Annual Report File

Seismic Hazard Investigations in Puget Sound (SHIPS): Analysis of Seismic Structure Data Acquired in a Cooperative Survey between the U.S. Geol. Survey, Geol. Survey of Canada, and six universities

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Program Element: PN (Pacific Northwest)
Key words: Puget Sound, seismic structure, Cascadia, earthquake hazards

Investigations Undertaken

A very large multidisciplinary seismic structure survey was carried out in the Pacific Northwest in March 1998 led by the U.S. Geol. Survey (M.A. Fisher, project leader) involving the Pacific Geoscience Centre, Geol. Surv. Canada, and six universities (U. Washington, U. Oregon, Univ. Texas, U. Victoria, U. British Columbia, and Dalhousie U.). The objectives were, (1) to define potentially active crustal faults in the densely populated urban area Seattle-Tacoma-Vancouver, B.C., (2) regional structure (region of Puget Sound, Georgia Strait, and Strait of Juan de Fuca) that provides tectonic control of earthquake generation in the region, especially giant subduction thrust earthquakes. The work extends previous work within Puget Sound (e.g., Johnson et al., 1994; Pratt et al., 1997; Mosher et al., 1998), by LITHOPROBE across Vancouver Island (e.g., Hyndman et al., 1990; 1995) and the GEOMAR/USGS studies across the northern Washington continental margin (e.g., Flueh et al., 1997).

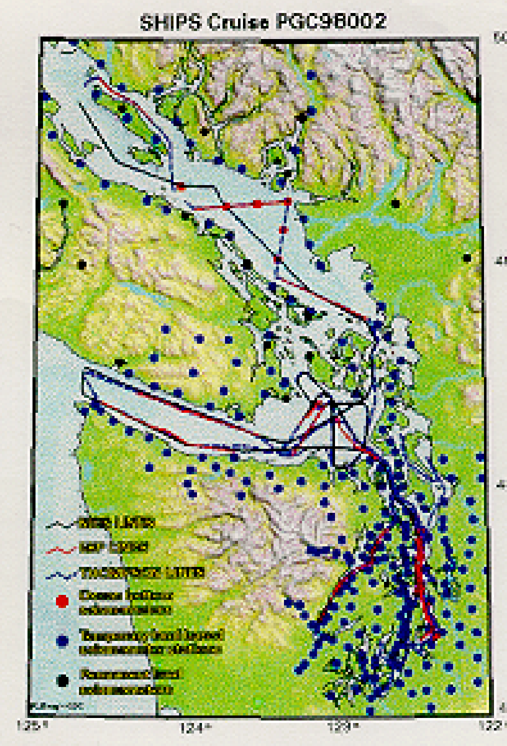

Figure 1. Map of SHIPS study area with multichannel lines, OBS site and land recording stations.

The survey involved two large ships, R/V Thompson from Univ. Washington, operated for the U.S. Geol. Survey, and the Canadian research ship CCGS J.P. Tully, operated for the Pacific Geoscience Centre, G.S.C., as well as two smaller ships used to deploy ocean bottom seismographs. The survey included, (1) multichannel seismic profiles in Puget Sound, Strait of Juan de Fuca and Georgia Strait from the Thompson, (2) recording of the airgun signals by15 ocean bottom seismographs, (3) recording of the signals at a large number of IRIS land stations deployed by a numerous of land parties. The airgun signals also were recorded on the permanent Univ. Washington and Pacific Geoscience Centre earthquake seismograph arrays, (4) expanding spread and constant offset recording of the airgun signals on a small multichannel array towed by the Tully. A huge amount of data was collected. Although the conditions were very difficult with extensive ship traffic, the multichannel data in places strongly affected by hard bottom multiples and reflections from the channel sides, there generally was good MCS resolution of both deep and shallow structure. Wide-angle arrivals were successfully recorded throughout the study area allowing detailed 3-D velocity models for the region. Locally, large-amplitude shear-wave refractions from the upper crust were recorded providing information needed to assess the ground shaking from a major earthquake.

