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Critical review

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Active faulting in the northern Juan de Fuca Strait: implications for Victoria, British Columbia

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Abstract: The Devil's Mountain Fault Zone extends east to west from Washington state to just south of Victoria in the northern Juan de Fuca Strait. Recently collected geophysical data were used to map this fault zone in detail, which show the main trace, and associated primary and secondary (conjugate) faults that occur within a 6 km wide deformation zone west of the Canada/U.S.A. boundary. The fault zone has been active in the Holocene as seen in the offset and disrupted upper Quaternary strata, seafloor displacement, and deformation within sediment cores taken close to the axis of the faults. Based on the length and previously estimated slip rates of the fault zone in Washington state, it appears to have the potential of producing a strong earthquake adjacent to Victoria, perhaps as large as magnitude 7.0 or greater.

Résumé : La zone de failles de Devil's Mountain s'étend d'est en ouest de l'État de Washington jusqu'à un point situé tout juste au sud de Victoria dans le nord du détroit Juan de Fuca. Des données géophysiques récemment acquises ont été utilisées afin de réaliser une cartographie détaillée de cette zone de failles, qui permet de visualiser la trace principale de la faille ainsi que les failles primaires et secondaires (conjuguées) associées, lesquelles sont contenues à l'intérieur d'une zone de déformation d'une largeur de 6 km à l'ouest de la frontière canado-américaine. La zone de failles a été active à l'Holocène, comme en témoignent les couches du Quaternaire supérieur morcelées et décalées, le déplacement du plancher océanique et la déformation observée dans des carottes de sédiments prélevées à proximité de l'axe des failles. Étant donné la longueur de la zone de failles dans l'État de Washington et les estimations antérieures de la vitesse de glissement le long de celle-ci, il semble exister une possibilité qu'un violent tremblement de terre, d'une magnitude aussi élevée que 7,0 ou même plus, survienne à proximité de Victoria.

INTRODUCTION

Geological mapping from mainland Washington State across Whidbey Island and eastern Juan de Fuca Strait has revealed extensive active crustal faults that trend westward toward the Canadian/U.S.A. boundary (Johnson et al., 2001). These faults result from the converging Cascadia forearc that is caught between a northward-migrating forearc sliver and a more stationary buttress of older crust in Canada. The area is subject to earthquakes from sources on the subduction zone interface, in the downgoing slab, and on shallow crustal faults in the upper plate. Little is known of the western extent of the crustal fault zones as they cross into Canada toward the city of Victoria, nor their potential for generating a sizable earthquake.

To address the seismic risk to Victoria, high-resolution geophysical surveys were undertaken in the north-central Juan de Fuca Strait as part of a larger Canada/U.S.A. program to map the Devil's Mountain fault zone (DMFZ) from Washington state to Vancouver Island. Our objective here was to determine if active faults occur near the city of Victoria, provide a detailed map of these faults, and give a preliminary assessment of the possibility of earthquakes on these features.

DEVIL'S MOUNTAIN FAULT ZONE

The Devils Mountain fault (Hobbs and Pecora, 1941) is associated with an alignment of aeromagnetic anomalies that extend more than 125 km from the Cascade Range foothills of Washington state to Vancouver Island and possibly merge with the Leech River and/or San Juan faults (Johnson et al., 2001). At its east end, the Devils Mountain fault merges with the north-trending Darrington fault zone (Tabor, 1994). The DMFZ trace then extends through Quaternary deposits of the Skagit River delta and Whidbey Island and into the eastern Juan de Fuca Strait. Based on interpretation of industry seismic-reflection data, Johnson et al. (1996) suggested that the fault continues its westerly trend across the strait.

Oblique convergence of the Juan de Fuca Plate below North America, along with larger scale shearing of the Pacific Plate against North American Plate, provides the driving force for crustal faulting and deformation (Fig. 1).

