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

Article *in* International Geology Review · July 2010

DOI: 10.1080/00206819809465216

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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.

International Geological Review, v. 40, p. 375-402, 1998 (reprinted, 1998, in Ernst, W. G., and Nelson, C.A., eds., Integrated Earth and Environmental Evolution of the Southwestern United States: The Clarence A. Hall, Jr., Volume, Bellwether Pub., Columbia, MD, p 393-420.).

Introduction.

Interactions between the North American plate and the plates of the northeastern Pacific basin have exerted a fundamental control on the tectonic development of the western United States and Mexico in Neogene time. The San Andreas transform system and its evolution through Neogene time is a clear manifestation of these interactions (e.g., Atwater, 1970, 1989), but a number of more subtle effects are also apparent. In particular, the piecewise demise of the subduction zone with the creation and evolution of slab-free regions beneath North America can be related to patterns of volcanism and uplift in the continent (e.g., Dickinson and Snyder, 1979; Crough and Thompson, 1977; Page and Engebretson, 1984; Atwater, 1989; Severinghaus and Atwater, 1990: Dickinson, 1997). Furthermore, it appears that deformation of the continental interior, including both extension and shear may be strictly modulated by geometric constraints of the plate interactions.

A crucial step in working out the plate interactions along the continental rim is the calculation of the relative positions of the Pacific plate with respect to stable North America for various past time steps. These calculations have been done in two ways: using either a global plate circuit or a fixed hotspot assumption (e.g., Stock and Molnar, 1988; Engebretson et al., 1985). The weak link in the former is the assumption of a non-deforming Antarctic plate, while that of the latter is the assumption of fixity between the Pacific and Atlantic hotspots. For the late Cenozoic reconstructions used here, we believe the former, the global plate circuit, is clearly the more dependable solution, and we have followed that method exclusively. There have been recent improvements in our knowledge of the details of the plate circuit, particularly in the southern oceans, due to additional fracture zone constraints from satellite gravity maps (e.g., Sandwell and Smith, 1997) and due to shipboard data acquisition in critical, but previously unstudied, parts of the world's ocean basins, especially in the regions around Antarctica (Cande et al., 1995; Royer and Chang, 1991). In this paper, we revise the global plate circuit reconstructions incorporating this new information. Of course, these revisions are an ongoing process; future surveys will continue to yield improvements in the plate circuit, and the results presented here may need to be further refined.

Another crucial step for plate reconstructions involves the undoing of internal North American deformations. While some of the observations needed for this job have long been known, breakthroughs of the past decade have greatly enhanced our ability to make credible reconstructions. The conceptual acceptance of >100% extension in the Basin and Range (e.g., Crittenden et al., 1980; Wernicke, 1992) and its spatial and temporal quantification (e.g. Wernicke et al., 1988; Snow and Wernicke, in press 1998; Wernicke and Snow, this issue) are vital advances for the reconstruction of the interior. Likewise, refinement of block rotation observations and models allows a tighter reconstruction of several southern California regions (e.g., Kamerling and Luyendyk, 1985; Luyendyk, 1991; Legg, 1991; Crouch and Suppe, 1993).

Furthermore, in the last decade there have been major advances in our conceptual understanding of plate interactions; examples include the idea that the Pacific-Farallon Ridge could still have been some distance west of the trench when Farallon plate fragmentation began (e.g., Lonsdale, 1991; Fernandez and Hey, 1991), and the idea that "slab capture" may have driven much of the coastal tectonic deformation after Farallon plate fragmentation took place (e.g., Nicholson et al., 1994; Bohannon and Parsons, 1995). These concepts have led to some changes in how one would reconcile the continental geology with the plate tectonic history. We attempt to integrate these new ideas into the results presented in this paper.

Reconstructions of the Relative Positions of the Pacific and North American Plates

Method

In our plate circuit calculations, we derive the relative positions of the Pacific and North American plates by adding finite rotations across a series of boundaries in sequence: Pacific to Antarctica across the Pacific-Antarctic Ridge, then Antarctica to Africa across the Southwest Indian Ridge, and finally Africa to North America across the Mid-Atlantic Ridge. Each calculation must be done for the same position on the magnetic-reversal time scale in each ocean basin, in order to be valid for that time in the past. This is not necessarily straightforward, since published reconstructions done for different ocean basins by different authors often use slightly different events on the magnetic-reversal time scale, and this must be taken into account. Pacific-Antarctic reconstructions (Cande et al., 1995) are available for selected positions, or "chrons", on the magnetic-reversal time scale which correspond approximately to a one m.y. time spacing (following Atwater and Severinghaus, 1989). However, for the other boundaries, reconstructions at this level of detail are not available; rather, the norm is a 5 or 10 m.y. interval between available reconstructions, using only the most prominent magnetic anomalies, i.e., chrons 5, 6, and 13 (Royer and Chang, 1991; Klitgord and Schouten, 1986). We call these the "global chrons". For our studies, we chose to augment the list of global chrons with some additional, intervening chrons, in order to make use of the extra detail now available in the south Pacific. We calculated circuit reconstructions for these intervening chrons by combining the actual reconstructions from the south Pacific with interpolations from the other oceans. This seems justifiable since spreading was quite slow in the other oceans so that any errors arising from the interpolations should be small.

We do our work in reference to seafloor magnetic isochrons, and thus we prefer to report our results in terms of chron numbers rather than millions of years, so that the solutions will remain valid through the continuing refinement of ages in the geomagnetic-reversal time scale. In this paper, whenever we address millions of years or rates, we use the chron ages listed in Table 1, from the new geomagnetic polarity time scale of Cande and Kent (1992) as revised by Cande and Kent (1995).

Uncertainties in the reconstructions for the global chrons 5, 6, and 13 are represented as covariance matrices following the formulation of Chang (1988) and Chang et al. (1990). The covariance matrices for the reconstructions across the Southwest Indian Ridge are given by Royer and Chang (1991) and those for the Pacific-Antarctic Ridge are part of the calculations used by Cande et al. (1995) (J. M. Stock, unpublished data). For the central Mid-Atlantic Ridge, covariance matrices were constructed from the partial uncertainty rotations given by Stock and Molnar (1988) following the technique described in Chang et al. (1990). The covariance matrices were then used to determine 95% confidence limits for the reconstructions. Uncertainties were only computed for the times of chrons 5o, 6o, and 13y (i.e., the old edges of chrons 5 and 6 and the young edge of chron 13), because these correspond most closely to the times for which covariance matrices were available for the Indian and Pacific oceans. Uncertainties for the intervening chrons are greater than those calculated for the global chrons, because of the additional uncertainty involved with using interpolations in the Atlantic and Indian oceans.

Results: Trajectories of Pacific Plate Points Relative to North America

In Figs. 1 and 2, we use our new plate circuit solutions to calculate displacements of the Pacific plate through time with respect to North America. We use stable North America as a fixed reference frame and we choose several arbitrary reference points on the Pacific plate to illustrate its displacements. The present locations of the Pacific reference points are shown as stars and their various reconstructed positions are labeled with chron numbers. By connecting the various positions of a given reference point, we create a time trajectory for that part of the Pacific plate with respect to stable North America.

In Fig. 1 we compare our new trajectories to those of the previous solutions by Stock and Molnar (1988) for the times of the global chrons 13y, 6o, and 5o and to solutions for present-day relative velocity extrapolated to chron 2ay. For the latter, we consider both the global NUVEL-1A plate motion model by DeMets et al., 1994 (black squares labeled 2ay), and a variation of this model with an updated rate for Pacific-North America by DeMets, 1995 (heavy open circles). In our new solutions, the reconstructions for chrons 13y and 6o are markedly different from the Stock and Molnar solutions, probably due to greatly improved mapping of small-offset fracture zones in the south Pacific and Indian Ocean. (Small-offset fracture zones, while more difficult to map than large-offset fracture zones, are more reliable indicators of past instantaneous plate motion directions, since they spend a much shorter time within the active transform fault and thus are less prone to overprinting by subsequent changes.) For chron 5o, our new positions for the reference points are very similar to positions resulting from the Stock and Molnar solution and are within the 95% confidence limits of those earlier calculations.

A change in Pacific-North America plate motion direction is clearly required by the global chron trajectories in Fig. 1, since the average motion direction from chron 5o (11 Ma) to the present is distinctly more northward than the older directions. Furthermore, the circles and squares labeled 2ay on Fig. 1 indicate a present-day velocity direction that is even more northerly than our 11 Ma average direction, suggesting that at least part of the change was younger than 11 Ma. In summary, the new solutions for the global chrons suggest a smooth trajectory between 33 and 11 Ma, and indicate one or more changes in direction since 11 Ma.

In order to take advantage of the very detailed kinematic model now available in the southwest

Pacific, we interpolated steps in the other two (slow spreading) oceans. When we included all the resulting 35 steps, the trajectory was, again, remarkably smooth, and a single change in direction was very clearly identified at or just preceding the time of chron 4, about 8 Ma. Furthermore, the direction and rate for the part of the track younger than chron 4 coincided almost exactly with that predicted by the Nuvel-1A extrapolation, described above.

Fig. 2 shows our preferred new trajectories for various reference points on the Pacific plate with respect to stable North America. These trajectories include reconstructions for the global chrons with their uncertainties plus selected intervening, partially interpolated chrons without uncertainties, to fill out the tracks. We see that the direction of Pacific-North America motion has been changing with time, becoming progressively more northerly, although the exact trajectories vary with location on the Pacific plate. Adjacent to California, the plate motion followed a bilinear trajectory: between chrons 13 and 4 the direction was fairly steady in a WNW direction; since chron 4 (about 8 Ma) it was again quite steady but in a NNW direction. Farther south, the trajectory appears to have been more curved, with the chron 4 kink less noticeable than it is to the north.

The net displacements of the Pacific plate since the times of chron 8 and younger are important for calculations of the amount of net plate boundary displacement that may need to be accommodated within the continental lithosphere of western United States. For this purpose, we calculate and list in Table 2, the net displacements and their directions for a modern Pacific plate reference point near the Mendocino Triple Junction over a few select time intervals. In Fig. 3, we plot the displacement and azimuth of this reference point through time. Again, the direction of motion is seen to be bilinear, changing at 8 Ma from about N60°W to about N37°W. The rate of motion also changed, from about 33 mm/yr to about 52 mm/yr, but the rate change seems to have occurred at about 12 Ma, earlier than the direction change.

We note in passing that, despite the differences in the positions of the points for chrons 6 and 13, the calculated values for coast-parallel slip are all within the uncertainties given by Stock and Molnar (1988) for the same chrons. Thus, the new results should not change conclusions regarding San Andreas-parallel displacement which have been based on the earlier reconstructions.

Discussion: Mio-Pliocene Change in Pacific-North America Plate Motion Direction

At the latitude of California, our new plate motion trajectory includes a very clear change in direction at chron 4. This change is related to a change in Pacific-Antarctic motion. Cande et al. (1995) discuss a major change in Pacific-Antarctic spreading direction at chron 3ay (about 5.9 Ma) whose timing is constrained most precisely from a change in orientation of seafloor spreading fabric that is visible on swath bathymetry. However, when the Pacific-Antarctic rotations are propagated into the Pacific-North America plate circuit, there are changes at both chrons 3ay and 4, but the chron 4 change has a stronger effect on the Pacific-North America spreading direction. Because plate motions for these chrons are interpolated in the Indian and Atlantic Oceans (that is, they are assumed to be steady) any variation in spreading directions in these oceans would further change these results.

Several authors have inferred that there were one or more resolvable Pliocene changes in Pacific-North America plate motion. Harbert (1991) concluded that changes occurred at 2.48 Ma and between 3.4 and 3.9 Ma, resulting in a 12° clockwise change in the relative plate motion vector along the Pacific-North America boundary in coastal California. Other estimates of the time of this change are about 5 Ma (Cox and Engebretson, 1985) and 3.2-5 Ma (Pollitz, 1986). These postulated changes are thought to have produced compression and uplift in the California Coast Ranges and offshore basins (Page and Engebretson, 1984; McCulloch, 1989; McIntosh et al., 1991) and development of strike-slip faults of more northerly trends within the San Andreas system (e.g., Harbert, 1991). Such changes are also thought to be linked to changes in the direction of absolute motion of the Pacific plate, manifested by an inferred subtle change in direction of the Hawaiian-Emperor chain which has been most recently assumed to be at 3 Ma (Wessel and Kroenke, 1997). None of these calculations included estimates of the uncertainties in the plate reconstructions.

