GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 23, PAGES 3381-3384, NOVEMBER 15, 1996

Relationship between the present-day stress field and plate boundary forces in the Pacific Northwest

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Abstract. The relationship between plate boundary forces and the observed stress field in the Pacific Northwest is established using numerical models of continental deformation. Because the orientation of the greatest horizontal principal stress throughout the Pacific Northwest differs considerably from the direction of convergence between the Juan de Fuca and North American plates, the relationship between the stress field and forces acting along the subduction zone has been unclear. To address this relationship, a two-dimensional finite element model developed by *Bird* [1989] is used that incorporates critical aspects of continental deformation such as a stratified rheology and interaction between thermal and mechanical components of deformation. Boundary conditions are specified in terms of either velocity or shear traction, depending on whether the computed shear stress at the plate boundary is less than or exceeds, respectively, a prescribed limit. Shear-stress limits on the subduction and transform plate boundaries are independently varied to determine the relative effect of forces along these boundaries on intraplate deformation. Results from this study indicate that the shear stress limit of both subduction and transform boundaries is low, and that the intraplate stress field is attributed, in part, to the normal component of relative plate motion along the transform boundaries. However, the models also indicate that although the subduction zone fault is weak, a minimum shear strength ($\geq$ 10 MPa) for the fault is necessary to explain the observed stress field. The balance among forces along the tectonic boundaries of North America results in a surprising degree of variation in the present-day stress field.

Introduction

The present-day state of stress throughout most of the Pacific Northwest region is characterized by N-S directed compressive stress, ostensibly unrelated to forces associated with the Cascadia subduction zone. Because the greatest horizontal principal stress direction differs considerably from the direction of convergence between the Juan de Fuca and North American plates, the shear strength of the Cascadia subduction fault is inferred to be low [*Zoback and Zoback*, 1991; *Wang et al.*, 1995]. Closer to the plate interface, geodetic data [*Savage et al.*, 1991] and P-axes from focal mechanisms [*Weaver and Smith*, 1983] indicate compression sub-parallel to the relative plate convergence direction and are cited as evidence for locking of part of the subduction fault during a period of interseismic strain accumulation. The stresses associated with elastic deformation during the earthquake cycle can be thought of as perturbations of the time-averaged stress field due to anelastic deformation of the overriding plate [*Dmowska et al.*, 1988]. Near the subduction fault, geodetic data measure these short-term perturbations of the stress field during the earthquake cycle, whereas crustal earthquakes provide a measure of the background stress field [*Sbar* 1983; *Wang et al.*, 1995].

Paper number 96GL03157

The objective of this study is to determine the relationship between the intraplate stress field and plate boundary forces. Recognizing the temporal dependence of deformation and the importance of using a realistic earth rheology, the approach taken in this study is to model the pattern of present-day stresses using a recently developed finite-element technique [*Bird*, 1989] that models the finite-strain of continents in relation to plate boundary forces. In this study, the shear strength of the subduction and transform faults are specified as independent variables. To determine optimal values for the strength of plate boundary faults, model results are compared to principal horizontal stress direction data and to the observed style of faulting.

Stress Provinces of the Pacific Northwest

Stress provinces have been defined for the North American stress field based on the constancy of the greatest horizontal principal stress direction (S_{Hmax}) and the style of faulting [*Zoback and Zoback*, 1991]. The Pacific Northwest encompasses two stress provinces. Near the coast and in the offshore region, the Cascade convergence province, poorly defined by sparse earthquake and borehole breakout data, is characterized by NE-directed compression approximately 30°-45° oblique to the convergence direction (CCSP, Figure 1). The Pacific Northwest stress province located east of the Cascade convergence province (Figure 1) is defined by N-S compression, manifested by dominant thrust faulting and secondary strike slip faulting in the north, in contrast to dominant strike-slip faulting and secondary thrust faulting in the south. Recent analysis of small crustal earthquakes by *Wang et al.* [1995] indicate a NW-SE orientation of S_{Hmax} from Puget Sound to Vancouver Island. *Wang et al.* [1995] suggests that S_{Hmax} parallels the continental margin, varying from a N-S orientation in Puget Sound to a NW-SE orientation in the Vancouver Island region. Neighboring stress provinces (Figure 1) include the Queen Charlotte and San Andreas transform provinces to the north and south respectively and two plate-interior provinces: the Basin and Range extensional province and Canadian mid-plate compressional province [*Adams and Bell*, 1991].

