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# Stress direction history of the western United States and Mexico since 85 Ma

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[1] A data set of 369 paleostress direction indicators (sets of dikes, veins, or fault slip vectors) is collected from previous compilations and the geologic literature. Like contemporary data, these stress directions show great variability, even over short distances. Therefore statistical methods are helpful in deciding which apparent variations in space or in time are significant. First, the interpolation technique of *Bird and Li* [1996] is used to interpolate stress directions to a grid of evenly spaced points in each of seventeen 5-m.y. time steps since 85 Ma. Then, a *t* test is used to search for stress direction changes between pairs of time windows whose sense can be determined with some minimum confidence. Available data cannot resolve local stress provinces, and only the broadest changes affecting country-sized regions are reasonably certain. During 85–50 Ma, the most compressive horizontal stress azimuth $\hat{\sigma}_{1H}$ was fairly constant at $\sim$68° (United States) to 75° (Mexico). During 50–35 Ma, both counterclockwise stress changes (in the Pacific Northwest) and clockwise stress changes (from Nevada to New Mexico) are seen, but only locally and with about 50% confidence. A major stress azimuth change by $\sim$90° occurred at 33 ± 2 Ma in Mexico and at 30 ± 2 Ma in the western United States. This was probably an interchange between $\hat{\sigma}_1$ and $\hat{\sigma}_3$ caused by a decrease in horizontal compression and/or an increase in vertical compression. The most likely cause was the rollback of horizontally subducting Farallon slab from under the southwestern United States and northwest Mexico, which was rapid during 35–25 Ma. After this transition, a clockwise rotation of principal stress axes by 36°–48° occurred more gradually since 22 Ma, affecting the region between latitudes 28°N and 41°N. This occurred as the lengthening Pacific/North America transform boundary gradually added dextral shear on northwest striking planes to the previous stress field of SW-NE extension. *INDEX TERMS:* 8164 Tectonophysics: Stresses—crust and lithosphere; 8157 Tectonophysics: Plate motions—past (3040); 9350 Information Related to Geographic Region: North America; 9604 Information Related to Geologic Time: Cenozoic; *KEYWORDS:* stress, North America, Cenozoic

## 1. Introduction

[2] After a century of field mapping of faults and their offsets, the broad outlines of the tectonic history of western North America in Cretaceous-Tertiary time are clear (Figure 1). Many authors have attempted to link these events to changes in plate geometry or relative motion at the western continental margin. The Sevier orogeny in the United States and the Hidalgo orogeny in Mexico, which involved eastward thrusting of thick sedimentary sheets, may have been driven by lateral expansion of a thick and elevated crustal welt created by subduction at the Pacific margin [*Burchfiel and Davis*, 1975; *Livaccari*, 1991]. The Laramide orogeny, in which shortening expanded eastward and involved Precambrian basement, was probably driven by an episode of horizontal subduction of the Kula and/or Farallon plates [*Dickinson and Snyder*, 1978; *Bird*, 1998]. Eocene extension in metamorphic core complexes of the Pacific Northwest may be related either to early rollback of horizontal subduction in this region, or to formation of dextral faults in British Columbia which absorbed a portion of Pacific/North America relative motion. Miocene extension of the Basin and Range province extending from Idaho to Zacatecas could be a kinematic result of the formation of the Pacific/North America transform margin, if the former margin trended more northerly than the relative plate velocity [*Ingersoll*, 1982] and/or a dynamic result of slab rollback in the southern latitudes [*Bird*, 1988]. The Pliocene-Quaternary phase of mixed dextral shear and extension in the northern Basin and Range clearly represents a fraction of Pacific/North America relative motion, and localized orogeny in the Transverse Ranges of southern California is apparently due to a transpressive left step in this transform boundary.

[3] Each of these hypotheses presumes that deviatoric stresses in the lithosphere provide a link between plate tectonic causes and their distant effects. Therefore these hypotheses can be tested by examining the quasi-independent record of paleostress directions contained in dikes, veins, and mesoscale structures. The serious difficulties include lack of data in many times and places, imprecise ages of many stress indicators, later tectonic rotation of some indicators, and a generally "noisy" data set which suggests that a large fraction of indicators might be biased by preexisting structures and therefore not reliable. In this paper I present a large collection of paleostress direction data from the literature and process them by objective numerical methods that are intended to extract only the regionally dominant stress directions, in which we can have high confidence.

## 2. Data

[4] My search of the recent geologic literature has yielded 369 paleostress direction indicators from the western United States and Mexico whose age is <85 Ma. Details of the compilation are in Appendix A, and the data (Table A1) and their citations are available as electronic supporting material[1]. (Note that the refer-

[1]Supporting material is available via Web browser or via Anonymous FTP from ftp://kosmos.agu.org, directory "append" (Username = "anonymous," Password ="guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic supplements is found at http://www.agu.org/pubs/esupp_about.html.


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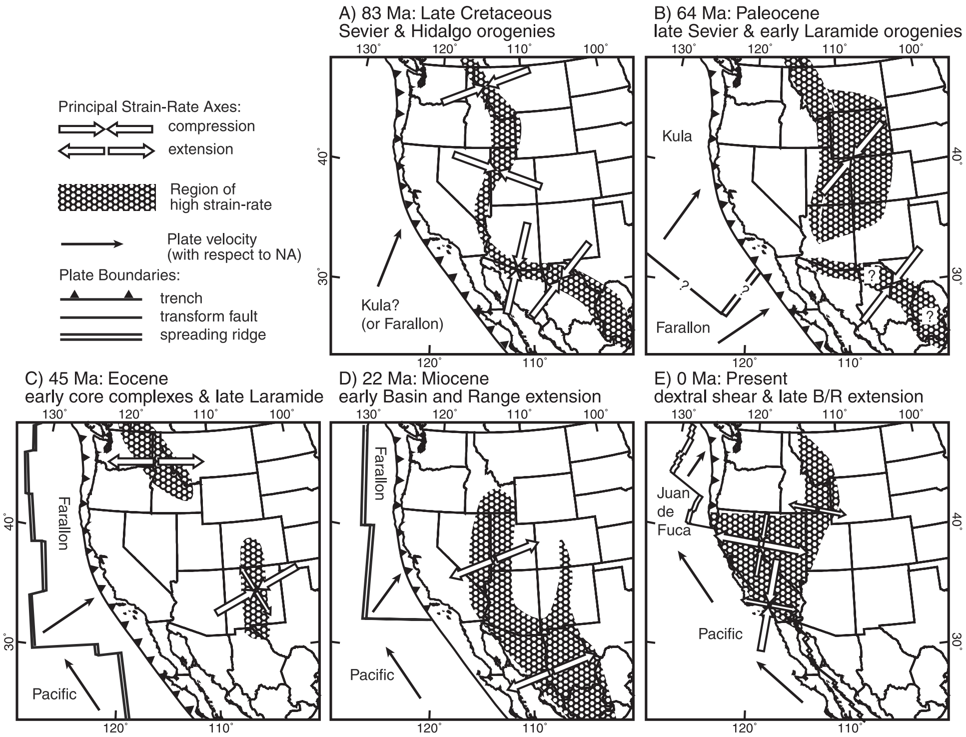


**Figure 1.** Schematic and qualitative tectonic history, based on *Engebretson et al.* [1985], *de Cserna* [1989], *Axen et al.* [1993], and *Bird* [1998]. No palinspastic restoration is attempted (except in the Pacific basin). Regions of highest strain rate at each epoch are shown with shading. Only the strain rate axes in the northern part of western North America (Figure 1b) and the southern part (Figure 1c) result from formal computations [*Bird*, 1998]; other axes are drawn perpendicular to the mean trend of dip-slip faults active at that time. Distribution of high strain rates (Figure 1e) is based primarily on historical seismicity.

ence list in this paper does not contain original citations for the paleostress data; these are provided in the supporting material.) Tabulated information for each indicator includes citation, type of indicator, location, azimuth of the greatest horizontal principal compressive stress ($\hat{\sigma}_{1H}$), uncertainty of the azimuth, maximum age, minimum age, and an indication of whether the stress direction persisted between the two time limits (“stage”) or is only bracketed by the two time limits (“window”).