In contrast to these earlier works, we cannot identify any resolvable changes during the Pliocene in our updated plate circuit. It is possible that there was a change and our interpolations for times younger than chron 5 missed some younger change of motion in either the Atlantic or Indian oceans. Our results suggest that this is not the case, however, because of the very close match between our chron 4-0 direction and the direction given by the Nuvel-1A solution of DeMets et al. (1994) (heavy open circles in Fig. 2). If a change in Pacific-North America motion had occurred between chron 3 and chron 2a, we would expect that the Nuvel-1A direction, which is based upon the youngest magnetic anomalies (chrons 2a, 2, and 1) from all of the world's oceans, would differ from our vectors for chron 3 and older times. In fact there is no resolvable difference between the Nuvel 1A direction and ours and no resolvable change in Pacific-North America motion direction younger than 8 Ma. Of course, some variations would be permitted within the uncertainties in the reconstructions, so we cannot rule out the possibility that small changes did take place in Pliocene time, but no such changes can actually be resolved.

The chron 4 change in motion of the Pacific plate relative to North America is clearly resolvable, but it is late Miocene in age (about 8 Ma). Thus, it may be too old to have caused the uplift and compression that have previously been attributed to a Pliocene change in Pacific-North America plate motion. An alternative explanation would be that this compression was caused by some change in the component of extension in the Basin and Range province, so that it is related to internal deformation partitioning within the North American plate rather than to any external control from changing plate motions. For example, a modest counter-clockwise rotation of the central Sierra Nevada/Great Valley block, postulated below for other reasons, could have caused the observed geological phenomena.

Reconstructed Locations of the Eastern Edge of the Oceanic Pacific Plate and their Constraints on Continental Deformations.

Our new reconstructions of the Pacific plate locations place various constraints on the time-space budget of deformation within western North America. The strongest constraint arises from the simple fact that oceanic and continental lithosphere cannot occupy the same surface area at the same time. If North America is kept in its present shape, past reconstructions of the edge of the Pacific plate result in significant, unacceptable overlaps of oceanic and continental lithosphere.

We illustrate this ocean-continent overlap problem in Fig. 4. In this figure, the gray line shows the known edge of the oceanic Pacific plate lithosphere at the time of chron 6o (20.1 Ma), located using our new chron 6o round-the-world plate circuit solution. Wherever the Pacific plate was in contact with the continent, this gray line traces the ocean-continent join along the base of the continental slope; wherever the Farallon or its derivative plates still lay between the Pacific and North American plates, the gray line traces transform faults and spreading centers along the active oceanic spreading system at the western edge of the Pacific plate. Assuming that the Pacific oceanic lithosphere has acted as a rigid plate, the overlap of the gray line over the edge of the continent shows the minimum total amount of retro-deformation within North American that is required in order to move its edge back out of the way.

In Fig. 5, we present reconstructions of edge of the oceanic Pacific plate lithosphere for selected Neogene time steps, including the edge just presented in Fig. 4. Note that the southern portions of the 6c, 6o and 5b lines all trace lengthy segments of the still-active spreading system; remnants of the Farallon plate lay between the Pacific plate and Baja California until about 12 Ma. Any deformations within North America that are related to Pacific-North America plate boundary interactions may be expected to reflect the step to step displacements of the Pacific edge that are illustrated in Fig. 5. Furthermore, while each overlap shown in Fig. 5 only literally constrains the deformation within the overlap area itself, it is likely that the continental edge was a smooth curve (or at least it was not pre-indented in just the right location), so that the displacement of a much greater length of coast can be inferred. We explore this possibility further, below.

In order to quantify the plate motion constraints for a North American deformation budget, we break down each motion/deformation estimate into coast-perpendicular and coast-parallel components of displacement, using N30°W as our approximate coast-parallel direction. The ocean-continent overlaps shown in Fig. 4 are, then, a measure of the minimum coast-perpendicular deformation required within the continent to solve the overlap problem; i.e., the continental coast-perpendicular total must equal or exceed that calculated in the Pacific-North America plate circuit solution. On the other hand, in the coast-parallel direction, the solutions supply the maximum internal deformation that might be expected. If we assume that the shear within the continent is driven by the plate interaction and that an unknown amount of slip may have occurred offshore, along the continent-ocean join, then the total coast-parallel component of deformation observed within the continent must be equal to or less than that calculated for Pacific-North America displacement. Furthermore, for reconstructions younger than 18 Ma, the plate circuit solutions may place even tighter constraints on the internal continental deformation budget, since some evidence suggests that the central California continental rim was completely coupled to the Pacific plate starting at about that time

(Nicholson et al., 1994). If this is true, the sum of continental deformations should be equal to the circuit displacements, within the uncertainties, for every time step.

For the reference point near Mendocino, the total displacement of the Pacific plate with respect to stable North America for each time step is given in Table 2. In Table 3 we break these down into their coast-perpendicular and coast-parallel components (right-hand columns labeled "Plate Circuit Total") and compare them to an estimated continental strain budget for the path from stable North America to the Colorado Plateau to central California to the Pacific plate. Strain budgets have been attempted in the past (e.g., Hornafius et al., 1986; Dickinson, 1996; Dickinson and Wernicke, 1997) and we build upon and expand these works.

Continental Strain Budgets and the Reconstruction of western North America for Past Times

Observations of Continental Deformation

The 1980s and 1990s have seen a number of advances in our knowledge of the space and time patterns of continental deformation within western North America, so that we may soon be able to make quite precise reconstructions for many time steps at various latitudes. Fig. 6 shows the major pieces of the continental puzzle, with letters, arrows, and rotation angles marking the various continental deformations for which there are quantitative estimates. These and other constraints and observations are summarized next.

1. For any time step, the **total continental strain** across western North America when compared to that calculated via the round-the-world plate circuit (Table 2) must equal or exceed the circuit solution in the coast-perpendicular direction (i.e., it should equal or exceed the amounts listed in the right-hand column of Table 3a). It must be equal to or less than the circuit solution in the coast-parallel direction, (i.e., it should be equal to or less than the amounts listed in the right-hand column of Table 3b). Furthermore, we hypothesize that the continental and circuit strain totals should be about the same since 18 Ma. Essentially this amounts to assuming that, prior to 18 Ma, right-lateral strike-slip faulting and/or convergence may have taken place offshore, either within the continental margin or along the continent-ocean contact zone, but since 18 Ma the continental margin has been attached to the Pacific plate.

2. The total Neogene opening across the **Rio Grande Rift** was small: 10-20 km. We assume, following Chapin and Cather (1994), that this deformation was accomplished by rotation of the Colorado Plateau 1.5° clockwise about a pole in northeastern Utah.

3. The **Colorado Plateau** acted as a rigid block without significant internal deformation.

4. The **Sierran-Great Valley block** acted rigidly, without significant internal deformation, except near its southern end. From paleomagnetic studies of the central portions of the Sierra Nevada, Frei (1986) reports a clockwise rotation of 6±8° (i.e., indistinguishable from zero) since the early-Late Cretaceous. In our reconstructions we violate this slightly, letting this block rotate counter-clockwise approximately 5° since 20.1 Ma. We do this in order to create smooth continental edges in the reconstructions, and we embrace it as a way to help create a triangular space for the Santa Maria Basin, described in number 8, below. We note that this postulated counter-clockwise rotation of the Sierran-Great Valley block would not violate the paleomagnetic data if it were counter-acting a rotation in the opposite sense during Laramide time, as suggested by Walcott (1993). Our rotation implies that Basin and Range opening was greater in northern Nevada than in the region described next.

5. The total opening since 16 Ma between the Colorado Plateau and the Sierra Nevada, across the **Basin and Range province** near the latitude of Las Vegas, Nevada, was very large (Wernicke et al., 1988; Snow and Wernicke, in press 1998). Wernicke and Snow (this issue) report the motions of two points, point A near Bishop, CA, and point B near Ridgecrest, CA (A and B on Fig. 6) as follows:

Since about 10 Ma point A moved about
160 km N46°W.
Since about 10 Ma point B moved about
185 km N68°W
Since 16 Ma point A moved about
265 km N65°W
Since 16 Ma point B moved about
325 km N77°W

Note that the displacements of these two points differ from one another. A literal use of both of these displacement paths implies that the Sierra Nevada block between the two points rotated 20° clockwise during the last 10 million years. This could be accomplished by rotation of the entire Sierran-Great Valley block (as suggested by Wernicke and Snow, this issue) but this conflicts with loose geometric constraints described in numbers 4, 8, and 11. Alternatively, it could indicate significant internal deformation and flexure within the southern part of the block, an interpretation that is supported by observations of significant present-day seismicity and geodetic deformation on several known and implied fault zones within the southern Sierra Nevada (Bawden et al., 1997; Bawden and Michael, personal communication). We adopt this flexural solution for now, even though it violates sparse paleomagnetic data suggesting minimal post-16 Ma rotation of the Tehachapi Mountains (described next). Yet another alternative is to assume that the track for one or the other of the Wernicke and Snow points is in error and may be ignored so that no young rotation is indicated. In that case, we would be required to use the larger (point B) displacement for the entire block in order to avoid an unacceptable oceanic overlap at the southernmost end, an assumption which seriously violates the displacement budget for the other track (point A) (Wernicke, personal communication).

Geodetic measurements of displacements across the Great Basin yield a total present-day rate of about 12 mm/yr with a coast-parallel shear rate of about 11 mm/yr across the eastern California shear zone (Feigl et al., 1993; Dixon et al., 1995; Bennett et al., 1998). We note that these rates are somewhat slower than the long term average implied by the point displacements described above.

6. The **Tehachapi Mountains,** at the southern edge of the Sierran-Great Valley block, are reported to have rotated 45°-60° clockwise (Kanter and McWilliams, 1982; McWilliams and Li, 1985) between 23 and 16 Ma. Both the timing and deformation configuration here and in the northern Mojave are subjects of considerable controversy (e.g., Plescia et al., 1994; Dokka and Ross, 1995; Glazner et al., 1996). This deformation remains an unknown in our reconstructions. It may be responsible for displacements of 40 km each in the coast-parallel and coast-perpendicular directions (Dickinson, 1996).

7. Strike-slip displacement along the **central San Andreas fault** since 23 Ma was 315 ± 10 km, in a N40°W direction, to reconnect the Pinnacles to the Neenach volcanics (Matthews, 1976; Sims, 1993). Of special interest is the partitioning of this strain over time, and in particular, the amount of this slip that occurred post-8 Ma. Dickinson (1996) suggested that the bulk of the displacement was late and budgeted about 255 km since 8 Ma, while Sims (1993) implied that the post-8 Ma amount was about 200 km. We find that the latter estimate is more compatible with other post-8 Ma estimates, as discussed below, and so adopt it for now.

8. In **coastal California**, west of the San Andreas fault, two independent estimates of deformation have been made. 1) In central California offsets on individual fault strands plus pervasive shear deformation of the ground between them yields an estimate of about 250 km total, with about 80 km since 8 Ma (Hornafius et al., 1986) in an approximate coast-parallel direction. 2) A 110° clockwise rotation of the western Transverse Ranges block amounts to a coast-parallel displacement of about 270 km, with about 60 km since 8 Ma (Hornafius et al., 1986). In the coast-perpendicular direction, an extension about equal to the width of the inner borderland, about 100 km, is indicated for southern California using the assumption that it and the Santa Maria Basin were formed by “core-complex-like" openings (Crouch and Suppe, 1993; Kamerling and Luyendyk, 1985). However, north of the Santa Maria Basin, in central California, very little coast-perpendicular extension is evident. Indeed, the triangular shape of the Santa Maria Basin is difficult to understand in terms of purely translational offsets; simple transtension in the wake of the rotating western Transverse Ranges would have created a rhomb-shaped space. This odd configuration probably requires a rotation of the Sierran-Great Valley block, as described in number 4, above.

9. The **Oregon Coast Ranges** rotated 18-36° clockwise about a pivot point in Washington since 30-20 Ma and 10-15° since 15-12 Ma (summarized in Wells, 1990). We follow the model put forward by Magill and Cox (1981), Frei (1986), and Walcott (1993) that the southern end of the Oregon Coast Ranges moved with the northern end of the Sierran-Great Valley block.