Model Description

The finite-element model developed by *Bird* [1989, 1992] incorporates aspects of anelastic deformation such as a frictional rheology in the upper crust, mechanical detachment and thermal discontinuity in the lower crust, lateral diffusion of crustal thickness contrasts, and mixed boundary conditions. The equations of motion for Stokesian flow are approximated in a vertically integrated form familiar as the thin-plate representation

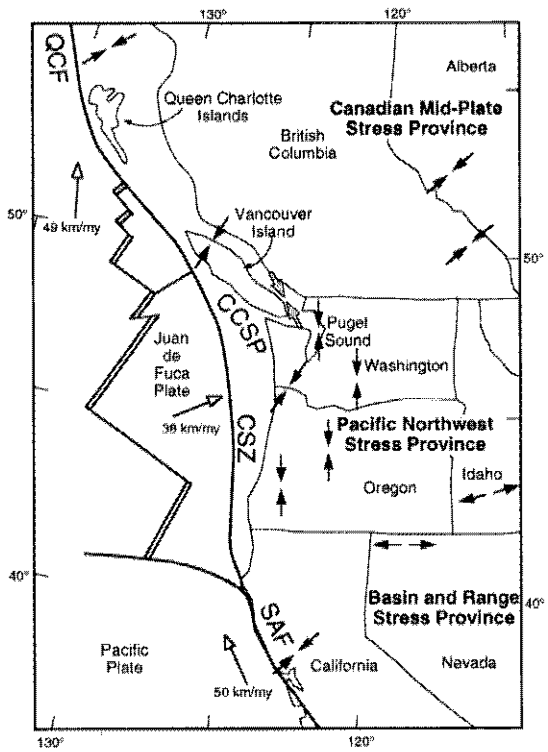

Figure 1. Summary of the present-day stress field in the Pacific Northwest modified from *Zoback and Zoback* [1991]. Inward- and outward-pointed arrows represent direction of greatest and least horizontal compressive stress, respectively. Shaded inward-pointed arrows represents greatest horizontal principal stress determined by *Wang et al.* [1995] for the southern Vancouver Island region. Single arrow represents direction of Juan de Fuca-North America relative motion [*Wilson,* 1993]. SAF, San Andreas fault; QCF, Queen Charlotte fault; CCSP, Cascade convergence stress province.

and implemented using a Galerkin finite-element technique with 6-node isoparametric elements. In addition, rather than assuming a linear and constant geotherm, an analytical technique for computing the temperature field at each time step is devised that takes into account the effects of thermal diffusion and shear strain heating.

Mechanical boundary conditions are dependent on the computed level of shear stress along the active boundaries. If the computed shear stress is less than a prescribed limit then velocity boundary conditions are used based on the plate motion reconstruction by *Engebretson et al.* [1985] with updated estimates of Juan de Fuca-North America plate motion by *Wilson* [1993]. If the shear stress limit is exceeded, then a shear traction boundary condition equal in magnitude to the shear stress limit is used. In the model for Cascadia deformation, basal shear traction is effectively applied over 100 km along the subduction thrust. In addition, a vertical traction due to the excess mass of the downgoing oceanic lithosphere is applied. Along the transform boundaries, a fault-normal velocity boundary condition is applied that is equal to the normal component of relative plate motion. Thus, for the case in which the shear stress limit is exceeded along the transform boundaries, mixed boundary conditions (velocity and shear traction) are invoked. Thermal boundary conditions specified at the base of the deforming lithosphere overlying the subducting plate results in cooling and strengthening of the continental lithosphere. Landward from the subduction zone, because of hingeline rollback during Cenozoic time, the continental lithosphere is thought to overlie newly forming lithosphere modeled as a thermal boundary layer. Further details of the model are given by *Bird* [1989, 1992].

