International Geological Review, v. 40, p. 375-402, May 1988
(to be reprinted, fall 1998, in Ernst, W. G., ed., Clarence Hall Symposium Volume)

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

Tanya Atwater
Department of Geological Sciences, University of California,
Santa Barbara CA 93106-9630
atwater@magic.geol.ucsb.edu

Joann Stock,
California Institute of Technology 252-21,
Pasadena, CA 91125
jstock@gps.caltech.edu

Abstract.

We use updated rotations within the Pacific-Antarctica-Africa-North America plate circuit to calculate Pacific-North America plate reconstructions for times since chron 13 (33 Ma). We find that the direction of motion of the Pacific plate relative to stable North America was fairly steady between chrons 13 and 4, and then changed and moved in a more northerly direction from chron 4 to the present (8 Ma to the present). No Pliocene changes in Pacific-North America plate motion are resolvable in these data, suggesting that Pliocene changes in deformation style along the boundary were not driven by changes in plate motion. However, the chron 4 change in Pacific-North America plate motion appears to correlate very closely to a change in direction of extension documented between the Sierra Nevada and the Colorado Plateau. Our best solution for the displacement with respect to stable North America of a point on the Pacific plate that is now near the Mendocino triple junction, is that from 30 to 12 Ma the point was displaced along an azimuth of about N60°W, with a rate of about 33 mm/yr; from 12 Ma to about 8 Ma the azimuth of displacement was about the same as previously, but the rate was faster (~52 mm/yr); and since 8 Ma the point was displaced along an azimuth of N37°W with a rate of about 52 mm/yr.

We compare plate circuit reconstructions of the edge of the Pacific plate to continental deformation reconstructions of North American tectonic elements across the Basin and Range province and elsewhere in order to evaluate the relationship of this deformation to the plate motions. The oceanic displacements correspond remarkably well with the continental reconstructions where deformations of the latter have been quantified along a path across the Colorado Plateau and central California. They also supply strong constraints for the deformation budgets of regions to the north and south, in Cascadia and northern Mexico.

We examine slab window formation and evolution in a detailed re-analysis of the spreading geometry of the post-Farallon microplates, 28-19 Ma. We find that the development of the slab window seems linked to early Miocene volcanism and deformation in the Mojave Desert, although detailed correlations await clarification of early Miocene reconstructions of the Tehachapi mountains. We then trace the post-20 Ma motion of the Mendocino slab window edge beneath the Sierran-Great Valley block and find that it drifted steadily north then stalled just north of Sutter Buttes about 4 Ma.

Table 1. Positions on magnetic-reversal time scale for which reconstructions are discussed in this paper.

Chron	Position on Magnetic Polarity Time Scale	Age (Cande and Kent, 1995)
2ay	young edge	2.581
3o	center of oldest normal in anomaly 3	5.105
4	center	7.752
5o	old edge	10.949
5a	center of 2nd normal within 5A	12.293
5b	center of 2nd normal	15.095
6o	old edge	20.131
6c	center of 3rd normal	24.059
8y	young edge	25.823
10y	young edge	28.283
12o	old edge	30.939
13y	young edge	33.058

Table 2. Total displacement through time, relative to the North American plate, of a reference point now near the Mendocino Triple Junction (38.5° N, 124° W). Uncertainties on reconstructions involving partial interpolations are not given, but they would be larger than the uncertainties calculated explicitly for chrons 5o and 6o.

Chron Interval and Time Span	Distance (degrees)	Distance (km)	Azimuth
0-3o (0-5.1 Ma)	2.53	280	N37°W
0-4 (0-7.8 Ma)	3.49	390	N37°W
0-5o (0-10.9 Ma)	5.13±0.18	570±25	N42°W±3°
0-5a (0-12.3 Ma)	5.71	635	N44°W
0-5b (0-15.1 Ma)	6.62	735	N45°W
0-6o (0-20.1 Ma)	8.22±0.30	910±35	N47°W±2°
0-6c (0-24.1 Ma)	9.20	1020	N48°W
0-8y (0-25.8 Ma)	9.70	1075	N48°W
0-10y (0-28.3 Ma)	10.48	1165	N48°W

Table 3a. Approximate coast-perpendicular displacement budget (kilometers N60°E) for a path across the Colorado Plateau and central California, compared to the plate circuit solution for a Pacific plate reference point near Mendocino.

Chron Interval and Time Span$^{\psi}$	Rio Grande Rift$^{\rho}$	Basin & Range* A or B	Cent. San Andreas^{+} 1 or 2	Coastal slip$^{\sigma}$	Continental Total$^{\lambda}$	Plate Circuit Total$^{\phi}$
0-6c (0-24.1 Ma)	15	150 or 235	60	0	225 or 310	310
0-6o (0-20.1 Ma)	15	150 or 235	60	0	225 or 310	265
0-5b (0-15.1 Ma)	10	130 or 215	60	0	200 or 285	190
0-5o (0-10.9 Ma)	5	45 or 115	50 or 55	0	100 - 175	120
0-4 (0-7.8 Ma)	5	40 or 105	40 or 50	0	80 - 155	45

Table 3b. Approximate coast-parallel displacement budget (kilometers N30°W) for a path across the Colorado Plateau and central California, compared to the plate circuit solution for a Pacific plate reference point near Mendocino.

