EHRP Final Technical Report

Neotectonic Mapping of Eastern Juan de Fuca Strait, Cascadia Forearc Region

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Title:	**Neotectonic Mapping of Eastern Juan de Fuca Strait, Cascadia Forearc Region**
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Abstract

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Technical Abstract:

The area of eastern Juan de Fuca Strait spans a concentration of modern crustal seismicity which extends northwards from Puget Sound. The region lies in a north-south compressional tectonic regime in addition to a west-east subduction setting. Although many earthquakes have been recorded in this area in modern times, there has been little evidence of any geologic expression of them or their Quaternary counterparts. Geologic evidence of earthquakes, e.g. recent faulting, however, can provide important information on earthquake hazard. Faulting is difficult to identify on land because of steep, rugged topography, heavy tree cover and the Pleistocene glaciations. In contrast, faults often can be readily recognized on and under the seafloor with acoustic imaging (seismic reflection and sidescan sonar). The objectives of the present program are to conduct an intensive geological/geophysical survey using multichannel and high resolution seismic reflection, sidescan sonar and piston coring to study, define and date the stratigraphy and evidence of neotectonic activity, such as earthquake-related faults, in the region. In addition, these data are relevant to the seismicity risk to adjacent urban centres, hazards to marine development and bear upon environmental and resource issues.

Two regional systematic marine geophysical surveys of the eastern Juan de Fuca Strait have been completed. Over 2200 line- km of multi- and single channel seismic reflection data were collected along with 39 shallow piston- and vibro-cores during the two surveys. The geophysical data show widespread evidence of faulting. In the shallow unconsolidated sediment section, this evidence is viewed as 1) normal growth faults with offsets on the order of meters, and 2) sediment deformation features with "dropouts" on the order of tens of meters. These deformation features occur in zones, typically several kilometers wide, which broadly correlate with known and projected Tertiary and younger fault systems mapped on land and from previous

marine surveys. Specifically, the Leech River/Southern Whidbey Island fault, the Devil's Mountain fault, the Hood Canal-Discovery Bay fault are readily identified from mapping these features. Deformation features can be seen on seismic reflection profiles to overlie fault offsets in basement rocks. Basement faults are observed to be normal, thrust and reverse-normal faults, sometimes throwing Tertiary basement rock over glacial sediments. Throw on these faults can be on the order of tens of meters. In most cases, observed faults or related deformation features cut through or affect the entire late Pleistocene glacial marine sedimentary section. In a few instances these features extend into the Holocene, although the Holocene section is typically thin, highly reworked and extremely variable in age and sediment type. Accurate dating of piston core samples will better constrain the age of latest displacements. The abundant evidence of recent faulting (since deglaciation) in an area of active seismicity is highly relevant to the assessment of earthquake hazard in the region.

Non-Technical Abstract

Earthquakes are common under the eastern Juan de Fuca Strait in northern Washington State. In modern history, some of these earthquakes have been damaging (e.g. southern Puget Sound, 1949 and 1965). The most recent notable event occurred north of Seattle in May, 1996 with a M5.4 (centered in Duvall). Geologic evidence of earthquakes, e.g. recent faulting, directly affects the earthquake hazard assessment and yet this evidence is hard to uncover on land. Faults can be readily recognized on and under the seafloor using marine geophysics (seismic reflection). A systematic geophysical survey of the eastern Strait of Juan de Fuca has just been completed. Results show features within unconsolidated sediments and bedrock that may represent faults. Their presence suggests that known ancient faults are still active. These results are highly relevant to the seismicity risk to adjacent urban centres and hazards to marine development.

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Abstract

The area of eastern Juan de Fuca Strait spans a concentration of modern crustal seismicity which extends northwards from Puget Sound. The region lies in a north-south compressional tectonic regime in addition to a west-east subduction setting. Although many earthquakes have been recorded in this area in modern times, there has been little evidence of any geologic expression of them or their Quaternary counterparts. Geologic evidence of earthquakes, e.g. recent faulting, however, can provide important information on earthquake hazard. Faulting is difficult to identify on land because of steep, rugged topography, heavy tree cover and the Pleistocene glaciations. In contrast, faults often can be readily recognized on and under the seafloor with acoustic imaging (seismic reflection and sidescan sonar). The objectives of the present program are to conduct an intensive geological/geophysical survey using multichannel and high resolution seismic reflection, sidescan sonar and piston coring to study, define and date the stratigraphy and evidence of neotectonic activity, such as earthquake-related faults, in the region. In addition, these data are relevant to the seismicity risk to adjacent urban centres, hazards to marine development and bear upon environmental and resource issues in these coastal waters.

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Introduction

The area of eastern Juan de Fuca Strait spans a concentration of modern crustal seismicity which extends northwards from Puget Sound. In modern history, some of these earthquakes have been damaging (e.g. southern Puget Sound, 1949 and 1965). The most recent notable event occurred north of Seattle in May, 1996 with a M5.4 (centered in Duvall). The region lies in a north-south compressional tectonic regime in addition to a west-east subduction setting. Although many earthquakes have been recorded in this area in modern times, there has been little evidence of any geologic expression of them or their Quaternary counterparts. Geologic evidence of earthquakes, e.g. recent faulting, however, can provide important information on earthquake hazard. Faulting is difficult to identify on land because of steep, rugged topography, heavy tree cover and subaerial erosion and weathering. In contrast, faults often can be readily recognized on and under the seafloor with acoustic imaging (seismic reflection and sidescan sonar). The objectives of the present program are to conduct an intensive geological/geophysical survey using multichannel and high resolution seismic reflection, sidescan sonar and piston coring to study, define and date the stratigraphy and evidence of neotectonic activity, such as earthquake-related faults, in the region. In addition, these data are relevant to the seismicity risk to adjacent urban centres, hazards to marine development and bear upon environmental and resource issues in these coastal waters.

Investigations Undertaken

Marine geophysical and geological investigations were conducted for this project during two research expeditions on the CCGS John P. Tully; cruise designations are PGC96006 and PGC97007. PGC96006 took place between October 15 and 31, 1996 and PGC97007 took place between August 5 and 16, 1997. A detailed and systematic grid of multi- and single channel seismic reflection lines were completed over the study area, totalling over 2100 line-km (Tables 1a-c, and Figures 1 and 2). In addition, 39 sediment cores (Table 2) were collected to provide geophysical groundtruth, establish a stratigraphic succession and provide material for age dating. Data from PGC96006 have been interpreted and results have been merged with existing geophysical data in a GIS environment. Results from PGC97007 are in the process of being interpreted and merged into the existing data base.

Methods

Seismic reflection

Multichannel seismic reflection (MCS), a tuned array of airgun single channel and Huntec high resolution subbottom profiles have been collected over the study area (Figs. 1 and 2). The multichannel system consisted of a Haliburton 0.65 L (40 $in^{3)}$ sleeve gun and an Innovative Transducers Inc. (ITI) 24-channel hydrophone solid array. The array had 3 hydrophones per group and 8 m separation between the centre hydrophone in each group. Separation between the gun and the centre element of the first group was 56 m. The streamer and gun was towed at 1 m below the sea surface. The gun was fired every 16 m using differential GPS to calculate the offset from the last shot. The sleeve gun was charged with a Rix air compressor capable of 30 standard cubic feet per minute, which maintained a pressure in the gun of about 2000 psi.

MCS data were digitized with a Geometrics StrataView® acquisition system with a sample interval of 500 μs over a record length of 2048 ms. This sample rate translates to a Nyquist frequency of 1000 Hz, well in excess of the bandwidth of the 40 in^3 source. The centre frequency of the source is about 150 Hz and the bandwidth extends from 0 to about 400 Hz. Data were written to an external SCSI hard drive, then archived to EXABYTE™ tape in SEG–2 format. Data were then downloaded to an HP 715 work station, converted to SEG–Y format, merged with navigation data, collated into line segments and processed. Trace data from channel 5 were extracted and printed. The configuration of the array allowed for a six-fold CDP stack of the data. Initial stacks with semblance velocity analysis were conducted on board the vessel during the survey. For this processing, the data were subsampled to 1 ms sample interval, with no loss of information, and terminated at a record length of 1024 ms.

The Huntec Deep Tow System was employed continuously during all surveying through both PGC96006 and PGC97007. It was maintained by Geoforce Consultants Ltd., and operated by Geoforce and Pacific Geoscience Centre staff. The system uses a boomer source with an internal and external hydrophone receiving array. The ED10G/C boomer source generates a broad band pulse with a centre frequency of about 2.5 kHz, but spans 0.5 to 6 kHz relatively cleanly. The system was operated at 500 Joules output. This source is highly repeatable, capable of resolving 10 cm vertically. Peak output intensity is 118 dB relative to 1 microbar at 1 metre, with a pulse duration of 120 microseconds. It was deep-towed between 30 and 60 m below the surface in this survey. Deep towing the system puts the source and receiver closer to the seafloor and away from surface heave. The system is depth and heave compensated. The internal hydrophone is a LC32 single element cartridge suspended from the boomer plate and is best for high frequency acquisition. The external array is a 15 ft-long, 10-element oil filled streamer (Benthos MESH 15/10P) towed behind the fish. It acquires a broader frequency band than the internal hydrophone, but is subject to heave and more external noise. The internal and external signals were displayed in analogue hardcopy on an EPC9800 thermal chart recorder, recorded on a Sony™ DAT 8-channel recorder and were digitized at 40 μs for a record length of 175 ms (deep-water delays were used to keep the record length short) and written to Exabyte tape with a MUSE® digital sonar acquisition system. This sample interval yields a Nyquist frequency of 12.5 kHz. The boomer source was fired at every 1.5 m, but was interrupted during acquisition of the multi-channel data. The external data were band pass filtered at 800-6000 Hz.

