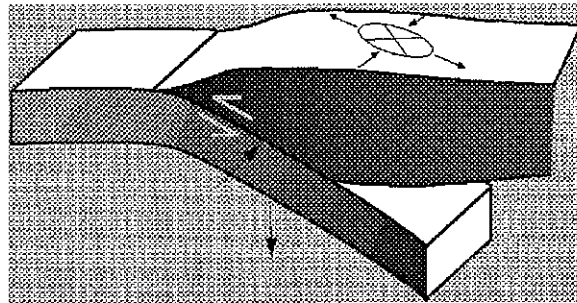


Western Region Coastal and Marine Geology

The Cascadia Megathrust and Tectonic Stress in the Pacific Northwest

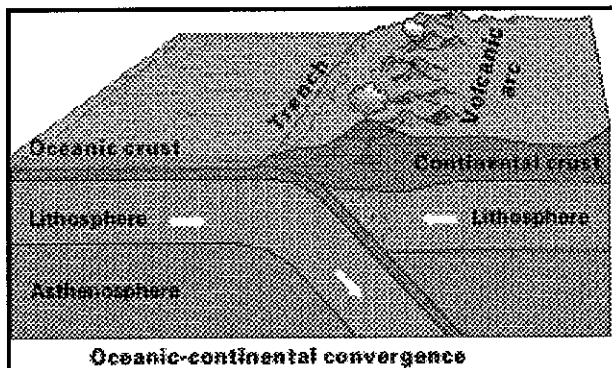


Source: Geist, Eric L., 1996. Relationship between the present-day stress field and plate boundary forces in the Pacific Northwest, *Geophysical Research Letters*, v. 23, p. 3381-3384.

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Overview



This Dynamic Earth

The Pacific Northwest (Northern California, Oregon, Washington, and British Columbia) is the site of the Cascadia subduction zone, where an oceanic tectonic plate (the Juan de Fuca plate) is being pulled and driven (i.e., subducted) beneath a continental plate (the North American plate). As a result of the interaction between the two plates, the continent overlying the subduction zone is actively deforming. Earthquakes in the Pacific Northwest are generally thought to occur in three different parts of the Cascadia subduction zone:

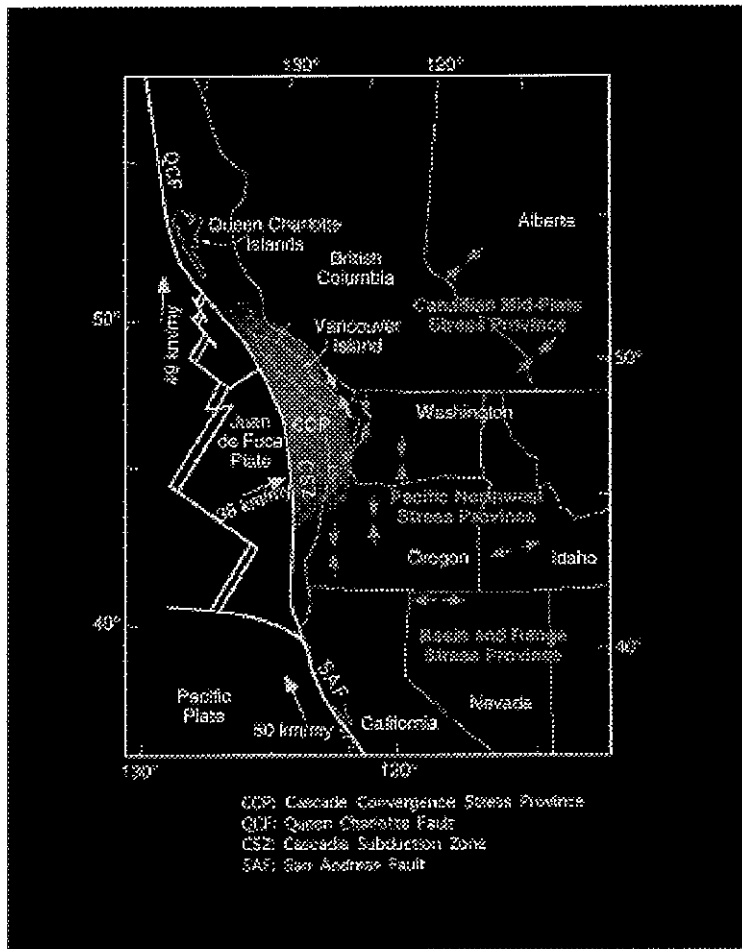
1. The deforming part of the North American plate
2. The contact between the two plates, termed the interplate thrust or megathrust
3. Within the down-going Juan de Fuca plate

