USGS
science for a changing world

Crustal Structure and Earthquake Hazards of the Subduction Zone in Southwestern British Columbia and Western Washington

Professional Paper 1661-C

U.S. Department of the Interior
U.S. Geological Survey

Earthquake Hazards of the Pacific Northwest Costal and Marine Regions

Robert Kayen, Editor

Crustal Structure and Earthquake Hazards of the Subduction Zone in Southwestern British Columbia and Western Washington

By Michael A. Fisher, Roy D. Hyndman, Samuel Y. Johnson, Thomas M. Brocher, Robert S. Crosson, Ray E. Wells, Andrew J. Calvert, Uri S. ten Brink

Earthquakes pose a serious hazard for urban areas of the Pacific Northwest. Marine geophysical data probe earthquake source regions and can help spur preparedness for possible major disasters.

Professional Paper 1661-C

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
P. Patrick Leahy , Acting Director

U.S. Geological Survey, Reston, Virginia: 2005

For sale by U.S. Geological Survey Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

This report and any updates to it are available online at:
http://pubs.usgs.gov/pp/pp1661-C

For additional information write to:
U.S. Geological Survey
Box 25046, Mail Stop 421, Denver Federal Center
Denver, CO 80225-0046

Additional USGS publications can be found at:
http://geology.usgs.gov/products.html

For more information about the USGS and its products:
Telephone: 1–888–ASK–USGS (1–888–275–8747)
World Wide Web: http://www.usgs.gov/

Cataloging-in-publication data are on file with the Library of Congress (URL http://www.loc.gov/).

Produced in the Western Region, Menlo Park, California
Manuscript approved for publication, January 3, 2005
Text edited by Peter Stauffer
Layout and design by Susan Mayfield and Judy Weathers

FRONT COVER
The RV *Thomas G. Thompson* acquiring data during the Seismic Hazards Investigation in Puget Sound (SHIPS) survey in Puget Sound. The Seattle cityscape is in the background, including the Space Needle on the right. The airgun array and multichannel seismic streamer are deployed off the stern. Photo courtesy D. Carver

Contents

Plates

[In pocket]

Figures

Tables

Crustal Structure and Earthquake Hazards of the Subduction Zone in Southwestern British Columbia and Western Washington

By Michael A. Fisher[1], Roy D. Hyndman[2], Samuel Y. Johnson[3], Thomas M. Brocher[1], Robert S. Crosson[4], Ray E. Wells[1], Andrew J. Calvert[5], and Uri S. ten Brink[6]

Abstract

Multichannel seismic (MCS) reflection data collected across the continental margin in the Pacific Northwest are compiled into two regional cross sections through the crust. Seismic-reflection traveltime was converted to depth using primarily velocities derived from tomographic analysis of arrival times of both airgun shots and earthquakes. One cross section extends eastward from the Cascadia Trench, where the oceanic Juan de Fuca Plate dives beneath the continent, nearly to the eastern end of the Strait of Juan de Fuca. The other section stretches northward from the city of Tacoma to the international border with Canada in the southern part of Georgia Strait. The east-west section shows that reflective midcrustal rocks extend eastward from within 50 km of the trench to the eastern end of the Strait of Juan de Fuca, where the top of reflective rocks attains depths as great as 40 km. The thickness of this reflective section increases from 8 km to about 10 km with increasing eastward distance from the trench. Perhaps owing to weakened reflections, however, the reflective rock section appears to thin sharply at depths exceeding 25 km. Earthquakes appear to nucleate within the rock wedge that overlies the reflective rocks. The lower depth limit for earthquakes, however, is not controlled by rock structure but by rock temperature. The north-south regional cross section shows that reflections from midcrustal rocks die out southward into Puget Sound. This loss of reflectivity results, at least in part, from sound attenuation within the Cenozoic strata that locally thicken southward to more than 8 km below Puget Sound.

Three sources for convergent-margin earthquakes are: (1) faults in the upper part of the continental crust, (2) the subduction-zone interface, and (3) mineral phase changes in the deeply subducted oceanic crust. This study provides structural information about earthquakes that occur within continental crust, as well as information about earthquakes that nucleate along the shallow part of the interplate thrust. Faults in the upper part of the continental crust are revealed by prestack depth migrated and poststack migrated MCS data, which show what is probably a reflection from the plane of the Seattle Fault. This fault dips 40º south. Probable Eocene volcanic rocks in the hanging wall of this fault override the thick (~8 km) fill within the Seattle Basin. Another inferred fault-plane reflection is evident from within the Kingston Arch, which is a large, east-west-trending anticline that delimits the Seattle Basin on the north. Other major faults within the study area, such as the Southern Whidbey Island and Devils Mountain Faults, are thought to extend beneath northern Puget Sound and the eastern Strait of Juan de Fuca. However, MCS data presented here lack the resolution necessary to show recent offset along these faults, nor do these data reveal how the faults merge downward into midcrustal rocks, where earthquakes nucleate. The second source for subduction-zone earthquakes lies along the interplate contact. The structure of the accretionary wedge might indicate the extent of rupture for interplate quakes. Near the mouth of the Strait of Juan de Fuca, the vergence of thrust faults in the outer part of the wedge changes from landward to seaward and the landward dip of the downgoing plate increases. Where these changes occur might be a candidate for a rupture-zone boundary for earthquakes along the interplate thrust. A third source for earthquakes, involving the deeply subducted oceanic crust, cannot be studied with data presented here because reflections from deep rocks die out southward below Puget Sound, far north of where recent earthquakes of this type have struck.

Introduction

The earthquake threat to urban centers in the Pacific Northwest is sufficiently compelling to have spurred intense research into the tectonics of the region that surrounds the nexus of international waterways where Puget Sound, the

---

[1] U.S. Geological Survey, Menlo Park, California

[2] Geological Survey of Canada, Pacific Geoscience Centre, British Columbia, Canada;

[3] U.S. Geological Survey, Santa Cruz, California

[4] University of Washington, Seattle, WA 98195

[5] Simon Fraser University, Burnaby, British Columbia, Canada

[6] U.S. Geological Survey, Woods Hole, Massachussetts

Strait of Juan de Fuca, and the Strait of Georgia merge (fig. 1). This region's subduction-zone setting is now known to have generated large-magnitude (about M9) earthquakes (see, for example, Heaton and Hartzell, 1987; Rogers, 1988; Bucknam and others, 1992; Clague and Bobrowsky, 1994; Satake and others, 1996; Atwater, 1996; Atwater and Hemphill-Haley, 1997; Clague, 1997; Kirby, 2000). In particular, evidence from tsunami deposits and from tree rings preserved in drowned coastal forests reveals that great earthquakes, having a variety of source mechanisms, have struck in the past millennium. About 1,100 years ago, a large (M7) earthquake was unleashed by a major fault that extends directly beneath the city of Seattle. In addition, tsunami deposits in Japan provide indirect evidence that during the year 1700, a great (M9) earthquake occurred along the Cascadia interplate thrust. In the year 2001 the large (M6.8) Nisqually earthquake originated at a depth of about 65 km, within the deeply subducted oceanic slab beneath the Puget Lowland. This event was similar in magnitude and depth to earthquakes that occurred in 1949 and 1965. Characterizing the varied source mechanisms for these earthquakes has required a broad research effort, and research findings thus far have emphasized that the populated shores of the interior waterways, especially along Puget Sound, are at risk from major earthquakes and resulting landslides and tsunamis.

The bedrock geology around Puget Sound and elsewhere in the study area generally lies obscured beneath dense forest and a thick mantle of Quaternary glacial deposits. For this reason geophysical techniques provide the primary means to scrutinize the main crustal structures and possible active faults. We focus this report on results from marine, multichannel seismic (MCS) reflection data. During the middle 1990's, the need for detailed subsurface information on the location and attitude of subduction zone faults and other structures gave

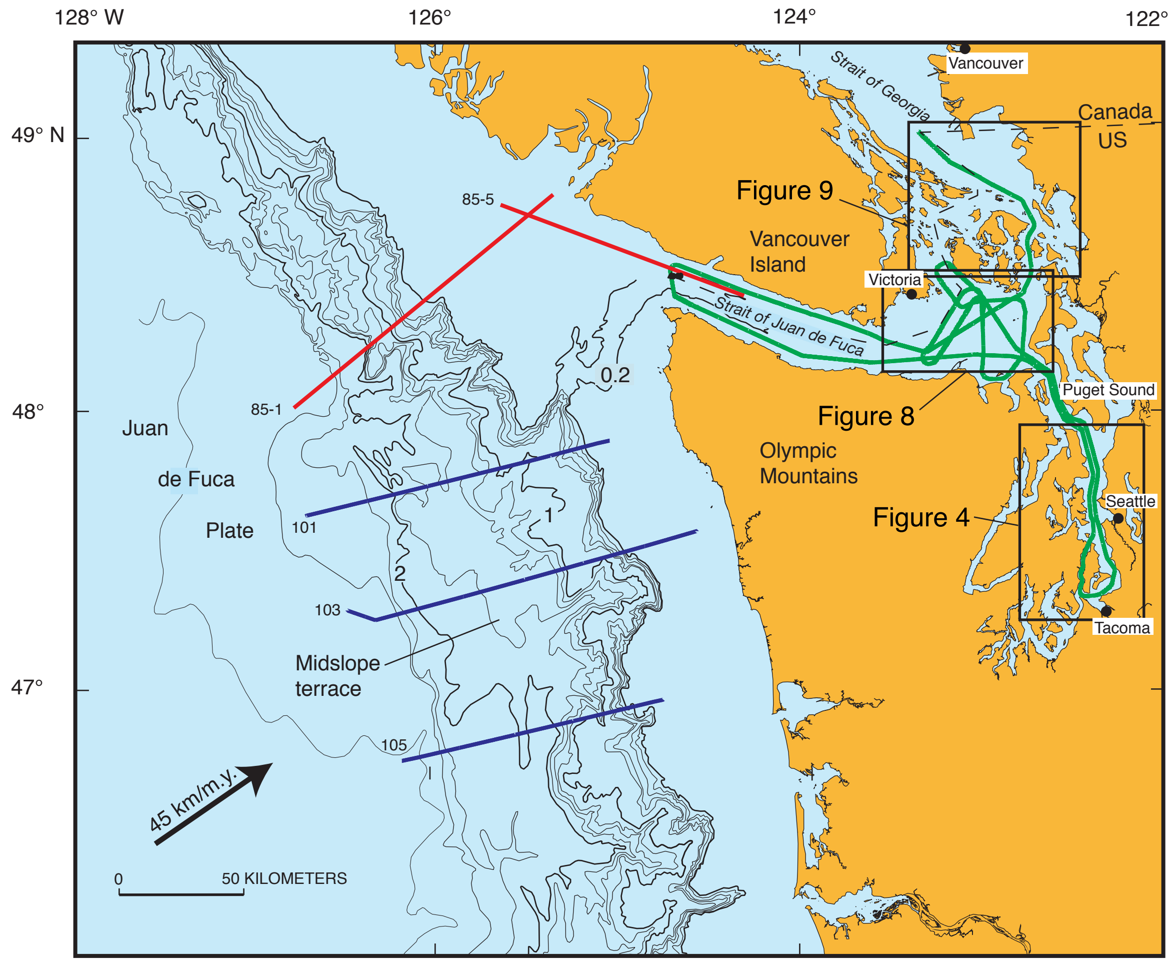

Figure 1 Location of the study area in western Washington State and southwestern British Columbia, showing the seismic-reflection lines (numbered) used in this report. Data along seismic lines 85-1 and 85-5 (red) were obtained by the Geological Survey of Canada. During the 1996 cruise of the RV *Sonne*, multichannel seismic data were collected along seismic lines 101, 103, and 105 (blue). Other lines (green) were surveyed during the SHIPS experiment. Also shown are the areas included in figures that show detailed maps of seismic reflection tracklines and geology. Bathymetry in kilometers; contour interval 100 m from 0.2 to 0.5 km, 250 m from 0.5 km down. Heavy arrow shows direction and rate of convergence between Juan de Fuca Plate and North America Plate.

Table 1. Attributes of seismic-reflection surveys used in this study.

Survey	Year	Airgun-away volume (in^3)	Steamer length (m)	Fold[1]	Group interval (m)	Record length(s)	Sample rate (ms)
GSC[2]	1985	6,100	3,000	30	25	16	4
Sonne[3]	1996	5,600	2,400	24	50	16	4
SHIPS[4]	1998	6,700/4,800	2,400	24	25	16	4

[1] Multiplicity of data coverage

[2] Geological Survey of Canada

[3] Cooperative USGS and GEOMAR survey using the RV *Sonne*

[4] Seismic Hazarda Investigation in Puget Sound

the impetus to mount two internationally sponsored seismic-reflection surveys that provided much of the MCS data used in this report. Other seismic data are from earlier surveys by the Geological Survey of Canada.

Below we describe the regional deep-crustal structure of the subduction zone, based on cross sections made from migrated and depth-converted MCS data (fig. 1). The east-west cross section connects the geology of the accretionary wedge with that below the Seattle-Tacoma urban corridor. The north-south cross section slices through this corridor. Discussion then focuses on particular structures within the subduction zone.

Seismic-Reflection Surveying

In this report we show seismic-reflection data obtained during three surveys (table 1; fig. 1). In 1985 and 1989, the Geological Survey of Canada collected MCS data over the accretionary wedge west of Vancouver Island (Yorath and others, 1987; Spence and others, 1991; Yuan and others, 1994). A commercial contractor processed MCS data collected during 1985 through migration after stack, and two seismic sections from this survey are shown here (plates 1 and 3).

During the 1996 cruise of the RV *Sonne*, researchers from GEOMAR (Kiel, Germany), the U.S.Geological Survey (USGS), and Oregon State University collected seismic reflection and wide-angle seismic data by recording airgun shots along a seismic streamer, with an array of ocean-bottom hydrophones and a deployment of onshore seismometers (Flueh and others, 1997). The USGS installed DFS-V seismic recording instruments, an airgun system, and a seismic streamer onboard the RV *Sonne*. Seismic-reflection data were processed through poststack time migration.

Most seismic-reflection data presented here were collected during the 1998 Seismic Hazards Investigation in Puget Sound (SHIPS) survey of Puget Sound and the Straits of Georgia and Juan de Fuca. This survey employed the University of Washington's ship, the RV *Thomas G. Thompson*, and the Canadian research ship, the RV *John P. Tully*. The branching waterways within the survey area provided a convenient means to use ship-towed airguns to obtain wide-angle and refraction seismic data with distributed source and receiver arrays, allowing three-dimensional tomographic analysis (Zelt and others, 2001; Brocher and others, 2001; T. Van Wagoner, written commun., 2001; Ramachandran and others, 2000). The USGS installed airgun and seismic-recording systems onboard the *Thompson*. During wide-angle surveying, a 110-L 16-airgun array was fired every 40 s; during separate seismic-reflection surveying, an 85-L, 14-airgun array was fired every 20 s. The Canadian Coast Guard ship *Tully* towed two 300-m streamers to record airgun shots during 10 constant-midpoint, expanding-spread profile runs that were scattered throughout the survey area. MCS data collected during the SHIPS experiment were processed through poststack time migration, and some data, particularly those collected over the Seattle Fault, underwent prestack depth migration. Seismic-reflection data collected over this fault also underwent specialized processing to investigate the detailed variation in refraction velocity near the fault (Calvert and Fisher, 2001).

A serious challenge to the successful conclusion of the SHIPS experiment stemmed from the urban environment of the survey area, with its attendant high noise level in the water. One particular problem involved high-amplitude, broadband noise generated by ships that passed the slow survey vessel in narrow waterways; such noise virtually precluded the use of prestack data-processing techniques, such as frequency-wavenumber filtering and depth migration. Most data processing required 24-fold stacking and the consequent reduction in random noise.

Airgun surveys are viewed askance by groups interested in the well-being of the marine environment. In fact, the 1996 survey by the RV *Sonne* of the area west of Washington and Oregon was nearly stopped by environmental regulators just days before the survey ship was to leave port. In the area of the SHIPS survey, marine mammals are plentiful—they are legally protected and highly valued by the local populace. To ensure that the SHIPS survey complied with all regulations, 18 months before the survey the SHIPS consortium began meeting with environmental groups and government regulators. The SHIPS group had to contend with stringent environmental regulations meant to safeguard marine mammals from possible injury due to the loud, underwater airgun sound. A chief environmental concern was that firing airguns in the confined waterways making up Puget Sound might cause intense sound to propagate inshore where many marine mammals congregate. However, we demonstrated by modeling underwater sound propagation that sound does not concentrate shoreward and that the survey would have insignificant impact in nearshore areas. Even so, regulators judged that the array's calculated, peak-to-peak, sound-pressure level of 260 dB re 1 µPa-m was loud enough to damage the hearing of marine mammals that approached the array too closely. Therefore, the permit for the survey obtained from the National Marine Fisheries Service stipulated that airgun operations had to cease if any marine mammal closed to within 100 m or 500 m of the airguns, the distance depending on the mammal species. Other permits were obtained from the Department of Fish and Wildlife (U.S.) and the Department of Fisheries and Oceans (Canada). To ensure our compliance with the various permit stipulations, the SHIPS consortium employed six biologists on the *Thompson* and six more on the *Tully* to monitor airgun operations. Observations of marine mammals were made from the survey ships, small launches, and an aircraft. Real-time monitoring of underwater acoustics from launches provided direct measurement of the sound levels to which some marine mammals were exposed and simultaneous observation of the mammals' behavior. The biological observers reported that no marine mammals were harassed during the SHIPS survey.

Geologic Setting

Plate convergence has occurred along the Cascadia subduction zone since the early Eocene, and late Miocene crust of the oceanic Juan de Fuca Plate is currently being subducted obliquely northeastward beneath the continent (at about 43 km/m.y. along N65°E; fig. 1; Engebretson and others, 1985; DeMets and others, 1990). Rocks forming the continental margin west of the magmatic arc, which lies along the Cascade Mountains, can be lumped into three subparallel belts. The belt farthest west, adjacent to the trench, includes the Cascadia accretionary wedge of sedimentary rocks as old as Eocene (fig. 2). The central rock belt is made up of rocks of Paleocene and Eocene age, mainly mafic volcanic rocks assigned to the Siletzia terrane. The eastern and northern belt is made up of varied Mesozoic and Paleozoic, mainly metamorphic and plutonic rocks.