Single Channel seismic reflection data were collected during PGC97007. The seismic source consisted of two Bolt airguns with various chamber sizes (mostly 2 x 10 in^3) suspended in a frame, 0.5 m apart and towed at a depth of 0.5 m depth and 15 m behind the stern of the ship. Airguns were pressurized to 1850 psi and fired every 4 m, based on differential GPS positioning. A single EDO model 141B hydrophone cartridge was deep-towed below the airguns to monitor every shot.The relative timing of the firing of the two guns was controlled by a 3-channel Bolt firing unit, permitting 0.1 ms accuracy in firing delay. The shotpoint source signature was monitored on a Zonic model 3525 spectral analyzer. The shot point hydrophone and analyzer provided real-time display of the source signature in the time and frequency domains. The source signature was then tuned to maximize the outgoing pulse for shape and frequency content by adjusting the relative firing time of the two guns.

Two hydrophone streamers were used to acquire the single channel seismic reflection data: the benthos array is oil-filled and consists of a single group of 50 elements with 6 inch spacing. It was towed just below the surface, 30 m behind the ship. The Teledyne array has a 25 m active section with 50 hydrophone cartridges. It was towed at 3 m depth, 50 m behind the ship. Signal from these arrays and the single cartridge shotpoint hydrophone were displayed as analogue hardcopy on an EPC 9800 chart recorder, logged to a SONY™ DAT recorder and digitized at 100 μs for a length of 1000 ms on EXABYTE™ tape with a MUSE® digital sonar acquisition system.

Sidescan Sonar

The sidescan sonar system used was a Simrad 992. It is a dual frequency system (120 and 330 kHz) set at 300 m range (300 m per side) for this survey. Data were output to an Alden 9315 continuous tone greyscale printer and were digitized at 2048 samples per side with the MUSE acquisition system. The sidescan fish was towed about 30 m above the seafloor with a 157 kg depressor. This system was used only occasionally to assess its effectiveness for the purposes of follow up studies.

Bathymetry

Water depth data, acquired through a hull-mounted Simrad EA500 12 kHz sounder, were logged continuously at five second intervals with navigation data during the two cruises. In addition, digital Canadian Hydrographic Service (CHS) and NOAA data were obtained and field sheet data were digitized by the investigator to augment data from the surveys. A swath bathymetry survey was conducted by the investigator along the Victoria water front in September, 1998 and these data have been combined with the other data.

Sediment Coring

Thirteen piston cores were collected during PGC96006 and a further 21 piston cores and 4 vibrocores were collected during PGC97007. For the piston cores, a standard benthos split-piston corer was used with a 2000 lb core head and 2x10 ft barrels. Cores are recovered inside a plastic liner which has an internal diameter of $2^5/_8$ inches. Cores were sealed and kept in refrigerated storage. The vibrocorer had limited success due to steep terrain. Cores from 1996 have been split and described and measured for physical properties (porosity, density, micro-resistivity, acoustic velocity, and shear strength). This project spawned the need and has resulted in the establishment of a physical properties laboratory at the Pacific Geoscience Centre.

Navigation

Navigation acquisition and post-processing were provided by Geoforce Consultants Ltd. Position data were acquired every 1 second using differential Global Positioning System (DGPS). The differential signal was acquired from Whidbey Island or Race Rocks stations and was stable throughout the survey, although some post-processing is still necessary. The navigation receiver was a Trimble 6-channel receiver. The GPS receiving attenna was mounted on the after mast of the CCGS John P. Tully, 15.3 m from the fantail. In addition to our own position data, the ship's navigation was acquired, which operates through attenae on the main mast and displays data in NAD27 datum, while ours was in NAD83. All data were acquired digitally and logged to hard drive. Water depth, acquired through a hull-mounted Simrad EA500 12 kHz sounder, was logged with navigation data.

Results and Discussion

All data collected and interpreted are digital and the interpreted data have been loaded into ARC/Info, a Geographic Information System (GIS) software package. These data have been merged with land topographic, coastline, cultural and existing digital geophysical data to produce a series of maps that can be integrated at equivalent scales.

Regional Potential Field Maps

Existing regional geophysical data include shipborne gravity and airborne magnetic data These data show two main geologic bedrock members; the high gravity, highly magnetic Crescent Terrane volcanic and crystalline rocks to the west, and the low gravity, low magnetic Pacific Rim Terrane sedimentary rocks to the east. The magnetic data (Fig. 3) show the contact between the two terranes with sharp contacts in magnetic signatures representing regional faults, such as the Leech River (south Whidbey Island) and Sooke Basin (Hood Canal) fault zones, as well as the Trial Island and Devil's Mountain faults. These data provide the framework for the more detailed investigations.

Surveys

Tables 1 and 2 and Figures 1 and 2 summarize the lines run with the three seismic systems and core locations in the survey area. 1350 line-km of multichannel seismic (MCS) data, and Huntec high resolution reflection data were collected in 1996 in a largely east-west grid with one nautical mile line spacing. 850 line-km of single channel seismic reflection (SCS) and Huntec high resolution reflection data were collect in 1997. The grid orientation is largely northeast-southwest. 39 piston and vibrocores were collected to provide groundtruth to the geophysical interpretations and to collect material for age dating. Coring targets included the different seismic facies encountered, stratigraphic successions in order to establish the Quaternary stratigraphy, and specific faults or reflectors which intersected faults.

Bathymetry

A bathymetric image of the study area is shown in Figure 4. Water depths range to a maximum of about 250 m. The area is composed of a number of shallow banks, some of which are supratidal, with intervening deep troughs. The most significant trough cuts southwest through the center of the study area at about the same location as the contact between the two underlying bedrock terranes. The gross morphology is believed to reflect the glacial/postglacial surface, with little modification through the Holocene. Bedforms of various scales reside on the seafloor, indicative of the dynamic current regime that presently exists in the region.

Quaternary Geology

High resolution seismic reflection data show three seismic units believed to represent three distinct near-surface geologic units. Interpretations are based on geophysical correlations with sediment descriptions from cores and shoreline outcrops. Physical property measurements in the cores have been used as a correlation tool. The base of the Quaternary section has been digitally "picked" and its surface morphology is shown in Figure 5. Above this horizon, the stratigraphically lowest unit is acoustically amorphous and attenuates the acoustic signal so no high resolution information is collected below it. Its surface varies considerably in depth, and usually outcrops or comes close to surface on the bank tops (Figs. 6 and 7). It is believed to represent till and/or diamict, likely deposited by ice from the most recent glacial episode (Fraser stade). This unit is overlain in a conformable fashion by acoustically stratified sediment that is up to 50 m thick (Fig. 6). It is believed to be a glacial marine section deposited during the recession of the last glaciation. The surface of this unit is frequently eroded, thus the topmost unit lies unconformably on the glacial marine section. The topmost unit represents Holocene deposition and is composed of reworked glacial and glacial marine sediments (Fig. 6). Its thickness varies from 0 up to 30 m. It is finely bedded with abundant sedimentary bedforms internally and on the seabed.

A surficial geology map has been generated from interpretation of high resolution seismic reflection data with results from coring to provide groundtruth (Fig. 7). This map shows outcropping at the seafloor of the unconsolidated sediment units discussed above. Till and/or diamict (unit 1) comprise the shallow banks. Glaciomarine sediments (unit 2) form the majority of the seafloor in the western regions of the study area. Holocene reworked material (unit 3) is more prelavent to the east; largely representing sediment supply from vast deposits of Pleistocene sediments on Whidbey Island.

Seismic reflection profiles show evidence of faulting in bedrock, and occasionally within the unconsolidated sediment section (Figs. 8, and 9). More common in the unconsolidated sediment section, however, are sediment deformation features (Fig. 10). There is strong suggestion that these deformation features correlate with basement faulting, at least in some cases (see Fig. 8). Figure 11 is a distribution map of faulting and sediment deformation features. Although there is abundant evidence of these features in the study area, there are only slight indications of any correlation with faults mapped out from magnetic data and land-based topography. These results suggest that faulting is active within the Holocene, sometimes affecting the present seafloor, but movement along the major crustal elements is not readily apparent from the shallow, near-surface faults and deformation features observed from the seismics. It must be noted, however, that the distribution of these features is biased to areas where the ship can travel and where seismic subbottom penetration is successful. For example, in some cases the bank tops are too shallow for a ship, and in many cases the banks represent areas where there is little subbottom penetration and abundant multiple interference.

Conclusions

The presence of fault offsets and deformation features in post-glacial sediments suggests that neotectonic activity has taken place within the Holocene. The exact timing of these offsets is not known but with core and seismic-stratigraphic data it will be possible to date at least some of these features. It is critical to establish the timing of these displacements in order to separate neotectonic activity resulting from present day tectonic stresses from post-glacial rebound activity. Mapping of the distribution of these features is not yet complete, but preliminary results suggests only small correlation with major terrane boundaries. Seismicity data do not correlate with these contacts either. The seemingly random distribution of seismicity and of the mapped shallow faults and deformation features suggests that neotectonic activity in the region may not be taking place along the major terrane boundaries but rather in isolated basins and within smaller tectonic elements. In addition, the amount and direction of movement of these faults is crucial in order to understand the modern tectonics of the region. Finally, fault locations need to be correlated with the pattern of modern shallow crustal seismic activity in order to understand the seismicity behaviour of the region. This work is crucial to understanding the seismic hazard of the Pacific Northwest region.