This project addresses two of the many questions regarding earthquake hazards in the Pacific Northwest:

1. The state of stress in the Pacific Northwest is generally N-S oriented horizontal compression. Because one would expect that the orientation of compression would be close to the direction that the Juan de Fuca plate is moving toward North America, what is the origin of the N-S compressive stress field in the Pacific Northwest?
2. A very unusual aspect of the Cascadia subduction zone is that there have been few, if any, earthquakes instrumentally recorded along the Cascadia megathrust. This fact, in combination with the fact that the seismogenic part (where earthquakes would be generated) of the Cascadia megathrust is located offshore, limits our understanding of the mechanics of this important fault. Can the observed stress field in the Pacific Northwest tell us anything about the fault itself? In light of the fact that very few earthquakes occur along the megathrust, is it otherwise mechanically similar to other major plate boundary faults around the world (e.g., the San Andreas fault)?

To address these questions, a modeling study was devised to relate the stress field within the North American plate to tectonic forces acting along the plate boundaries.

Tectonic Setting and Stress Field



Explanation

Inward pointing red arrows: Orientation of principal compressive stress

Outward pointing red arrows: Orientation of principal tensional stress

Inward pointing green arrows: Orientation of principal compressive in Puget Sound

Yellow arrows: Relative plate motion between the oceanic plates (Pacific and Juan de Fuca) and the North American plate

Stress Provinces

Pacific Northwest Stress Province: N-S oriented compressive stress

Cascade Convergence Stress Province (CCP): NNE-SSW oriented compressive stress

Basin and Range Stress Province: E-W oriented tensional stress

Canadian Mid-Plate Stress Province: NE-SW oriented compressive stress

Questions

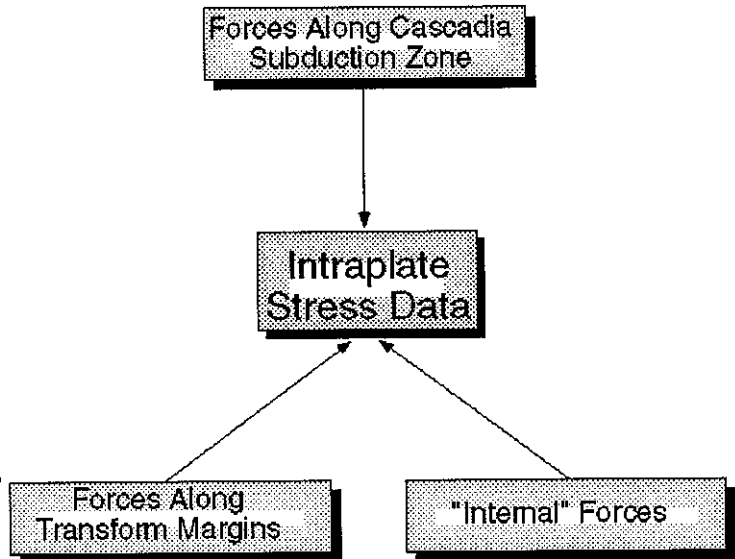
1. Is the N-S oriented compressive stress in the Pacific Northwest Stress Province related more to Pacific-North America relative plate motion than Juan de Fuca-North America relative plate motion?
2. Is the direction of stress in the Cascade Convergence Stress Province related to increase coupling along the subduction zone offshore of Washington?

