Advanced Structural Geology, Fall 2022

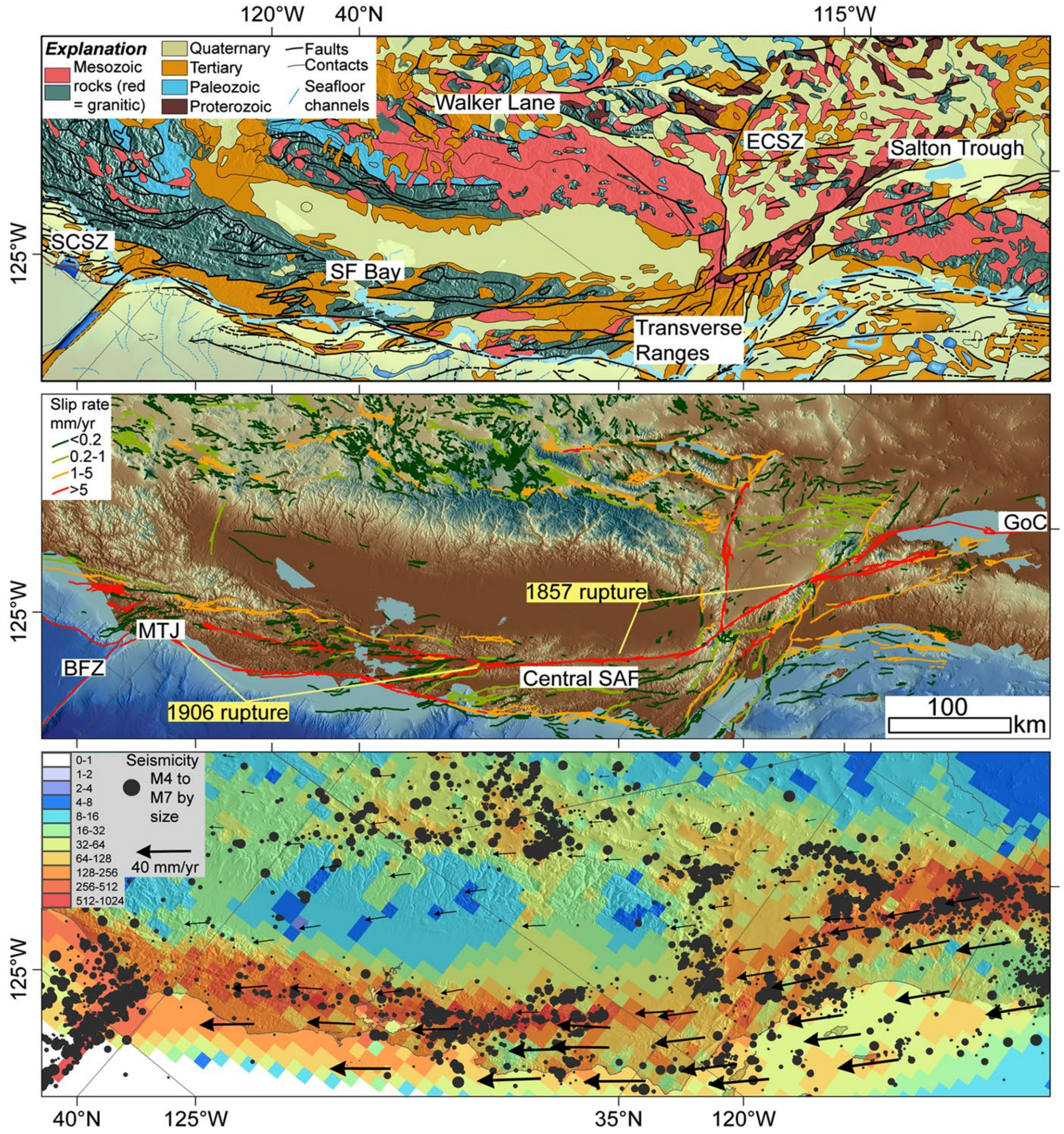
SW North American Cordillera since 36 Ma: San Andreas Fault system and Basin and Range

Ramón Arrowsmith

ramon.arrowsmith@asu.edu

School of Earth and Space Exploration
Arizona State University

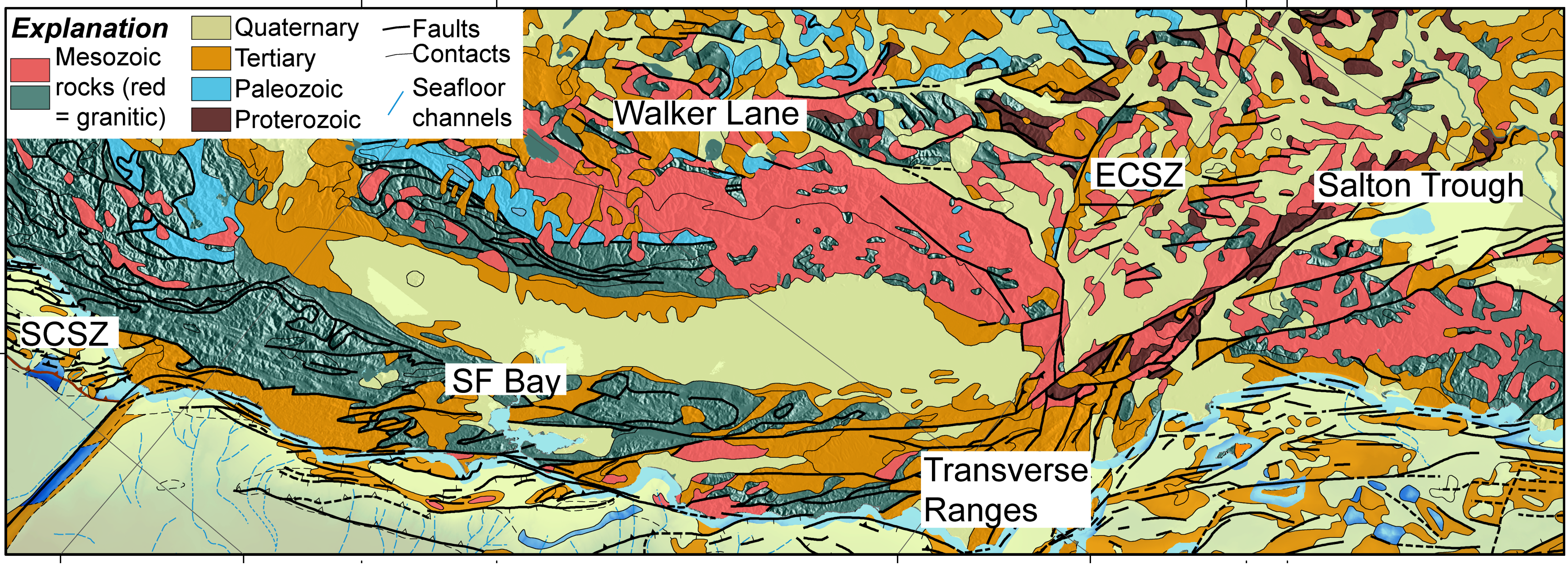
Minimum Ingredients



Geology
(USGS https://ngmdb.usgs.gov/gmna)

Topography and active faults *(GMRT and USGS and CGS 2021 QFAULTS)*

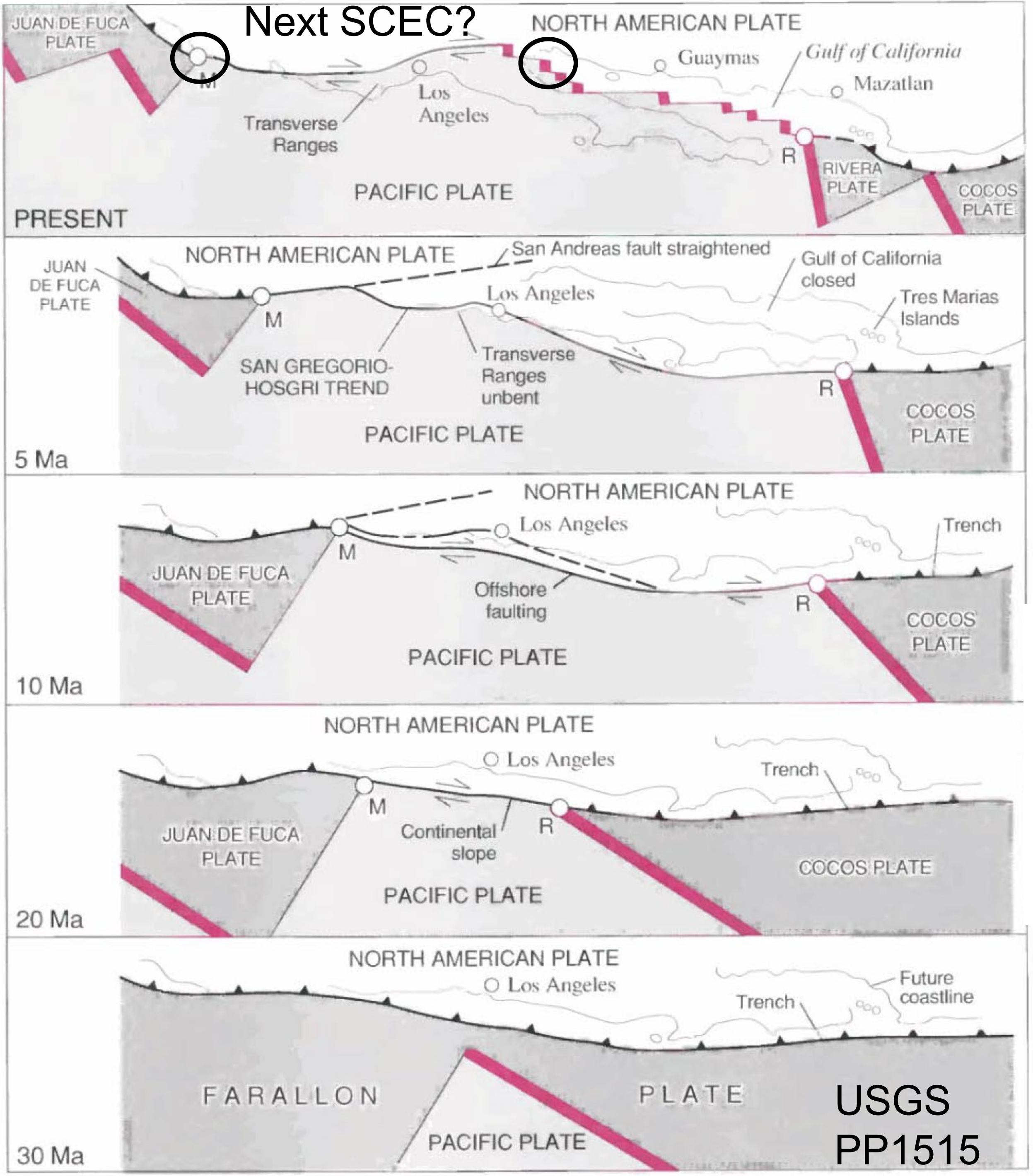
Strain rate and seismicity
(Kreemer, et al., and USGS)



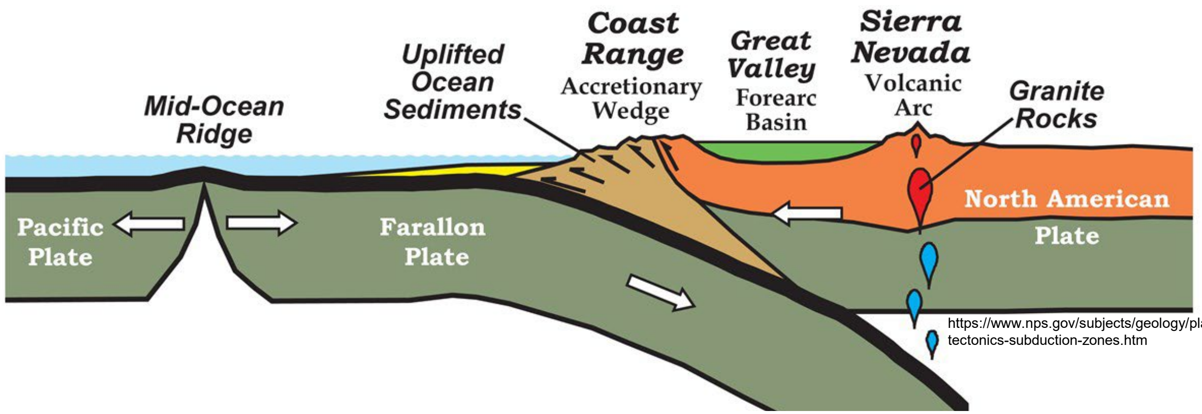
The geologic template of the plate boundary system is a first order control on its behavior. The breadth of the system and its variation in evolutionary state provide a valuable opportunity to access a range of processes and configurations via substitution of space for time.

Progressively dismembering an andean-style convergent margin built on a late Proterozoic passive margin

Next SCEC?



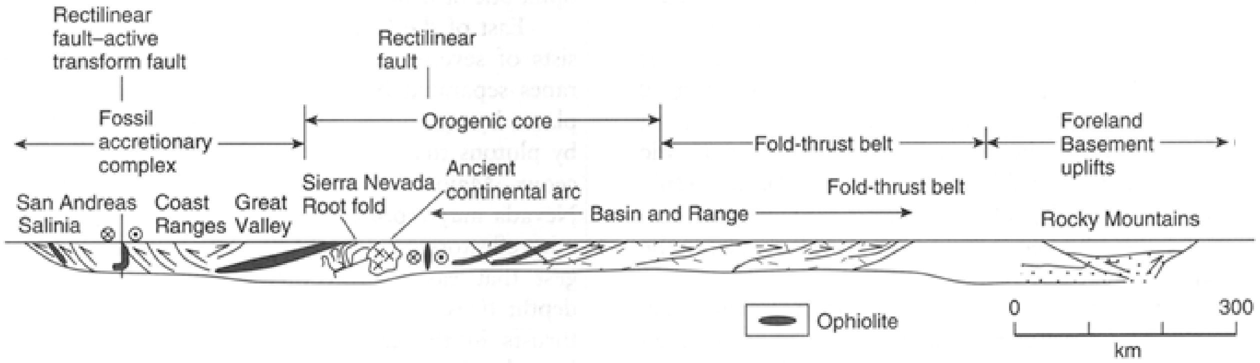
USGS PP1515



https://www.nps.gov/subjects/geology/plate-tectonics-subduction-zones.htm

Andean plate boundary—simplified model

- San Andreas system cuts obliquely across
- Southern Cascadia as remainder
- Baja California transfer at ~5 Ma



Moores & Twiss, 1995

Spreading center

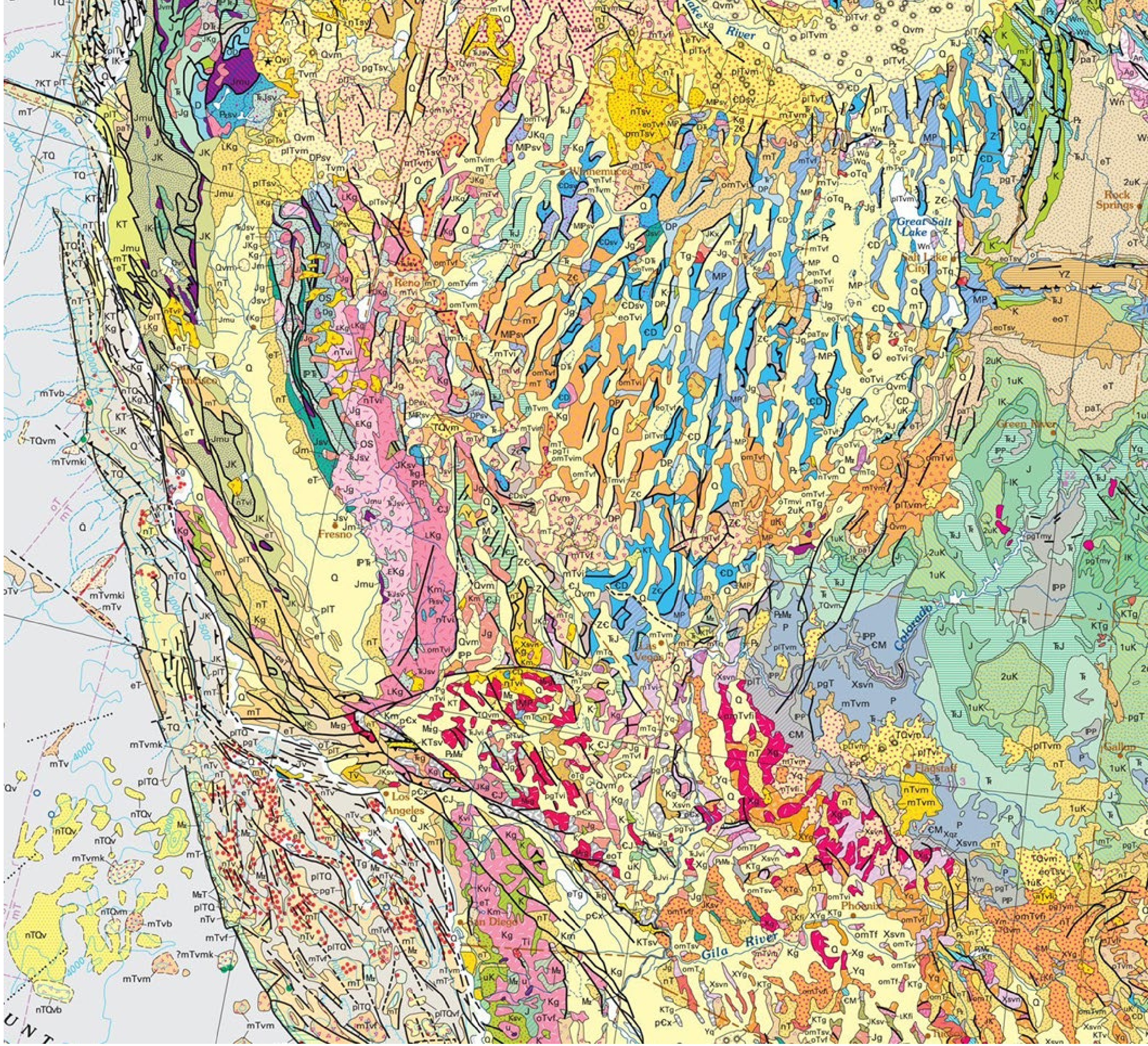
Subduction zone—Dashed where approximately located. Sawteeth on upper plate

Fault—Dashed where approximately located. Arrows indicate direction of relative movement