10. The **Baja California Peninsula** moved about 300 km in a direction parallel to the Gulf of California transform faults since about 5 Ma. Since about 12 Ma, a coast-parallel dextral displacement of 250 - 300 km is postulated on the Pacific side of the Peninsula, along the offshore Tosco-Abreojos fault zone of Spencer and Normark (1979) in order to account for the offset of the Magdalena Fan (Lyle and Ness, 1991). Also, a substantial but unknown amount of Miocene and/or younger extension with a major coast-perpendicular component occurred in northeastern Baja California, Sonora, and east of the Sierra Madre Occidental (e.g., Stock and Hodges, 1989; Gans, 1997; Henry, 1997).

11. We assume that the Early Cenozoic **continental edge** formed a smooth curve from Vancouver Island, British Columbia, to Manzanillo, Mexico. Thus, reconstructions of some points along the continental edge can be used to estimate the placement of the rest of it.

Continental Reconstructions and Strain Budgets

Fig. 6 illustrates many of the constraints just described, and Figs. 7a and 7b show our attempts to reconstruct North America and the Pacific plate using these constraints for chron 6o (20.1 Ma) and for chron 5o (10.9 Ma), respectively. There is only one complete path between stable North America and the Pacific plate along which we can attempt a quantitative reconstruction. This is the Colorado Plateau - central California path described in numbers 2-8, above. The approximate quantitative budgets for this path are listed in Tables 3a and 3b. We reconstruct the other parts of the Fig. 7 maps using the other numbered observations and letting the unquantified regions take up the slack.

The coast-perpendicular budgets estimated in Table 3a constitute a very stringent constraint for mid-Cenozoic reconstructions. Indeed, the 24 Ma reconstruction can only be made to fit along this path if the largest allowed continental displacements are assumed (i.e., using point B in number 5). This very tight fit in the coast-perpendicular component is encouraging, suggesting that we are near to the actual solution. Furthermore, it implies that no significant additional area of the Pacific plate existed offshore at 24 Ma that has been subducted since that time. (The existence of such an area would require an even greater deformation within the continent in order to make room for it offshore.) This is a very important conclusion, as it allows us to use the present nearshore seafloor patterns to describe the original Pacific-North America encounter, an assumption that is almost universally made. On the other hand, it does imply that layers imaged in coastal seismic refraction profiles that have been interpreted as underthrust Pacific plate (e.g., Page and Brocher, 1993) may need to be reinterpreted. They could, instead, be stalled pieces of the Farallon plate, or they could be mafic materials that were underplated onto the base of the continent during the opening of a slab window.

Ironically, by 8 Ma the budget problem is reversed: significantly more coast-perpendicular deformation is implied by the post-8 Ma continental deformation than is needed to balance the plate motions. During this time interval, the Pacific plate reference point was outboard of the central Sierran-Great Valley block, so one way to resolve this difference would be to call on the block rotation advocated in number 4 and assume that that rotation occurred post-8 Ma.

For the coast-parallel budgets, Table 3b, the continental and oceanic totals are equivalent within the broad uncertainties of the continental data for ages younger than 18 Ma, as expected. In the fourth column ("Cent. San Andreas") we list the two alternative time-partitions of offset described in number 7, above. Note that the assumption that the offset on the San Andreas is mostly young (i.e., post-8 Ma) leads to a continental total (bottom row) which is too large.

Uncertainty concerning Rotations of the Sierran-Great Valley Block

An important uncertainty that arose several times in the above descriptions of continental deformations concerned the possible Cenozoic rotations of the Sierran-Great Valley block. Because of the important and pervasive implications of this problem, we reiterate and summarize it here. Paleomagnetic studies imply that since Cretaceous the main part of this block has not experienced a significant net rotation, but these results do not rule out any Cenozoic rotations that may have occurred but were then counteracted by other rotations in the opposite sense. Indeed, such a scenario might be expected, given the very different tectonic regimes of the Early and Late Cenozoic: Laramide subduction followed by San Andreas transtension (Walcott, 1993). Thus, at present we are quite free to postulate any convenient Neogene rotation for this block.

In our reconstructions, we assumed that the Paleogene continental edge (a subduction margin) formed a smooth curve and we accomplished this by assuming the main Sierran-Great Valley block rotated about 5° counter-clockwise during the Neogene (i.e., we rotate it back 5° clockwise to make our 20 Ma reconstruction). We also stated that a rotation in the same sense may help explain the triangular shape of the Santa Maria Basin, but we note here that the geometry of that basin actually suggests 15-30° of counter-clockwise Neogene rotation of its northeastern edge, depending on how the edges of the basin are chosen. Wernicke and Snow (this issue) also mention a Neogene rotation of the Sierran-Great Valley block as a possible solution for the strain differences between their two reconstruction paths, but they call on a rotation in the opposite sense: 20° clockwise in the last 10 m.y. The situation is complicated by the likelihood that the southern end of the Sierran-Great Valley block has undergone major rotation, 45°-60° clockwise, apparently mostly in the early Miocene, and an internal deformation that is still ongoing.

Our present preference is to assume that the main Sierran-Great Valley block experienced a modest, late Neogene counter-clockwise rotation while the southern end experienced a major clockwise flexure, partly in early Miocene time in response to Mojave expansion and partly in the last 10 m.y. to satisfy the Wernicke and Snow reconstructions. We note, however, that this model is quite ad hoc. It mostly serves to emphasize the importance of obtaining more paleomagnetic information from Cenozoic rocks from all parts of the Sierran-Great Valley block.

Implications for Northern and Southern Strain Budgets

In Cascadia, north of the Sierran-Great Valley block, the coast-perpendicular deformation budget can be estimated by combining the central California solutions with the assumption of a smooth coastline described in number 11. This component of the deformation budget is fit very well by the Coast Range rotations, as has been noted by various authors, described in number 9. However, a substantial coast-parallel shortening, about 200 km since 16 Ma, is also mandated by the displacements of the Sierran-Great Valley block (as listed in the third column, labeled "Basin & Range" in Table 3b). To our knowledge, this aspect of the Sierran-Coast Range coupling has not previously been examined. Some of this shortening may have been accomplished by the thrust faults that surround the Olympic Peninsula and by a number of dextral shear zones that obliquely cross the Cascade arc (Snavely, 1987; Wells, 1990; Mann and Meyer, 1993). Furthermore, ongoing N-S compression is suggested by focal mechanisms and traces of active faults beneath the Puget Lowlands (Ludwin et al., 1991; Ma et al., 1996; Pratt et al., 1997). However, it remains to be seen whether NNW shortening on the order of 200 km can be documented.

In the Mexican portion of Figs. 7a and 7b, we undo the oblique spreading that formed the Gulf of California, as described in number 10 and arbitrarily close up the Mexican Basin and Range province by the amount necessary to avoid overlap of Pacific oceanic plate with the continental crust of Baja California. We arbitrarily keep the Sierra Madre Occidental block in the middle of the Mexican Basin and Range province during these reconstructions. The correct placement for this block is unknown; it is clear that there has been major Neogene extension on both sides of the Sierra Madre Occidental, but present geologic data are insufficient to constrain the relative strain histories on the two sides (e.g., Gans, 1997; Henry, 1997). Note that in our reconstructions (Figs. 7a and 7b), some of the expected coast-perpendicular extension occurs between chron 6o and chron 5o and some occurs after chron 5o time (i.e., after 10.9 Ma).

A quantitative discussion of the amount of coast-parallel slip offshore of the Mexican portion of the reconstructions is only meaningful for times since chron 5a (12.3 Ma), because prior to this time there was an active subduction zone immediately west of the southern half of the Baja California Peninsula (e.g., Lonsdale, 1991; Stock and Hodges, 1989). For times since 12 Ma, there is no obvious discrepancy between the coast-parallel slip determined from the plate circuit and that determined from summing the geological estimates (including closure of plate boundary slip in the Gulf of California and postulated offset on the Pacific side of the Baja Peninsula, as described in number 10 above).

Creation and Evolution of Slab Windows beneath Western North America

An important and long recognized consequence of the intersection of the East Pacific Rise with the North American subduction zone is the creation of slab-free regions or "slab windows" beneath the continental plate. These windows, in turn, have been correlated to volcanic, uplift and rifting events in the overriding plate (e.g., Dickinson and Snyder, 1979; Dickinson, 1997). However, there is not general agreement about the shapes of the windows, the relative robustness and importance of their various edges, their locations with respect to the overriding North American plate, or even what they actually represented in terms of the lateral variations in the region of the downgoing slab (e.g., Severinghaus and Atwater, 1990; Bohannon and Parsons, 1995). Thus, a careful analysis of the possible geometry of these windows seems warranted at this time.

Breakup of the Farallon Plate

During the Late Cretaceous, the Farallon-Pacific spreading system spanned 90 degrees of latitude and both plates were very large. During the Cenozoic, the Farallon plate has gradually broken up into various medium and small sized plates, as summarized in Atwater (1989). A break at about chron 24 (about 52 Ma) spawned a semi-independent plate in the north, the Vancouver plate (the predecessor to the Juan de Fuca plate). This break occurred across a neck in the Farallon plate between the Pioneer and Murray fracture zones. The trace of this break, the Pacific-Farallon-Vancouver triple junction, is recorded in the isochron 23-13 pattern that presently stretches across the seafloor west of Monterey, California. It can also be seen as a subtle but distinct difference in trends of the Pioneer, Mendocino, and other northern fracture zones as compared to the trends of the Murray and all other fracture zones to the south. It appears that the new Vancouver plate remained somewhat coupled to the Farallon plate until chron 10y (28 Ma) because the directions and rates of the two plates continued to be quite similar (Rosa and Molnar, 1988). This first break probably did not create a significant slab window beneath the continent, but it did establish a weak zone for later, major breakage.

The isochron patterns in the seafloor just west of central California, shown in Fig. 8, provide a detailed record of the approach, breakup, and demise of the East Pacific Rise in this area, as follows. By the mid Cenozoic, the spreading center just south of the Pioneer fracture zone had come very near to the North American subduction zone. At the time of chron 10y (28 Ma), the last narrow section of the intervening plate broke, abruptly, into two small plates, the Monterey and Arguello micro-plates (Lonsdale 1991; Atwater, 1970, 1989; Severinghaus and Atwater, 1990; Fernandez and Hey, 1991). We also, by somewhat arbitrary convention, change the name of the northern plate from Vancouver plate to Juan de Fuca plate at this time. Subduction became very slow in the adjacent subduction segment. The remaining larger oceanic plates to the north and south, the Juan de Fuca and Farallon plates, continued their fast subduction but became more erratic in their motions with respect to the Pacific plate and with respect to one another, suggesting that the contact between them had been lost (Wilson, 1988; Atwater, 1989).

The timing of this sudden breakup of the fast-subducting plates is quite important because of its on-land geologic implications. The changes in direction and rate are clearly recorded in the isochron patterns within the Pacific plate. They suggest that the breakup occurred between chrons 10 and 9, about 28 Ma on the time scale of Cande and Kent (1995). This is 2 m. y. younger than previously generally reported, primarily due to revisions of the polarity reversal time scale.

After the breakup, the Monterey and Arguello microplates continued to spread away from the Pacific, albeit slowly and obliquely, and to subduct beneath North America, also very slowly. At about chron 5E (about 18 Ma) the last remnant of the Monterey-Pacific spreading center stalled and the Monterey microplate was "captured" by the Pacific plate. With this microplate capture, the Pacific-North America plate boundary was completed all along the coast from Cape Mendocino to Santa Lucia Bank, near Point Conception, a segment 700 km in length.

In our reconstructions, we assume that the central California segment of the continental rim has been rigidly attached to the Pacific plate and moving with it since the capture of the Monterey microplate about 18 Ma. While this is not the only possible assumption, we feel quite confident that it is valid. Significant strike-slip along the toe of the continent (i.e., between the Pacific plate and the continental edge) seems ruled out by the deep seismic imaging of the Morro fracture zone beneath the continental shelf. If significant ocean-continent shear had occurred since its emplacement, this feature would no longer be aligned with its offshore counterpart (Nicholson et al., 1994).

