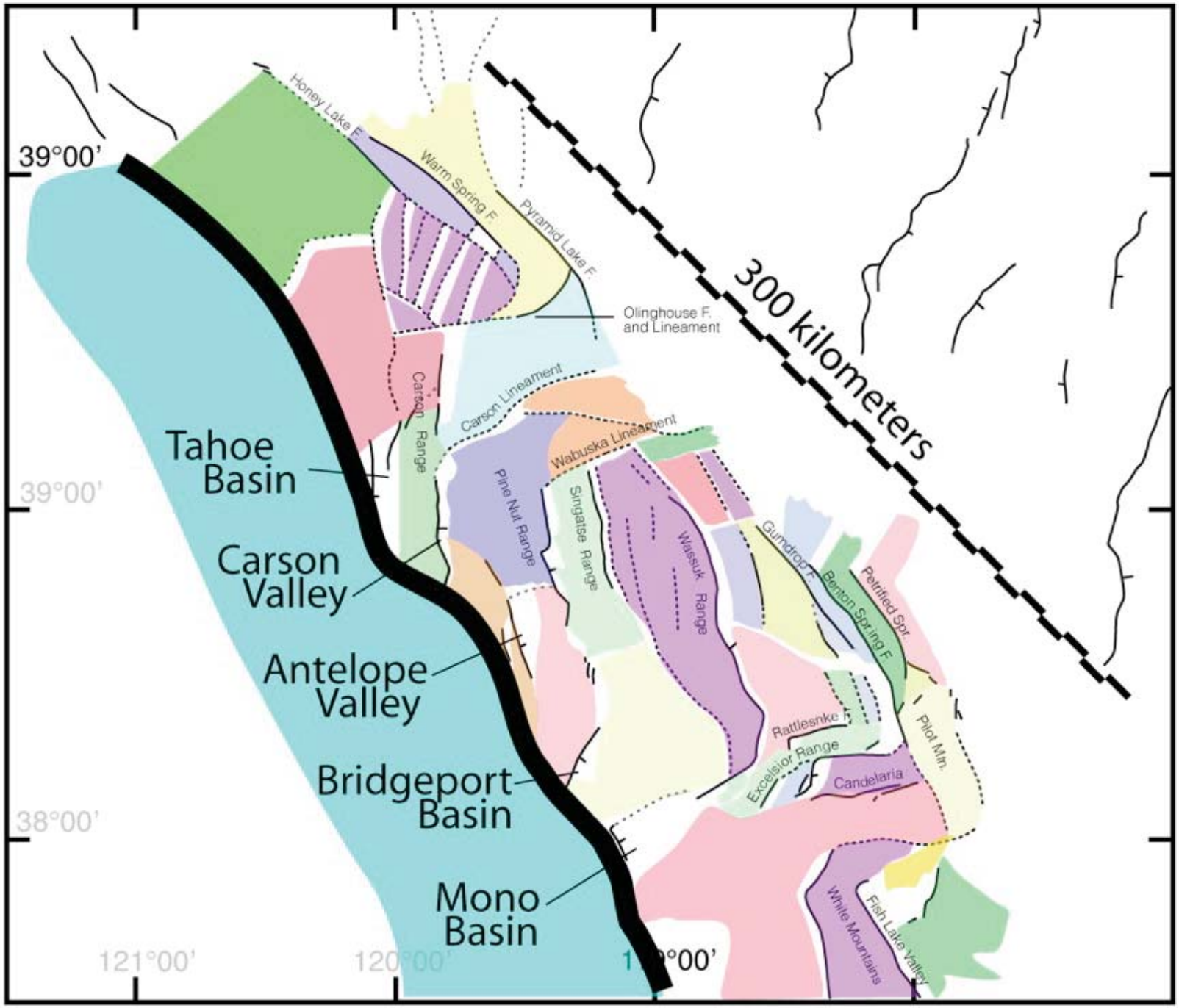


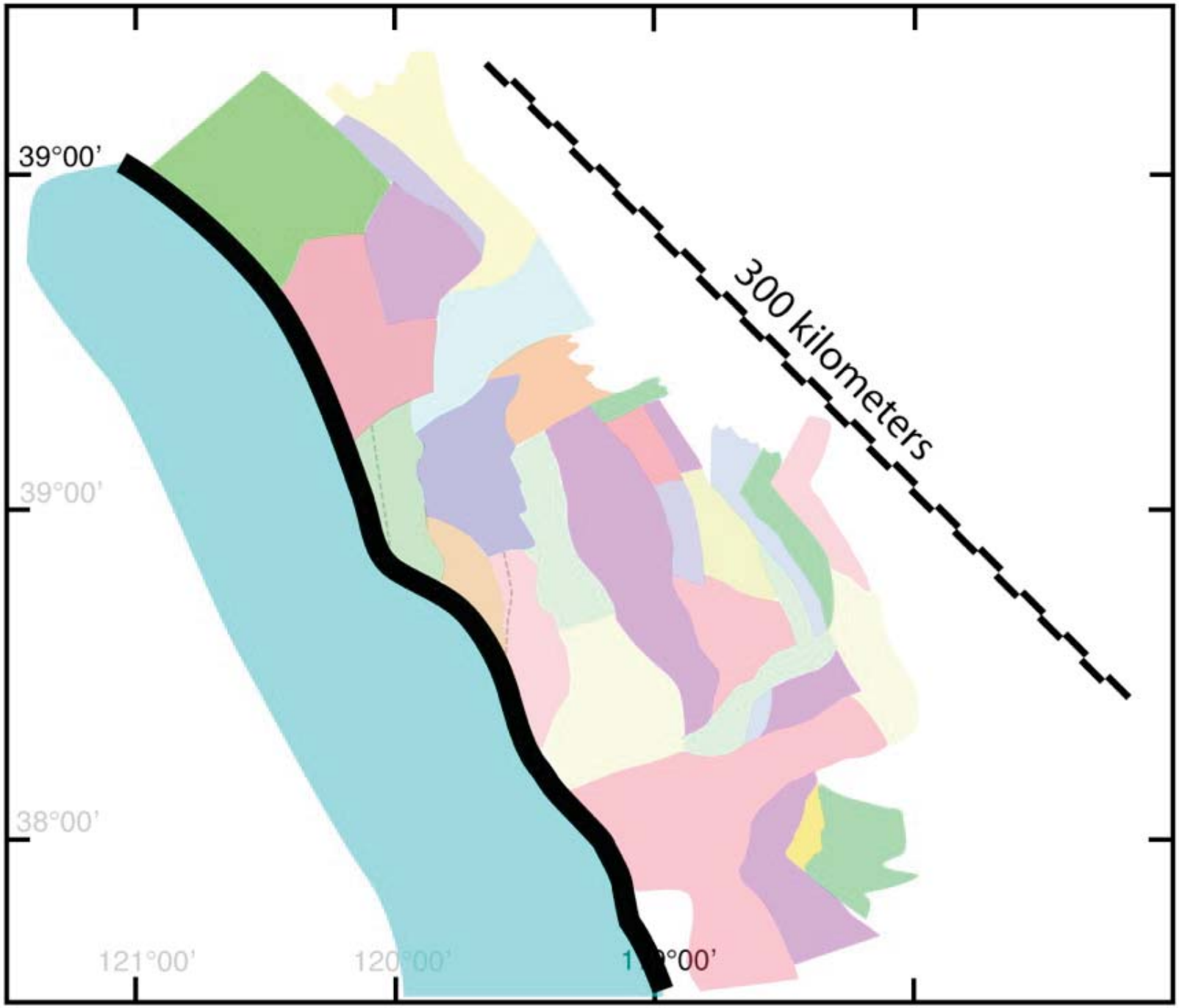
San Andreas fault system

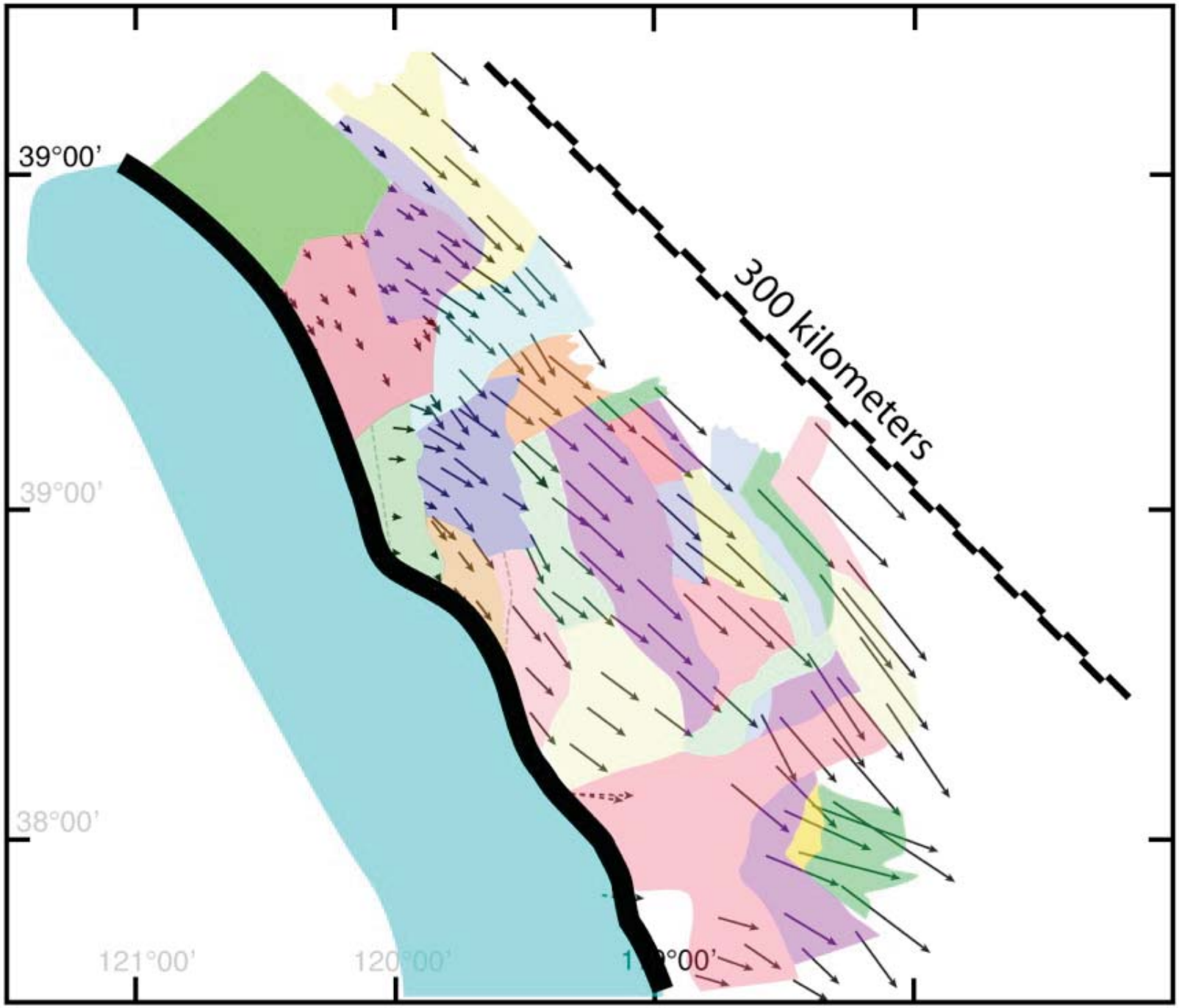


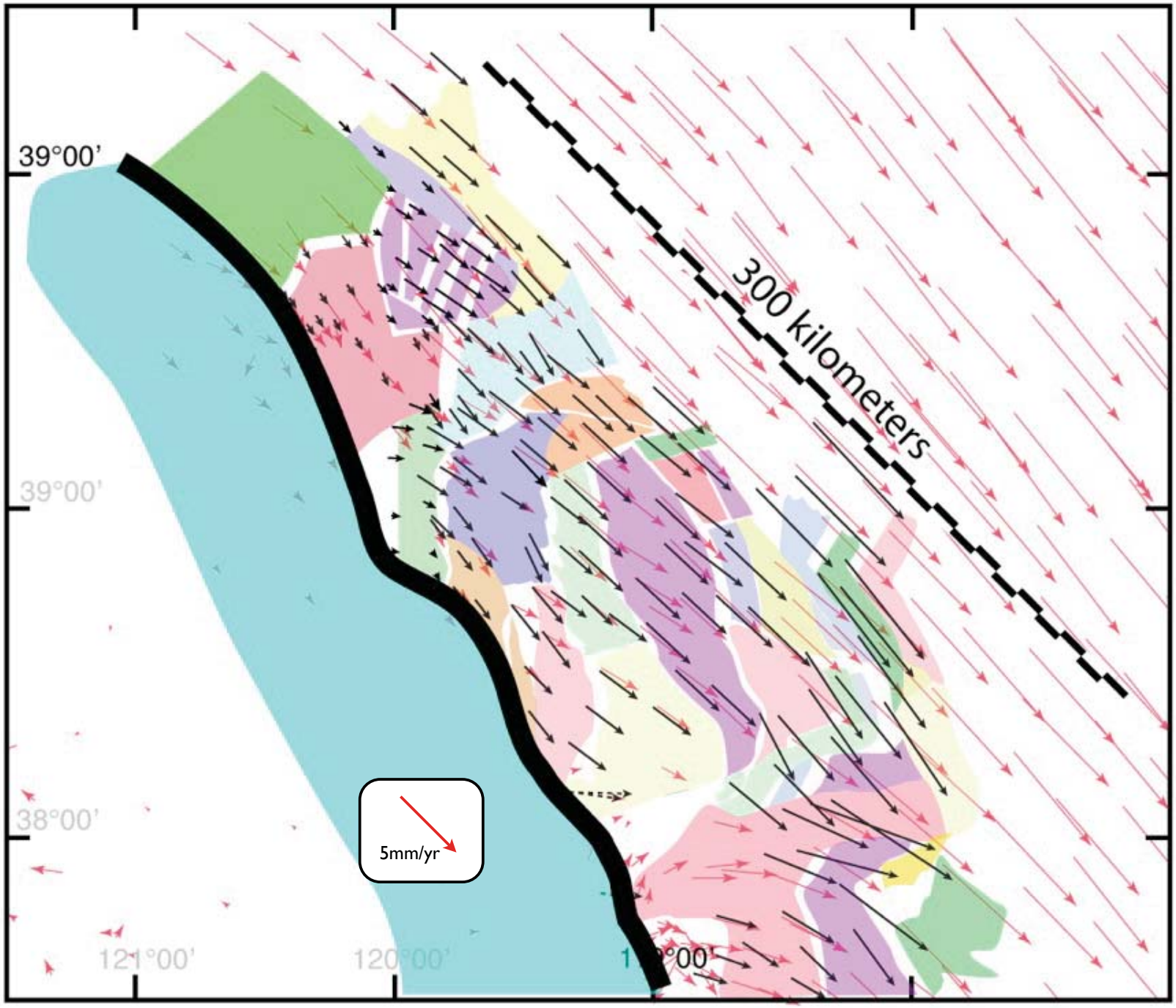
Greater cumulative slip and a component of compression along the San Andreas system leads to a simpler pattern of active faulting than observed along the transtensional Walker Lane system