Chron Interval and Time Span$^{\psi}$	Rio Grande Rift$^{\rho}$	Basin & Range* A & B	Cent. San Andreas^{+} 1 or 2	Coastal slip$^{\sigma}$	Continental Total$^{\lambda}$	Plate Circuit Total$^{\phi}$
0-6c (0-24.1 Ma)	5	220	310	250	785	972
0-6o (0-20.1 Ma)	5	220	310	250	785	870
0-5b (0-15.1 Ma)	0	205	290 or 310	230	725 or 745	710
0-5o (0-10.9 Ma)	0	150	260 or 290	110	520 or 550	560
0-4 (0-7.8 Ma)	0	130	200 or 255	80	410 or 465	385

$^{\psi}$ Magnetic reversal chron ages from Cande and Kent (1995).

$^{\rho}$ Rio Grande rift extension after "Miocene" rotation of Chapin and Cather (1994), as described in number 2 in the text.

* Total of Basin and Range extension and dextral shear between the Sierran-Great Valley block and the Colorado Plateau, for point A near Bishop and for point B near Ridgecrest, as described in number 5 in the text. Components calculated from displacement estimates of Wernicke and Snow (this issue)

$^{+}$ Displacements on the central San Andreas fault system, Pinnacles-Neenach offset. Partitioning of offset over time, as described in number 7 in the text: 1. assuming significant early offset after Sims (1993), or 2. assuming almost all offset was post-10 Ma, after Dickinson (1996). Coast-perpendicular displacements in Table 3a arise from the fact that the San Andreas fault is not parallel to the coast.

$^{\sigma}$ Displacements west of the central San Andreas fault, after Hornafius et al. (1986) described in number 8 in the text.

$^{\lambda}$ Sums of columns two through five. Up to 40 km of displacement might be added to each from the rotation of the Tehachapi mountains, as described in number 6 in the text.

$^{\phi}$ Displacements of a reference point on the Pacific plate, from Table 2, broken into components (a) perpendicular and (b) parallel to N30°W.

Figure 1. Map showing tracks of two arbitrary reference points on the Pacific plate, moving relative to a fixed North American plate. Present positions of the points are marked with small stars labeled "0". Past positions of these points are shown for the times of global chrons 5o, 6o, and 13y, reconstructed using the Pacific-Antarctica-Africa-North America global plate circuit. Ellipses represent the 95% confidence limits on the locations of these points. Locations of squares labeled "2ay" were calculated by extrapolating present-day velocities in the Nuvel-1A model (DeMets et al., 1994) to 2.58 Ma. Heavy open circles were located with a similar extrapolation, but using DeMets' (1995) modification of the Pacific-North America rate for Nuvel-1A. Dashed tracks with triangles labeled "5", "6", and "13" show past positions of the same reference points as previously determined by Stock and Molnar (1988), with their 95% confidence ellipses shaded in gray, for comparison. Note the differences between the new reconstructions and the older ones for chrons 6 and 13.

Figure 2. Map showing tracks of arbitrary reference points assumed to move with the Pacific plate relative to a fixed North America plate. Present positions of the points are marked with symbols labeled "0". Past positions of these points are shown for the chrons whose ages are listed in Table. 1. Ellipses for chrons 5o, 6o, and 13y represent the 95% confidence limits on the locations of these points. Ellipses for other times are not shown but would be larger, because those reconstructions involve interpolations of rotations along the Southwest Indian Ridge and the Mid-Atlantic Ridge. Points now on the Pacific plate are shown only for the times that they have been present on the sea floor (e.g., a point located on seafloor of chron 10 age is not shown for times older than chron 10). Points now on North America (open symbols) are shown to illustrate the direction of motion that would be expected if the Pacific plate had been dragging North American crust with it. Note the major change in direction of Pacific-North America plate motion at chron 4 time (7.8 Ma). Heavy open circles are the locations predicted by extrapolating DeMets' (1995) modification of the Pacific-North America rate in the Nuvel-1A model to chron 2ay, 2.58 Ma, as in Fig. 1. Note the close correspondence of these circles to our chron 2ay circuit solutions.

Figure 3. Displacement of a point now on the Pacific plate at 38.5°N, 124.0°W, near the Mendocino Triple Junction, calculated from the global plate circuit solutions illustrated in Figure 2. A clear change in the rate of displacement is shown by a change in slope in the top plot at about 12 Ma. A clear change in the azimuth of displacement is seen in the bottom plot at about 8 Ma (chron 4). Note that the changes do not coincide in time.

Figure 4. Location of Pacific plate oceanic lithosphere at the time of chron 6o (20.1 Ma), relative to a fixed North America, plotted upon the present shape of North America. Heavy gray line is the eastern edge of known oceanic crust, drawn to trace either the spreading system that was active at chron 6o time, or, where spreading and subduction had ceased, the edge of oceanic crust at the base of the continental slope. Light lines are older isochron patterns within the Pacific plate ocean floor, after Atwater and Severinghaus (1989). Solid line west of the North American coastline is the present-day base of the continental slope, inferred to be the present location of the western edge of North American continental crust. The overlap of the Pacific plate east of this line is an unacceptable overlap of oceanic and continental lithosphere. It demonstrates the minimum amount of internal deformation that is required to have occurred within the continent since 20.1 Ma if the plate reconstructions are correct.

Figure 5. Successive locations of the eastern edge of Pacific plate oceanic lithosphere, relative to a fixed North America, plotted upon the present shape of North America. The edge for each time step was drawn as described for Fig. 4. The overlaps demonstrate the amount of internal deformation required within North America at each past time in order to avoid an unacceptable overlap of oceanic and continental lithosphere.