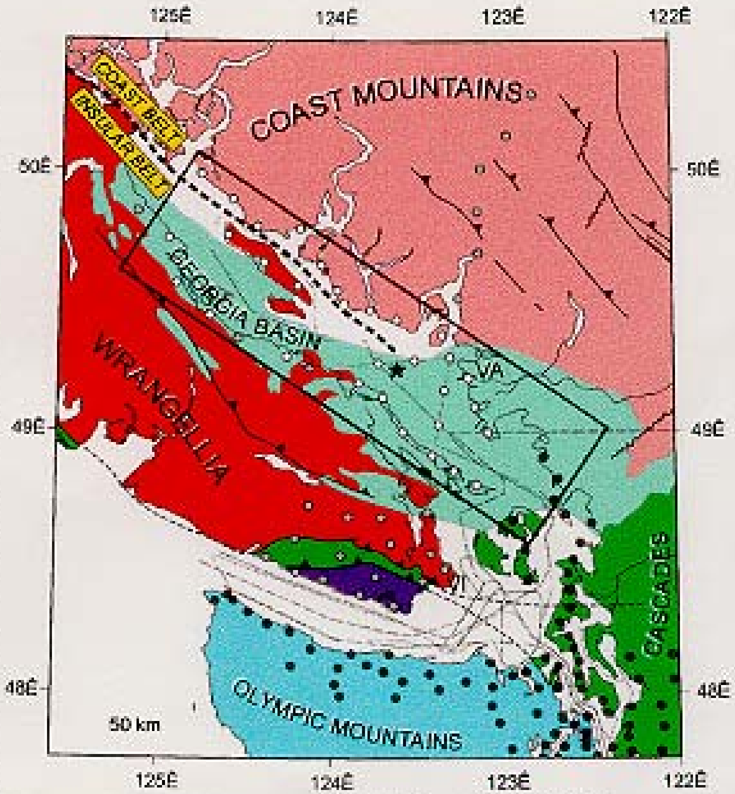

Figure 2. **Northern part of SHIPS study with ships tracks. The dots show the locations of land recorders. The box is the area of tomographic inversion for the structure beneath the Georgia Basin.**

This NEHRP grant was directed primarily at Georgia Strait and Strait of Juan de Fuca data, although close collaboration with the other groups involved has allowed integration of the data for the whole survey area.

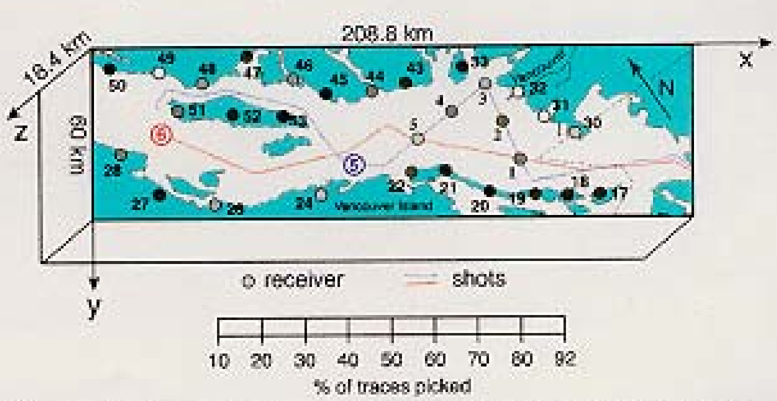

Figure 3. **Land stations and OBSs and marine airgun shot lines used for tomographic inversion study.**