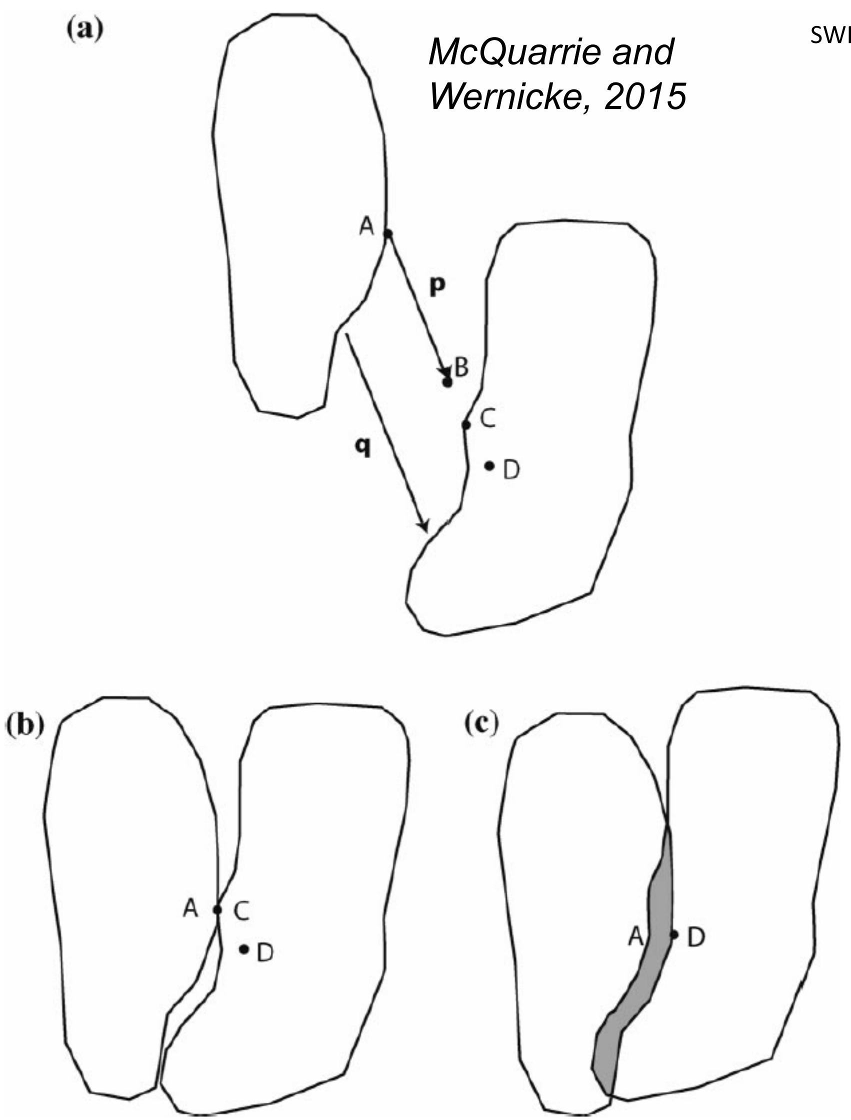
M **Mendocino triple junction**

R **Rivera triple junction**

https://www.usgs.gov/media/images/geologic-map-north-america



science for a changing world

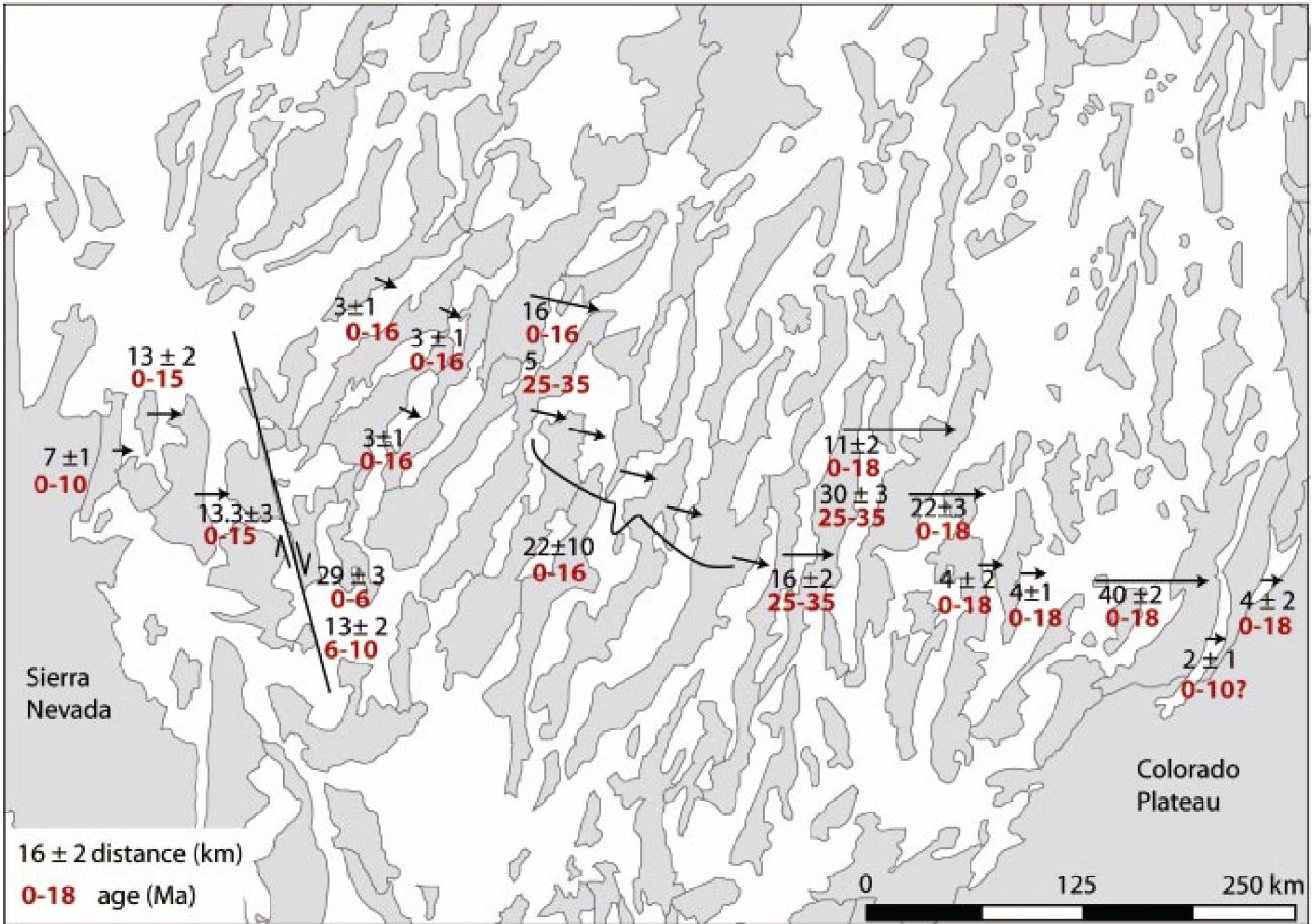


SWP1_	SWP1_ID	LEGEND	RANGES	RANGE_ID	DIRECTION	DISTANCE	ROTATION	TIME_MY	X_COORD_UT	Y_COORD_UT	X_COORD_LO	Y_COORD
2588	2587	Sf	Mojave M1	1	0.00	0.00	0.00	0	-1964204.63178	-237101.34245	-117.71142	34.
2588	2587	Sf	Mojave M1	1	-65.00	3.00	0.00	2	-1962936.77699	-239820.26581	-117.69092	34.
2588	2587	Sf	Mojave M1	1	-65.00	19.83	0.00	4	-1954556.25686	-257792.34923	-117.55567	34.
2588	2587	Sf	Mojave M1	1	-65.00	27.83	0.00	6	-1942794.79064	-283014.89494	-117.36670	34.
2588	2587	Sf	Mojave M1	1	-65.00	31.83	0.00	8	-1929342.85137	-311862.67180	-117.15178	34.
2588	2587	Sf	Mojave M1	1	-67.00	18.57	0.00	10	-1922086.97431	-328956.44693	-117.03258	34.0
2588	2587	Sf	Mojave M1	1	-60.00	10.55	0.00	12	-1916811.97431	-338093.01494	-116.95430	33.9
2588	2587	Sf	Mojave M1	1	-14.00	30.60	0.00	14	-1887120.92509	-345495.82495	-116.62278	33.9
2588	2587	Sf	Mojave M1	1	13.00	50.75	0.00	16	-1837671.64430	-334079.55894	-116.12705	34.
2588	2587	Sf	Mojave M1	1	24.00	42.51	0.00	18	-1798836.82690	-316789.18424	-115.75538	34.
2588	2587	Sf	Mojave M1	1	35.00	34.45	0.00	24	-1770617.03897	-297029.47601	-115.50056	34.0
2588	2587	Sf	Mojave M1	1	-111.59	0.00	0.00	30	-1770617.03897	-297029.47601	-115.50056	34.0
2588	2587	Sf	Mojave M1	1	-111.59	0.00	0.00	36	-1770617.03897	-297029.47601	-115.50056	34.0
2580	2579	Sf	Mojave M2	2	0.00	0.00	0.00	0	-1924595.87293	-231547.50851	-117.30358	34.
2580	2579	Sf	Mojave M2	2	-65.00	3.00	0.00	2	-1923328.01814	-234266.43187	-117.28315	34.
2580	2579	Sf	Mojave M2	2	-65.00	18.83	0.00	4	-1915370.11627	-251332.20750	-117.15521	34.
2580	2579	Sf	Mojave M2	2	-65.00	26.83	0.00	6	-1904031.26831	-275648.44543	-116.97369	34.
2580	2579	Sf	Mojave M2	2	-65.00	30.83	0.00	8	-1891001.94730	-303589.91450	-116.76623	34.
2580	2579	Sf	Mojave M2	2	-69.00	17.43	0.00	10	-1884755.59394	-319862.22134	-116.66018	34.
2580	2579	Sf	Mojave M2	2	-60.00	10.55	0.00	12	-1879480.59394	-328998.78935	-116.58209	34.
2580	2579	Sf	Mojave M2	2	-14.00	30.60	0.00	14	-1849789.54472	-336401.59935	-116.24991	34.
2580	2579	Sf	Mojave M2	2	13.00	50.75	0.00	16	-1800340.26393	-324985.33334	-115.75219	34.
2580	2579	Sf	Mojave M2	2	25.00	36.11	0.00	18	-1767613.48974	-309724.58791	-115.43913	34.
2580	2579	Sf	Mojave M2	2	35.00	34.45	0.00	24	-1739393.70181	-289964.87968	-115.18294	34.
2580	2579	Sf	Mojave M2	2	170.24	0.00	0.00	30	-1739393.70181	-289964.87968	-115.18294	34.
2580	2579	Sf	Mojave M2	2	170.24	0.00	0.00	36	-1739393.70181	-289964.87968	-115.18294	34.

Figure 1. Schematic diagram illustrating the method of using regional structural constraints to limit possible displacement paths in tectonic reconstructions. See text for discussion and explanation of letters.

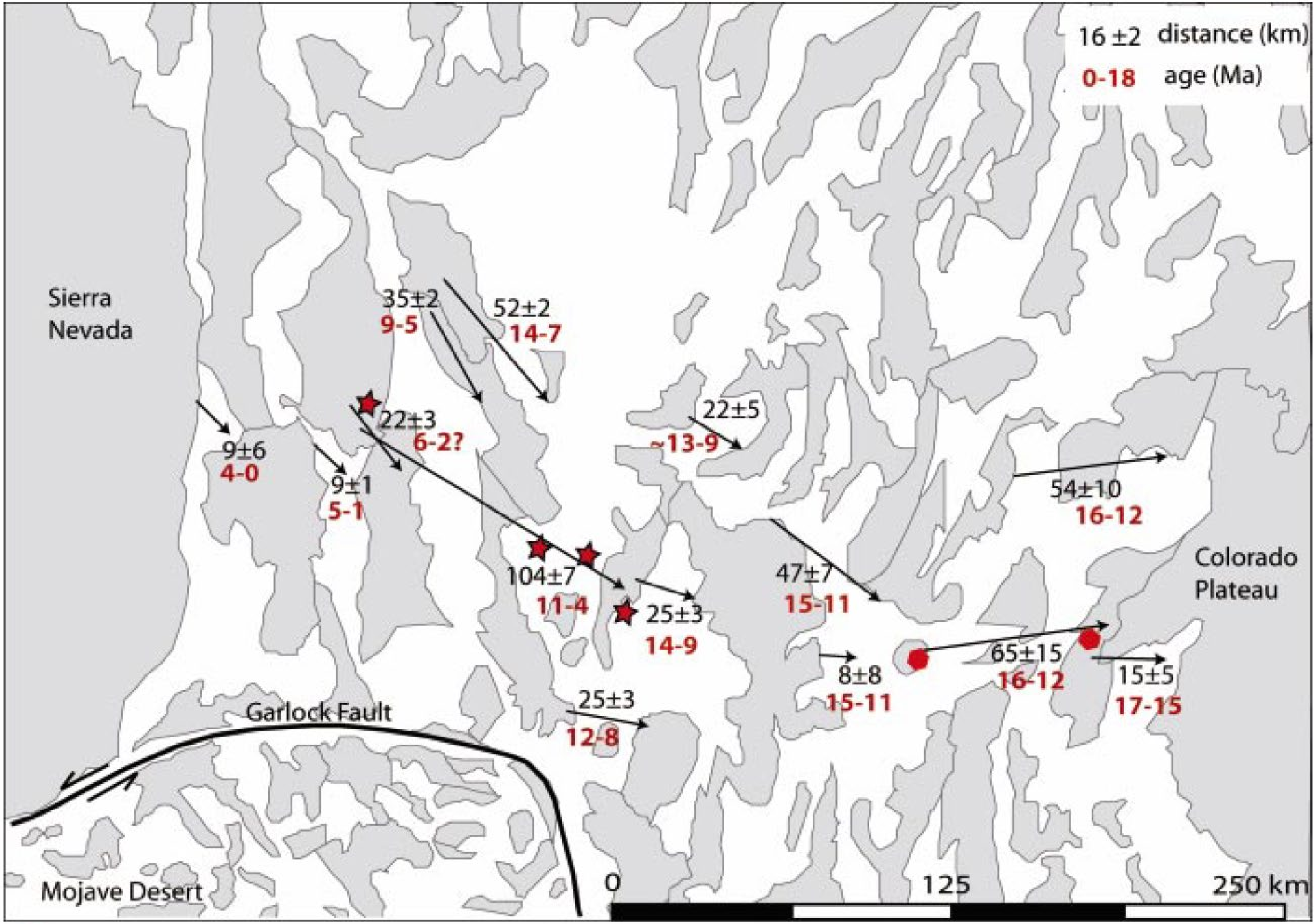
Movement table (supplemental documents)

[1]GSA Data Repository item 2005200, Appendix 1, Movement Table, paleogeographic maps, and ArcGIS files (shape files for each reconstructed time step), is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA