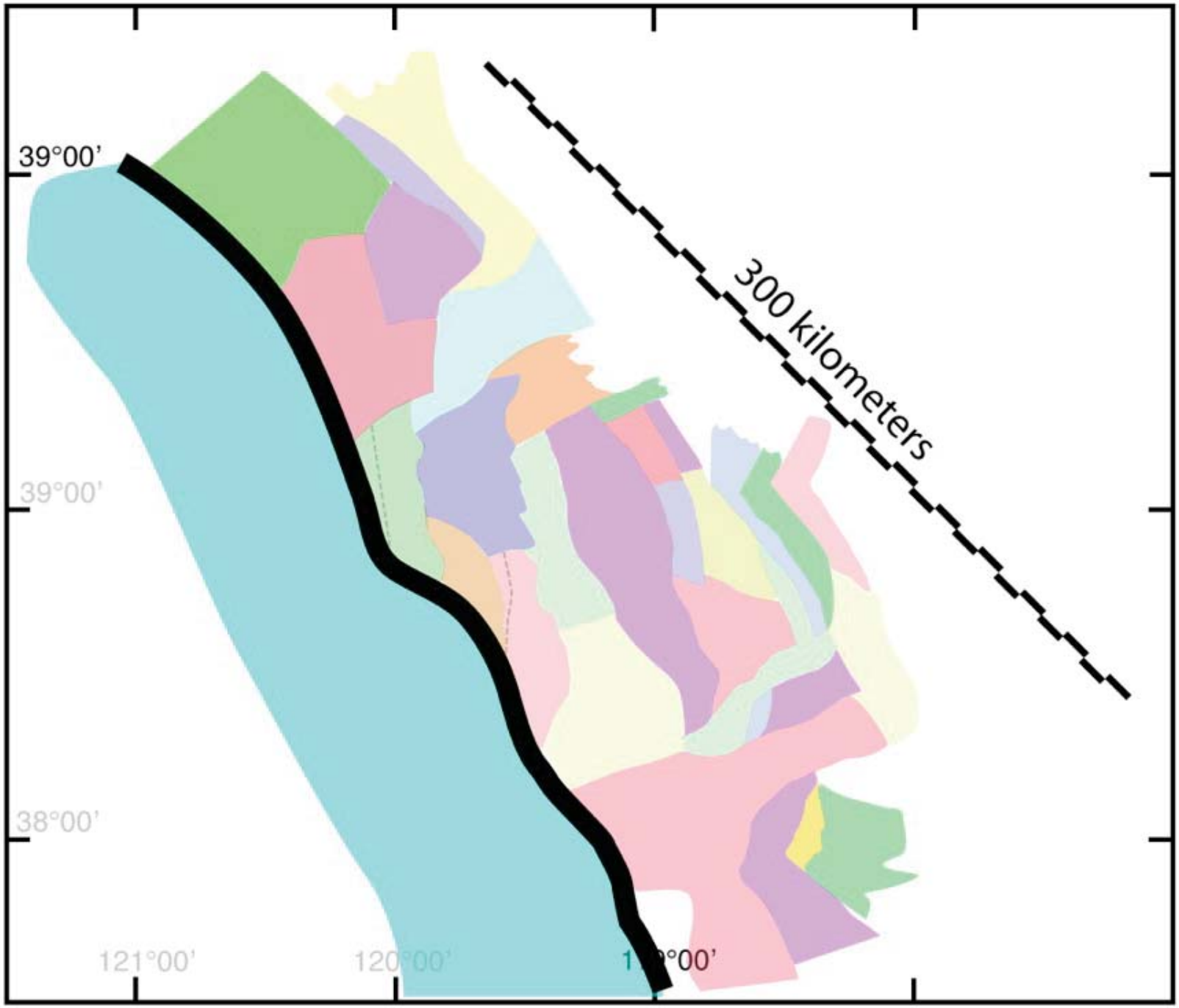

39°00'
39°00'
38°00'
121°00'
120°00'
119°00'
300 kilometers

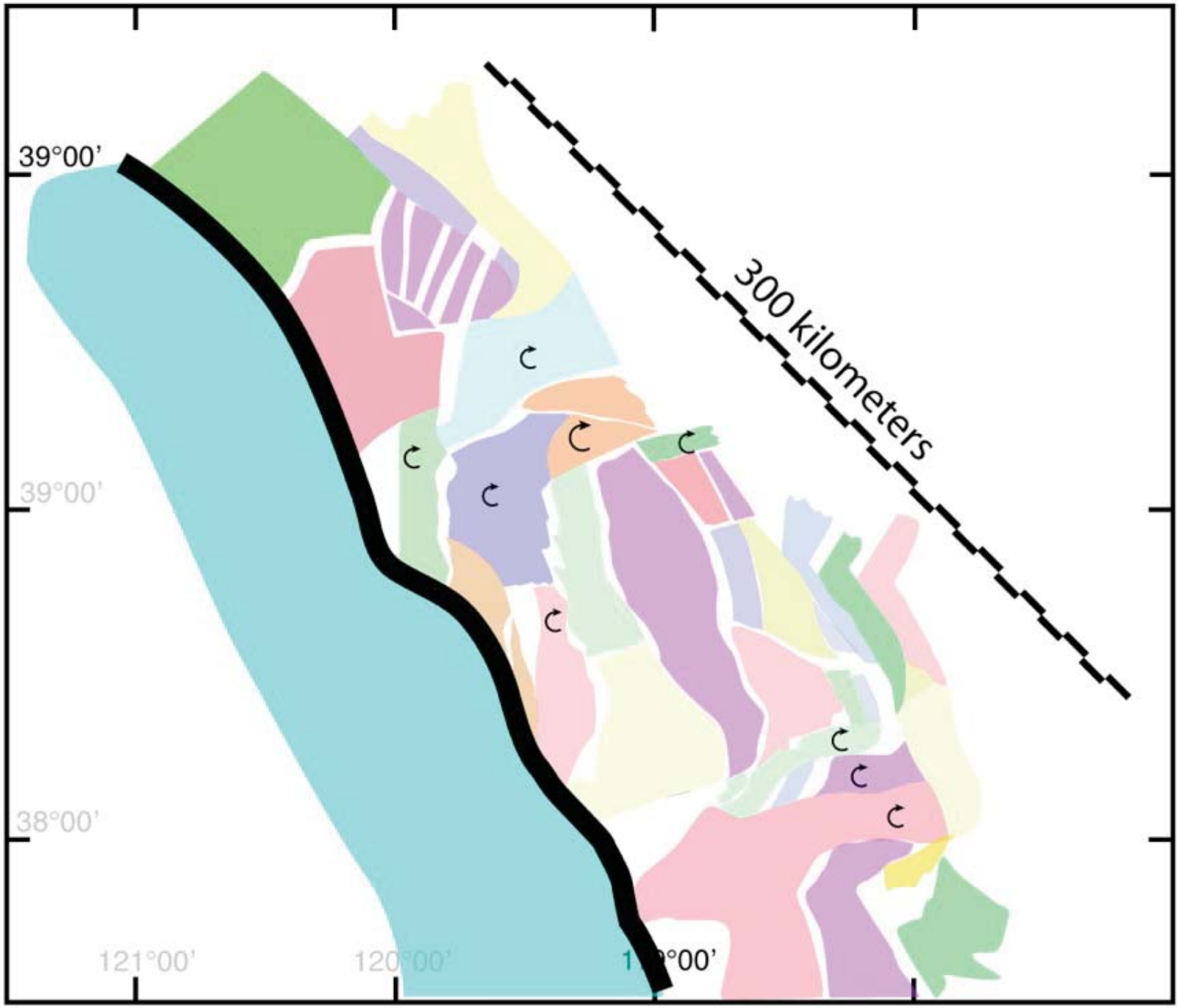

39°00'
39°00'
38°00'
121°00'
120°00'
Honey Lake F.
Warm Spring F.
Pyramid Lake F.
Olinghouse F.
and Lineament
300 kilometers
Carson Range
Carson Lineament
Wabuska Lineament
Pine Nut Range
Singatse Range
Wassuk Range
Gumdrop F.
Benton Spring F.
Petrified Spr.
Rattlesnke F.
Excelsior Range
Candelaria
Pilot Mtn.
White Mountains
Fish Lake Valley
Tahoe Basin
Carson Valley
Antelope Valley
Bridgeport Basin
Mono Basin


39°00'
39°00'
38°00'
121°00'
120°00'
300 kilometers


39°00'
39°00'
38°00'
121°00'
120°00'
300 kilometers


39°00'
39°00'
38°00'
121°00'
120°00'
300 kilometers
5mm/yr


39°00'
39°00'
38°00'
121°00'
120°00'
300 kilometers

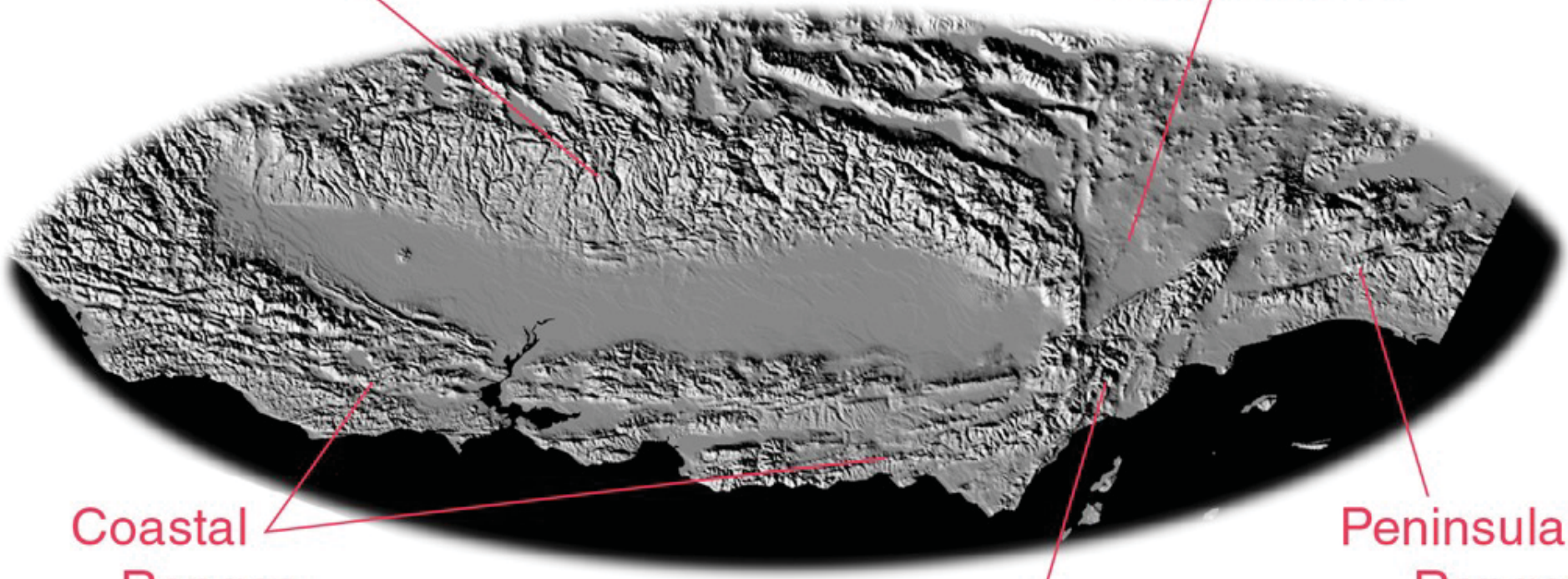

39°00'
39°00'
38°00'
121°00'
120°00'
300 kilometers

Transverse Range , California
Thrusting in A Strike-Slip Environment

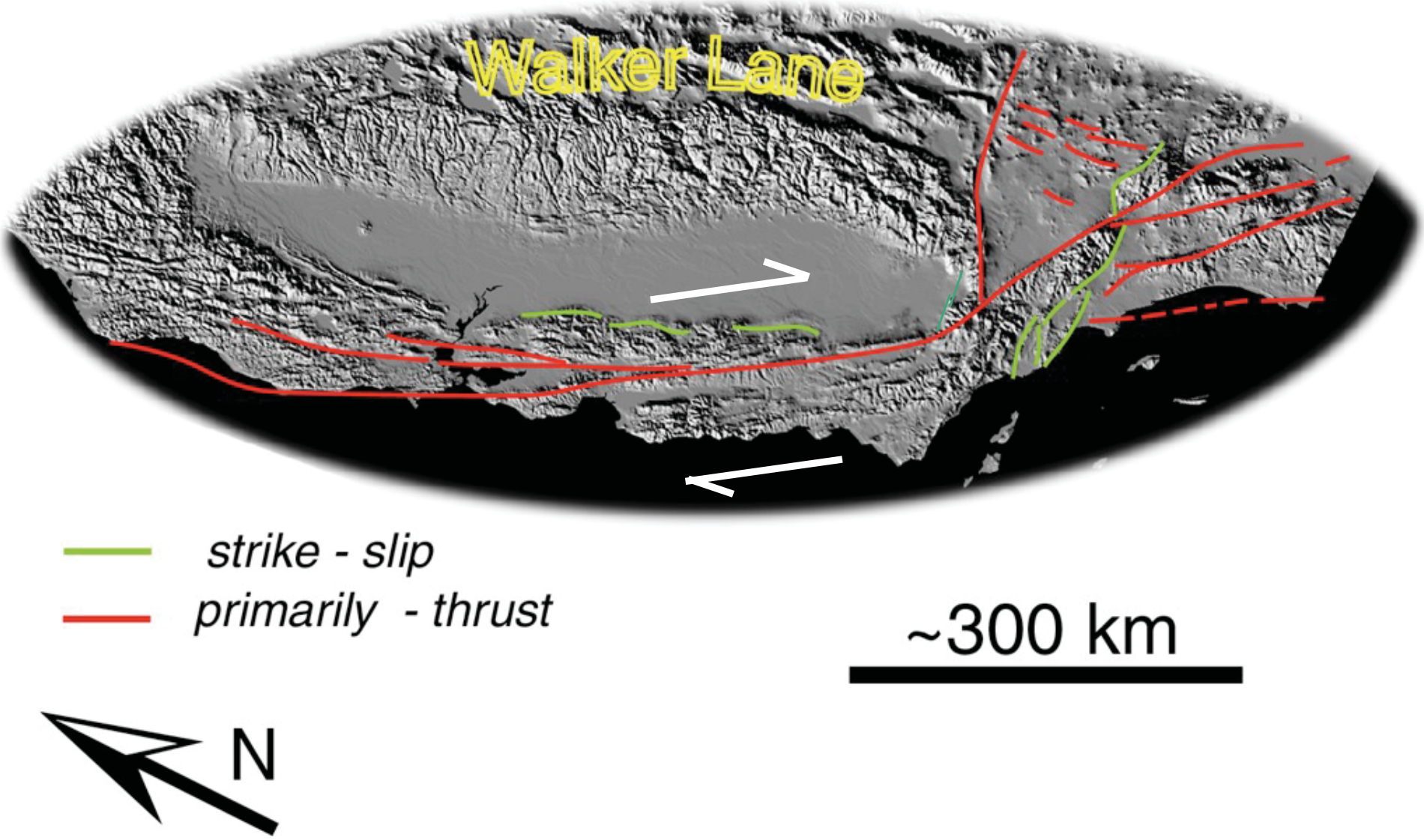
Trieste 2013 Wesnousky

with thanks to James Dolan
who provided the majority of the following slides
and did much of the work described.