The Accretionary Belt

The belt of accreted sedimentary rocks in Cascadia spans from the trench at the toe of the continental margin eastward to near the coastline, except for the area of northern Washington State, where accreted rocks extend eastward through the Olympic Mountains, nearly to the west side of the Puget Lowland (fig. 2). The eastern boundary of this belt is exposed locally as the Hurricane Ridge thrust fault that wraps around the north and east sides of the Olympic Mountains and dips outward from these mountains. This fault's upper plate comprises thick mafic volcanic rocks of the Siletzia terrane. Elsewhere the boundary between the two rock belts is obscured beneath late Cenozoic rocks, but presumably this boundary includes a combination of strike-slip and thrust faults (Tabor and Cady, 1978; Snavely, 1987; Brandon and Calderwood, 1990; Johnson and others, 1994, 1996b; Hyndman and Wang, 1995; Pratt and others, 1997; Parsons and others, 1999; Stanley and others, 1999; Wells and others, 1999; Crosson and others, 2000; Brocher and others, 2001). The oldest rocks in the accretionary belt are in Eocene melange that is exposed only in the Olympic Mountains, in the northwestern corner of Washington State (fig. 2). Other rocks of the accretionary belt exposed in these mountains are melange and broken sedimentary formations as young as middle Miocene (Tabor and Cady, 1978; Brandon and Vance, 1992; Orange and others, 1993).

Where the accretionary wedge adjacent to the trench has been investigated using marine multichannel seismic-reflection data, the wedge exhibits a complex distribution of compressional, strike-slip, and extensional deformation. West of central and southern Oregon and west of Vancouver Island, thrust faults in the outer part of the accretionary wedge verge seaward. In between, however, thrust faults verge predominantly landward (Seely, 1977; Snavely, 1987; Davis and Hyndman, 1989; Hyndman and others, 1990; Niem and others, 1992; MacKay and others, 1992; MacKay, 1995; Calvert, 1996; McNeill and others, 1997; Fisher and others, 1999a). McCaffrey and Goldfinger (1995) and Goldfinger and others (1997) proposed that, near the trench, the accretionary wedge is fragmented into large blocks that are bounded by strike slip faults and rotate clockwise.

Rocks within the upper part of the accretionary wedge are undergoing extensional collapse of two kinds. The first and more extensive style of collapse occurs where seaward-dipping, listric, normal faults deform rocks under the outer shelf and upper slope (McNeill and others, 1997). West of Washington State, these faults dip mainly seaward and offset rocks as deep as 2 to 3 km. This kind of extension apparently began during the late Miocene and, at least locally, has continued during the Holocene. Listric faults sole out downward along what may be the top of late Miocene and older accreted rocks. Elevated pore pressure within these deep, accreted rocks and their plastic yielding may promote the listric normal faulting in superjacent rocks and sediment. The second style of extensional collapse involves large sections of the lower continental margin off Oregon that apparently have moved downslope in major slump masses (Goldfinger and others, 2000).

Eocene Volcanic belt

The second of the three main rock belts that make up the upper plate of the central Cascadia subduction zone includes primarily Eocene subaerial and submarine mafic volcanic rocks and subsidiary gabbro and sedimentary units, all of which are part of the Siletzia terrane. Below Puget Sound and much of the surrounding lowland such rocks are as thick as 25 km (Pratt and others, 1997; Symons and Crosson, 1997; Brocher and others, 2001; Van Wagoner and others, 2002). These rocks were emplaced into the continent circa 50 Ma and extend northward from Oregon to central Vancouver Island (Snavely and others, 1958; Simpson and Cox, 1977; Duncan, 1982; Massey, 1986; Dehler and Clowes, 1992; Trehu and others, 1994; Snavely and Wells, 1996; Clowes and others, 1997; Gerdom and others, 2000). MCS and drilling data from Puget Sound and offshore Vancouver Island show that the upper part of this terrane includes interlayered basalt and sedimentary rocks (Shouldice, 1973; Johnson and others, 1994; Pratt and others, 1997; Brocher and Ruebel, 1998; Rau and Johnson, 1999). On southernmost Vancouver Island the boundary is exposed as the Leech River Fault (Massey, 1986, Green and

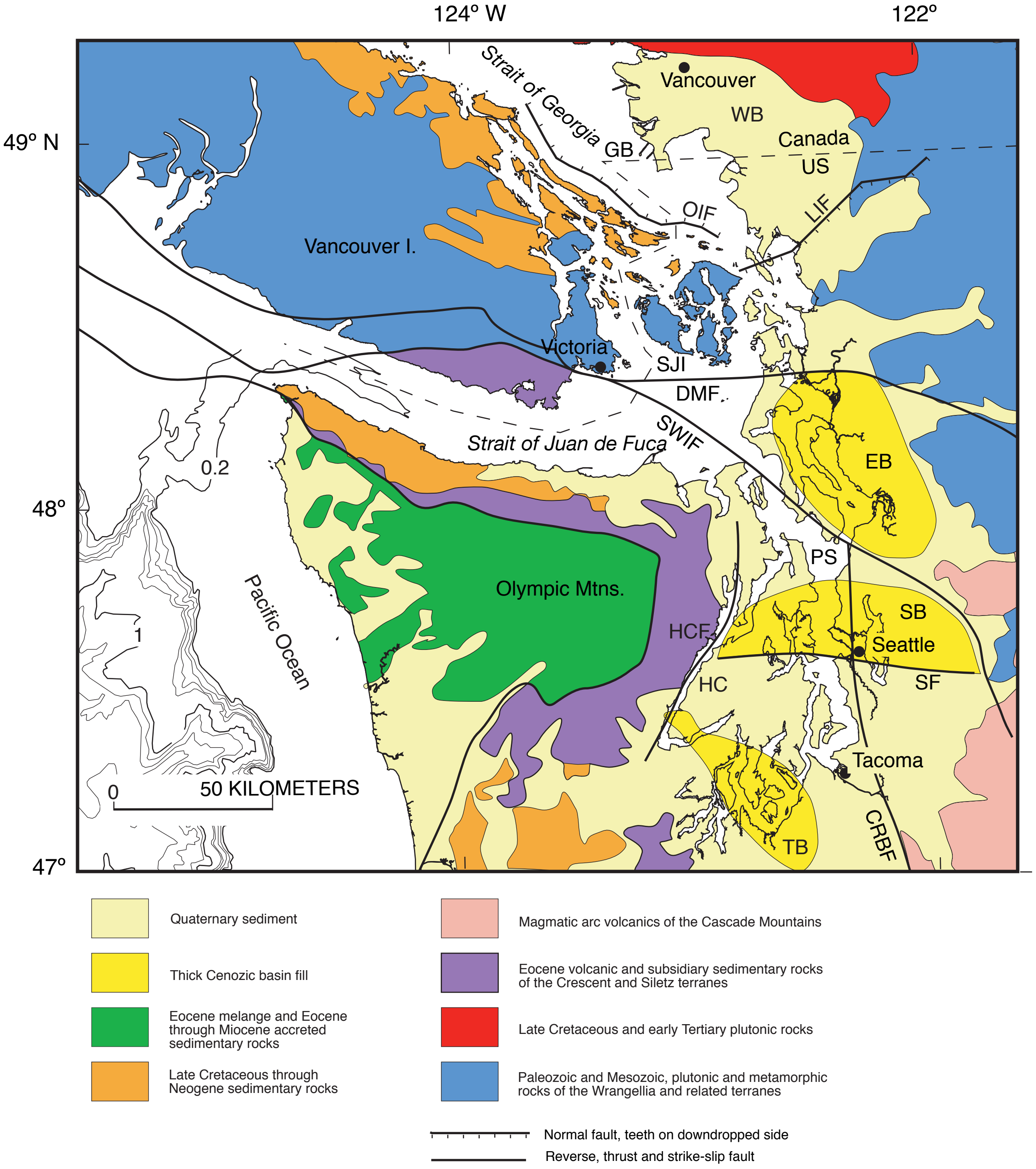

Figure 2. Geology (Brandon and others, 1988; England and Bustin, 1998) of the study area. Bathymetry in kilometers; contour interval 100 m from 0.2 to 0.5 km, 250 m from 0.5 km down. Abbreviations: CRBF, Coast Range Boundary Fault; DMF, Devils Mountain Fault; EB, Everett Basin; GB, Georgia Basin; LIF, Lummi Island Fault; OIF, Outer Islands Fault; SB, Seattle Basin; SWIF, Southern Whidbey Island Fault; SJI, San Juan Islands; TB, Tacoma Basin; WB, Whatcom Basin.

others, 1987). Beneath Puget Sound and the eastern Strait of Juan de Fuca, the Coast Range Boundary Fault and the Southern Whidbey Island Fault Zone (fig. 2) are thought to form the eastern and northeastern boundaries, respectively, of the Eocene volcanic rocks (Johnson, 1984; Johnson and others, 1996b). Such rocks crop out in a horseshoe-shaped exposure that bounds the Olympic Mountains on the north, east, and south. Tomographic-velocity data have been interpreted to show that under Hood Canal, the volcanic rocks end in the west along a near-vertical fault (Brocher and others, 2001; Van Wagoner and others, 2002).

Since early Eocene time, the entire length of the Siletzia terrane has formed the backstop for sediment accretion at the trench. Two proposals have been advanced to explain the development of the Siletzia terrane. It may have formed as an oceanic, volcanic island that subsequently was emplaced into the continent (Duncan, 1982; Trehu and others, 1994); alternatively, part of the continental margin may have passed over a mantle hot-spot to undergo regional uplift and extension and consequent intrusion by mafic volcanic rocks (Babcock and others, 1992).

Paleozoic and Mesozoic Crystalline belt

In faulted contact against the eastern and northeastern margins of the Eocene volcanic rocks lie the diverse Paleozoic and Mesozoic volcanic, sedimentary, metamorphic, and plutonic rocks that make up the basement beneath the Cascade Mountains and the region north of the Strait of Juan de Fuca (fig. 2) (Brandon and others, 1988; Monger, 1991; Johnson and others, 1996b; England and Bustin, 1998). These diverse rocks were accreted to the North American continent by Late Cretaceous or earliest Tertiary time. North of the Leech River Fault on Vancouver Island, the basement complex includes rocks as old as Paleozoic that are assigned to the Wrangellia terrane. East of Vancouver Island, under the San Juan Islands, metaigneous and metasedimentary basement rocks are exposed in an imbricate thrust stack that was emplaced northward during the Late Cretaceous over rocks of the Wrangell terrane (Brandon and others, 1988). Rocks forming the San Juan Islands chronicle the tectonic assembly and subsequent deformation of a wide variety of smaller terranes, some of them far traveled and of oceanic and island-arc affinity. These constituent terranes include rocks that range in age from early Paleozoic to middle Cretaceous.

Vibroseis seismic-reflection data collected across Vancouver Island during the Lithoprobe program reveals that east-dipping rocks of the Wrangellia terrane are about 20 km thick and are imbricated along numerous thrust faults (Clowes and others, 1987a; Green and others, 1987). These data also reveal that a thick succession of reflective rocks make up the middle and lower crust. The importance of this finding is that similar reflections are evident in seismic-reflection data collected in the Strait of Juan de Fuca by the Geological Survey of Canada (Hyndman, 1988; Cassidy and Ellis, 1993; Calvert, 1996) and in SHIPS seismic-reflection data that we present below. Reflections from the midcrust end seaward where they merge downwards with the reflection from the subducting oceanic crust (Calvert, 1996). Our data show (below) that these reflections were recorded from beneath the eastern end of the Strait of Juan de Fuca, and arise from rocks as deep as 50 km.

Wrangellian basement rocks underlie the southern part of Georgia Strait and basin, north of the San Juan Islands (England and Bustin, 1998). Zelt and others (2001) assumed that sound velocity measured at the top of these basement rocks would be about 6 km/s; if so, then the top of Wrangellian basement under the southern part of the Georgia Basin is about 8-9 km below sea level.

Late Cretaceous and Cenozoic Sedimentary Rocks

Beneath the region that encompasses Puget Sound and the southern part of Georgia Strait, an overlap rock assemblage consists of locally thick forearc-basin deposits (fig. 2). These individual basins differ considerably in basement type, age of fill, and structural style. Basins under the Puget Lowlands overlie a basement composed mainly of Eocene volcanic rocks, except under the eastern part of these lowlands, where basement includes pre-Cenozoic rocks (see, for example, Johnson and others, 1994; Pratt and others, 1997; Brocher and others, 2001). In contrast, basement rocks beneath the Georgia Basin are Devonian to Jurassic crystalline units of the Wrangellia terrane (England and Bustin, 1998; Zelt and others, 2001).

The maximum age of basin fill also varies geographically. The Tacoma, Seattle, and various lesser basins that underlie the lowlands surrounding Puget Sound contain rocks no older than Eocene, though the fill in the Seattle Basin is 7-10 km thick. The Georgia Basin contains rocks as old as Late Cretaceous (England and Bustin, 1998) that are as thick as 8-9 km under the southeastern part of the Georgia Strait (Zelt and others, 2001)

Regionally, the forearc basins differ greatly in structural style. Under the Puget Lowland, the basins developed along west- and northwest-trending thrust faults and folds, whereas the Georgia Basin occupies a large trough that strikes northwest-southeast and is bounded on the southwest by the Cowichan fold belt that probably resulted from collision and emplacement into the continent of the Siltez terrane. The north-south compression needed to forge the east-west structures in the southern part of the survey area derived from oblique plate convergence (see, for example, Wells and others, 1999). The resulting small component of northward terrane motion appears to end at a backstop near the Devils Mountain fault (fig. 2) (Johnson and others, 1994; Pratt and others, 1997; Wells and others, 1999; Khazaradze and others, 1999). One goal in collecting MCS data in the Strait of Juan de Fuca was to investigate the crustal structure of this backstop.

Basins under Puget Sound are a focus for intense earthquake-hazard research because the bowl-like shape of some basins and the thick, young fill within them can amplify ground shaking during an earthquake (Brocher and others, 2000; Frankel and Stephenson, 2000; Frankel and others, 1999; Hartzell and others, 2000). Furthermore, these basins typically developed along major faults and are near or directly under urban areas; thus the basin-forming faults constitute one of the main potential sources for damaging earthquakes. Pratt and others (1997), for example, estimated that the Seattle Fault could generate an M 7.6-7.7 earthquake.

The deep structure of basin-forming faults below Puget Sound remains unresolved, despite its importance to the analysis of earthquake hazards. These faults and the deep basins related to them occupy a relatively narrow (70 km wide) corridor, under the Puget Lowland, that stretches from near the city of Olympia north-northeastward to the foothills of the Cascade Range, east of the San Juan Islands (Johnson and others, 1994; Pratt and others, 1997). Under the southern Puget Lowland the basins and crustal faults may have developed within a north-directed thrust sheet that involves most of the crust above 20-km depth (Pratt and others, 1997). The Seattle Fault deforms this thrust sheet—between Earth's surface and 6-km depth, the fault is estimated to dip about 45° south, but at greater depth the dip flattens to about 20° (Pratt and others, 1997). In an alternative structural model, Brocher and others (2001) interpret wide-angle-velocity and hypocentral data from Puget Sound to propose that the main crustal faults, like the Seattle Fault, dip steeply (70º-80º) and, maintaining these steep dips, transect much or all of the continental crust, perhaps to the base of the Siletz volcanic terrane.

Earthquake Sources

Major earthquakes loom in the Pacific Northwest because of the region's subduction-zone setting. The sector of the oceanic Juan de Fuca Plate being subducted at the trench is hot because the spreading center is close to the continent, so the subducting plate is young. Also, subduction here occurs relatively slowly (43 km/m.y.). These factors affect all three of the mechanisms by which large earthquakes nucleate. Two mechanisms are associated with the downgoing oceanic plate and the third involves movement along upper-crustal faults.

The first earthquake mechanism might unleash M8-9 earthquakes from the interplate thrust at relatively shallow depth, mainly offshore. An earthquake possibly as great as M9 had this origin 300 years ago (Satake and others, 1996; Atwater, 1996; Clague, 1997). The constraints on the area of earthquake rupture have been analyzed in considerable detail (see, for example, Hyndman and Wang, 1995; Oleskovich and others, 1999; Wang and He, 1999); one main result is that earthquake rupture along the interplate thrust fault may be restricted to where the rock temperature along this fault is colder than that of the brittle-ductile transition (350-450 °C) in the crust, which separates unstable from stable interplate sliding. This thermal control on frictional mechanism suggests that earthquake rupture will lie mainly west of the Pacific Ocean shorelines of Oregon, Washington, and Vancouver Island (Hyndman and Wang, 1995).

The second, deep-earthquake mechanism is also associated with the downgoing plate, but this mechanism in interpreted to involve metamorphic reactions, which occur worldwide at depths between 40 km and 90 km within subducting slabs (Kirby, 2000). Dehydration of the oceanic crust and basalt-eclogite transformation cause a net reduction in rock volume. Earthquakes are proposed to release the accumulated strain. Below Puget Sound, the largest earthquakes of this type occur at a depth near 50 km, directly below some of the main urban areas. These earthquakes are deep seated, so that for a given earthquake size, the ground shaking is relatively small. Nonetheless, such quakes are important hazards because they affect large areas and because historical earthquakes of this type struck in 1949, 1965, and 2001.

The third earthquake mechanism involves earthquakes that strike close beneath urban areas, along faults in the upper, brittle part of the continental crust. For example, studies based on tomographic velocities, derived from airgun-shot and local-earthquake arrivals, indicate that below Puget Sound crustal seismicity occurs mainly within the strong mafic volcanic rocks of the Siletzia terrane (Crosson and others, 2000; Van Wagoner and others, 2002). The Seattle Fault and other, recently recognized faults are sources for this type of earthquake. The Seattle Fault, for example, extends east-west beneath the city of Seattle and appears to have caused a M7 quake about 1,100 years ago (for example, Bucknam and others, 1992, 1999). An earthquake along this fault might be especially damaging because it could produce strong reverberations within the shallow part of the Seattle Basin, on which the city of Seattle rests (see, for example, Frankel and others, 1999; Frankel and Stephenson, 2000).

Upper-plate earthquakes tend to cluster (Ludwin and others, 1991) below Puget Sound and to emanate mainly from brittle rocks that make up the midcrust at a depth of about 20 km. In contrast, below Georgia Strait and southernmost Washington, the threat from forearc crustal earthquakes appears to be less. In the north a concentration of crustal seismicity lies west of the city of Vancouver (Cassidy and others, 2000; Mosher and others, 2000), where an M4.6 earthquake occurred along a shallow (3-4 km), offshore thrust fault. Farther north, below central Vancouver Island, crustal earthquakes struck in 1918 and 1946 and indicate a high seismic risk.

Findings: Regional Crustal Cross Sections

Orthogonal, regional cross sections show several large-scale reflective features within the subduction zone in the Pacific Northwest (index map in pl. 1). Some reflective features reveal information about the subduction-interface and upper-crustal sources for earthquakes that are discussed just above. The east-west section from the trench to the eastern end of the Strait of Juan de Fuca illustrates both the shallow, subduction-interface and deep-slab earthquake source regions. The north-south cross section includes two parts that bifurcate within the eastern Strait of Juan de Fuca. The main part of this section extends from southern Puget Sound northward into southern Georgia Strait and images potentially active upper-crustal sources for earthquakes.

