

Depth to the Juan de Fuca Slab Beneath the Cascadia Subduction Margin— A 3-D Model for Sorting Earthquakes

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Abstract

We present an updated model of the Juan de Fuca slab beneath southern British Columbia, Washington, Oregon, and northern California, and use this model to separate earthquakes occurring above and below the slab surface. The model is based on depth contours previously published by Flück and others (1997). Our model attempts to rectify a number of shortcomings in the original model and update it with new work. The most significant improvements include (1) a gridded slab surface in geo-referenced (ArcGIS) format, (2) continuation of the slab surface to its full northern and southern edges, (3) extension of the slab surface from 50-km depth down to 110-km beneath the Cascade arc volcanoes, and (4) revision of the slab shape based on new seismic-reflection and seismic-refraction studies. We have used this surface to sort earthquakes and present some general observations and interpretations of seismicity patterns revealed by our analysis. For example, deep earthquakes within the Juan de Fuca Plate beneath western Washington define a linear trend that may mark a tear within the subducting plate. Also earthquakes associated with the northern strands of the San Andreas Fault abruptly terminate at the inferred southern boundary of the Juan de Fuca slab. In addition, we provide files of earthquakes above and below the slab surface and a 3-D animation or fly-through showing a shaded-

relief map with plate boundaries, the slab surface, and hypocenters for use as a visualization tool.

Introduction

The Juan de Fuca oceanic plate descends beneath the Pacific Northwest continental margin along the Cascadia subduction fault (fig. 1). The location and shape of the subducted oceanic plate or slab beneath the margin is a key element for understanding the seismotectonics of this complex plate boundary. Of particular interest are seismicity patterns in North American continental crust above the Juan de Fuca slab that may correlate with mapped, shallow crustal faults (see for example, McCrory, 2002). To isolate seismic events in the upper plate relevant to shallow crustal faults requires identifying the subduction fault interface. To this end we created a geo-referenced, three-dimensional (3-D) model of the interplate boundary that allowed us to separate earthquakes occurring above and below the Juan de Fuca slab surface. This model surface also has broad application to studies of interplate strain accumulation, slab seismicity, and slab metamorphism. This contribution provides three data sets—(1) a 3-D grid of depth to the slab surface in kilometers below sea level, (2) a catalog of earthquakes occurring above the surface, and (3) a catalog of earthquakes occurring below the surface. In addition, we provide

a 3-D animation of the combined data sets as a visualization tool.

Approach

We base our new model of the Juan de Fuca slab surface on depth contours previously published by Flück and others (1997) (fig. 2A), adjusted in places by results of recent seismic surveys. The Flück and others (1997) depth contours were based on three main data types—(1) regional earthquake hypocenters, (2) teleseismic travel-time data, and (3) seismic reflection and refraction transects. We updated the shape of their surface using recent wide-angle seismic results described in the next section (see table 1 for references) (fig. 2B). We extended the surface east to beneath the Cascade volcanic arc using hypocenter and teleseismic data. We modeled the slab surface to its full northern and southern edges using both a regional study of first-arrival data from a 1994 Mendocino earthquake (fig. 2C) and a reconstruction of Juan de Fuca Plate magnetic isochrons (Wilson, 2002). These new constraints and the changes they produced in the slab surface model are described in the next section.

A primary constraint on the location and shape of the slab surface comes from profiles of *P*-wave velocities obtained by modeling the travel times of active source seismic experiments. The oceanic Mohorovic discontinuity (Moho), which marks the boundary between the crust and upper mantle is typically observed as a strong reflector with a sharp velocity gradient on these profiles. Available wide-angle experiments resolve this boundary to about 40- to 50-km deep, depending on the length of the transect. The top of the slab—the boundary of interest in this study—typically does not produce a strong reflector or sharp *P*-wave velocity gradient.

We infer this surface to be located about 7 km above the Moho on the basis of the young age of the slab (Gutscher and others, 2000; Tréhu and others, 2002).

For the deeper portion of the subducted slab, we primarily rely on studies of teleseismic travel-time data and hypocenter profiles in areas where earthquakes occur down to depths of 70 to 100 km. In general, our slab model is drawn as a smooth surface with constant dip between wide-angle transects, teleseismic transects, and hypocenter profiles (fig. 2B). In areas where overlapping data sets yield conflicting depth assignments, the data providing the smoothest contours are preferentially chosen. This choice may sometimes result in over-smoothing the slab's actual geometry, but resolving local complexities is not possible with currently available data.