Results

1. Analysis Seismic Wide Angle Data Georgia Strait-N. Puget Sound

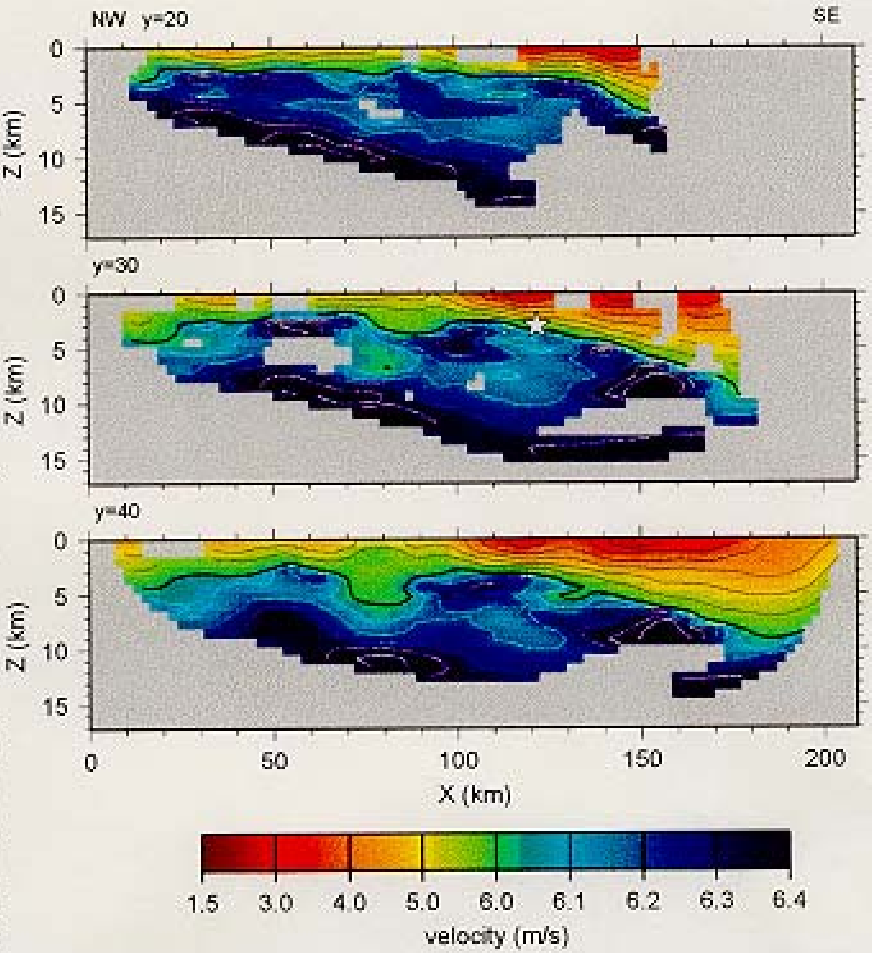

Figure 4. Three velocity cross-sections across Strait of Juan de Fuca based mainly on new SHIPS land station data.

In this part of the SHIPS analysis we have used first-arrival wide-angle seismic refraction data to derive a 3-D model of the upper crustal velocity structure beneath the Strait of Georgia - N. Puget Sound. This region which marks the boundary between the Coast Belt to the east and the Insular Belt of British Columbia to the west. A special focus of this study is the region of several moderate sized shallow earthquakes (3-5 km) 1997 M=4.6 and 1975 M=5, and numerous micro-earthquakes that may be on an east-west fault similar to the Seattle fault. Thus the focus is on the upper crustal structure. Crustal structure is constrained to a maximum depth of 10 km. We used data recorded at twenty-five land based stations and five ocean bottom seismographs.

The most significant feature of the final model is a wedge shaped region in the southeast with relatively low velocities (2-5 km/s) representing Georgia Basin sedimentary rocks of the Cretaceous and Tertiary Nanaimo Group and overlying younger sediments. The underlying basement rocks, probably Wrangellia or Jura-Cretaceous intrusive rocks of the Coast Belt, have velocities of 6-6.5 km/s, with significant lateral variation. In cross section, the base of the basin dips at about 4 degrees to the southeast to at least 7 km depth; however, the maximum thickness may be attained further to the southeast, outside our region of constraints. Depths for the 1997 and 1975 earthquakes estimated from the regional network places their hypocentres at the base of the dipping interface.

Future work on this study will include addition of data from the northern-most stations in Washington which may allow extending the model further to the southeast in Washington, thereby allowing better tie with the tomography models from the Puget Sound area. This data also may allow imaging the deep basin described above further to the southeast and possibly locate the position of maximum thickness. A 3-D tomographic analysis of the array data on southern Vancouver Island will

also be undertaken. Also a larger scale inversion that includes all data from stations in S. Vancouver Island and N. Washington needs to be undertaken to permit the tying of structures imaged beneath the Canadian and U.S. stations.