Rock-Velocity Models for Time-to-Depth Conversion

Velocity-depth models are critical input to producing depth sections from MCS data. During the late 1990s, much effort was expended in the Pacific Northwest to collect wide-angle seismic data in sufficient density to allow detailed results about rock velocity to emerge from tomographic analysis. The sources for the velocity information used to produce the depth cross sections in plate 1 are summarized in figure 3.

The final velocity distribution used to convert time to depth for the east-west cross section (pl. 1) was derived from three disconnected models (numbers 9, 5, and 1 in fig. 3). Velocity data for rocks below the eastern Strait of Juan de Fuca (R. S. Crosson written commun., 2001; 9 in figure 3; Ramachandran and others, 2000) were derived from joint tomographic analysis of arrivals from earthquakes and from SHIPS airgun shots. During this analysis, the cell size was 5 km on a side. The resulting velocities extend downward to a depth of 60 km. Velocity values, however, only extend westward to about longitude 124º W (fig. 3). Velocity data give the depth to the Moho under the eastern Strait of Juan de Fuca. Information about Moho depth from more seaward locations comes from Spence and others (1985; 1 in figure 3), who used ray-tracing techniques to determine the velocity structure of the accretionary wedge and deeper rocks. In constructing the velocity model used here for time-to-depth conversion, these Moho depths were connected by a straight line, and shallower velocity layers were adjusted to fit this linear interpolation. To treat seismic-reflection data from the western part of the Strait of Juan de Fuca, we used velocities derived from SHIPS airgun shots (Graindorge and others, 1999; Ramachandran and others, 2000).

The velocity distribution used to convert time to depth for the part of the east-west cross section that images the accretionary wedge is a merger of the velocity models in Spence and others (1985; 1 in figure 3) and (Flueh and others, 1998; 2 in figure 3). This velocity model was also used to produce four, migrated and depth-converted seismic reflection sections from across the accretionary wedge west of Vancouver Island and Washington State (pl. 2).

The velocity distribution used to convert seismic travel-time to depth for the north-south cross section is mainly from the joint tomographic analysis of airgun shots and earthquake arrivals (R.S. Crosson, written commun., 2001; 10 in figure 3). This distribution extends from the south end of the cross section northward as far as the San Juan Islands. For the part of the north-south cross section that shows reflection from below the San Juan Islands and Georgia Strait, the velocities from the surface down to 15 km depth are from the tomographic analysis of SHIPS airgun arrivals by Zelt and others (2001; 7 in figure 3). For depths greater than 15 km, we extrapolated the results from source 10 in figure 3 to the north end of the cross section.

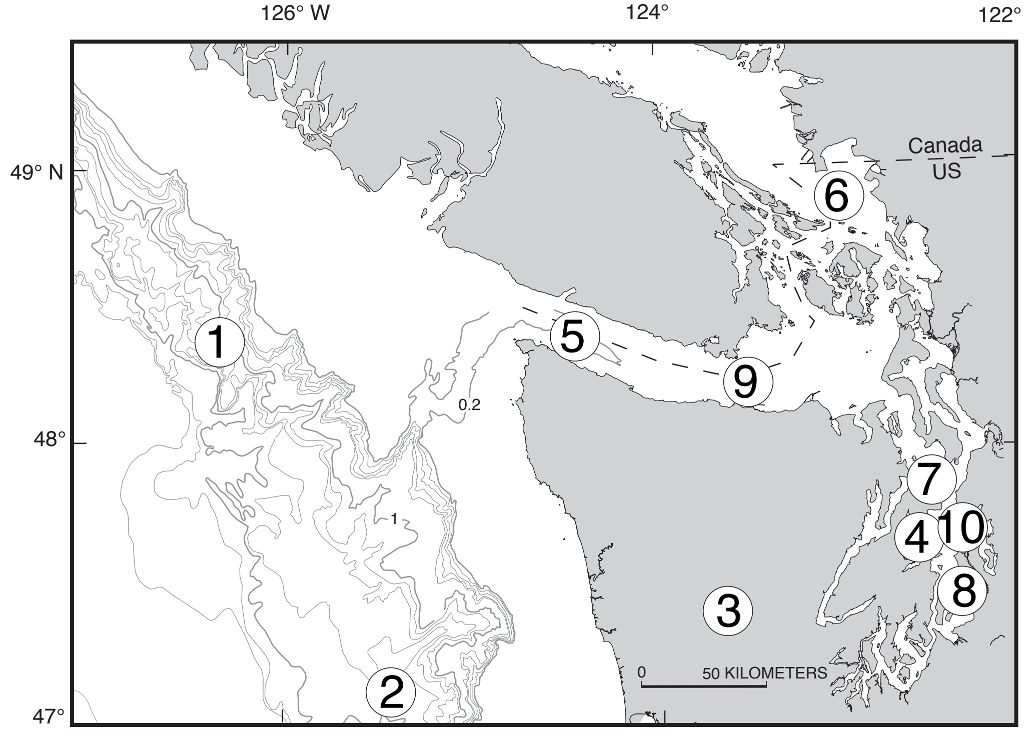

Figure 3. Locations and source references for velocity models that were assembled and used to depth-convert the seismic-reflection data that make up the regional east-west and north-south cross sections (pl. 1). 1, Spence and others, 1985; 2, Flueh and others, 1998; 3, Parsons and others, 1999; 4, T. E. Parsons, written commun., 1999; 5, Graindorge and others, 1999; 6, Zelt and others, 2001; 7, Brocher and others, 2001; 8, Van Wagoner and others, 2002; 9 and 10, R.S. Crosson, written commun., 2001.Bathymetry in kilometers; contour interval 100 m from 0.2 to 0.5 km, 250 m from 0.5 km down.

The locations of hypocenters shown on plate 1 are from joint tomographic inversion of earthquake-arrival times and wide-angle seismic data collected during the SHIPS experiment (R.S. Crosson, written commun., 2001). The hypocenters fall within a corridor that extends to 10 km to either side of the cross sections.

The East-West Cross Section

The chief goal in constructing the two regional cross sections (pl. 1) was to trace strong middle and lower crustal reflections, known from earlier seismic surveys, from near the accretionary wedge eastward to the urban corridor. We then intended to trace these reflections southward within this corridor to near the cities of Tacoma and Olympia, where deep in-slab earthquakes have repeatedly occurred. This goal was only partly met, owing to (1) the large two-way traveltimes of deep reflections, which exceeded out record length, and (2) the sound absorption that affected seismic signals propagating through the thick Cenozoic deposits under much of Puget Sound.

The east-west regional cross section extends from the oceanic plate through the Strait of Juan de Fuca, so the section crosses much of the continental margin obliquely, at about 30 ° from the perpendicular. This cross section combines rock velocity and reflectivity, as well as hypocenters, to show the geologic structure and tectonics of the shallow part of the interplate decollement and of the deeply subducted rocks, including the oceanic crust. These parts of the decollement and downgoing plate pertain to two of the earthquake mechanisms discussed above.

The accretionary wedge, as shown in seismic-reflection data (sections 85-01 and 85-05) collected by the Geological Survey of Canada, is deformed by seaward vergent thrust faults. Below seismic line 85-1, the reflective part of this wedge is relatively narrow, being only about 25 km wide (top section in pl. 1). We emphasize below, in discussing plate 3, that this vergence direction is anomalous within the study area, because west of Washington State, most faults in the outer part of the accretionary wedge verge oppositely, toward the land. The east-west cross section (pl. 1) shows that reflections from the oceanic crust were recorded about 60 km eastward from the trench, where a thick section of reflective rocks, between 10 and 20 km deep, makes up the lower part of the subduction zone (Clowes and others, 1987b; Hyndman, 1988, Hyndman and others, 1990; Calvert and Clowes, 1990, 1991; Calvert, 1996). Hyndman and others (1990) discuss the similarity between these deep reflections and ones evident in seismic-reflection data collected across Vancouver Island during the Lithoprobe program. These authors compiled seismic data from across this continental margin and island, and they show that reflections from the oceanic crust were recorded from below the trench eastward to where the crust of the continental margin attains a thickness of nearly 40 km below Vancouver Island. Reflections recorded during Lithoprobe operations occur in distinct, vertically isolated bands, whereas presumably correlative reflections in SHIPS data are not so strongly layered (pl. 1).

The thick section of subduction-zone rocks evident beginning about 60 km east of the trench (pl. 1) might be strongly reflective for several reasons. These reflections could reveal the metamorphic foliation within fossil shear zones, ductile-strain features, underplated fragments of igneous oceanic crust, subducted sedimentary rocks, or water trapped within rock pores below a front of metamorphic mineralization (Kurtz and others, 1986; Hyndman, 1988; Hyndman and others, 1990; Calvert and Clowes, 1990, 1991; Calvert, 1996).

SHIPS seismic-reflection data show that deep reflective rocks gradually thicken eastward beneath the Strait of Juan de Fuca (pl. 1) to where they attain a maximum thickness of about 20 km. Farther east the thickness of reflective rocks decreases gradually with depth. This decrease may be due to a changing environment with depth, that is, increasing temperature and pressure may alter rock reflectivity, or perhaps more likely, seismic signals were attenuated and not recorded because of the long travel path. In any case, dipping reflections are evident from rocks as deep as 40 km. For greater depths, the reflective rocks follow a zone of relatively low velocity between 6.5 and 7.0 km/s.

Reflections from deep within the subduction zone have been recorded over a broad area. They are evident in Lithoprobe data from across Vancouver Island (see, for example, Clowes and others, 1987a, b), and they are revealed by SHIPS data collected in the Strait of Juan de Fuca. In particular, such reflections are present in data collected along a SHIPS seismic line that extends north-south across the Strait of Juan de Fuca (middle part of plate 1, section labeled PS-2). Reflective rocks below this seismic line are between 35 and 45 km deep, and they underlie the area that includes the southern San Juan Islands and the mouth of Puget Sound. The depth to the reflective rocks appears to increase southward into Puget Sound, but this may be an artifact of errors in the velocity distribution used to convert time to depth. In any case, deep reflections die out a short distance to the south into Puget Sound, beneath the southward-thickening Cenozoic sedimentary section.

SHIPS seismic-reflection data show a strong, seaward-dipping reflection from the upper crust, which Spence and others (1985) interpreted as the offshore extension of the Leech River Fault. On Vancouver Island this fault separates volcanic rocks of the Siletzia terrane from pre-Cenozoic rocks.

The North-South Cross Section

The north-south crustal cross section, made from SHIPS seismic-reflection data, extends northward from near the city of Tacoma into southern Georgia Strait (pl. 1). Like the east-west section, this one integrates seismic reflections, tomographic velocities, and earthquake hypocenters.

The main goals for collecting SHIPS seismic-reflection data along the north-south cross section (pl. 1) were (1) to probe the crustal structure of the backstop for accretion that has been inferred to lie along or near the Devils Mountain fault and (2) to examine the belt of anomalous east-west thrust faulting that underlies the San Juan Islands, which could be similar to the Seattle Fault. We have already mentioned our failed attempt to trace deep reflections, like those evident on the east-west section, southward through seismic-reflection data collected in southern Puget Sound to investigate earthquakes in the downgoing plate. Similarly, SHIPS seismic-reflection data do not image either the backstop or the thrust belt. Thrust faults under the San Juan Islands are located in areas where sharp bottom topography, most likely of glacial origin, causes strong sideswipe in seismic-reflection data. These faults are thus obscured in seismic data.

The main correlation from deep-crustal data along the north-south cross section (pl. 1) is that hypocenters are concentrated in the high-velocity middle crust, between 15 and 30 km depth, as pointed out by van Wagoner and others (2002).

The southern part of the north-south section extends along the axis of Puget Sound and shows the Seattle Basin and Seattle Fault; the latter is presumed to be the main earthquake threat to the Seattle urban area. The 5-km grid size used during velocity-tomographic analysis caused low velocities to be estimated for rocks deep within the Seattle Basin. These deep velocities should be compared to the higher resolution analysis of velocities in the upper 15 km of the crust (Brocher and others, 2001). Even so, the Seattle Basin appears to be filled with sedimentary rocks about 8 km thick where the Seattle Fault bounds the south side of this basin.

Under the southern part of Georgia Strait, the Outer Islands normal fault bounds the Late Cretaceous and Cenozoic Georgia Basin on the southwest and has a throw of about 5-6 km (England and Bustin, 1998). SHIPS seismic-reflection data show this fault and reveal a throw of about 5 km. Zelt and others (2001) propose that the sound velocity at the top of the Wrangellian basement of this basin is about 6 km/s, in which case the basin is about 5-6 km deep.

Discussion

Earthquake Sources Within the Upper Continental Crust

Earthquakes generated within the brittle part of the continental crust constitute a serious potential hazard to urban areas because these earthquakes nucleate at relatively shallow depth, which can be directly below densely populated areas. The large number of earthquakes below Puget Sound that occur within the depth range of 15-25 km (for example, Ludwin and others, 1991), apparently nucleate within the widespread mafic volcanic rocks that make up the Siletzia terrane (Van Wagoner and others, 2002). One goal for the SHIPS survey in Puget Sound was to investigate faults that extend downward to the main seismogenic depth where the volcanic rocks make up the middle crust.

Seismic-reflection data (see, for example, Pratt and others, 1997; Johnson and others, 1994, 1996b, 1999) and gravity and magnetic data (Yount and Gower, 1991; Gower and others, 1985; Blakely and others, 2002) have provided most information on crustal faults. Pratt and others (1997) for example, used MCS data collected by the petroleum industry as a basis to propose that rocks below the Puget Lowland form a north-directed thrust sheet that is 15 to 20 km thick. According to this hypothesis, beneath the central part of this lowland, basins and intervening structural highs are controlled by thrust faults that splay upward from the decollement at the base of this thrust sheet.

A large number of active or recently active faults that could be sources for crustal earthquakes have been identified (for example, Johnson and others, 1994; 1996a; Pratt and others, 1997; Brocher and others, 2001), and the evident variety in fault structure increases the difficulty of estimating the detailed hazard from earthquakes. During the SHIPS survey, MCS data were collected across some of the main faults below Puget Sound, among them the Southern Whidbey Island Fault (fig. 2) and the Seattle Fault (figs. 2 and 4).

Interpreted seismic-reflection sections show that the southern Whidbey Island Fault Zone has been active during the Quaternary (Johnson and others, 1996b). This fault zone is a complicated, northwest-trending, transpressional zone that includes strike-slip, reverse, and thrust faults. This fault zone is thought to be a terrane suture, along which Eocene mafic volcanic rocks of the Siletzia terrane, on the southwest, abut a complicated assemblage of pre-Cenozoic rocks, on the northeast.

The Seattle Fault is a north-vergent thrust or reverse fault that strikes east-west beneath Puget Sound and the city of Seattle (fig. 4). This fault has been active since at least the Miocene (Johnson and others, 1994). Offset along the Seattle Fault is thought to have caused the flexural subsidence of the adjacent Seattle Basin, which is filled with Eocene and younger rocks (Pratt and others, 1997; Johnson and others, 1999). This fault has the potential to generate large earthquakes. Bucknam and others (1992) measured 7 m of uplift along the fault that may have occurred during a single M > 7 earthquake about 1,100 years ago. Furthermore, Pratt and others (1997) calculated the total surface area of this fault, using the fault geometry interpreted from seismic-reflection data, and concluded that the fault might generate earthquakes greater than M 7.

The Seattle Fault coincides with large gravity and magnetic anomalies (Danes and others, 1965; Finn and others, 1991; Blakely and others, 2002), and it forms the boundary between uplifted mafic volcanic rocks of the Siletzia terrane and other Tertiary rocks, on the south, and the deep (about 8 km) Seattle Basin, on the north (Johnson and others, 1994; Pratt and others, 1997; Brocher and others, 2001). The structure of the Seattle Fault appears to be complicated by fault segmentation, splays, and tear faults. Johnson and others (1999) described marine high-resolution seismic-reflection data over this fault and concluded that at shallow depth this fault encompasses a 4-6-km wide zone of south-dipping reverse faults. Joint interpretation of aeromagnetic anomalies and outcrop geology (Blakely and others, 2002) also indicates

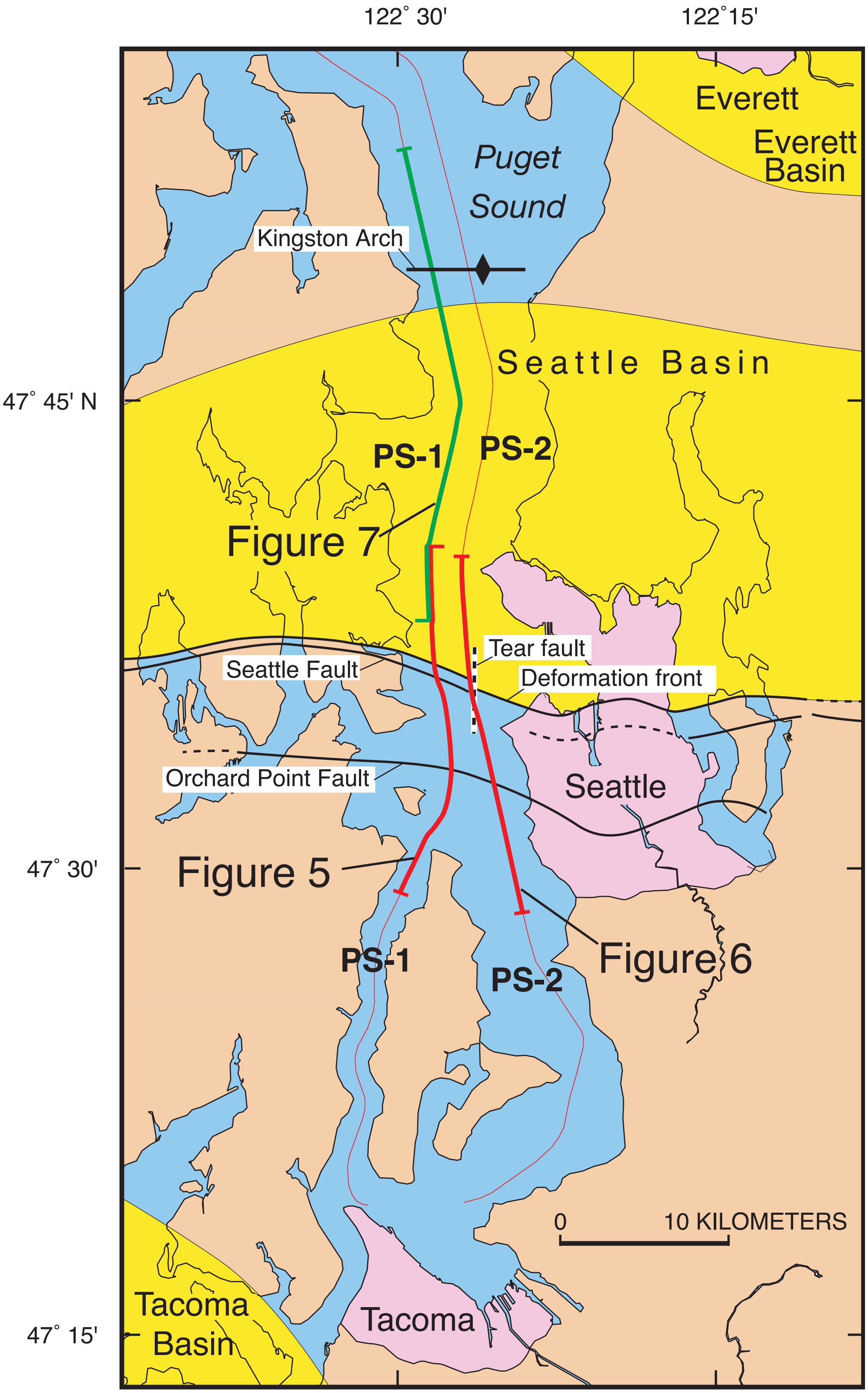

Figure 4. The main sedimentary basins, faults, and seismic-reflection tracklines (red and green) from the SHIPS survey in Puget Sound. Cities shown in purple. Location of seismic-reflection data collected over the Seattle Fault, shown in figures 5 and 6, and of data collected over the Kingston Arch, shown in figure 7, are also indicated.

that the Seattle Fault comprises a similarly wide deformation zone, and rocks in the fault's lower plate are deformed into a large drag fold. Strata on the south limb of this fold dip steeply (~70º) north. High-resolution tomographic analysis of arrival times measured along the MCS streamer deployed during the SHIPS cruise have been interpreted to show that within 1 km of the Earth's surface, the Seattle Fault is made up of three strands that dip south and show reverse offset (Calvert and Fisher, 2001). Lateral segmentation of the Seattle Fault is evident. The frontal fault of the Seattle Fault Zone, for example, is about 2.5 km farther north below western Puget Sound than it is below the eastern part of this sound. This northward offset may result from a combination of tear faulting, uneven fault propagation, and fault curvature (Johnson and others, 1996a; Blakely and others, 2002) (fig. 4).