Figure 6. Present-day locations of continental elements and known quantitative constraints (listed in the text) for their reconstructions to early Miocene locations. Dark gray = rigid Pacific plate. Light gray = continental blocks that are believed to have suffered relatively little internal deformation during the Late Cenozoic. White = continental regions believed to have suffered significant Neogene deformation. A and B are reference points of Wernicke and Snow (this issue) and arrows with dots show their trajectories 16 Ma − 10 Ma − 0 Ma, as described in number 5 in the text. P and N are the Pinnacles and Neenach locations for reconstruction of the central San Andreas fault offset, as described in number 7 in the text. T. R. western Transverse Ranges block; T. M. Tehachapi Mountains.

Figure 7a. Reconstruction for Chron 6o, 20.1 Ma, compared with the present configuration from Figure 6. Individual continental elements (light gray) have been reconstructed using the relationships shown in Figure 6 and described in the text. Pacific seafloor with isochrons (dark gray) has been moved using the global circuit solution for chron 6o, as illustrated in Figs. 1, 2, 4 and 5. For reference, dark line on left-hand image shows the location of isochron 6o within the present-day Pacific seafloor.

Figure 7b. Reconstruction for Chron 5o, 10.9 Ma, compared with the present configuration from Figure 6. Individual continental elements (light gray) have been reconstructed using the relationships shown in Figure 6 and described in the text. Pacific seafloor with isochrons (dark gray) has been moved using the global circuit solution for chron 5o, as illustrated in Figs. 1, 2, and 5.

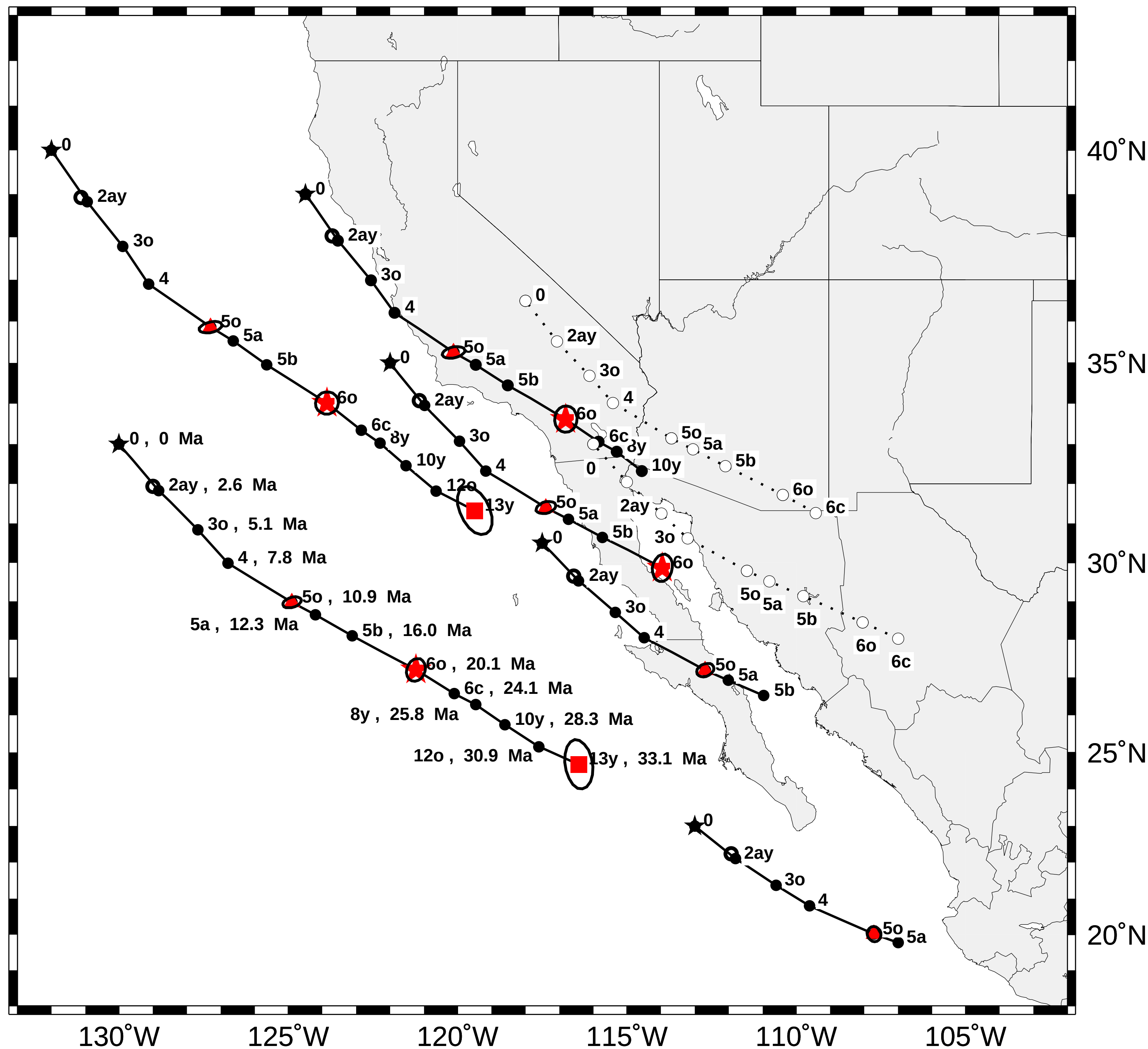
Figure 8. Present-day seafloor isochron patterns and fracture zones mapped in the Pacific seafloor off central California, after Severinghaus and Atwater (1990). Heavy dotted line marks the location of the stalled Pacific-Monterey spreading center, after Lonsdale (1991). Labels are magnetic reversal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