(See below for **Answers!**)

The Model

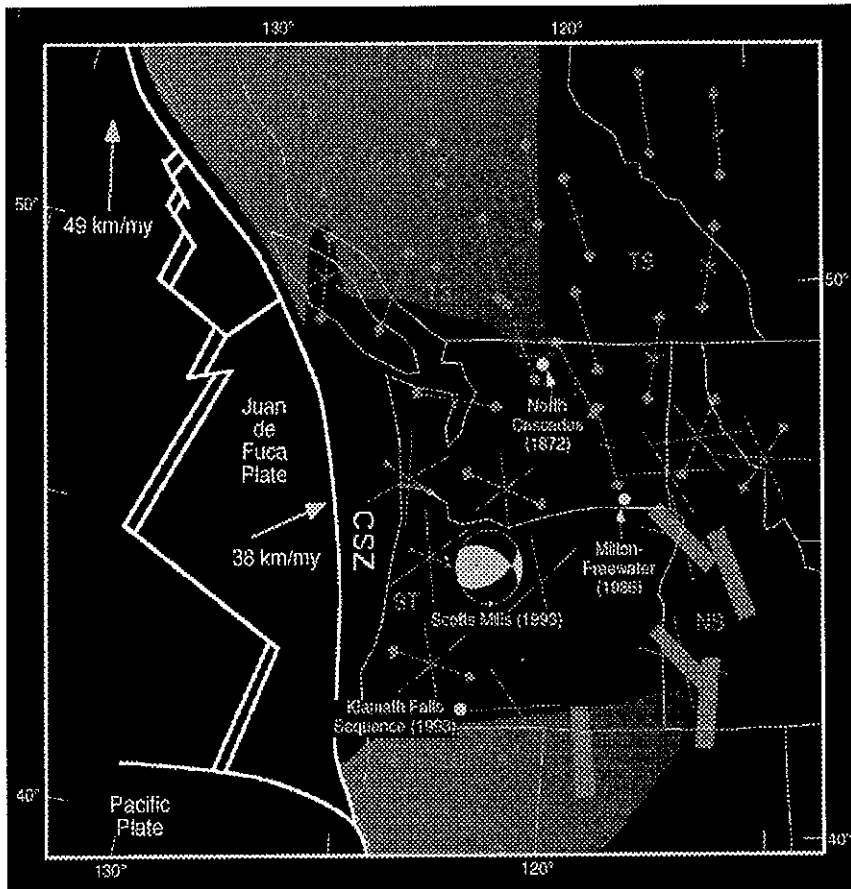
To understand the tectonic cause of stress and deformation in the Pacific Northwest, we need to consider not only forces acting along the Cascadia Subduction zone, but also forces acting along the tectonic margins to the north (Queen Charlotte fault) and to the south (San Andreas fault).

In addition, over millions of years, mountain ranges are built that locally affect stress and deformation within the North American plate (i.e., internal forces in diagram at right). In general, the present day state of stress depends, in part, on how the continent was deformed in the past. In other words, the present-day rate of deformation has a "memory" of past deformation episodes.



As one might be lead to believe from the previous discussion, modeling the deformation of continents is very complex. The model chosen for this study (LARAMY) was developed over several years by Dr. Peter Bird at UCLA (Earth and Space Sciences). This model incorporates many aspects of continental deformation observed in the field and laboratory measurements of how rocks deform under different pressure and temperature conditions. In particular, LARAMY is quite successful in modeling the formation of the Rocky Mountains using reconstructions of plate motions along the western margin of North America. For this study, however, we focus on the last time step of the model--the present day state of stress and rate of deformation.

Results



Explanation

Red Symbols: Orientation of faults predicted by the model. Rectangle represents normal faulting, line with diamond ends represents thrust faulting, and X represents two possible orientations of strike-slip faulting (see [faults](#)).

Shaded Blue Regions: Regions deforming at a higher rate than the interior part of North America.