Fault dip plays an important role in estimating the ground motion that would result from a major earthquake along the Seattle Fault (Frankel and others, 1999; Frankel and Stephenson, 2000). Modeling of this motion has indicated that the great thickness of young, low-shear-strength sediment in the Seattle Basin would prolong reverberation of seismic waves, and this basin's bowl-like shape would tend to concentrate seismic energy upward. Despite the importance of fault dip to these estimates of seismic hazard, the detailed structure of the Seattle Fault at depths of 15 to 20 km remains uncertain. Pratt and others, (1997) analyzed seismic reflection and stratigraphic data and modeled fault-bend folds to suggest that deeper than 5 to 6 km, the Seattle Fault dips steeply south, at about 45º. At depths greater than 6 km, this fault dips 20-25° south. Similar dips of 40º south (ten Brink and others, 2002) and 55º south (Calvert and Fisher, 2001) were estimated from combined analysis of wide-angle seismic and MCS data collected during the SHIPS experiment and from tomographic analysis of first arrivals along the MCS streamer, respectively. Other estimates of fault dip range upward to as much as 70º, on the basis of the velocity structure determined from tomographic analysis of wide-angle seismic data and the location and a near-vertical alignment of earthquake hypocenters (for example, Wells and Weaver, 1992; Brocher and others, 2001).

Central Puget Sound

During the SHIPS survey, seismic-reflection data were collected along two north-south tracklines that extend perpendicularly across the Seattle Fault and Basin (fig. 4). Seismic-reflection data from both tracklines were migrated using two strategies. First, data from across the fault were migrated after stack, which has the advantage of robust noise attenuation by the 24-fold summation of traces before migration. This attenuation turned out to be necessary for these data, which were collected in a high-noise, urban environment. Depth conversion of seismic data migrated after stack was accomplished using velocity data from tomographic analysis of wide-angle seismic data collected during the SHIPS experiment (T.E. Parsons, written commun., 1999). For the second migration technique, constant-offset gathers were migrated before stack. This technique has the potential to reveal considerable structural detail, but prestack migration is susceptible to distortion and masking that is caused by the smearing, during the prestack migration process, of random noise bursts. Another problem that complicated prestack migration was gaps in recording necessitated by the proximity of marine mammals to the survey ship.

The two SHIPS MCS lines that cross the Seattle Fault yield different images of this fault's subsurface structure. MCS line PS-1 (fig. 4), poststack migrated and depth-converted (fig. 5), shows that fill in the Seattle Basin above the top of the Crescent Formation is about 8 km thick. The formation top is taken from Pratt and others (1997). This thickness estimate is within the range reported elsewhere (for example, Brocher and others, 2001; Van Wagoner and others, 2002). MCS section PS-1 (fig. 5) shows that the deformation front of the Seattle Fault (Johnson and others, 1999) lies along the axis of the syncline in lower-plate rocks. Dips imaged in the fold are less than 30º, but steep dips, like the nearly 70º measured in hanging-wall outcrop near the Seattle Fault, cannot be imaged by the poststack migration. The plane of the Seattle Fault may dip south from the deformation front, along the upturned ends of strata within this fold. If so, then the upper part of this fault would dip about 40º south.

The deformation front of the Seattle Fault is offset by 700 to 800 m to the south between seismic lines PS-1 and PS-2, because of offset along a tear fault that crosscuts the Seattle Fault (Johnson and others, 1999) (fig. 4). Reflections from within the Seattle Basin lose continuity toward the Seattle Fault (fig. 6*A*), and a drag fold in the fault's lower plate is not as readily apparent on section PS-2 as on section PS-1 (fig. 5). Perhaps the loss of reflection continuity indicates more sharply upturned bedding. The poststack migrated version of section PS-2 (fig. 6*A*) shows a reflection, possibly from the plane of the Seattle Fault, that extends as deeply as 5-6 km (fig. 6*A*). This reflection is also apparent on the prestack migrated version of seismic section PS-2 (fig. 6*B*).

A difficulty with the interpretation of the dipping reflection (fig. 6*A*) as the plane of the Seattle Fault results from the fact that seismic line PS-2 crosses the Seattle Fault near the tear fault (fig. 4). The dipping event may be from some out-of-plane feature, perhaps related to the tear fault. If the dipping event does reveal the plane of the Seattle Fault, then this fault dips about 40º south within the upper 5 km of the crust. The dip of the fault plane appears to decrease downward.

The Kingston Arch is an antiform that strikes east-west below Puget Sound and forms the northern limit of the Seattle Basin (fig. 4). This arch is asymmetrical, with a more steeply dipping north limb (Johnson and others, 1994; Pratt and others, 1997). Pratt and others (1997) hypothesized that the Kingston Arch is a fault-bend fold that results from movement of rocks over a step in a basal decollement, at a depth of about 12 km. Alternatively, according to these authors, the arch could have developed as a fault-propagation fold above a blind thrust fault that was not imaged in the available seismic-reflection data. SHIPS seismic data from line PS-1 (fig. 7) show essentially the same fold geometry as did earlier studies. The detailed seismic section in the top part of fig. 7 shows a planar reflection that crosscuts seismic events from within the basin fill and extends upward to end at shallow depth. These reflections are difficult to interpret, and might best be interpreted as from out of the plane of section.

The Eastern Strait of Juan de Fuca

The southern Whidbey Island Fault, the Devils Mountain Fault, and the Utsaledy Point Fault (SWIF, DMF and UPF, respectively, on figure 8) are potential seismogenic structures below the eastern Strait of Juan de Fuca. The southern Whidbey Island Fault separates various crystalline rocks of the continental basement, on the east and north, from thick Eocene volcanic rocks of the Siletzia terrane, on the south (Johnson and others, 1996b, 2001b; Mosher and others, 2000). Deformed and offset strata evident in onshore outcrops, marsh deposits and offshore seismic-reflection data collected in northern Puget Sound reveal that the southern Whidbey Island Fault is active (Kelsey and others, 2004). The Devils Mountain Fault strikes nearly east-west from the Cascade Range to Vancouver Island (fig. 8), and east of this report's study area the fault forms the northern boundary of the onshore Everett Basin. This left-lateral, oblique-slip fault is active, as indicated by high-resolution seismic reflection sections, which show that Quaternary strata are faulted and (or) folded (Johnson and others, 2001a). The Utsalady Point Fault lies between the Devil's Mountain and southern Whidbey Island Faults and forms the south boundary of an uplifted block of pre-Tertiary basement. Johnson and others (2001a, 2003, 2004) document recent activity along this fault, based on seismic-reflection data, faulted coastal rock sections, offset subsurface stratigraphy shown by well logs, and trenching investigations.

Below the eastern Strait of Juan de Fuca, offshore rocks can be grouped into three units, based on their appearance on seismic sections (Johnson and others, 2001b). The lower, nonreflective unit is probably pre-Cenozoic basement rock, the middle unit includes Tertiary sedimentary rocks, and the overlying unit consists of variably reflective glacial and interglacial deposits. These strata are believed to be of uppermost Pliocene(?) and Quaternary age. The contact between basement and overlying sedimentary units is locally is a strong reflection.

The SHIPS survey collected seismic-reflection data along widely spaced tracklines (fig. 8; pl. 2) to determine the crustal structure of the Southern Whidbey Island and Devils Mountain Faults. Unfortunately, these faults' crustal structure is not clearly resolved, because penetration of seismic energy into shallow basement rocks was poor or the reflectivity of basement rocks is low. Seismic-reflection data (pl. 2) have been migrated after stack, converted to depth, and shown without vertical exaggeration. The main feature evident in all

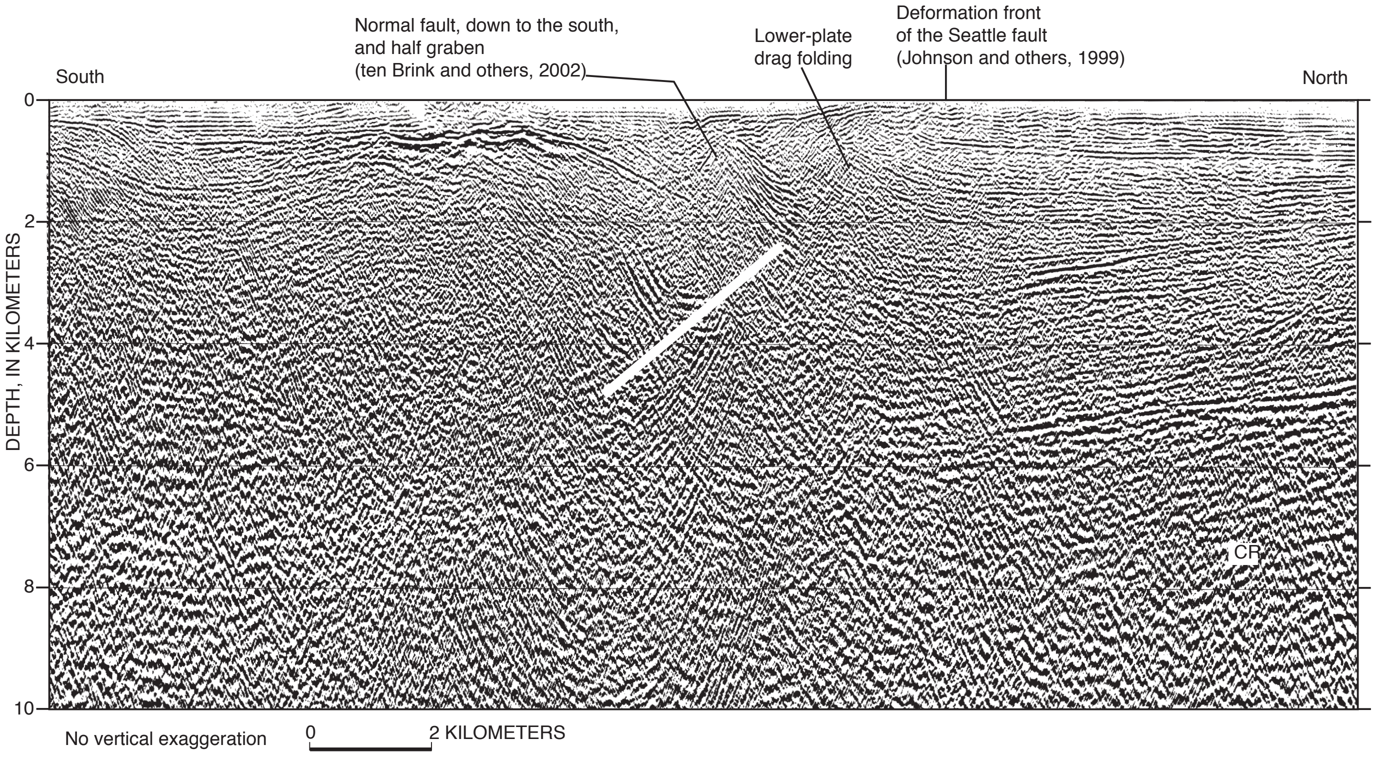

Figure 5. Part of SHIPS seismic-reflection section PS-1 obtained over the Seattle Fault. Data have been migrated after stack and then depth coverted. The white bar shown in these data depicts the 40° dip for the Seattle Fault interpreted from wide-angle velocities and MCS data by ten Brink and others (2002). The deformation front of the Seattle Fault is from Johnson and others (1999). CR, top of the Siletzia terrane (Pratt and others, 1997).

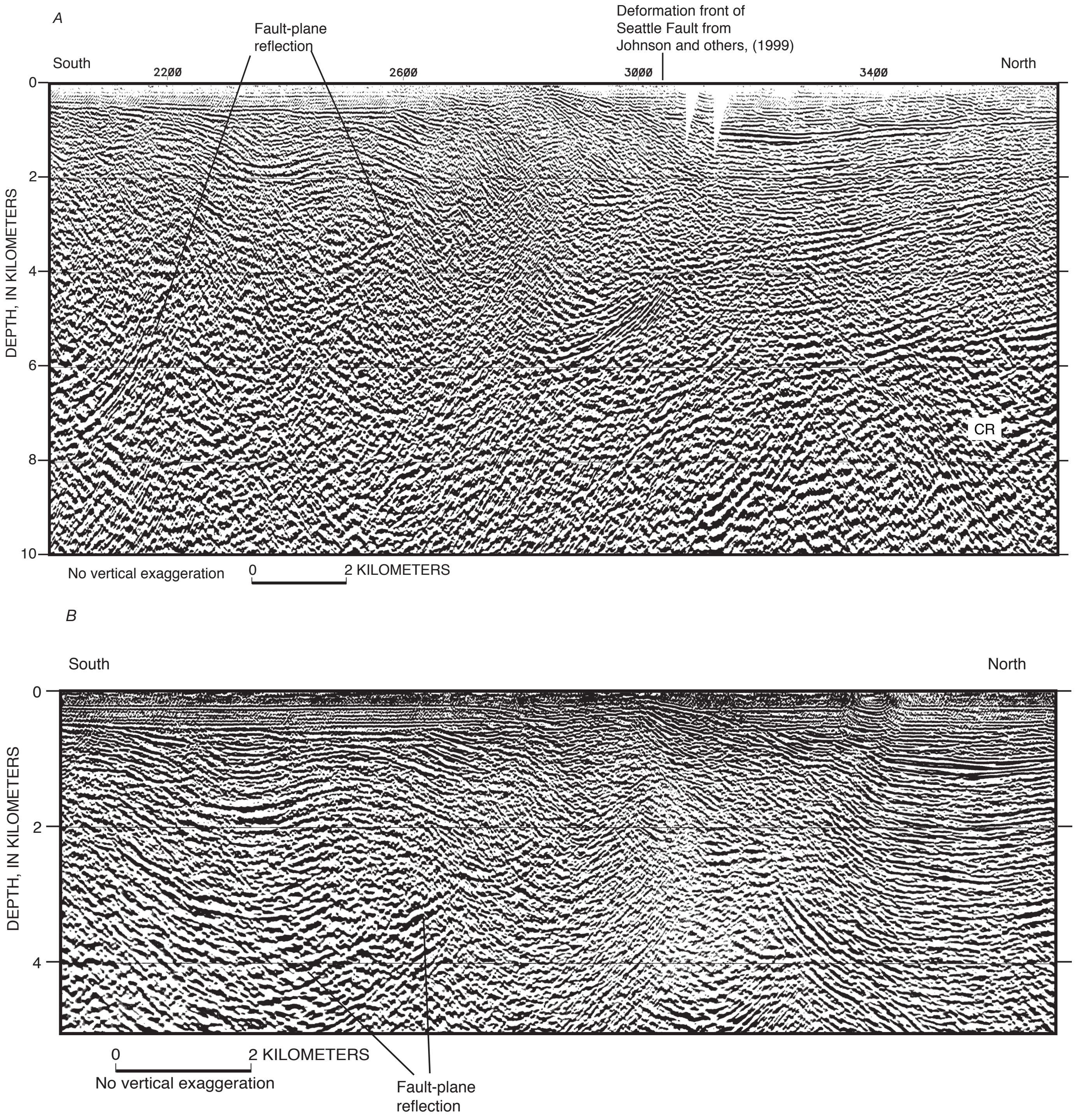

Figure 6. Part of SHIPS seismic-reflection section PS-2 obtained over the Seattle Fault, showing what is probably a reflection from the plane of this fault, which dips 40° south. *A*, Seismic data migrated after stack and then depth converted. CR indicates top of the Siletzia terrane (Pratt and others (1997). *B*, Seismic data migrated and depth converted in one process before stack.

seismic-reflection sections from the SHIPS survey is a generally strong, undulating reflection from the unconformity that separates reflective Tertiary and Quaternary strata (horizon A on pl. 2) above from either Mesozoic crystalline or Eocene volcanic rocks below. Basement is about 1 km deep in the eastern and western parts of the survey area, and basement deepens locally to about 2 km below the southern half of seismic line JDF-4.

SHIPS seismic-reflection data provide additional documentation of the location and geometry of faults in the eastern Strait of Juan de Fuca, including the Devils Mountain Fault, the Utsalady Point Fault, and the southern Whidbey Island Fault. These faults can be locally difficult to identify because of a variety of factors including (1) lack of reflections in basement rocks, (2) local absence of Tertiary strata due to deep glacial erosion in the Pleistocene, and (3) presence of a thick Quaternary section characterized by hummocky, discontinuous reflections. On line JDF-4 (pl. 2), Johnson and others (2001a; their fig. 23) previously interpreted the Devils Mountain Fault as a predominantly blind, north-dipping thrust or reverse fault that in many places underlies an asymmetric anticline. Line JDF-5 (pl. 2), in a similar location to Canadian Geological Survey line 37 (fig. 25 of Johnson and others, 2001a), similarly shows the Devils Mountain Fault in the core of a structural upwarp. This fault may be imaged on line SG-1 by reflection of truncations at depths of about 500 to 1,000 m; geologic relationships deeper in the profile at this location are obscured by concave-upward bands of migration noise. The trace of the Devils Mountain Fault is not obvious on line JDF-6, but its mapped location (Johnson and others, 2001a,b) coincides with the northern extent of the high-amplitude reflection couplet inferred to be the top of basement and with the southern extent of a panel of gently south-dipping Tertiary(?) strata.