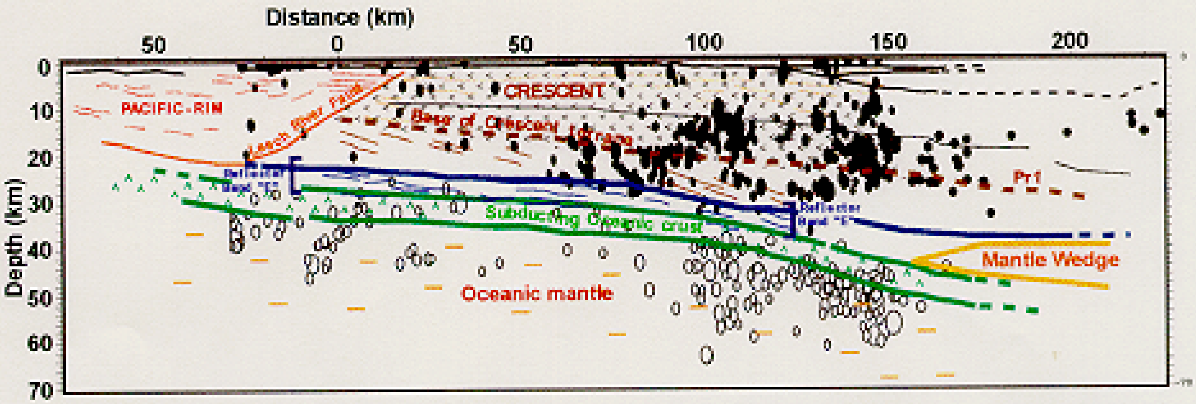

Figure 5. Cross-section beneath the north side of the Strait of Juan de Fuca based on SHIPS Vancouver Island land stations, and the SHIPS and previous LITHOPROBE multichannel data. The earthquake hypocentres are from Univ. Washington/USGS and Pacific Geoscience Centre data files. The filed circles are in the continental crust; the open circles are Benioff-Wadati earthquake in the underthrusting Juan de Fuca oceanic plate.

2. Deep Structure Beneath Strait of Juan de Fuca

The extensive land station data on Vancouver Island on the north side of the Strait of Juan de Fuca has allowed the deep structure of the subduction zone to be constrained. The first analysis used only stations on the north side, but initial integration has started with the data from the Olympic Peninsula on the south side analysed by Anne Trehu, Oregon State University, the U.S.G.S. and University of Washington.

During the 1998 SHIPS experiment, 16 Reftek seismographs deployed on southern Vancouver Island recorded wide-angle arrivals from the large airgun array on R/V Thompson, fired along to profiles extending the length of the Juan de Fuca Strait (**Figure 1**). Several expanding spread profiles (ESPs) about a fixed centre point were also acquired in western and eastern Juan de Fuca Strait, by recording the airgun signals on a short streamer behind the second ship CCGS Tully. Some objectives of the wide angle program were to determine the depth of the Eocene-age Crescent terrane as well as the top and base of the underthrusting subducting Juan de Fuca Plate on which great earthquakes may occur. A subset of 4 seismographs along the north side of the Strait were used for 2D traveltime inversion using the ray trace method of Zelt and Smith (1992), with additional constraints provided by the ESPs. Strong first arrival P-waves (apparent velocity 6.0-6.5 km/s) were observed to the maximum offsets of 100 km, and strong converted S-waves (apparent velocity 3.5 km/s) were also recorded. These arrivals correspond to turning rays with the accreted Crescent basalts. Prominent secondary P-waves from an eastward-dipping reflector also were observed. They

were particularly strong in the central Juan de Fuca Strait. On the ESP profile in the eastern Strait, a strong reflection band occurred at a time of more than 16 s (60 km depth). These deep reflections beneath the strait may represent the base of the subducting oceanic crust, or they may be related to a shear zone between the subducting and overriding plate similar to the "E" zone reflector band previously observed on LITHOPROBE data.

Figure 5 shows a cross-section beneath the north side of the Strait of Juan de Fuca based on this analysis and on the previous LITHOPROBE multichannel data. The earthquake hypocentres are from Univ. Washington/USGS and Pacific Geoscience Centre data files. The filled circles are in the continental crust; the open circles are Benioff-Wadati earthquake in the underthrusting Juan de Fuca oceanic plate.

3. Shallow MCS Sections and Recent Earthquakes; Strait of Georgia and Strait of Juan de Fuca

In this part of the study we processed the multichannel seismic reflection data to extract as much high-resolution information as possible from the top 4 seconds (two-way time) of the seismic records. The focus was to image the shallow structure of the Georgia Basin beneath Georgia Strait and eastern Strait of Juan de Fuca. Of particular interest is whether there are more east-west thrust fault structures similar to the Seattle Fault that cuts across Puget Sound (e.g., Johnson et al, 1994; 1999), which are interpreted to result from north-south compression in the forearc. The SHIPS data are an important complement to previous shallow seismic and other geophysical surveys in these areas directed at locating active faults and earthquake controlling structures (e.g., Mosher et al., 1998; Mosher and Hamilton, 1998). One especially important structure has been located in central Georgia Strait in an area of several significant earthquakes (e.g., M=4.6 in 1997). An initial analysis is reported by Mosher et al. (1999).