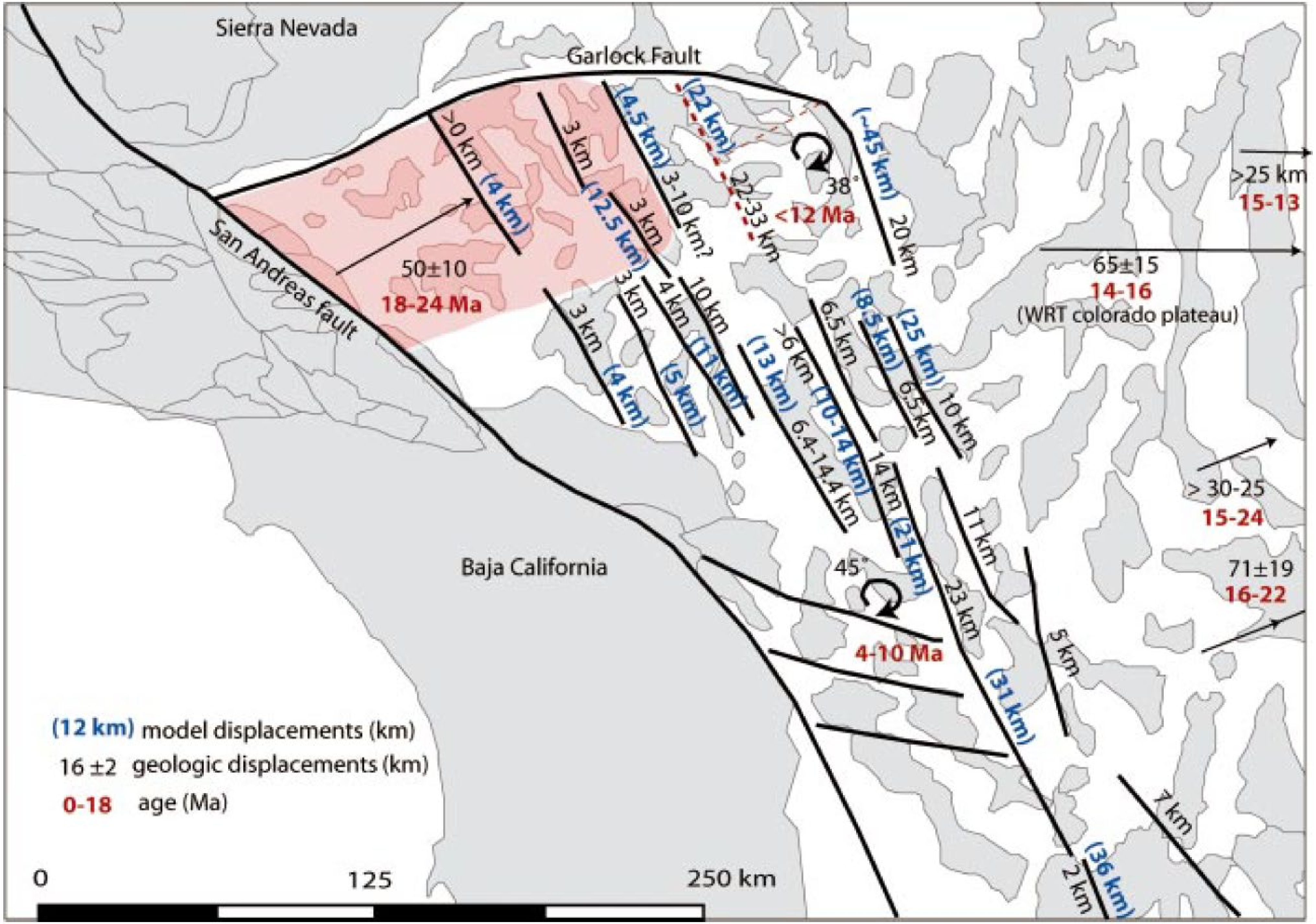
McQuarrie and Wernicke, 2015

McQuarrie and Wernicke, 2015

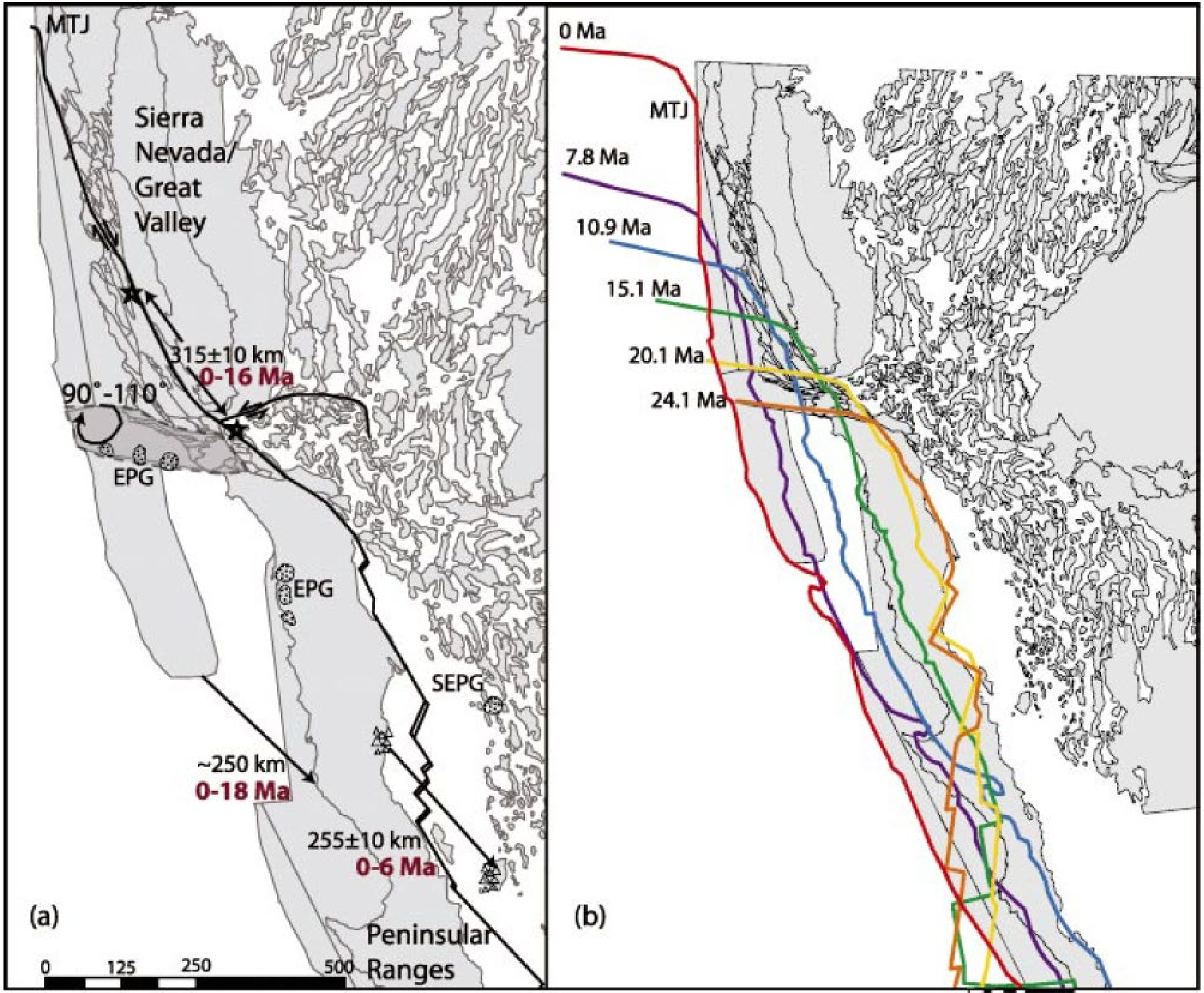


★ Outcrops of the mid-Miocene Eagle Mountain Formation

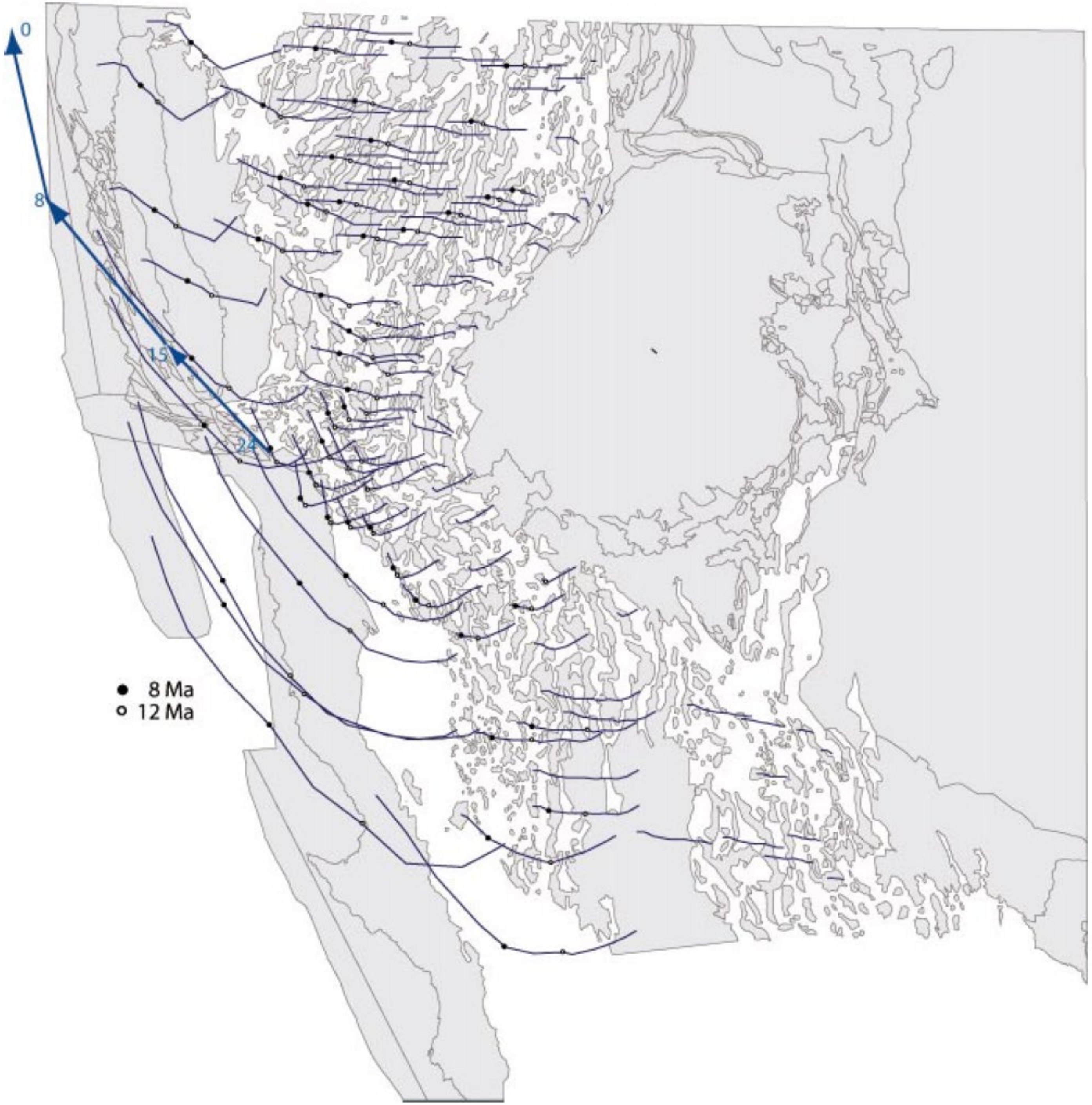
● Distinctive megabreccia clasts in Frenchman Mountain from Gold Butte



McQuarrie and Wernicke, 2015

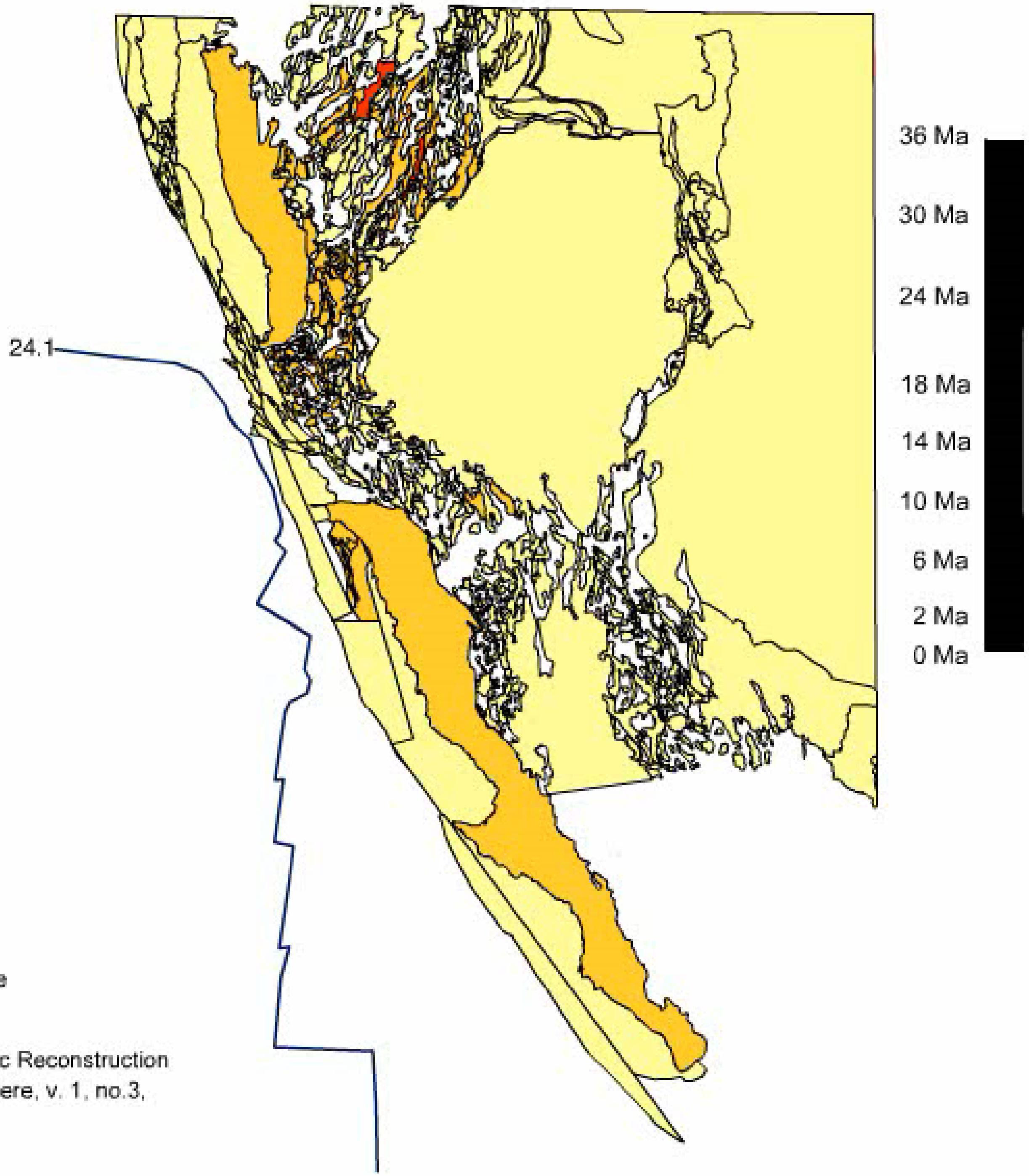


McQuarrie and Wernicke, 2015



McQuarrie and Wernicke, 2015

Fault and block-based reconstruction of the SW North American Margin



motion not constrained by data

motion constrained by fault data

color change indicates when faults are active

McQuarrie and Wernicke, 2005, An Animated Tectonic Reconstruction of Southwestern North America since 36 MA: Geosphere, v. 1, no.3, doi: 10.1130/GES00016.1

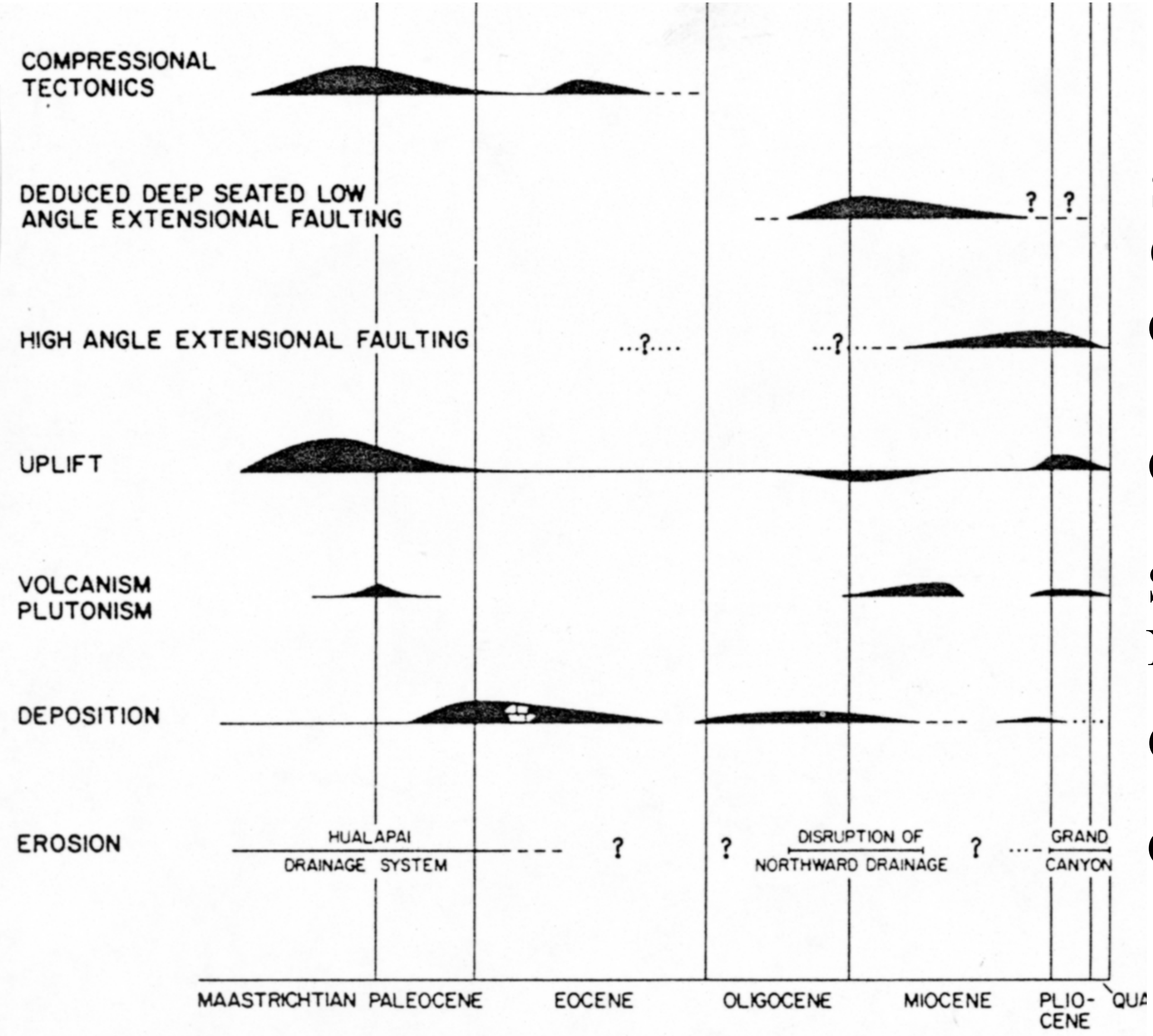


Figure 20. Temporal relationships between tectonics, sedimentation, and erosion in the Grand Canyon region, Arizona, during Laramide and post-Laramide time

Monoclines

South Mountains
Catalinas, etc.