Line SG-1 (pl. 2) also displays a significant north-dipping reverse fault south of the Devils Mountain Fault (~ shotpoint 2725), which we interpret as the western extent of the Utsalady Point Fault of Johnson and others (2001a). If this is the case, it extends the known trace of the fault approximately 10 km farther west. This fault is the most impressive structure imaged on the four SHIPS profiles in the eastern Strait of Juan de Fuca, consistent with recent inferences about the importance of this structure for regional tectonics and earthquake hazards. Recent paleoseismic investigations of fault scarps along this structure on northwestern Whidbey Island document at least one and probably two significant (M > 6.5) ground-rupturing earthquakes on this structure in the last ~ 2,200 years (Johnson and others, 2003, 2004).

Line SG-1 is the only SHIPS profile that displays any structural disruption along the extended trace of the southern Whidbey Island Fault. This lack of expression is consistent with the findings of Johnson and others (2001a,b), who similarly were unable to map this structure west of about 123° and speculated that offset was transferred to other faults in the region. The fault is clearly imaged on seismic-reflection profiles farther southeast, and Kelsey and others (2004) recently documented a late Holocene earthquake on this structure.

Southern Georgia Strait

A single SHIPS seismic reflection trackline weaves around the east side of the San Juan Islands and into southern Georgia Strait (fig. 9). The reasons for collecting data in this area included (1) investigating the crustal structure of the east-west thrust faults that deform rocks making up the San Juan Island and (2) examining the intersection of these thrust faults with the more recent Lummi Island normal fault and the Outer Islands Fault, which forms the western boundary of the Georgia Basin.

Crustal earthquake activity is generally lower below the Strait of Georgia compared to that below Puget Sound (Rogers 1988; Cassidy and others, 2000). However, two recent earthquakes below Georgia Strait occurred in 1975 (M5) and 1997 (M4.6). Aftershocks of the 1975 earthquake define a fault plane that strikes nearly east at shallow depth (2-4 km) and dips 53° NNW (Cassidy and others, 2000).

Seismic-reflection data collected through the San Juan and other islands do not show any reflections from the deep crust nor from the shallow-crustal, east-west thrust faults that crop out onshore. The primary limitation in the quality of these data is intense side echoes from islands and probable glacial features having sharp sea-floor relief, so these data are generally of low quality. No fault-plane reflections are evident, and rock velocities, derived from tomographic analysis of first arrivals along the multichannel streamer, show no sharp contrast in velocities across a fault.

Below southern Georgia Strait, the Outer Islands normal fault strikes northwest and bounds the Georgia Basin on the southwest (England and Bustin, 1998). Movement along this fault is middle Oligocene and younger in age. SHIPS seismic-reflection data show an abrupt end to the strong, shallow reflection from the top of Wrangellian basement (fig. 10). Farther north, strong reflections from rocks about 5 km deep may be from the downdropped top of this basement. The Outer Islands Fault separates the shallow and deep basin.

Earthquake Sources Along the Subduction-Zone Interface

Subduction of oceanic crust along the part of the continental margin in Cascadia that faces the Juan de Fuca Plate was once thought to occur aseismically, but this evaluation changed to accord with reassessments of the regional earthquake potential (see, for example, Heaton and Hartzell, 1987; Rogers, 1988; Clague, 1997). Geodetic measurements show that the continent and the downgoing oceanic plate are locked across the subduction-zone interface and that strain has been accumulating (Dragert and Hyndman, 1995; Henton and others, 1999; Miller and others, 2001). Paleoseismic and historical evidence has amassed to show that during the late

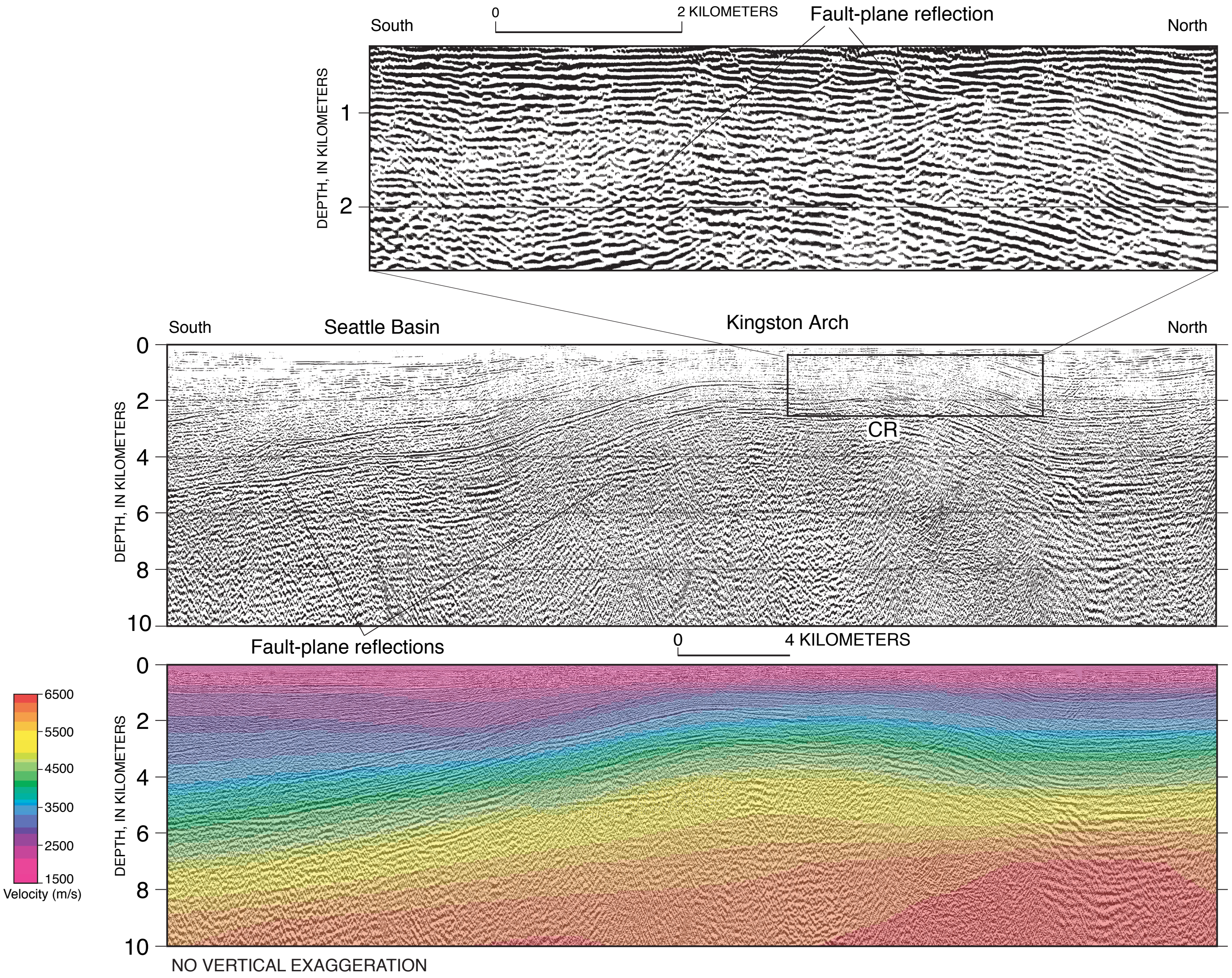

Figure 7. Part of SHIPS multichannel seismic (MCS) section PS-1 obtained over the Kingston Arch, which forms the northern boundary of the Seattle Basin. Middle section is depth-converted MCS data migrated after stack, showing several discontinuous reflections from what may be the plane of a single, low-angle thrust fault that pierces the Kingston Arch. CR, top of the Siletzia terrane (Pratt and others, 1997). Detail (top) shows a shallow reflection from the plane of a south-dipping thrust fault. Bottom section shows rock velocity (T. Parsons, written commun., 1999) in color.

Holocene, major earthquakes occurred repeatedly along the subduction-zone interface (for example, Heaton and Hartzell, 1987; Clague and Bobrowsky, 1994; Atwater and others, 1995; Nelson and others, 1996; Satake and others, 1996; Atwater and Hemphill-Haley, 1997; Obermeier and Dickenson, 2000). Hence the interplate contact zone is now believed to pose a serious earthquake threat to population centers in the Pacific Northwest. The most recent subduction-zone interplate earthquake occurred early during A.D. 1700 (Satake and others, 1996), and magnitude estimates for this event range up to M 9.

The hazard that interplate earthquakes pose provides incentive to understand the mechanics of the accretionary wedge and shallow subduction zone and how they relate to the extent of thrust rupture and tsunami generation. Three salient features of the continental margin that are evident in MCS data are an extensive midslope terrace, a major change along the trench in the structure of accreted rocks, and an arch in the downgoing oceanic plate.

The wide midslope terrace stands out clearly in regional bathymetric data (fig. 1). In the south, the terrace ends west of the mouth of the Columbia River; in the north, the end of the terrace lies west of the Strait of Juan de Fuca. The continental margin west of southern Oregon and that west of Vancouver Island both descend more steeply than does the terrace. The diverse margin morphology just described is accompanied by major variations in the structural style of accreted rocks, as shown by seismic-reflection data (pl. 3) that were migrated after stack and then converted to depth, following the procedure outline above in the section on velocity models. West of southern Oregon, where the terrace is absent, thrust faults in the toe of the accretionary wedge verge predominantly seaward (Snavely, 1987; MacKay, 1995). West of Washington State, where the midslope terrace attains its greatest width, thrust faults in the wedge toe and under much of the terrace verge consistently landward (Seeley, 1977; Niem and others, 1992; Fisher and others, 1999b; Gutscher and others, 2001), as

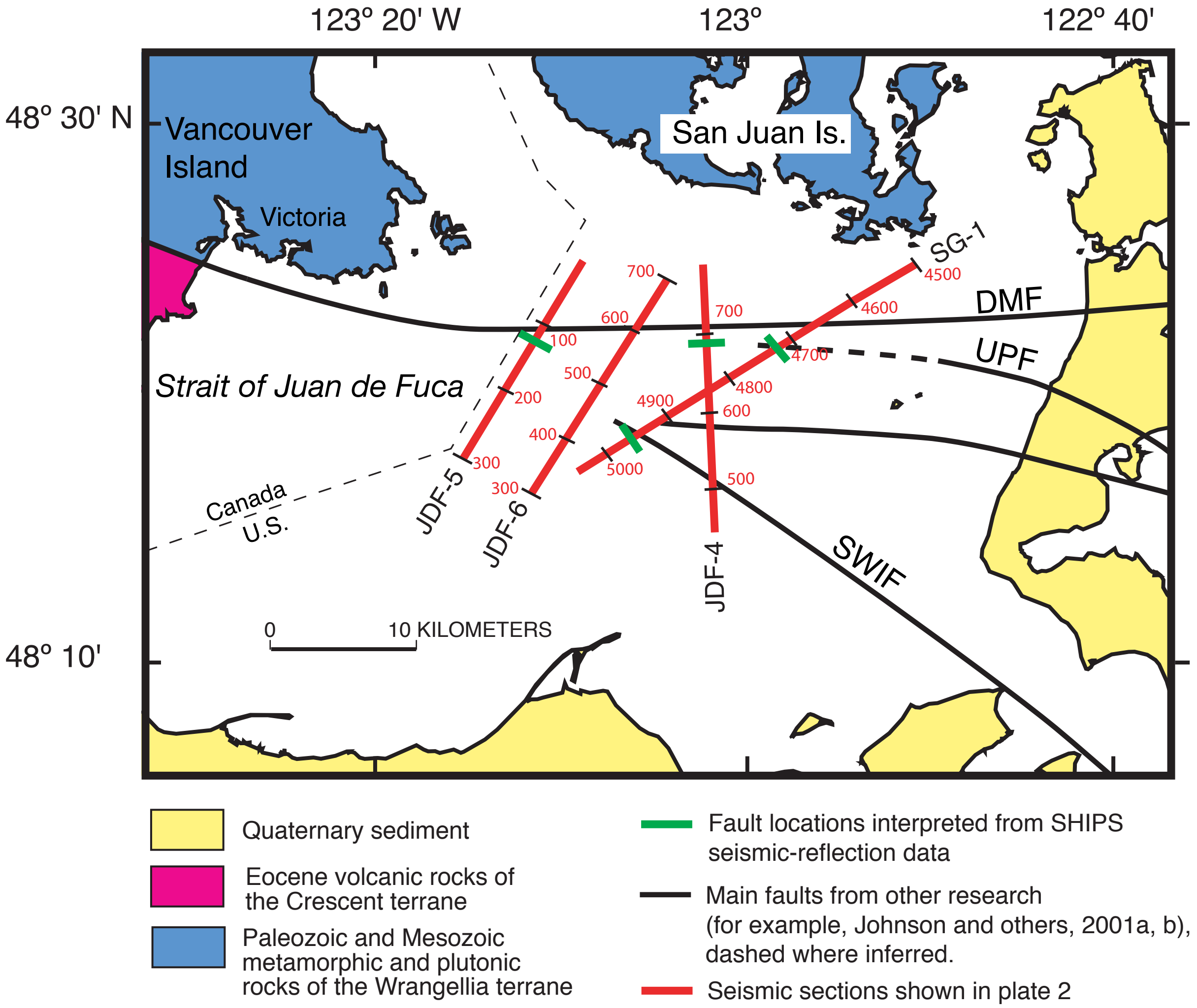

Figure 8. Tracklines of SHIPS multichannel seismic data and locations of seismic sections in the eastern Strait of Juan de Fuca shown in plate 2. Shotpoint numbers are in red along the section lines. Abbreviations: DMF, Devils Mountain Fault; SWIF, Southern Whidbey Island Fault; UPF, Utsalady Point Fault.

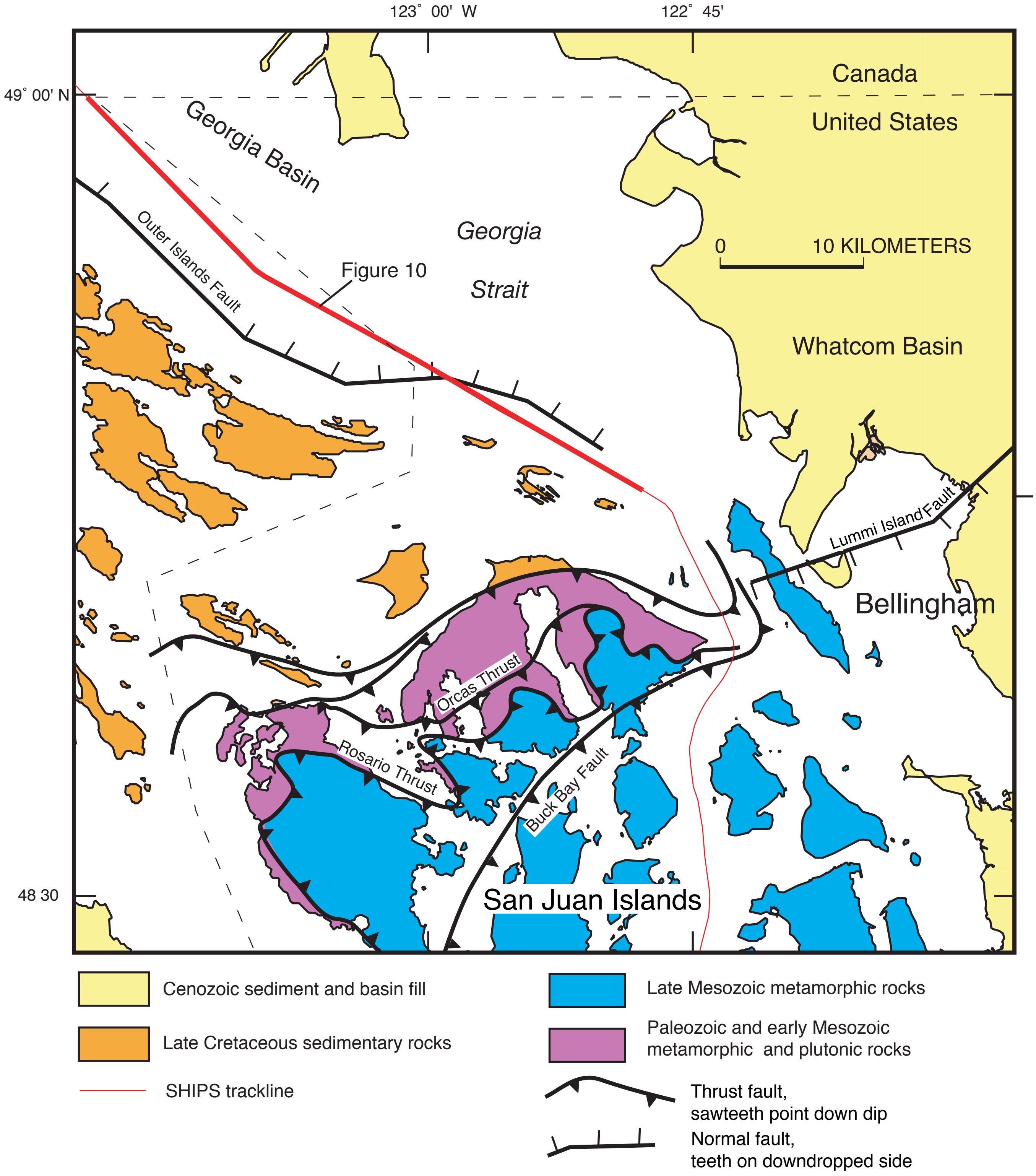

Figure 9. Trackline of SHIPS multichannel seismic (MCS) data in southern Georgia Strait, and location of MCS data shown in figure 10. Geology from Brandon and others (1988) and England and Bustin (1998).

shown by seismic sections 105, 103, and 101 (pl. 3). West of Vancouver Island, the terrace pinches out entirely, and thrust faults verge seaward (Davis and Hyndman, 1989; Calvert, 1996), as shown by GSC seismic section 85-1 (pl. 3).