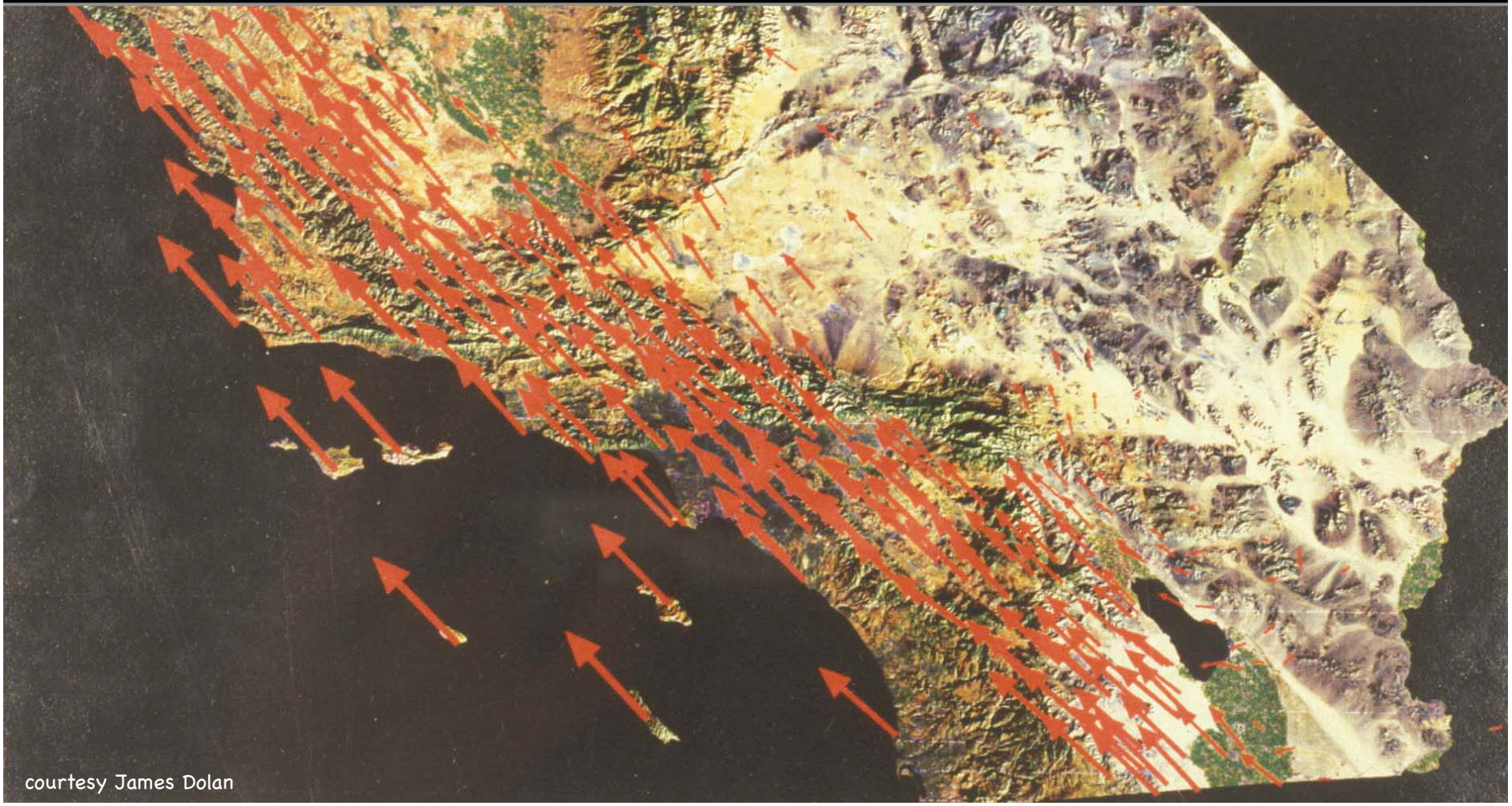
Physiographic Provinces of California



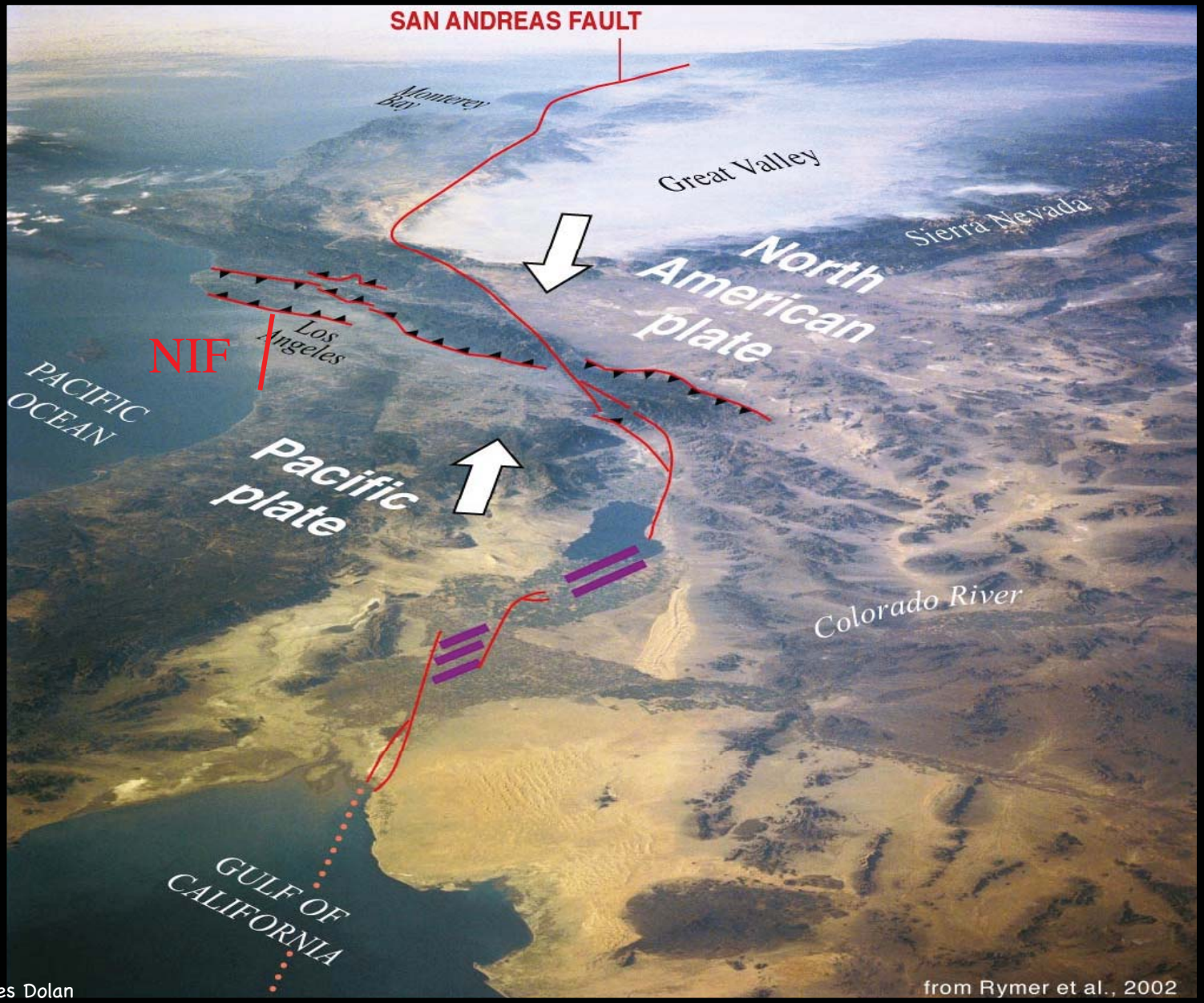
Thrust faulting tends to occur where the San Andreas is not aligned with the Pacific-North American plate motion vector.



GPS Site Velocity Vectors for Southern California

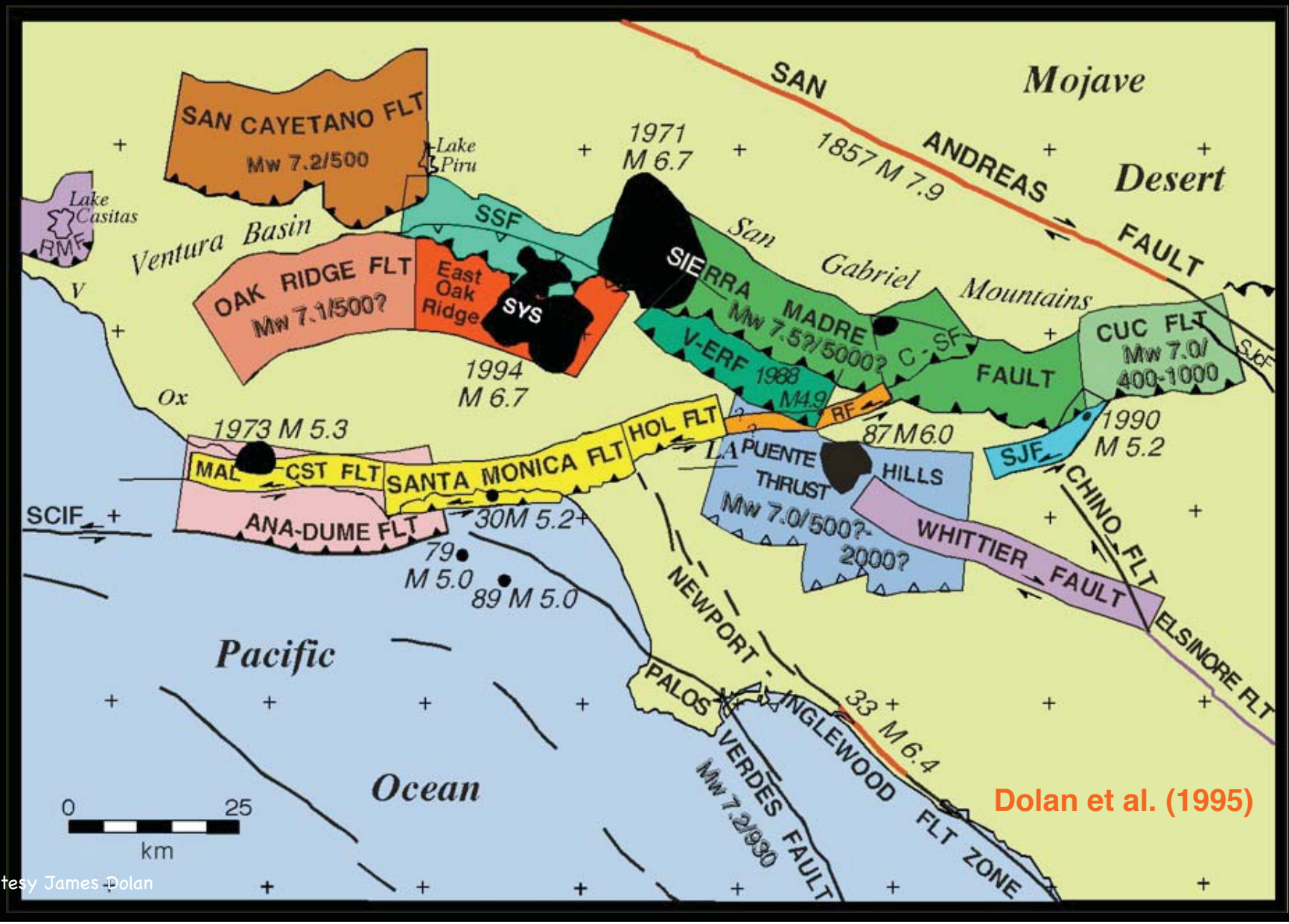


The San Andreas fault in Southern California



courtesy James Dolan

Major faults of the Los Angeles region



courtesy James Dolan

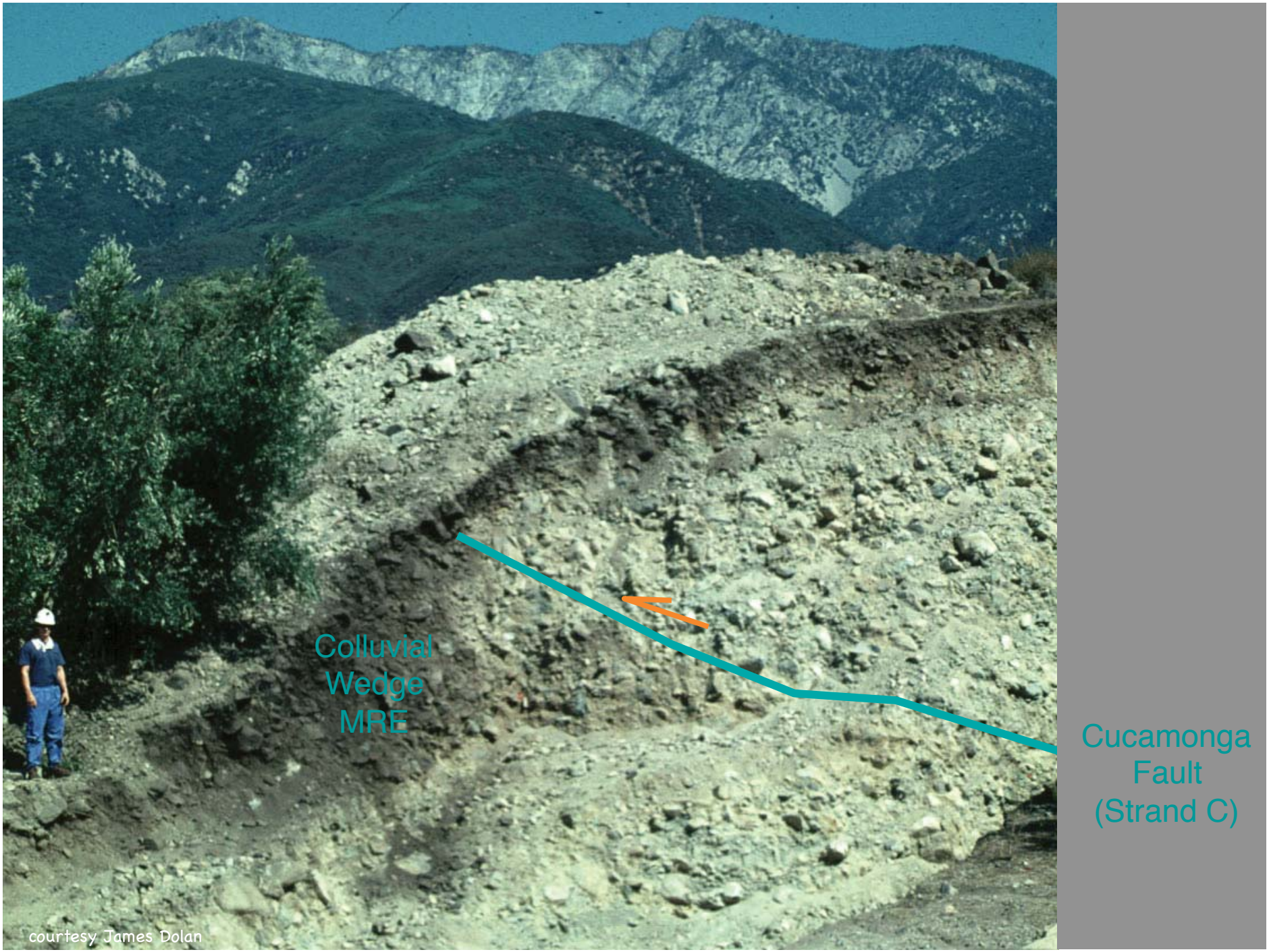
courtesy James Dolan

Cucamonga Fault Strands

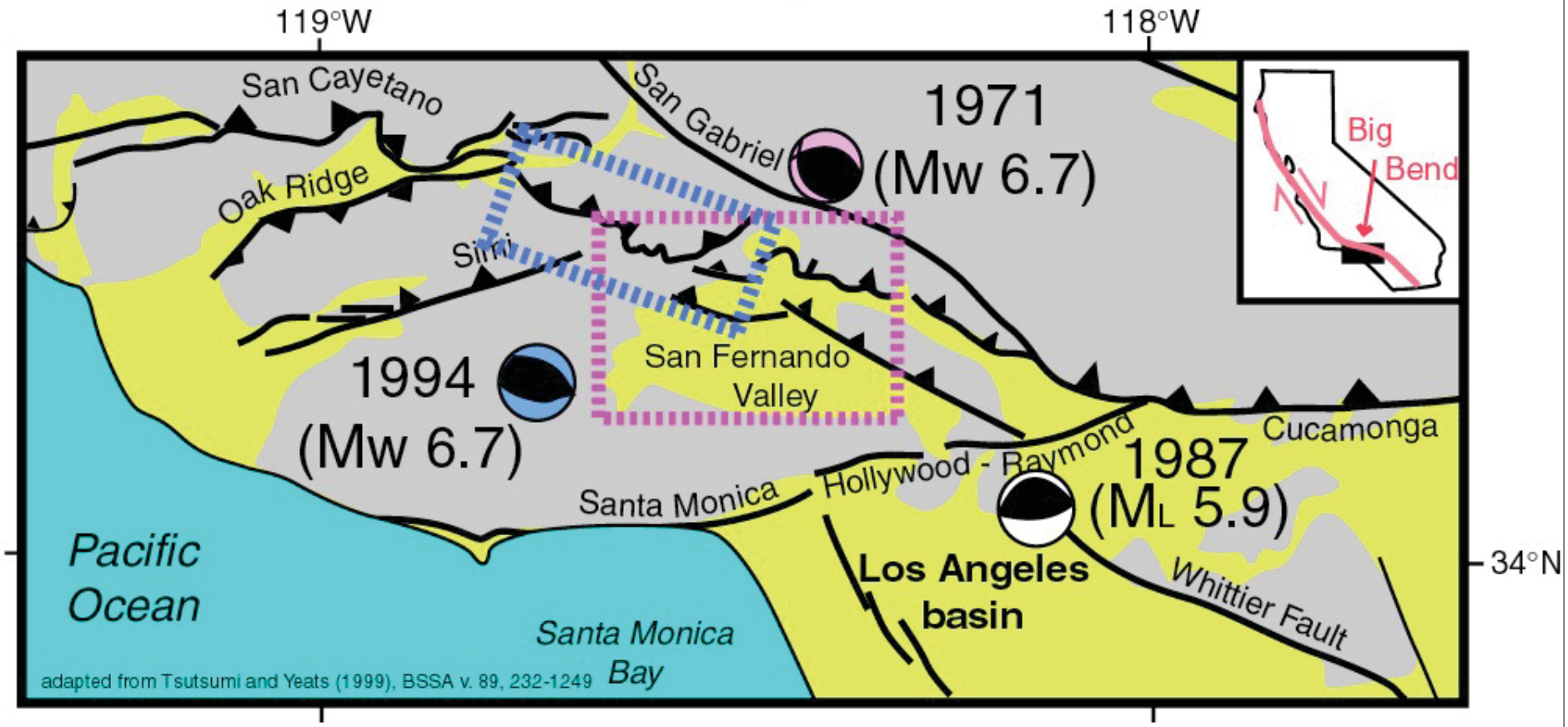
courtesy James Dolan


trench

Cucamonga Fault (Strand C)