Future Work

The major data collection phase is complete. There remains a lot of interpretative work of the seismic and core data. Processing and interpretation of the 1997 data is incomplete. The seismic data requires multiple removal to improve record interpretation and the data need to be loaded into digital horizon picking software to be combined with the 1996 data. Physical properties and description of the 1997 cores need to be completed. Radiocarbon AMS age dating of sampled shell material from the cores is yet to be completed. One PhD student (Antony Hewitt) is being supported to conduct some of this work, and will result in his dissertation topic.

A result of the work in this project is the recognition of the need for deep structural information to tie to shallow features. The principal investigator, therefore, has been involved with the SHIPS experiment (Seismic Hazards Investigations in Puget Sound) and is actively processing data which ultimately will be used in the interpretation of the data herein.

A major collaborative effort is in place to combine results from this project with those of Drs. Samuel Johnson and Shawn Dadisman, amongst other investigators of the USGS and the GSC, in the easternmost portion of the Strait of Juan de Fuca, to produce a digital CD-release atlas of the data. Expected mapsheets and related authors follow:

Atlas of the Geology, Geophysics, and Neotectonics of the Eastern Strait of Juan de Fuca: Victoria to Puget Sound (CDRom format)

Mosher and Kung to manage overall compilation

1) BASE MAP: 48°00' - 48° 30', 122° 20' - 123° 45', UTM 10, 1:100,00
2) DIGITAL TERRANE: Topography and Bathymetry. Kung and Mosher,
Sam - provide digital topography for US land
Mosher - contact NOAA for US bathymetry (esp. close to shoreline)
And to get hydrographic field sheets digitized for Can waters (close to shoreline).
3) SURFICIAL GEOLOGY: Hewitt
Offshore - largely complete, Sam to provide his high frequency profiles.
Onshore - map only Quaternary, Tertiary and Pre-Tertiary Units (Hewitt)

4) SEISMICITY - Taimi Mulder/John Cassidy
Epicenter points with attributes (e.g. < 10 km depth, 10-20 km depth, > 20 km depth; magnitude)
With profiles and focal mechanism plots
5) MAGNETICS - Blakely and Lowe
Merge US and Canadian data
6) GRAVITY - Lowe and Blakely
Merge US and Canadian data
7) TRACKLINES: Mosher
Sam/Sue to send USGS trackline data (and possibly industry trackline data)
Mosher - GSC trackline and pos. SHIPS
8) BASE OF Q: Johnson
Mosher provide Q picks to Johnson
9) POST-GLACIAL ISOPACH: Hewitt
10) SCATTER MAP: Mosher
Control points for fault interpretations with attributes - e.g. Bedrock, Quaternary,
Post-glacial ... Industry, 2-sec data and Huntec
Sam- to provide control points for his picks
11) NEOTECTONIC MAP: Faults and Folds: Johnson and Mosher
Johnson - east half - supply interpretations to Kung to compile
Mosher - west half - integrate with Johnson's interpretations and supply to Kung.

Reports Published

Mosher, D.C., Kung, R., Hewitt, A.T., and Hamilton, T.S. 1997. Neotectonic Activity in the Eastern Juan de Fuca Strait: Quantitative Seismic Reflection Mapping. American Geophysical Union annual Meeting, Program with Abstracts, December, 1997, San Francisco.

Mosher, D.C., MacDonald, R., Hewitt, A.T., and Hill, W.T., 1998b. Small airgun arrays for high resolution geophysical surveying. Current Research, 1998D, Geological Survey of Canada p. 43-50.

Web Pages: http://www.pgc.nrcan.gc.ca/marine/neotecto.htm

Johnson, S.Y. , S.V. Dadisman, D. C. Mosher , R.J. Blakely, J. R. Childs, R.E. Wells, and S.B. Rhea. 1998. Neotectonics of the eastern Strait of Juan de Fuca region, northwestern Washington and southwestern British Columbia. American Geophysical Union annual Meeting, Program with Abstracts, December, 1998, San Francisco.

List of Tables

List of Figures

Table 1a: PGC96006 Seismic Lines

Line	Start Time	End Time	Start Shot	End Shot	Tape
1	290/2130	291/0650	1187	4558	1,2,3
2	291/0700	291/1536	4874	8295	3,4
3A	291/1602	291/1911	8304	9455	4
3B	292/0511	292/1217	9456	12287	5
4	292/1302	292/2122	12297	15856	5
5A	292/2200	293/0617	16032	19265	6
6	293/0700	293/1718	19560	23627	6
7	293/2030	294/0634	24129	28412	7
8A	294/0738	294/1043	28653	30097	7
9A	294/1143	294/1546	30223	31927	7,8
10	294/1604	294/1734	31929	32573	8
11	294/1836	295/0458	32576	36927	8
8B	295/0531	295/1311	37156	40404	8,9
9B	295/1437	295/2137	40409	43365	9
12	295/2213	296/0043	43370	44420	9
13	296/0058	296/0332	44422	45415	10
14	296/0348	296/1041	45418	48368	10
15	296/1202	296/1636	48369	50313	10
16	296/1711	296/1834	50329	50910	10
17	296/1900	296/2149	50966	52360	10
18	296/2152	296/2325	52362	52998	11
19	296/2335	297/0809	53071	56579	11
20	297/0809	297/0836	56580	56765	11
21	297/0836	297/1919	56766	51510	11,12
22	297/2019	297/2349	61511	62999	12
23	298/0015	298/0344	63002	64488	12
24	298/0408	298/0717	64677	66069	12
25	298/0800	298/1032	66070	67371	12
26	298/1039	298/1243	67372	68291	13
27	298/1258	298/1310	68202	68369	13
28	299/0130	299/0906	68403	72004	13
29	299/0938	299/1220	72005	73246	13
30	299/1252	2991329	73247	73440	13
31	299/1408	299/1440	73441	73669	13
32	299/2209	300/0703	73661	77953	13,14
33	300/0841	300/1706	77956	81597	14
34	301/0209	301/0608	81599	83113	14,15
35	301/0615	301/1036	83114	85116	15
36	301/1050	301/1217	85117	85787	15
37	301/1221	301/1819	85788	88258	15
46	302/1113	302/1530	88267	90327	16

Table 1b: PGC97007 seismic lines

Line	Start Time	End Time
1	219/0450	219/1218
2	219/1352	219/1410
3	219/1424	219/1441
4	219/1441	219/1514
5	219/1519	219/1532
6	219/1544	219/1600
7	220/0320	220/0656
8	220/0802	220/1125
9	220/1245	220/1455
10	221/0228	221/0500
11	221/0556	221/1119
12	221/1205	221/1447
13	221/1456	221/1656
14	221/2246	222/0754
15	222/0805	222/1034
16	222/1205	222/1633
17a	222/2319	223/0150
18	223/0235	223/0256
17b	223/0332	223/0645
19	223/0715	223/1129
20	223/1200	223/1633
21	223/1640	223/1904
12b	223/1927	223/2312
22	223/2358	224/0452
23	224/0532	224/0650
24	224/0654	224/1100
25	224/1147	224/1533
26	225/0130	225/0403
27{1}	225/0424	225/0829
28	225/0850	225/1032
29	225/1120	225/1542
30	226/0227	226/0748
31	226/0748	226/0834
32	226/0834	226/1309
33	226/1316	226/1602
34	226/1611	226/1801
35	227/0522	227/0816
36	227/0906	227/1300
37	227/1220	227/1300
38	227/2136	227/2300
39	227/2318	228/0045
40	228/0054	228/0300
41	228/0327	228/0535
42	228/0535	228/0647
43	228/0659	228/0816
44	228/0956	228/1215
45	228/1239	228/1354
46A	228/1418	228/1523
46B	228/1609	228/1738

Table 1c: Sidescan Sonar Lines

Line	Start Time	End Time	Tapes	File Numbers
38	302/0049	302/0126	18	1
39	302/0142	302/0219	18	3
41	302/0504	302/0529	18	5
42	302/0613	302/0647	18	6-7
43	302/0851	302/0918	18	8
44	302/0930	302/1000	18	9
45	302/1016	302/1041	18	10
56	303/0529	303/0543	19	1
57	303/0616	303/0656	19	2
58	303/0724	303/0809	19	3
59	303/0853	303/0936	19	4
60	303/1000	303/1042	20	1
61	303/1110	303/1156	20	2
62	303/1220	303/1306	21	1
63	303/1328	303/1415	21	2
64	303/1436	303/1524	21	3
65	303/1543	303/1636	21	4-6
66	303/1650	303/1728	21	7
67	303/1813	303/1859	21	8
68	303/1932	303/2015	21	9
69	303/2050	303/2137	21	10

Table 2: Core Locations

Core	Time (UTC)	Position		Length	Type
TUL96B001	298/1605	48° 11.734'	-123° 40.663'	121 cm	Piston
TUL96B002	298/1739	48° 11.725'	-123° 40.486'	164 cm	Piston
TUL96B003	298/1854	48° 22.01'	-123° 29.275'	376 cm	Piston
TUL96B004	299/1605	48° 17.01'	-122° 50.05'	363 cm	Piston
TUL96B005	299/1742	48° 16.988'	-122° 50.206'	583 cm	Piston
TUL96B006	299/1942	48° 16.983'	-122° 50.337'	565 cm	Piston
TUL96B007	299/2049	48° 16.97'	-122° 50.61'	347 cm	Piston
TUL96B008	300/1835	48° 22.99'	-122° 47.27'	403 cm	Piston
TUL96B009	300/1957	48° 23.006'	-122° 52.864'	370 cm	Piston
TUL96B010	300/2151	48° 18.008'	-123° 06.34'	19 cm	Piston
TUL96B011	300/2250	48° 17.984'	-123° 06.402'	26 cm	Piston
TUL96B012	301/0113	48° 24.08'	-123° 23.64'	203 cm	Piston
TUL96B013	301/2052	48° 17.087'	-123° 27.855'	----	Piston
TUL96B014	301/2200	48° 23.00'	-123° 12.52'	204 cm	Piston
TUL96B015	301/2355	48° 22.97'	-123° 13.93'	----	Piston