The depth-converted seismic reflection section 105 (pl. 3) shows five closely spaced thrust faults and numerous subsidiary ones that deform rocks within the outer 30 km of the wedge toe. All faults verge landward. The main faults extend downward to nearly intersect with the top of the oceanic crust, which means that almost all incoming sediment is being accreted at present. The main faults are strongly reflective, especially those in the outermost part of the wedge toe. The reflectivity might result from migrating fluids, as suggested for similar faults off central Oregon (MacKay, 1995; Cochrane and others, 1996). In contrast to the accretionary zone's shallow folding and irregular sea floor near the toe of the wedge, shallow strata under the terrace farther landward are little deformed and the sea floor over the terrace has low relief. Shallow extensional stress oriented east-west under the shelf edge and uppermost slope resulted in the development of listric normal faults that penetrate downward 2 to 3 km and are downthrown on the west. The reflection from the top of the oceanic crust can be traced about 30 km landward from the deformation front.

Seismic reflection section 103 crosses the continental margin where the midslope terrace is widest (pl. 3). One version of this seismic section on plate 3 has no vertical exaggeration in order to show the true attitude of structural features and the very gradual taper of the entire accretionary wedge. The outer 35 km of the accretionary wedge is rumpled along numerous landward-vergent thrust faults that are strongly reflective. These faults flatten downward. The sea floor over the terrace has very low seaward dip, and most folds below the terrace disrupt neither the sea floor nor shallow strata. Evidently, below the terrace a period of intense fold growth was succeeded by deposition of strata that have remained little deformed, pointing to a locally decreased rate of deformation. Listric normal faults under the shelf break extend downward to deform rocks about 2-3 km deep.

A significant result from surveying along seismic line 103 is that the reflection from the top of the oceanic crust was recorded nearly 100 km landward from the deformation front and to a depth of more than 10 km. This image of the downgoing crust is the best one obtained during the 1996 seismic survey by the RV *Sonne*.

Seismic reflection section 101 crosses the oceanic plate near the apex of the Nitinat deep-sea fan. Fan sediment was derived from the Strait of Juan de Fuca and the Fraser River. The reflection from the top of the oceanic crust was recorded 50 km landward from the deformation front. The outer part of the accretionary wedge is deformed by numerous landward-vergent thrust faults that are strongly reflective. Many of them intersect, or nearly so, the top of the oceanic crust.

GSC seismic-reflection section 85-1 crosses the accretionary wedge west of Vancouver Island, where the midslope terrace is absent (pl. 3). This section shows that thrust faults in the wedge toe verge seaward. Rocks in the accretionary wedge, except for those that make up the wedge toe, are in general weakly reflective. A body of poorly reflective rocks (annotated on pl. 3) extends downslope to within about 15 km of the deformation front and probably represents a part of the wedge that is older than the adjacent and underlying reflec-

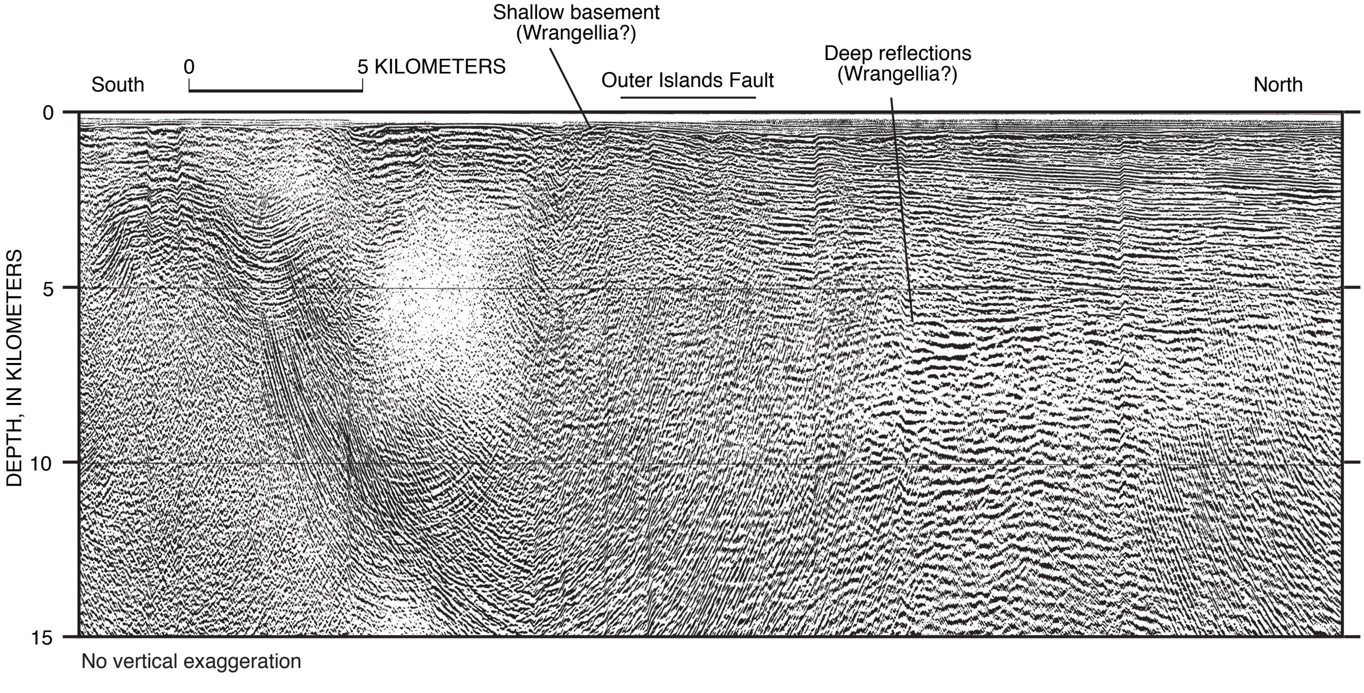

Figure 10. Part of the depth-converted, poststack migrated section of multichannel seismic line SG-1 collected over the Outer Islands Fault and Georgia Basin below the southern Georgia Strait.

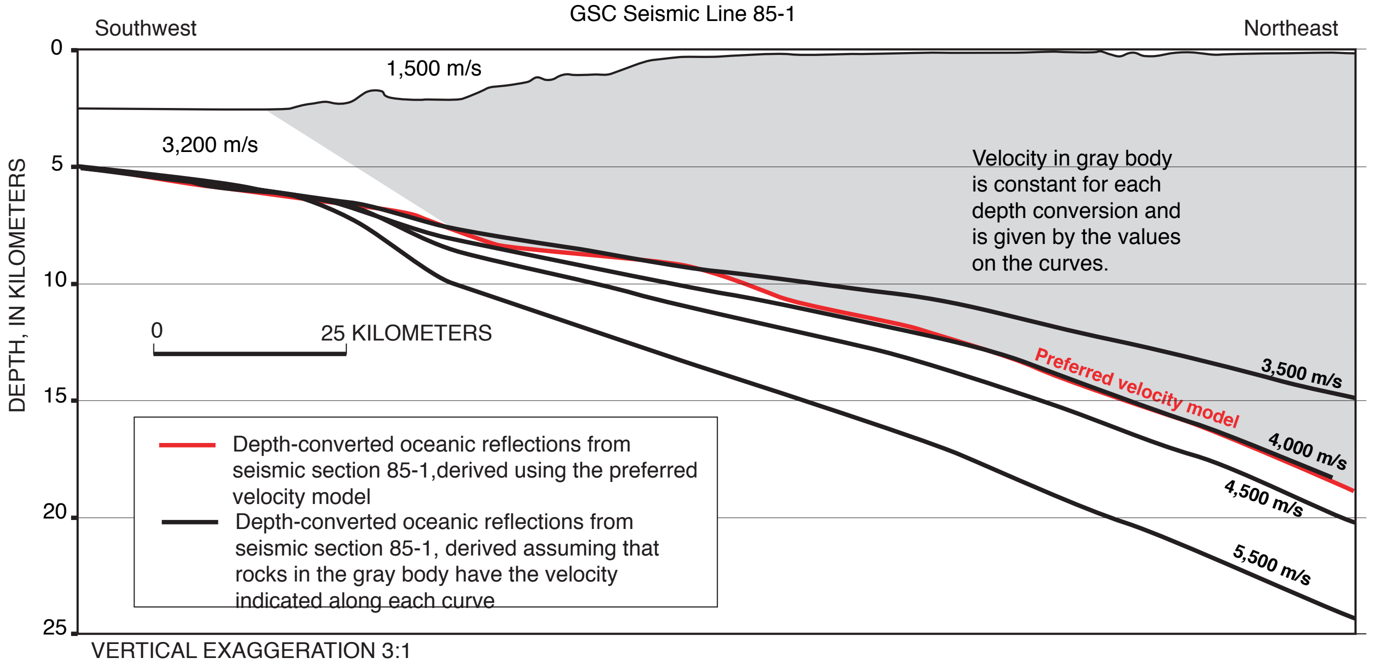

Figure 11. Cross section along Geological Survey of Canada multichannel seismic line 85-1, showing depths to the top of the downgoing oceanic plate interpreted using different rock-velocity models. Sound velocities in the water layer and in the oceanic sediments are constant at 1,500 m/s and 3,200 m/s, respectively. Rock velocity within the gray body is constant and has the assumed value annotated on each curve. A constant velocity of 4,000 m/s for the gray body yields a depth to the downgoing plate that nearly equals that derived from the preferred velocity model. See figure 1 for location of section.

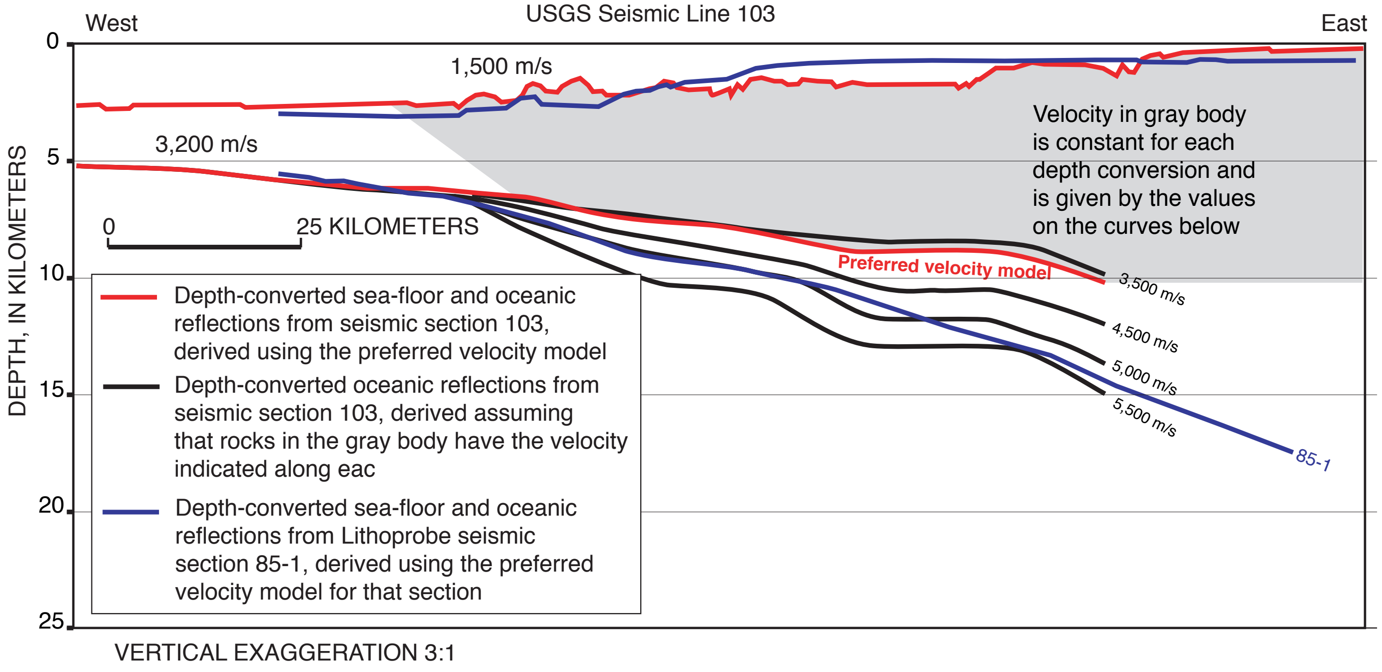

Figure 12. Cross section along U.S. Geological Survey multichannel seismic line 103, showing depths to the top of the downgoing oceanic plate interpreted using different rock- velocity models. Sound velocities in the water layer and in the oceanic sediments are constant at 1,500 m/s and 3,200 m/s, respectively. Rock velocity within the gray body is constant and has the assumed value annotated on each curve. A constant velocity of about 3,600 m/s for the gray body yields a depth to the downgoing plate that nearly equals that derived from the preferred velocity model. Also shown are the sea floor and downgoing plate derived from MCS section 85-1 using the preferred velocity model for that area. See figure 1 for location of section.

tive strata (Davis and Hyndman, 1989). The top of this body curves downward, forming a “nose” where the body’s top and bottom meet near the trench. Thick, reflective oceanic strata have been thrust beneath this body. In general, the planes of accretionary thrust faults do not return strong reflections, and the faults are planar. The downgoing oceanic crust produces reflections that can be followed nearly to the eastern end of the seismic section, which represents a distance of about 100 km (Davis and Hyndman, 1989).

We highlight the differences in accretionary-wedge structure indicated by seismic sections 85-1 and 103 (pl. 3). Specifically, on section 85-1 the zone of reflective rocks that make up the toe of the wedge is narrow in comparison to the great width of highly reflective strata and fault planes that are evident on section 103. Furthermore, thrust-fault vergence is opposite in the two areas: thrust faults are curved and landward-vergent in the south but planar and seaward-vergent in the north. The difference in the steepness of the margin taper in the two areas is clear from data in plate 3. A feature analogous to the structural “nose” identified on seismic section 85-1 might be present along the eastern limit of the midslope terrace under seismic line 103. This is where reflective, accreted rocks appear to end in the east.

Various estimates indicate that a future worst-case earthquake along the subduction zone interface might have a magnitude around M 9. Such an event would fall within the class of rare, immensely powerful subduction-zone earthquakes, like those that struck Chile in 1960 (M9.5) (Linde and Silver, 1989) and Alaska in 1964 (M9.2) (Plafker, 1969; Page and others, 1991). Rupture zones of these earthquakes extended for about 1,000 km and 800 km, respectively, along the strike of the subduction zones. Rogers (1988) estimated that if the entire segment of interplate thrust that faces the subducting Juan de Fuca were to rupture, then the resulting earthquake magnitude would be about M 9.

Thermal modeling of the subduction zone has been used to estimate the downdip extent of an earthquake rupture zone. This modeling suggests that deep below the continental shelf, rock temperature along the interplate decollement exceeds that of the brittle-ductile transition (Hyndman and Wang, 1995; Oleskovich and others, 1999; Wang and He, 1999). West of the shelf edge, where rocks may still be brittle, interplate coupling might be sufficient to cause great earthquakes to nucleate.

Applying information about thrust-fault vergence and margin morphology to the assessment of earthquake hazards is difficult, because superimposed on the accretionary structure in Cascada is a locally complicated distribution of strike-slip and extensional features. For example, rocks that make up the front part of the margin off Oregon form large, rotating blocks that are bounded by strike-slip faults (McCaffrey and Goldfinger, 1995; Goldfinger and others, 1997). Furthermore, the continental margin there has been eroded by the mobilization of major slump masses (Goldfinger and others, 2000). West of Washington State, listric normal faults under the shelf and upper slope dip mainly seaward and offset rocks as deep as 2-3 km within the margin (pl. 3) (McNeill and others, 1997). These faults strike subparallel to the shelf break and are discontinuous, each one extending for no more than 5-10 km along strike.

The major morphologic and structural transitions described above that occur within the Cascadia accretionary wedge may have originated because of two primary factors: the type of abyssal sediment and the dip of the downgoing plate (Fisher and others, 1999b). Abruptly increased sediment influxes from the Columbia and Fraser Rivers during the late Pleistocene and Holocene caused thick sediment to blanket the continental margin and adjacent abyssal plain. The part of the continental margin west of Washington State stands opposite the Nitinat fan; farther south, the margin off Oregon faces the Astoria fan. Increased sedimentation could have affected the wedge’s critical taper (Davis and others, 1983), and differences in sediment thickness and type are other possible influences on the structural style of the margin.

Gutscher and others (2001) analyzed MCS data from the 1996 survey by the RV *Sonne* and used analog modeling of subduction-zone mechanics to determine that a layer at the base of the accretionary wedge in Cascadia thickens gradually landward and has a high rock velocity, as estimated from wide-angle and stacking velocities. The rock velocity in the basal part of the wedge increases from about 3.5 km/s below the trench to 4.5 km/s at a location 20 km landward from the trench. MCS data reveal no evidence that faults pierce this unit; consequently Gutscher and others (2001) interpret the high velocity and lack of faulting to mean that the layer deforms viscoelastically. They posit further that, because of the specific mechanical properties of this layer, the rupture zone of an interplate earthquake could extend as far seaward as the deformation front, in agreement with results from thermal calculations (Hyndman and Wang, 1995)

The second factor that might have affected the margin morphology and structure is the geometry of the downgoing plate. This plate arches about an east-west axis beneath the Olympic Mountains (Crosson and Owens, 1987; Weaver and Baker, 1988; Brandon and Calderwood, 1990). The plate dips at a lower angle under the mountains, and presumably also beneath the part of the accretionary wedge that lies west of these mountains, than it does elsewhere. Such a change in basement dip would have direct effect on the critical taper of the accretionary wedge (Davis and others, 1983).

Depth-converted seismic sections 85-1 and 103 (pl. 3) provide significantly different estimates of the depth to the downgoing plate. These depths accord with the general shape of the plate’s arch known from earthquake hypocenters. Seismic section 103 shows that 80 km east of the deformation front the top of the downgoing plate is about 10 km deep, whereas section 85-1 shows that at this same distance from the deformation front, the plate top is about 5 km deeper.

The difference in plate dip beneath the outer shelf could be real, or this difference could signify that either (1) the two seismic sections reveal different reflective features or (2) the velocity structures beneath the two seismic lines are greatly different. The first possibility, involving different reflective features, is unlikely because no other rock body but the top of the downgoing plate is likely to produce such strong, nearly continuous reflections. In the second case, the plate depths on seismic lines 85-1 and 103 could be the same or similar but the velocity structures below these lines could be substantially different.

To test the latter possibility, we computed plate locations below seismic line 85-1 by assuming various rock-velocity models (fig. 11). First, the plate location is shown for the "preferred" velocity model, the one used to make the east-west regional cross section (pl. 1). This plate location is compared to four others derived using different velocity models. For each of these models, the continental crust above the top of oceanic crust (the gray body in fig. 11) is assumed to have a constant rock velocity, and the depth to the top of the oceanic plate was calculated. The constant rock velocity that was assigned to the continental crust (gray body) is given along each curve (fig. 11). In all calculations, the rock velocity of the oceanic section was held constant at 3,200 m/s, and sound velocity in water was assumed to be 1,480 m/s. For the section 85-1 the constant velocity of 4,000 m/s for the continental crust produces an estimated depth to the top of the plate that is close to that derived using the preferred velocity model.