## 3. Interpolation and Comparison

[5] The two challenges are to find the regional-average $\hat{\sigma}_{1H}$ stress direction for any given epoch, and to determine the times and places where the direction changed by a significant angle. Both tasks require an ability to interpolate stress direction to locations between data points. In order to put the detection of changes on a firm basis, it is important that the method of interpolation should give a measure of the uncertainty of the result.

[6] Stress directions cannot be interpolated by kriging because their values (azimuths) lie on a cyclical axis. However, insights developed from decades of kriging (or “geostatistics”) are useful. When data collected in the field have essentially no error, it is appropriate to combine adjacent data using weighting factors that become arbitrarily large as the interpolation point approaches any datum location. The result then “honors” each datum, in the sense that the interpolated value at the datum location equals the datum value. Such processing is usually used for gravity data and water table elevations. However, when data are noisy (when the limit of the variance as distance goes to zero is large) the statistical best estimate is obtained by using limited weights for adjacent data [*Hohn*, 1988]. The result is an interpolated field that is smoother than the data and does not honor each one in detail. Such processing is typically applied to heat flow data and ore concentrations.

[7] *Bird and Li* [1996] analyzed the 6000 contemporary data of the World Stress Map [*Zoback*, 1992], and showed that it is noisy data. For example, comparing stress azimuths measured <200 km apart, they found that 44% of pairs have discrepancies over 30°, and 16% have discrepancies over 60°. They designed two variants of a statistical interpolation method with limited local weights to deal with such data. The first of their methods is applied in this paper to paleostress directions. All details of the method are contained in Appendix B.

[8] Figure 2 shows examples of this interpolation method applied to paleostress data and contemporary stress data from the same region. Since the time window for selecting the paleostress data was Pliocene-Pleistocene (5–0.01 Ma), we expect both data sets to give similar results, and they do. Both maps show $\hat{\sigma}_{1H}$ entially N-S in Mexico; in the paleostress map this direction continues through the United States, while in the contemporary map it swings clockwise to the north, by an average of 12°. This difference may be due to the limited quantity of paleostress data available; however, I will argue in Section 4.5 that it represents a

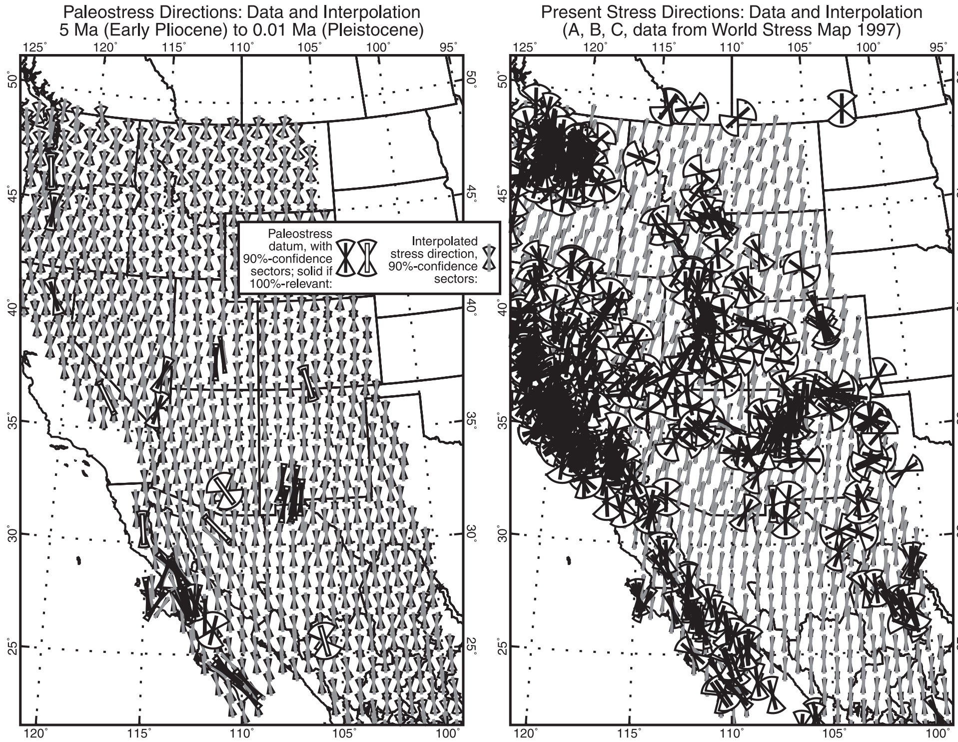


**Figure 2.** Comparison of 39 paleostress direction data (Figure 2, left, from the most recent 5-m.y. time window) with 706 quality "A," "B," or "C" contemporary stress direction data from the World Stress Map (Figure 2, right, from B. Mueller et al., The 1997 release of the World Stress Map, available at http://www-wsm.physik.uni-karlsruhe.de/pub/introduction/introduction.html, 1997). Each data set has been interpolated with the same algorithm (Appendix B). All symbols show the azimuth of $\hat{\sigma}_{1H}$, the most compressive horizontal principal stress direction. Because stress direction data are noisy, statistical interpolation by the method of *Bird and Li* [1996] gives only limited weight to the nearest data, and it results in very smooth fields of interpolated directions (shaded bars). An alternative view is that most high-quality data are basically correct, and that the stress direction field is separated into small provinces by sharp transitions [*Zoback and Zoback*, 1980]. The difference in interpolated $\hat{\sigma}_{1H}$ azimuths from the United States portion of the left map to the right map is $\sim$12°, which could be an artifact of the limited amount of paleostress data. (The difference would be within the 90%-confidence limits shown.) However, this paper argues that the effect is real, because it is the continuation of a gradual clockwise rotation of stress directions that began $\sim$22 Ma.

real clockwise rotation of stress in time that began $\sim$22 Ma and continues today.

[9] *Zoback and Zoback* [1980] interpreted the contemporary data from this region as indicating a number of stress direction "provinces" separated by narrow transitions. Two regions of notably different $\hat{\sigma}_{1H}$ (WNW-ESE) were recognized in the northern Rocky Mountains and in the Colorado Plateau. A potential problem is that the interpolation method used in this paper does not recognize these provinces (Figure 2) because it gives only limited weight to local data. On the other hand, both of these anomalous provinces are defined largely (though not entirely) by earthquake focal mechanisms of normal-faulting events, which are rather inaccurate stress indicators because most earthquakes occur on old faults, not new ones. It is also a plausible interpretation that in these regions the crust has a Laramide (or older) system of WNW-ESE trending faults, which are reactivated by present E-W relative tension (N-S $\hat{\sigma}_{1H}$). Naturally, no focal mechanisms are included in the paleostress data set, so such problems are less likely to occur with paleostress interpolations.

[10] Because my interpolation method yields standard deviations for all interpolated stress azimuths, it is easy to use standard statistical methods to decide whether an apparent change in stress direction can be assigned a high confidence. I have used the *t* test to compare stress directions from both adjacent and widely separated time windows of 5 m.y. duration. In most parts of this paper I only discuss changes in stress direction which exceed a defined confidence limit (50%, 80%, or 90%). These are shown in "stress change maps," which are maps showing the apparent angle of change in $\hat{\sigma}_{1H}$, but only in areas of significant change. Again, details will be found in Appendix B.

## 4. Results

[11] The results of these calculations included a set of 17 epoch maps and $\sim$50 stress change maps. Many are repetitive, and it is not necessary or practical to display them all. I will discuss the important findings in historical order.