The processing focussed on the highest frequency components in the SHIPS MCS data. The Strait of Georgia profiles showed four seismostratigraphic units (Mosher et al., 1999). The basal unit is represented by a package of coherent, largely parallel reflectors except in the region near the Foreslope hills off the Fraser delta. North of the Foreslope hills there is a general loss in coherency of the reflectors. This loss is evident at two distinct intervals, each 5-8 km wide. Reflectors are disrupted, offset, and dipping at various angles and directions. Reflector offsets within these zones appear to describe listric normal or normal faults. Beneath the Foreslope hills, seismic reflectors fold upwards. The northern deformation zone correlates with a transition in the aeromagnetic data from one of moderately high intensity in the south to low intensity to the north, and with a narrow wavelength high-amplitude magnetic anomaly (**Figure 6**). It is within this deformation zone and the coincident shallow magnetic anomaly that the June 1997 and numerous previous small earthquakes occurred. Interpretations of the seismic and magnetic data indicate a series of steep, apparent north-dipping faults, with dip and strike in general agreement with the earthquake analyses. Two techniques were used to identify the active fault associated with the earthquake sequence: (1) determination of focal mechanisms for the largest events, to estimate the nature and orientation of the earthquake ruptures, (2) relocation of the mainshock and larger foreshock and aftershocks using wave form cross-correlation and joint hypocentral determinations to obtain precise relative earthquake locations. The results are shown in **Figure 6.**