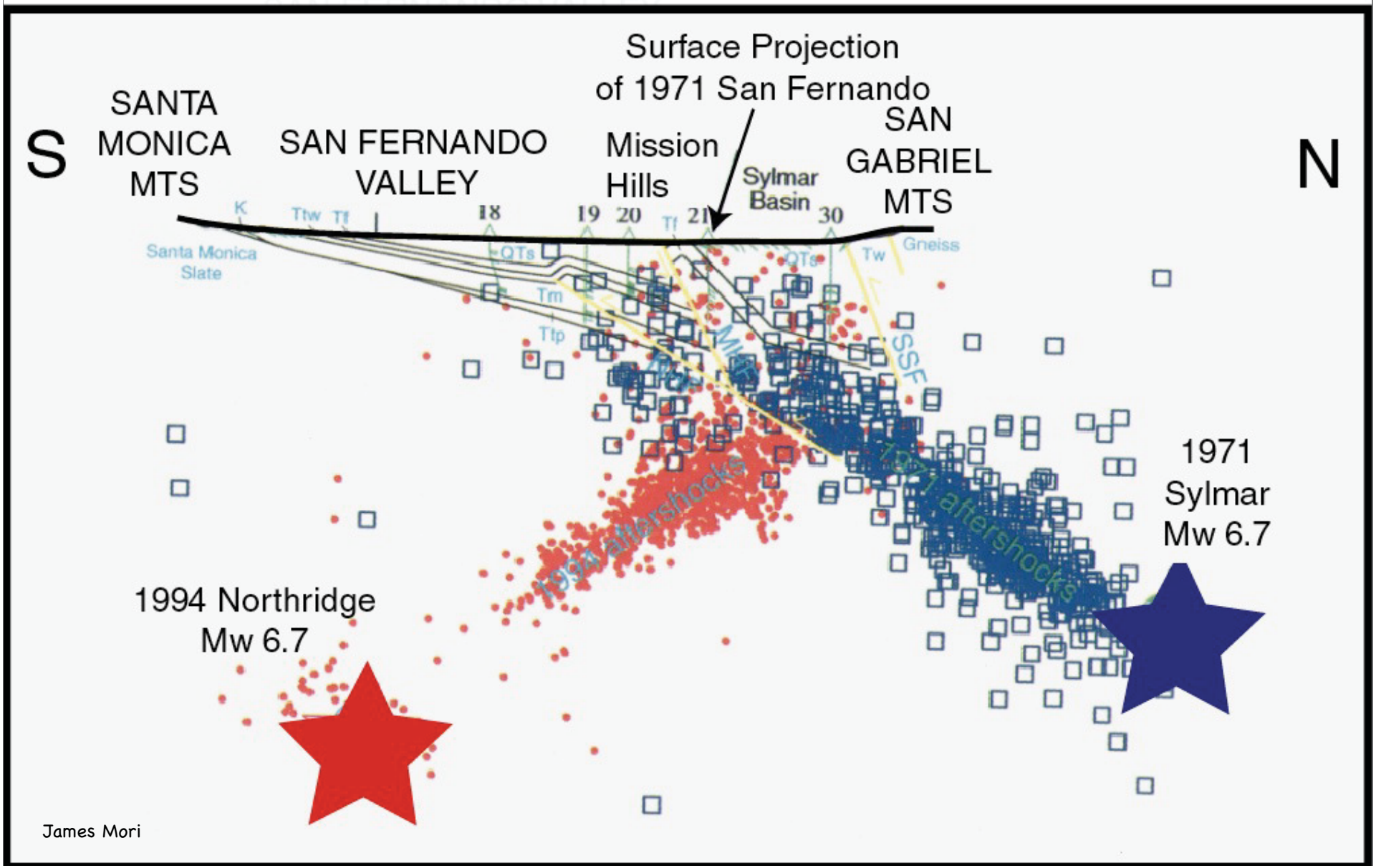

Colluvial
Wedge
MRE
Cucamonga
Fault
(Strand C)
courtesy James Dolan

Thrusting occurs where San Andreas is out of alignment with plate motion vector



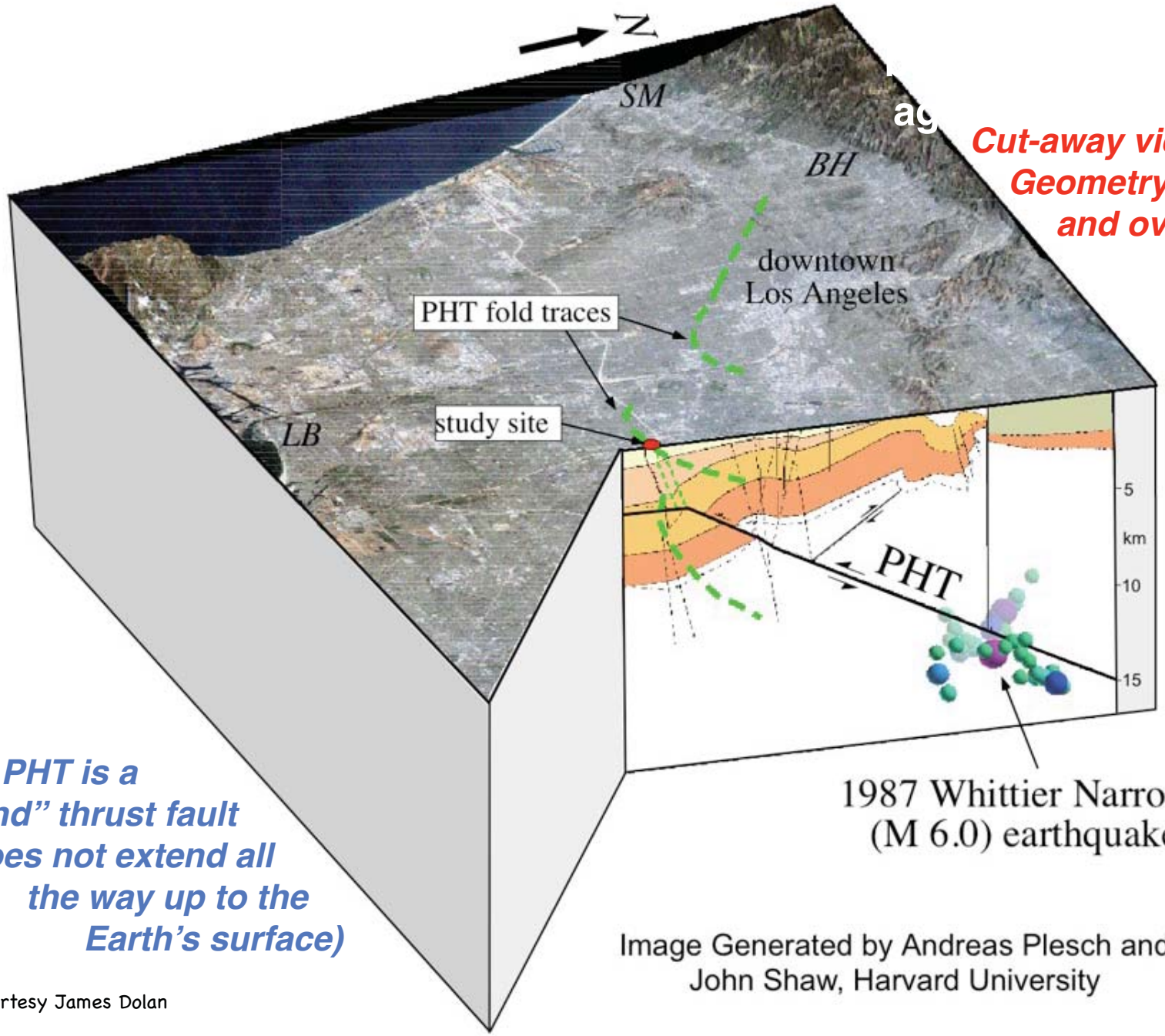
February 9, 1971 San Fernando Earthquake
October 1, 1987 Whittier Narrows Earthquake
January 17, 1994 Northridge Earthquake

Not all thrusts reach the surface
"Blind thrusts"



courtesy James Dolan

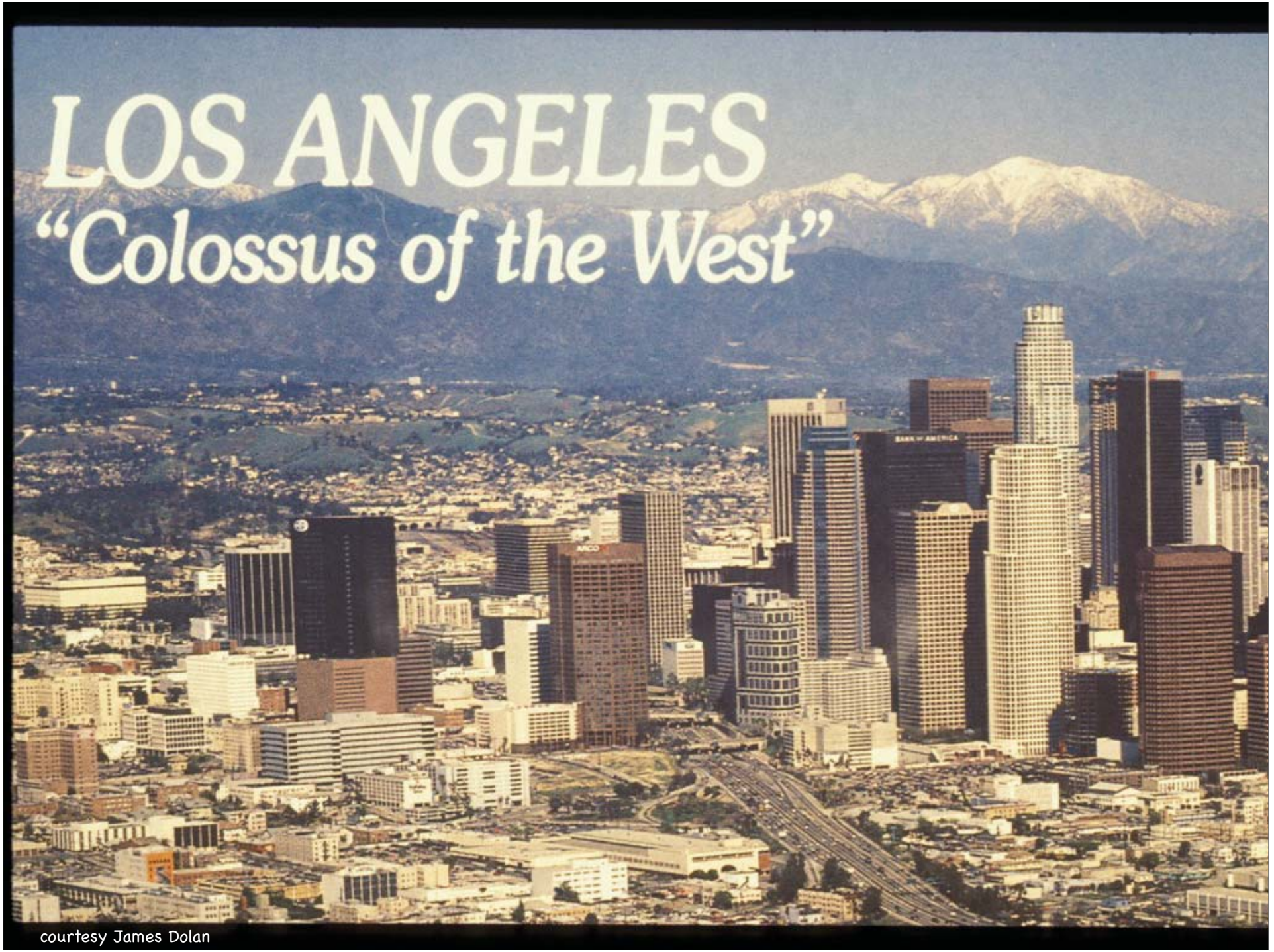
The Puente Hills Thrust fault (PHT)

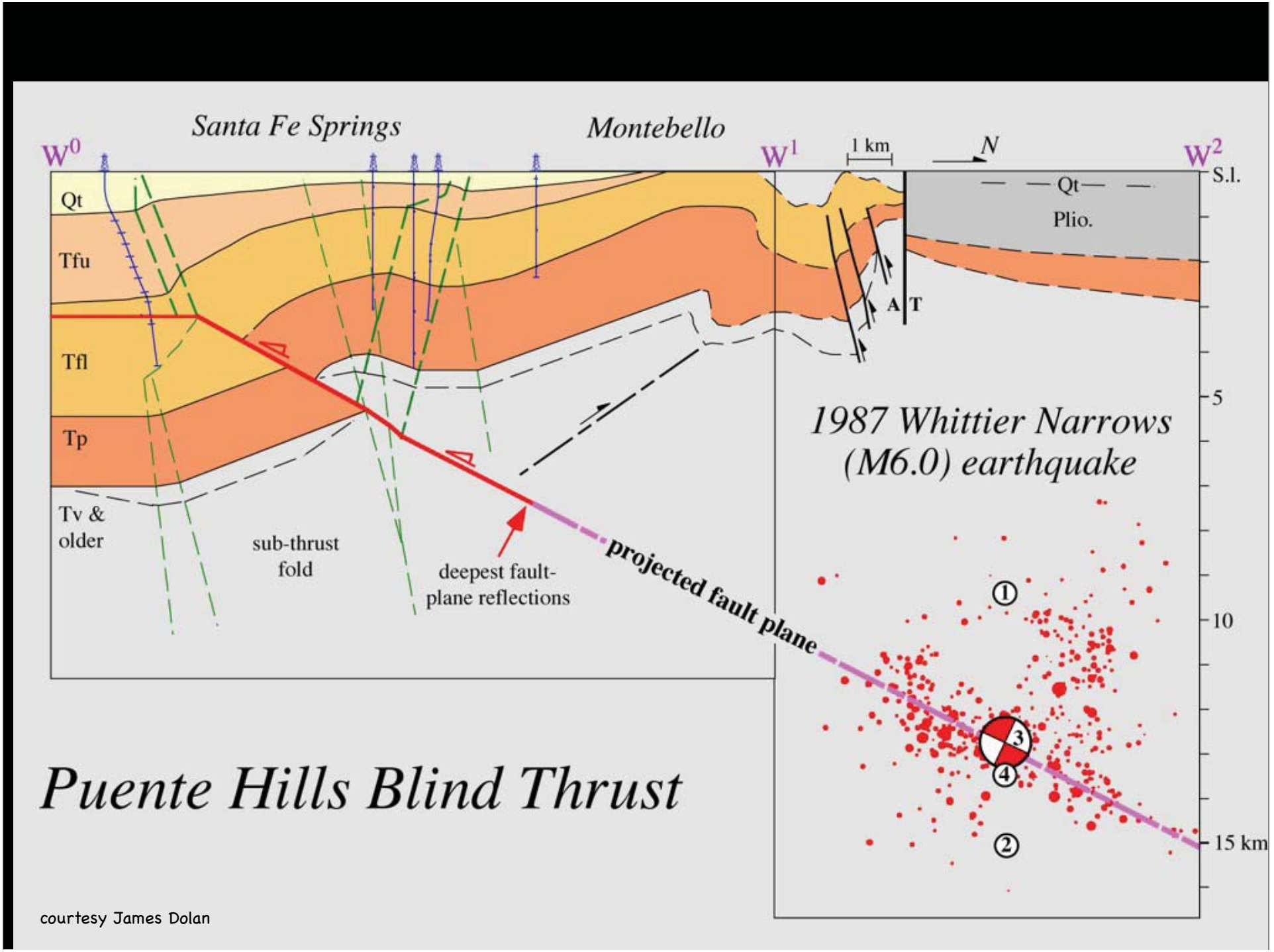


Cut-away view of Geometry of PHT and overlying fold

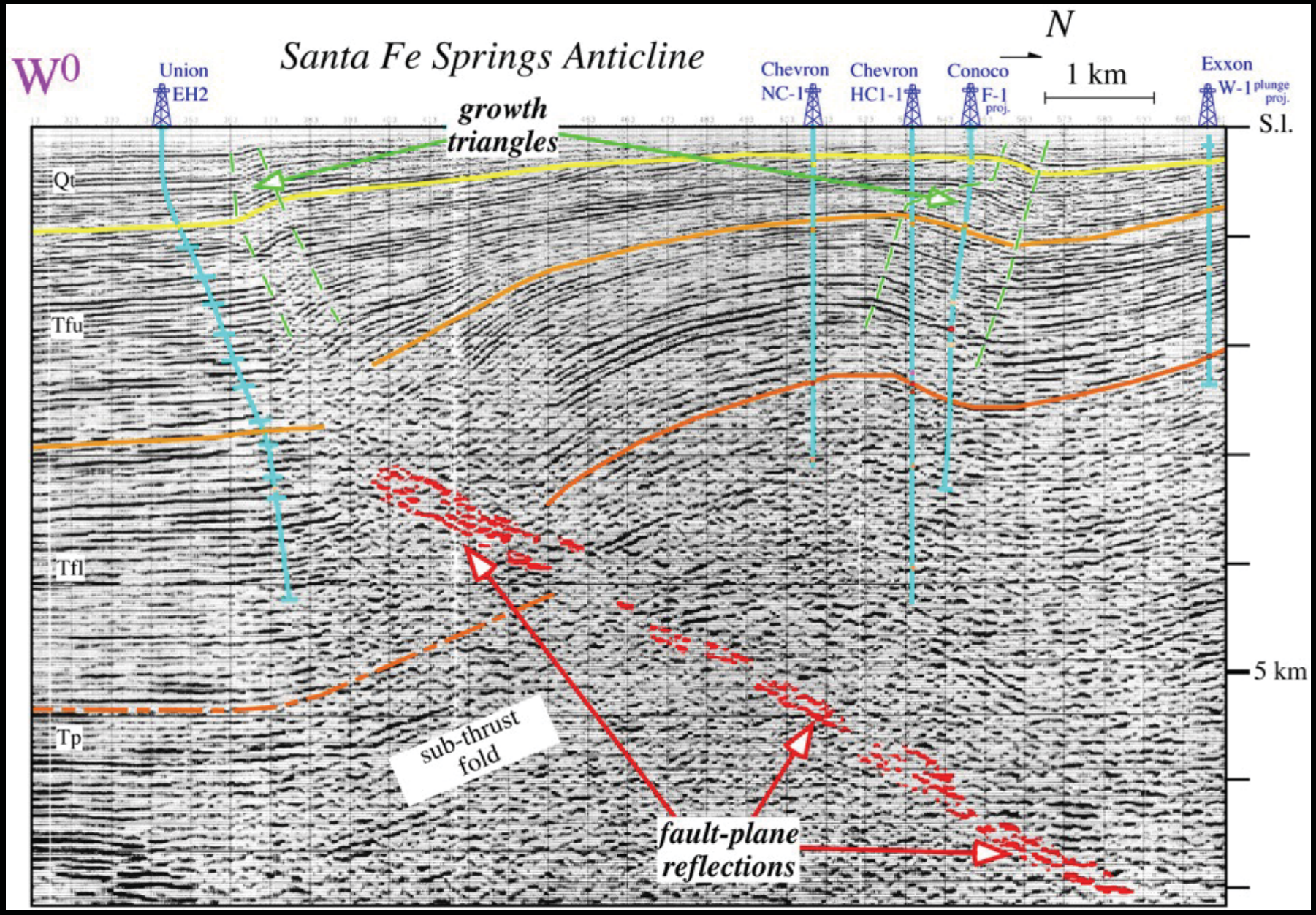
The PHT is a "blind" thrust fault (does not extend all the way up to the Earth's surface)