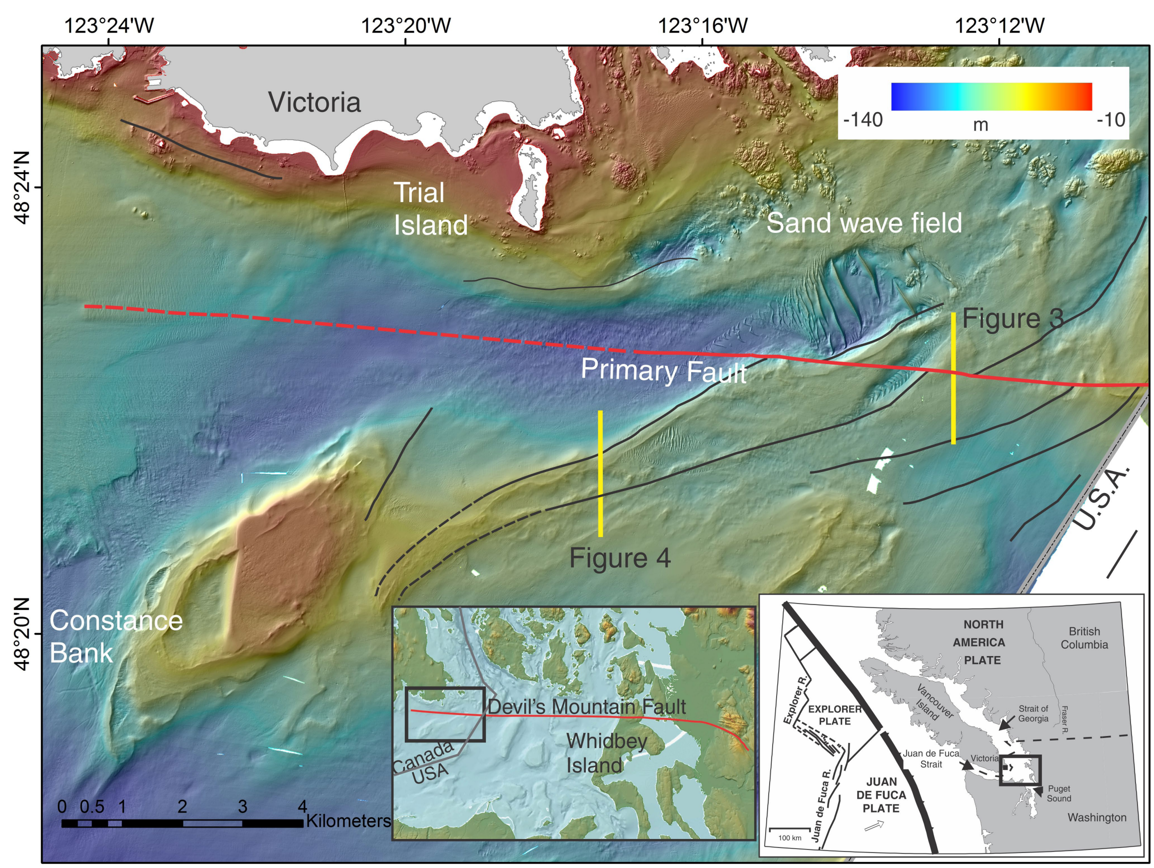

Figure 1. Multibeam swath bathymetry image of northern Strait of Juan de Fuca adjacent to the city of Victoria, showing mapped active faults of the DMFZ. Locations of Figures 3 and 4 are shown.

The Washington coast Range and Olympic mountains represent part of a forearc sliver that is moving northward relative to the Cascade Range and is buttressed to the north by pre-Tertiary basement in the San Juan Islands and on Vancouver Island (Johnson et al., 2001; Kelsey et al., 2012).

Loveseth (1975) suggested left-lateral slip on the DMFZ, based on its on land linearity and juxtaposition of upper Eocene to lower Oligocene continental and marine strata. Based on marine data, Johnson et al. (2001) concluded that the DMFZ is a transpressional left-lateral, oblique slip 'master fault' with no obvious piercing points. Johnson et al., (1996) noted that on seismic-reflection data from the eastern Juan de Fuca Strait, the DMFZ is locally imaged as a north-dipping reverse fault. The DMFZ has numerous adjacent obliquely oriented faults and folds that form a deformation zone with a width greater than 10 km.

Johnson et al. (2001) estimated vertical slip on the DMFZ of 0.05 to 0.31 mm/yr. They suspected that the lateral component of slip may be larger, but probably no more than about 0.75 mm/y, based on regional geological considerations. The long-term shortening rate in the Puget Sound Gulf/San Juan Islands region, which includes the DMFZ, following the removal of the subduction-related interseismic loading of the margin and signal owing to the postglacial rebound from the total GPS velocity field, is approximately 5 mm/y (Mazzotti et al., 2002; Hyndman et al., 2003).