In this study, Neogene simulations based on *Bird's* [1992] model are used to examine the present-day stress field of the Pacific Northwest. The only modification made to the model (other than hardware and software specific modifications) was the addition of independently specifying the shear stress limit on the subduction and transform boundaries. This allows one to vary the long-term shear strength of the subduction fault independently from the shear strength of the San Andreas and Queen Charlotte faults.

Table 1. Varying Shear Stress Limit on Subduction Boundary

Shear Stress Limit		
Subduction Boundary	Transform Boundaries	RMS Prediction Error ε_{stress}
5 MPa	28 MPa	40°
10 MPa	28 MPa	19°
15 MPa	28 MPa	22°
20 MPa	28 MPa	24°
30 MPa	28 MPa	27°

Results

A set of experiments were run using different values for the shear stress limit along the subduction boundary, holding the shear stress limit along the Queen Charlotte and San Andreas transform boundaries constant (Table 1). To test the effect that boundary conditions along the transform margins have on intraplate deformation, another set of experiments were run in which only the value for the shear stress limit along the transform margins was varied (Table 2). For each experiment, deformation was modeled from 20 Ma to the present at one million year time steps, using the results from *Bird's* [1992] model as initial conditions. Results from both sets of experiments are compared with the observed orientation of S_{Hmax} and style of faulting in the Pacific Northwest. A weighted RMS (root mean square) error (ε_{stress}) is computed between the predicted orientation of S_{Hmax} and data compiled by *Zoback and Zoback* [1991]. Weights were assigned to the data based on quality factors listed by *Zoback and Zoback* [1991], using a method described by *Bird and Kong* [1994]. Prediction errors for each of the models considered are listed in Tables 1 and 2. As described below, the models are also qualitatively evaluated based on a comparison between the predicted and observed style of faulting in the Pacific Northwest [*Pezzopane and Weldon,* 1993].

Table 2. Varying Shear Stress Limit on Transform Boundaries

Shear Stress Limit		
Subduction Boundary	Transform Boundaries	RMS Prediction Error ε_{stress}
15 MPa	1 MPa	22°
15 MPa	10 MPa	22°
15 MPa	28 MPa	22°

Results for the first set of experiments confirm the observation that a weak Cascadia subduction zone fault is necessary to explain the present-day stress field [*Zoback and Zoback*, 1991; *Wang et al.*, 1995]. The long-term shear strength of the subduction fault is estimated to be between 10 and 15 MPa. This result also agrees with findings by *Wang et al.* [1995], who indicate that the shear strength along the subduction zone is probably 10 MPa or less, based on heat flow data. However, results from this study indicate that if 5 MPa is used for the shear stress limit, Basin and Range-type extensional deformation unbalanced by subduction forces would occur throughout the Pacific Northwest: clearly an unacceptable condition. Although, the model with a shear strength of 10 MPa best fits the principal stress direction data, this model predicts extensional deformation too far to the north. The model with 15 MPa shear strength seems to best fit the data in term of both the principal direction of stress and the style of faulting observed in the Pacific Northwest (Figure 2).