courtesy James Dolan


LOS ANGELES
"Colossus of the West"
courtesy James Dolan

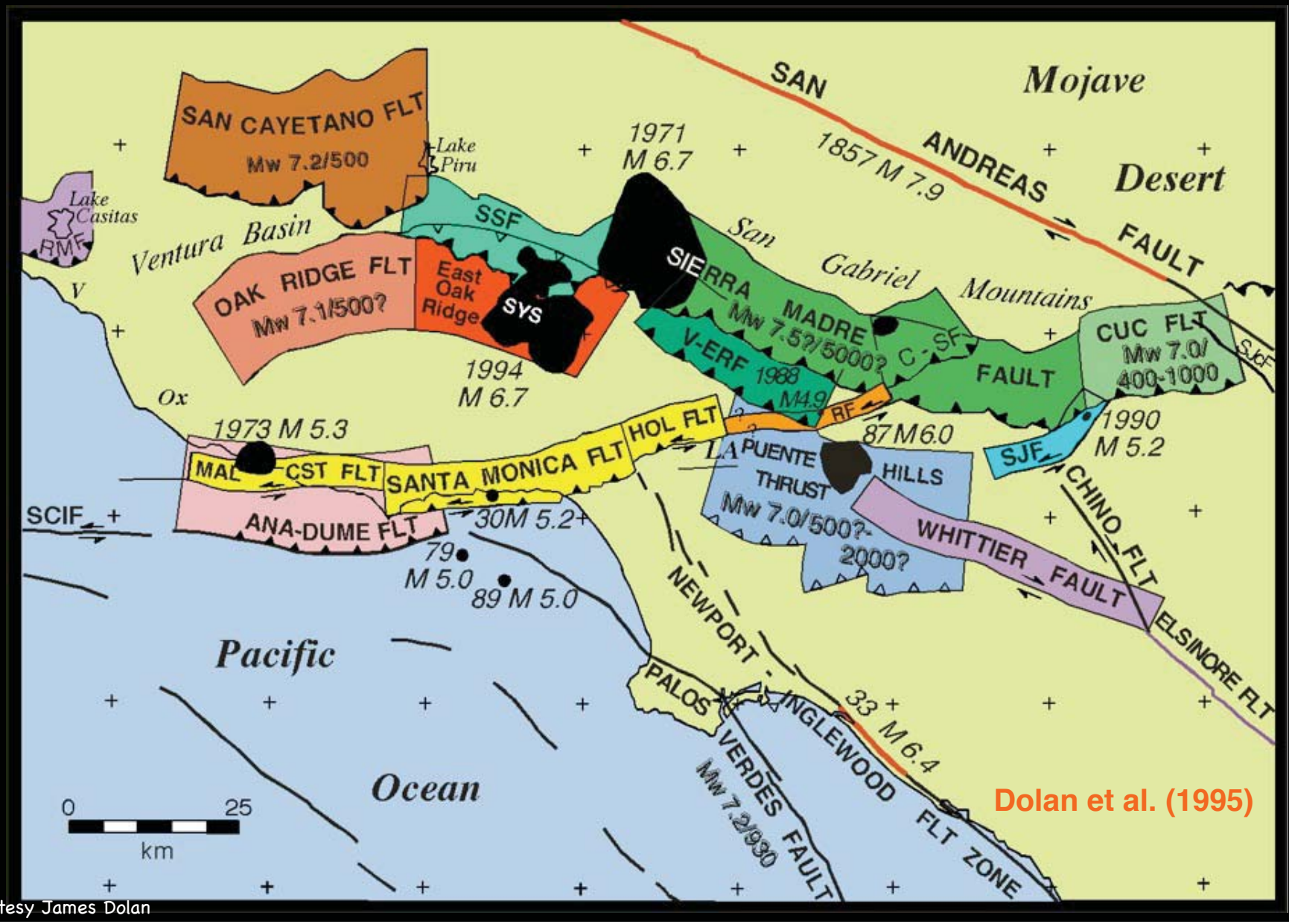


courtesy James Dolan



courtesy James Dolan - work of Shaw and students

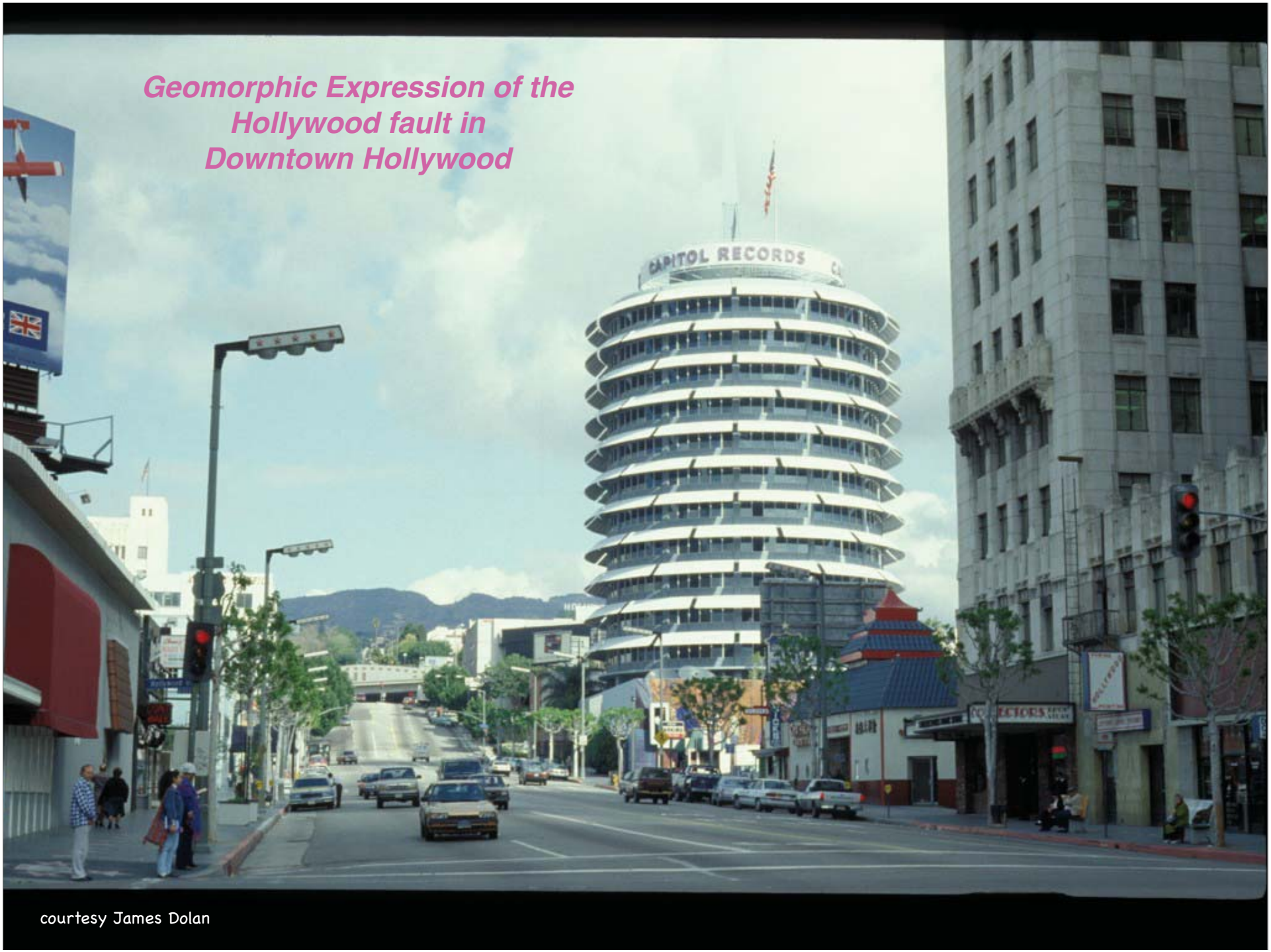
Major faults of the Los Angeles region



courtesy James Dolan

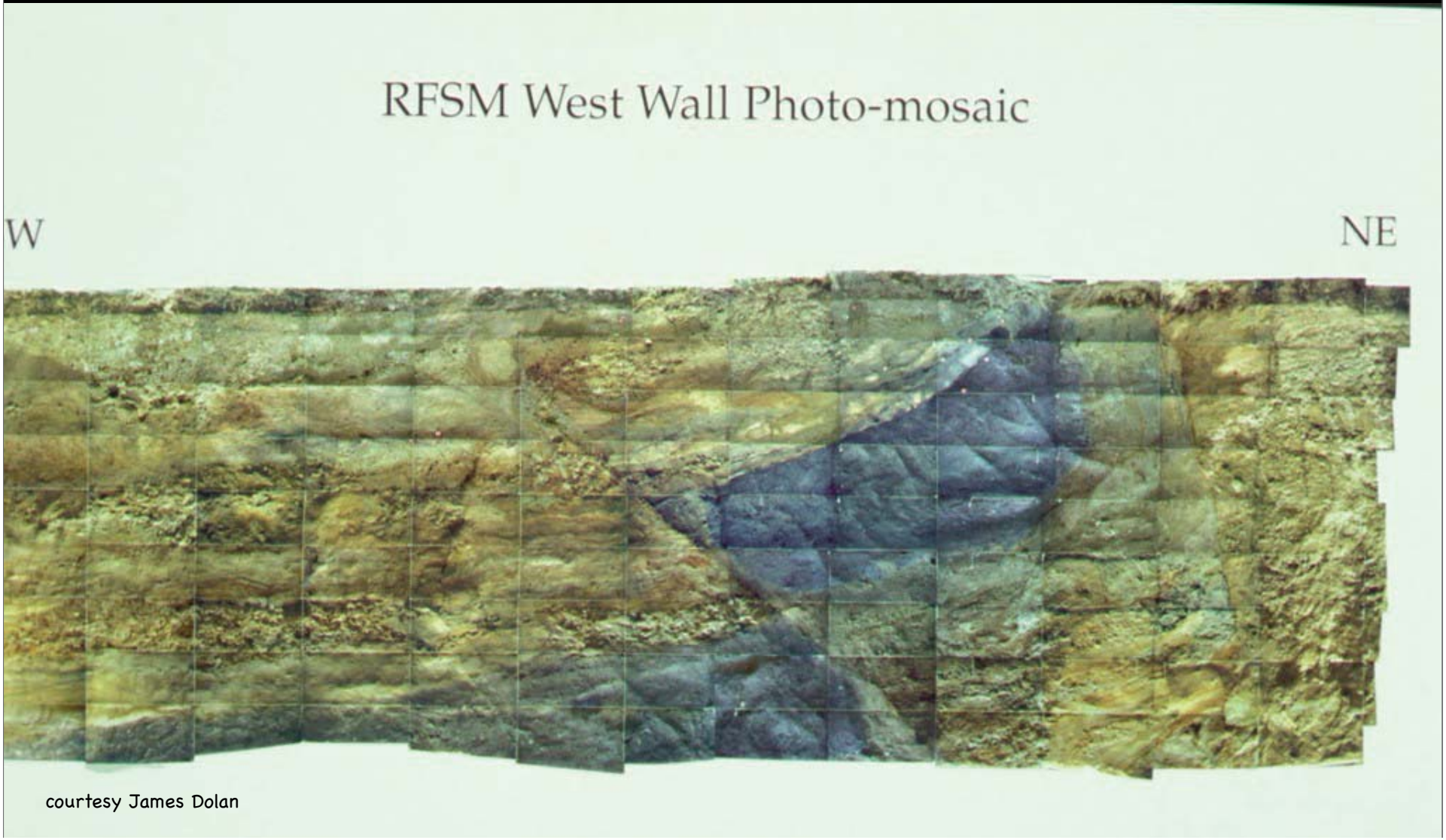
courtesy James Dolan

Geomorphic Expression of the Santa Monica fault in West LA


Geomorphic Expression of the
Hollywood fault in
Downtown Hollywood
CAPITOL RECORDS
courtesy James Dolan

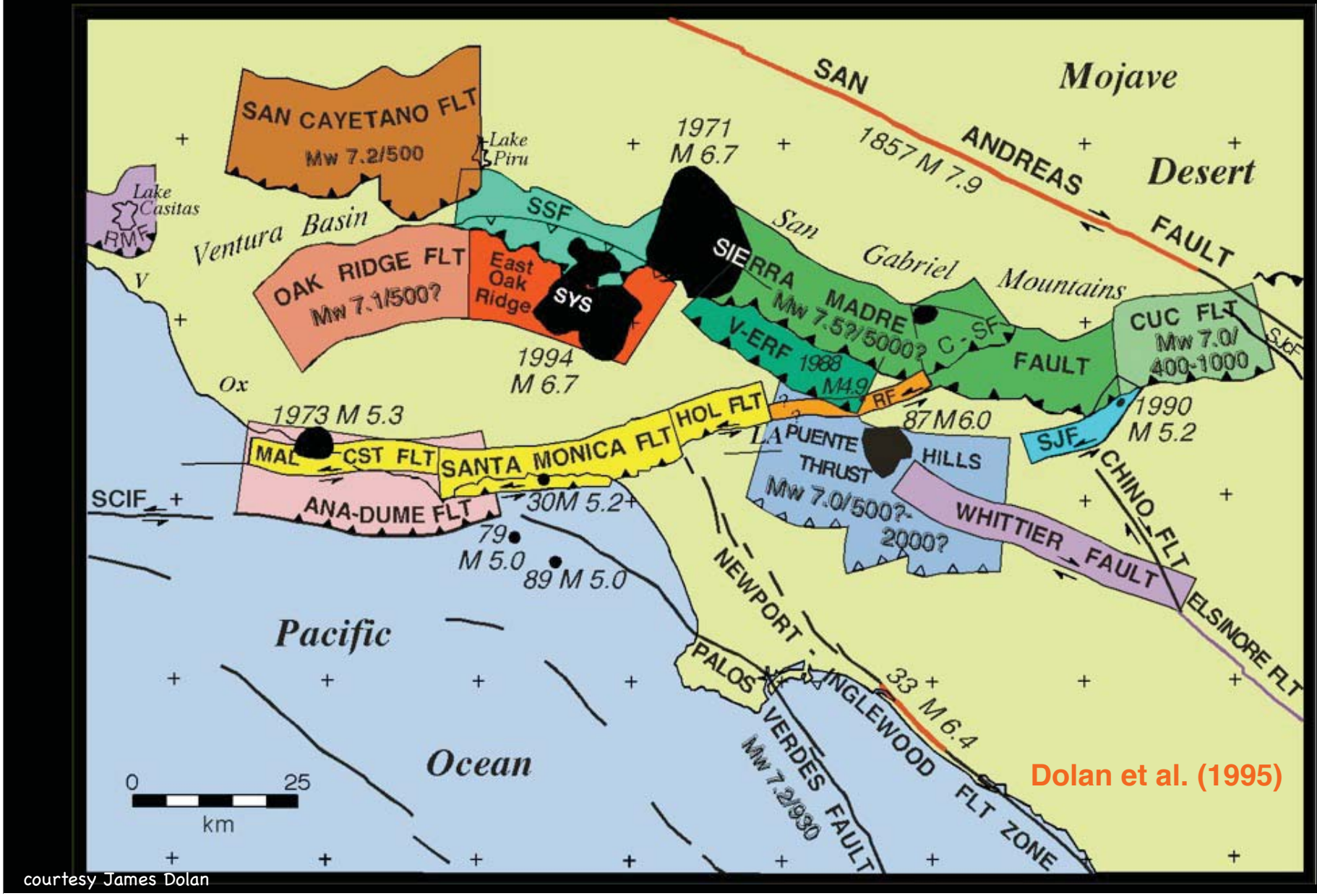
Raymond fault,
Sierra Madre Blvd.,
San Marino