The Utsalady Point fault and Strawberry Point fault that cross Whidbey Island are interpreted to be a reverse fault strands associated with the DMFZ (Johnson et al., 2001). Trenches across the Utsalady Point fault reveal evidence of at least one and probably two late Holocene earthquakes (Johnson et al. 2004). Glaciomarine drift exposed in the trenches reveals evidence of about 95 to 150 cm of vertical and 200 to 220 cm of left-lateral slip. Radiocarbon ages from a buried soil suggest that this faulting occurred 100 to 400 calendar years BP. In one trench, evidence exists for two earthquakes: one that occurred between 100 and 500 calendar years BP, and another between 1100 and 2200 cy BP, but deformation during a single earthquake is also possible. The displacement versus magnitude relation suggests that the two earthquakes were about M 6.7, or about M 7.0 if movements represent one earthquake. The offshore rupture may have produced a local tsunami with an amplitude similar to the vertical displacement.

Previous work reports that to the southeast of Victoria the DMFZ is associated with a large vertical displacement of the pre-Tertiary basement and Tertiary to Quaternary sedimentary rocks, along the major strand of the fault zone (Hayward et al., 2006). Pre-Quaternary rocks in the hanging wall (north of the major fault strand) exhibit anticlinal folding associated with movement on the DMFZ. Terminations of reflections on either side of the fault zone and north-dipping reflections further north constrain the dip of the fault to be sub-vertical to north dipping at an angle greater than 30 degrees (Hayward et al., 2006). Ramachandran (2012) showed that spatial velocity gradients can be effectively used in identifying subsurface discontinuities in the horizontal and vertical directions. This interpretation resulted in inferring the Washington state location of the DMFZ much more clearly. Portions of the DMFZ in Washington state imaged from gradient data appear to correlate with earthquake hypocenters, suggesting its seismogenic nature in those regions.

Hyndman et al. (2003) estimated a recurrence interval for large upper-plate fault earthquakes of magnitude 7.0 and greater in Puget Lowland–Georgia Strait region to be about 200 years based on the seismic moment rate required to accommodate the deformation rates derived from GPS and geological data. They suggested that additional large earthquakes in the upper plate may occur in this region shortly after great-plate-boundary earthquakes.

DATA ACQUISITION

Our identification of the fault zone was initially based on multibeam echosounder (MBES) swath bathymetry and backscatter that was acquired between 2000 and 2007 using a hull-mounted Kongsberg-Simrad EM1002 system, which operates at a frequency of 95 kHz utilizing 127 beams (Fig. 1). The data were collected on surveys carried out from the *CCGS Vector* by the Canadian Hydrographic Service, in co-operation with the Geological Survey of Canada. The tracks were positioned so as to insonify 100% of the seafloor with 50 to 100% overlap. Positioning was accomplished with broadcast differential GPS and the MBES data were corrected for sound velocity variations in the stratified water column using sound speed casts. The data were edited for spurious bathymetric and navigational points and subsequently processed using CARIS™ software. The gridded data were exported as ASCII files and imported into ArcInfo™ software for processing and image production.

Using the MBES bathymetry data to define the fault zone, surveys were undertaken in April 2008 aboard *CCGS Vector* in the north-central Juan de Fuca Strait from the U.S.A./Canada boundary west toward the city of Victoria, and in April 2013, a detailed survey of the DMFZ was completed using the same vessel. The 2013 survey undertook detailed surveys of the DMFZ from Whidbey Island in Washington state to Victoria, but only the detailed work near Victoria is presented here.

Survey data includes over 360 km of Huntec DTS high-resolution sparker sub-bottom profiles across the fault zone (Fig. 2), which allowed for penetration up to 100 m. The 2013 survey was run as a north-south-oriented grid with a line spacing of 200 m to allow for 3D imaging of the faults. Based on the profile data, 10 piston cores were collected (3 in 2008 and 7 in 2013) based on locations selected from the sub-bottom profile data. In the laboratory, cores were split, photographed and sampled for radiocarbon dating. In