We use the resultant surface (fig. 3) to separate those earthquakes that occur in North American continental lithosphere from those that occur in Juan de Fuca oceanic lithosphere. Uncertainties in the location of the Moho reflector (approximately ± 5 percent of its modeled depth) and the uncertainties in the location of the earthquakes (approximately ± 3 km) preclude identifying interplate earthquakes—those that occur on the Cascadia subduction fault. However, only one earthquake to date has been identified as possibly occurring at the plate interface—the 1992 (moment magnitude, M_w 7.1) Cape Mendocino earthquake (Oppenheimer and others, 1993; National Earthquake Information Center (NEIC) at http://neic.usgs.gov/neis/eqlists/large_usa.html).

TABLE I. List of published references and unpublished data used to construct the grid of the Juan de Fuca slab surface (see fig. 2B for the location of transects and profiles).

ORIGINAL SLAB DEPTHS FROM:

Flück, Hyndman, and Wang, 1997

REVISED SLAB DEPTHS FROM:

WIDE-ANGLE (ACTIVE SOURCE) TRANSECTS

Transects H ₁ H ₁ ' , H ₂ 'H ₂ '', and H ₃ H ₃ '	Beaudoin and others, 1998
Transect JJ'	Brocher, Thomas M., and others, 1994, unpubl. data
Transect NN'	Gerdom and others, 2000
Transect OO' *	Tréhu and others, 1994
Transect QQ' *	Tréhu and others, 1994
Transect SS'S''	Parsons and others, 1999
Transects SS' and UU'	Flueh and others, 1998
Transect YY' and Region W	Creager and others, 2002
	Tréhu and others, 2002
Transect Z ₁ Z ₁ ' and Z ₂ Z ₂ ' *	Hyndman and others, 1990

TELESEISMIC (PASSIVE SOURCE) TRANSECTS

Transect LL'	Harris and others, 1991
Transect MM'	Bostock and others, 2002
Transect R ₁ R ₁ ' , R ₂ R ₂ ' , and R ₃ R ₃ '	Michaelson and others, 1986

SEISMICITY PROFILES

Profile a ₁ a ₁ '	this study
Profile a ₂ a ₂ '	McCrary, 2000
Profile bb'	Walter, 1986
Profile c ₁ c ₁ '	this study
Profile c ₂ c ₂ '	this study
Profile dd'	Chaio, 1991
Profile ee'	Zhao and others, 2001

RESISTIVITY TRANSECT

Transect PP'	Wannamaker and others, 1989
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WORK IN PROGRESS (TO BE INCLUDED IN FUTURE REVISIONS):

Transect H ₂ H ₂ '	Tréhu, Anne M., and others, 1993; 1994, unpubl. data
Transect KK'	Brocher, Thomas M., and others, 1994, unpubl. data
Transect MM'	Nabelek, John L., 1993, unpublished data
Transects TT,' U'U'', VV', and XX'	Pecher, Ingo, and others, 1996, unpublished data

*References incorporated into Flück and others (1997) model

Main Improvements to the Slab Model

Few wide-angle seismic reflection and refraction transects had been conducted along the Cascadia subduction margin when Flück and others (1997) constructed their model (fig. 2A). Several new transects have been completed along the continental margin of Washington, Oregon, and northern California (table 1) since that time. These new results prompted our updating the 3-D slab geometry before sorting earthquakes into North American or Juan de Fuca Plate events. The main change in slab shape occurs beneath the Puget Sound region, where seismic reflection and refraction experiments (for example, the Seismic Hazard Investigation in Puget Sound (SHIPS) Experiment; Brocher and others, 1999; Brocher and others, 2002) have resulted in improved *P*-wave velocity models that image the oceanic Moho. These models depict a less pronounced curvature to the arched slab geometry (fig. 2B) beneath western Washington than the earlier model.

Geophysical transects already completed in northern California (for example, Tréhu, 1994, written commun.; table 1), will likely refine the shape of the slab adjacent to the Mendocino fracture zone, where it is deforming in response to north-south compression across the fracture zone (Wilson, 1993). For example, seismicity profiles depict arcing and thickening of the slab where it abuts the Pacific plate offshore northern California, with the axis of arching trending east-west (fig. 4).