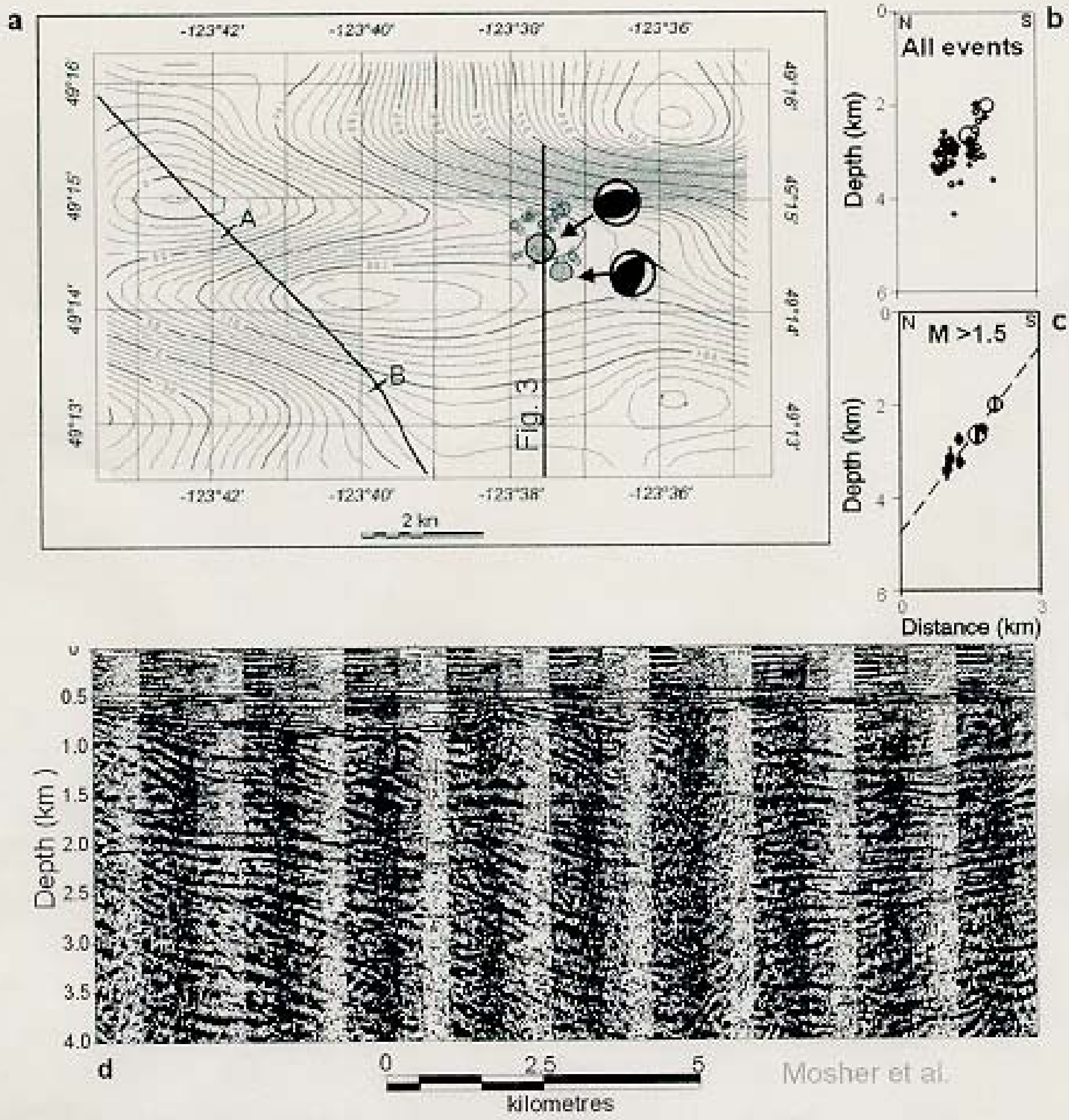

Figure 6. Upper left: The location of the SHIPS MCS line in Georgia Strait shown on the aeromagnetic anomaly map. The locations of the 1997 mainshock and aftershocks, and two thrust mechanisms are also shown. Upper right: a cross-section of the mainshock and aftershocks showing the dip and strike of the inferred fault. Lower: Migrated depth section of the SHIPS MCS reflection profile for the upper 4 km, showing the significant deformation and faulting between A and B (location in upper left map), interpreted to be associated with the active fault.

The SHIPS MCS reflection data thus provide the first correlation of shallow geological structure with recent crustal seismicity in this area. The MCS data show broad folding of sedimentary rocks in most of the area, but there are two broad deformation zones within which reflectors show changing dip directions, loss of coherency, and offsets interpreted to be normal faults. The northern deformation zone, 30 km west of Vancouver B.C. correlates with a region of frequent historical shallow crustal seismicity.

Papers referenced above

Hyndman, R.D., The Lithoprobe corridor across the Vancouver Island continental margin: the structural and tectonic consequences of subduction, Can. J. Earth Sci., 32, 1777-1802, 1995.

Hyndman, R.D., C.J. Yorath, R.M. Clowes, and E.E. Davis, The northern Cascadia subduction zone at Vancouver Island : seismic structure and tectonic history. Can. J. Earth Sci., 27, 313-329, 1990.

Fisher, M.A., T.M. Brocher, R.D. Hyndman, A.M. Trehu, C.S. Weaver, K.C. Creager, R.S. Crosson, T. Parsons, A.K. Cooper, D. Mosher, G. Spence, B.C. Zelt, P.T. Hammer, U. ten Brink, T.L. Pratt, K.C. Miller, J.R. Childs, G.R. Cochrane, S. Chopra, and R. Walia, Seismic survey probes urban earthquake hazards in Pacific Northwest, Eos, Trans. Am. Geophys. Un., 80, 13-15, 1999.

Flueh, E., et al., Scientific teams analyse earthquake hazards of the Cascadia subduction zone, Eos Trans. Am. Geophys. Un., 78, 153-157, 1997.

Johnson, S.Y., C.J. Potter, and J.M. Armentrout, Origin and evolution of the Seattle fault and Seattle basin, Washington, Geology, 22, 71-74, 1994.

Johnson, S.Y., S.W. Dadisman, J.R. Childs, and W.D. Stanley, Active tectonics of the Seattle fault and central Puget Sound, Washington - implications for earthquake hazards, Geol. Soc. Am. Bulletin, 111, 1042-1053, 1999.

Mosher, D.C., R. Macdonald, A.T. Hewitt, and W.T. Hill, Small airgun arrays for high resolution geophysical surveying, in Current Research 1998-D, Geol. Surv. Canada, p 43-50, 1998.

Mosher, D.C., and T.S. Hamilton, Morphology, structure, and stratigraphy of the offshore Fraser delta and adjacent Strait of Georgia, in Geology and Natural Hazards of the Fraser River Delta, British Columbia, (ed. J.J. Clague, J.L. Luternauer, and D.C. Mosher), Geol. Survey of Canada, Bulletin 525, p. 147-160, 1988.

Pratt, T.L., S. Johnson, C. Potter, W. Stephensen, and C. Finn, Seismic reflection images beneath Puget Sound, western Washington state: the Puget Lowland thrust sheet hypothesis, J. Geophys. Res., 102, 27,469-27,489, 1997.