Core Number	Time(Z)	Lat (NAD83)	Long (NAD83)	Core Length(cm)	Water Depth (m)	Type
TUL97B001	218/1642	48 24.991	123 25.785	263	36.1	piston
TUL97B002	218/1825	48 24.921	123 25.578	236	42.7	piston
TUL97B003	218/2014	48 24.588	123 24.999	370	55.4	piston
TUL97B004	219/1646	48 22.97	122 47.33	448	85.7	piston
TUL97B005	219/1930	48 21.484	122 59.425	513	nr	piston
TUL97B006	219/2315	48 21.374	122 59.470	319	153.3	piston
TUL97B007	220/1617	48 13.993	123 10.092	165	155.7	piston
TUL97B008	220/1736	48 16.972	123 10.544	347	121.6	piston
TUL97B009	220/1934	48 17.984	123 03.104	457	156.5	piston
TUL97B010	220/2040	48 17.999	123 03.858	59	101	piston
TUL97B011	220/2139	48.17.996	123 02.381	lost;washed	173.7	piston
TUL97B012	221/1830	48 23.97	123 24.817	373	60.4	piston
TUL97B013	221/2058	48 20.005	123 30.785	93	96	piston
TUL97B014	222/1919	48 23.511	122 44.223	86	73.3	piston
TUL97B015	222/2036	48 20.932	122 48.539	483	104.9	piston
TUL97B016	222/2148	48 20.943	122 48.477	511	103.6	piston
TUL97B017	224/1752	48 25.153	122 56.416	110	94.9	piston
TUL97B018	224/2042	48 16.744	122 54.042	337	114.8	piston
TUL97B019	224/2137	48 17.024	122 53.909	54	107	piston
TUL97B020	224/2257	48 14.018	122 48.093	69	72	piston
TUL97B021	225/1759	48 20.158	122 57.236	383	132.5	piston
TUL97B022	225/2329	48 22.983	123 13.967	no recovery		vibro
TUL97B023	226/2042	48 20.013	122 30.780	131		vibro
TUL97B024	226/2236	48 22.973	123 14.025	1 bag	94.6	vibro
TUL97B025	226/2258	48 22.490	123 14.099	153	98.6	vibro
TUL97B026	226/2330?	48 22.971	123 13.972	1 dixie cup	76.6	vibro