### 4.1. Sevier/Hidalgo Orogeny

[12] At the beginning of the period covered by this study (85 Ma), the Sevier orogeny was under way in the Overthrust belt of

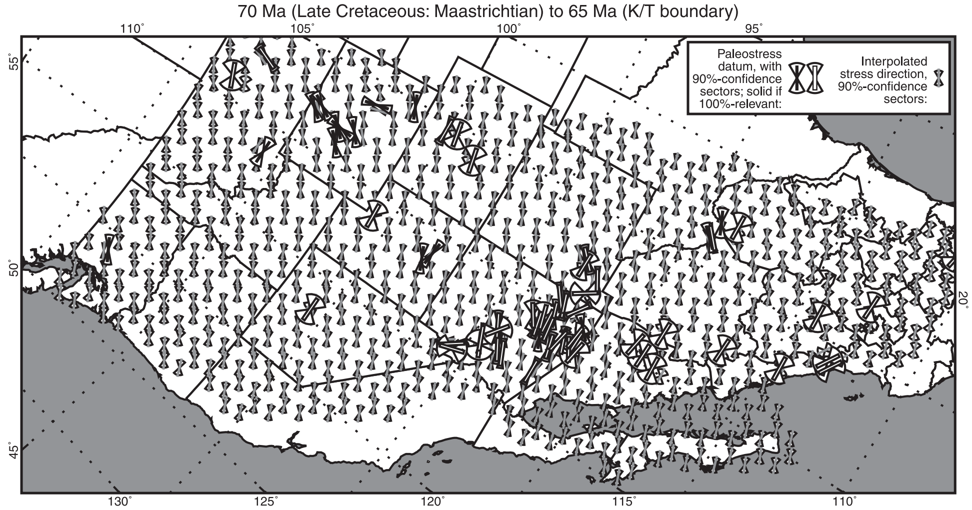


**Figure 3.** Geologic data on the direction of the most compressive horizontal principal stress $\hat{\sigma}_{1H}$ (solid or open-box bars) and interpolated $\hat{\sigma}_{1H}$ directions (shaded bars) during the time step 70–65 Ma (Late Cretaceous: Maastrichtian). Data are plotted at present coordinates, without palinspastic restoration. Oblique Mercator projection, which is conformal. Open-box symbols indicate data which have only fractional relevance to this time step. Note that data in Nevada, Utah, and Colorado could be interpreted as establishing a different (E-W) direction. However, most of these data have fractional relevance and large uncertainties.

Idaho-Wyoming-Utah. Thrusts known (or permitted) to be active at this time can also be found extending the belt through eastern California, southern Arizona, and into northeast Mexico (Hidalgo orogen; Figure 1a). Since the strike of the thrust belt varied so much (more than 90°) with latitude, it would be very interesting to know if stress directions varied as well. Unfortunately, I found only 5 data relevant to the period 85–75 Ma (one in Washington, one in California, one in Arizona, and two in Texas). All data show $\hat{\sigma}_{1H}$ in the azimuth range 45°–67°, without the large variations suggested by Figure 1a. This casts some doubt on the hypothesis of local gravity tectonics and suggests that perhaps the relative velocity between the Sevier-Hidalgo hinterland and the foreland was coherent in direction. (Under this hypothesis, the location of the orogen would necessarily be a preexisting belt of weakness, possibly determined by sedimentary isopachs.) However, the formal interpolation result across most of the area is $\hat{\sigma}_{1H}$ of ~51° ±70° (90%-confidence limits), and with these huge uncertainties neither hypothesis can be ruled out at this time.

## 4.2. Laramide Orogeny

[13] About 75 Ma, basement-involved thrusting began further east and formed the Rocky Mountains of the United States (Figure 1b). The Hidalgo orogeny may also have continued up to 57–52 Ma [*de Cserna*, 1989], although constraints are few. The relative rarity of dikes in the data set before 47.5 Ma (Appendix A) is consistent with a vertical orientation of least compression ($\hat{\sigma}_3$), as expected in a thrusting regime. (The fact that there are any dikes at all can be taken as evidence that locally, $\hat{\sigma}_3$ was horizontal in localities with a strike-slip stress regime.)

[14] Laramide volcanism and faulting provided more opportunities for paleostress to be recorded, and the 90%-confidence limits therefore improve, to about ±22°. The mean $\hat{\sigma}_{1H}$ azimuth in the United States was 68°, with more eastward azimuths of ~75° in Mexico (Figure 3). The computed directions are extremely stable from 75–50 Ma; this is largely due to the number of data with long durations. (Some are stage data valid for long periods; others are window data with very uncertain ages.) Actual variations in direction may have been greater, but this cannot be demonstrated from information presently available.

[15] If the Hidalgo orogen were still active, the prediction would be that late thrusting should have a sinistral component, becoming dominant in southern Arizona. The mean azimuth of 68° in the United States is rather different from the mean shortening azimuth of 40° computed by *Bird* [1998, Figure 7]. It matches the velocity of the subducted Farallon plate (with respect to North America) better than it matches the velocity of the Kula plate. Thus both studies are consistent with the *Dickinson and Snyder* [1978] hypothesis that the Laramide orogeny was caused by basal drag from horizontal subduction, but they do not agree on the difficult question of the identification of the subducted plate. Probably this will have to be resolved by finding evidence of the former Farallon/Kula/North America triple junction along the Pacific margin.

[16] There have been some suggestions in the literature (reviewed by *Bird* [1998]) that during the Laramide orogeny the azimuth of compression rotated from 75°–85° counterclockwise to 10°–30°. These results do not support any such counterclockwise rotation of $\hat{\sigma}_{1H}$. The only change seen here is a marginally significant clockwise rotation by 15°–30° at ~45–40 Ma affecting some areas from eastern Nevada to New Mexico. Figure 4 attempts to show this by including all stress differences which are significant with 50% confidence. Even with this low threshold, significant change is seen at only about half of the points in eastern Nevada, northern Utah, northern Wyoming, and New Mexico. This is an example of a stress change which could either be real, or an artifact of the small size of this data set. *Bird* [1998] found a similar event in kinematic reconstructions which used some of the same stress indicators (but fewer) and also used fault slip histories and paleo-

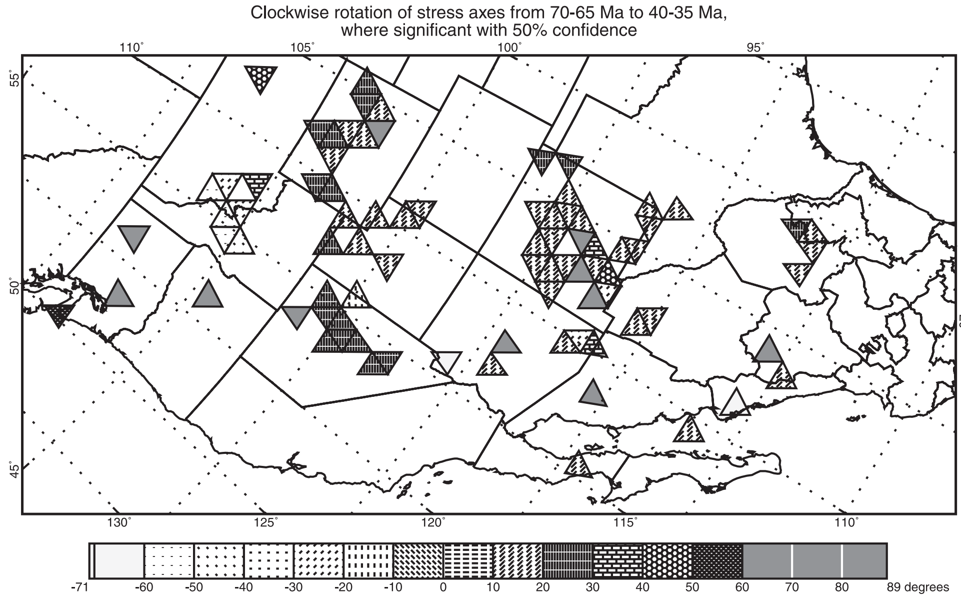


**Figure 4.** Stress change map, comparing "early Laramide" time step 70–65 Ma (Late Cretaceous: Maastrichtian) with "late Laramide" time step 40–35 Ma (middle-late Eocene). Triangles merely show the geographic region associated with each interpolation grid point. Color of triangle indicates the amount of rotation of $\hat{\sigma}_{1H}$ from the earlier time to the later. Triangles are only plotted around grid points where rotation is significant with 50% or greater confidence, according to a *t* test. The most common rotations are 10°–30° clockwise, in scattered areas such as east central Nevada, Wyoming, and New Mexico. Counterclockwise rotation is seen mainly in the areas of the Eocene dike swarm of *Hyndman et al.* [1988] in Idaho-Montana. Oblique Mercator projection, showing present state lines without palinspastic restoration.