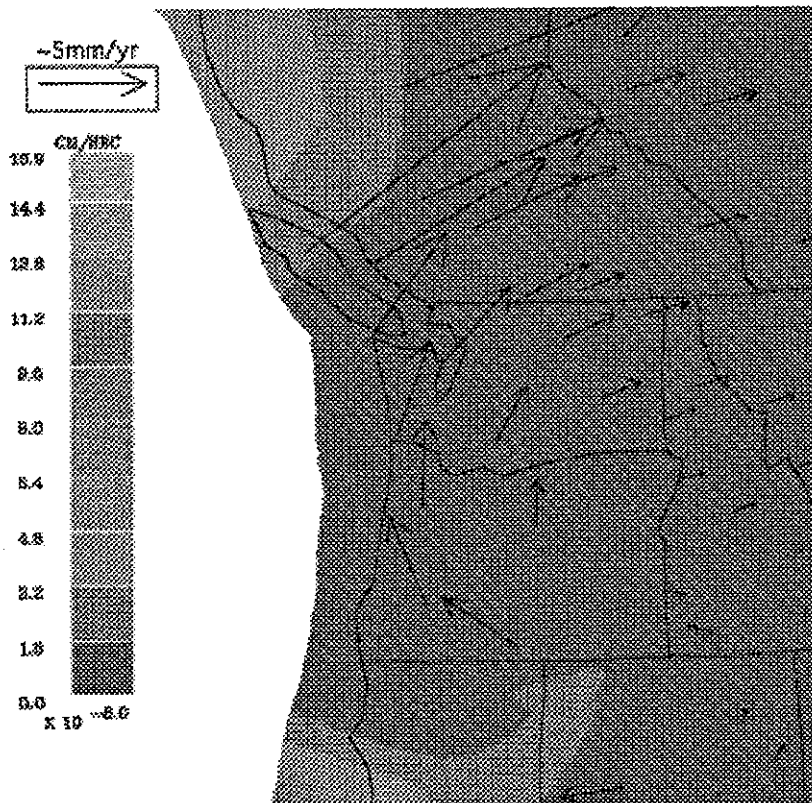
Yellow Dots: Recent and important historical earthquakes in the Pacific Northwest.

The model shown above provides the best fit to the present-day stress and deformation field. For this model, the basal shear traction along the Cascadia megathrust is 15 MPa. Sensitivity analysis demonstrates that basal shear traction lower or higher than 15 MPa result in a greater misfit to the stress data and style of faulting. Conversely, the present-day stress field appears to be insensitive to shear traction less than 30 MPa along the transform margins. (Many independent studies indicate that the long-term traction along the San Andreas is less than 20 MPa.)

Tectonic Cause of Deformation in the Pacific Northwest

If shear traction along the San Andreas fault is not causing the deformation observed in the Pacific Northwest then what is? A clue is apparent by looking at the vector velocity field for the Pacific Northwest which can best be described as a broadly clockwise rotating velocity field:

Shear Stress Limit on Subduction Zone: 15 MPa



The highest velocity is in coastal British Columbia and is in a direction approximately parallel to the component of Pacific-North America plate motion that is perpendicular to the Queen Charlotte Fault. Plate motion studies demonstrate that the motion between the Pacific and North American plates is not exactly parallel to the Queen Charlotte fault, resulting in compressive stress perpendicular to the fault. This study suggests that this compressive stress contributes to deformation in the Pacific Northwest

Another way to view the major plate bounding faults is that although the Queen Charlotte, Cascadia megathrust, and San Andreas faults are weak in terms of overall shear strength, small components of compressive stress perpendicular to the fault

plane can lead to significant deformation within the continental plate.

It is important to note that a minimum basal shear traction is required along the Cascadia megathrust to explain the observed deformation. If the basal shear traction is less than 10 MPa, then Basin-and-Range normal faulting that is typically mapped in Nevada would occur throughout the Pacific Northwest--clearly contrary to the observed style of faulting. Spreading of the continental crust in the Basin-and-Range region, however, may also be driving deformation in the Pacific Northwest.