JUAN DE FUCA STRAIT -- CRUISE NAVIGATION, OCTOBER 1996

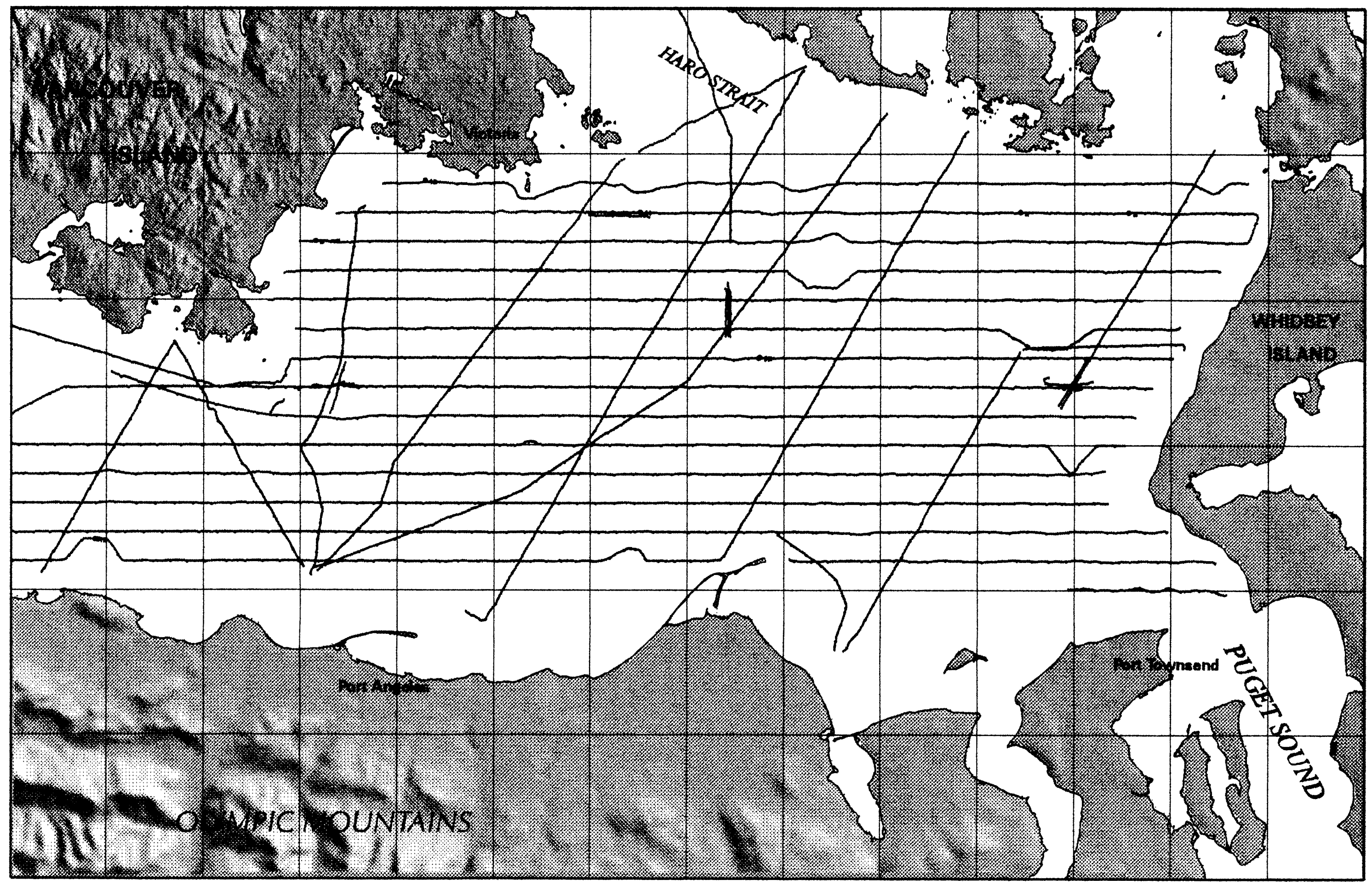


Figure 1

JUAN DE FUCA STRAIT -- CRUISE NAVIGATION, AUGUST 1997

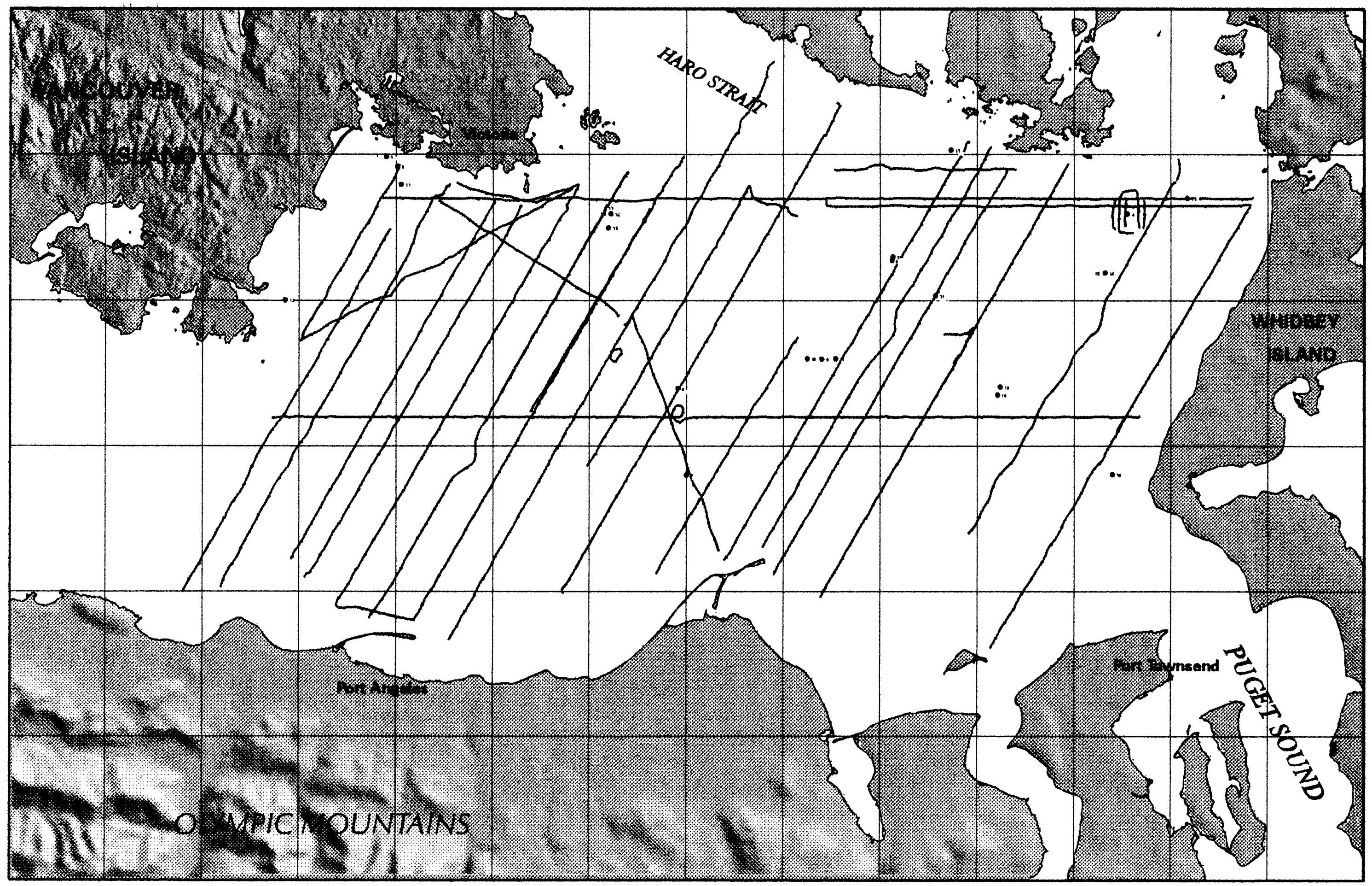
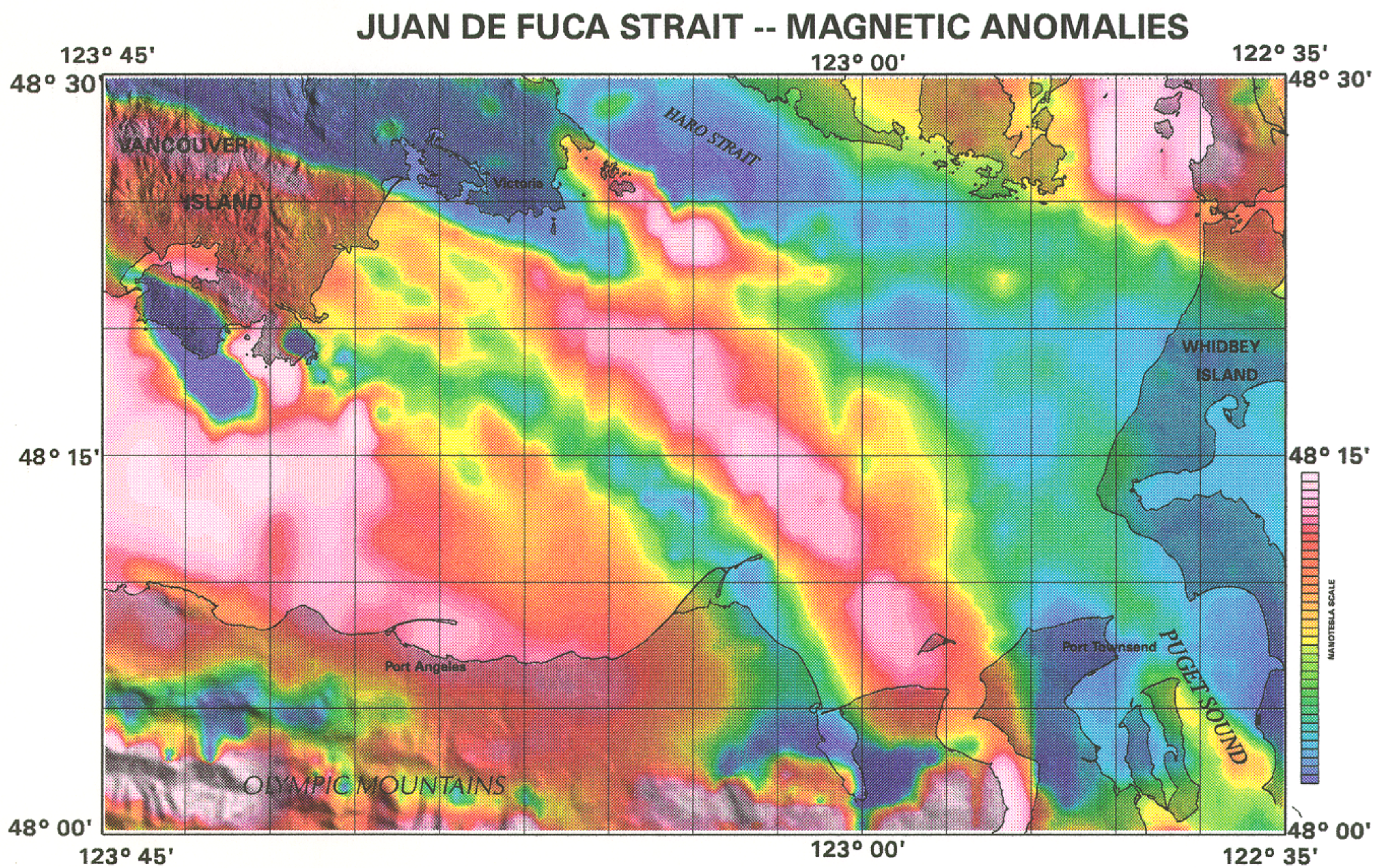


Figure 2



JUAN DE FUCA STRAIT -- MAGNETIC ANOMALIES
123° 45'
123° 00'
122° 35'
48° 30'
48° 15'
48° 00'
VANCOUVER
ISLAND
Victoria
HARO STRAIT
WHIDBEY
ISLAND
Port Angeles
Port Townsend
PUGET SOUND
OLYMPIC MOUNTAINS
NANOTESLA SCALE

Figure 3

JUAN DE FUCA STRAIT -- BATHYMETRY

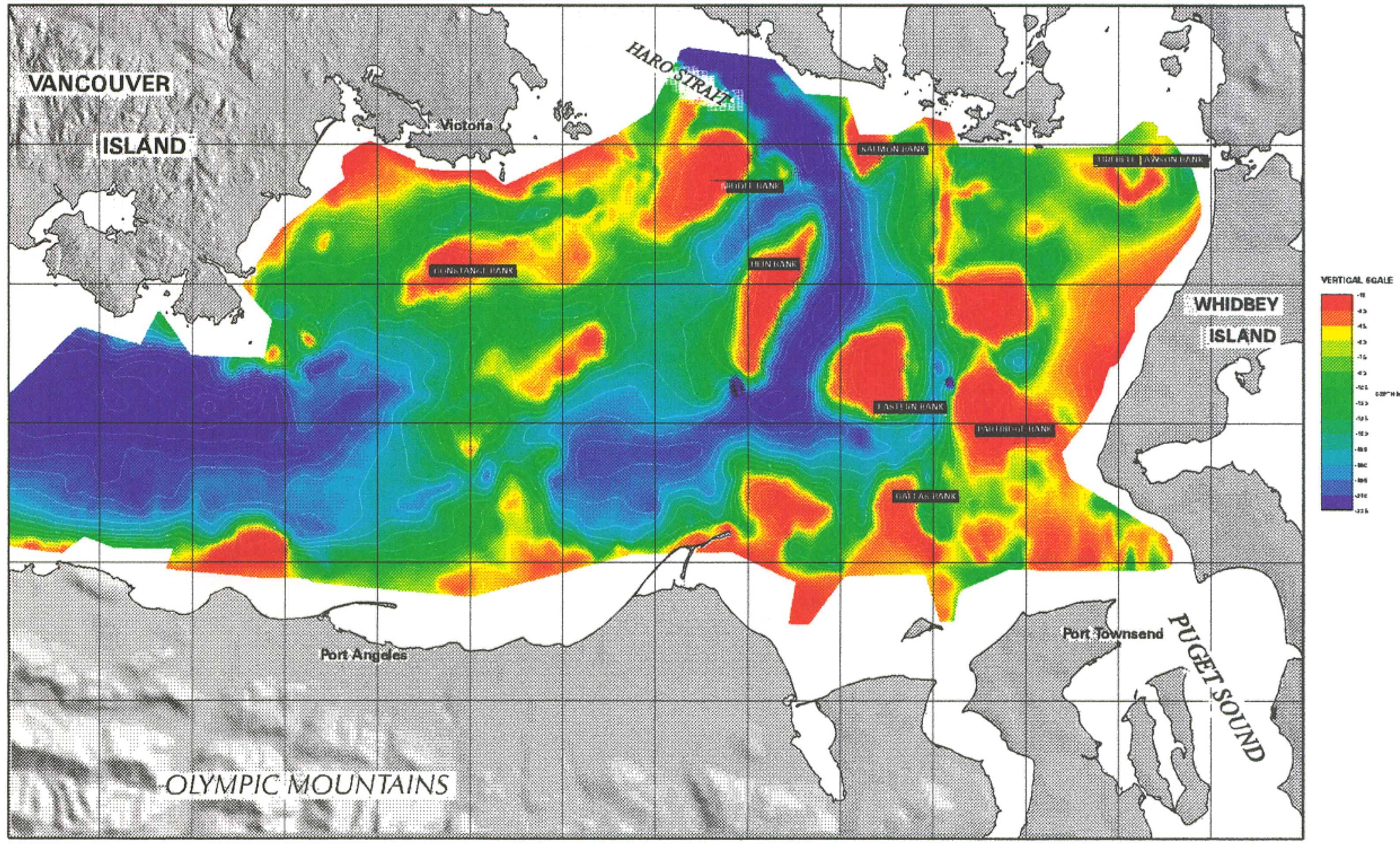


Figure 4

Base of Quaternary (traveltime)