magnetic rotations as data; he saw a clockwise shift of principal strain rate directions by ~15° at ~50 Ma in Colorado and New Mexico. If these are the same event, and if it is not an artifact of limitations in the data, then one possible explanation is that the directions of tractions on the base of North American lithosphere changed because of the subduction of a Kula-Farallon transform (Figures 1b–1c) [*Engebretson et al.*, 1985; *Bird*, 1998, Figure 9], that is, before the transition stresses in western North America were controlled by basal tractions from the Kula plate, and after they were controlled by basal tractions from the Farallon plate.

### 4.3. Eocene Extension in the Pacific Northwest

[17] One surprising result of this study is that no dramatic change in stress directions is resolved in the northwestern United States at around 50 Ma. It is well known that extensional detachment faulting began ~52 Ma in southern British Columbia and Washington [*Marquis and Irving*, 1990; *Harms and Price*, 1992]. *Constenius* [1996] has shown that extension in Idaho and Montana began ~49 Ma, that the hiatus after the previous Sevier-Laramide orogeny was no more than 5 Ma, and that in some cases the same faults that had been thrusts were reactivated as normal faults. One might expect to see a 90° change in $\hat{\sigma}_{1H}$ at this time. In fact, Figure 4 shows that large stress direction changes can only be assigned 50% or greater confidence at the grid points associated with late Eocene (specifically, 40–35 Ma) data, but not at grid points where the late Eocene direction was obtained by interpolation. This may be an example of poor performance by the interpolation algorithm, which is apparently overinfluenced by data far to the southeast because no balancing data were available on the Canadian side to the north.

[18] Even if we set aside the interpolation algorithm and examine the data directly, the apparent local change in stress directions was only ~45°. Dikes of 52–43 Ma age east of the Republic graben in Washington have azimuth 20° [*Holder et al.*, 1990]; 48–46 Ma dikes in northern Washington are N-S [*Christiansen and Yeats*, 1992]; the Eocene dike swarm of Idaho-Montana has various azimuths of 6°–38°. Averaging these Eocene data together would suggest that $\hat{\sigma}_{1H}$ only rotated ~45° counterclockwise (from ~65° azimuth during the Cretaceous-Paleocene to ~20° in the Eocene).

[19] Reversal of dip slip from thrusting to normal sense on an established fault does not require an interchange, or even rotation, of the two horizontal principle stresses; it is sufficient for the vertical stress (at fixed elevation) to become more compressive (because of uplift) or for both horizontal stresses to become less compressive. However, the northwest striking faults of Idaho and western Montana would not have been optimally oriented in the new stress field, and they are predicted to display components of dextral slip. This example is a warning that strikes of active dip-slip faults cannot be considered to be stress direction indicators unless it is known that the faults were newly formed in homogeneous isotropic lithosphere. An analogous situation in the contemporary stress field may be the widespread occurrence of normal faulting on northwest striking faults in the northern Rocky Mountains (Figure 2), even though data from surrounding regions indicate a $\hat{\sigma}_{1H}$ azimuth which is slightly east of north.

[20] Since the late Eocene (post-40 Ma), $\hat{\sigma}_{1H}$ was somewhere between 20° azimuth (the average of local indicators) and 50° (a typical result of interpolation), the least compressive principal stress $\hat{\sigma}_3$ must have had an azimuth of 290°–320°, or N55W ±15°.

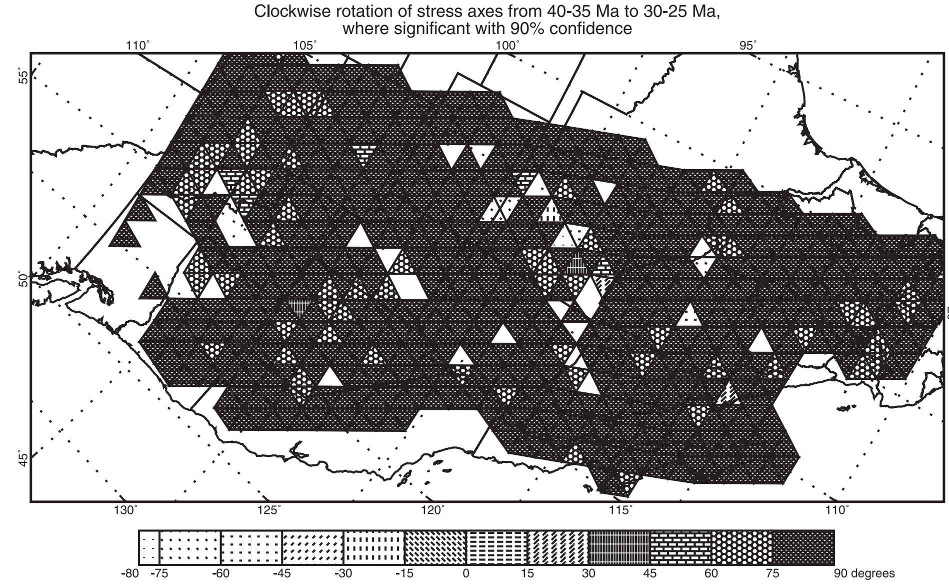


**Figure 5.** Stress change map, comparing the 40–35 Ma (middle-late Eocene) time step with the 30–25 Ma (mid-Oligocene) time step. Conventions as in Figure 4, except that here all rotations shown are significant with 90% confidence. A dramatic change in $\hat{\sigma}_{1H}$ azimuth by nearly 90° (the greatest possible change) has affected the whole region. This is interpreted as an interchange of the most compressive and least compressive stress axes.

This does not suggest gravitational slumping directed toward the nearest trench, which probably lay to the WSW. Instead, the tension direction "points to" the dextral fault systems of British Columbia (Pinchi-Fraser River, Yalakom, and Central-Coast Range-Work Channel-Harrison faults). The age of movement of these faults is poorly known, but it is likely that one or more of them was activated in parallel with the coastal Queen Charlotte transform, which was created when the Kula plate merged with the Pacific plate around 50 Ma [*Engebretson et al.*, 1985]. The termination of these faults near the international border would have created a void if it had not been accommodated by distributed extension in the Pacific Northwest.

## 4.4. Oligocene Extension in the Basin and Range

[21] The most dramatic stress change in the entire history occurred in the early Oligocene, and it affected all of the western United States and Mexico. Changes of $\hat{\sigma}_{1H}$ from roughly WSW-ENE to roughly NNW-ESE are almost everywhere over 60° and in more than half the area are 75° to 90° (Figure 5). Almost everywhere, there is 90% confidence that the change is significant. The new N-S orientation of $\hat{\sigma}_{1H}$ following the transition is shown in Figure 6. It appears that this transition occurred somewhat earlier in Mexico than in the United States.