Figure 9. Mid-Cenozoic slab-free window configurations, constructed using the seafloor isochron patterns shown in Fig. 8 and assuming symmetrical spreading and no slab dip.
a. Inferred plate configurations at chron 10y (28.3 Ma), the moment of formation of the Monterey and Arguello microplates. Light gray shows undersea regions. New plate breaks are arbitrarily assumed to have occurred along a transform fault between the microplates and along a line about 50 km beneath the lip of the continent (serrated gray line with <'s), although the latter break line could have been somewhat farther east. Break between the Juan de Fuca and Farallon plates is shown in its previously established position (wide, serrated gray line with x's).
b. Inferred plate and window configurations at chron 6c (24.1 Ma). Light gray shows undersea regions. Dark gray shows slab window regions beneath the continent where no slab exists. Window edges: heavy lines are window edges located with some confidence; serrated edges with <'s mark window edges that were arbitrarily located in Figure 9a then displaced with their respective plates; serrated gray edges with x's mark the inherited diffuse boundary between the Juan de Fuca and Farallon plate. Letters A through D refer to sections of the windows that are located with differing degrees of confidence, as discussed in the text. Only regions A and B are well located.
c. Inferred plate and window configurations at chron 6y (19.0 Ma). Light gray shows undersea regions. Dark gray shows slab window regions beneath the continent where no slab exists. Shading and window edges same as in Fig. 9b.

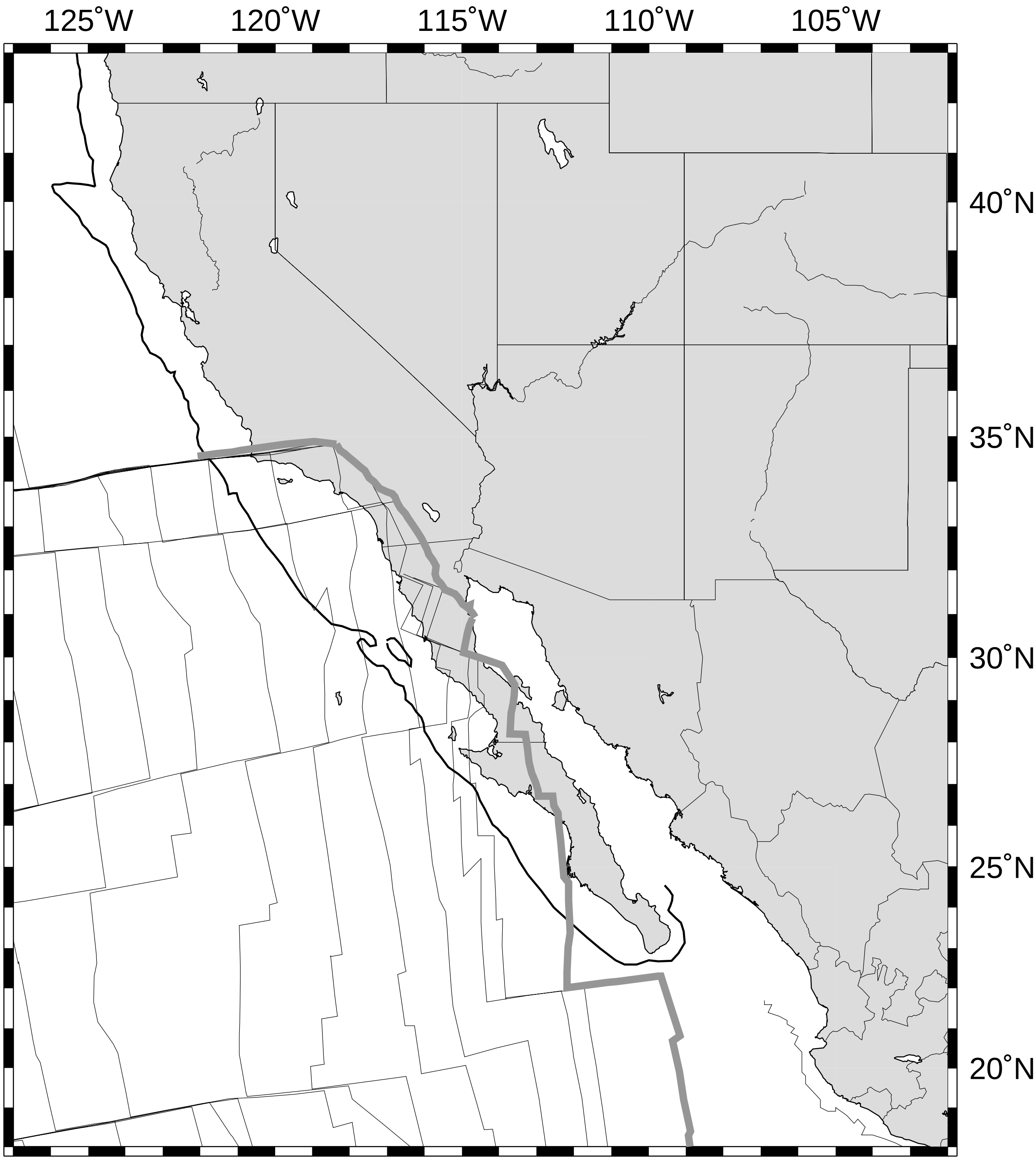
Figure 10. Mid-Cenozoic slab window evolution with respect to the overriding North American plate. Slab window shapes (gray shading) from Fig. 9 are located beneath the 20 Ma reconstruction of continental elements from Fig. 7a, using the circuit solutions of Fig. 5 for coast-parallel placement and assuming that the continent expanded to keep pace with the coast-perpendicular motion of the oceanic plate. Oceanic plates: PP Pacific plate, JFP Juan de Fuca plate, MP Monterey plate, and AP Arguello plate. Continental elements: SN and GV Sierran-Great Valley block, CP Colorado Plateau, BC Baja California, and TR western Transverse Ranges in their pre-rotated position. A and B are the Basin and Range reconstruction points and P and N are the Pinnacles and Neenach points for San Andreas fault reconstruction, all as illustrated in Figs. 6 and 7 and described in numbers 5 and 7 in the text. Window shapes have been shortened 5% toward the coast to simulate an 18° slab dip and are shown fading out to the east to simulate loss of contact between the slab and overriding plate. Note that, because pre-20 Ma continental deformation is not included in these figures, the positions of the slab elements relative to North American geological features are progressively more uncertain going back in time.
a. Configuration at 28.3 Ma, showing breaks in the slab inferred to have formed when the Monterey and Arguello microplates separated from the larger plates.
b. Configuration at 24.1 Ma. Dark gray shows the window regions that developed 28 - 24 Ma beneath North America.
c. Configuration at 19.0 Ma. The Pacific-Monterey spreading center is about to stall. Dark gray shows the new window regions that developed 24 - 19 Ma beneath North America; light gray shows slab-free regions formed earlier. From this time on, only the northern, Mendocino edge is believed to be a significant geologic factor. The underthrust Monterey microplate (white space beneath TR) has reached its maximum extent prior to its "capture" by the Pacific plate, although its eastern edge may have extended farther east if the Chron 10y plate break occurred farther beneath the continental edge than assumed in Fig. 9a.