Mid-Cenozoic Slab Window Evolution

The fragmentation of the Farallon plate, just described, is known from seafloor isochron patterns that have been mapped in the offshore Pacific plate. These patterns also have implications for the geometry of the breaks that must have occurred within the subducting plates that lay beneath North America. In Fig. 9 we present images of the possible evolution of these sub-continental breaks and the resulting slab windows during their period of formation, 28-18 Ma. For these constructions, we assumed no slab dip. Various additional assumptions had to be made in order to construct each of the various portions of the windows, identified by the letters A through D on Fig. 9b, with quite different resulting uncertainties, as follows.

Window Region A. This window is the gap formed starting at 28 Ma when the Monterey microplate broke off and moved southeast away from the Juan de Fuca plate. An opening of this area in about this location is required by the isochron geometry. We feel most confident about the existence, location and geometry of this part of the window.

Window Region B. This is the slab window region that would have formed starting about chron 7 (26 Ma), if the Mendocino-Pioneer spreading center segment entered the subduction zone directly, with no creation of microplates. Such a direct entry seems likely, since the Mendocino-Pioneer strip of the subducting plate was attached across the Mendocino fracture zone to the old, strong, easily subducted plate to the north. This geometry is similar to – and even more pronounced than – the present configuration of the South Chile Rise, where a segment of the spreading center is half subducted without any sign of slowing or breakage of the subducting plate (Herron et al., 1981; Tebbens et al., 1997). Alternatively, if a microplate did break off along the subducted Mendocino fracture zone, (e.g., as postulated by Bohannon and Parsons, 1995) a slab window region would still be formed with the area shown; its location would simply be shifted eastward. Furthermore, such a microplate, if it did form and attach itself to the Pacific plate, would have been surrounded by windows on the south and east and a fast subducting plate on the north, so probably would not have stayed attached to the surface Pacific plate for long.

Window Regions C and D. These two window regions are the least well located. They were drawn to illustrate the gaps that would have appeared somewhere in the downgoing slab after the Monterey and Arguello microplates broke away and slowed, assuming that the previously subducted parts of the Juan de Fuca and Farallon plates farther east remained intact and continued to subduct. We made the arbitrary assumption that the original break occurred along a line about 50 km inboard of the trench (gray zig-zag line with <'s on Fig. 9a). If the break had been closer to the trench, we assume that subduction would have stopped. Since the microplates continued to subduct, we suppose that the break occurred at or farther east than the position of this line. The assumption that the portions of the subducting slabs east of regions C and D remained intact is suspect since they were quite young when they subducted and thus had had little time beneath the ocean to cool and strengthen (Severinghaus and Atwater, 1990). Furthermore, in order to draw regions C and D, we assumed that the boundary between the two microplates was a transform fault in the direction of relative motion between the microplates and we assumed that the break between the fast subducting Juan de Fuca plate and the medium-fast subducting Farallon plate was in the middle of the Pioneer-Murray panel, utilizing the long-term Vancouver-Farallon break already established there (ragged gray region with x's on Fig. 9b). These are the simplest geometric assumptions but they are not necessarily true. Given the arbitrary aspects of all of these various assumptions, we conclude only that slab-free areas about equivalent to the spaces marked C and D should have appeared at about these latitudes at these times, at or to the east of the locations shown, but their actual locations and shapes are unknown.

Slab Window locations with respect to North American Features

The most interesting aspect of the slab windows is their possibly causal relationship to tectonic features and events in the overriding North American plate. In Fig. 10 we used our new circuit solutions to place the windows beneath our 20 Ma continental reconstruction, combining information from Figs. 5, 7a, and 9. We do not know the dip of the mid-Cenozoic slab, but we supposed that it was similar to the 15-20° dip presently observed for the uppermost parts of the Cascadia slab (Crosson and Owens, 1987; Clowes et al., 1995) and of many other slabs (Jarrard, 1986). In fact, in Fig. 10 we simulated an 18° slab dip by shortening the patterns from Fig. 9 toward the coast by 5%. In general, the resulting windows lie beneath the Mojave desert and southernmost Great Valley, as asserted by previous workers (e.g., Dickinson, 1997, Dokka and Ross, 1995; Dokka et al., 1998) although they extend farther north beneath the Sierran-Great Valley block than has been previously proposed. In detail, the placement depends upon the deformation, timing and configuration of the Tehachapi mountains, as described in number 6 above, reiterating the importance of continued work on the early Miocene tectonics in that area.

The windows in Figs. 9 and 10 were drawn assuming that the coastline followed the Pacific plate westward, i.e. that the coast-perpendicular motion of the continental rim matched that of the Pacific plate. This amounted to about 65 km of continental expansion in the interval from 26 to 20 Ma. The earliest Miocene is a time of large-magnitude detachment-style extension in the Mojave desert (e.g., Dokka, 1986, 1989; Walker et al., 1990, 1995; Fletcher et al., 1995; Ingersoll et al., 1996; Fillmore and Walker, 1996) and abrupt deepening of the southernmost San Joaquin valley (Davis and Legoe, 1988; Goodman et al., 1989; Graham et al., 1990; Goodman and Malin, 1992), so a continental expansion at this time seems likely. However, since the details of the early Miocene continental deformation have not been quantified, we used our 20 Ma reconstruction for all the reconstructions in Fig. 10, recognizing that this is only a crude approximation. Also, we drew the continental edge as straight, but we note that a local bulge in the coastline, possibly formed during this early localized extension, would permit the granites that are now in the Salinian block to have been pulled west of the main Cretaceous batholithic belt, in a position where they could easily be sliced off and carried northwestward along the coast (e.g., Mattinson and James, 1985; Mattinson, 1990; James, 1992).

The configurations shown in Fig. 10 were placed assuming an 18° slab dip. The subducting Farallon and Vancouver slabs are thought to have re-established a standard dipping configuration by this time (following a postulated Laramide flat-slab episode) but if the dip were steeper or shallower than 18°, all window patterns in Fig. 10 must be shifted westward or eastward, respectively. Also, as the slabs descended into the mantle, they would have lost contact with the overriding plate at some point. This phenomenon is depicted as speckled fadeouts along right-hand sides of Fig. 10, but we do not know how far inland this actually occurred. Furthermore, we assume that as a slab window forms, asthenosphere rises to fill the gap and freezes onto the continental underside. Thus, the effective geologic life span of a given portion of a window should be short. To illustrate this, in Fig. 10c we show the older slab window regions as light gray and only the youngest portions as dark gray. In any event, we conclude that after about chron 6o time, 20 Ma, the only geologically relevant slab window edge beneath the United States was the northern, Mendocino edge.

Coming forward in time, the Mendocino slab window edge migrated northward with the Pacific plate. In Fig. 11 we construct the time displacement of this edge with respect to the Sierran-Great Valley block. We drew these displacements by combining the motions of the Pacific plate implied by our circuits with the motions of the Sierran-Great Valley block described by Wernicke and Snow (this issue), and since the rotation of the main Sierran-Great Valley block is uncertain, we assumed no rotation for this construction. After 6 Ma the motion of the Juan de Fuca/Gorda plate with respect to the Pacific plate shifted from eastward to ESE, changing the direction of subduction. We adopt the careful analysis of Wilson (1989) of these plate motion changes and the resulting shapes of the 6, 4, 2, and 0 Ma edges of the downgoing slab. (The differences between our map view and that of Wilson arose because we added the motion of the Sierran-Great Valley block with respect to stable North America.) The most noteworthy aspect of our successive reconstructions, Fig. 11, is that from 4 Ma to the present, the slab edge is stationary beneath the Sierran-Great Valley block at a (present) latitude of about 39.5°N, just north of Sutter Butte.

One other interesting aspect of the Fig. 10 constructions is the configuration of the underthrust Monterey microplate (white region beneath the western Transverse Ranges, TR, in Figs. 10b and 10c). This microplate is interpreted to have stalled and attached itself to the Pacific plate at about 18 Ma. The subsequent displacement of this flap of Pacific plate beneath the western Transverse Ranges block is suggested by Nicholson et al. (1994) to have caused the unusual rotation of the overriding block. Furthermore, the underthrust plate area shown in Fig. 10c is the minimum area of oceanic microplate underthrust. Some of this oceanic plate might still be present beneath southern California today, and it may be the piece of oceanic lithosphere postulated to be presently descending into the mantle beneath the western Transverse Ranges and northwestern Mojave Desert (Bird and Rosenstock, 1984; Humphreys, 1995).

Discussion

Our ultimate objective in determining the Pacific-North American plate reconstructions is to compare them to the geology within the North American continent, with particular emphasis on two issues: the relationship of the plate displacements to the magnitude and direction of continental extension and shear and the relationship of the slab windows to the tectonics of the overlying plate.

Our results do suggest a close relationship between the relative Pacific-North America plate displacements and the magnitude and direction of continental extension in the Basin and Range province. The most recent update of the history of extension at the latitude of Las Vegas, Nevada is given by Wernicke and Snow (this issue) from integrating the displacement direction and timing of various normal and strike-slip fault systems between the Sierra Nevada, California, and the Colorado Plateau. These geological observations show that the direction of motion of the Sierran-Great Valley block, relative to the Colorado Plateau, was approximately east-west during the interval from 16 to 10 Ma, and then changed to become more northwesterly from 10 Ma to the present. The exact direction of northwesterly motion varied with latitude, but nevertheless, the northwestward change of the displacement direction at about 10 Ma is quite striking. We speculate that this 10 Ma change may correlate with the chron 4 northward change in direction of relative motion between the Pacific and North America plates (Fig. 2). The uncertainties in the geological data are such that this change in direction of slip within the Basin and Range province could have occurred at chron 4, 8 Ma, rather than 10 Ma. Note that we do not expect the direction of extension in the Basin and Range province to exactly match the plate motion direction either before or after the clockwise change in plate motion, because some of the plate boundary deformation was taken up on the San Andreas and related faults.

The slab windows shown in Fig. 10 were drawn assuming that the slabs had an 18° dip and were rigid. In any interpretation of the relationship of the slab windows to the geology of the overlying North America plate, it must be remembered that (1) the paleo-dip of the slabs is not known, in fact, so that the boundaries of the windows could be shifted somewhat to the east or to the west; and (2) the downgoing plate may, in fact, not have been rigid; it may have suffered plastic deformation and stretching and contortion in the vicinity of the slab windows. Thus, despite the precision with which we can reconstruct the relevant plate motions and the expected slab window shapes, the locations of the slab window edges may never be very well known, especially in their east-west placements.

The inter-relationship of the plate boundary geometry with plate margin volcanism is also an interesting issue. This relationship has been recently summarized by Dickinson (1997). Our updated Pacific-North America plate circuit does not fundamentally change any of his conclusions, since the positions of the triple junctions along the margin are similar to previous estimates (Stock and Molnar, 1988).

Conclusions

We present a new global plate circuit solution for the Late Cenozoic displacement of the Pacific plate with respect to North America. The new reconstruction for "global chron" 5 (10.9 Ma) matches the previous solution very closely, but those for "global chrons" 6 and 13 (20.1 and 33.1 Ma) are significantly changed. We also include reconstructions for some intervening semi-interpolated chrons to augment the solution. The resulting displacement path is much smoother, in both rate and azimuth, than previous solutions, and at the young end it agrees quite precisely with the semi-independent Nuvel-1A solution.

Our best solution for the displacement of a point on the Pacific plate, now near the Mendocino Triple Junction, relative to stable North America, 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 still about N60°W, but the rate was faster, about 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.

Our solutions for the latitude of central California include a distinct direction change at chron 4 time (about 8 Ma), from more offshore to more coast-parallel. Previous models included a similar change and the onsets of various compressive events in coastal California have been attributed to that change. However, the change was generally believed to occur in Pliocene time, while we calculate the primary change to be at about 8 Ma, distinctly older.

Our new circuit solutions yield coast-parallel displacements through time that are quite similar to those predicted by previous models. On the other hand, for times older than 10 Ma we calculate significantly greater coast-perpendicular displacements than in previous models. We calculate more than 300 km of coast-perpendicular displacement since chron 6c (24 Ma), which, in turn, requires a Neogene coast-perpendicular expansion of the North American continental lithosphere of 300 km or more. Our reconstructions and space budgets thus rely very heavily upon the very large-magnitude extensions reported and quantified for the detachment-faulted terranes of the Basin and Range province by Wernicke and Snow (this issue). Indeed, our results require these large deformations in order to avoid the unacceptable overlaps of oceanic and continental lithosphere that otherwise result.