A similar analysis for seismic section 103 (fig. 12) shows that a constant rock velocity of about 3,600 m/s yields the same depth to the top of the downgoing plate as does the

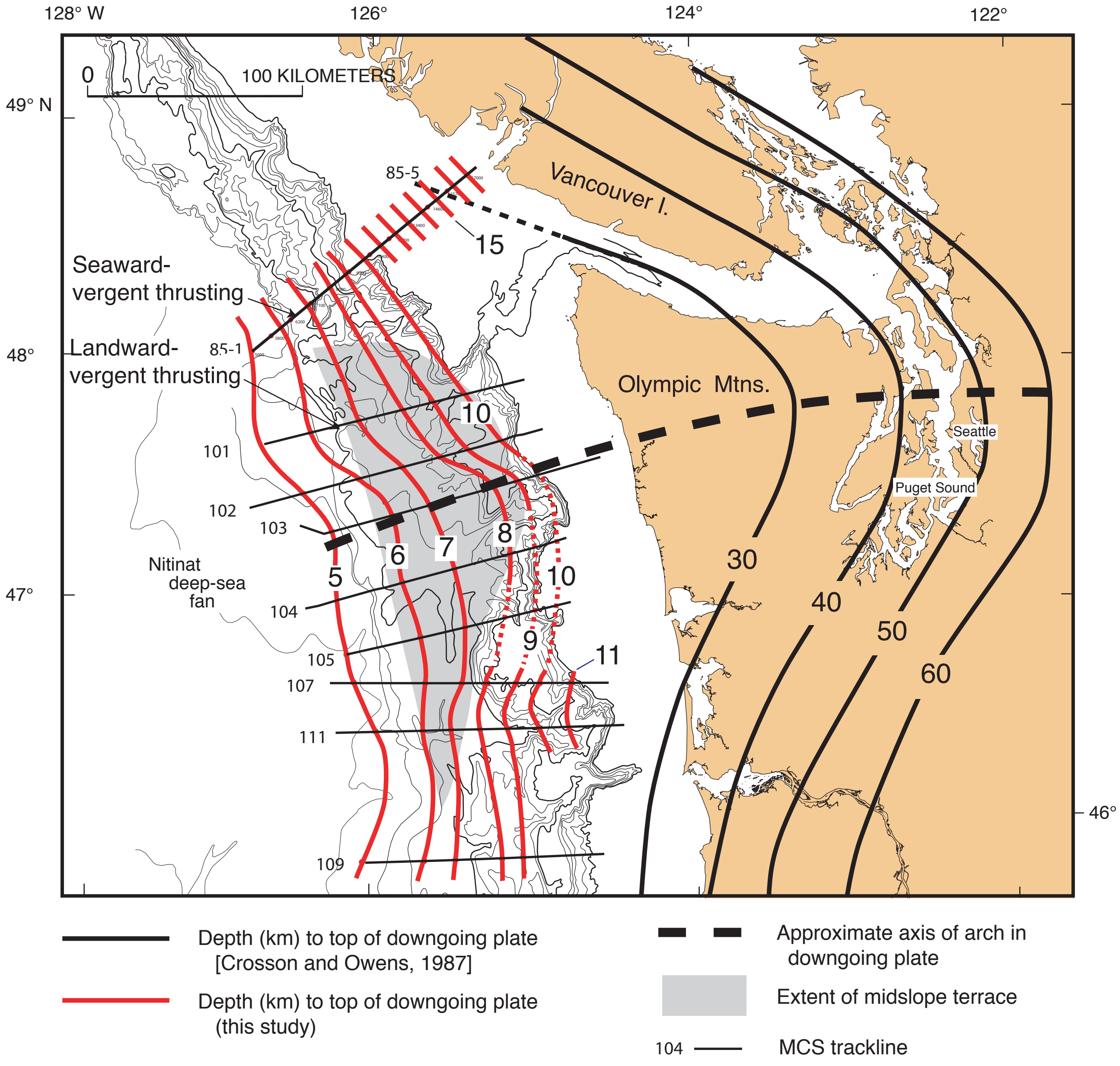

Figure 13. Map of study area showing coincidence in location among the midslope terrace, the axis in the arch of the downgoing plate, and the change in vergence of thrust faults in the accretionary wedge. Bathymetry as in figure 1.

"preferred" velocity model. fig. 12 shows that to match the plate depth derived from seismic section 85-1 using the preferred velocity model, the reflection from the plate on seismic line 103 would have to be converted to depth with a constant velocity of between 5,000 and 5,500 m/s. We believe that sufficient information exists from stacking velocities to preclude the possibility that the average rock velocity below seismic line 103 is nearly 2 km/s higher than it is below line 85-1.

We conclude that the velocity structures below seismic lines 85-1 and 103 are similar and that the greatly different traveltimes to the oceanic crust measured below these two lines are caused by real differences in plate depth. The top of the downgoing plate is nearly 5 km deeper below seismic line 85-1 than it is in an equivalent position below line 103. This result agrees with the conclusion derived from the analysis of earthquakes, which indicates that the plate below the Olympic Mountains is arched about an east-west axis (Crosson and Owens, 1987; Flueh and others, 1997) (fig. 13).

The east-west plate arch, the broad midslope terrace over the accretionary wedge, and the apex of the Nitinat deep-sea fan all coincide in location along the trench (fig. 13). The low plate dip near the axis in the plate's arch decreases the critical taper of the accretionary wedge. The type of sediment making up the fan strongly influences the mechanical properties of rocks pierced by the interplate thrust (Gutscher and others, 2001). In our opinion, based on these accretionary-wedge attributes, the stretch of this wedge between seismic lines 85-1 and 103 could be a boundary between earthquake rupture zones.

Conclusion

Depth-converted MCS data were used to construct two regional cross sections of the continental margin in the Pacific Northwest. One east-west cross section stretches eastward from the trench through the Strait of Juan de Fuca and shows that a highly reflective crust extends eastward to where data recording ceased in the far eastern part of the Strait of Juan de Fuca. The companion, north-south cross section shows that the deep crustal reflections are not from out of plane but instead are from depths between 35-45 km. Unfortunately, the deep reflections are not imaged to the south, beneath northern Puget Sound and do not illuminate the crustal structure under the city of Tacoma, where several large earthquakes have struck from within the subducted plate.

Using MCS data, we investigated two types of earthquake sources: (1) earthquakes that originate in the brittle part of the Earth's crust to a depth of about 15-25 km below the interior lowlands and (2) earthquakes that originate along the subduction-zone interface and could attain a magnitude of about M 9. Regarding crustal earthquakes, we used migrated and depth-converted MCS data to show a reflection that appears to be from the Seattle Fault Zone. If so, then this part of that fault probably dips 40º south. This dip estimate is close to the 45º dip derived from analysis of thrust faults (Pratt and others, 1997) and is substantially lower than the 70º-80º dip that was interpreted from tomographic velocities and hypocenters (Brocher and others, 2001).

Faults that deform rocks under the eastern Strait of Juan de Fuca and areas farther north are extensional and contrast with the compressive structures evident under Puget Sound. The Lummi Island normal fault is a significant structure in onshore areas, but it does not extend far enough west to have been crossed by the SHIPS seismic-reflection line. On the other hand, the Outer Islands Fault has a throw of about 5 km.

Within the accretionary wedge, a boundary between rupture zones of major interface quakes might extend westward across the accretionary wedge from near the mouth of the Strait of Juan de Fuca.

References

Atwater, B.F., 1996, Coastal evidence for great earthquakes in western Washington, *in* Rogers A.M., Walsh, T.J., Kockelman, W.J., and Priest, G.R., eds, Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest: U.S. Geological Survey Professional Paper 1560, p. 77-90.

Atwater, B.F., and Hemphill-Haley, E., 1997, Recurrence intervals for great earthquakes of the past 3,500 years at northwestern Willapa Bay, Washington: U. S. Geological Survey Professional Paper 1576, 108 p.

Atwater, B.F., and Moore, A.L., 1992, A tsunami about 1000 years ago in Puget Sound, Washington: Science, v. 258, p. 1614-1617.

Atwater, B.F., Nelson, A.R., Clague, J.J., Carver, G.A., Yamaguchi, D.K., Bobrowsky, P.T., Bourgeois, J., Darienzo, M.E., Grant, W.C., Hemphill-Haley, E., Kelsey, H.M., Jacoby, G.C., Nishenko, S.P., Palmer, S.P.; Peterson, C.D., and Reinhart, M.A.,1995, Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone: Earthquake Spectra, v. 11, p. 1-18.

Babcock, R.S., Burmester, R.F., Engebretson, D.C., Warnock, A., and Clark, K. P., 1992, A rifted margin origin for the Crescent basalts and related rocks in the northern Coast Range volcanic province, Washington and British Columbia: Journal of Geophysical Research, v. 97, p. 6799-6821.

Blakely, R.J., Wells, R.E., Weaver, C.S. and Johnson, S.Y., 2002, Location, structure, and seismicity of the Seattle Fault zone, Washington; evidence from aeromagnetic anomalies, geologic mapping, and seismic-reflection data: Geological Society of America Bulletin, v. 114, p. 169-177.

Brandon, M.T., and Calderwood, A.R., 1990, High-pressure metamorphism and uplift of the Olympic subduction complex: Geology, v. 18, p. 1252-1255.

Brandon, M.T., and Vance, J.A., 1992, Tectonic evolution of the Cenozoic Olympic subduction complex, Washington state, as deduced from fission track ages for detrital zircons: American Journal of Science., v. 29, p. 565-636.

Brandon, M.T., Cowan, D.S., and Vance, J.A., 1988, The Late Cretaceous San Juan thrust system, San Juan Islands, Washington: Geological Society of America Special Paper 221, 81 p.

Brocher, T.M., and Ruebel, A.L., 1998, Compilation of 29 sonic and density logs from 23 oil test wells in western Washington State: U.S. Geological Survey Open File Report 98-249, 60 p.

Brocher, T.M., Pratt, T.L., Creager, K.C., Crosson, R.S., Steele, W.P., Weaver, C.S., Frankel, A.D., Trehu, A.M., Snelson, C.M., Miller, K.C., Harder, S.H.and ten Brink, U.S., 2000, Urban seismic experiments investigate Seattle fault and basin: Eos, Transactions, American Geophysical Union, v. 81, n. 46, p. 545, 551-552.

Brocher, T.M., Parsons, T., Blakely, R.J., Christensen, N.I., Fisher, M.A., Wells, R.E., and the SHIPS Working Group, 2001, Upper crustal structure in Puget Lowland, Washington; results from the 1998 seismic hazards investigation in Puget Sound: Journal of Geophysical Research, v. 106, p. 13,541-13,564.

Bucknam, R.C., Hemphill-Haley, E., and Leopold, E.B., 1992, Abrupt uplift within the past 1700 years at southern Puget Sound, Washington: Science, v. 258, p. 1611-1614.

Bucknam, R.C., Sherrod, B.L., and Elendahl, G., 1999, A fault scarp of probable Holocene age in the Seattle Fault zone, Bainbridge Island, Washington [abs.]: Seismological Research Letters, v. 70, p. 223.

Calvert, A. J., 1996, Seismic reflection constraints on imbrication and underplating of the northern Cascadia convergent margin: Canadian Journal of Earth Sciences, v. 33, p. 1294-1307.

Calvert, A.J., and Clowes, R.M., 1990, Deep, high amplitude reflections from a shear zone above the subducting Juan de Fuca Plate: Geology, v. 18, p. 1091-1094.

Calvert, A.J., and Clowes,, R.M., 1991, Seismic evidence for the migration of fluids within the accretionary complex of western Canada: Canadian Journal of Earth Sciences, v. 28, p. 542-556.

Calvert, A. J., Fisher, M. A., and the SHIPS Working Group, 2001, Imaging the Seattle Fault with high-resolution seismic tomography: Geophysical Research Letters, v. 28, p. 2337-2341.

Cassidy, J. F., and Ellis, R. M., 1993, S wave velocity structure of the northern Cascadia subduction zone: Journal of Geophysical Research, v. 98, p. 4407-4421.

Cassidy, J.F., Rogers, G.C., and Waldhauser, F., 2000, Characterization of active faulting beneath the Strait of Georgia, British Columbia: Bulletin of the Seismological Society of America, v. 90, p. 1188-1199.

Clague, J.J., 1997, Evidence for large earthquakes at the Cascadia subduction zone: Reviews of Geophysics, v. 35, p. 439-460.

Clague, J.J., and Bobrowsky, P.T., 1994, Evidence for a large earthquake and tsunami 100-400 years ago on western Vancouver Island, British Columbia: Quaternary Research, v. 41, p. 176-184.

Clowes, R. M., Brandon, M. T., Green, A. G., Yorath, C. J., Sutherland Brown, A., Kanasewich, E. R., and Spencer, C., 1987a, LITHOPROBE-Southern Vancouver Island; Cenozoic subduction complex imaged by deep seismic-reflections: Canadian Journal of Earth Sciences, v. 24, p. 31-51.

Clowes, R. M., Yorath, C. J., and Hyndman, R. D., 1987b, Reflection mapping across the convergent margin of western Canada: Geophysical Journal of the Royal Astronomical Society, v.89, p.79-84.

Clowes, R.M, Baird, D.J., and Dehler, S.A., 1997, Crustal structure of the Cascadia subduction zone, southwestern British Columbia, from potential field and seismic studies: Canadian Journal of Earth Sciences, v. 34, p. 317-335.

Cochrane, G. R., Moore, J. C., and Lee, H. J., 1996, Sediment pore-fluid overpressuring and its affect on deformation at the toe of the Cascadia accretionary prism from seismic velocities, *in* Bebout, G.E., Scholl, D.W., Kirby, S. H., and Platt, J.P., eds. Subduction Top to Bottom: American Geophysical Union Geophysical Monograph 96, p. 57-64.

Crosson, R. S., and Owens, T. J., 1987, Slab geometry of the Cascadia subduction zone beneath Washington from earthquake hypocenters and teleseismic converted waves: Geophysical Research Letters, v. 14, p. 824-827.

Crosson, R.S., Symons, N.P., Van Wagoner, T.M., Medema, G.F., Creager, Kenneth C., Preston, L.A., Brocher, Thomas M., Parsons, Tom, Fisher, Michael A., Trehu, Anne M., and-Miller, Kate C. 2000, 3-D velocity structure of the Cascadia forearc region from tomographic inversion; results from full integration of data from multiple active source experiments and earthquake observations in Washington: Eos, Transactions American Geophysical Union, v. 81, n. 48, p. 870-871.

Danes, Z.F., Bonno, M., Brau, E., Gilham, W. D., Hoffman, T. F., Johansen, D., Jones, M. H., Malfait, B., Masten, J., and Teague, G. O., 1965, Geophysical investigation of the southern Puget Sound area, Washington: Journal of Geophysical Research, v. 70, p. 5573-5580.

Davis, E. E., and Hyndman, R. D., 1989, The structure and tectonic history of the northern Cascadia subduction zone; recent accretion and deformation: Geological Society of

America Bulletin, v. 101, p. 1465-1480.

Davis, D., Suppe, J. and Dahlen, F.A., 1983, Mechanics of fold-and-thrust belts and accretionary wedges: Journal of Geophysical Research: v. 88, p.1153-1172.

Dehler, S.A., and Clowes, R. M., 1992, Integrated geophysical modeling of terranes and other structural features along the western Canadian margin: Canadian Journal of Earth Sciences, v. 29, p. 1492-1508.

DeMets, C., Gordon, R. G., Argus, D. F., and Stein, S., 1990, Current plate motions: Geophysical Journal International, v. 101, p. 425-478.

Dragert, H., and Hyndman, R.D., 1995, Continuous GPS monitoring of elastic strain in the northern Cascadia subduction zone: Geophysical Research Letters, v. 22, p. 755-758.

Duncan, R.A., 1982, A captured island arc chain in the Coast Range of Oregon and Washington: Journal of Geophysical Research, v. 87, p. 10827-10837.

Engebretson, D. C., Cox, A., and Gordon, R. G., 1985, Relative motions between oceanic and continental plates in the Pacific Basin: Geological Society of America Special Paper 206, p. 1-59.

England, T.D.J, and Bustin, R.M., 1998, Architecture of the Georgia Basin, southwestern British Columbia: Bulletin of Canadian Petroleum Geology, v. 46, p. 288-320.

Finn, C.A., 1990, Geophysical constraints on Washington convergent margin structure: Journal of Geophysical Research, v. 95, p. 19533-19546.

Finn, C., Phillips, W. M., and Williams, D. L., 1991, Gravity anomaly and terrain maps of Washington: USGS Geophysical Investigations Map GP-988, scale 1:1,000,000 and 1:500,000.

Fisher, M.A., Brocher, T.M., Hyndman, R.D., Trehu, A.M., Weaver, C.S., Creager, K.C., Crosson, R.S., Parsons, T.E., Cooper, A.K., Mosher, D.C., Spence, G.D., Zelt, B.C., Hammer, P.T., ten Brink, U.S., Pratt, T.L., Miller, K.C., Childs, J.R., Cochrane, G.R., Chopra, S., and Walia, R., 1999a, Seismic survey probes urban earthquake hazards in Pacific Northwest: Eos, Transactions American Geophysical Union, v. 80, p. 13, 16-17.

Fisher, M. A., Flueh, E. R., Scholl, D. W., Parsons, T., Wells, R. E., Trehu, A. E., ten Brink, U., and Weaver, C. S., 1999b, Geologic processes of accretion in the Cascadia subduction zone west of Washington State: Geodynamics, v. 27, p. 277-288.

Flueh, E., Fisher, M., Scholl, D., Parsons, T., ten Brink, U., Klaeschen, D., Kukowski, N., Trehu, A., Childs, J., Bialas, J., and Vidal, N., 1997, Scientific teams analyze earthquake hazards of the Cascadia subduction zone: Eos, Transactions American Geophysical Union, v. 78, p. 153-157.

Flueh, E.R., Fisher, M.A., Bialas. J., Childs, J.R., Klaeschen. D., Kukowski. N., Parsons, T, Scholl, D.W., ten Brink, U., Trehu, A.M., and Vidal, N., 1998, New seismic images of the Cascadia Subduction Zone from Cruise S0108-ORWELL: Tectonophysics, v. 293, p. 69-84.

Frankel, A., and Stephenson, W., 2000, Three-dimensional simulations of ground motions in the Seattle region for earthquakes in the Seattle Fault zone: Bulletin Seismological Society America, v. 90, p. 1251-1267.