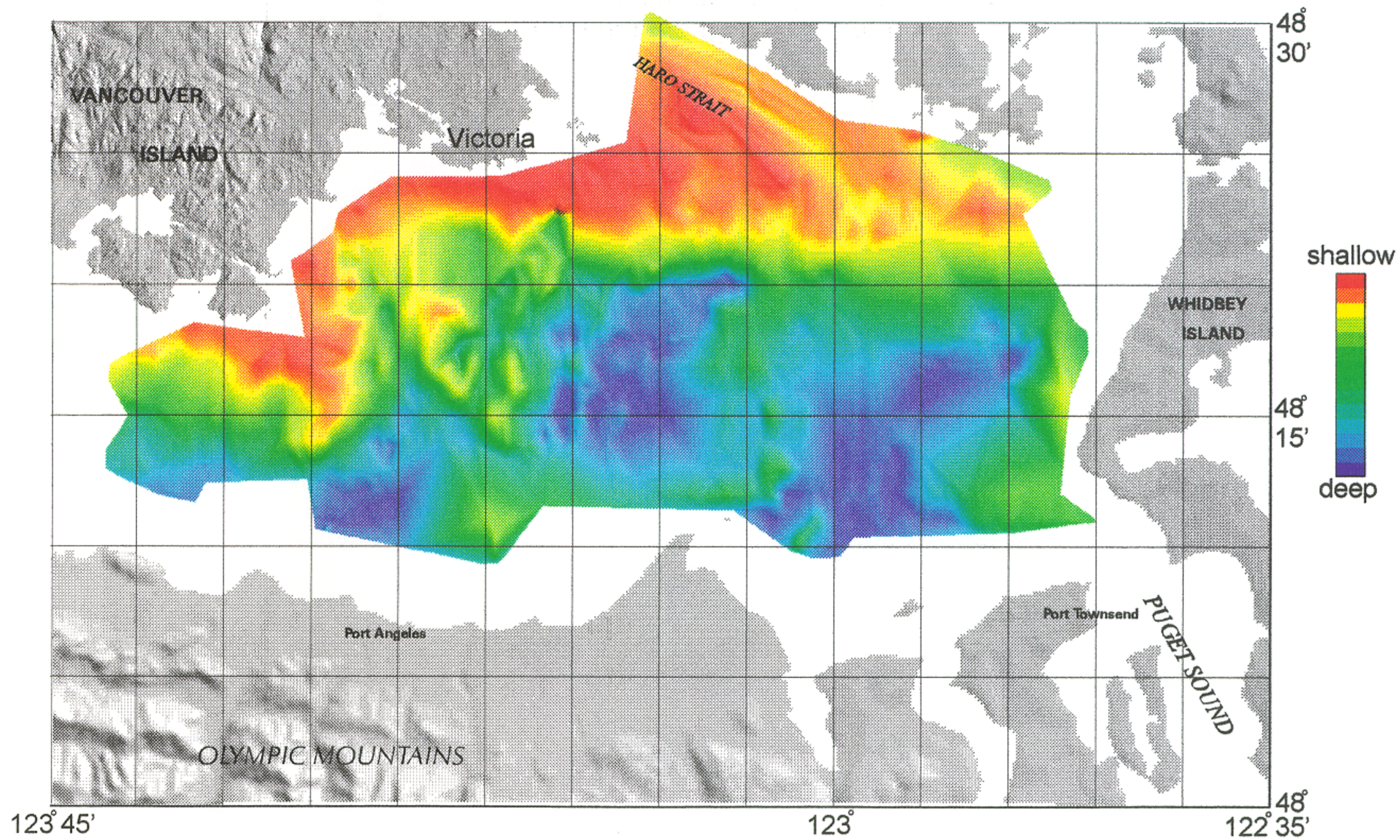


Figure 5

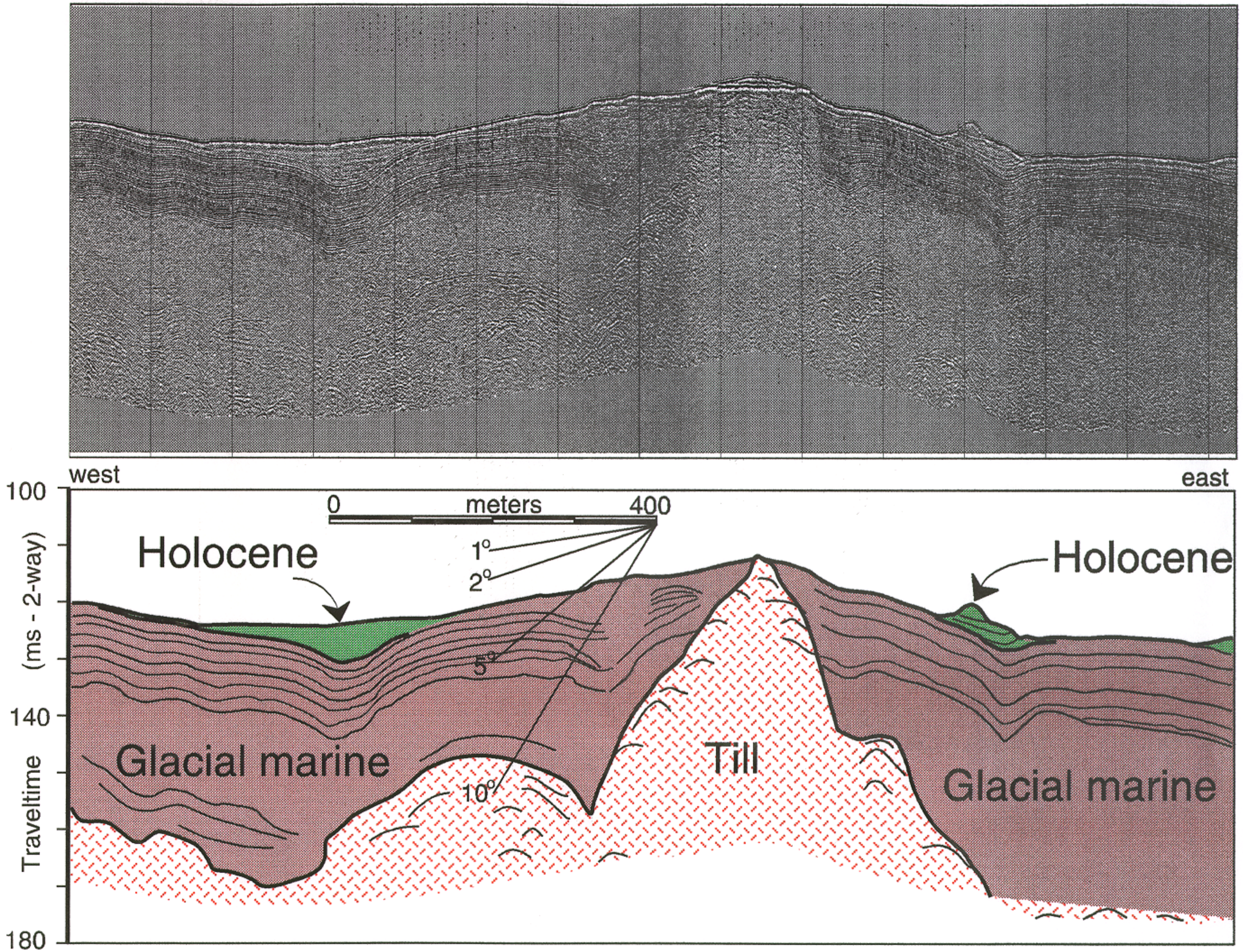

west
east
100
140
180
Traveltime (ms - 2-way)
0
meters
400
1°
2°
5°
10°
Holocene
Holocene
Glacial marine
Glacial marine
Till