Our reconstructions place the early Pacific-North America plate contact region in southern California. The final reconstruction of mid-Cenozoic North America thus particularly depends upon the deformation budgets of the Mojave region and of the southernmost part of the Sierra Nevada block. The future quantification of the Neogene deformation of these regions, presently a subject full of controversies, takes on even more urgency.

At present, a quantitative reconstruction of the mid-Cenozoic continent can only be attempted along one path: stepping from stable North America to the Colorado Plateau to the Sierran/Great Valley block to the central California margin. The fact that this reconstruction path gives a deformation budget very similar to the one independently derived via the oceanic circuit gives us confidence that we are on the right track. A single additional assumption, that the margin of the continent had a smooth shape inherited from the preceding subduction era, allows us to then make estimates for the deformation budgets in regions to the north and south. In the north, we predict a substantial (about 200 km) coast-parallel shortening in addition to the long-recognized rotations of the Cascadia Coast Ranges. In Mexico, the budgets require percentages of coast-perpendicular expansion similar to those known from the Basin and Range province in the United States, both east and west of the Sierra Madre Occidental block.

We use isochron patterns in the Pacific plate to trace the evolution of the Farallon, Juan de Fuca, Monterey, and Arguello plates during their mid-Cenozoic interaction with the rim of North America.

From these patterns, we construct potential shapes and sizes of the resulting "slab windows" beneath the continent. Our reconstructions place the most robust window beneath the Mojave region during the 26-19 Ma time step, reinforcing suggestions that the early Miocene volcanism and extension of this region may have resulted from asthenospheric upwelling into a sub-lithospheric slab window there.

Finally, we examined the 20-0 Ma drift of the Mendocino slab window edge beneath California. We did this by combining our circuit solutions for Pacific plate motions with a construction by Wilson of the shape of the southern edge of the subducted Juan de Fuca/Gorda plate and with the estimates of Wernicke and Snow for the motions of the Sierran-Great Valley block. This analysis suggests that the edge migrated north quite steadily until 4 Ma, at which time it stalled with respect to the Sierran-Great Valley block just north of Sutter Buttes.

Acknowledgments

We thank Brian Wernicke and J. Kent Snow for allowing us to use their results in advance of publication. We thank Gene Humphreys, John Crowell, Bruce Luyendyk, Craig Nicholson, Gary Axen, Michael Singer, and Marcy Davis for helpful reviews and Brian Wernicke, Doug Wilson, Gene Humphreys, Rob Twiss, Bob Butler, Wayne Thatcher, and Peter Weigand for helpful conversations, advice and suggestions. We thank the Hall Symposium participants for lively feedback and Gary Ernst for his reviews, advice, and patient good humor. This work was supported by NSF Grant EAR-9614674 to J. Stock.

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Tables

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.

Figures

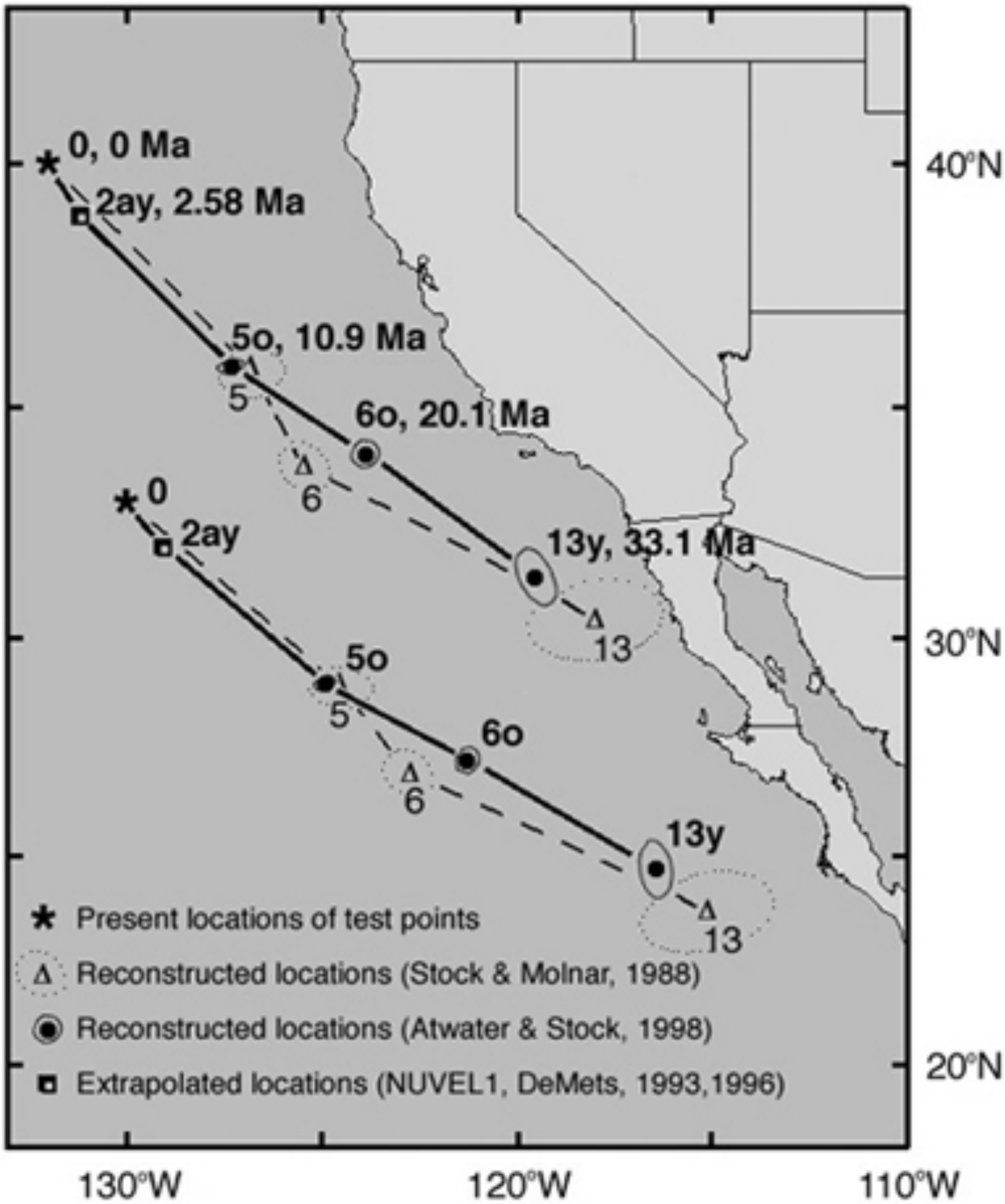

Figure 1. Map showing tracks of two arbitrary reference points on the Pacific plate, moving relative to a fixed North American plate. Present positions of the points are marked with small stars labeled "0". Past positions of these points are shown for the times of global chrons 5o, 6o, and 13y, reconstructed 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.

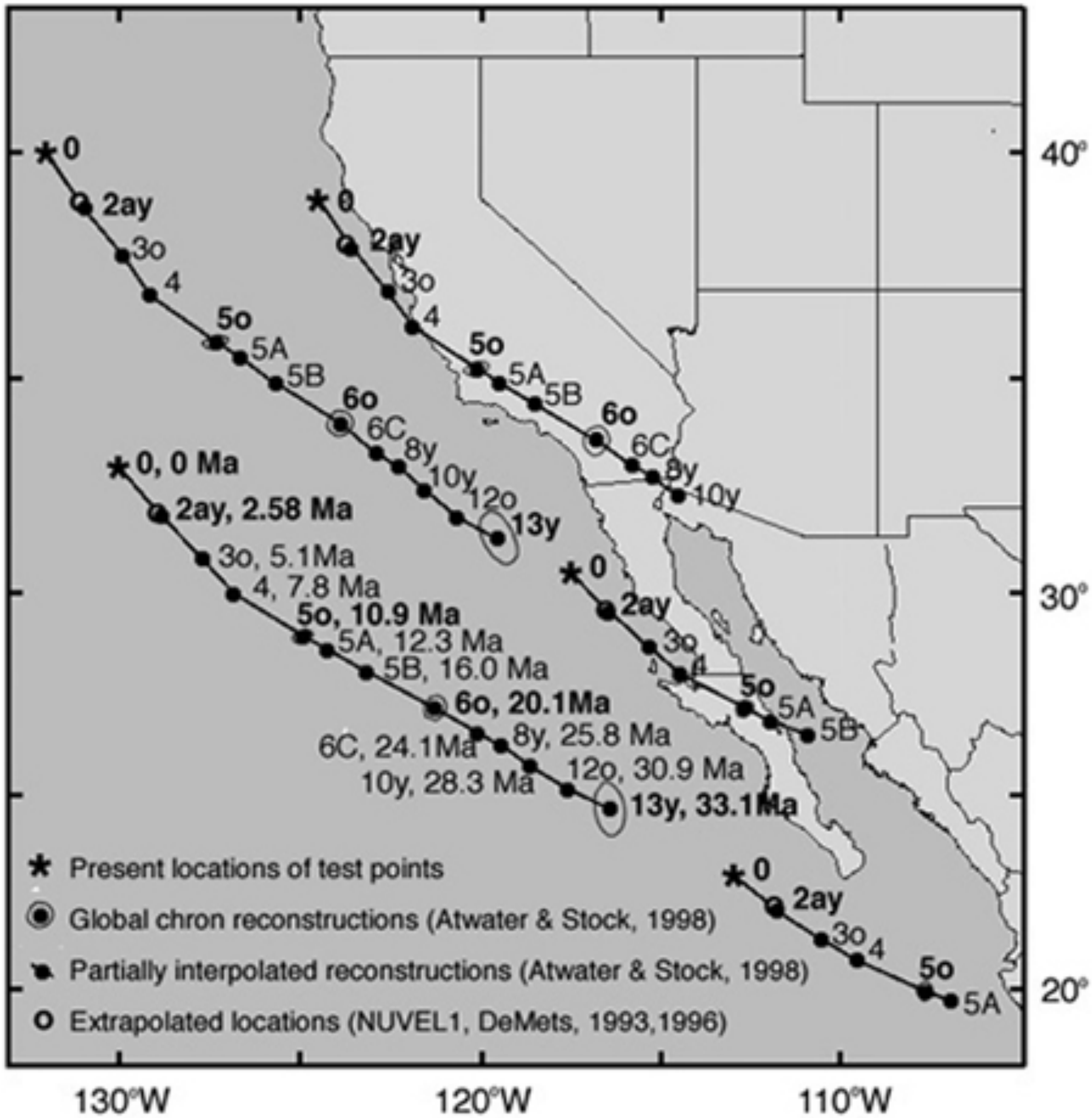

Figure 2. Map showing tracks of arbitrary reference points assumed to move with the Pacific plate relative to a fixed North America plate. Present positions of the points are marked with symbols labeled "0". Past positions of these points are shown for the chrons whose ages are listed in Table. 1. Ellipses 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.