Good Predictions

The N-S orientation of horizontal compressive stress (resulting in E-W oriented thrust faulting--see faults) is generally reproduced by the model. Also, the predicted clockwise rotation of the compressive stress axis towards coastal Oregon and Washington is consistent with stress data within the Cascade Convergence Stress Province, suggesting a smoothly varying stress field not ascribed to N-S changes in shear traction along the subduction zone (magnitude of basal shear traction specified as constant in the model).

The predicted style of faulting is consistent with geologic mapping of recent faulting in the Pacific Northwest. That is, E-W thrust faulting in NW Washington (such as the Seattle fault); thrust faulting mixed with N-S strike-slip faulting (such as observed in the St. Helens region and the 1993 Scotts Mills earthquake) in NW Oregon and SW Washington; and normal faulting in eastern Oregon and Idaho.

Bad Predictions

The model results do not correctly predict long-term deformation local to the triple-junctions. Specifically, in the northern Vancouver Island region and near Cape Mendocino. The mismatch between the predicted and observed stress and deformation suggests that the imposed boundary conditions are not correct for the Explorer plate (offshore Vancouver Island) or the Gorda deformation zone. The model does not predict extensional deformation in southeastern Oregon, site of the [1993 Klamath Falls earthquake sequence](#).

Implications

Coastal Uplift and Locking of the Megathrust between Big Earthquakes

Measurements of uplift along coastal Washington and Oregon have been interpreted that the Cascadia megathrust is currently locked--typical of the deformation that occurs in the period between major earthquakes along a subduction zone megathrust. An important distinction must be made between long-term deformation (millions of years) such as in this study and deformation associated with the earthquake cycle (typically hundreds of years).

The long-term uplift along coastal Washington and Oregon is predicted by the model to be very low, supporting the interpretation that the measured uplift is almost solely due to strain accumulation between megathrust earthquakes. The predicted long-term uplift is significantly higher in coastal British Columbia and is ascribed to shortening of the continent perpendicular to the Queen Charlotte fault.

Patterns of Seismic Strain Release in the Pacific Northwest

The predicted rate of deformation of the continent in Oregon and southern Washington is relatively low compared to regions to the north and south. This is consistent with the rate of seismic strain release calculated from 80 years of earthquakes in the Pacific Northwest. Keep in mind, however, that significant hazards are associated with individual events within the low deformation rate regions such as the [1993 Scotts Mills earthquake](#) and especially major earthquakes that may occur on the Cascadia megathrust.

Deciphering Historical Earthquakes

For some older earthquakes in the Pacific Northwest, we have insufficient data to determine the sense of movement and the style of faulting. Of particular interest is the 1872 North Cascades earthquake which was estimated to be a magnitude 7.4 event. The map in the [Results](#) section shows that this earthquake is located in a region of dominant thrust faulting. Another important earthquake, the Milton-Freewater earthquake in southeastern Washington, is more difficult to decipher. It apparently is located in a complex transition between dominant normal faulting (Nevada), thrust faulting (central Washington) and strike-slip faulting (Oregon).

Basic Mechanics of the Cascadia Megathrust

From this study, the long-term basal shear traction along the Cascadia megathrust is estimated to be 15 MPa +/- 5 MPa. Given that the Cascadia subduction zone is in many respects unique among subduction zones, the basal shear traction is surprisingly similar to estimates of shear traction for other subduction zones around the world. The shear traction along the San Andreas fault too is thought to be less than 20

MPa, suggesting that many mature, plate boundary faults are weak (i.e., a low *apparent* coefficient of friction). An explanation for why these faults are weak is an area of intensive research. The important point to remember is that although these faults are mechanically weak, they are capable of generating major earthquakes.

Answers to Questions

1. N-S oriented compressive stress in the Pacific Northwest appears to be a result of the combined influence of basal traction along the Cascadia megathrust *and* the component of Pacific-North America relative plate motion perpendicular to the Queen Charlotte fault.
2. An increase in the basal shear traction along the Cascadia megathrust from south to north is not necessary to explain the clockwise rotation of the compressive stress axis that is associated with the Cascade Convergence Stress Province.

Other Links