Figure 6

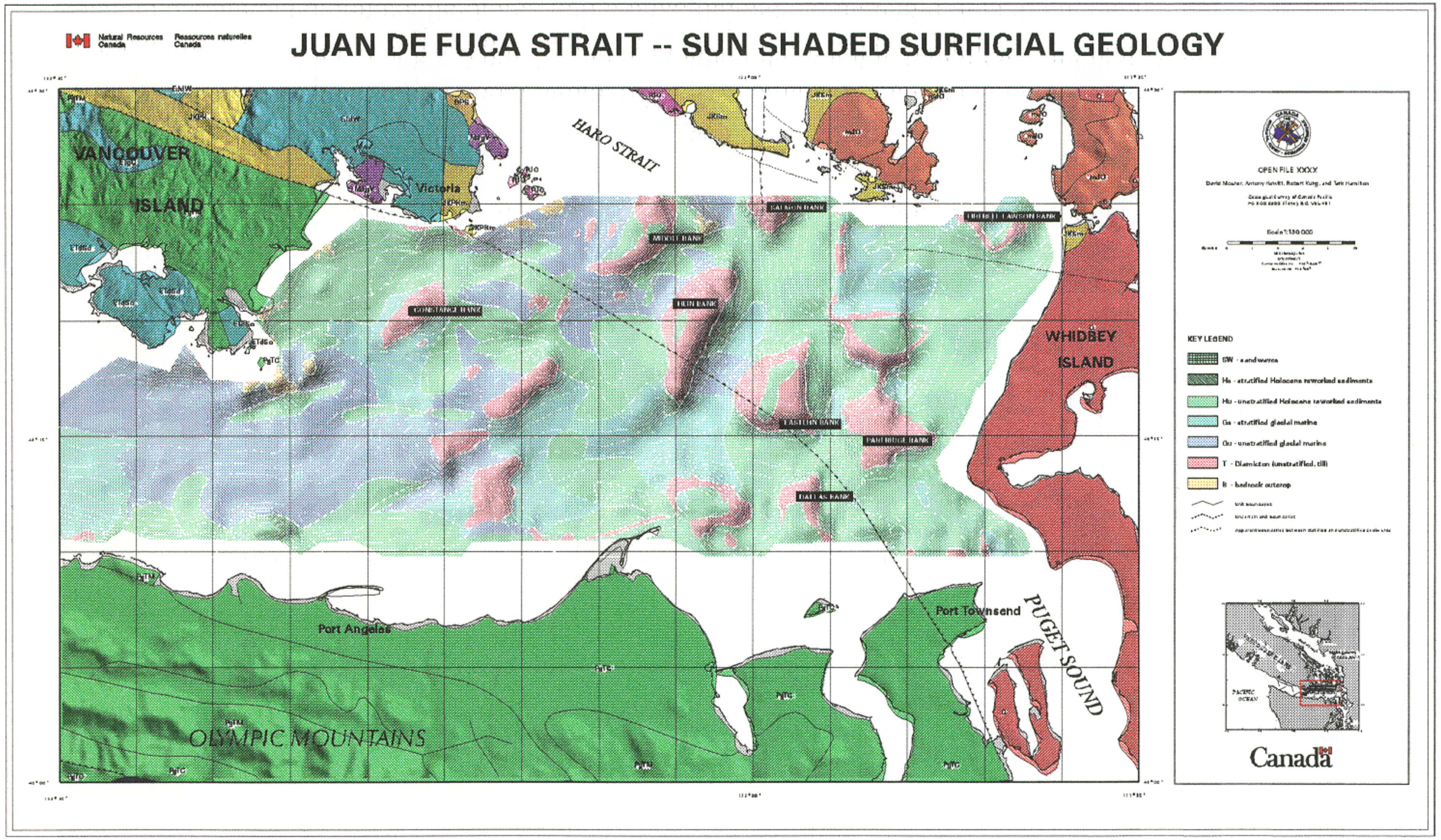

Natural Resources Canada
Ressources naturelles Canada
JUAN DE FUCA STRAIT -- SUN SHADED SURFICIAL GEOLOGY
VANCOUVER ISLAND
Victoria
HARO STRAIT
WHIDBEY ISLAND
Port Townsend
PUGET SOUND
Port Angeles
OLYMPIC MOUNTAINS
CONSTANCE BANK
MIDDLE BANK
HEIN BANK
SALMON BANK
EASTERN BANK
PARTRIDGE BANK
DALLAS BANK
OPEN FILE XXXX
David Mosher, Antony Hewitt, Robert Kung, and Tark Hamilton
Scale 1:130 000
KEY LEGEND
SW - sandwaves
Hs - stratified Holocene reworked sediments
Hu - unstratified Holocene reworked sediments
Gs - stratified glacial marine
Gu - unstratified glacial marine
T - Diamicton (unstratified, till)
B - bedrock outcrop
PACIFIC OCEAN
Canada

Figure 7

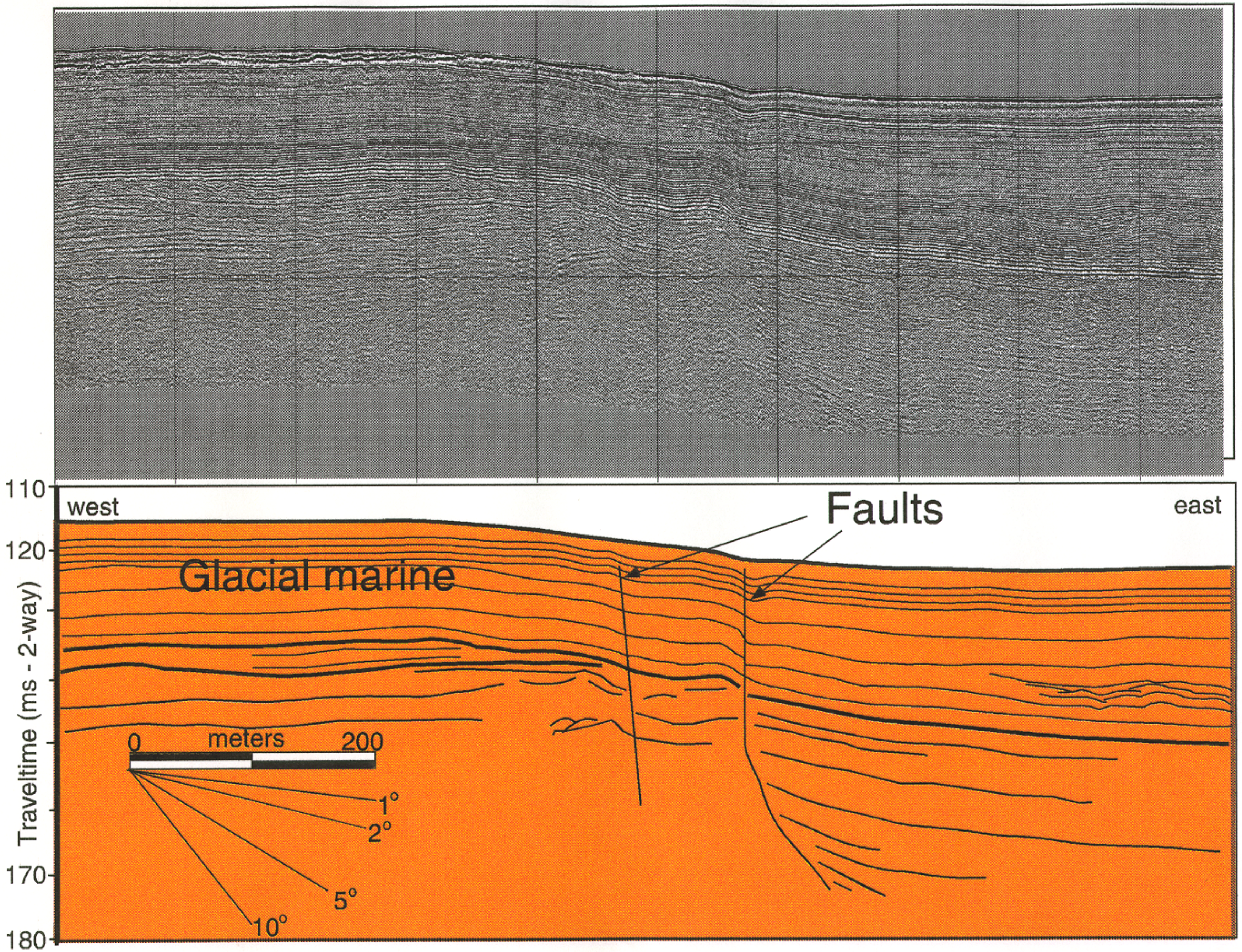

110
120
170
180
Traveltime (ms - 2-way)
west
east
Faults
Glacial marine
0
meters
200
1°
2°
5°
10°