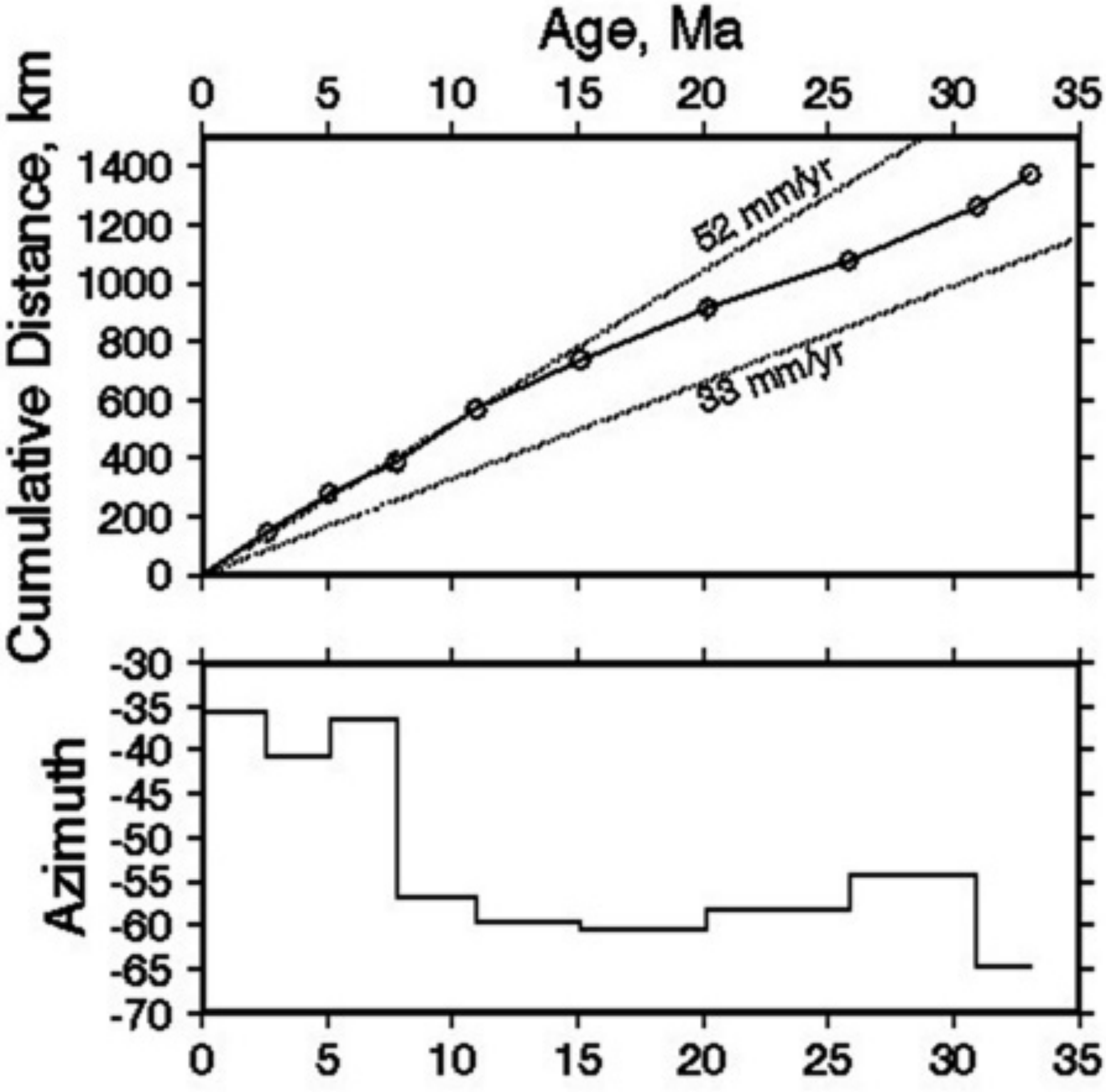

Figure 3. Displacement of a point now on the Pacific plate at 38.5°N, 124.0°W, near the Mendocino Triple Junction, calculated from the global plate circuit solutions illustrated in Figure 2. A clear change in the rate of displacement is shown by a change in slope in the top plot at about 12 Ma. A clear 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.

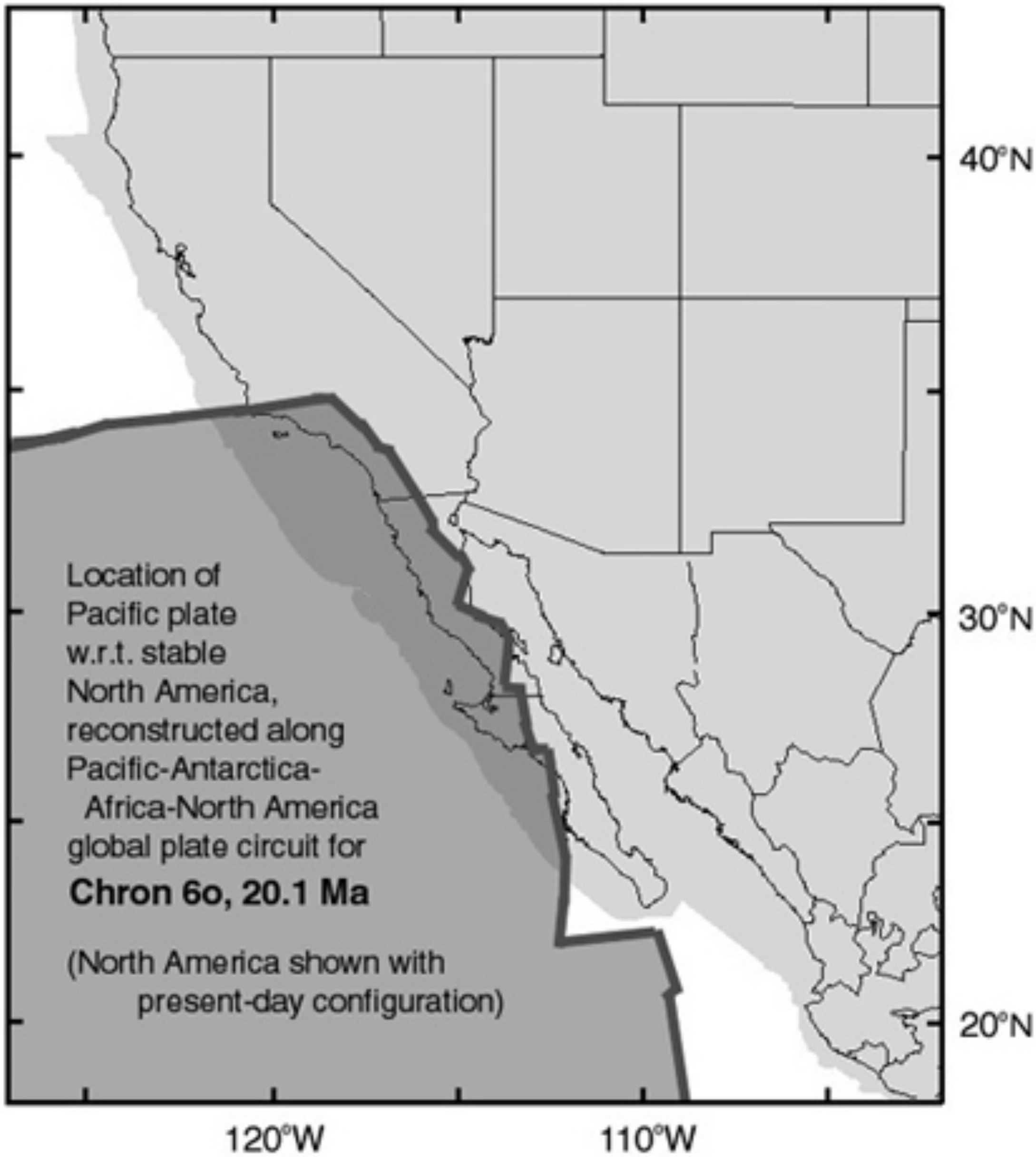

Figure 4. Location of Pacific plate oceanic lithosphere at the time of chron 6o (20.1 Ma), relative to a fixed North America, plotted upon the present shape of North America. Heavy gray line is the eastern edge of known oceanic crust, drawn to trace either the spreading system that was active at chron 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.

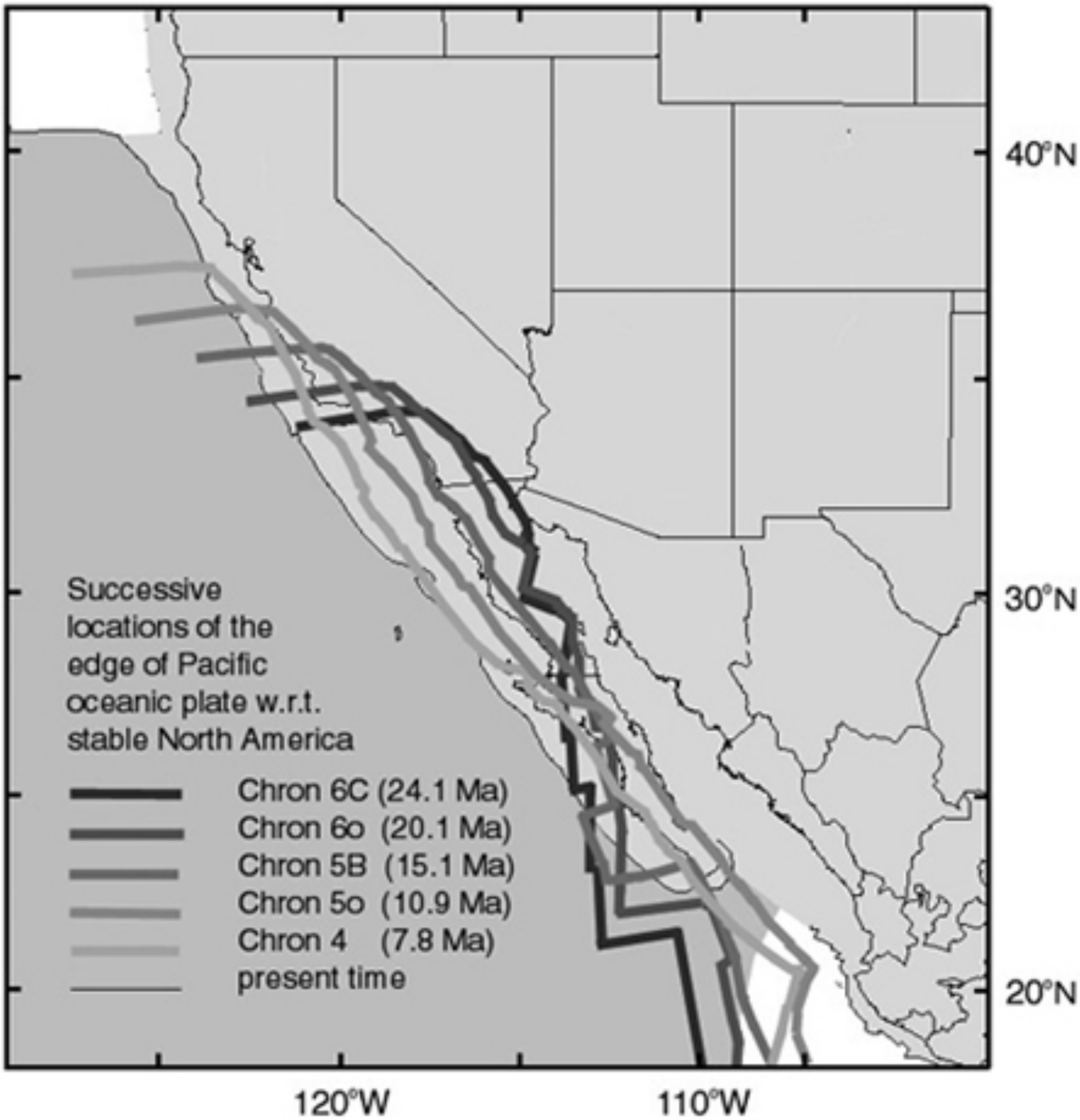

Figure 5. Successive locations of the eastern edge of Pacific plate oceanic lithosphere, relative to a fixed North America, plotted upon the present shape of North America. The edge for each time step was drawn as described for Fig. 4. The overlaps demonstrate the amount of internal deformation required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

