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Summary

This is the final technical report for USGS grant 14-08-0001-1803, "Earthquake Hazard Investigations in the Pacific Northwest and Alaska" during the period 2/1/92 - 2/28/93. The objective of our research is to investigate earthquake hazards in the Pacific Northwest and Alaska including problems related to large scale plate interactions and possible large subduction earthquakes. Improvement in our understanding of earthquake hazards is based on better understanding of the regional structure and tectonics.

A primary source of our data is the Washington Regional Seismograph Network (WRSN), and our studies require cooperation and collaboration among a number of individuals and projects. Investigations by our research group include source moment estimation for Cascadia earthquakes, an investigation of the velocity structure of the North American continental plate along an east-west cross-Cascades profile in Washington state, and completing our kinematic modeling studies of the subducting Juan de Fuca and Alaska slabs. Appendix 1 includes abstracts funded under this grant.

Source scaling and moment estimation using S-coda amplitudes

We have developed a technique of estimating seismic moment of local earthquakes using coda amplitudes recorded by regional network stations. Assuming a single-scattering coda model, coda amplitude measurements from earthquakes recorded by the Washington Regional Seismograph Network (WRSN) with duration magnitudes from 2.4 to 5.0 were used to estimate source spectra in a narrow band (2 to 12 Hz). We found that an omega-square, constant stress drop, far-field scaling source model was most consistent with our data, and inferred a static stress drop of 3.2 MPa. Using this scaling law and an event with known moment and corner frequency to calibrate the moment estimation procedure, we are able to estimate moments for other earthquakes. This material is being prepared for submission to BSSA (Dewberry and Crosson, in preparation).

Focal mechanism studies and other stress indicators have shown that NS compression is the dominant source of tectonic stress in the continental crust. Since this stress orientation does not agree with the plate convergence stress and geodetic strain measurements, we are pursuing further stress studies in an attempt to understand the origin of the difference.

East-west cross-Cascades velocity structure profile

A master's thesis by Andreas Schultz entitled "A 2-D Velocity Structure for a Cross-Cascades Profile Using Earthquake Sources" is attached as Appendix 2. The aim of this study was to develop a 2-D velocity model across the Cascade Range of Washington state, connecting the velocity regime of the Columbia Plateau with that of the Puget Sound. By using PmP (Moho reflections) as well as Pn (headwaves) and direct arrivals from earthquake sources along the profile, we were able to place constraints on both the dip of and the depth to the continental Moho between Bremerton and Walla-Walla, Washington.

The final velocity model minimized travel-time residuals for refracted rays traveling both east-to-west and west-to-east, adequately modeled timing of wide-angle Moho reflections, and reasonably matched the Bouguer gravity anomaly over the Cascades. The final model has a continental Moho which dips to the east beneath the Puget Sound, and to the west in eastern Washington; consistent with a root beneath the Cascade core. The maximum crustal thickness under the high Cascades was 47 km, shallowing to 34 km in eastern Washington and to 35.5 km under the Puget Sound.

Kinematic Modeling

Because of a concave-oceanward bend in the trench axis located seaward of the Olympic Mountains, the subducted Juan de Fuca slab has a geometric space problem analogous to a table cloth hanging over the corner of a table. This induces along-arc compression within the slab surface which can be relieved by forming an arch or by an along-arc buckling structure.

We developed a non-linear finite-element optimization scheme to find the slab configuration that minimizes in-plane deformation for a very thin subducting slab surrounded by much less viscous material, while satisfying boundary conditions consistent with the Cascadia subduction zone (known relative plate convergence rate and partial geometric constraints obtained from

Wadati-Benioff earthquake locations).

Our numerical experiments suggest that the arch-like structure observed in the Cascadia slab is a consequence of the response of a subducted slab to the concave-oceanward bending of the trench. The geographic positions where both the observed and theoretical slab dips equal 10° are offshore everywhere except along the arch, beneath the Olympic Mountains. According to the Critical Taper Theory (Dahlen, 1990), the height of an accretionary wedge will grow landward until the slab dip exceeds about 10°. This provides a plausible explanation for the origin and geographic location of the Olympic Mountains accretionary prism. The concentration of seismicity beneath the Puget Sound area appears to be the result of bending the already arched slab. The computed deformation is dominated by N-S compression in the Puget Sound area and the peak compressional strain-rate is around $2\times10^{-16}s^{-1}$ which is comparable to the value estimated from seismic moment release rates of the last century. A manuscript describing the results will be submitted to JGR.