Central AZ basins

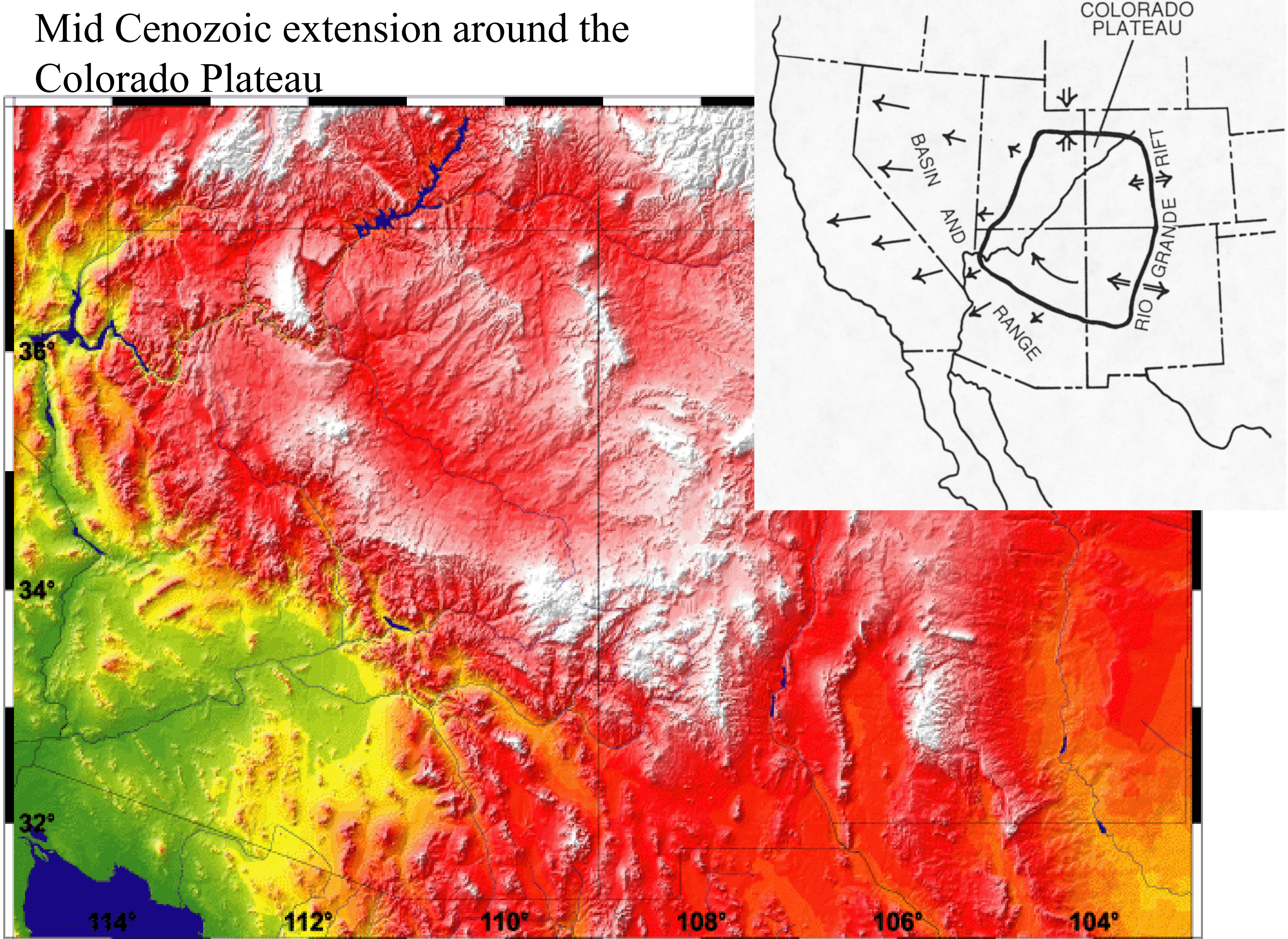
Colorado Plateau

Superstitions
N. AZ Volcanics

Central AZ basins

Colorado Plateau

Mid Cenozoic extension around the Colorado Plateau



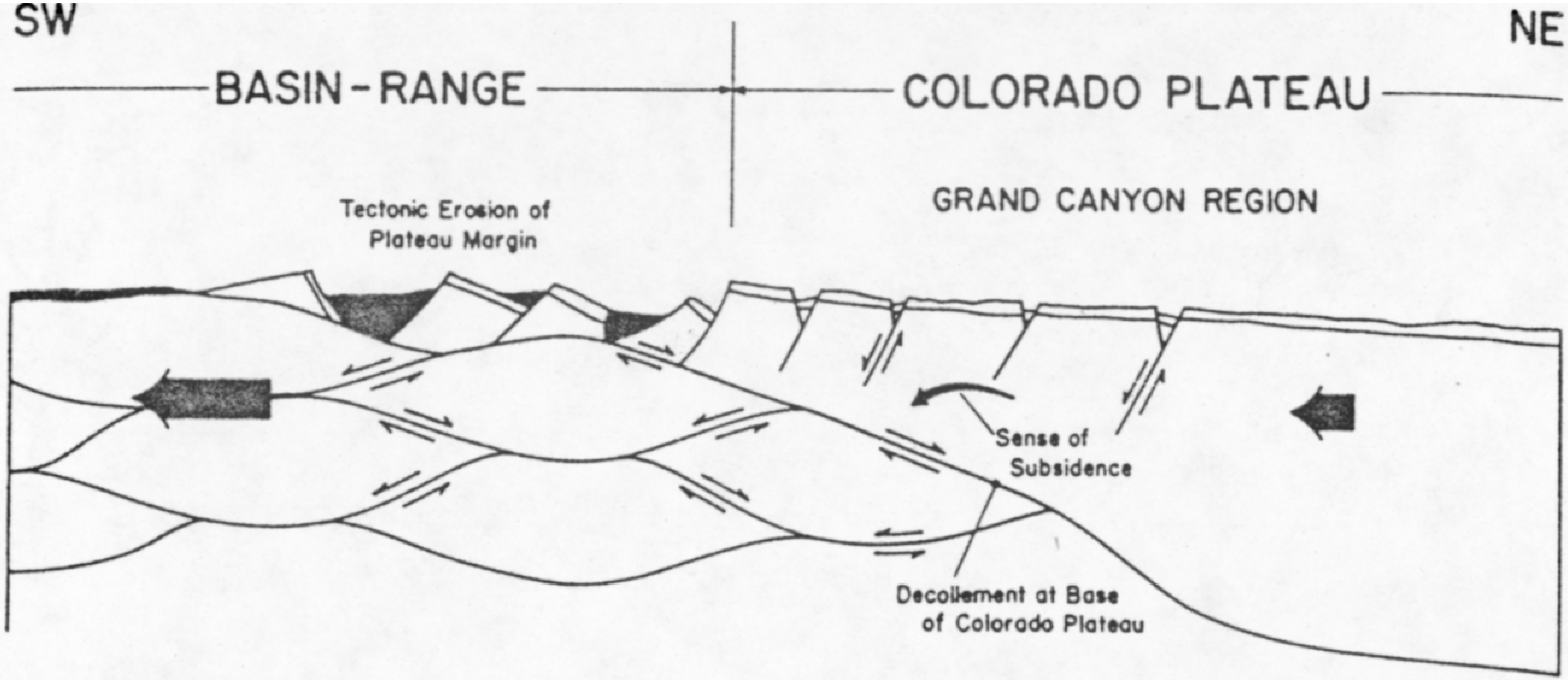
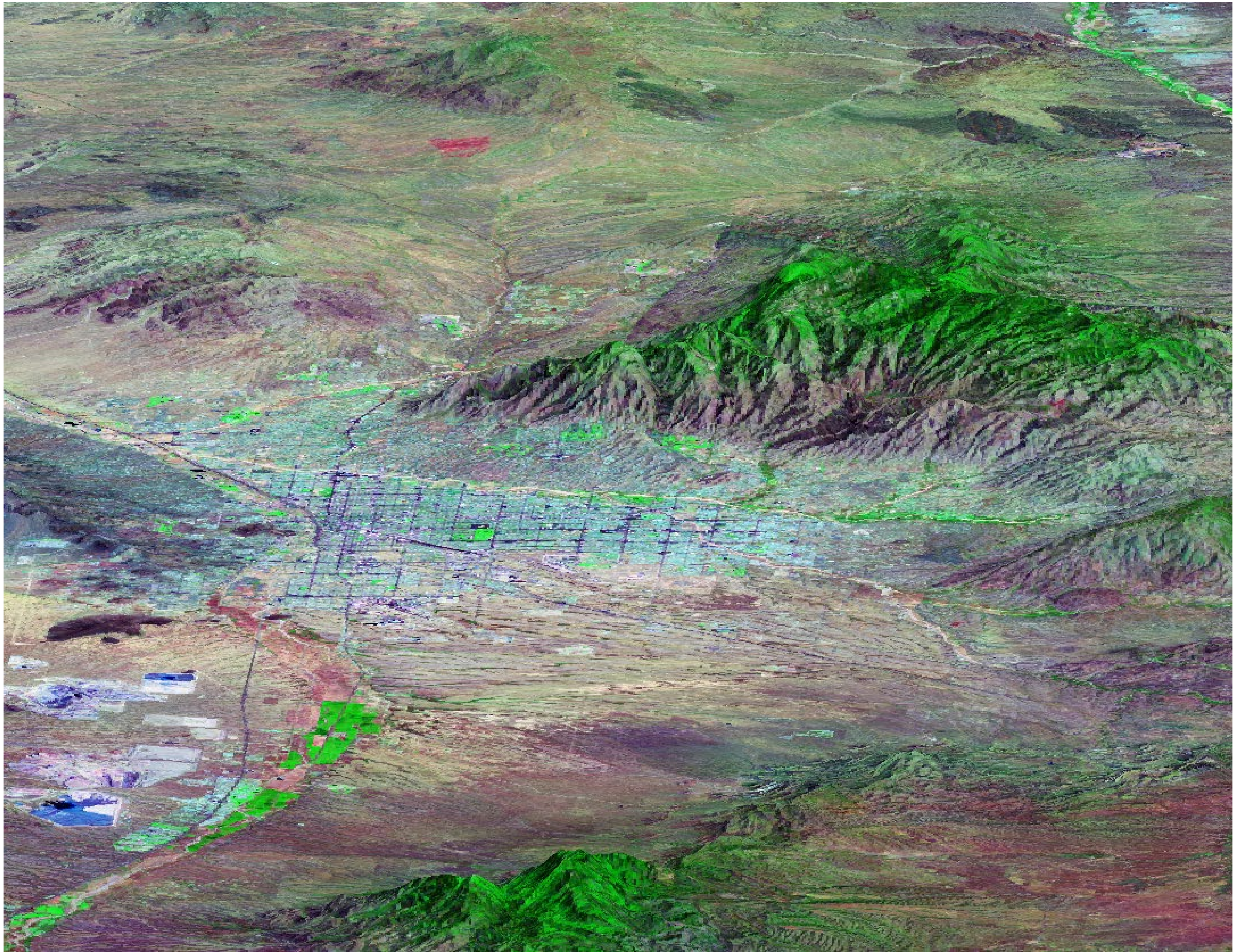
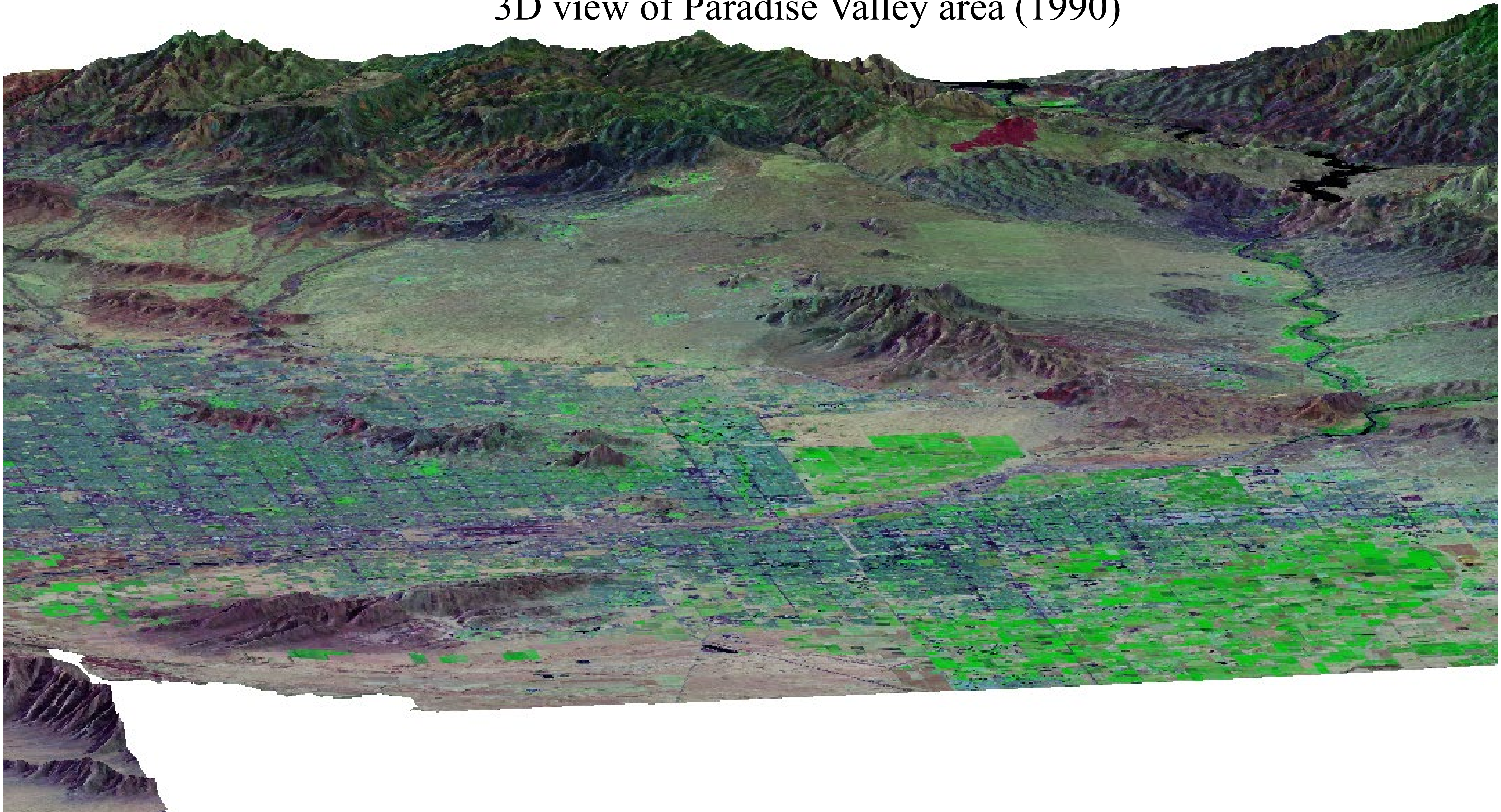


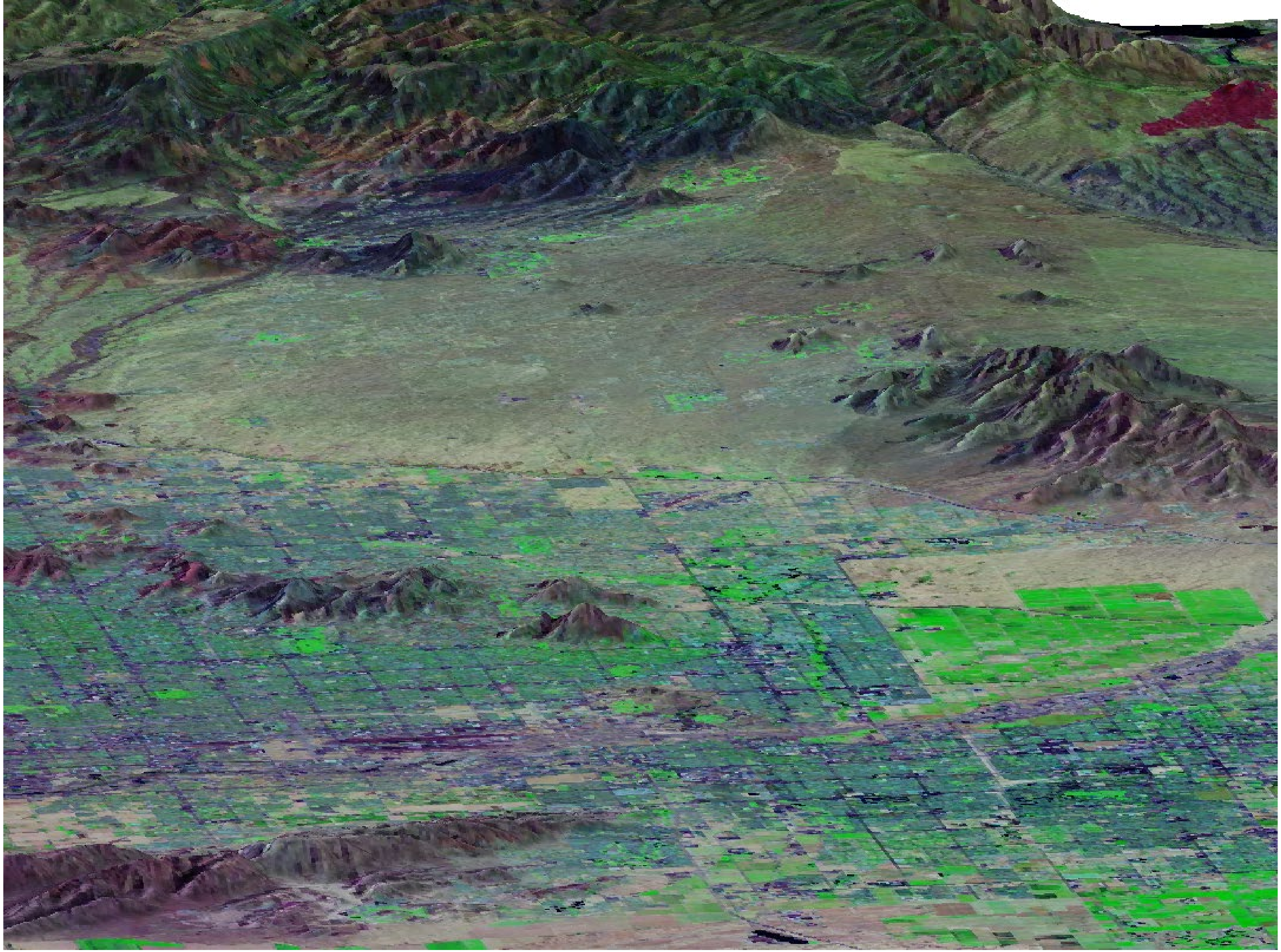
Figure 14. Cartoon illustrating tectonic erosion and subsidence along the southwestern edge of the Colorado Plateau over extending shear-bounded lenses in Late Oligocene-Early Miocene time. Lense concept from Hamilton (1982). Heavy arrows show absolute motions within the Basin-Range and Colorado Plateau provinces. Fine arrows show relative motions between shear surfaces. Notice that the relative motion between the lenses causes the crust to both thin and lengthen. Vertical scale greatly exaggerated, particularly at top

3D view from south of Tucson (1990)



3D view of Paradise Valley area (1990)