Raymond fault trench-wall photo mosaic



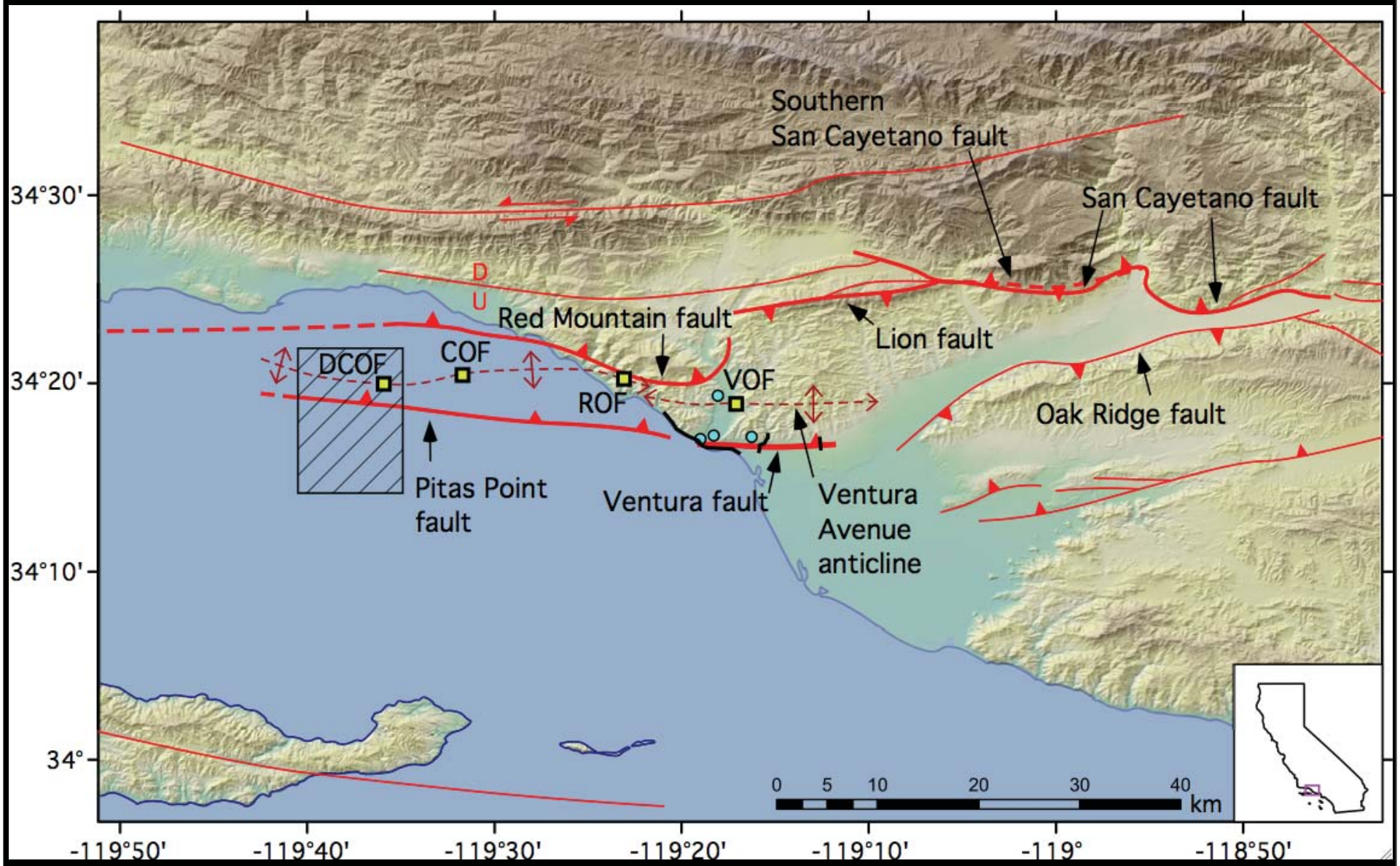
courtesy James Dolan

Major faults of the Los Angeles region



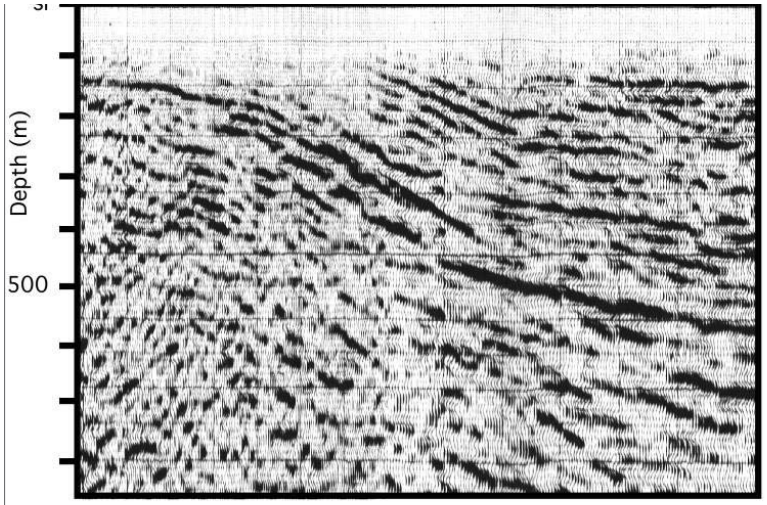
courtesy James Dolan

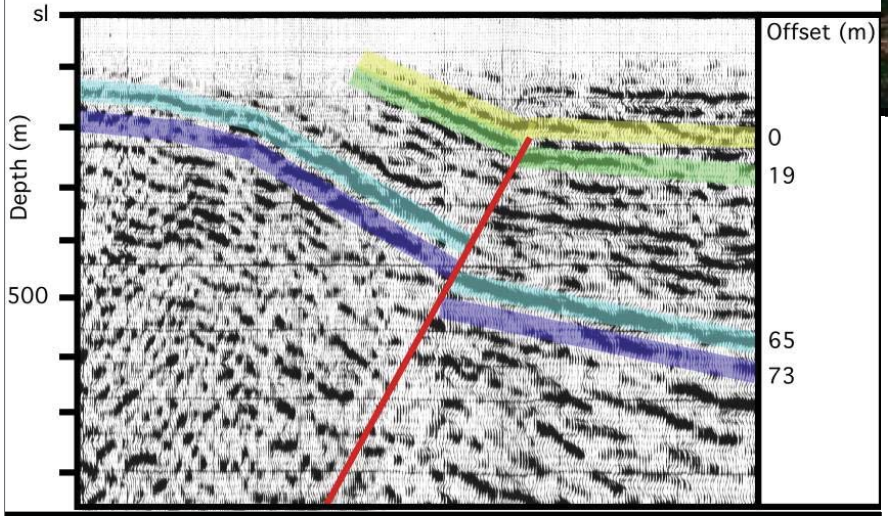
Ventura Region?

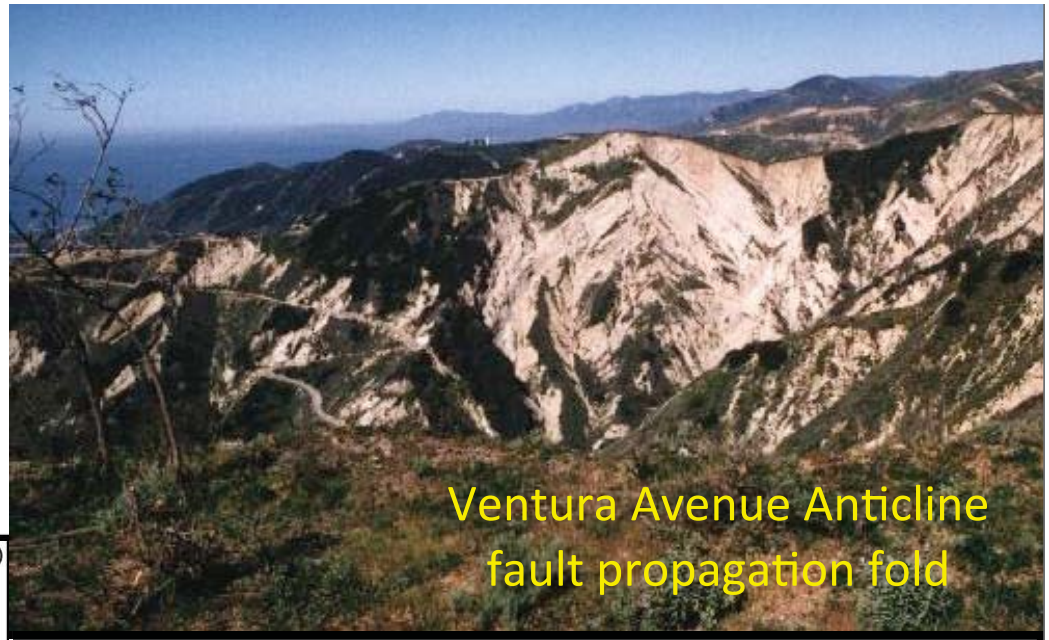


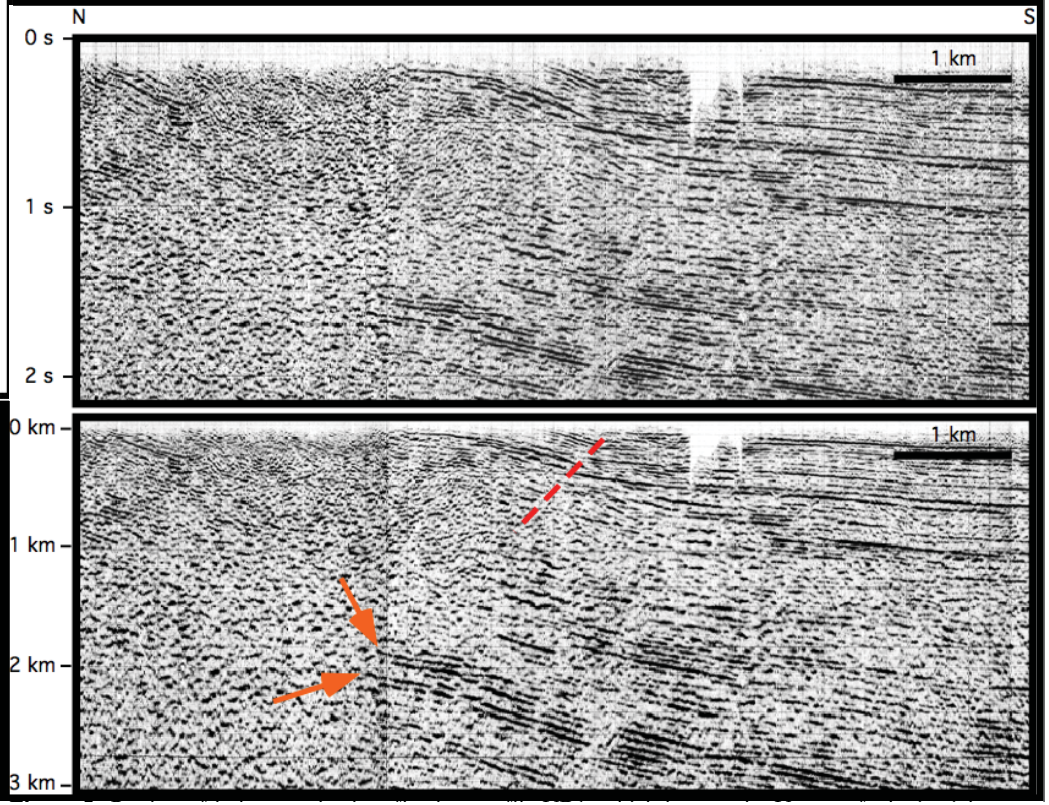
courtesy James Dolan

Hubbard et al., in review







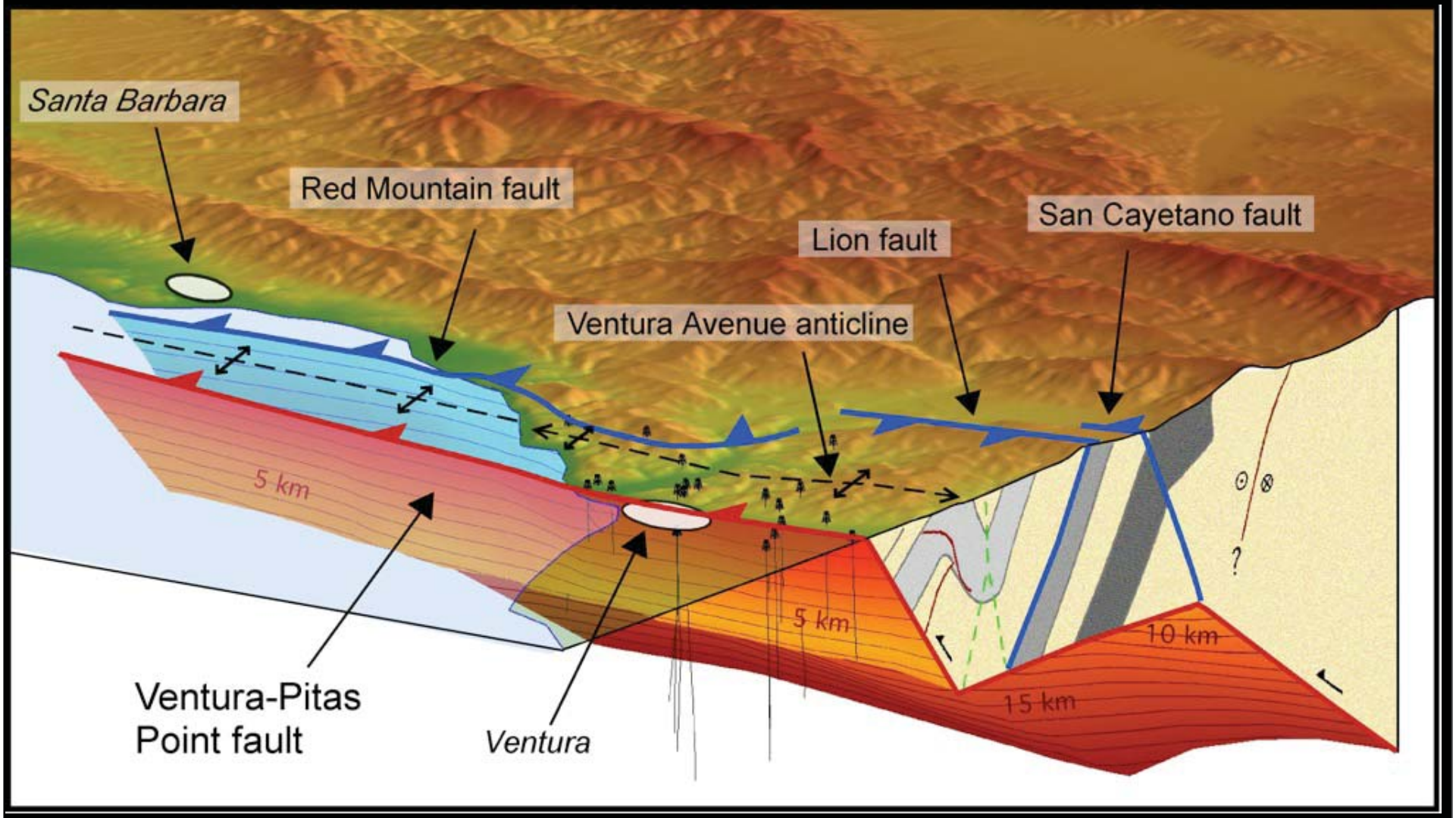


Industry Seismic Reflection Profile Across the Ventura fault

Note decreasing fault separation updip, and lack of fault offset of shallowest horizons

courtesy James Dolan

The Ventura-Pitas Point fault system



Hubbard et al., in review

courtesy James Dolan

Borehole/cpt transect across Ventura fault scarp

Prominent scarp associated with Ventura fault

acquired in 2010
hole (yellow)/CPT (green) locations

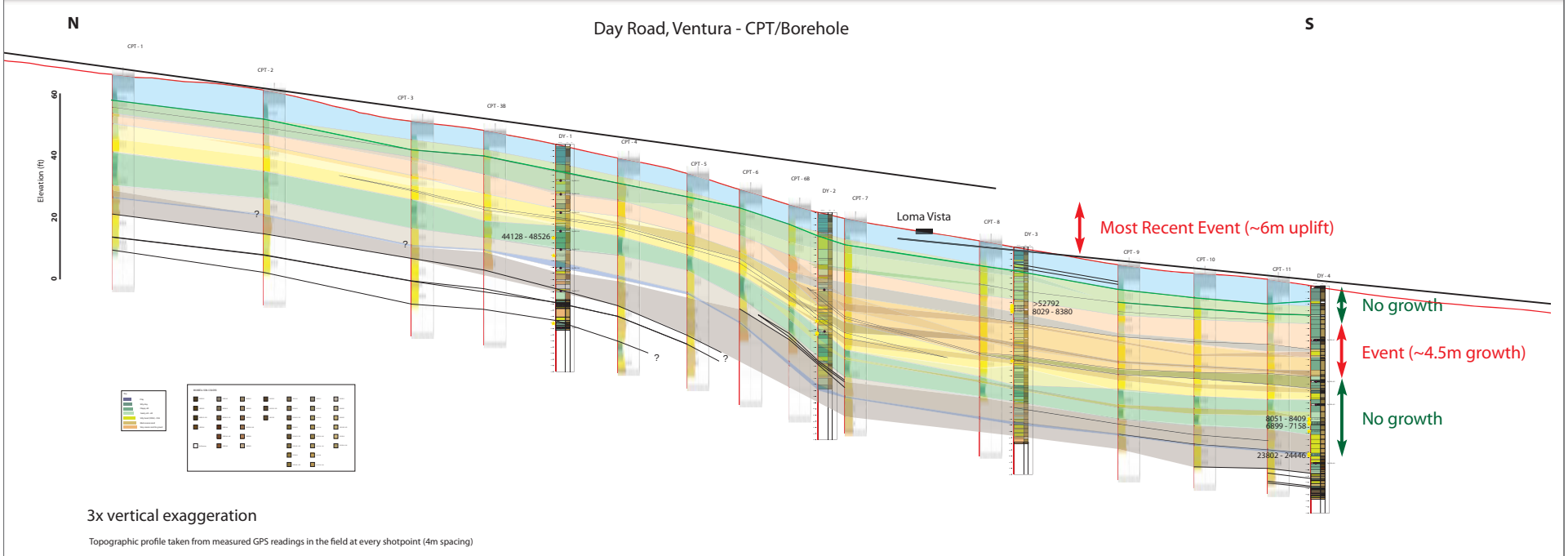
CPT location
Borehole location
Fold scarp

Key Study Location: Most streams are deeply incised where they cross the Ventura fault scarp

But the Day Road Canyon drainage is not incised, instead depositing an active alluvial fan across the Ventura fault scarp

courtesy James Dolan

Borehole/cpt transect across Ventura fault scarp



Upshot: (1) Prominent 6.5-m-high fold scarp records uplift in most recent earthquake. This event is quite recent, as the active fan has not had time to begin burying the scarp.