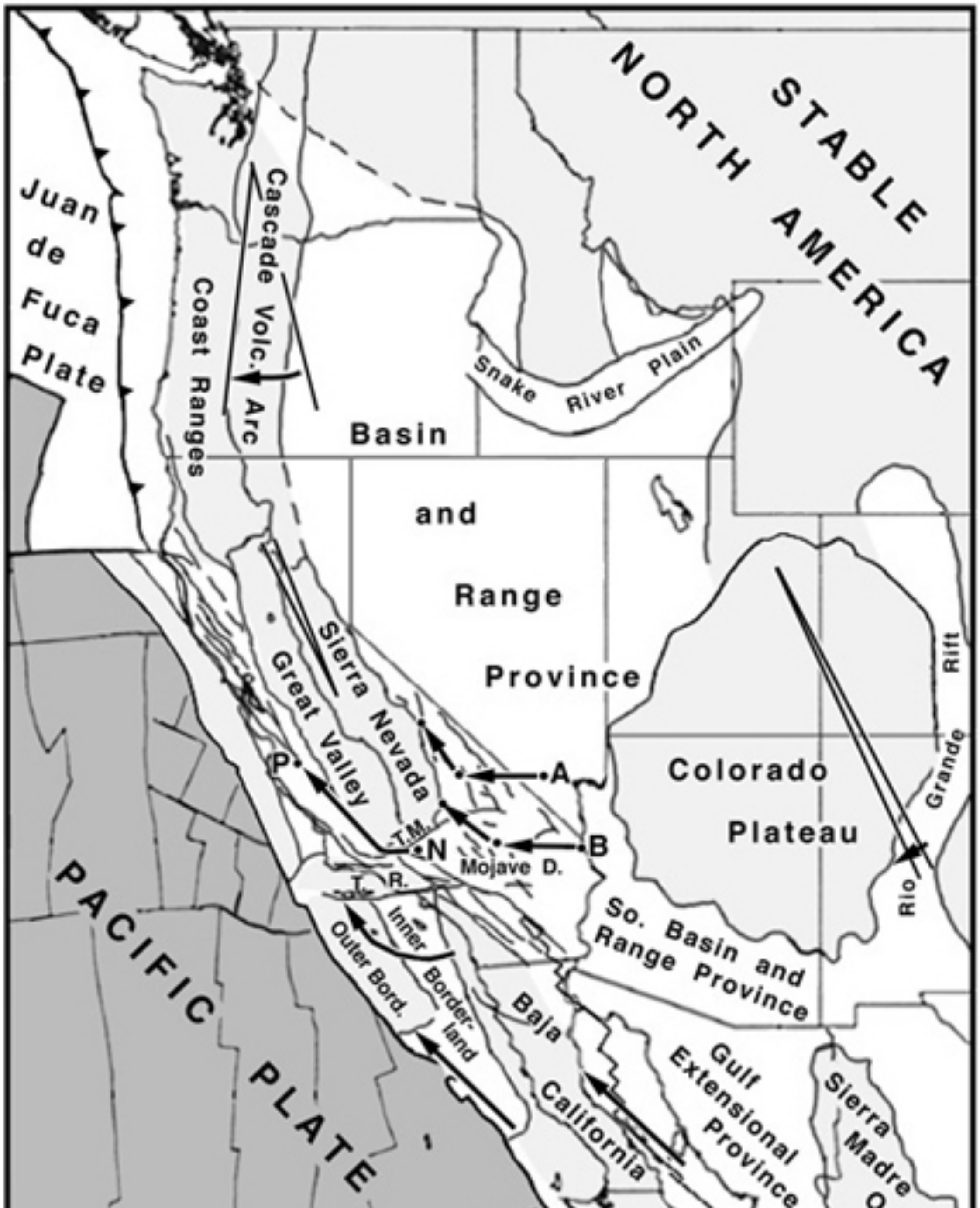

Figure 6. Present-day locations of continental elements and known quantitative constraints (listed in the text) for their reconstructions to early Miocene locations. Dark gray = rigid Pacific plate. Light gray = continental blocks that are believed to have suffered relatively little internal deformation 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.

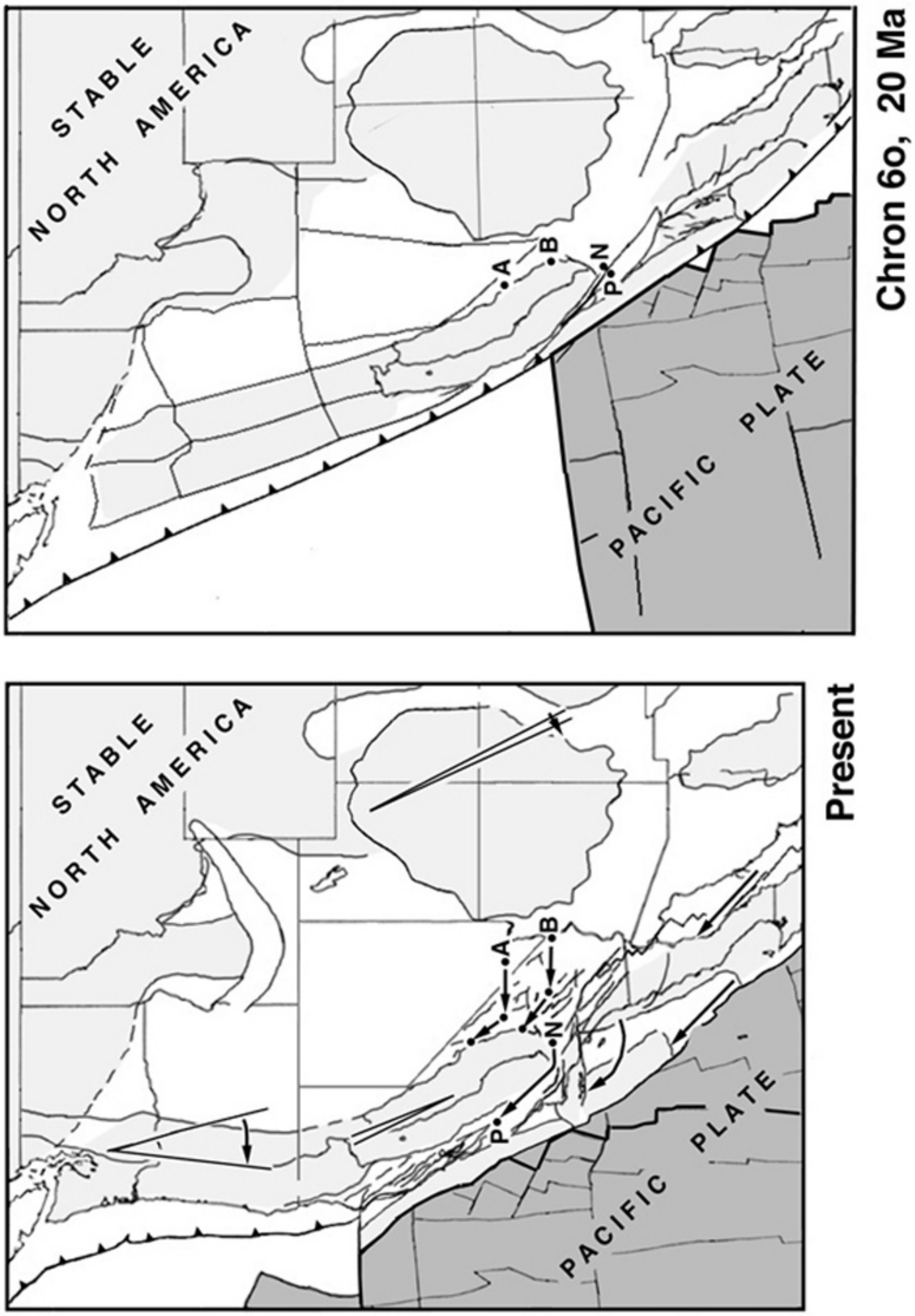

Figure 7a. Reconstruction for Chron 6o, 20.1 Ma, compared with the present configuration from Figure 6. Individual continental elements (light gray) have been reconstructed using the relationships shown in Figure 6 and described in the text. Pacific seafloor with isochrons (dark gray) has been moved 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.

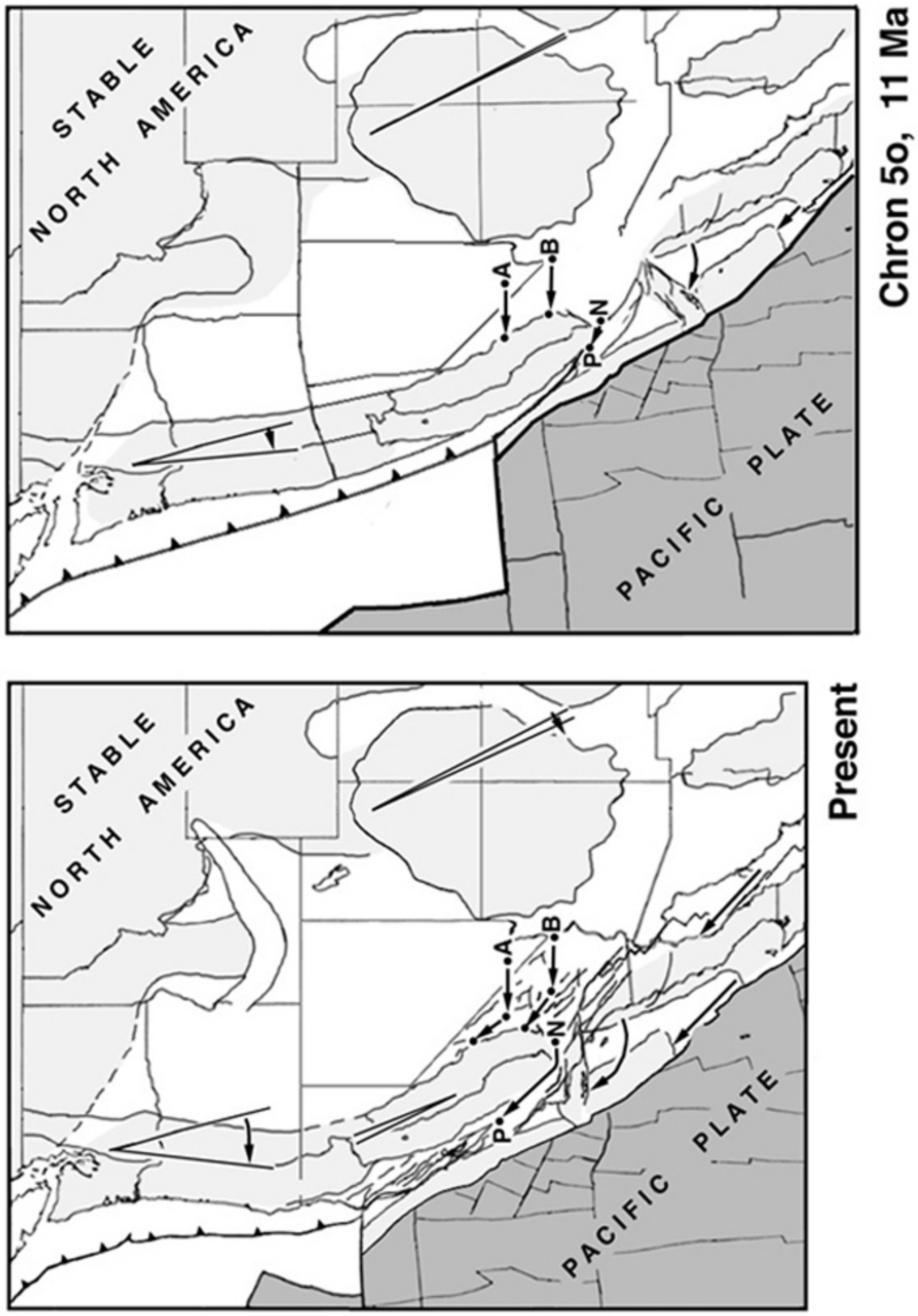

Figure 7b. Reconstruction for Chron 5o, 10.9 Ma, compared with the present configuration from Figure 6. Individual continental elements (light gray) have been reconstructed using the relationships shown in Figure 6 and described in the text. Pacific seafloor with isochrons (dark gray) has been moved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