[22] In Mexico, one might argue that the change occurred as early as 35 Ma, which is the time at which the E-W $\hat{\sigma}_{1H}$ indicators cease to be the majority, and a group of roughly N-S indicators become predominant. The interpolation method, however, also gives weight to a group of ENE-WSW indicators in west Texas, which persist into the 35–30 Ma time step. Therefore the interpolated directions in Mexico have very large uncertainties in the 35–30 Ma time step, and the *t* test only shows significant stress changes when the 40–35 Ma step is compared to the 30–25 Ma step, not when adjacent time steps are compared. I conclude that the transition in Mexico was at 33 ± 2 Ma.

[23] In the United States the transition is seen as a crisp change between the 35–30 Ma time step (which is only slightly different from the previous step) and the 30–25 Ma time step (which is only slightly different from the following step). This gives the transition time in the western United States as 30 ± 2 Ma.

[24] Many previous authors have noted this event, based on smaller data sets; it is not practical to cite every paper which refers to it. However, there has been confusion about the timing. *Rehrig and Heidrick* [1976] bracketed this transition as 50–35 Ma in Arizona. *Dreier* [1984] dated it as 35–30 Ma in the same region. *Price and Henry* [1984] dated it as 32–30 Ma in west Texas. *Aldrich et al.* [1986] noted a period of confused, nearly isotropic stress in New Mexico from 38–32 Ma followed by the establishment of ENE-WSW extension. *Best* [1988] presented a different view, that intrusive complexes record a later stress transition at 26–18 Ma, while metamorphic core complexes show no transition. *Ren et al.* [1989] emphasized a continuous clockwise rotation of stress since 40 Ma rather than a single transition, and concluded that NE-SW extension only occurred after 22 Ma. I support the conclusions of (only) the first four studies cited above, and suggest that the stress change occurred over the entire region in no more than 7 m.y. (35–28 Ma) and possibly in only 3 m.y. (33–30 Ma).

[25] I interpret this stress change as a reversal of stress sense from ENE-WSW horizontal compression to ENE-WSW horizontal (relative) tension. This stress reversal was once generally attributed to the end of subduction at the Pacific margin, but we now know that formation of the Pacific/North America transform margin (Figure 1d) was a gradual process beginning at 28 Ma [*Nicholson et al.*, 1994]. Therefore it happened too late to be the principal cause of this stress change. Another explanation that can be rejected is the idea that the region was thrown into extension by gradual uplift that was caused by the decreasing age of the subducting Farallon plate over time. While this younging definitely occurred, and it probably caused isostatic uplift, it would have had the same effect on the coastal forearc. Therefore (assuming con-

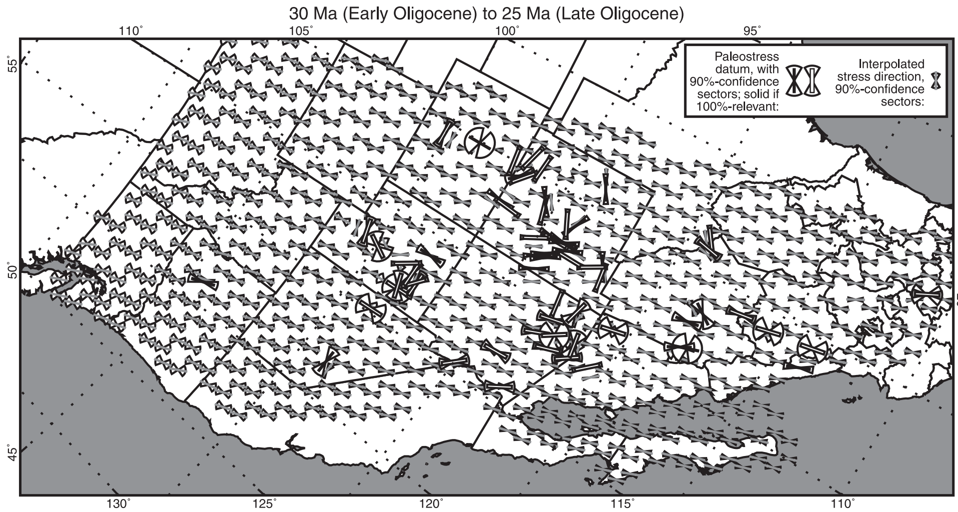


**Figure 6.** Geologic data on the direction of the most compressive horizontal principal stress $\hat{\sigma}_{1H}$ (solid or open-box bars) and interpolated $\hat{\sigma}_{1H}$ directions (shaded bars) during the time step 30–25 Ma (mid-Oligocene). Conventions as in Figures 2 and 3.

stant coupling to the subducting plate) the horizontal compression should have increased by exactly the same amount as the vertical compression. This is a mechanism that can change absolute, but not relative, stress intensities.

[26] My interpretation is that the stress reversal should be correlated with the ''ignimbrite flare-up'' volcanic event of 35–30 Ma in the Basin and Range province, and that both resulted from the rollback or delamination of the horizontally subducting Farallon slab from the base of North America [*Coney*, 1978; *Bird*, 1988]. This rollback can be followed in the migration of the volcanic arc front from east to west across the southwestern United States that occurred during 35–25 Ma [*Dickinson and Snyder*, 1978] and which is shown in Figure 7. Loss of contact with the oceanic slab would have greatly reduced the shear tractions acting on the base of North America in the ENE direction, reducing the horizontal compression in this direction. Simultaneously, delamination of the slab would have caused isostatic uplift by ~1 km, increasing the vertical topographic compression (at a fixed elevation). The net effect was apparently to interchange the $\hat{\sigma}_1$ and $\hat{\sigma}_3$ axes, switching rapidly from a compressional to an extensional regime.

## 4.5. Miocene-Present Stress Rotation

[27] Between the time steps from 30 Ma to the present, there are no sudden shifts; no step shows $\hat{\sigma}_{1H}$ changed from the previous value over a large region with 90% confidence. However, there is a noticeable tendency for a progressive clockwise rotation of $\hat{\sigma}_{1H}$.

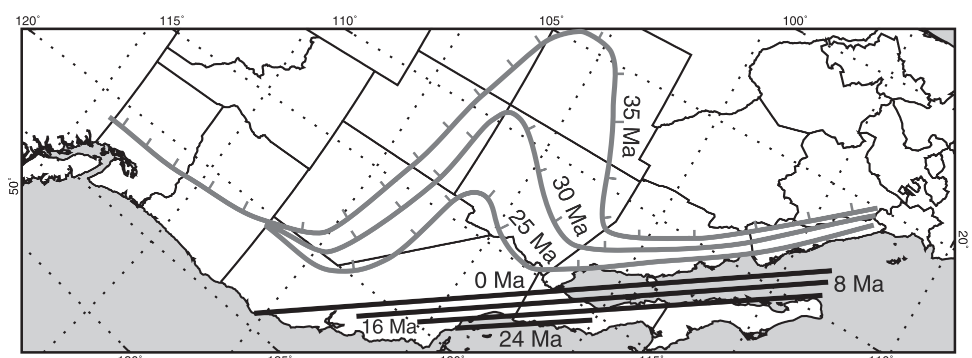


**Figure 7.** Possible causes for the two greatest stress reorientations found in this study. Shaded lines labeled 35, 30, and 25 Ma mark the western limits of arc volcanism at each of those times, according to *Dickinson and Snyder* [1978] and *Urrutia-Fucugauchi* [1986]. Lands to the southwest of these lines were underlain by oceanic lithosphere of the Farallon plate, subducting horizontally to the northeast. The progressive loss of contact with the Farallon plate decreased horizontal coupling to North America and decreased the northeastward compression, while simultaneously causing uplift and increased vertical compression. Solid lines labeled 24, 16, 8, and 0 Ma show the latitudinal extent (but not the correct longitude) of the Pacific/North America transform margin (see Figures 1d and 1e), according to *Engebretson et al.* [1985]. Increasing transform length probably caused increased transmission of northwestward tractions from the Pacific plate to North America. Superposed on the preexisting NE-SW extensional stress field, this caused a clockwise rotation of principal stress axes.