We have continued the slab surface southward to its inferred southernmost edge beneath northern California (fig. 1) on the basis of earthquake data and plate reconstruction. We use first-arrival data from the 1 September 1994 (M_w 7.1)

Mendocino earthquake to map the slab edge. This earthquake occurred in the vicinity of the Mendocino fracture zone and its moment tensor solution (NEIC; http://neic.usgs.gov/neis/bulletin/neic_vmaj_m.html) indicates right-lateral slip occurred on a near vertical plane with a strike of 095° , consistent with failure of the fracture zone. Projecting this orientation landward, the pattern of first-motion readings recorded by short period seismometers operated by the Northern California Seismic Network (NCSN) should be consistent with this azimuth. That is, compressional or "up" first motions should be recorded north of this projected azimuth. Instead, we observe a pattern that describes an azimuth of about 120° and intersects the coast near the Mendocino triple junction (fig. 2C). We interpret this pattern as imaging the southern edge of the subducted Juan de Fuca Plate.

Although we have not modeled the travel-time data, we interpret the unusual first-motion pattern to be the result of a seismic wavefront that diffracted into the subducted slab near the Mendocino triple junction. The slab presumably has a higher velocity than the overlying continental lithosphere. Thus, energy that refracted up to the Earth's surface from the slab arrived at seismographic stations before the direct *P*-wave arrival through the slower North American plate. The polarity of these diffracted/refracted rays reflects the polarity of the wave-front as it diffracted into the slab at the coast, and the azimuth separating the polarities east of the Mendocino triple junction roughly defines the southern boundary of the subducting Juan de Fuca Plate.

This boundary is consistent with the location of the slab edge extrapolated by Wilson (2002) from reconstruction of subducted magnetic isochrons. Our boundary is also consistent with the

western, northwest-striking portion of slab edge mapped by Jachens and Griscom (1983) from isostatic residual gravity data. We also use the magnetic-isochron model of Wilson (2002) to constrain the location of the northern slab edge beneath central Vancouver Island (fig. 1). His boundary is consistent with the general location mapped by Cassidy and others (1998) by receiver function analysis of earthquake data.

Poorly Constrained Regions

Few data are available to constrain the slab geometry below a depth of about 50 km. This deeper region is poorly resolved in wide-angle experiments. Seismicity is typically used to map the Wadati-Benioff zone of subduction systems elsewhere, but is quite sparse for the Cascadia subduction system. We have used published teleseismic studies along with seismicity profiles to provide some constraint on this deeper portion of the slab.

Slab densification is inferred to occur at a depth of about 50 km during metamorphism of the oceanic crust (Bostock and others, 2002; Peacock and others, 2002; Brocher and others, 2003a; Preston and others, 2003). In fact, such densification appears to correlate with an abrupt shift from a flatter slab dip of about 10° to a steeper dip of about 30° beneath Puget Sound (fig. 5). Similar dip increases of this degree likely occur along the entire subducted slab, but can only be resolved with available data at a few locations.

A few small earthquakes extend to 70+ km beneath Vancouver Island, and to 80+ km beneath northern California (fig. 6). These events apparently occur within the subducted slab (Walter, 1986; Zhao and others, 2001) and locally constrain its location at depth. Slab seismicity is notably absent beneath the Oregon continental

margin. Here slab geometry is constrained solely by wide-angle experiments that employ either active sources (detonations) or passive sources (teleseismic events), and one magnetotelluric transect (Wannamaker and others, 1989).

Recent studies that use teleseismic data to create low resolution, tomographic images, indicate that dip of the slab beneath Oregon increases from about 15° to 30° at a depth of 40 km (Bostock and others, 2002). Older teleseismic studies (Michaelson and Weaver, 1986; Ramussen and Humphreys, 1988; Harris and others, 1991) commonly provide much steeper dip estimates (as much as 60°). For Oregon, we have assumed that the recent analyses more accurately depict the slab location. However, the lack of well-constrained profiles leaves open the geometry of the deeper slab beneath Oregon.

For the purposes of this study, we have extrapolated a constant dip from the deeper profiles and transects down to a projected depth of 90 to 110 km beneath the arc volcanoes. This likely oversimplification of the surface in the 50- to 110-km depth range is mitigated by the lack of deep earthquakes that might be missorted using a surface that is roughly located. No deep seismic reflection or refraction data are available in the northernmost portion of the slab, so we project the slab surface at a constant dip along strike from the closest seismicity profile (Zhao and others, 2001) across Vancouver Island, 150 km to the south (fig. 2B).