Frankel, A., Carver, D., Cranswick, E., Meremonte, M., Bice, T., and Overturf, D., 1999, Site response for Seattle and source parameters of earthquakes in the Puget Sound region: Bulletin Seismological Society of America, v. 89, p. 468-483.

Gerdom, M., Trehu, A. M., Flueh, E. R., and Klaeschen, D., 2000, The continental margin off Oregon from seismic investigations: Tectonophysics, v. 329, p. 79-97.

Goldfinger, C., Kulm, L. D., Yeats, R. S., McNeill, L., and Hummon, C., 1997, Oblique strike-slip faulting of the central Cascadia submarine forearc: Journal of Geophysical Research, v. 102, p. 8217-8243.

Goldfinger, C., Kulm, L.D., McNeill, L.C., and Watts, P., 2000, Super-scale failure of the southern Oregon Cascadia margin: Pure and Applied Geophysics, v. 157, p. 1189-1226.

Gower, H.D., Yount, J.C., and Crosson, R.S., 1985, Seismotectonic map of the Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigation Series MI -1613, scale 1:250,000.

Graindorge, D., Spence, G., Mosher, D. C., Hyndman, R. D., Charvis, P., Collot, J. Y., and Trehu, A. M., 1999, Structure beneath southern Vancouver Island and Juan de Fuca Strait from onshore-offshore and two-ship wide-angle seismic data: Seismological Research Letters, v. 70, p.254.

Green, A. G., Milkereit, B., Mayrand, L., Spencer, C., Kurtz, R., and Clowes, R. M., 1987, Lithoprobe seismic reflection profiling across Vancouver Island; results from reprocessing: Geophysical Journal of the Royal Astronomical Society, v. 89, p. 85-90.

Gutscher, M.A., Klaeschen, D., Flueh, E., and Malavieille, J., 2001, Non-Coulomb wedges, wrong-way thrusting, and natural hazards in Cascadia: Geology, v. 29, p. 379-382.

Hartzell, S., Carver, D., Cranswick, E., and Frankel, A., 2000, Variability of site response in Seattle, Washington: Bulletin of the Seismological Society of America, v. 90, p. 1237-1250.

Heaton, T. H., and Hartzell, S. H., 1987, Earthquake hazards on the Cascadia subduction zone: Science, v. 236, p. 162-168.

Henton, J. A., Dragert, H., Hyndman, R. D., Wang, K., and

Schmidt, M., 1999, GPS monitoring of crustal deformation on Vancouver Island: Seismological Research Letters, v. 70, p. 245.

Hyndman, R.D., 1988, Dipping reflectors, electrically conductive zones and free water beneath a subduction zone: Journal of Geophysical Research, v. 93, p. 13391-13405.

Hyndman, R. D., and Wang, K., 1995, The rupture zone of Cascadia great earthquakes from current deformation and the thermal regime: Journal of Geophysical Research, v. 100, p. 22133-22154.

Hyndman, R. D., Yorath, C. J., Clowes, R. M., Davis, E. E., 1990, The northern Cascadia subduction zone at Vancouver Island; seismic structure and tectonic history: Canadian Journal of Earth Sciences, v. 27, p. 313-329.

Johnson, S. Y., 1984, Evidence for a margin-truncating transcurrent fault (pre-late Eocene) in western Washington: Geology, v. 12, p. 538 541.

Johnson, S.Y., Potter, C.J., and Armentrout, J.M., 1994, Origin and evolution of the Seattle Fault and Seattle Basin, Washington: Geology, v. 22, p. 71-74.

Johnson, S.Y., Dadisman, S.V., Childs, J.R., Stanley, W.D., Bucknam, R.C., and Haugerud, R.A, 1996a, The Seattle Fault is offset by two active dextral strike-slip faults in Puget Sound, Washington; implications for earthquake hazards [abs.]: Geological Society of America Abstracts with Program, v. 28, p. A415.

Johnson, S.Y., Potter C.J., Armentrout, J.M., Miller, J.J.. Finn, C., and Weaver, C.S., 1996b, The southern Whidbey Island fault, western Washington—An active structure in the Puget Lowland, Washington: Geological Society of America Bulletin, v. 108, p. 334-354.

Johnson, S.Y., Dadisman, S.V., Childs, J.E., and Stanley, W.D., 1999, Active tectonics of the Seattle Fault and central Puget Sound, Washington—implications for earthquake hazards: Geological Society America Bulletin, v. 111, p. 1042-1053.

Johnson, S.Y., Dadisman, S.V., Mosher, D.C., Blakely, R.J., and Childs, J.R., 2001a, Active tectonics of the Devils Mountain Fault and related structures, northern Puget Lowland and eastern Strait of Juan de Fuca region, Pacific Northwest: U. S. Geological Survey Professional Paper 1643, 45 p., 2 map sheets.

Johnson. S.Y., Mosher, D.C., Dadisman, S.V., Childs, J.R., and Rhea, S.B., 2001b, Tertiary and Quaternary structures of the eastern Juan de Fuca Strait, *in* Mosher, D.C., and Johnson, S. Y., eds., Neotectonics of the eastern Strait of Juan de Fuca; a digital and geophysical atlas: Geological Society of Canada Open File Report 3931, compact disk.

Johnson, S.Y., Nelson, A.R., Personius, S.F., Wells, R.E., Kelsey, H.M., Sherrod, B.L., Okumura, K., Koehler, R., Witter, R., Bradley, L.A., and Harding, D.J., 2003, Maps and data from a trench investigation of the Utsalady Point fault, Whidbey Island, Washington: U.S. Geological Survey Miscellaneous Investigations Map 2420, 1 plate.

Johnson, S.Y., Nelson, A.R., Personius, S.F., Wells, R.E., Kelsey, H.M., Sherrod, B.L., Okumura, K., Koehler, R., Witter, R., Bradley, L.A., and Harding, D.J., 2004, Evidence for late Holocene earthquakes on the Utsalady Point fault, northern Puget Lowland, Washington: Seismological Society of America Bulletin, v. 94, p. 2299-2317.

Jones, D.L., Silberling, N.J., and Hillhouse, J., 1977, Wrangellia—a displaced terrane in northwestern North America: Canadian Journal of Earth Sciences, v. 14, p. 2565-2577.

Kelsey, H.M., Sherrod, B.L., Johnson, S.Y., and Dadisman, S.V., 2004, Land-level changes from a late Holocene earthquake in the northern Puget Lowland, Washington: Geology, v. 32, p. 469-472.

Khazaradze, G., Qamar, A., and Dragert, H., 1999, Tectonic deformation in western Washington from continuous GPS measurements: Geophysical Research Letters, v. 26, p. 3153-3156.

Kirby, S. H., 2000, Taking the temperature of slabs: Nature, v. 403, p. 31-34.

Kurtz, R. D., DeLaurier, J. M., and Gupta, J. C., 1986. A magnetotelluric sounding across Vancouver Island detects the subducting Juan de Fuca plate: Nature, v. 321, p. 596-599.

Linde, A. T., and Silver, P.G., 1989, Elevation changes and the great 1960 Chilean earthquake; support for aseismic slip: Geophysical Research Letters, v.16, p.1305-1308.

Ludwin, R. S., Weaver, C. S., and Crosson, R. S., 1991, Seismicity of Washington and Oregon, *in* Slemmons, D. B., Engdahl, E. R., Blackwell, E., and Schwartz, D., eds., Neotectonics of North America: Boulder, Colorado, Geological Society of America, Decade of North American Geology, Decade Map Volume 1, p. 77-98.

MacKay, M.E., 1995, Structural variation and landward vergence at the toe of the Oregon accretionary prism: Tectonics, v. 14, p. 1309-1320.

MacKay, M.E., Moore, G.F, Cochrane, G.R., Moore, J.C., and Kulm, L.D., 1992, Landward vergence and oblique structural trends in the Oregon margin accretionary prism; Implications and effect on fluid flow: Earth and Planetary Science Letters, v. 109, p. 477-491.

Massey, N.W.D., 1986, Metchosin Igneous Complex, southern Vancouver Island; ophiolite stratigraphy developed in an emergent island setting: Geology, v. 14, p. 602-605.

McCaffrey, R., and Goldfinger, C., 1995, Forearc deformation and great subduction earthquakes; implications for Cascadia offshore earthquake potential: Science, v. 267, p. 856-858.

McNeill, L. C., Piper, K. A., Goldfinger, C., Kulm, L. D., and Yeats, R. S., 1997, Listric normal faulting on the Cascadia continental margin: Journal of Geophysical Research, v.102, p. 12123-12138.

Miller, M.M., Johnson, D.J., Rubin, C.M., Dragert, H., Wang, K., Qamar, A., and Goldfinger, C., 2001, GPS-determination of along strike variation in Cascadia margin kinematics; implications for relative plate motion, subduction zone coupling, and permanent deformation: Tectonics: v. 20, p. 161-176.

Monger, J.W.H., 1991, Late Mesozoic to Recent evolution of the Georgia Strait-Puget Sound region, British Columbia and Washington: Washington Geology, v. 19, p. 3-7.

Mosher, D.C., Johnson, S.Y., Rathwell, G., Kung, R., Rhea, S., Blakely, R., Brocher, T.M., Hewitt, A., Lowe, C., and Mulder, T.L., 2000, Neotectonics of the eastern Juan de Fuca Strait; a digital geologic and geophysical atlas: Eos, Transactions American Geophysical Union, v. 81, no. 48, p.1168.

Nelson, A. R., Shennan, I., and Long, A.J., 1996, Identifying coseismic subsidence in tidal-wetland stratigraphic sequences at the Cascadia subduction zone of western North America: Journal of Geophysical Research, v. 101, p. 6115-6135.

Niem, A. R., MacLeod, N. S., Snavely, P. D., Huggins, D., Fortier, J. D., Meyer, H. J., Seeling, A., and Niem, W. A., 1992, Onshore-offshore geologic cross section, northern Oregon Coast Range to continental slope: Oregon Department of Geology and Mineral Industries Special Paper 26, 10 p., 11 sheets, various scales.

Obermeier, S.F., and Dickenson, S.E., 2000, Liquefaction evidence for the strength of ground motions resulting from late Holocene Cascadia subduction earthquakes, with emphasis on the event of 1700 A.D.: Bulletin Seismological Society of America, v. 90, p. 876-896.

Oleskevich, D. A., Hyndman, R.D., and Wang, K., 1999, The updip limits to great subduction earthquakes; thermal and structural models of Cascadia, south Alaska, SW Japan, and Chile: Journal of Geophysical Research, v. 104, p. 14965-14991.

Orange, D. L., Geddes, D. S., and Moore, J. C., 1993, Structural and fluid evolution of a young accretionary complex; the Hoh rock assemblage of the western Olympic Peninsula, Washington: Geological Society of America Bulletin, v. 105, p. 1053-1075.

Page, R. A., Biswas, N.N., Lahr, J.C., and Pulpan, H., 1991, Seismicity of continental Alaska, *in* Slemmons, D.B., Enghal, E.R., Zoback, M.D., and Blackwell, D.D., eds., Neotectoncs of North America: Boulder, Colorado, Geological Society of America, Decade of North American Geology, Decade Map Volume 1, p. 47-76.

Parsons, T., Wells, R.E., Fisher, M.A., Flueh, E., and ten Brink, U.S., 1999, Three -dimensional velocity structure of Siletzia and other accreted terranes in the Cascadia forearc of Washington: Journal of Geophysical Research, v. 104, p. 18015-18039.

Plafker, G., 1969, Tectonics of the March 27, 1964, Alaska earthquake: U. S. Geological Survey Professional Paper 0543-I, 74 p.

Pratt, T.L., Johnson, S., Potter, C., Stephenson, W., and Finn, C., 1997, Seismic reflection images beneath Puget Sound, western Washington state; the Puget Lowland thrust sheet hypothesis: Journal of Geophysical Research, v. 102, p. 27469-27489.

Ramachandran, K., Dosso, S.E., Zelt, C.A., Spence, G., and Hyndman, R.D., 2000, Upper crustal velocity structure of south western British Columbia from 3D nonlinear first arrival traveltime tomography: Eos, Transactions American Geophysical Union, v. 81, no. 48, p. 871-872.

Rau, W. W., and Johnson, S. Y., 1999, Well stratigraphy and correlations, western Washington and northwestern Oregon: U. S. Geological Survey Geologic Investigations Report I-2621, 31 p., 3 sheets.

Rogers, G.C., 1988, An assessment of the megathrust earthquake potential of the Cascadia subduction zone: Canadian Journal of Earth Sciences, v. 25, p. 844-852.

Satake, K., Shimazaki, K., Tsuji, Y., and Ueda, K., 1996, Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700: Nature, v. 379, p. 246-249.

Seely, D.R., 1977, The significance of landward vergence and oblique structural trends on trench inner slopes, *in* Talwani, M., and Pitman, W.C., eds., Island arcs, deep sea trenches, and back-arc basins: Washington, D.C., American Geophysical Union, Maurice Ewing Series, Volume 1, p. 187-198.

Shouldice, D. H., 1973, Western Canadian Continental Shelf, *in* The future petroleum provinces of Canada; their geology and potential: Calgary, Alberta, Canadian Society of Petroleum Geologists, p. 7-35.

Simpson, R.W. and Cox, A., 1977, Paleomagnetic evidence for tectonic rotation of the Oregon Coast Range: Geology, v. 5, p. 585-589.

Snavely, P.D., Jr., 1987, Tertiary geologic framework, neotectonics, and petroleum potential of the Oregon-Washington continental margin, *in* Scholl, D.W., Grantz, A., and Vedder, J.G., eds., Geology and Resource Potential of the Continental Margin of Western North America and Adjacent Ocean

Basins, Beaufort Sea to Baja California: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, v. 6, p. 305-335.

Snavely, P.D., Jr., and Wells, R.E., 1996, Cenozoic evolution of the continental margin of Oregon and Washington, *in* Rogers, A.M., Walsh, T.J., Kockelman, W J., and Priest, G.R., eds., Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest, U.S. Geological Survey Professional Paper 1560, p.161-182.

Snavely, P.D., Jr., Brown, R.D., Jr., Roberts, A.E., and Rau, W.W., 1958, Geology and coal resources of the Centralia-Chehalis district, Washington: US. Geological Survey Bulletin 1053, 159 p.

Spence, G.D., Clowes, R.M., and Ellis, R.M., 1985, Seismic structure across the active subduction zone of western Canada: Journal of Geophysical Research, v. 90, p. 6754-6772.

Spence, G D., Hyndman, R D., Davis, E E., and Yorath, C.J., 1991, Seismic structure of the northern Cascadia accretionary prism; evidence from new multichannel seismic-reflection data, *in* Meissner, R.O., Brown, L.D., Duerbaum, H.J., Franke, W., Fuchs, K., and Seifert, F., eds., American Geophysical Union, Washington, D.C., Geodynamics Series, v. 22, p.257-263.

Stanley, D., Villasenor, A., and Benz, H., 1999, Subduction zone and crustal dynamics of western Washington; a tectonic model for earthquake hazards evaluation: U.S. Geological Survey Open-File Report, 99-311, 64 p.

Symons, N.P., and Crosson, R.S., 1997, Seismic velocity structure of the Puget Sound region from 3-D non-linear tomography: Geophysical Research Letters, v. 24, p. 593-596.

Tabor, R. W., and Cady, W. M., 1978, The structure of the Olympic Mountains, Washington—analysis of a subduction zone: United States Geological Survey Professional Paper 1033, 38 p.

ten Brink, U.S., Molzer, P.C., Fisher, M.A., Blakely, R.J., Bucknam, R.C., Parsons, T., Crosson, R.S., and Creager, K.C., 2002, Subsurface geometry and evolution of the Seattle fault zone and the Seattle Basin, Washington: Bulletin of the Seismological Society of America, v. 92, p. 1737-1753.

Trehu, A.M., Lasudeh, M., Brocher, T.M., Luetgert, J., Mooney, W.D., Nabelek, J.L., and Nakamura, Y., 1994, Crustal architecture of the Cascadia forearc: Science, v. 266, p. 237-243.

Van Wagoner, T. M., Crosson, R.S., Creager, K.C., Medema, G., Preston, L., Symons, N.P., and Brocher, T.M., 2002, Crustal structure and relocated earthquakes in the Puget Lowland, Washington, from high-resolution seismic tomography: Journal of Geophysical Research, v. 107, doi:10.1029/2001JB000710, 23 p.

Wang, K., and He, J., 1999, Mechanics of low-stress forearcs; Nankai and Cascadia: Journal of Geophysical Research, v. 104, p. 15191-15205.

Wang, K., Mulder, T., Rogers, G. C., and Hyndman, R. D., 1995, Case for very low coupling stress on the Cascadia subduction fault: Journal of Geophysical Research, v. 100, p. 12907-12918.

Weaver, C. S., and Baker, G. E., 1988, Geometry of the Juan de Fuca Plate beneath Washington and northern Oregon from seismicity: Bulletin of the Seismological Society of America, v. 78, p. 264-265.

Wells, R.E., and Weaver, C.S., 1993, Rotating crustal blocks and big earthquakes in western Oregon and Washington [abs.]: Geological Society of America, Abstracts with Program, v. 24, no. 5, p. 89.

Wells, R. E., Snavely, P. D., Jr., Bukry, D., MacLeod, N. S., and Kelley, M., 1992, Geologic map of the Tillamook highlands, NW Oregon coast—a Paleogene magmatic record of continental margin rifting [abs.]: Geological Society of America Abstracts with Program, v. 24, no. 5, p. 89.

Wells, R.E., Weaver, C.S., and Blakely, R.J., 1999, Fore-arc migration in Cascadia and its neotectonic significance: Geology, v. 26, p. 759-762.

Yorath, C. J., Clowes, R. M., MacDonald, R. D., Spencer, C., Davis, E. E., Hyndman, R. D., Rohr, K., Sweeney, J. F., Currie, R. G., Halpenny, J. F., and Seemann, D. A., 1987, Marine multichannel seismic reflection, gravity and magnetic profiles—Vancouver Island continental margin and Juan de Fuca Ridge: Geological Survey of Canada, Open File Report 166, 10 p.

Yount, J.C., and Gower, H.D., 1991, Bedrock geologic map of the Seattle 30’ by 60’ quadrangle, Washington: U.S. Geological Survey Open File Report 91-147, 37 p., 5 map sheets, scale 1:100,000.

Yuan, T., Spence, G.D., and Hyndman, R.D., 1994, Seismic velocities and inferred porosities in the accretionary wedge sediments at the Cascadia margin: Journal of Geophysical Research, v. 99, p. 4413-4427.

Zelt, B.C., Ellis, R.M., Zelt, C.A., Hyndman, R.D., Lowe, C., Spence, G.D., and Fisher, M.A., 2001, Three-dimensional crustal velocity structure beneath the Strait of Georgia, British Columbia: Geophysical Journal International, v. 144, p. 695-712.