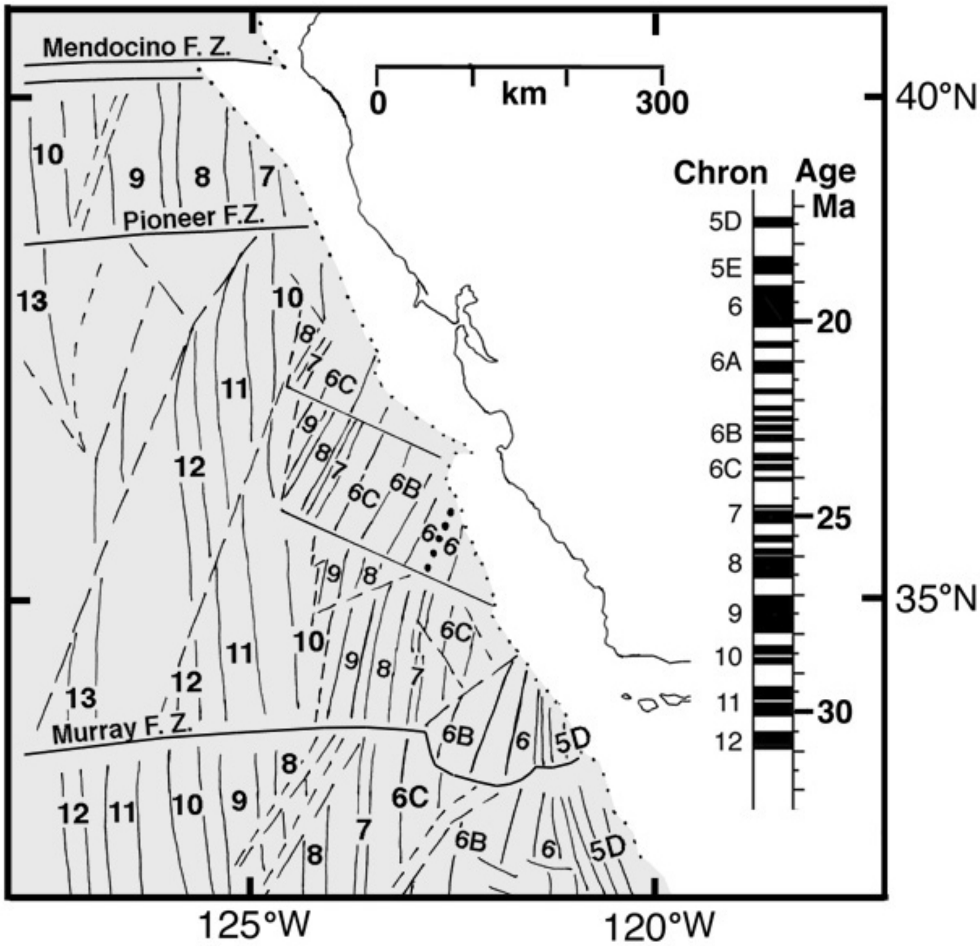

Figure 8. Present-day seafloor isochron patterns and fracture zones mapped in the Pacific seafloor off central California, after Severinghaus and Atwater (1990). Heavy dotted line marks the location of the stalled Pacific-Monterey spreading center, after Lonsdale (1991). Labels are magnetic reversal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

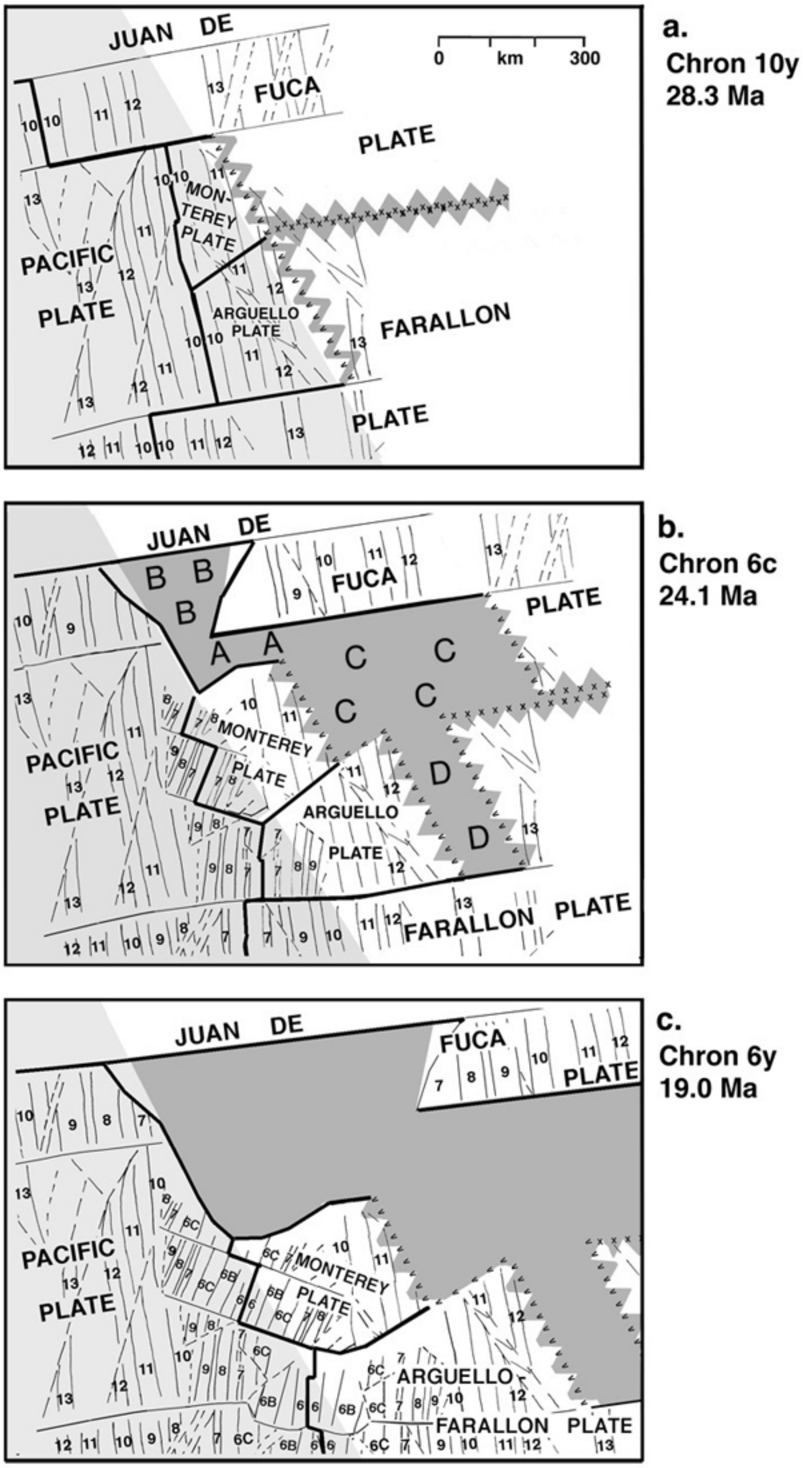
a.
Chron 10y
28.3 Ma
JUAN DE FUCA PLATE
0 km 300
MON-TEREY PLATE
PACIFIC PLATE
ARGUELLO PLATE
FARALLON PLATE
b.
Chron 6c
24.1 Ma
JUAN DE FUCA PLATE
MONTEREY PLATE
PACIFIC PLATE
ARGUELLO PLATE
FARALLON PLATE
c.
Chron 6y
19.0 Ma
JUAN DE FUCA PLATE
MONTEREY PLATE
PACIFIC PLATE
ARGUELLO
FARALLON PLATE

Figure 9.

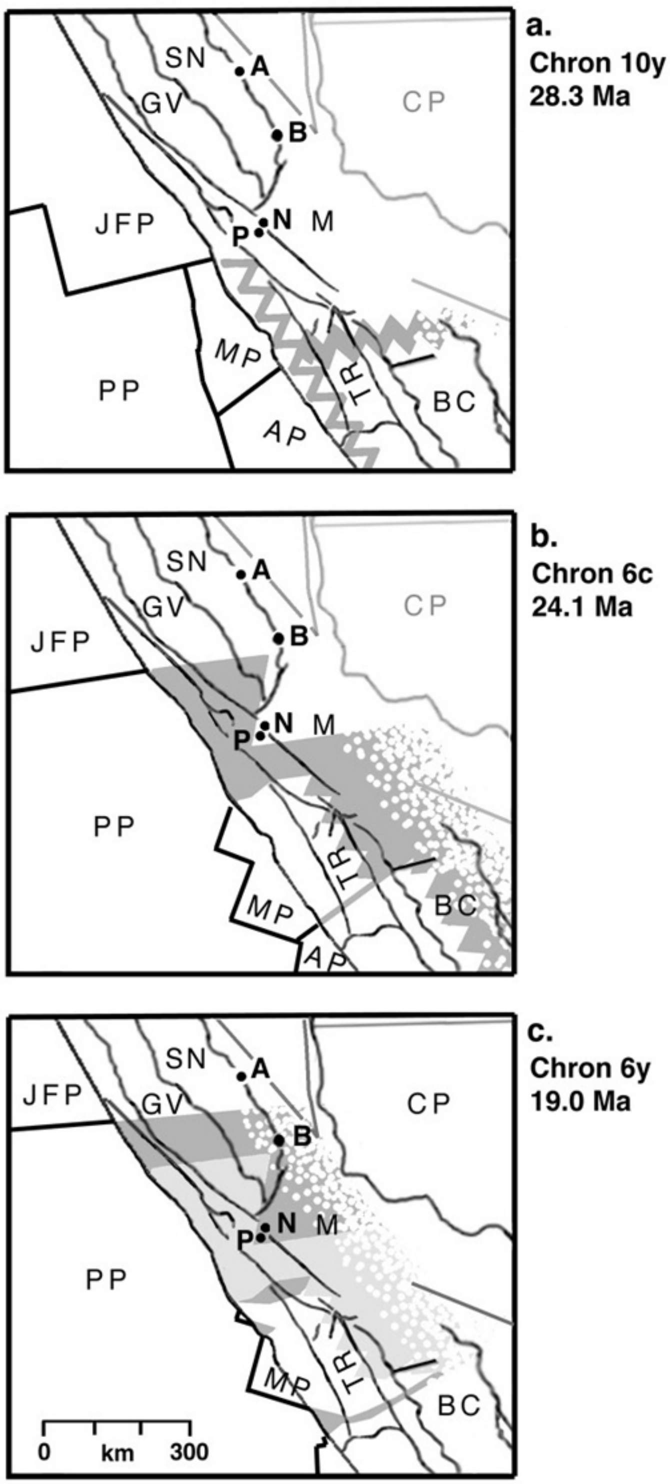
a.
Chron 10y
28.3 Ma
SN
A
GV
B
CP
JFP
N
M
P
MP
PP
TR
BC
AP
b.
Chron 6c
24.1 Ma
SN
A
GV
CP
JFP
B
N
M
P
PP
TR
MP
BC
AP
c.
Chron 6y
19.0 Ma
SN
A
JFP
GV
CP
B
N
M
P
PP
TR
MP
BC
0
km
300

Figure 10.

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.

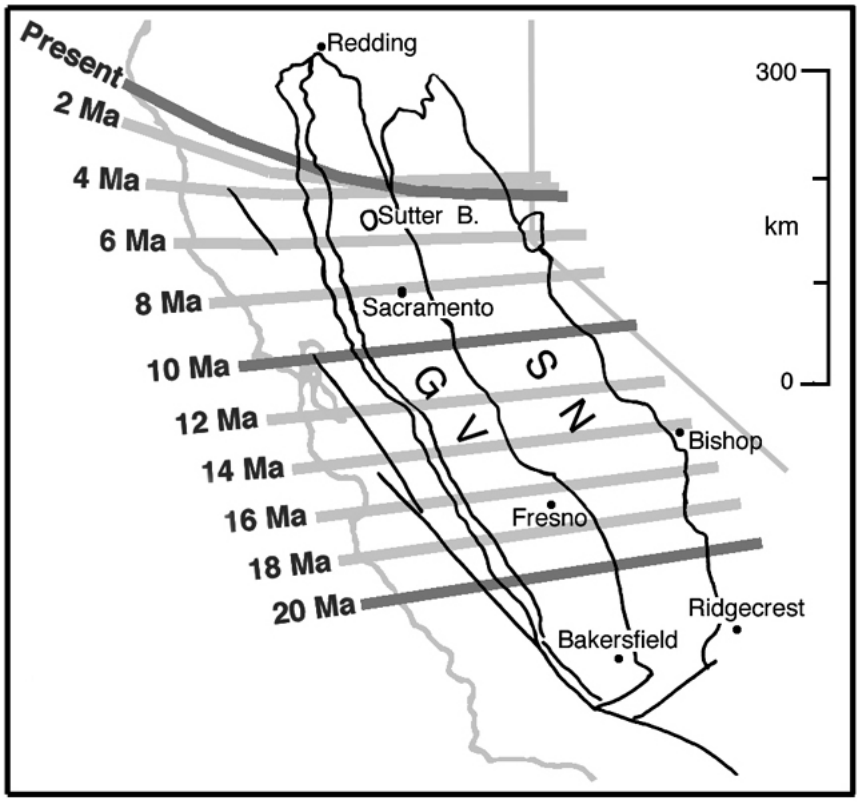

Figure 11. Placement of the Mendocino edge of the subducting Juan de Fuca plate beneath the Sierran-Great Valley block, 20 Ma to present. Drift of oceanic plates are interpolated from our circuit solutions; displacement of the Sierran-Great Valley block drawn following Wernicke and Snow (this issue); 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.