The dip of the shallow slab at the southern end of the subduction zone is constrained mainly by *P*-wave velocity data. The resultant dip is somewhat steeper than the dip of a band of concentrated seismicity interpreted as occurring within the oceanic slab. Thus in 3-D, the slab seismicity appears to “punch” through the slab surface

at about 20-km depth (see animation). This effect may be somewhat exaggerated by evidence that seismicity in the shallow western portion of the slab occurs in the upper mantle, whereas seismicity in the deeper eastern portion of slab occurs in the crust (Preston and others, 2003). This shift in lithospheric source causes an apparent flattening of the Wadati-Benioff zone. Further refinement of this mismatch awaits joint inversion of the seismicity and seismic velocity data, as has been conducted for the Puget Sound region (see for example, Creager and others, 2002). For the purpose of this publication, we have assumed that the seismic-velocity data more accurately constrain the dip of the slab offshore, where seismographic stations are lacking, and have preferentially utilized these data.

Seismicity Catalog Details

We have used our slab surface (fig. 3) to sort Pacific Northwest earthquakes into two categories—Juan de Fuca Plate events and North American Plate events. We use the composite earthquake catalog maintained by ANSS (Advanced National Seismic System) at University of California, Berkeley (<http://quake.geo.berkeley.edu/cnss/cnss-catalog.html>) as our starting earthquake database. The earthquake data sets included in this publication contain a filtered subset of seismic events that occurred from 1975 through 2002. We begin our catalog at 1975 because the regional Northern California Seismic Network (NCSN) was first established in northwestern California at this time (the seismic network run by Pacific Geoscience Centre, PGC, has been operating nominally since 1976; the Pacific Northwest Seismic Network, PNSN, since 1969). Location accuracy and minimum magnitude thresholds have improved as

new seismograph stations are installed (Brocher and others, 2003b) and as more realistic velocity models are implemented. Therefore, some biases are inherent in the catalog at lower magnitudes. In addition, the lack of offshore stations significantly reduces the location accuracy of recorded offshore events and increases the magnitude threshold for catalog completeness. Finally, additional depth uncertainty stems from the fact that the datum for the slab surface depth is sea level, whereas the datum for earthquake depth is the land surface. In areas with significant relief, this misfit can be as large as 3 km.

As the Pacific Northwest is notable for its general lack of seismicity, we have included earthquakes down to magnitude 1.0 to aid in identifying seismogenic structures. We have filtered the seismicity data on the basis of three simple quality standards—(1) hypocenter depth of 2 km or deeper, (2) earthquake location based on data from eight or more seismograph stations, and (3) travel-time residual RMS ≤ 0.3 sec (Root-Mean-Square refers to a common statistical method used, in this case, to estimate the uncertainty in location of each event) for regional networks (such as NCSN, PGC, or PNSN) or ≥ 0.3 sec and ≤ 1.0 sec for global networks that record teleseismic data (in this case NEIC). These quality filters eliminate about 40 percent of the earthquakes tabulated in the ANSS catalog.

Most earthquakes eliminated by filtering are offshore and thus lack the station density and azimuthal control needed for accurate location. In fact, many eliminated events remained at default depths (that is, 5 km, 10 km or 33 km) during routine processing—indicating poor depth control. Our attempts to employ a modest azimuthal gap filter (angular distance between stations) were abandoned as they resulted in an almost complete elimination

of offshore events owing to the lack of offshore seismic stations. Our present scheme provides a reasonable filter for eliminating offshore events that are poorly located.

GIS Grid and Animation Details

We constructed new depth contours (lines of equal depth in kilometers below sea level) for the subducted Juan de Fuca slab by combining the distribution of new data points that constrain its depth with the previous contours of Flück and others (1997). We geo-referenced these new contours and converted them into a gridded surface using the TOPOGRID tool in ESRI (Environmental Systems Research Institute) ArcInfo Workstation Program. ArcInfo was then used to identify whether earthquakes in the filtered data set were inside or outside the map extent of the grid. For hypocenters within the map extent of the slab grid, we used the LATTICESPOT command to calculate the vertical distance between each hypocenter point and the grid surface. This value was subtracted from the hypocenter-depth value for each point to yield either positive values (above the slab surface) or negative values (below the slab surface). This procedure allows each hypocenter to be classified as above the slab grid, below the slab grid, or outside its spatial extent. The hypocenter points were assigned colored symbols according to their depth relative to the land surface. The resultant files were used to create map views of earthquakes above and below the gridded surface (figs. 6 and 7).