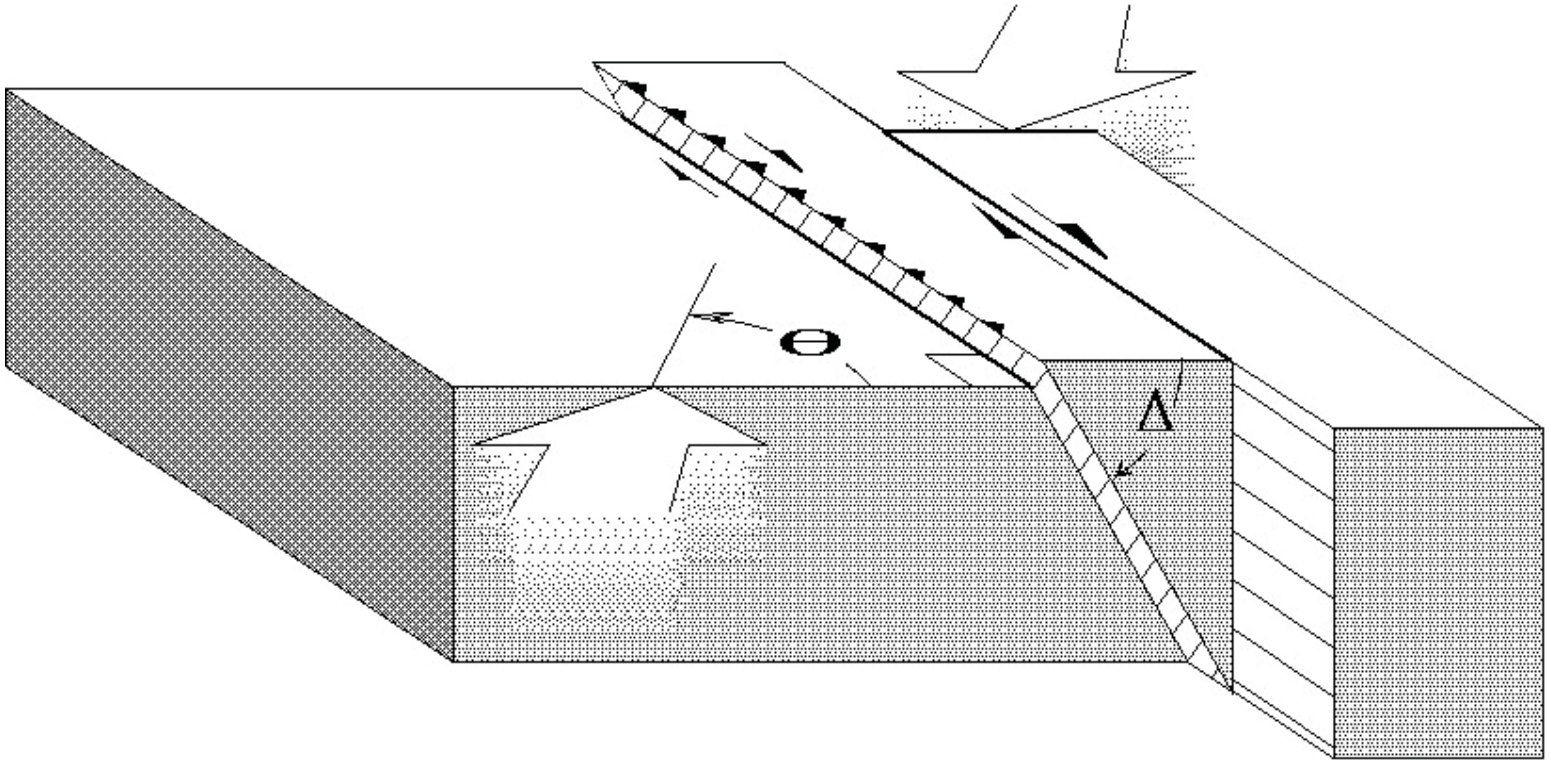
(2) Sedimentary growth (yellow unit) against buried fold scarp records 4-5 m of uplift during penultimate earthquake.

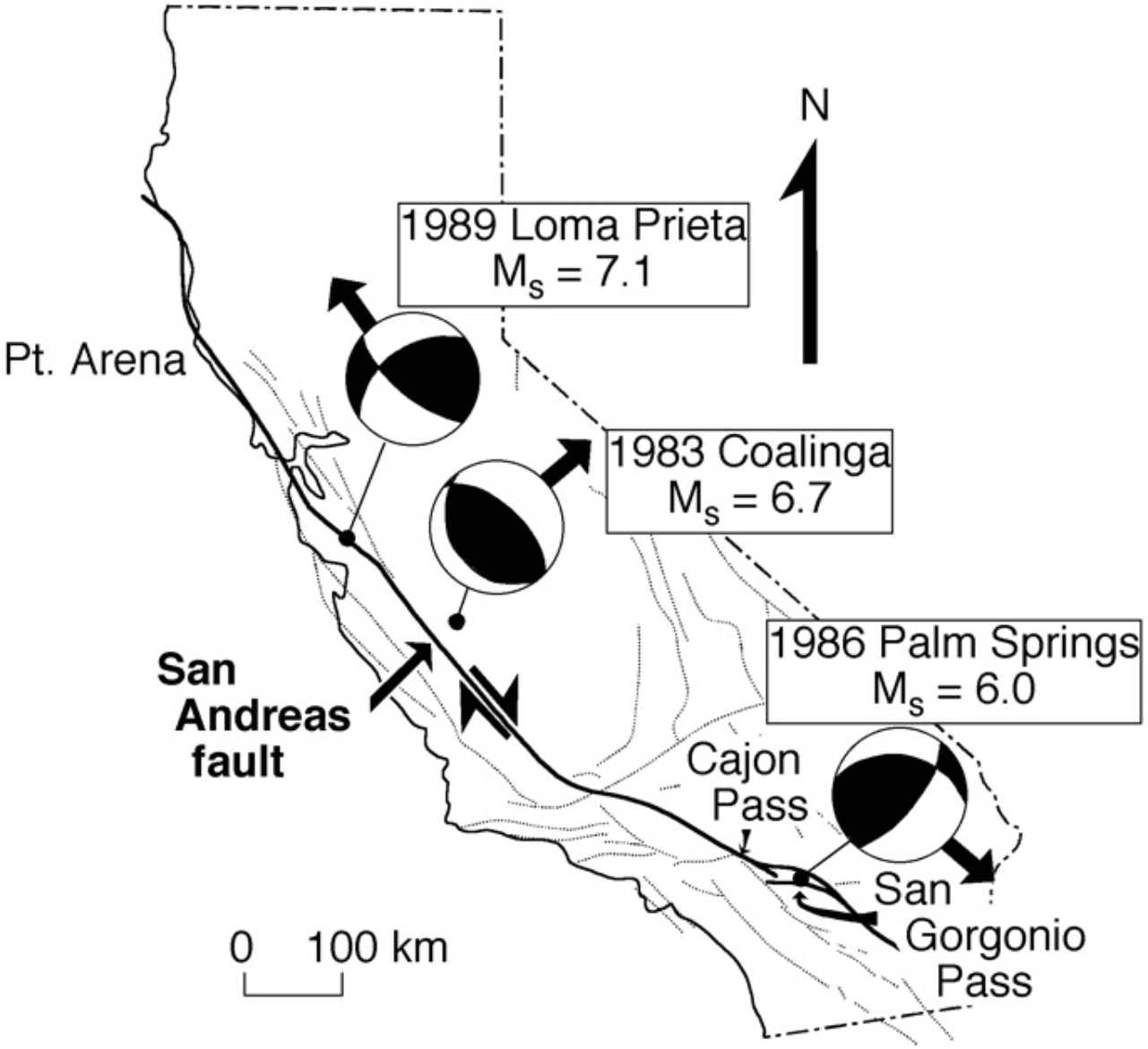
McAuliffe et al. (in prep.)

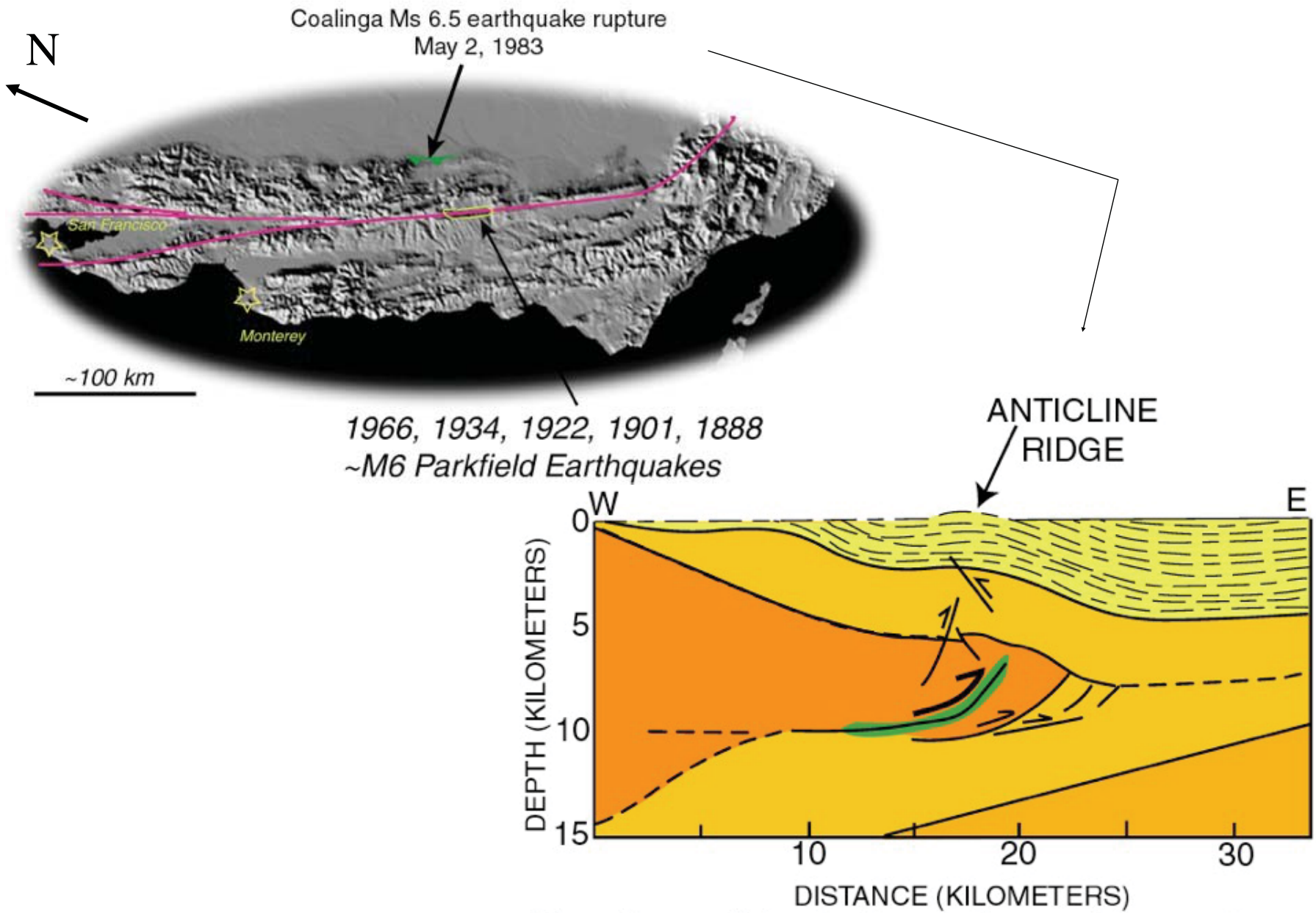
courtesy James Dolan

Thrust faults not only in Transverse Range - ant any point where San Andreas not oriented perfectly to accommodate strike-slip....