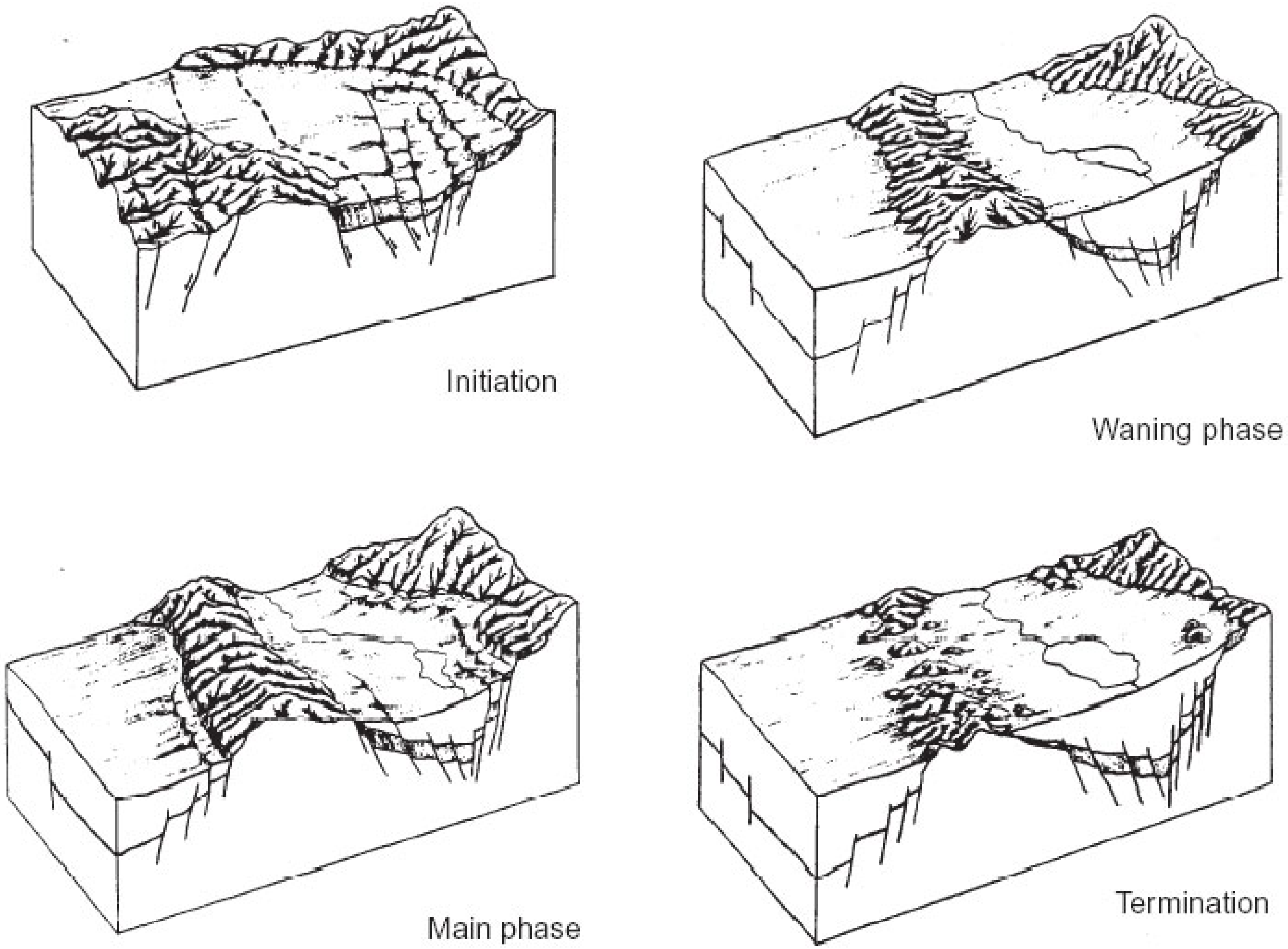
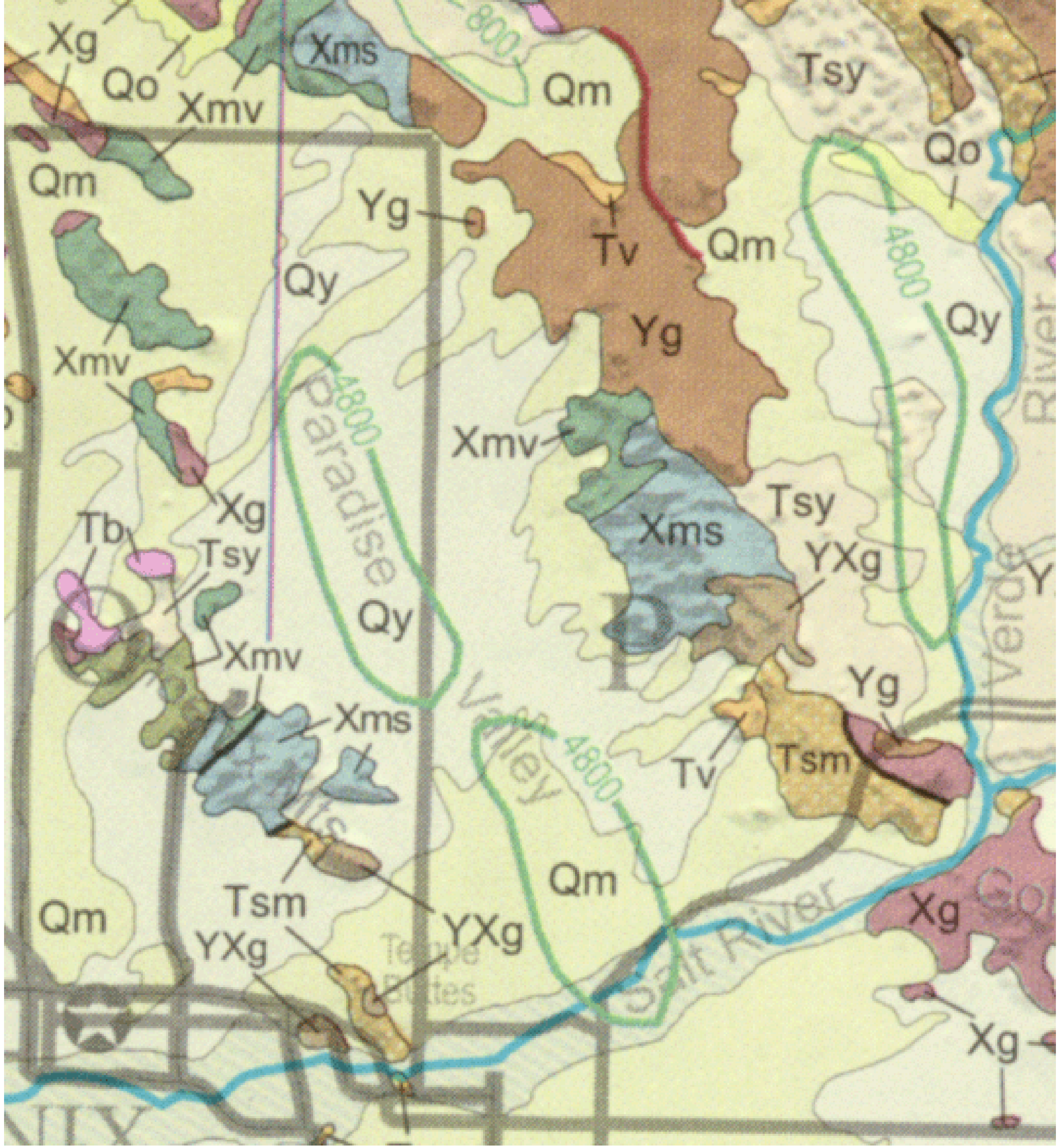
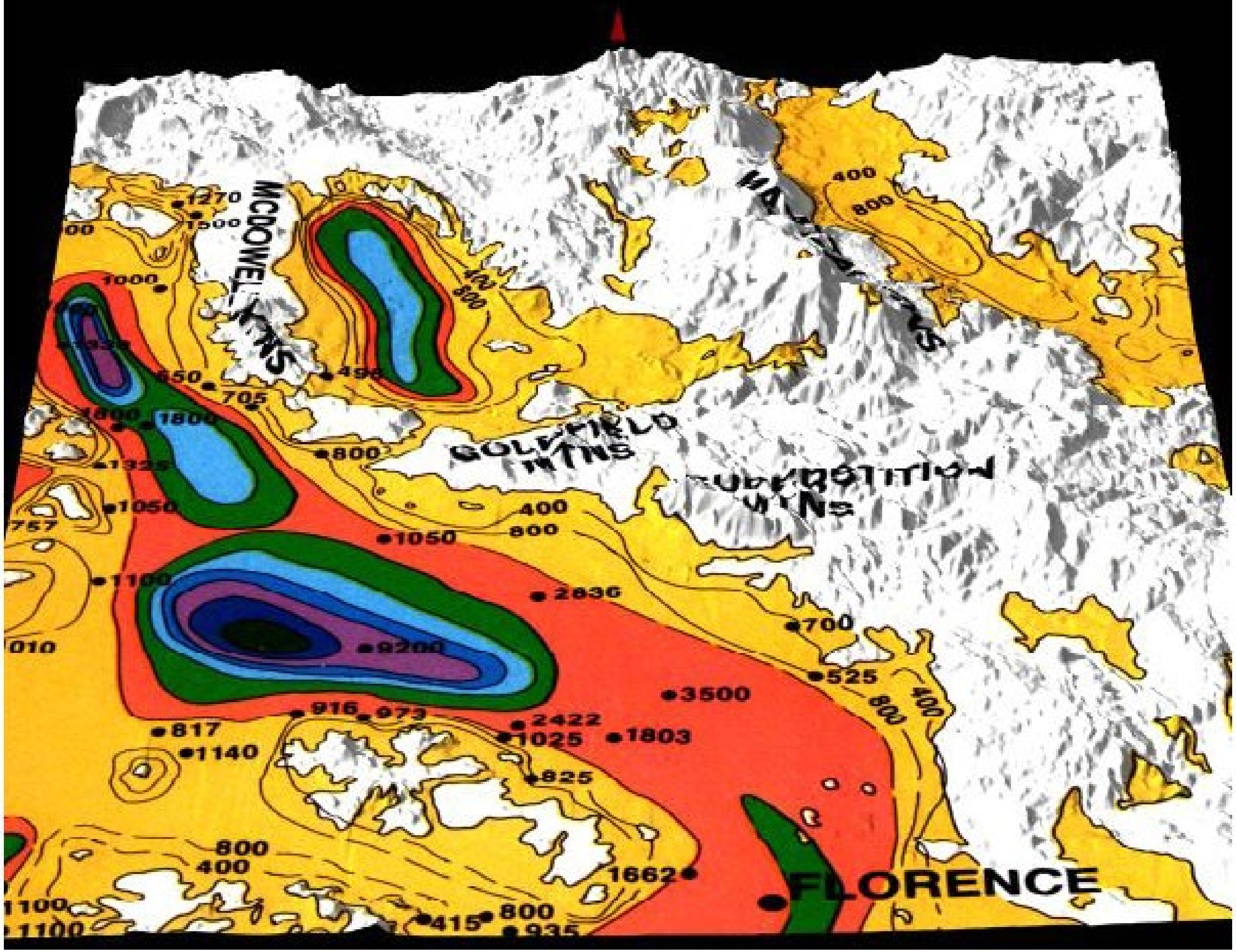


Figure 4: An idealized sequence of landforms developed during evolutionary stages of the Basin-Range disturbance in Arizona (from Menges and Pearthree 1989). Many of the ranges in the area developed as a fault bounded range during the extension of the Basin and Range disturbance and owe their current form to the culmination of such a sequence of events. The throughgoing drainage depicted in the termination phase would be the Salt River and other large rivers of the greater Phoenix area.

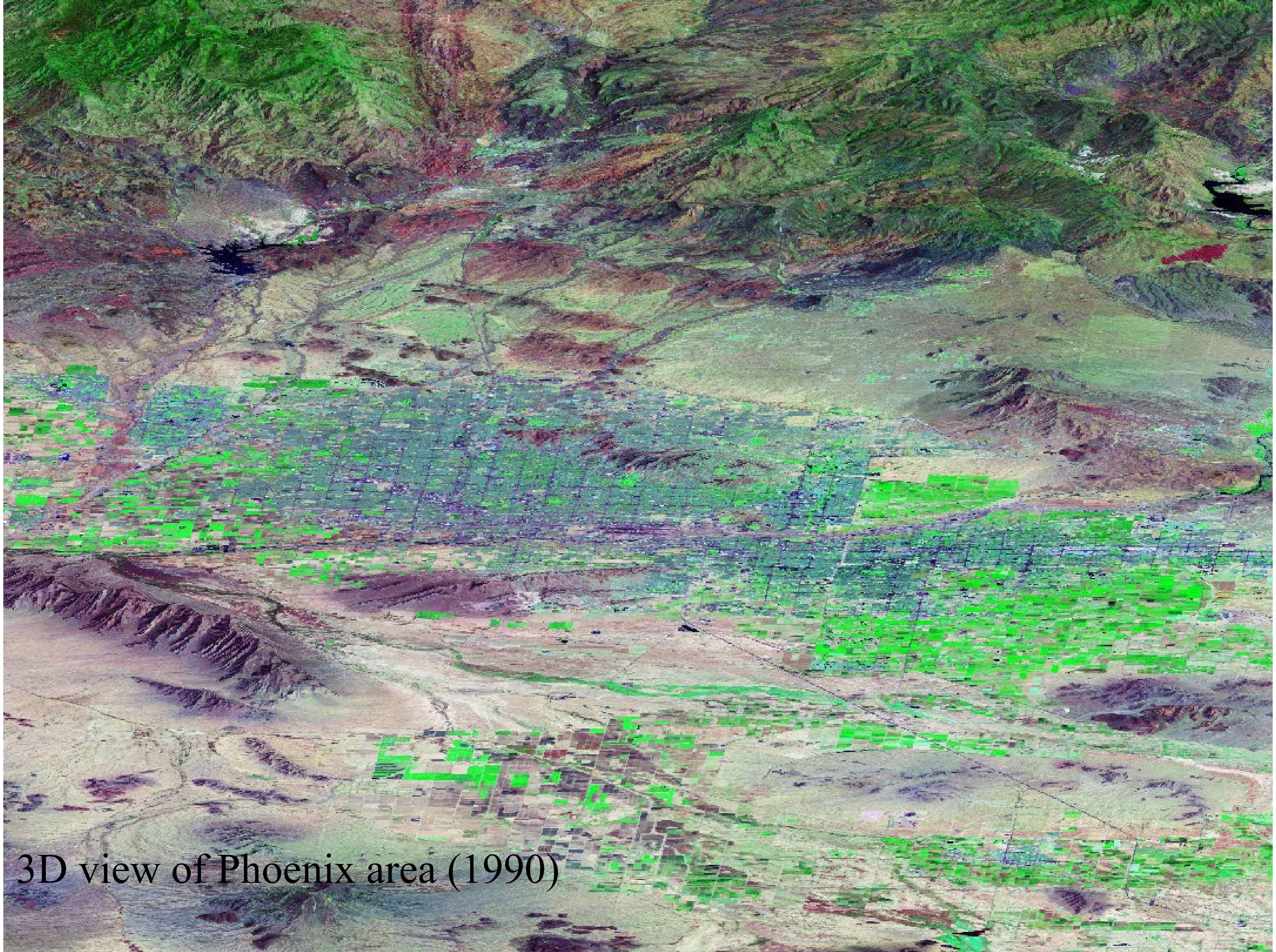


Geology and depth to bedrock (in feet) from Richards, et al, State of Arizona Geologic map, 2000

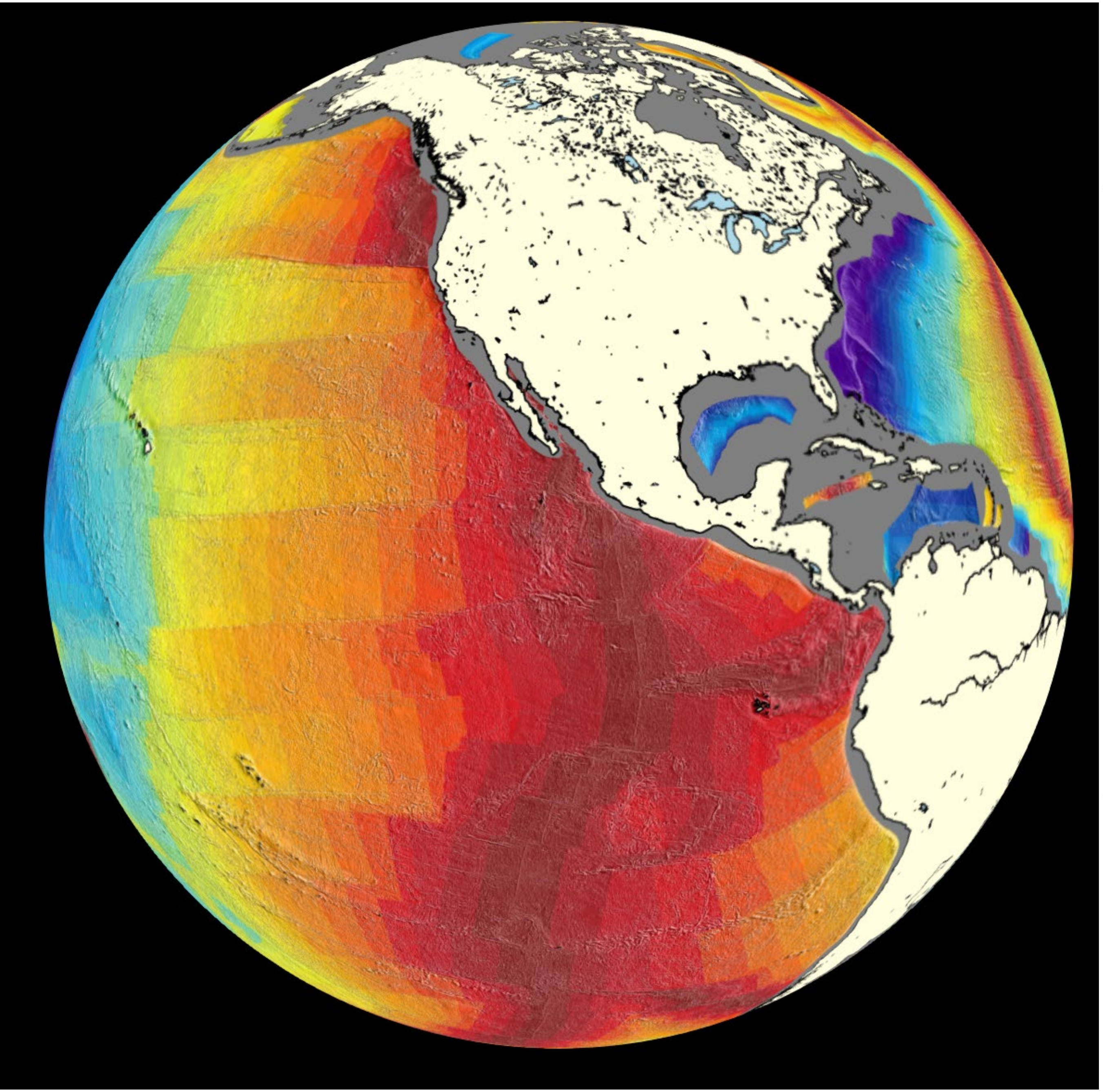


Depth to Bedrock

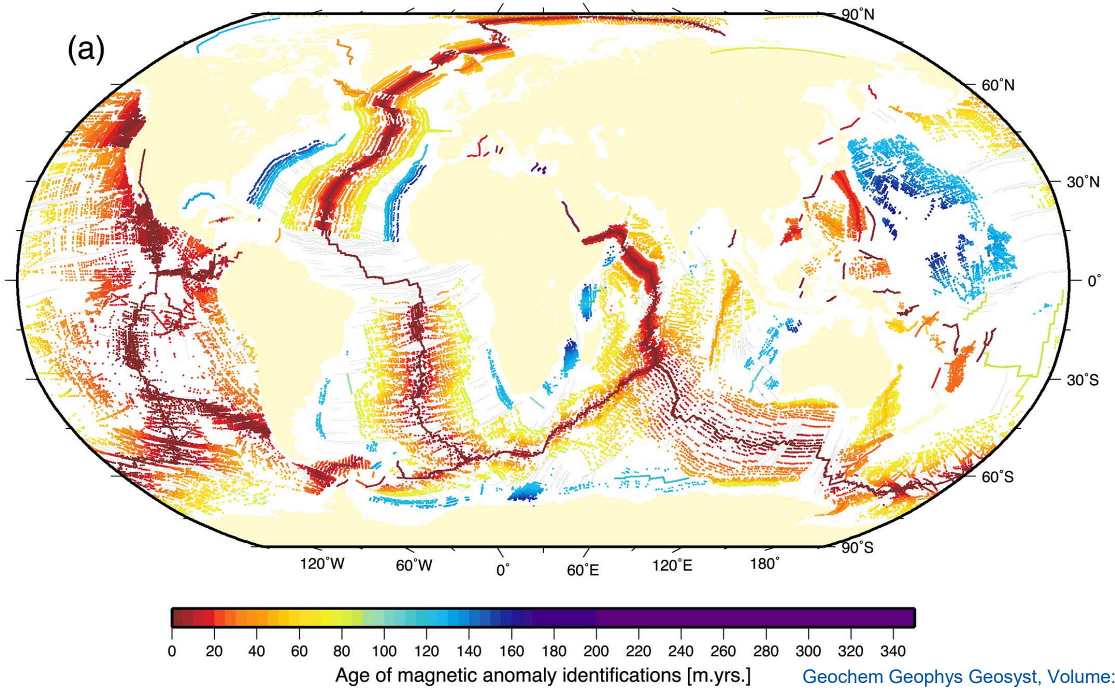
http://geology.asu.edu/%7Esreynolds/azgeophys/azdepth3d_map.htm



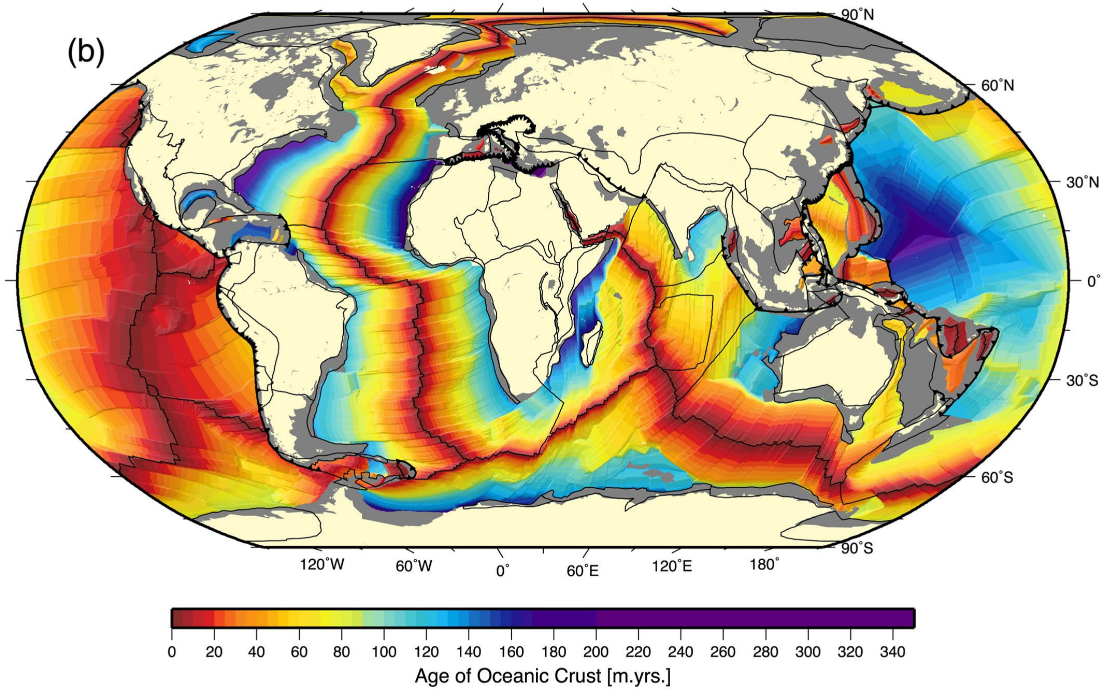
3D view of Phoenix area (1990)



http://portal.gplates.org/cesium/?view=AgeGridP



Geochem Geophys Geosyst, Volume: 21, Issue: 10, First published: 17 September 2020, DOI: (10.1029/2020GC009214)



Pacific–North America Plate Tectonics of the Neogene Southwestern United States: An Update

Article in International Geology Review · July 2010
DOI: 10.1080/00206819809465216

2 authors:

Tanya Atwater
University of California, Santa Barbara

Joann Miriam Stock
California Institute of Technology

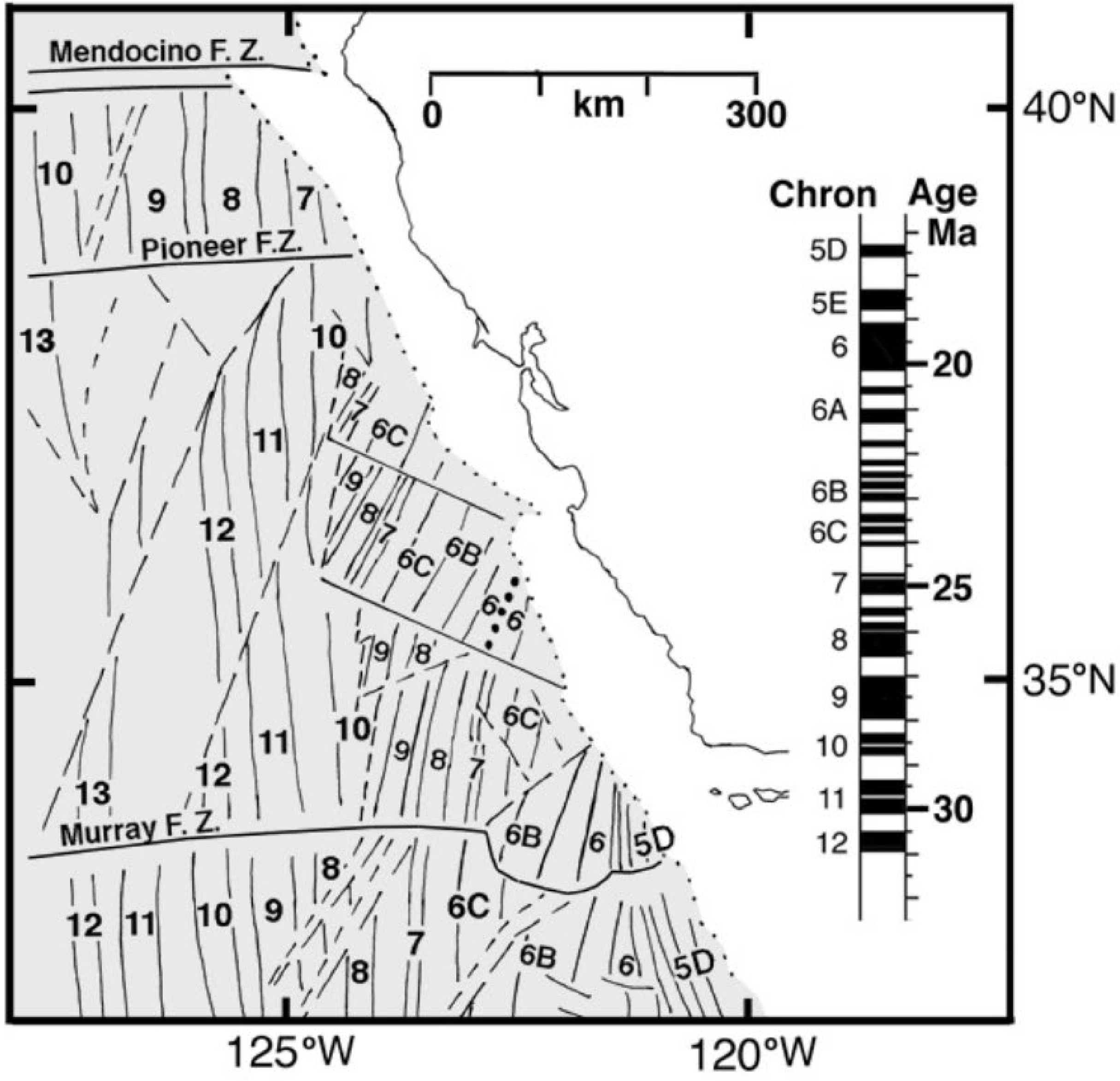
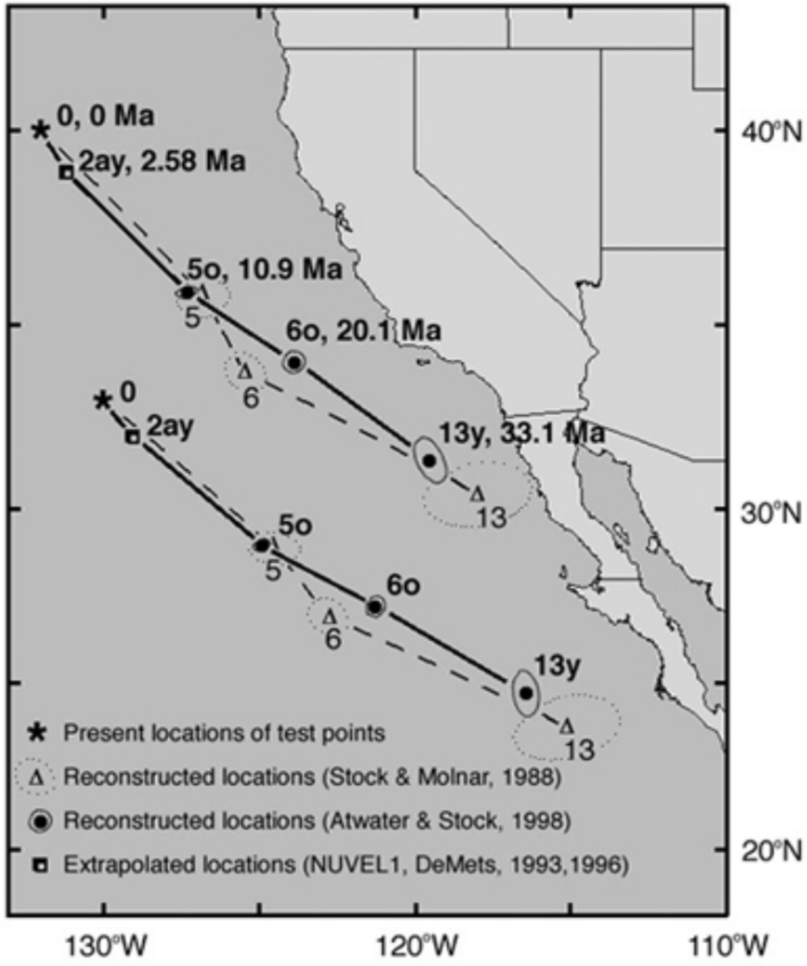
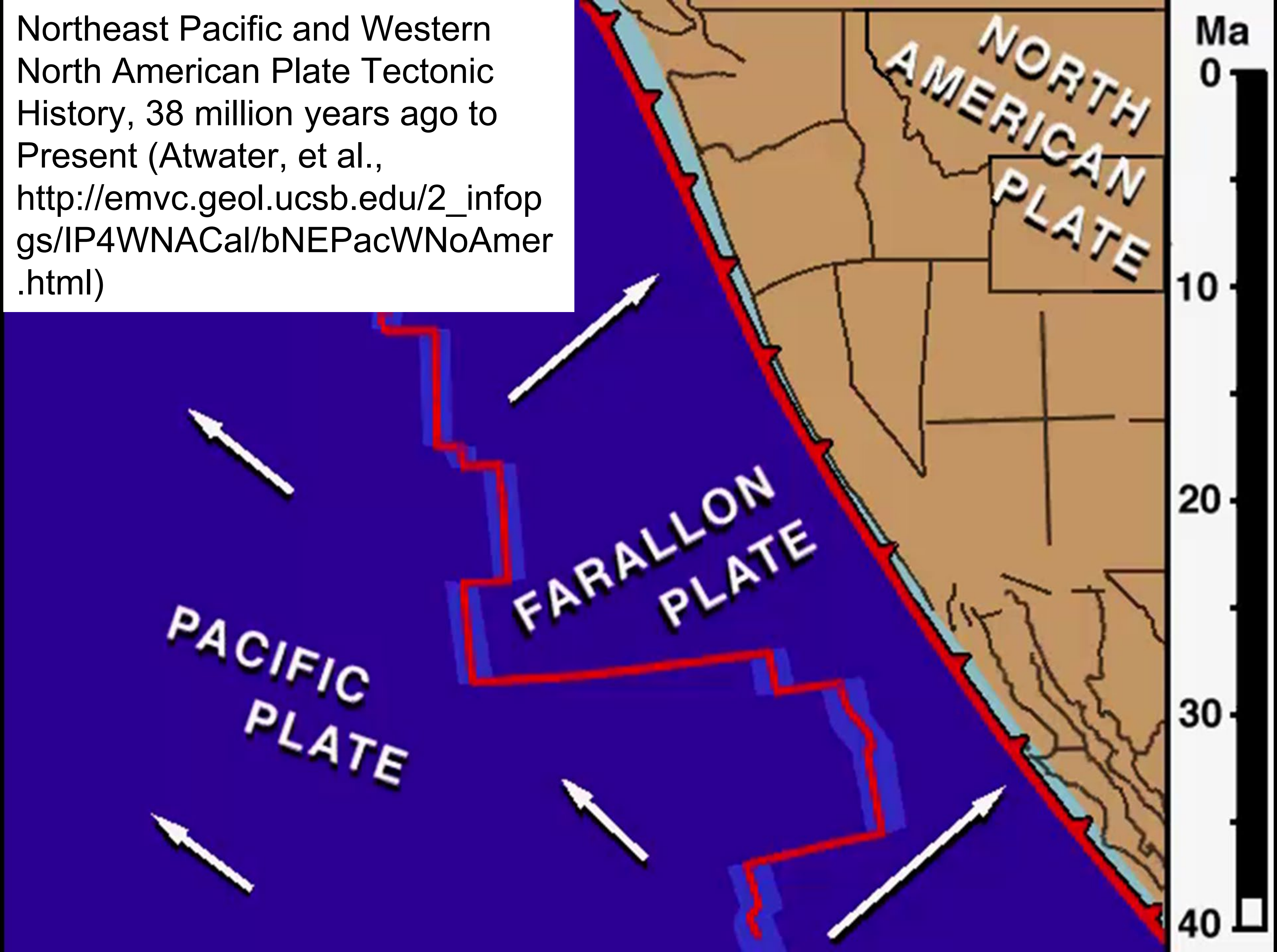


Figure 8. Present-day seafloor isochron patterns and fracture zones mapped in the Pacific seafloor off central California, after Severinghaus and Atwater (1990). Heavy dotted line marks the location of the stalled Pacific-Monterey spreading center, after Lonsdale (1991). Labels are magnetic reversal chron numbers. Magnetic reversal time scale shows ages of the relevant chrons according to Cande and Kent (1995).

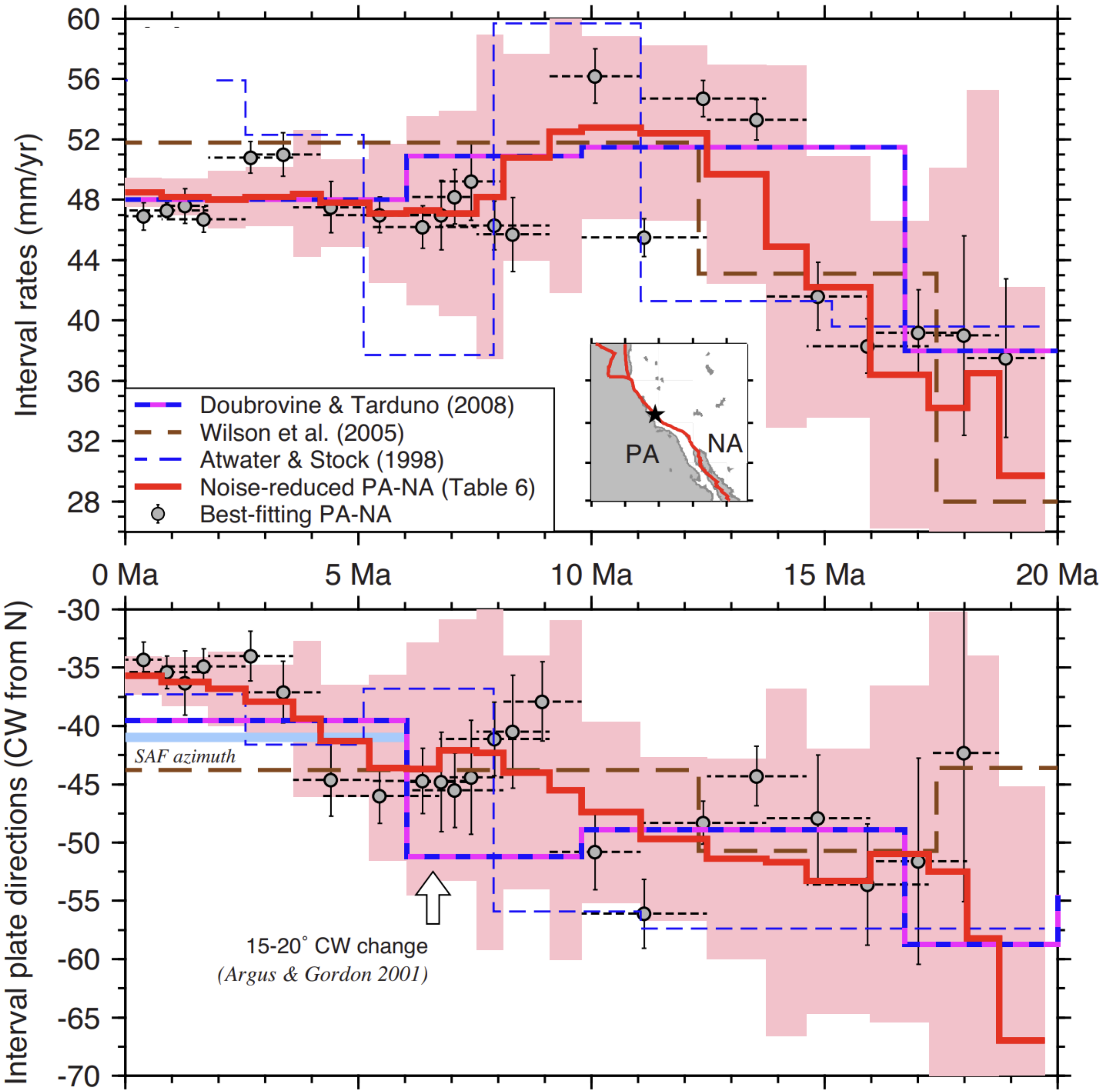


Northeast Pacific and Western North American Plate Tectonic History, 38 million years ago to Present (Atwater, et al., http://emvc.geol.ucsb.edu/2_infopgs/IP4WNACal/bNEPacWNoAmer.html)

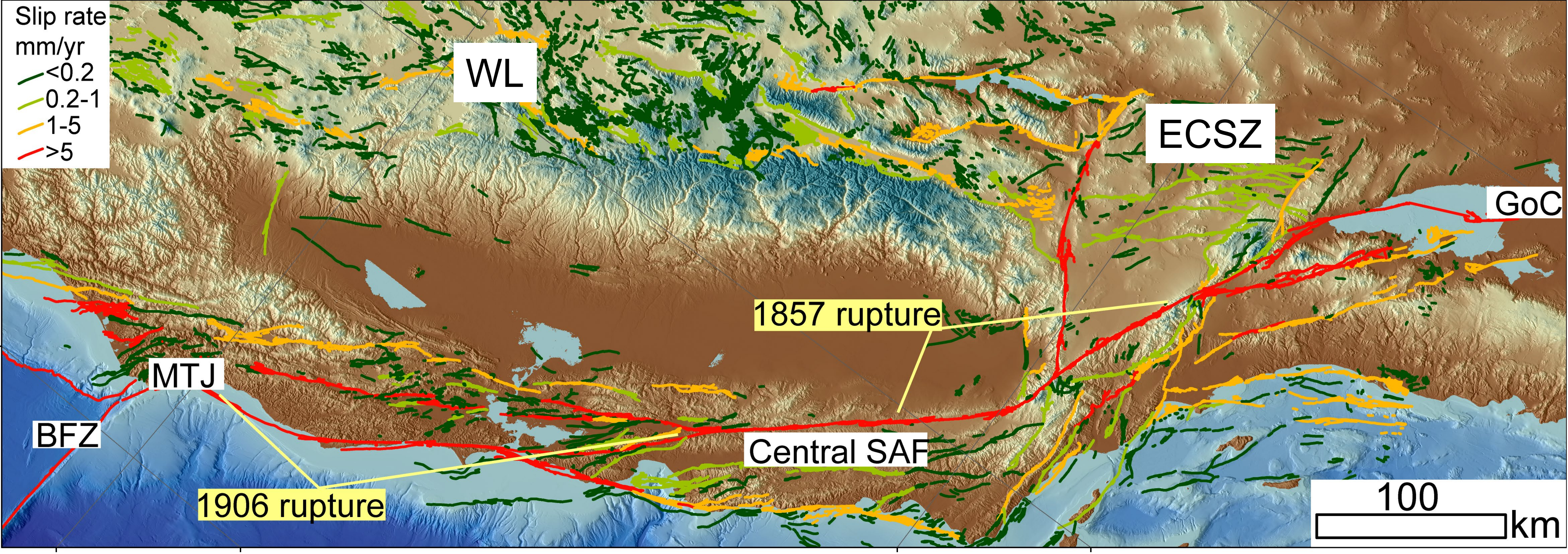


High-resolution reconstructions of Pacific–North America plate motion: 20 Ma to present

- 70% increase in relative velocity: 30 mm/yr at 19.7–18.7 Ma to 52 mm/yr at 12 Ma
- Relative plate motion rates since 8 Ma within 2% of average at 47.8±0.7 mm/yr
- 24° clockwise rotation with 5-7° since 5.2Ma.
- Oblique convergence beginning at 5.2 Ma induces transpression consistent with onset of folding and reverse faulting in Central CA



DeMets and Merkouriev, GJI, 2016



First order segmentation of the plate boundary system (Allen, 1968):

- ~300 km long 1906 and 1857 earthquake along SAF anchored by bends
- Abundant microseismicity and creep in SE, central, and NW
- Breath of deformation includes Eastern California shear zone and Walker Lane, reverse faults of the Coast Ranges and Transverse Ranges, and distributed shear across the Borderland, San Francisco Bay region and northern Coast Ranges