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.

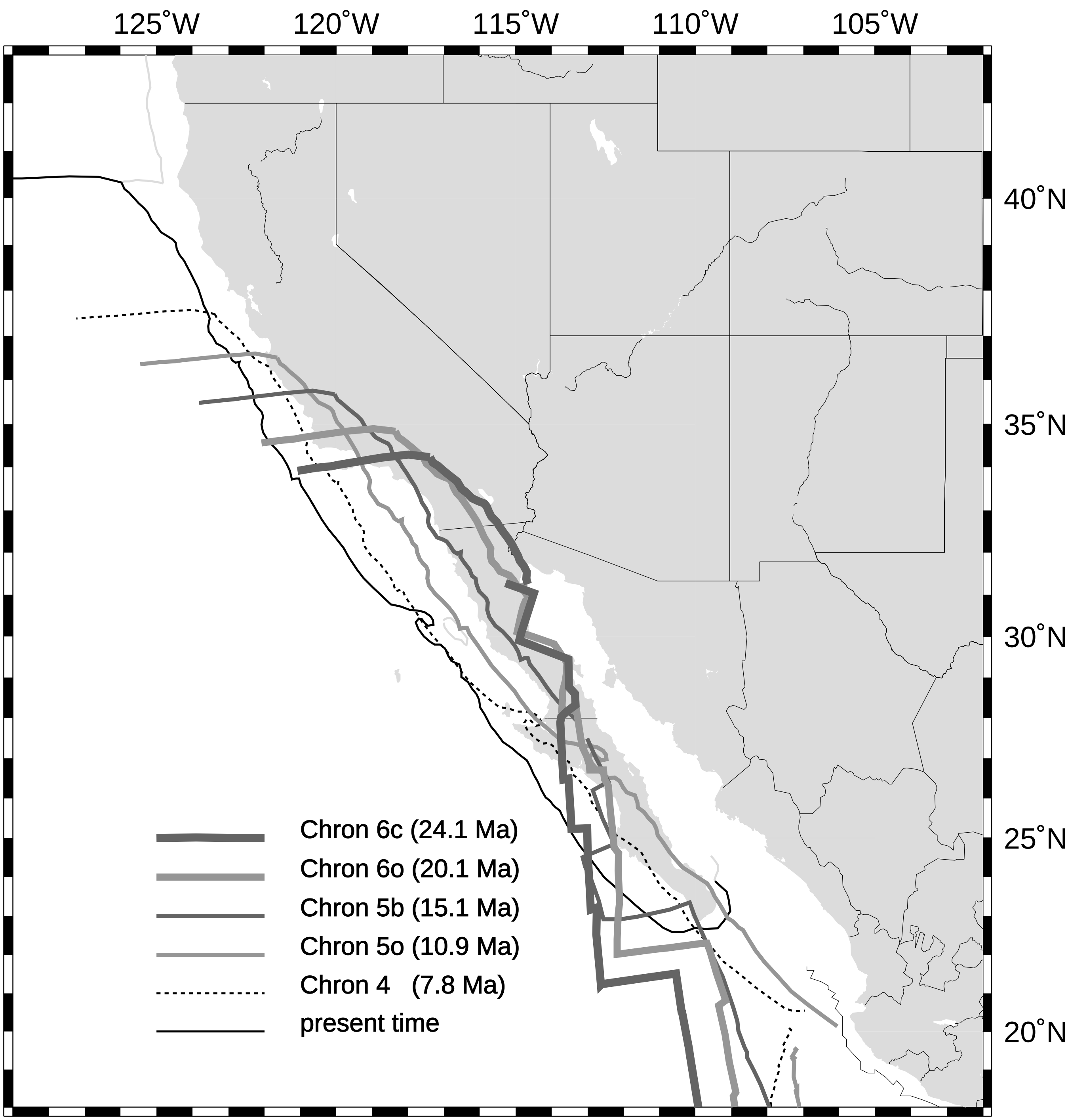
Figure 2, Atwater & Stock

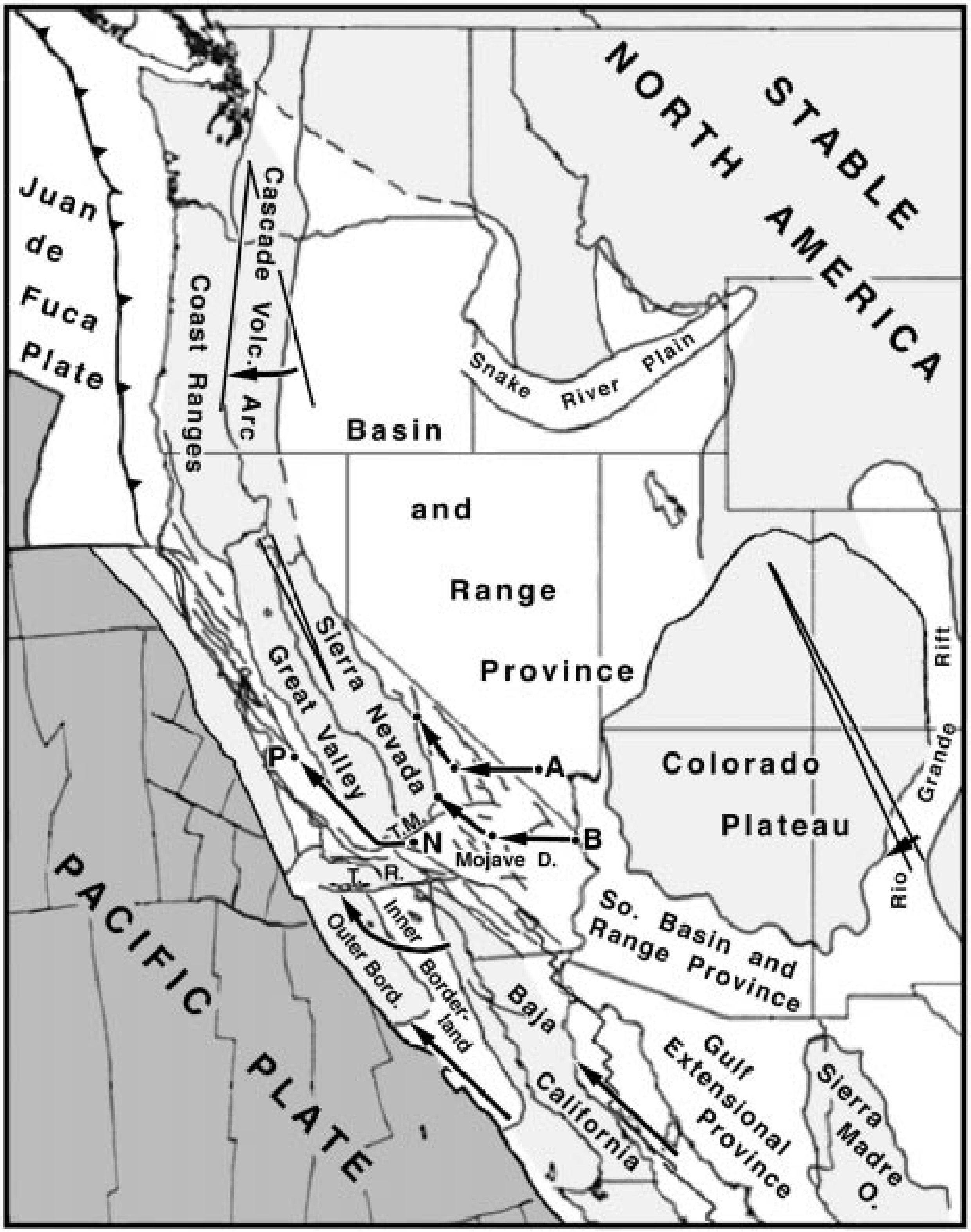