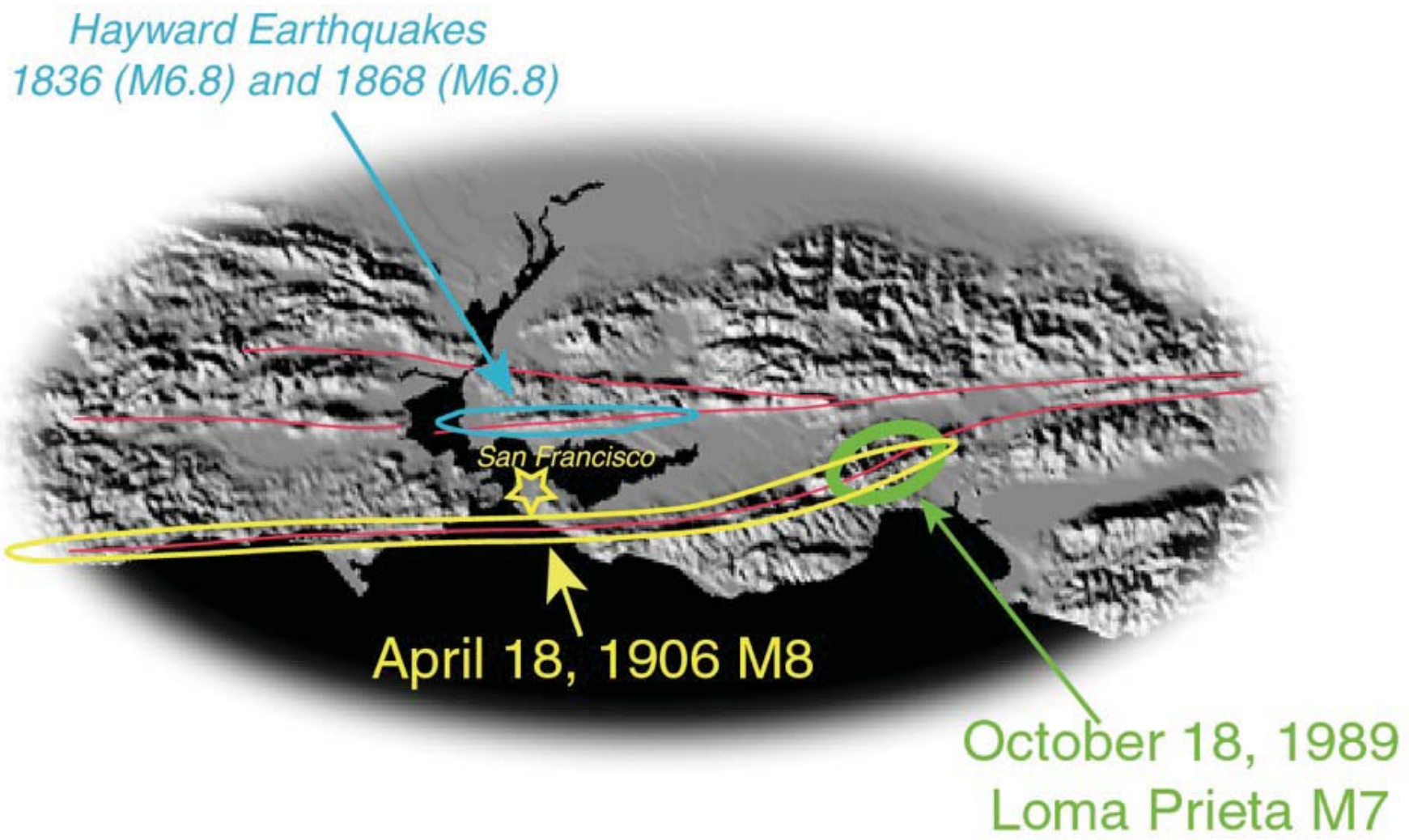
Oblique Convergence

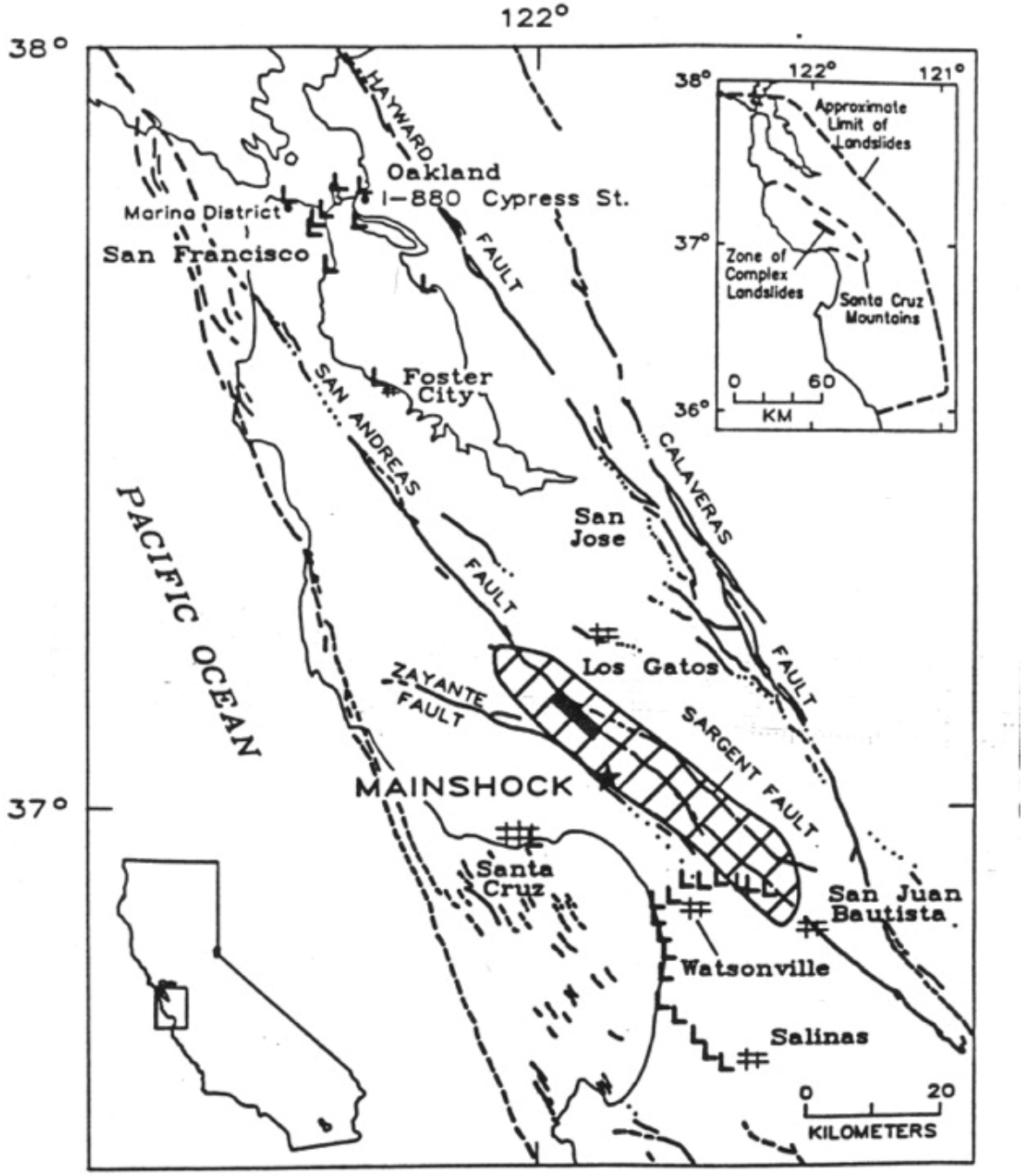


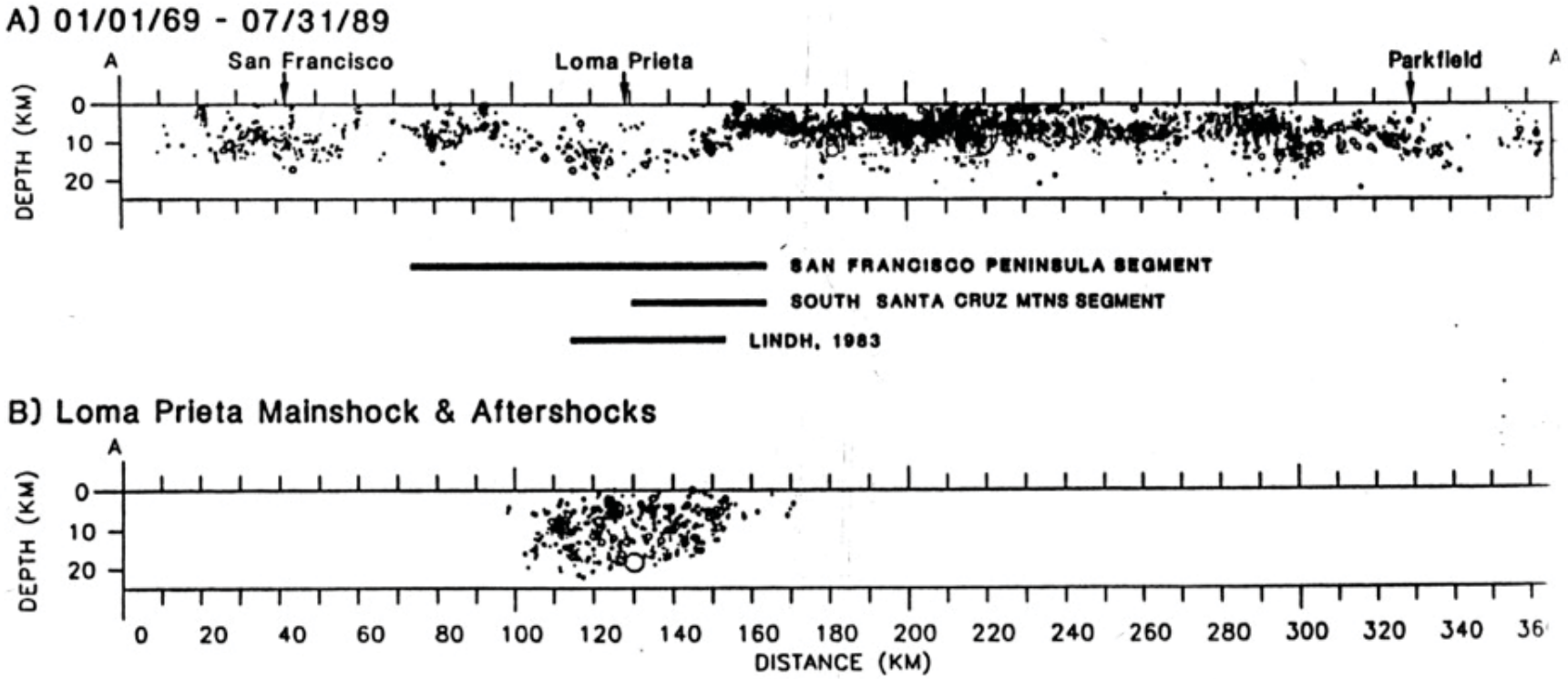

N
1989 Loma Prieta
M_s = 7.1
Pt. Arena
1983 Coalinga
M_s = 6.7
1986 Palm Springs
M_s = 6.0
San
Andreas
fault
Cajon
Pass
San
Gorgonio
Pass
0 100 km

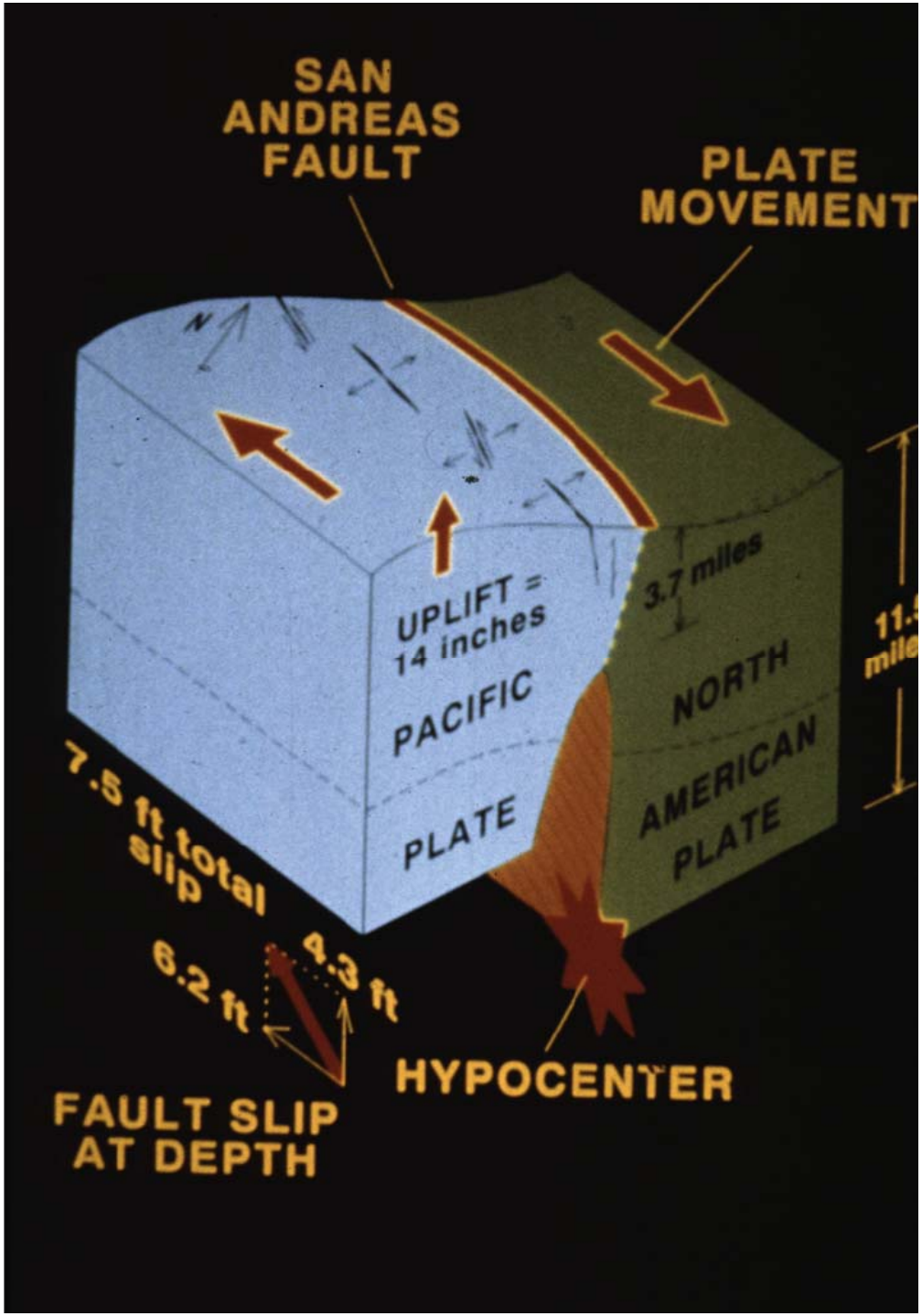


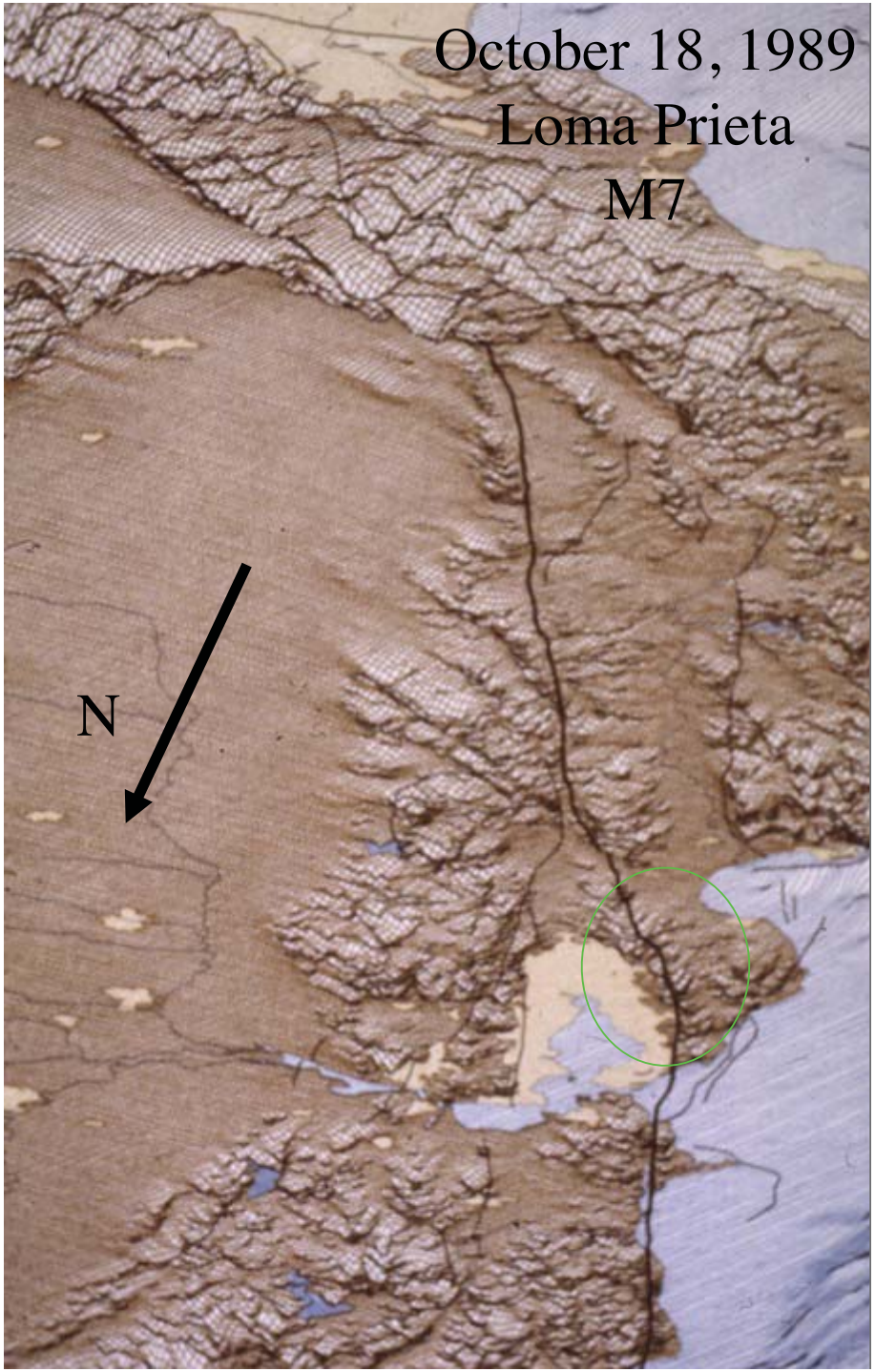
Coalinga Ms 6.5 earthquake rupture
May 2, 1983

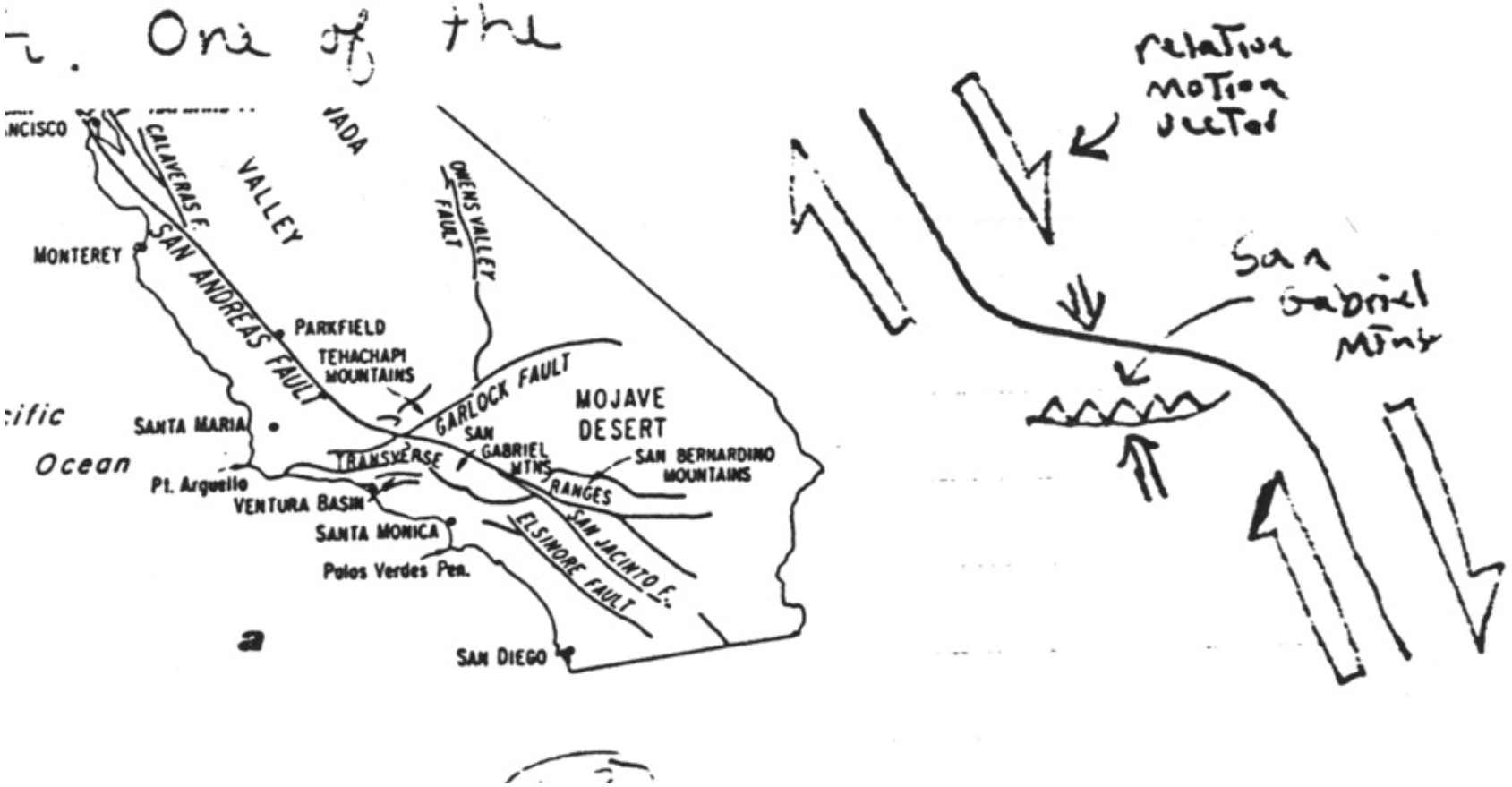

Hayward Earthquakes
1836 (M6.8) and 1868 (M6.8)
San Francisco
April 18, 1906 M8
October 18, 1989
Loma Prieta M7


122°
38°
37°
HAYWARD
FAULT
Oakland
I-880 Cypress St.
Marina District
San Francisco
Foster
City
SAN ANDREAS
FAULT
San
Jose
CALAVERAS
FAULT
Los Gatos
ZAYANTE
FAULT
SARGENT FAULT
PACIFIC OCEAN
MAINSHOCK
Santa
Cruz
San Juan
Bautista
Watsonville
Salinas
0 20
KILOMETERS
38°
122°
121°
Approximate
Limit of
Landslides
37°
Zone of
Complex
Landslides
Santa Cruz
Mountains
0 60
KM
36°


A) 01/01/69 - 07/31/89
A
San Francisco
Loma Prieta
Parkfield
A
DEPTH (KM)
0
10
20
SAN FRANCISCO PENINSULA SEGMENT
SOUTH SANTA CRUZ MTNS SEGMENT
LINDH, 1983
B) Loma Prieta Mainshock & Aftershocks
A
DEPTH (KM)
0
10
20
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
DISTANCE (KM)


SAN ANDREAS FAULT
PLATE MOVEMENT
UPLIFT = 14 inches
3.7 miles
PACIFIC PLATE
NORTH AMERICAN PLATE
7.5 ft total slip
6.2 ft
4.3 ft
HYPOCENTER
FAULT SLIP AT DEPTH


October 18, 1989
Loma Prieta
M7
N


relative motion vector
San Gabriel Mts
NCISCO
CALAVERAS F.
VALLEY
SAN ANDREAS FAULT
OWENS VALLEY FAULT
MONTEREY
PARKFIELD
TEHACHAPI MOUNTAINS
GARLOCK FAULT
MOJAVE DESERT
SANTA MARIA
SAN GABRIEL MTNS
TRANSVERSE RANGES
SAN BERNARDINO MOUNTAINS
Pt. Arguello
VENTURA BASIN
SANTA MONICA
ELSINORE FAULT
SAN JACINTO F.
Palos Verdes Pen.
SAN DIEGO
a