Non-technical Summary

The Pacific Northwest has been subjected to many earthquakes in historic times, a number of which have caused significant damage (Puget Sound, 1949 - M =7.1 and 1965 - M=6.5; Vancouver Island, 1918 - M=7 and 1946-M=7.3). These examples were similar in size to the January 17, 1995 Kobe, Japan, earthquake (M=6.9), which demonstrated the vast destruction possible in an urban area when an earthquake occurs on a shallow crustal fault. Although geologic evidence for

past subduction earthquakes along the outer Cascadia margin is clear, basic information about crustal and subcrustal earthquakes occurring beneath urban centres in the Pacific Northwest region is lacking. To understand the seismic activity beneath this region it is necessary to know better the subsurface structure and to identify faults and other evidence of tectonic activity. Such information can be gained through the collection of active seismic reflection and refraction experiments. Between March 10 and 23, 1998, a major marine seismic investigation in Puget Sound, Strait of Juan de Fuca and Strait of Georgia was conducted, led by the United States Geological Survey (USGS) and involving the Geological Survey of Canada and 6 university research institutes (3 of which were Canadian). The objective was to study the velocity structure and tectonic framework of the region, including the location and configuration of fault zones upon which earthquakes may occur. This experiment was known as SHIPS (Seismic Hazard Investigations in Puget Sound). It involved two large research ships, the R/V Thomas G. Thompson University of Washington provided by USGS and CCGS John P. Tully provided by the Geol. Survey of Canada. There also were two smaller ships, an aeroplane, a network of several hundred temporary land and ocean bottom seismometers. Over 2000 km of seismic reflection and refraction data were collected. Ten earthquakes occurred in the region during the experiment. The data will improve our understanding of the distribution of crustal faults in the region of Puget Sound and Georgia Strait, link the known, shallow structure of faults to features at great depth where many earthquakes occur, better determine the geometry of the Seattle and Georgia sedimentary basins, provide an improved understanding of the seismic velocities in rocks at depth which will be used to improve calculated earthquake locations, and examine the effect of sediments and sedimentary basins on amplifying strong ground motions at sites across the region. This progress report deals with some of the preliminary results from the northern part of the survey, especially the shallow structure and possible active faults in E. Strait of Juan de Fuca and Strait of Georgia, the deeper structure that may control active faults in these areas.

Availability of Data, Format and Contact Person

SHIPS data may be available by contacting Dr. Michael Fisher, U.S.G.S. (mfisher@octopus.wr.usgs.gov) or Dr. R.D. Hyndman, Geol. Surv. Canada (hyndman@pgc.nrcan.gc.ca).

Meeting Organized

Seismological Society of America, Annual Meeting, Seattle, May 3-5, 1999.
Special session on Pacific Northwest Earthquake Hazards and Tectonics I & II, organized by M. Fisher and R.D. Hyndman. Primarily papers on NEHRP support SHIPS project.

Reports Published or Submitted

Fisher, M.A., T.M. Brocher, R.D. Hyndman, A.M. Trehu, C.S. Weaver, K.C. Creager, R.S. Crosson, T. Parsons, A.K. Cooper, D. Mosher, G. Spence, B.C. Zelt, P.T. Hammer, U. ten Brink, T.L. Pratt, K.C. Miller, J.R. Childs, G.R. Cochrane, S. Chopra, and R. Walia, Seismic survey

probes urban earthquake hazards in Pacific Northwest, Eos, Trans. Am. Geophys. Un., 80, 13-15, 1999.

Mosher, D.C., J.F. Cassidy, C. Lowe, Y. Mi, R.D. Hyndman, G.C. Rogers, and M. Fisher, Neotectonics in the Strait of Georgia: first tentative correlation of seismicity with shallow geological structure in southwestern British Columbia, *in* Geological Survey of Canada, Current Research 2000-A22, 9 pp., 2000.

Zelt, B.C., R.M. Ellis, and C.A. Zelt, Three-dimensional crustal velocity structure beneath the Strait of Georgia, British Columbia, J. Geophys. Res., submitted, 2000.

Papers, Presentations, Abstracts

(on work supported by this project)

Crosson, R.S., K.C. Creager, N.P. Symons, T. van Wagoner, Y. Xu, L.A. Preston, T.M. Brocher, T. Parsons, M.A. Fisher, T.L. Pratt, C. Weaver, U.S. ten Brink, K. Miller, A. Trehu, R.D. Hyndman, G. Spence, High-resolution 3-D regional P wave velocity tomography of the Puget basin region from SHIPS first-arrival data, Abstract, Am. Geophys. Union Annual Meeting, Eos, Trans. AGU, 80, F750, 1999.