We also used ESRI ArcGIS software to manipulate the earthquake data and create cross sections, and used ArcScene to create a 3-D fly-through animations. The filtered ANSS hypocenters were first imported into ArcGIS as a point theme, along with

additional spatial-data layers that include a combined bathymetric and topographic DEM (Digital Elevation Model) surface (from GEBCO (GEneral Bathymetric Chart of the Oceans) at <http://www.ngdc.noaa.gov/mgg/gebco/gebco.html>), tectonic plate boundaries (Wilson, 1993), the coastline, and seismographic-station locations, as well as the Juan de Fuca slab surface.

We created 3-D visualizations of these data sets using the ArcScene module of ArcGIS; 3-D software that allows the assembly of point, line, polygon, and grid themes into a single dynamic and interactive model. The hypocenter points were assigned colored symbols according to their location relative to the slab grid (above, below, or outside). The fly-through animation was constructed to illuminate and examine seismicity patterns of interest. To improve our ability to distinguish features such as misfits between the slab surface and coherent earthquake populations, we use a vertical exaggeration of 2.5 for the slab surface and hypocenters. In our animation, we raised the shaded-relief image 10 km above its actual location to make it easier to examine shallow seismicity.

Simple Correlations

The filtered earthquake catalog illuminates several seismotectonic features. For example, the fracture zones offshore, the Gorda and Explorer deformation zones within the Juan de Fuca Plate, and the slab where it arches beneath western Washington and northwestern California are all marked by relative concentrations of earthquakes (fig. 3). The two eastern strands of the northernmost San Andreas Fault system (Maacama, and Bartlett Springs) are marked by continental seismicity (fig. 3).

Our slab model and earthquake data sets offer some specific seismotectonic correlations. In general, slab seismicity dies out at depths greater than 60 km (fig. 6). However, it persists down to 100-km depth beneath Puget Sound, to 80-km depth beneath northern California, and to 70-km depth beneath central Vancouver Island (fig. 6). The south side of the slab arch beneath Puget Sound is bounded by a linear trend of small- to moderate-sized earthquakes that illuminate a downdip increase in dip from 8° to 32° (McCrory and others, 2001) (Figure 5). This linear trend marks the southern boundary of a region of relatively high seismicity beneath Puget Sound. The trend may also mark a zone of structural complexity or a kink within the slab where earthquakes such as the recent 2001 (magnitude, M6.8) Nisqually earthquake may nucleate (McCrory and others, 2003).

The sparse slab seismicity in the 60- to 70-km depth range beneath southern British Columbia and Washington forms a curvilinear trend in map view (fig. 6) that mimics the inferred shape of the arched slab beneath Puget Sound. The shape of this trend is consistent with the shape derived from the wide-angle experiments and seismicity profiles.

Continental seismicity in the North American Plate is generally diffuse. However, the sorted catalog of earthquakes illuminates some patterns in the continental lithosphere such as the concentration of events above the arched slab in Washington and California (fig. 7). Seismicity associated with the two northeastern fault traces (Maacama, and Bartlett Springs Faults) of the Pacific-North American plate boundary terminates near the southern edge of the slab (fig. 1) inferred from the first-arrival data and the magnetic-isochron reconstruction.

Significant seismicity occurs in the North American Plate along and east of the

Cascade volcanic arc in northern California and southern Oregon (fig. 7). Some of these earthquakes may correlate with mapped faults (Weldon and others, 2003) attributed to trans-tension in the northwestern portion of the Basin and Range tectonic province. Other earthquakes are likely related to volcanic activity. There are other planar patterns in areas such as northern California that likely correspond to active faults or folds (see animation). Discussion of specific correlations between mapped faults and earthquakes is beyond the scope of this publication.

North American earthquakes sharply decrease in number west of the 40-km-deep slab contour in southernmost British Columbia, Washington, and northernmost Oregon (fig. 7). This abrupt change may reflect a change in seismogenic conditions in the continental crust (that is, change in rock type at depth) or a change in the strength of coupling between the two plates along the Cascadia subduction fault. Discussion of this observation is beyond the scope of this publication.

Future Updates

We plan to update the slab surface geometry as new data provide additional constraints. Revisions will be made available on a U.S. Geological Survey (USGS) web site. In addition, we plan to update the two seismicity data sets (Juan de Fuca and North American) each year by including sorted and filtered events from the previous year. These updated files will also be posted on the web and should be substituted for the pre-existing files. If future ANSS catalogs provide additional parameters to allow more sophisticated means to select well-located events (for example, horizontal or vertical error), we will re-post an improved version of the

filtered catalog subset on the USGS web site as well.