Like Cascadia, the trench off Alaska has concave-oceanward curvature. Given this geometry and the assumption that the slab is continuous, our calculations (Creager and Chiao, 1992) predict that the slab under central Alaska should have a shallow dip relative to the dip under the Aleutian Islands to the west and under the Wrangell Mountains to the east. Our models also predict along-arc compressive strain rates under Alaska and along-arc extensional strain rates under the central Aleutians. New observations from the Alaska network of seismic stations are providing evidence for along-arc compression in the region where we predict it. Along-arc compression is rare at this depth, a likely cause is the geometric constraints from the backward bend in the trench. The observed subduction geometry and along-arc extension in the central Aleutians inferred from seismic moment tensors are also in agreement with our models.

The results of this work were presented at the Wadati Conference in Fairbanks, Alaska in September, 1992, and at in a series of talks at Taiwan National University in Taipei, Taiwan. We have begun to compare Cascadia and Alaska with other subduction zones to see if this style of modeling is generally valid. The places we have looked so far (Kuril-Japan-Izu-Bonin, and

Ryukyu show features both in the slab geometry and the strain-rates estimated from moment tensors that are consistent with the predictions of our membrane strain-rate calculations.

Publications funded under this grant

Articles

Chiao, L.-Y., and K.C. Creager, in preparation, Geometry and Lateral Membrane Deformation Rate of the Subducting Cascadia Slab, to be submitted to JGR

Dewberry, S.R., and R.S. Crosson, in preparation, Source scaling and moment estimation for the Washington Regional Seismograph Network using S-coda amplitudes, to be submitted to the BSSA.

Ma, L., R.S. Crosson, and R.S. Ludwin, 1991, Focal Mechanisms of western Washington earthquakes and their relationship to regional tectonic stress, USGS Open File OF-91-441-D, will also be published in a USGS Professional Paper - "Assessing and Reducing Earthquake Hazards in the Pacific Northwest")

Mundal, I., M. Ukawa, and R.S. Crosson, 1991 (in preparation), Normal and anomalous P phases from local earthquakes, and slab structure of the Cascadia Subduction zone, BSSA

VanDecar, J.C., R.S. Crosson and K.C. Creager, (in preparation), Travel-time inversion for subduction zone structure: I. The effect of three-dimensional ray tracing on resolution analysis, to be submitted to JGR.

Theses

Schultz, A., 1993, A 2-D Velocity Structure for a Cross-Cascades Profile Using Earthquake Sources: Master's Thesis, University of Washington Geophysics Program, Seattle, WA.

Abstracts

Creager, K. C. and L.-Y. Chiao, 1992, Membrane Deformation Rate and Geometry of Aleutian-Alaska Subduction, Wadati Conference on Great Subduction Earthquakes, Geophysical Institute, University of Alaska, Fairbanks, Alaska.

Creager, K.C. and Chiao, L.Y, 1992, Relationships among surface geology, seismicity, and three-dimensional models of Cascadia Slab Flow, GSA 88th Annual Cordilleran Section, 1992 Abstracts with Programs, V. 24(5), p. 17.

Crosson, R.S. and R.S. Ludwin, 1992 (Invited), Cascadia Subduction Zone: Constraints on slab structure from seismic observations, GSA 88th Annual Cordilleran Section, 1992 Abstracts with Programs, V. 24(5), p. 18.

Crosson, R.S., and J.C. VanDecar, 1992, Cascadia Subduction Zone: Large scale structure from receiver function analysis, seismicity, and teleseismic arrival time tomography, Wadati Conference on Great Subduction Earthquakes, Geophysical Institute, University of Alaska, Fairbanks, Alaska.

VanDecar, J.C., R.S. Crosson, and K.C. Creager, 1990, Teleseismic travel-time inversion for Cascadia subduction zone structure employing three-dimensional ray tracing (extended abstract), Proceedings, XXII General Assembly of the European Seismological Commission, Barcelona, Spain, V. 1, pp. 115-120.

Acknowledgments

Work under this grant could not be carried out without the data collected by the Washington Regional Seismographic Network; we recognize the contribution of the electronics technicians, data analysts, and seismologists of the WRSN.