Atwater & Stock - Figure 4

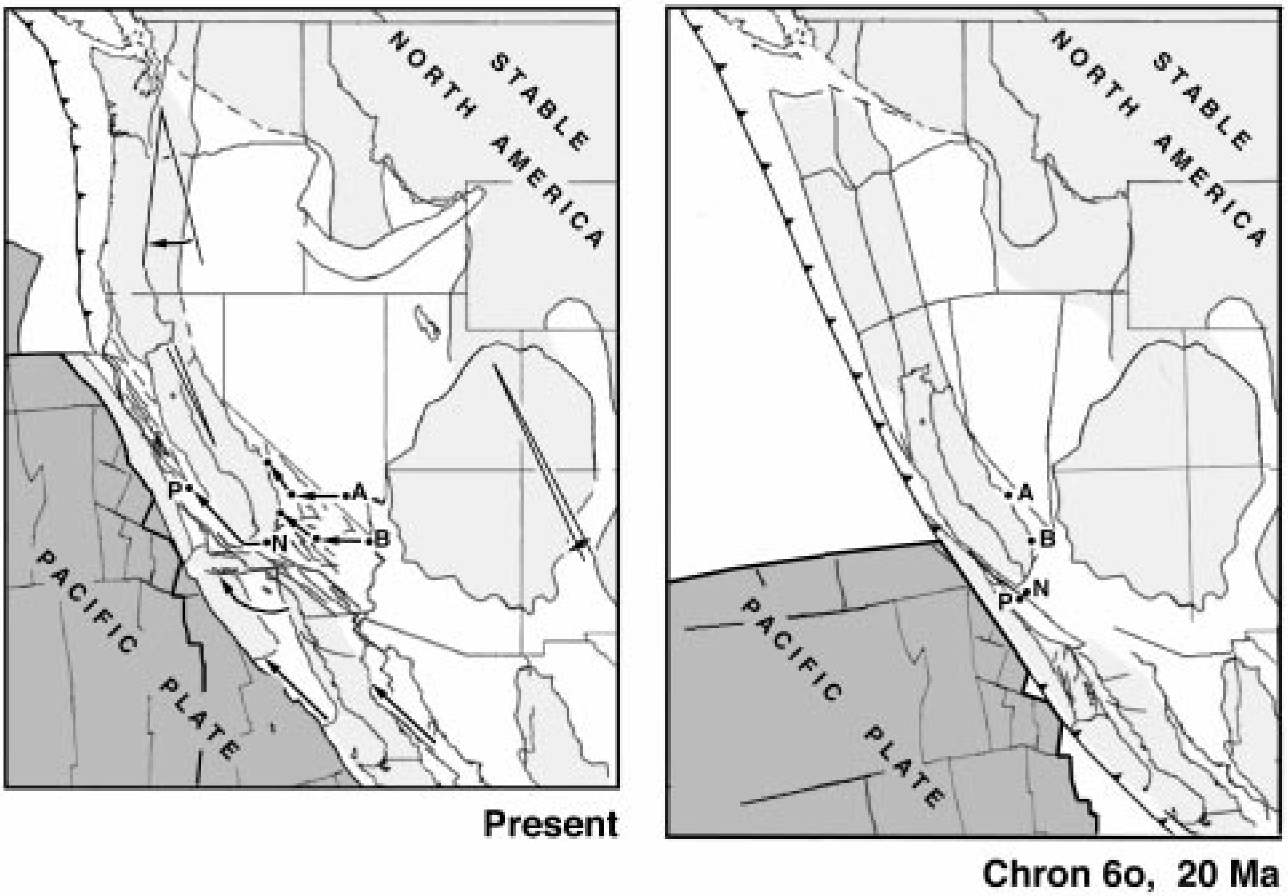


Atwater & Stock - Figure 5

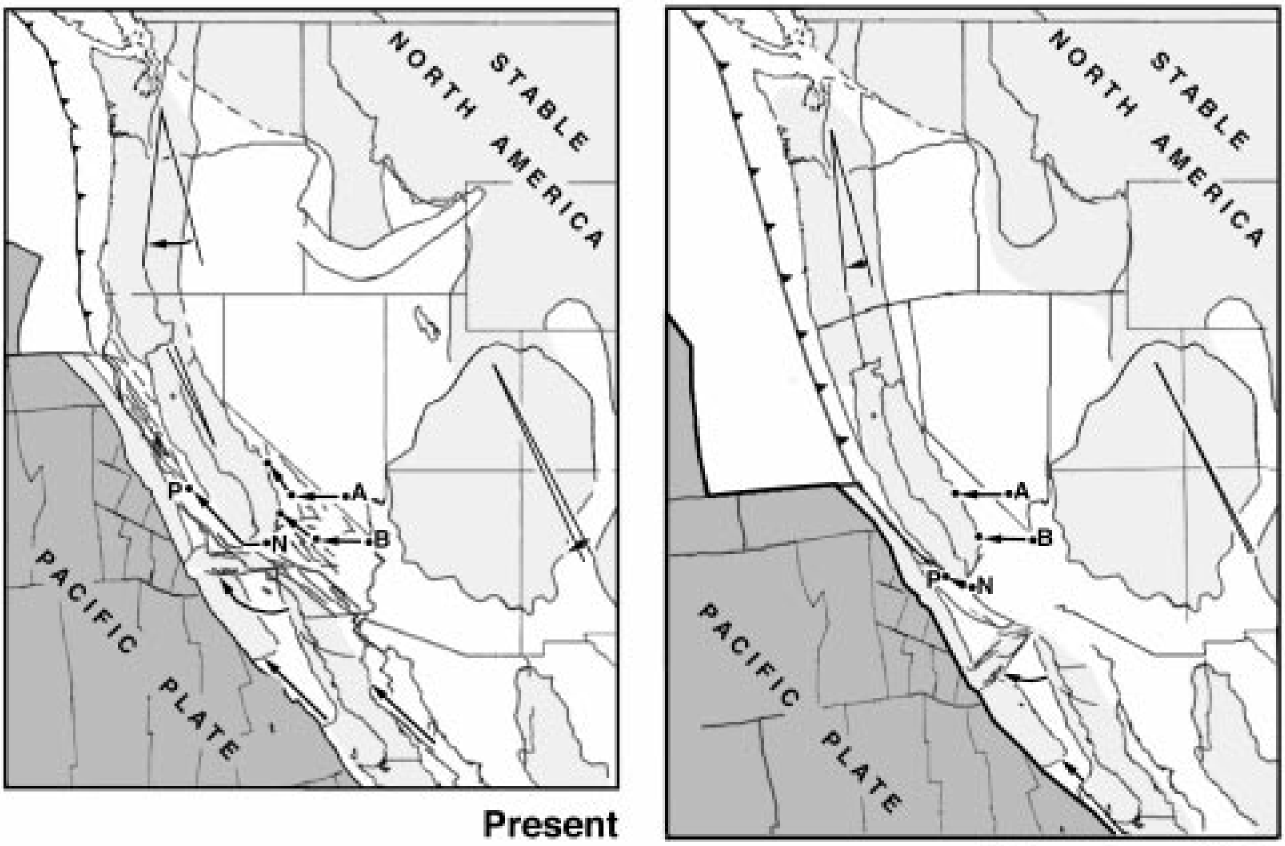