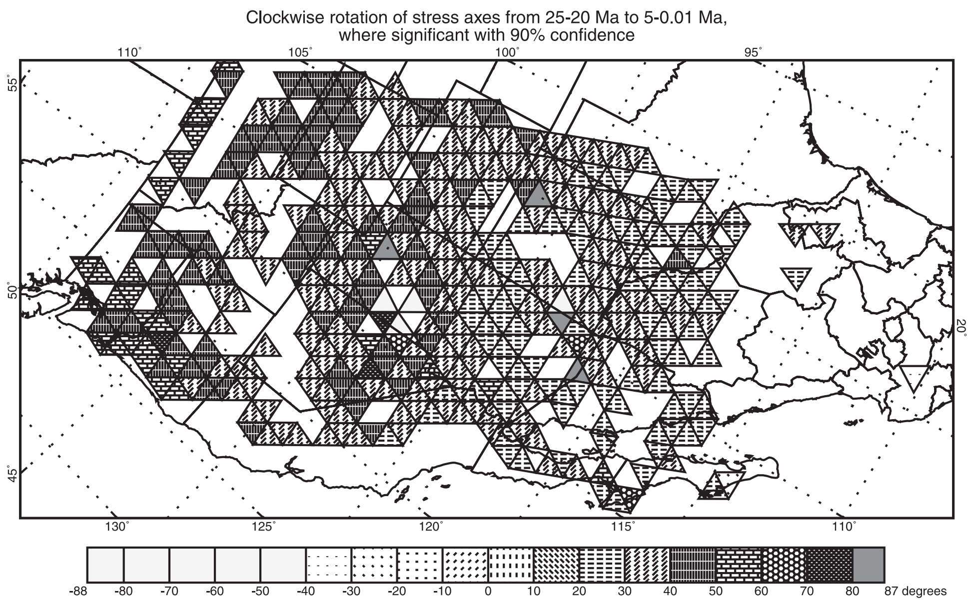


**Figure 8.** Stress change map, comparing the 25–20 Ma (late Oligocene-early Miocene) time step with the 5–0.01 Ma (Pliocene-Pleistocene) time step. Conventions as in Figure 4, except that here all rotations shown are significant with 90% confidence. This reveals the cumulative effects of a slow clockwise rotation of $\hat{\sigma}_{1H}$.

This can be confirmed by a stress change map comparing the 25–20 Ma and the 5–0.01 Ma time steps, which is shown in Figure 8. Net clockwise rotation was most commonly 24° to 36°, but locally was much as 56°. The rotation is significant with 80% confidence at almost all points from latitude 22°N (Zacatecas) to 49°N (the Canadian border, which was the northern limit of this study). Rotation is significant with 90% confidence at most points in the central section, from latitude 28°N (Chihuahua) to a line that passes from Lake Tahoe, California (38°N, 120°E) to Yellowstone, Wyoming (44°N, 111°E).

[28] A clockwise shift of extension directions during the Miocene was first discovered by *Zoback and Thompson* [1978] and further discussed by *Zoback et al.* [1981]. They interpreted a discrete clockwise shift of principal stress directions by 47° in Nevada during 15–5 Ma. My result is similar except that it shows a gradual rotation taking ~20 m.y. and affecting a much larger area. The discrepancy between their sudden-change model and my gradual-change model is not easily resolved, because the data locations shift over time and no one place has a continuous record. However, the model of gradual rotation is strengthened by the ~12° azimuth difference between 5–0.01 Ma paleostress data and contemporary stress data that was previously noted in Figure 1. If this is added to the rotation seen within the paleostress data set, the total rotation since 22 Ma becomes 36°–48°.

[29] I concur with *Zoback and Thompson* [1978] that this stress rotation is most likely the effect of increasing dextral shear stress on NW striking vertical planes, caused by the lengthening Pacific/North America transform system, being gradually superposed on the previous extensional field. That is, before the creation of the Pacific/North America transform margin, $\hat{\sigma}_{1H}$ (which was probably $\hat{\sigma}_2$) was roughly parallel to the coastline, $\hat{\sigma}_3$ was roughly perpendicular to the coastline, and there was no shear stress on vertical planes parallel to the coast. As the Pacific plate came into contact with North America along a lengthening transform boundary, northwest directed traction was exerted on a lengthening segment of North America plate margin by the Pacific plate. This gradual addition of vertical-plane area with dextral shear traction parallel to the coast caused regional-average $\hat{\sigma}_{1H}$ and $\hat{\sigma}_{1H}$ to rotate clockwise until they reached orientations of approximately E-W and N-S, respectively. Since ~10 Ma, another factor has contributed to increased shear coupling between the Pacific and North America plates: increased resistance and coupling at the left step of the San Andreas fault system in the Transverse Ranges of California.

## 5. Conclusions

[30] A plot of interpolated $\hat{\sigma}_{1H}$ azimuth and its uncertainty over time at a representative central point conveys a simple overview of these results. Figure 9 shows such a plot for "Four Corners" (common point of Colorado, Utah, Arizona, and New Mexico: 37°N, 109°W) in the western United States. This point was selected as the interpolation point because it is in a structurally simple region, it sits near the center of the data set, but it is not too close to any individual datum. Figure 9 shows three of the changes in $\hat{\sigma}_{1H}$ direction that were discussed in Section 4.

[31] Horizontal compression directions during the Sevier-Hidalgo orogeny are represented by only 5 data, so formal uncertainties are huge. However, these data show compression azimuths of 45°–67° at all latitudes, suggesting that tectonic transport may have been more uniform than the varying strike of the orogen. Perhaps its location was determined by a preexisting belt of weakness.

[32] Compression azimuths during the Laramide orogeny and late Hidalgo orogeny were stable at ~68° in the United States and 75° in Mexico. This is approximately parallel to the direction of relative motion between the Farallon plate and North America and consistent with the hypothesis that the orogeny was due to shear tractions from horizontally subducting oceanic lithosphere. The

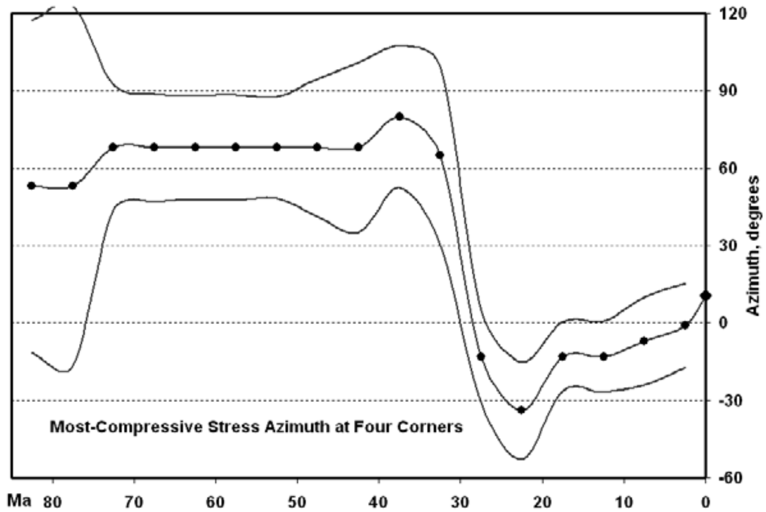


**Figure 9.** History of most compressive horizontal principal stress ($\hat{\sigma}_{1H}$) azimuth at "Four Corners" (37°N, 109°W) in the southwestern United States since 85 Ma. Fine bounding lines show 90%-confidence limits at each time step. (Smooth curves are drawn through discrete values computed for 5 m.y. steps, although it was necessary to assume constant azimuth within each time step in order to do the calculations.) Diamond at (0 Ma, 11°) shows the result from the contemporary stress field of Figure 2.

difference between this stress direction and most compressive principal strain rate azimuth of 40° [*Bird*, 1998] remains unexplained and complicates the problem of deciding whether the Kula or Farallon plate was responsible. A slight increase in $\hat{\sigma}_{1H}$ azimuth by ~15° at ~50 Ma is very marginally significant (50% confidence). There is no evidence for progressive counterclockwise rotation of stress during the orogeny as some have proposed.