Figure 8

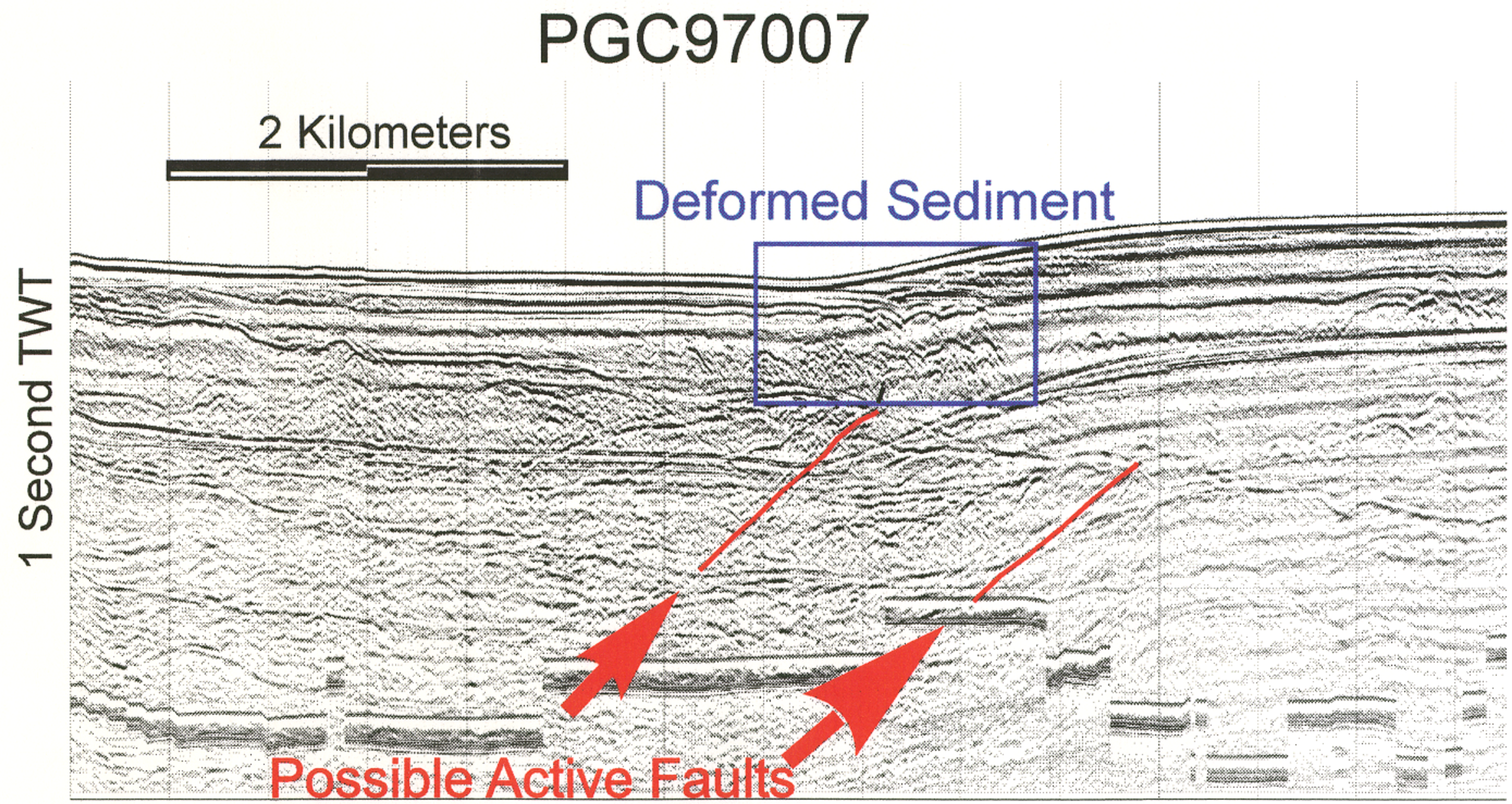

PGC97007
2 Kilometers
Deformed Sediment
1 Second TWT
Possible Active Faults

Figure 9

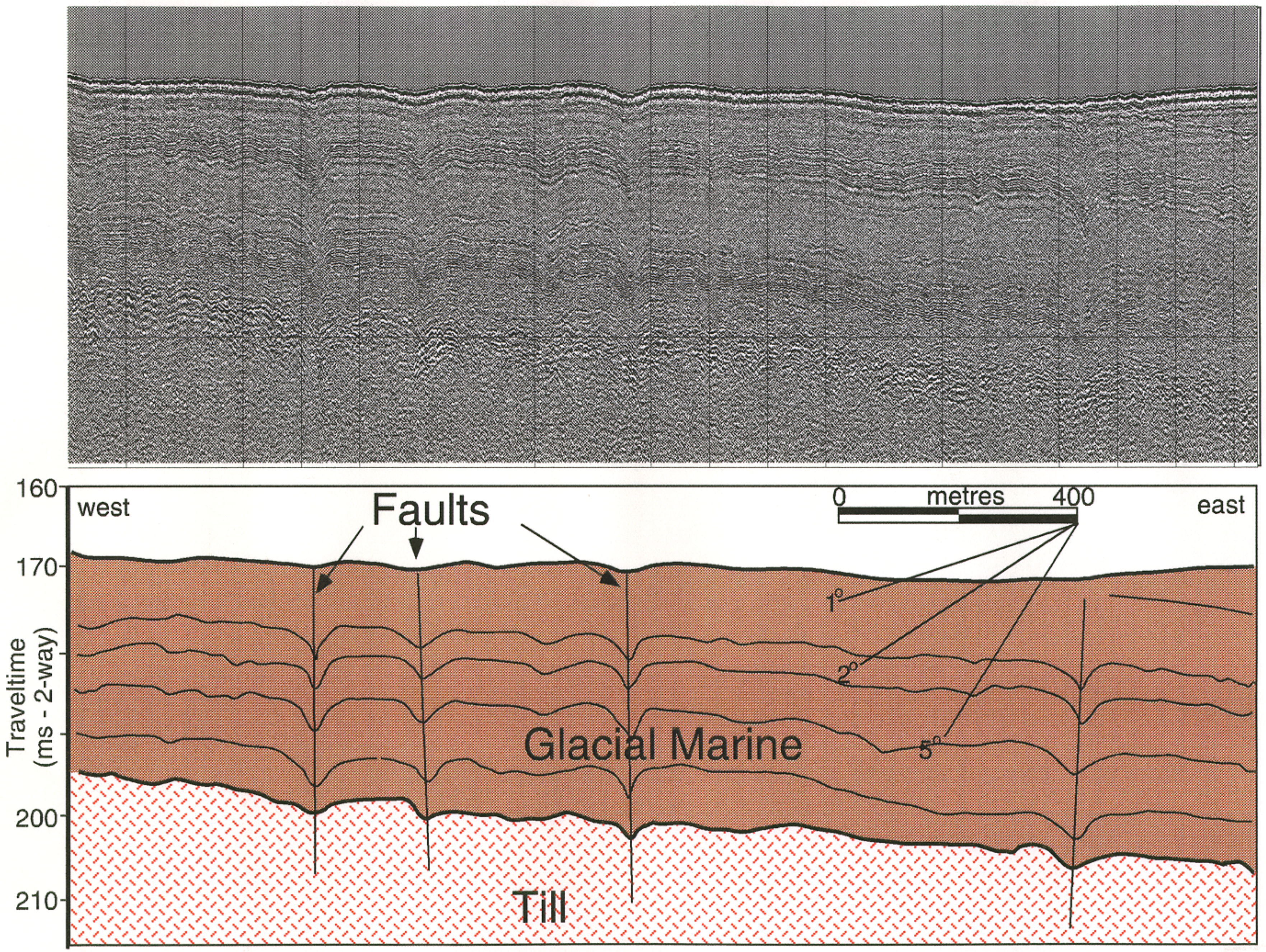

160
170
Traveltime
(ms - 2-way)
200
210
west
Faults
0
metres
400
east
1°
2°
5°
Glacial Marine
Till

Figure 10

JUAN DE FUCA STRAIT -- MAPPED FAULTS

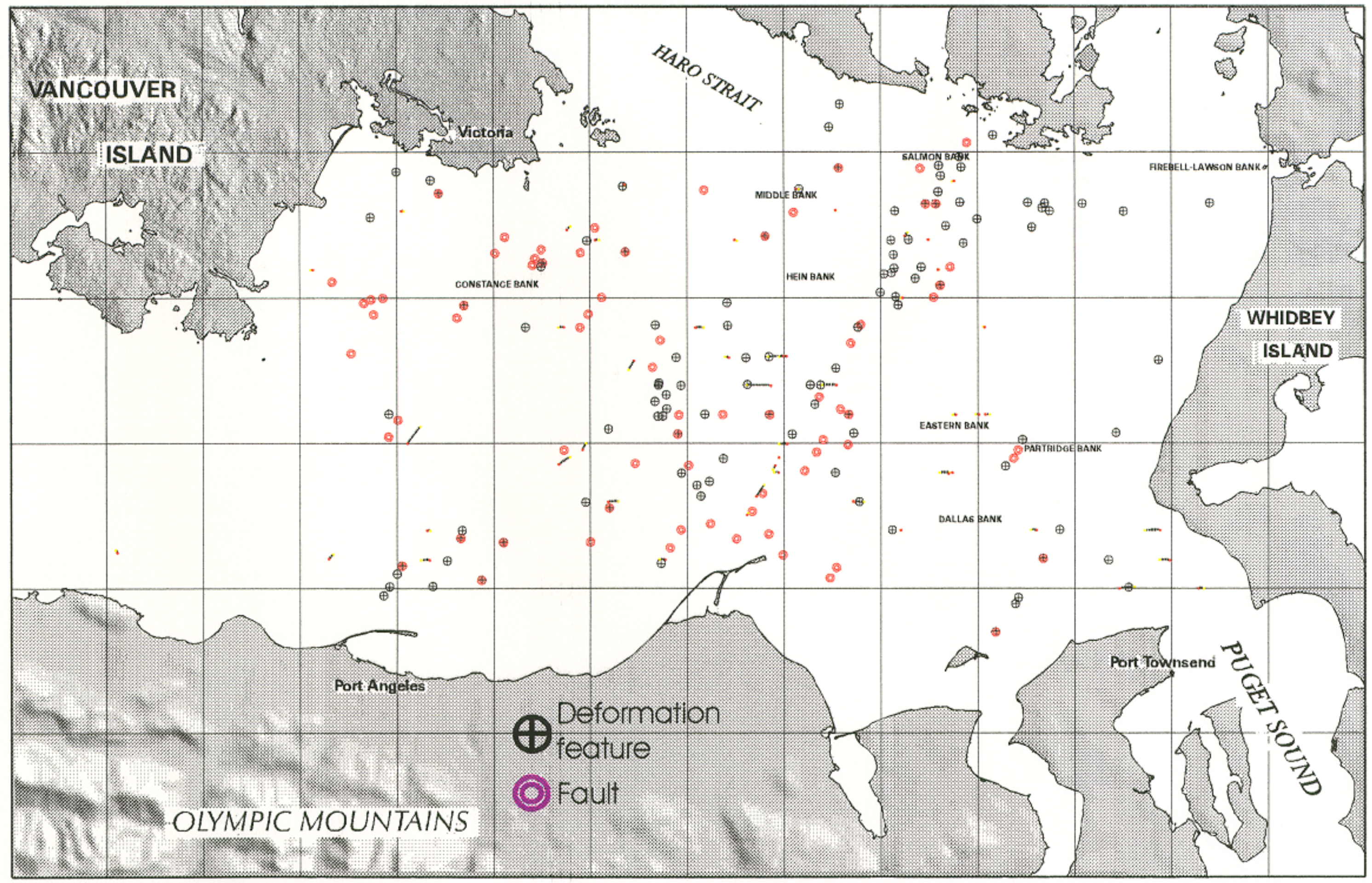


Figure 11