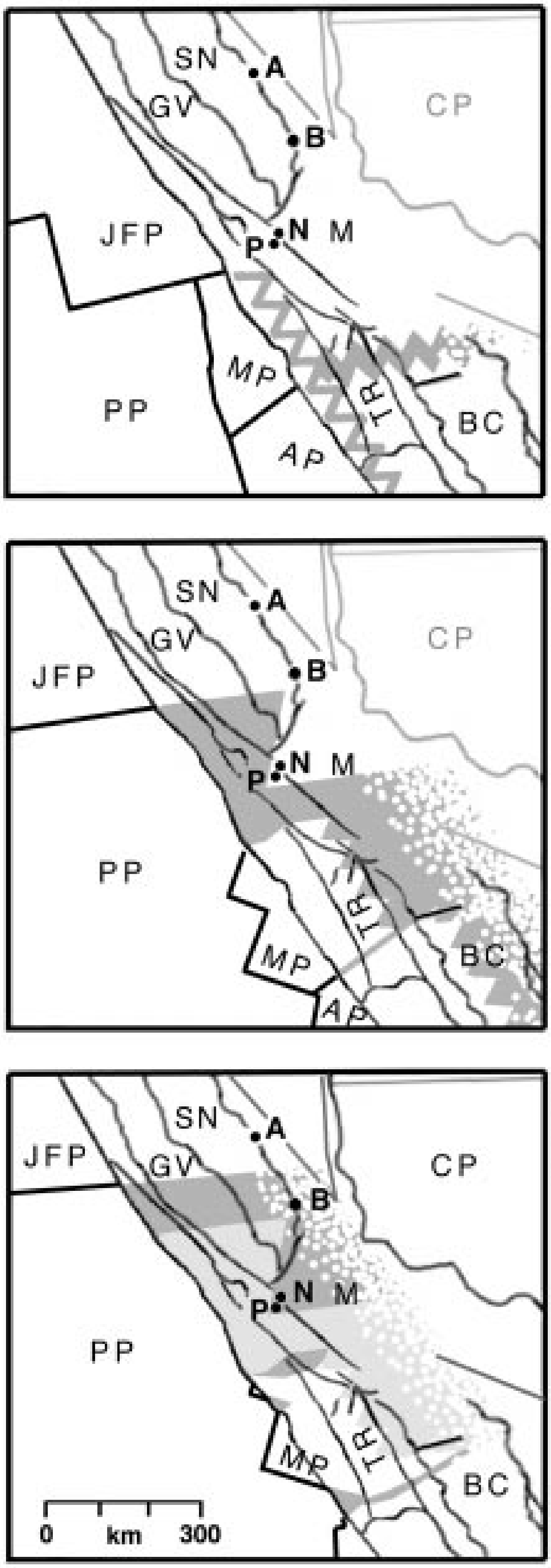
Atwater & Stock - Figure 6



Atwater & Stock - Figure 7a



Atwater & Stock - Figure 7b