[33] In the Eocene (~50 Ma), when thrust faults in Montana and Idaho reversed their sense to become normal faults and early core complexes formed to the west, there was no large rotation of stress directions. The least compressive horizontal stress remained in the northwest quadrant. This suggests that extension was driven by activity of the northwest trending dextral faults of British Columbia, rather than gravitational slumping from the Rocky Mountains to an adjacent coastal trench.

[34] The most dramatic change in this history was the stress reversal from ENE-WSW compression to ENE-WSW (relative) tension, which occurred across the entire region at 33 ± 2 Ma in Mexico and 30 ± 2 Ma in the United States. This happened too early to be caused by the formation of the Pacific/North America transform plate boundary. I attribute it to rapid rollback or delamination of the horizontally-subducting Farallon slab, which also caused the ignimbrite flare-up volcanic episode.

[35] Since 22 Ma, the principal stress directions have rotated gradually clockwise by a total of 36°–48°. This probably reflects the increasing shear force applied to North America by the Pacific plate along the lengthening San Andreas transform system, perhaps with a final increment caused by the formation of the transpressive left step of the San Andreas in southern California.

## Appendix A: Collection of Paleostress Direction Data

[36] There are three main types of datable stress direction indicators, and each type has its potential problems.

1. Igneous dikes which intrude upward through homogeneous isotropic rock should strike along the trend of the most compressive horizontal principal stress $\hat{\sigma}_{1H}$ at the time of intrusion. These dikes can usually be dated by radiometric methods. In some cases, however, dikes may follow preexisting joints. Another technical disadvantage of a dike is that it may have formed in a single day and therefore only records the stress direction on that particular day. (However, we have no reason to expect large changes in stress axes on short timescales.)

2. Hydrofractures formed by pressurized pore waters should also strike along the $\hat{\sigma}_{1H}$ direction at the time of formation. In many cases, these cracks are propped open and preserved by hydrothermal mineral deposits, forming veins. It is rare that these minerals can be directly dated. However, many vein observations are from mining districts in which detailed studies of the chemistry and three-dimensional distribution of veins allow them to be associated with plutons that can be dated. Vein sets often permit the measurement of hundreds or thousands of strikes of similar age, decreasing (but not eliminating) the risk that the mean strike will be controlled by anisotropy of the country rock. However, there is the danger that an adjacent pluton has rotated stress directions from their regional averages by superposing its own stress field.

3. Slip vectors of faults (from structural analysis or from slickensides) are believed to record the rake of the maximum shear traction in the plane of the fault, even if the fault was formed previously in a different stress field. If many such observations are combined in an inverse calculation [e.g., *Gephart*, 1990], the orientation of the principal stress axes can be inferred. Unfortunately, the age of deformation can only be determined indirectly, by crosscutting relations or from the stratigraphy of molasse in adjacent basins. A compensating advantage is that faults can slip at any time in geologic history, so the record they provide is not restricted to igneous provinces and epochs. Additional stress direction indicators include the teeth of stylolites which form in carbonates, and the regional alignments of fold axes; these are less

desirable because they are more difficult to date. However, the database includes a few examples from regions with no other constraints.

[37] I have compiled 369 such indicators (with ages of 85 Ma or less) from the western United States and Mexico. This compilation was part of a larger project which involved scanning the major English-language journals and monographs since 1990 ($\sim$1000 papers), with diversions into earlier cited literature (scanning $\sim$1100 additional papers). It is not exhaustive or complete, but is about 6 times larger than any published previously. The following compilations make up significant fractions ($\geq$2%) of the database: 19 directions from *Rehrig and Heidrick* [1976]; 50 directions from *Swanson et al.* [1979]; 18 directions from *Angelier et al.* [1981]; 12 directions from *Zoback et al.* [1981]; 24 directions from *Heidrick and Titley* [1982]; 64 directions from *Dreier* [1984]; 9 directions from *Price and Henry* [1984]; 54 directions from *Aldrich et al.* [1986]; 25 directions from *Best* [1988]; and 7 directions from *Ren et al.* [1989]. In terms of type of indicator, 182 (49%) are dikes, 82 (22%) are vein sets, 41 (11%) are fault sets, and 59 (16%) are composites formed by the original authors cited.

[38] Most of the entries in the data set are not from single field observations but are mean directions from a number of measurements. I attempt to distinguish two cases. Notation ''stage'' indicates that the stress indicators averaged had a range of ages (summarized by the maximum and minimum age attached to the datum), and that they indicate roughly constant stress direction during that span of time. Notation ''window,'' on the other hand, means that the stress had the indicated direction at some time between the maximum age and minimum age quoted, but not necessarily for the whole duration. When authors gave no error estimates for radiometric dates, I inserted an assumed minimum uncertainty of ±1 Ma. In the cases of fault sets which were merely identified as ''Laramide'' by the original authors, I have used the durations of the Laramide orogeny determined by *Dickinson et al.* [1988] or by *Muehlberger* [1980].

[39] The standard deviations ($\delta$) reported for each $\hat{\sigma}_{1H}$ azimuth in the electronic supporting material were not quoted by the original authors cited. Instead, I have assigned them on the basis of their reported maps of dikes, rose diagrams of veins, stereographic projections of principal stresses, etc. I applied the principle that the range $\pm 2\delta$ about the mean azimuth should encompass 90% of the observations. In some cases where the primary observations were not reported, I rather arbitrarily assigned a standard deviation obtained in another study of similar type. In general, uncertainties are least for dike sets, intermediate for fault slip sets, and greatest for vein sets.

[40] Some regions are known (from paleomagnetic evidence) to have undergone large rotations about vertical axes since 85 Ma, such as the Transverse and Coast Ranges of California, and the Coast Range of Oregon. No data are tabulated from these regions, since their interpretation would be difficult. It is still possible that some indicators in this data set have been rotated; for example, the directions reported by *Angelier et al.* [1985] from the Hoover Dam region of Nevada-Arizona may have been affected by rotations along the Lake Mead fault zone [*Geissman*, 1986].

[41] One striking feature of the data set is the preponderance of fault slip and vein observations during Sevier and Laramide time. Among the 95 stress direction data with maximum ages between 85 and 47.5 Ma, dike sets are only 12 (13%). This contrasts with 170 dike sets among 274 indicators (62%) with maximum ages of 47.5 Ma or less. Although various observer biases are possible, this is probably due to the relative rarity of Laramide-age dikes in the field. If the least compressive stress direction ($\hat{\sigma}_3$) was vertical at most places during Laramide time, then dike intrusions would have been suppressed in favor of sills and laccoliths. Unfortunately, I cannot go further than this in investigating stress regimes (i.e., thrusting, strike slip, or normal faulting) with this data set, since most direction indicators are not associated with regime information.

## Appendix B: Interpolation and Comparison of Paleostress Directions

[42] In this paper, I attempt to discern a regional history of stress direction by averaging as many indicators as possible, and by using statistical measures that can indicate which apparent stress direction changes are reliable. A basic assumption is that the (measurable) conditional probabilities which relate two stress indicators today can be used as estimates of the (unmeasurable) conditional probabilities in the past. This permits us to make use of the extensive and well-documented World Stress Map data set of *Zoback* [1992] as a basis for statistics.