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Figure Captions

FIGURE 1. Map showing plate kinematic setting of the Cascadia subduction system. Red lines denote active plate boundaries. Dashed red lines denote inferred location of Juan de Fuca slab edges beneath continental margin. Red triangles denote active arc volcanoes, orange triangles denote inferred late Cenozoic slab-window volcanoes (modified from Armstrong and others, 1985). Black arrows denote velocity vectors of tectonic plates and main forearc block relative to fixed North America (Douglas S. Wilson, 1998, written commun.; McCrory, 2000). Inverted black triangles denote current distribution of seismographic stations. *Mf* denotes the Maacama Fault; *Bsf* denotes the Bartlett Springs Fault.

FIGURE 2. Maps showing data used to constrain depth to top of Juan de Fuca slab beneath North America. 2A, Shows configuration of slab surface beneath the western margin of North America as constructed by Flück and others (1997). Blue contours denote depth to top of subducted Juan de Fuca Plate in kilometers below sea level. Lines are solid where location is relatively well constrained; dashed where relatively poorly constrained. Dashed black lines denote wide-angle transects used to construct this model. See table 1 for sources of transects. See figure 1 for explanation of other map symbols. 2B, Compares configuration of Flück and others (1997) surface to the updated surface. Blue contours denote the Flück and others (1997) surface; gray contours denote new surface in kilometers below sea level. Map also shows location of wide-angle transects and seismicity profiles used to constrain location of updated slab surface. Shaded green area beneath western Washington denotes the location of regional slab models of Creager and others (2002) and Tréhu and others (2002). Green lines denote location of transects and profiles used in this slab version but not in original one by Flück and others (1997). Dashed black lines denote transects that were incorporated into both compilations. Yellow lines denote existing but unpublished wide-angle transects that will be incorporated into future versions when available. See table 1 for sources of published and unpublished data. 2C, Shows first-arrival polarities for 1994 Mendocino fracture zone right-lateral, strike-slip earthquake recorded across central and northern California. Pattern of first motions is used to constrain southern edge of slab beneath northern California. Black arcs represent schematically, the wavefronts passing through the faster oceanic lithosphere and diffracting into the subducting slab. These diffracted waves arrive at the surface ahead of the direct arrival that propagates through the slower continental lithosphere.

FIGURE 3. Map showing all filtered (see text for discussion of filtering standards) ANSS (Advanced National Seismic System) catalog earthquakes within study area before separation using the geo-referenced slab surface. Gray lines denote contours of equal depth to the Juan de Fuca slab surface in kilometers below sea level. Contours are solid for 10-km intervals; dashed for supplemental 5-km contours. Profile 1 is 25-km wide and shown in figure 4; profile 2 is 60-km wide and shown in figure 5. See figure 1 for explanation of other map symbols.

FIGURE 4. North-south seismicity profile in northwestern California showing apparent arching and thickening of Juan de Fuca Plate adjacent to the Mendocino fracture zone. A 25-km wide swath of seismicity is projected onto the profile. Solid gray line denotes the location of the oceanic crust inferred from slab model. Dashed gray line denotes the location of the San Andreas (SA) Fault trace. Blue circles denote hypocenters located above the modeled slab surface; orange circles denote hypocenters located below the surface; green circles denote hypocenters located south of the slab surface. LS Fault denotes the Little Salmon Fault zone in the North American Plate; MR Fault denotes the Mad River Fault zone. See figure 3 for location of profile.

FIGURE 5. Southwest-northeast seismicity profile in western Washington showing apparent increase in slab dip at about 50-km depth. A 60-km wide swath of seismicity is projected onto the profile. See figure 3 for location of profile. See figure 4 for earthquake magnitude key. Solid gray line denotes the location of the oceanic crust inferred from slab model; dashed gray line denotes approximate location of continental Moho. Blue circles denote hypocenters located above the modeled slab surface; orange circles denote hypocenters located below the surface. See figure 3 for location of profile.

FIGURE 6. Map showing seismicity within Juan de Fuca Plate, below the inferred slab surface, selected by a geo-referenced sort of ANSS (Advanced National Seismic System) catalog earthquakes. See figure 1 for explanation of map symbols.

FIGURE 7. Map showing seismicity within North American plate, above slab surface, selected by the geo-referenced sort of ANSS (Advanced National Seismic System) catalog earthquakes. See figure 1 for explanation of map symbols.