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Dahlen, F.A., 1990, Critical Taper model of fold-and-thrust belts and accretionary wedges, Ann. Rev. Earth Planet Sci., V. 18, pp. 55-99.

APPENDIX 1

Recent Abstracts

Membrane Deformation Rate and Geometry of Aleutian-Alaska Subduction

K.C. Creager (*Geophysics Program, AK-50, University of Washington, Seattle, WA 98195*) and L-Y Chiao (*Institute of Oceanography, National Taiwan University, Taipei, Taiwan, R.O.C.*)

Whereas a 'typical' island-arc configuration, such as the Aleutian Arc, is characterized by a trench with a broad convex-oceanward curvature, some trenches, such as that south of Alaska, exhibit the opposite curvature. A concave-oceanward bend in the trench axis causes a geometric space problem for the subducted slab, analogous to a table cloth hanging over the corner of a table. This induces along-arc compression within the slab surface which can be relieved by forming an arch or by an along-arc buckling structure. Indeed, a shallow-dipping arch-type structure is observed in the slab geometry associated with nearly all oceanward concave trenches. This may explain the observation that the slab dip under Central Alaska is shallow relative to under the Aleutians to the west and under the Wrangell Mountains to the east. To model this configuration requires a three-dimensional analysis of convection. In order to make a three-dimensional flow calculation both tractable and interpretable, we consider the limiting case that the subducting slab is very thin, and that its viscosity far exceeds that of the surrounding crust and mantle. With these assumptions, we have developed a non-linear finite-element optimization scheme to find the slab configuration and flow field which produces the smallest total dissipation power, while satisfying boundary conditions such as the known relative plate convergence rates. Linear and power-law viscous rheologies are considered. We also impose weak geometric constraints obtained from Wadati-Benioff earthquake locations. We find that the ideal (least deformation rate) slab geometry produces an arch-structure beneath Central Alaska which is in close agreement with the observed geometry. Also, the principal axes of the predicted membrane strain-rate tensor vary from along-arc extension under the central Aleutians to along-arc compression beneath Alaska, consistent with observations of earthquake focal mechanisms. Peak strain rates are about 10^{-15} s^{-1}. Northwest of the Wrangell Mountains the slab is aseismic. One potential explanation is that the slab is torn and missing from this corner. Our calculations argue against this possibility, however, because the slab is predicted to be under along-arc compression, so that even if it is torn, the slab should exist in the aseismic region. An intriguing feature of our models is that the predicted strain rates are reduced by nearly an order of magnitude in this aseismic region.

RELATIONSHIPS AMONG SURFACE GEOLOGY, SEISMICITY AND THREE-DIMENSIONAL MODELS OF CASCADIA SLAB FLOW

CREAGER, K.C. and CHIAO, L.-Y., Geophysics Program, AK-50, University of Washington, Seattle, WA 98195; 206-543-6626

Several aspects of the surface geology of the Pacific Northwest, such as volcanism and crustal deformation, are related to mantle flow associated with subduction. Along-arc variations in the geology require a three-dimensional analysis of convection. In order to make a three-dimensional flow calculation both tractable and interpretable, we consider the limiting case that the subducting slab is very thin, and that its viscosity far exceeds that of the surrounding crust and mantle. With these assumptions, we have developed a non-linear finite-element optimization scheme to find the slab configuration with the least amount of membrane (in-plane) deformation rate while satisfying boundary conditions such as the known relative plate convergence rates, and partial geometric constraints obtained from Wadati-Benioff earthquake locations. Because of a concave-oceanward bend in the trench axis located seaward of the Olympic Mountains, the subducted slab has a geometric space problem analogous to a table cloth hanging over the corner of a table. This induces along-arc compression within the slab surface which can be relieved by forming an arch or by an along-arc buckling structure. Our numerical experiments suggest that the arch-like structure, revealed from seismic observations, is a natural consequence of the subducted slab responding to the concave-oceanward bending of the trench. The locus of points where both the observed and theoretical slab dips are less than 10° is offshore everywhere except along the arch, beneath the Olympic Mountains. According to the *Critical Taper Theory*, the height of an accretionary wedge will grow landward until the slab dip exceeds about 10°. This provides a plausible explanation for the origin and geographic location of the Olympic Mountains accretionary prism. The concentration of seismicity beneath the Puget Sound area appears to be the result of bending the already arched slab. The computed deformation is dominated by N-S compression in the Puget Sound area and the peak compressional strain-rate is around 2×10^{-16} s^{-1} which is comparable to the value estimated from seismic moment release rates of the last century. Preliminary experiments in both the Alaska-Aleutian and NW-Pacific subduction zones also indicate that arch structures revealed from seismic observations are natural consequences of slabs subducting in concave-oceanward trench geometries.