### B1. Assumptions

[43] The statistical method adopted here rests on three assumptions:

1. The part of the scatter (or variance) in indicated stress directions which is due to the actual spatial complexity of the stress field and/or to the effects of anisotropic country rock has not changed over time. (This assumption cannot currently be tested, because we do not have enough paleostress direction indicators of exactly equal age. However, it is reasonable to think that both true stress directions, and stress direction indicators, are rotated away from the regional-average stress directions by preexisting structures and fabrics in the Precambrian metamorphic basement of continents, by an extent which has not changed over time.)
2. The measurement error involved in detecting and recording a stress direction indicator is no larger for the geologic data set than it is for the contemporary data set. (In fact, it may be smaller. Almost all of the azimuths used here were measured with the Brunton pocket transit or some equivalent, which is accurate to $\pm 1^\circ$ if care is taken to avoid local magnetic declination anomalies. In contrast, present-day data from seismic fault plane-solutions can easily have $10^\circ$ errors due to wave refraction effects and/or limited numbers of arrivals. Present-day data from wellbore breakouts can be affected by twist in the drill string.)
3. If the stress direction has rotated over time, and if direction indicators of different ages are interpreted as a group without considering this, then the sample variance of directions will exceed the time average of the actual population variance. (This is a well-known property of statistics: If unrelated populations are sampled without distinction, the variance is increased.)

[44] If these assumptions are valid, then we can use the statistical distributions of the present-day global stress field as a guide to interpretation of paleostress direction data, and we will obtain computed uncertainties which are either accurate or too

large. We will never obtain an uncertainty which is artificially low.

## B2. Interpolation of Stress Directions

[45] In order to study changes in stress direction over time, it is first necessary to transfer these directions to a common set of geographic points. In order to collect enough stress data to support this interpolation, it is necessary to divide the history into time steps, and to make the approximation that directions did not change within a step. These discretizations of space and time both introduce some error by eliminating high spatial and temporal frequencies. The error introduced by interpolation will be controlled by the statistical technique of *Bird and Li* [1996]. The error involved in discretizing time will be reduced by introducing a concept and variable called "relevance"; however, it will still be necessary to remember the loss of time resolution during the interpretation of results.

[46] Each datum was associated with one or more of seventeen 5-million-year-long time steps spanning 85–0 Ma. Association of a datum with a time step is described by a variable called relevance, which is the estimated probability that the stress direction recorded by the indicator was valid at some time during that time step. Relevance is zero for datum/time step pairs which have no overlap in time. Relevance is unity for stage data in all the time steps which they overlap. Relevance for "window" data is partitioned between all the time steps overlapped, so that the relevances add to unity for that datum. For example, the Roberts Mountains dike swarm and flow field in Nevada reported by *Zoback et al.* [1994] has been dated 8 times, with ages ranging from 18.6 to 13.6 Ma. Considering the uncertainties of each date, the minimum duration of magmatism was from 17.9 to 14.0 Ma. This is considered as a stage datum and has 100% relevance to both the 20–15 Ma and the 15–10 Ma time steps. However, the mineralized joints in the Sierra Nevada of California reported by *Segall et al.* [1990] are constrained as forming during 85-79 Ma, with no implication of extended duration. This is considered a window datum, which is assigned 83% relevance to the 85–80 Ma time step and 17% relevance to the 80–75 Ma time step.

[47] Next, a grid of equally spaced points was established across the western United States and Mexico. These points lie at the centers of 120-km equilateral triangles formed by the sixth-level subdivision of a global icosahedron [*Baumgardner*, 1983].

[48] In those (few) triangles which contain one or more data relevant to the time step, the stress direction and its uncertainty was taken from the datum with the highest relevance. Since only stress changes with regional coherence are discussed in this paper, any change in this rule would not affect its conclusions.

[49] At all other points (the great majority), the $\hat{\sigma}_{1H}$ direction was interpolated by the method of *Bird and Li* [1996]. All data from <22° arc distance with positive relevance were used. The probability density function for paleostress directions of various azimuths at the interpolation point was formed as the product of two-point conditional probability densities (one per datum) which Bird and Li determined from the contemporary World Stress Map data set of *Zoback* [1992]. These conditional probability densities are empirical functions (actually, histograms) whose independent variables are angular discrepancy and arc distance between the datum and the interpolation point. The curves for probability as a function of angular discrepancy change gradually from quasi-Gaussian peaked distributions at short distances to a nearly flat distribution at 22°. The only innovation in the interpolation for this project was that the relevances were applied as exponents on the conditional probability densities from each datum, before forming the product probability density function at the interpolation point. (Compare the use of relevance variable $q_k$ in equation (1) of *Bird* [1998].) The result is, for example, that 6 data of 33% relevance have the same weight in the interpolation as 2 data of 100% relevance.

[50] *Bird and Li* [1996] presented two variants of their stress interpolation method: with and without clustering of neighboring data prior to forming the product of probability densities. The simpler method (without clustering) is used here, for two reasons. First, most of the entries in this data set have already been clustered by the original authors. (That is, most are the means or modes of multiple azimuth measurements in a small geographic area, from features of about the same age.) Second, this method makes it possible to weight the data by their relevances, which is essential for paleostress interpolation.

[51] This method does not assume that the errors in the data, nor the variances added by separation in space and time, have Gaussian distributions. The raw probability density function is obtained for each interpolation point in each time step. To plot maps, the peaks of the distributions (most probable azimuths) are selected as the best estimates of $\hat{\sigma}_{1H}$ directions. Then the probability density distributions (as a function of azimuth) are integrated to both sides of those azimuths until 90% probability is encompassed; these limits are the 90%-confidence limits on the results. When an uncertainty measure comparable to the standard deviation is wanted, I determine the angle on each side of the most probable azimuth that encompasses 34% of the probability (or, 68% within ±1 standard deviation). Since $\hat{\sigma}_{1H}$ azimuths are cyclical with 180° period, a 90%-confidence limit of ±81°, or a standard deviation of 61°, is the worst possible outcome, and indicates that $\hat{\sigma}_{1H}$ could not be constrained at all.

## B3. Testing for Significant Stress Direction Changes

[52] Once we know the interpolated stress direction and its uncertainty at each grid point in each time step, it is possible to test for the significance of apparent stress direction changes between time steps. Statistics provides the $t$ test, which has a simple form for unpaired distributions when each has a large number of degrees of freedom. If distribution A has mean of $x_a$ and standard deviation of $\sigma_a$, while distribution B has mean of $x_b$ with standard deviation of $\sigma_b$, then (for many degrees of freedom) $t \equiv |(x_a - x_b)| \Big/ \sqrt{\sigma_a^2 + \sigma_b^2}$. For increasing values of $t$, there is increasing confidence that the difference does not arise by chance, and that the true difference between the distributions has the same sign as the difference of the means; for example, $t$ = 1.282 gives 80% confidence that the difference is real and has the apparent sign; $t$ = 1.644 gives 90% confidence, etc.

[53] It is important to test many pairs of time steps, because it is not known in advance that stress direction changes were necessarily rapid. A slow, continuous rotation might not yield significant differences between adjacent time steps, but only between time steps with some separation. Or, a sudden stress change within one time step (e.g., at 33 Ma) might cause that step (35-30 Ma) to have interpolated stress directions with large uncertainties. Then, comparisons with adjacent steps might not show a significant change because the large uncertainty would result in smaller $t$ values. However, a comparison skipping over the change (e.g., comparing

40–35 Ma with 30–25 Ma) would reveal the shift. My method is to prepare stress change maps comparing both adjacent and widely separated pairs of time steps. In each map I plot a colored triangle around any interpolation point whose stress direction change is significant at a certain confidence level, such as 90%. The color of the triangle indicates the amount of stress rotation. Using this graphic, one can easily find stress rotations which are both statistically significant and regionally coherent. "Significant" changes affecting only a single interpolation point are usually local effects of one (or very few) data within the associated triangle, and are not discussed here. Figure 4 is an example of one of these stress change maps, illustrating two localized rotations which may be real but which cannot be assigned a high confidence.

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