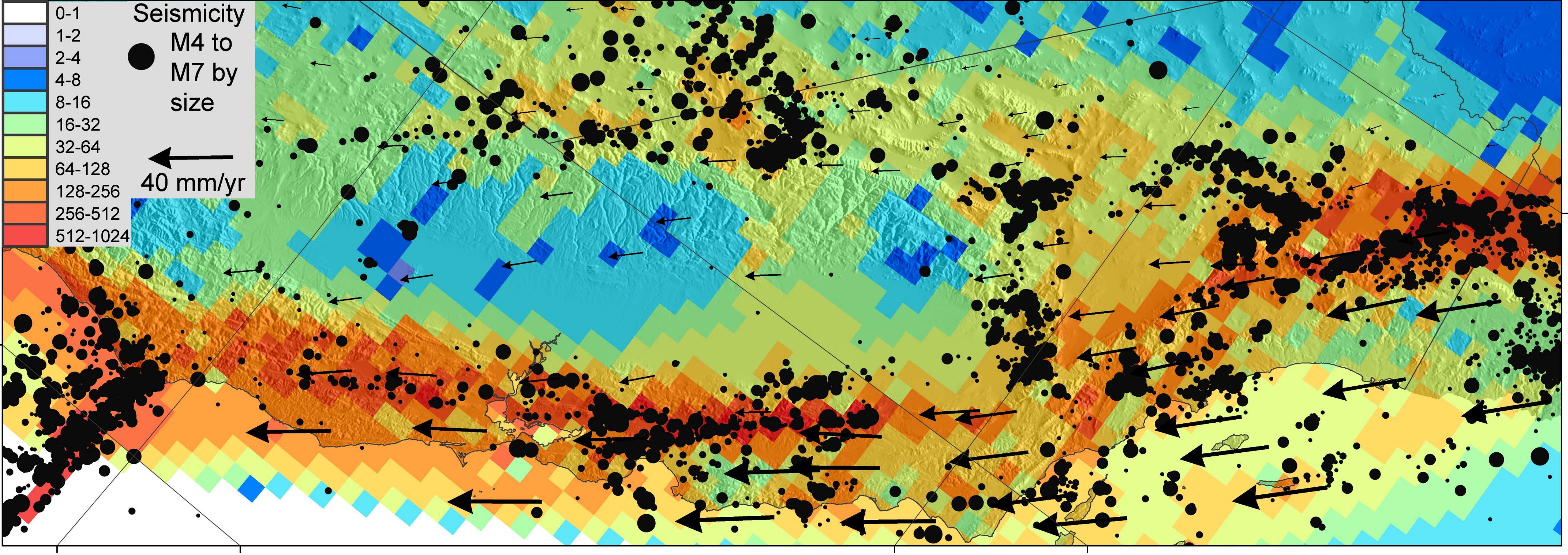
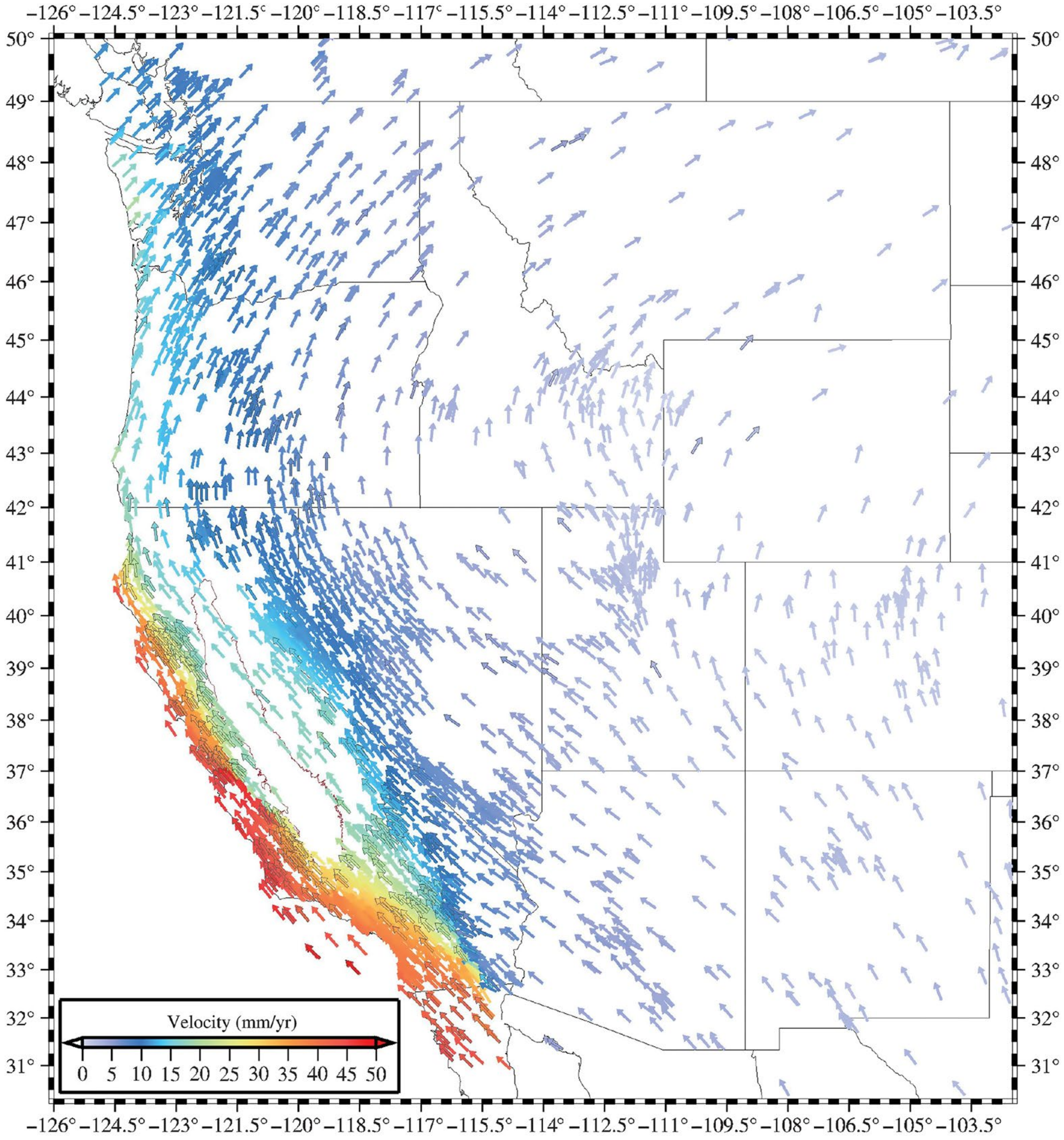


Plate boundary shearing and seismicity (Kreemer, et al.)

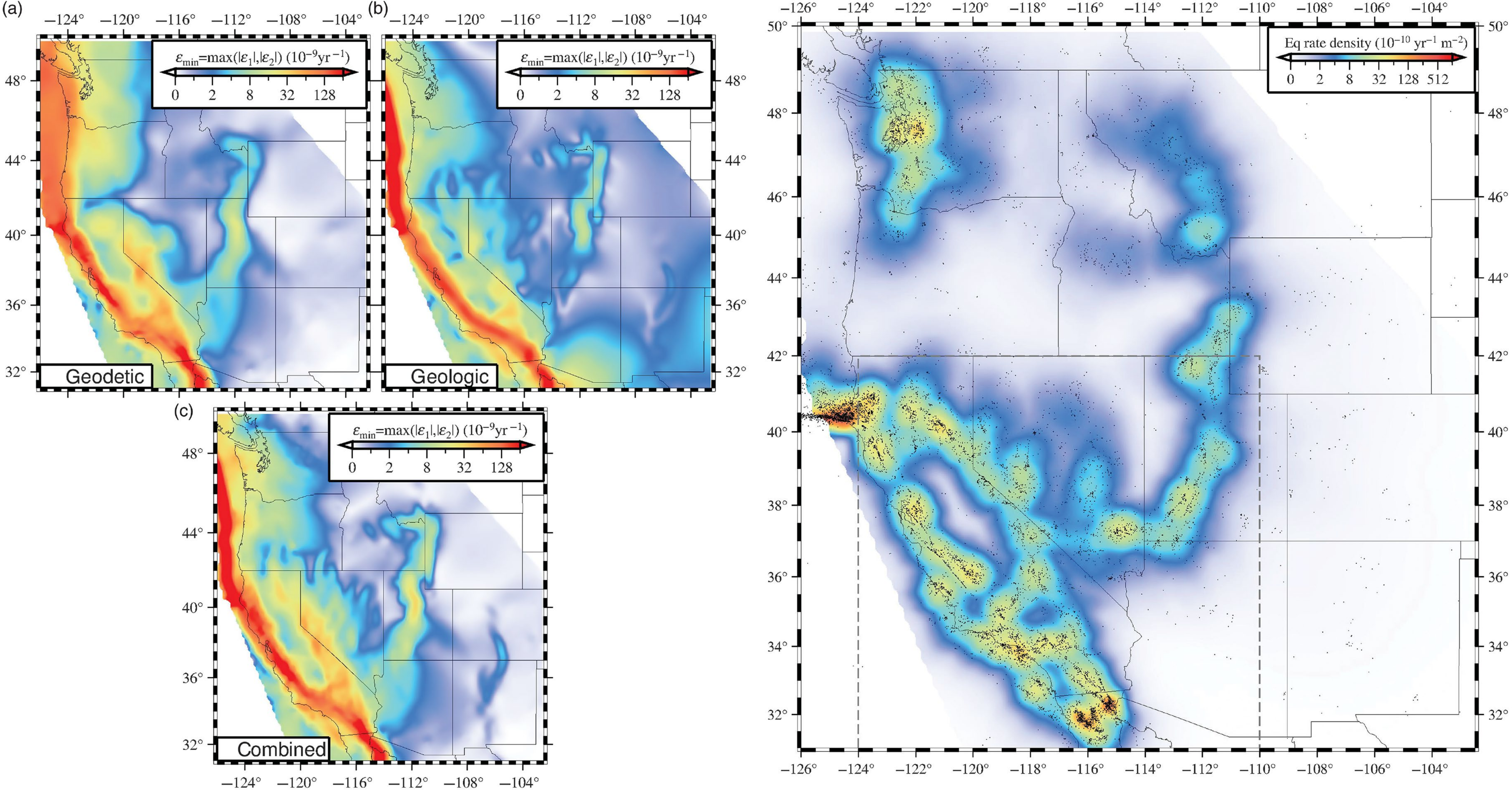
- Marked changes in the degree of strain localization, fault continuity, heat flow, stress state, and the mode of strain release
- Anthropogenically driven deformation and seismicity

Growing access to earth observation data and refined networks and processing to enhance understanding of the active system, including earthquake early warning

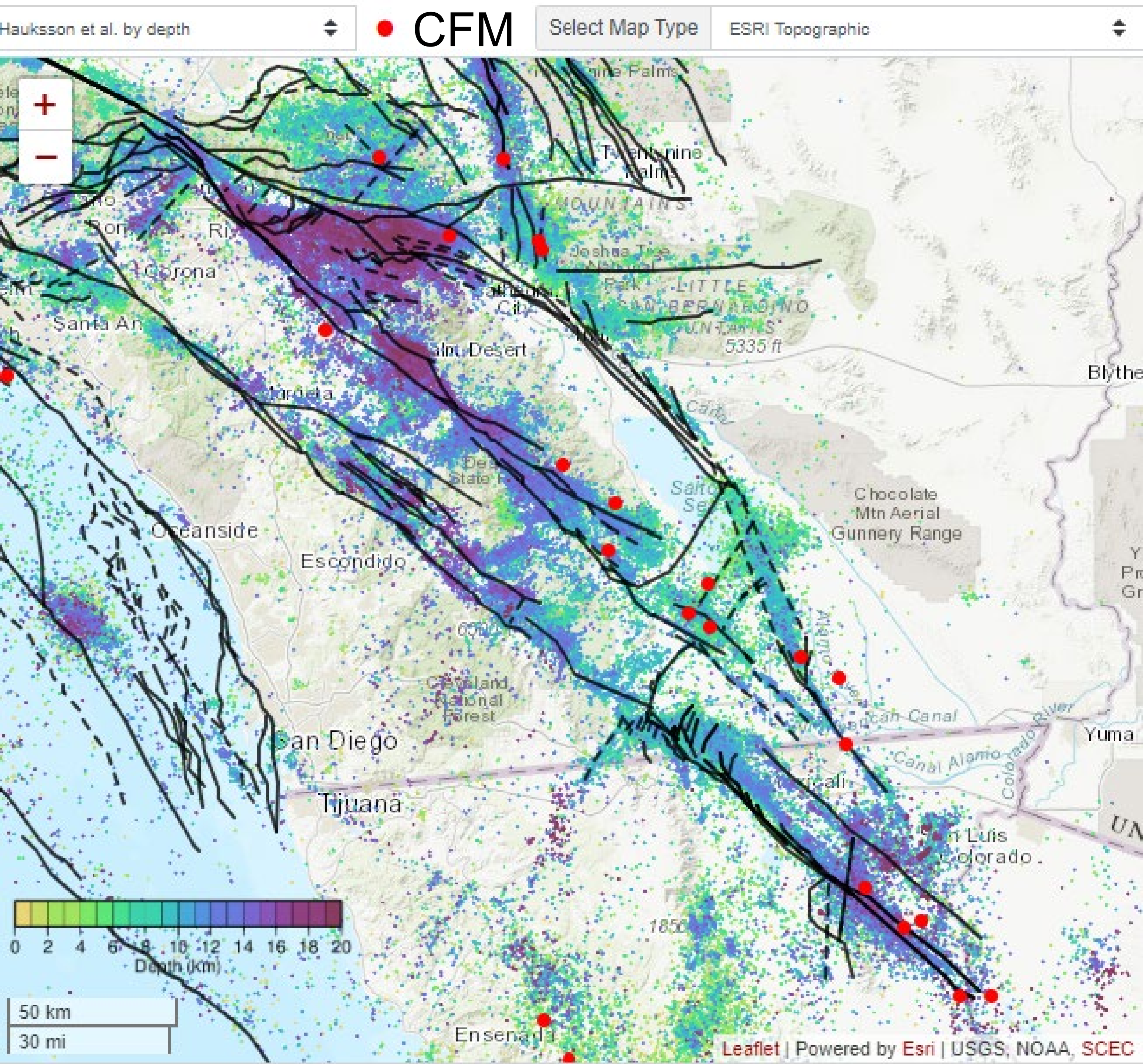


Crustal Strain Rates in the Western United States and Their Relationship with Earthquake Rates
Corné Kreemer; Zachary M. Young
Seismological Research Letters (2022)
https://doi.org/10.1785/0220220153

Coherent decadal-scale and interseismic velocity model (largely from GNSS)



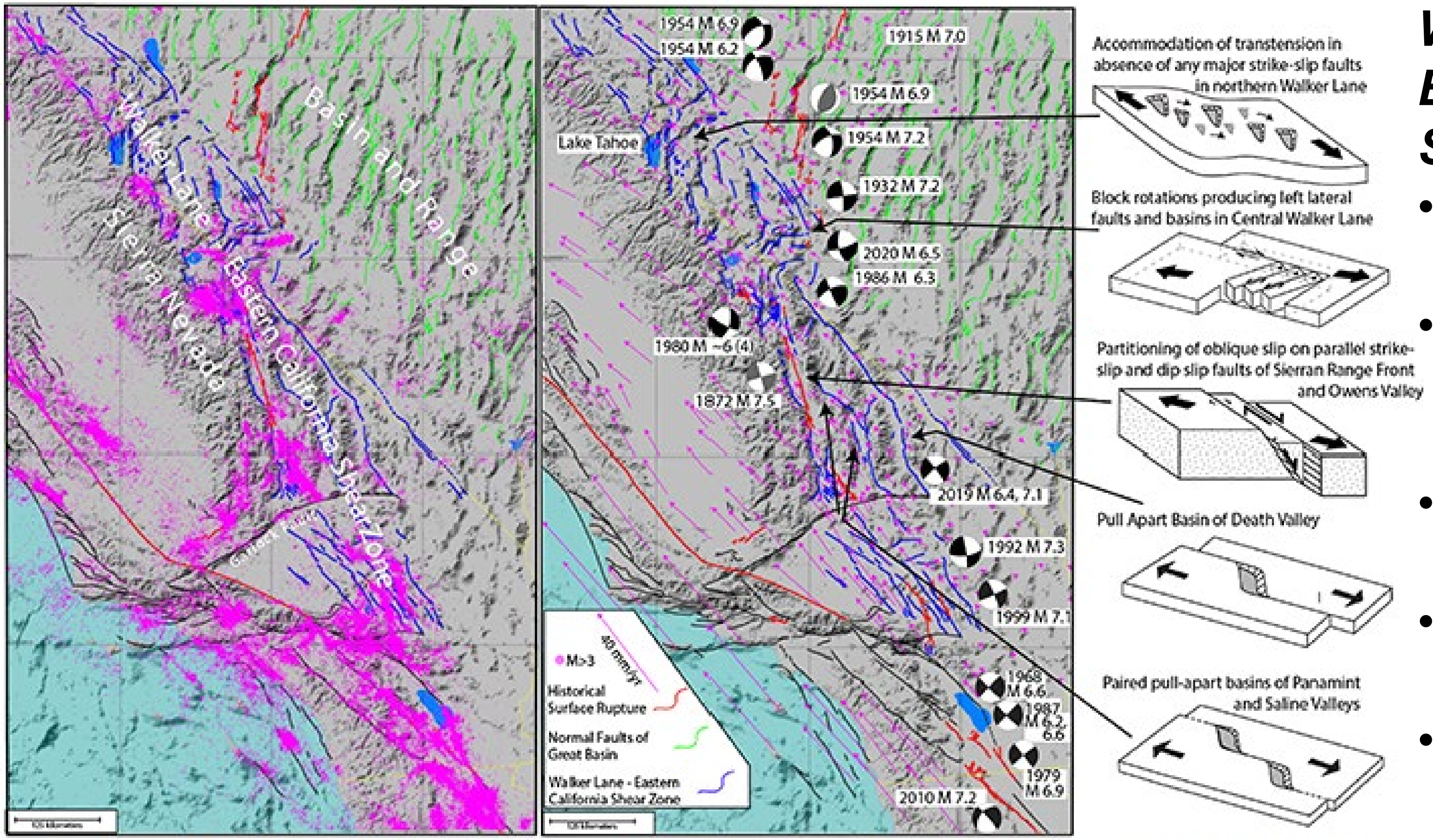
Kreemer and Young, 2022



Northern Gulf of California and Salton Trough rift

- Major earthquakes and abundant <u>microseismicity and fault creep</u>
- Modulation of crustal stresses from <u>water level variation</u> in Lake Cahuilla/Salton Sea and from anthropogenic manipulations associated with <u>geothermal energy production</u>
- Normal faulting, rapid subsidence, high heat flow, and voluminous sediment infill by the Colorado River delta characterizes <u>new crust formation</u> within the axial rift zone.
- Stress state transitions from