Fisher, M., T. Parsons, T.M. Brocher, R.D. Hyndman, Trehu, A.M., K.C. Creager, R.S. Crosson, N.P. Symons, T. Pratt, C.S. Weaver, and U. ten Brink, Abstract, SSA 1999 Annual Meeting, Seism. Res. Lett., 70, 210, 1999.

Fisher, M. A., T.M. Brocher, T. Parsons, R.S. Crosson, K.C. Creager, A.M. Trehu, D.L. Mosher, R.D. Hyndman, R.J. Blakely, U.S. ten Brink, G. Spence, T.L. Pratt, D. Graindorge, and B.C. Zelt, Results From the 1998 SHIPS Experiment, Regarding Urban Earthquake Hazards in Cascadia, Abstract, Am. Geophys. Union Annual Meeting, Eos, Trans. AGU, 80, F750, 1999.

Graindorge, D., Spence, G.D., D. Mosher, R.D. Hyndman, P. Charvis, J.-Y. Collot, and A. Trehu, Structure beneath southern Vancouver Island and Juan de Fuca Strait from onshore-offshore and two-ship wide-angle seismic data, Abstract, SSA 1999 Annual Meeting, Seism. Res. Lett., 70, 254, 1999.

Hyndman, R.D., Geophysical modelling of Cascadia great earthquakes, Abstract, SSA 1999 Annual Meeting, Seism. Res. Lett., 70, 211, 1999.

Mosher, D.C., Y. Mi, J.F. Cassidy, R.D. Hyndman, The Shallow Component of the SHIPS Multichannel Reflection Data in the Strait of Georgia: Evidence of Neotectonics, Abstract, Am. Geophys. Union Annual Meeting, Eos, Trans. AGU, 80, F750, 1999.

Mosher, D.C., S.Y. Johnson, S.V. Dadisman, R.D. Hyndman, and M.A. Fisher, Evidence for Quaternary neotectonics in the marine record of the Pacific Northwest and southwestern British Columbia, Abstract, SSA 1999 Annual Meeting, Seism. Res. Lett., 70, 220, 1999.

Pratt, T., T. Brocher, T. Parsons, M. Fisher, K. Creager, R. Crosson, C. Weaver, R. Hyndman, A. Trehu, K. Miller, and U. ten Brink, Abstract, SSA 1999 Annual Meeting, Seism. Res. Lett., 70, 219, 1999.

Pratt, T.L., T.M. Brocher, T. Parsons, M.A. Fisher, K.C. Creager, R.S. Crosson, C. Weaver, R.L. Hyndman, A.M. Trehu, and K. Miller, Site Response in the Puget Lowland, Western Washington State, Determined From the SHIPS 3-Dimensional Geophone Array, Abstract, Am. Geophys. Union Annual Meeting, Eos, Trans. AGU, 80, F750, 1999.

Trehu, A.M., T.M. Brocher, S. Clarke, M.A. Fisher, T. Parsons, R.D. Hyndman, R. Clowes, E. Flueh, M. Gerdom, S. Gulick, A. Meltzer, B. Beaudoin, K. Miller, T. Pratt, G. Spence, and U. ten Brink, Structure of the Cascadia subduction zone from seismic reflection and refraction data: Relation to seismic activity, Abstract, SSA 1999 Annual Meeting, Seism. Res. Lett., 70, 210, 1999.

Trehu, A.M., T.M. Brocher, M.A. Fisher, T. Parsons, R.D. Hyndman, and G. Spence, Structure and reflectivity of the subducting Juan de Fuca plate beneath the Straits of Juan de Fuca and Northern Olympic Peninsula, Abstract, SSA 1999 Annual Meeting, Seism. Res. Lett., 70, 254, 1999.

Trehu, A.M., T.M. Brocher, M.A. Fisher, T. Parsons, K.C. Creager, R.S. Crosson, T.L. Pratt, C.S. Weaver, R.D. Hyndman, G. Spence, U.S. ten Brink, and K. Miller, Structure and Reflectivity of the Subducting Juan de Fuca Plate Beneath the Straits of Juan de Fuca and Northern Olympic Peninsula, Abstract, Am. Geophys. Union Annual Meeting, Eos, Trans. AGU, 80, F750, 1999.

Zelt, B.C., and R.M. Ellis, Seismic velocity structure across the boundary between the Insular and Intermontane belts, southwestern British Columbia, Abstract, SSA 1999 Annual Meeting, Seism. Res. Lett., 70, 238, 1999.