Despite the complexity of deformation observed in the Pacific Northwest, the model shown in Figure 2 reproduces many aspects of recent deformation noted by other researchers. In Puget Sound the orientation of S_{Hmax} is approximately N-S as determined from formal inversion of focal mechanisms in the region [*Ma et al.*, 1991]. The predicted orientation of S_{Hmax} rotates to a NW-SE orientation near Vancouver Island in agreement with regional studies of small crustal earthquakes [*Wang et al*, 1995] and to a NE-SW orientation in northeastern Washington, southern British Columbia, and northeastward toward the Canadian mid-plate compressional province [*Adams and Bell*, 1991]. The pattern of dominant thrust faulting in Washington (TS in Figure 2) versus dominant strike-slip faulting (e.g., the St. Helens seismic zone) to the south (ST in Figure 2) is also reproduced by the model. The model predicts a NE-SW orientation of S_{Hmax} near coastal Washington consistent with the stress orientation determined by focal mechanisms [*Weaver and Smith*, 1983]. The predicted orientation of thrust faulting in this region also correlates with the WNW-ESE striking nodal plane for the 1993 Scotts Mills earthquake [*Nábělek and Xia*, 1995]. Thus, the change from N-S compression in the Pacific Northwest stress province to NE-SW compression in the Cascade Convergence stress province can be interpreted either as a result of the long-term deformation or elastic deformation during the interseismic period of the earthquake cycle. However, because the long-term rates of coastal uplift predicted from the model are very low (< 0.1 mm/yr), the geodetic measured uplift patterns along the Cascadia margin [*Hyndman and Wang*, 1995] are best explained as a result of elastic strain accumulation along the subduction fault. The regions that had the highest discrepancy between the predicted and observed orientation of S_{Hmax} were northern Vancouver Island and Cape Mendocino (i.e., near the triple junctions).

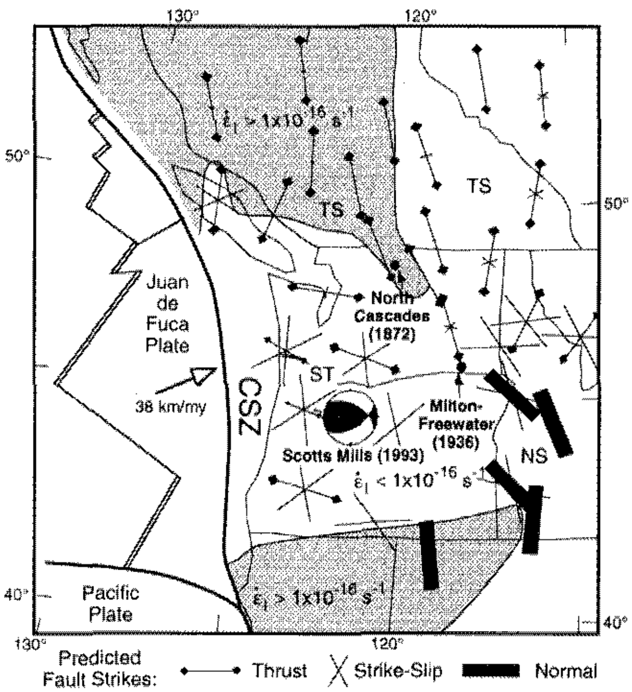

Figure 2. Style of faulting predicted by the model for which the shear stress limit along the subduction zone is 15 MPa. Symbols represent the strike of faults expected in the region. Symbol representing the primary style of faulting plotted at the same size, regardless of the magnitude of the maximum principal strain-rate. The secondary style of faulting is scaled relative to the primary style of faulting. The two-letter mnemonic (e.g., ST, TS, NS) indicates the primary (first letter) and secondary (second letter) style of faulting (T-thrust, S-strike-slip, N-normal). For further explanation on how the style of faulting relates to the present-day state of stress see *Bird* [1989]. Shaded regions represent areas where the maximum principal strain-rate is greater than $1\times10^{-16} s^{-1}$. Locations of earthquakes discussed in the text are shown on the figure. Focal mechanism for the 1993 Scotts Mills earthquake determined by *Nábělek and Xia* [1995].