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CASCADIA SUBDUCTION ZONE: CONSTRAINTS ON SLAB STRUCTURE FROM SEISMIC OBSERVATIONS

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Our current understanding of Cascadia subduction zone (CSZ) structure stems in large part from diverse seismic observations. Critical seismic velocity structure of the subducted oceanic slab comes from marine refraction and reflection measurements, and shallow subduction zone structure is constrained by onshore/offshore active experiments. Reference continental seismic velocity structure comes from refraction measurements and inversion of earthquake arrival time data, with new refraction/reflection measurements emerging. In the forearc region of western Washington, the slab is active seismically while exhibiting only weak seismicity to the north beneath British Columbia and to the south beneath Oregon. Thus, seismicity give us a restricted, although information rich, window on subduction zone structure.

Independent and complementary interpretations of slab structure between 40 and 55 km depth have been made from receiver function analyses at selected continental sites along the subduction zone. These, combined with seismicity, give us the clearest picture of an upwarp in the slab beneath the Olympic - central Puget Sound region. This upwarp accommodates the plate deformation required by the trench geometry, and provides a rational mechanism for the Olympic uplift. Beneath the Olympic - central Puget Sound region, the slab dips about 10° to the east or east northeast. Steeper dips of 15-20° are typical at the same distance from the trench to the north and south. A few intraslab earthquakes have anomalous P phases which we interpret as resulting from propagation in a low velocity waveguide within the subducted oceanic crust. The rarity of these phases indicates that most intraslab earthquakes originate below the subducted oceanic Moho.

Slab structure deeper than 80-100 km is most readily imaged by teleseismic tomography. Recent work by VanDecar has shown that the slab steepens to a 50° subduction angle beneath Washington but that the deep slab signature decreases from southern Washington southward to Oregon, leading to speculation of slab tearing possibly resulting from changes in subduction kinematics.

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Cascadia Subduction Zone: Large Scale Structure from Receiver Function Analysis, Seismicity, and Teleseismic Arrival Time Tomography

R.S. Crosson (Geophysics Program, University of Washington, Seattle, WA 98195) and J.C. VanDecar (Department of Theoretical Geophysics, University of Utrecht, The Netherlands, and Geophysics Program, University of Washington, Seattle, WA 98195)

Our current understanding of Cascadia subduction zone structure stems largely from diverse seismic observations. Critical seismic velocity structure of the subducted slab comes from marine refraction and reflection measurements, and shallow subduction zone structure is constrained by onshore/offshore active experiments. Reference continental seismic velocity structure comes from refraction measurements and inversion of earthquake arrival time data, with new refraction/reflection results emerging. In the forearc region of western Washington, the slab is active seismically while exhibiting only weak seismicity to the north beneath British Columbia and to the south beneath Oregon. Thus, seismicity gives us a restricted, although information rich, window on subduction zone structure.

Independent and complementary interpretations of slab structure have been made from receiver function analysis at selected continental sites along the subduction zone. These, combined with seismicity, give us the clearest picture of an upwarp in the slab beneath the Olympic-central Puget Sound region. The upwarp accommodates plate deformation required by the trench geometry, and provides a rational mechanism for the Olympic uplift. Beneath the Olympic-central Puget Sound region, the slab dips about 10° to the east or east northeast. Steeper dips of 15-20° are typical at the same distance from the trench to the north and south. Independent evidence from the observation of anomalous P phases suggests that the subducted oceanic crust acts as a low velocity waveguide where the slab lies beneath the continental Moho. Most intraslab earthquakes appear to originate within the subducted oceanic "upper mantle" region.

Slab structure deeper than 80–100 km is most readily imaged by teleseismic tomography. Recent work has shown that the slab steepens to a 50° subduction angle beneath Washington, but that the deep slab signature decreases from southern Washington southward to Oregon, leading to speculation of slab tearing possibly resulting from changes in subduction kinematics.

APPENDIX 2

Master's Thesis, 1993: Andreas Schultz
"A 2-D Velocity Structure for a Cross-Cascades Profile Using Earthquake Sources"