c.f. Salton Trough Collaboratory, Rockwell

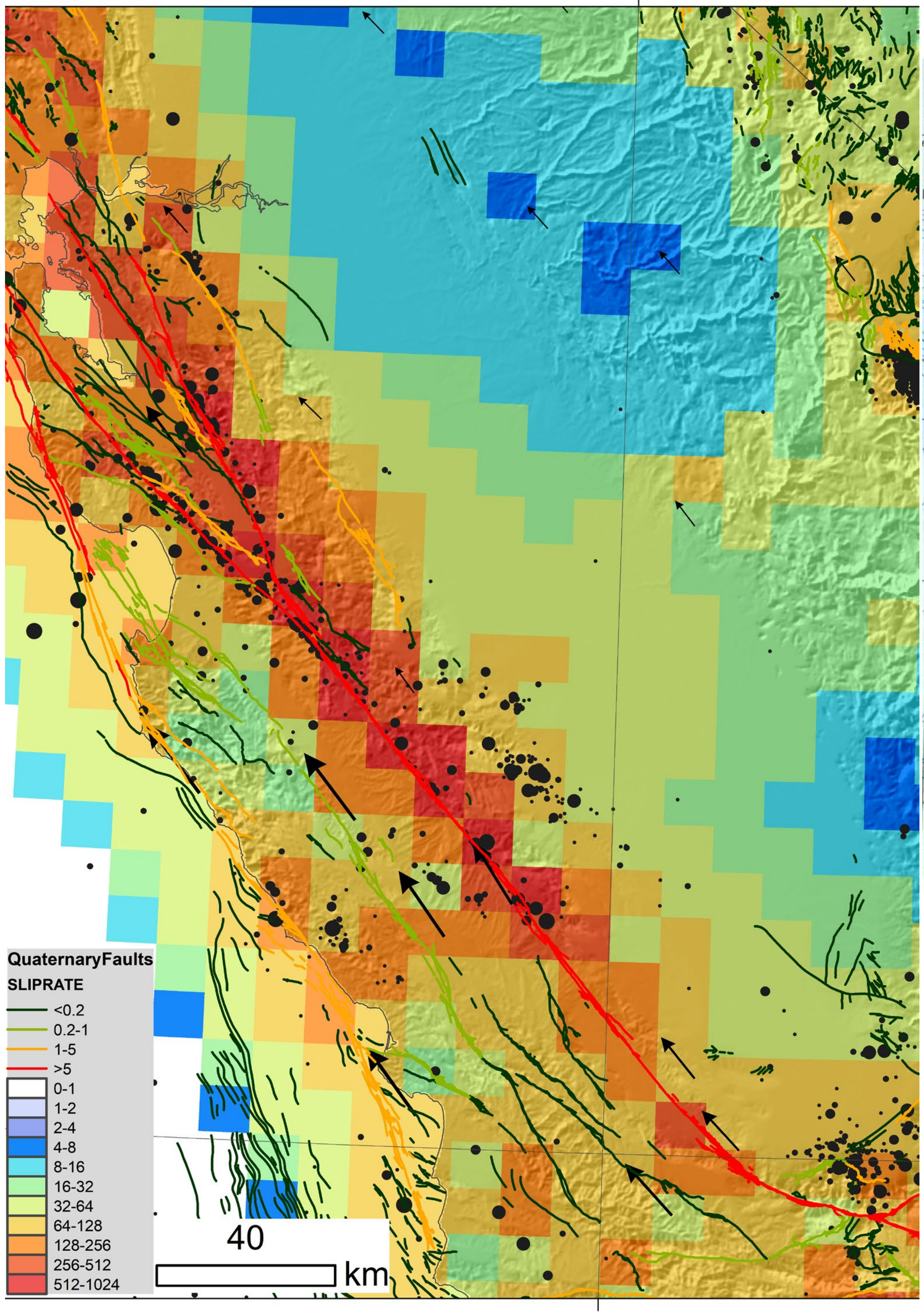


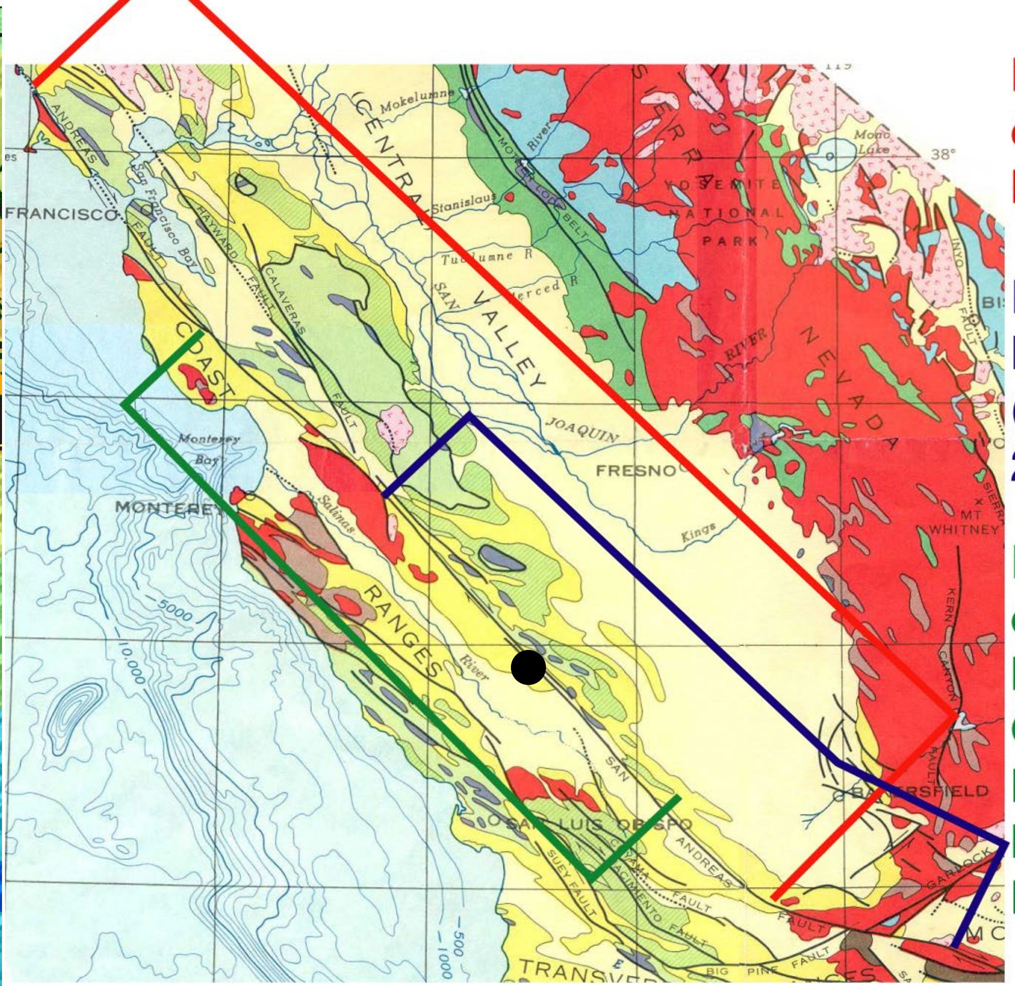
Seismicity, faults, and geodetic vectors along the Walker Lane - Eastern California Shear Zone with sketches illustrating how Pacific-North America motion is accommodated along its length. Data from: USGS, 2020a; USGS, 2020b; and Zeng and Shen, 2016.

Walker Lane and Eastern California Shear zone

- Numerous historic M6-7 earthquakes
- Transtensional contrast to Coast Ranges
- Geometric complexity
- Young and distributed faulting
- Strong heat flow and crustal thickness contrasts

c.f. The Walker Lane: A Potential Target for SCEC Studies?, Wesnousky





Basement offset (~600 km)

Pinnacles-Neenach offset (315 km, post 23.5 Ma)

Paleobathemetry offset (325-330 km, post late Oligocene-early Miocene; 320-325 km, post early Miocene)

SAFOD!

Central San Andreas Fault

Coffey, et al., 2022 paleo eqs

Localized plate boundary

Oldest part of SAF

Large bedrock offsets

Creeping SAF bracketed by Parkfield and transitions to locked sections (1906 and 1857

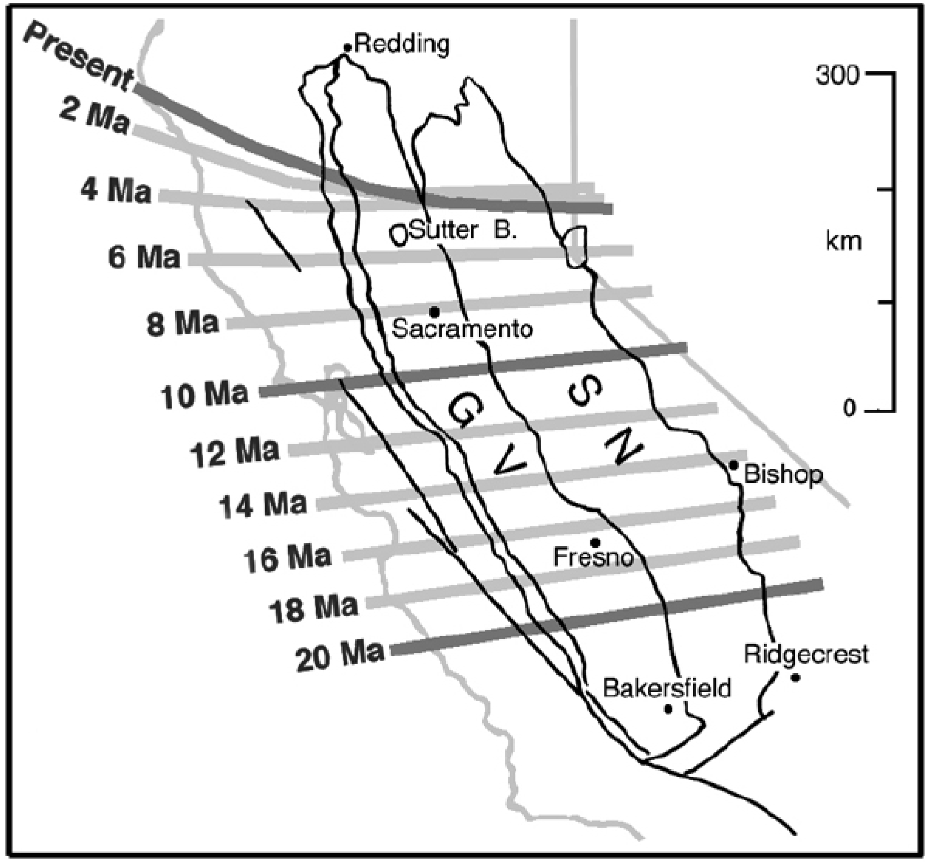
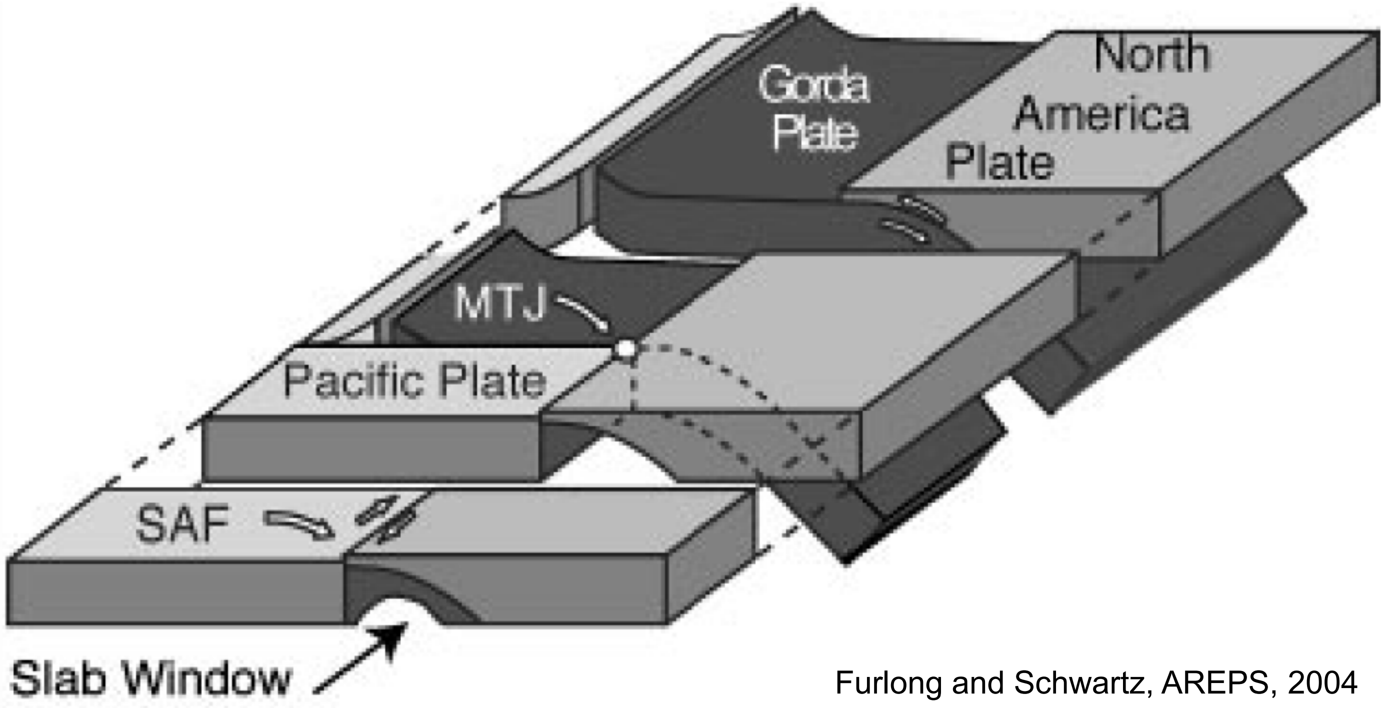
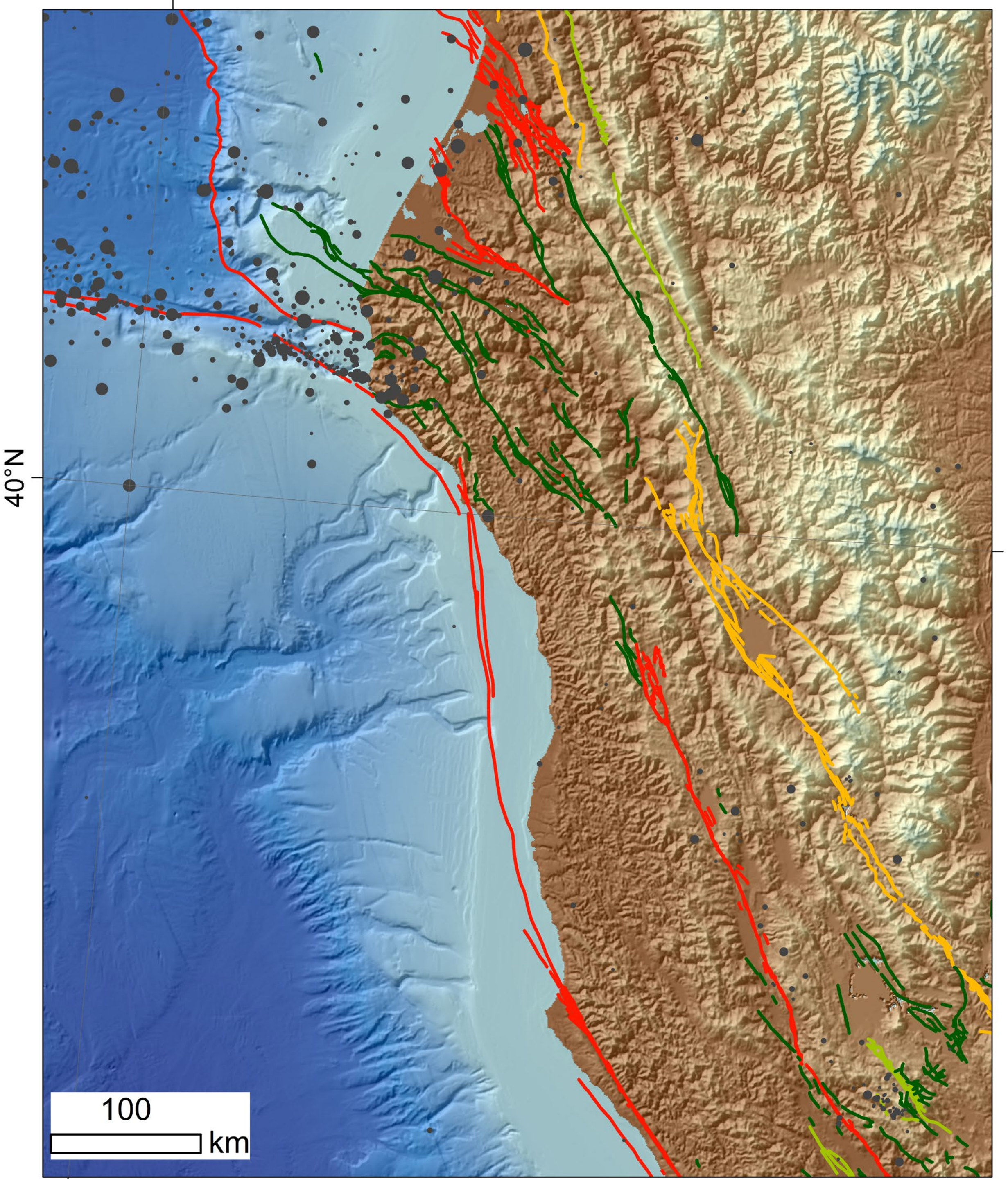


Figure 11. Placement of the Mendocino edge of the subducting Juan de Fuca plate beneath the Sierran-Great Valley block, 20 Ma to present. Drift of oceanic plates are interpolated from our circuit solutions; displacement of the Sierran-Great Valley block drawn following Wernicke and Snow (this issue); shape of the Mendocino edges 6-0 Ma from Wilson (1989). Light gray coastline and state boundaries are given in their present day locations for orientation, only.

Atwater and Stock, 2010

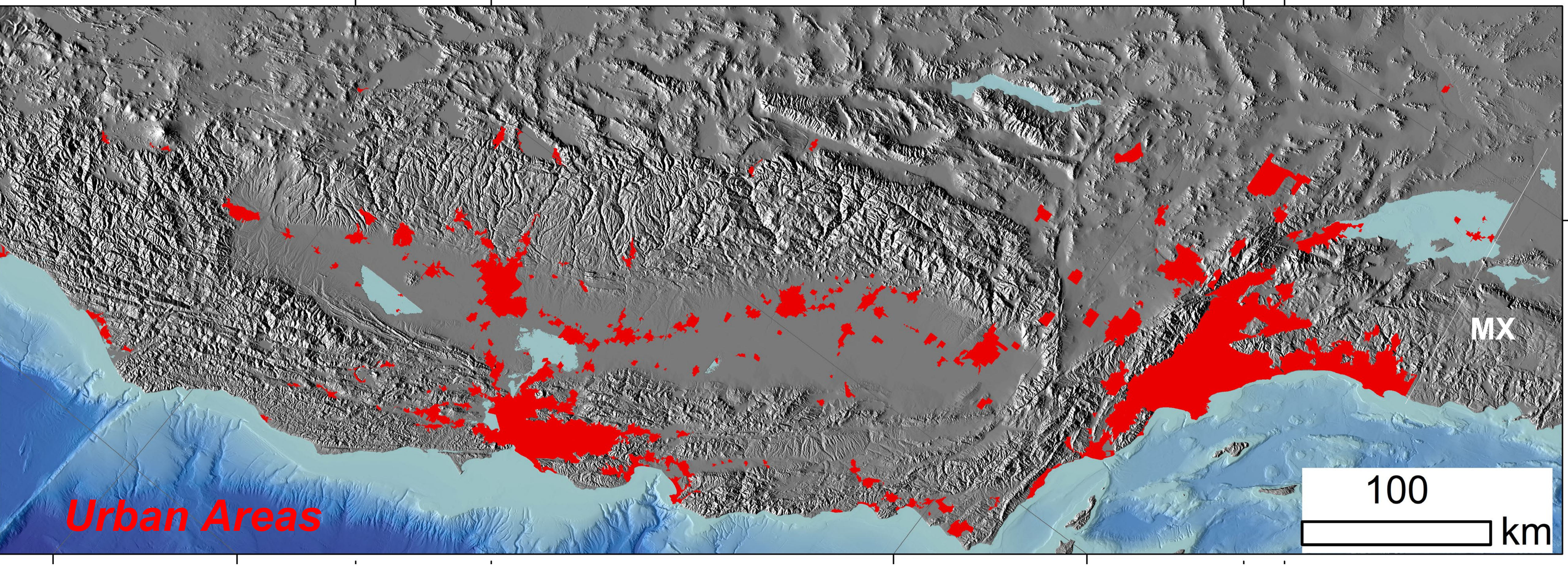


Furlong and Schwartz, AREPS, 2004



Mendocino Triple Junction (MTJ): northern San Andreas Fault system links to the Blanco Transform and the southern Cascadia Subduction zone

- Area of <u>high moment release and rapid rock uplift</u>
- Northern Coast Ranges are a broad mountain belt formed of uplifted Franciscan formation rocks and <u>supported dynamically by upwelling mantle</u> behind the migrating Gorda slab.
- Important <u>template</u> for understanding the seismotectonic development of areas to the south
- High heat flow, abundant microseismicity, fault creep, and geothermal energy production



>39.6 million people & >$3 trillion economy

>60% of US Annualized Economic Losses

Great risk to large population centers in NW Mexico