Discussion

Previous to this study, the dominantly N-S compressive field in the Pacific Northwest stress province has been explained as a consequence of Pacific-North America relative plate motion [*Spence*, 1989; *Zoback and Zoback*, 1991]. Using an elastic-plastic model, *Spence* [1989] indicated that the regional stress field was induced by the Pacific plate via the Gorda/Juan de Fuca plate system, requiring strong coupling along the Cascadia subduction zone. Results from this study, in which progressive deformation driven by Neogene plate motions, indicate that the regional stress field is caused by, primarily, the normal component of relative plate motion along the Queen Charlotte fault (Figure 1). Correspondingly, the highest rate of uplift predicted by the model occurs along coastal British Columbia correlating with high uplift rates < 10 Ma determined from fission track analysis [*Parrish*, 1983]. Secondarily though, the stress field in the Pacific Northwest is also affected by basal shear traction along the subduction zone. Unbalanced by subduction-derived compression, Basin and Range extension would occur throughout the Pacific Northwest. Normal traction along the transform boundaries appears to have a much larger influence on intraplate deformation than shear traction along the transform boundaries. This is because the San Andreas and, by inference, the Queen Charlotte transform are inherently weak in terms of shear strength [*Zoback and Zoback*, 1991]. Independent evidence indicates that the strength of the San Andreas fault is no greater than 20 MPa [*Lachenbruch and Sass*, 1992]. Thus, the shear strength of the Cascadia subduction zone is comparable to that of the San Andreas fault. The fact that variation of the shear strength of the transform faults between 1 and 28 MPa does not significantly affect the stress field in the Pacific Northwest (Table 2) suggests that intraplate deformation in the Pacific Northwest is not a consequence of the margin-parallel component of Pacific-North America relative motion.

Although not all deformation is released seismically, the modeled rate of deformation can be used to estimate the relative magnitude of the long-term rate of seismic moment release throughout the Pacific Northwest (not including seismic moment release along the subduction thrust). The magnitude of the maximum principal strain-rate from the model is highest north of Washington (due to compression along the Queen Charlotte fault) and near the Mendocino triple junction (Figure 2). The trend in strain-rates determined from the summation of seismic moment tensors [*Pezzopane and Weldon*, 1993] is in agreement with the model. In Oregon and southern Washington, the seismic moment tensor analysis indicates that the maximum principal strain-rate is less than $1\times10^{-16}s^{-1}$, whereas to the north and south, the strain-rate is greater than this value (cf., Figure 2). For comparison, the characteristic strain-rate in a highly deforming region such as the Aegean Sea is approximately $4\times10^{-15}s^{-1}$ [*Jackson and McKenzie*, 1988]. The low rate of deformation in Oregon predicted by the model suggests that the observed intraplate seismic quiescence is a long-term phenomenon.

Results from the model also help determine the tectonic context of large earthquakes for which no focal mechanisms are available. The 1872 North Cascades earthquake is thought to be the largest historic earthquake to occur in the Pacific Northwest (M 7.4, *Malone and Bor*, 1979) and probably was a crustal event based on intensity and aftershock data [*Ludwin et al.*, 1991]. The most likely epicenter of the earthquake as determined by *Malone and Bor* [1979] is located in a region of higher strain-rate and NE-directed compression (Figure 2). Thrust faulting is the dominant style of faulting in this region. The origin of 1936 Milton-Freewater earthquake (M~6, *Ludwin et al.*, 1991) is less clear. The epicenter is located in a transition region among three stress regimes: NNE-direction compression to the west; NE-directed compression to the north; and Basin and Range extension to the south. Therefore, the dominant style of deformation, let alone the tectonic cause of the Milton-Freewater earthquake is difficult to ascertain.

Conclusions

The present-day stress field in the Pacific Northwest is a result of fault normal compression along the Queen Charlotte transform boundary and basal shear traction along the Cascadia subduction zone. The normal component of traction along the transform boundaries appears to have a dominant influence on the intraplate stress field. In addition, the shear strength of the subduction zone interface must be at least 10 MPa, comparable to the strength of the San Andreas fault, to explain the principal direction of stress and style of faulting in the Pacific Northwest.

Though the boundary conditions for the model are relatively simple, the resulting stress field is richly varied. Except near the triple junctions, the predicted orientation of S_{Hmax} corresponds with the available stress data. The complexity of the observed stress field can be envisioned as the superposition of stresses originating from forces resolved along both subduction and transform boundaries. As such, along-strike variations in the strength of the subduction zone are not necessary to explain spatial variations observed in the present-day stress field.

Acknowledgments. I thank M. L. Zoback, T. Parsons, K. Wang, and P. Bird for their constructive reviews of the manuscript. Computations performed at the San Diego Supercomputer Center.

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(Received January 29, 1996; revised June 6, 1996;
accepted June 13, 1996.)