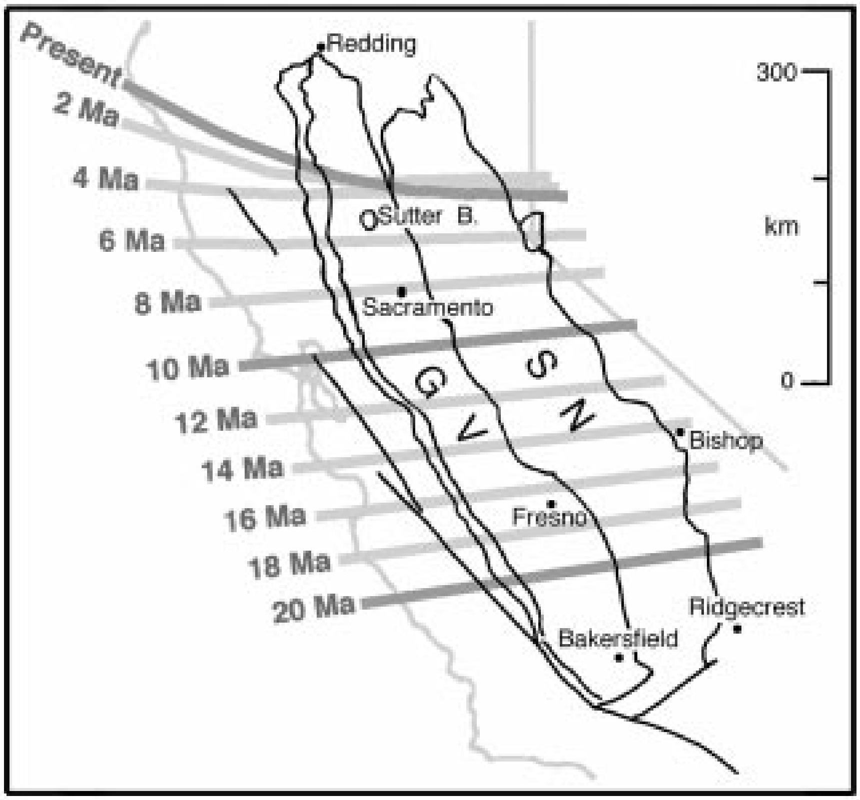


a.
Chron 10y
28.3 Ma

b.
Chron 6c
24.1 Ma

c.
Chron 6y
19.0 Ma

Atwater & Stock - Figure 10



Atwater & Stock, Fig. 11.