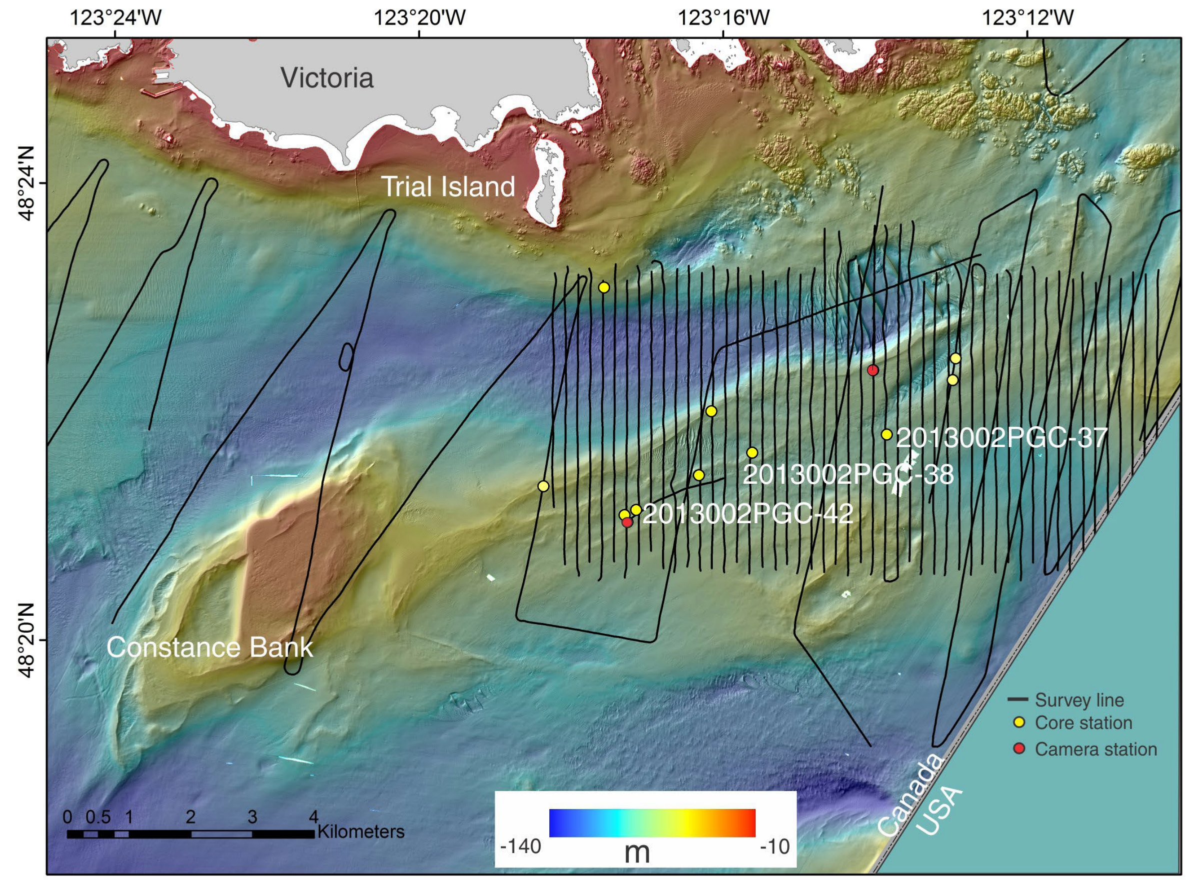

Figure 2. Survey coverage of Huntec DTS sparker sub-bottom profiles and locations of sediment cores and seabed camera stations, overlain on the multibeam swath bathymetry.

addition, seabed photographs were collected (150 photos total) at 2 camera stations (Fig. 2) along faults within the DMFZ deformation (thrust and fold) zone.

RESULTS

Based on the interpretation of the sub-bottom profiles an area 6 km wide is defined as the DMFZ, which extends from the U.S.A./Canada boundary westwards to offshore central Victoria, and consists of a main strand, primary, and secondary (conjugate) faults (Fig. 1). At 123° 15′W (Fig. 1), the surface expression of the main east-west trending strand of the fault zone becomes a subtle bathymetric expression continuing to the west. East of 123° 15′W a series of reverse to thrust and near vertical normal faults form a thrust-and-fold belt conjugate to the main strand. Termination of reflections on either side of the primary thrust or reverse fault (Fig. 3) constrain the dip of the fault to be sub-vertical to north dipping at an angle usually greater than 45 degrees.

Within a distinct deformation zone, expressed on the seafloor as uplifted folded and faulted highs (Fig. 1), conjugate faults in a northeast-southwest trend branch off the primary fault. At least eight conjugate faults, three north and five south of the primary fault, have been mapped on the Canadian side of the international boundary within north-central Juan de Fuca Strait.

The southwest-trending conjugate fault pair, west of 123° 13′W has a distinctive profile and always a seabed surface expression (Fig. 4). A south-dipping to nearly vertical fault, with flower-like structure (Fig. 4) breaks to seabed surface, often in a minor (4 m deep) seafloor valley or trench. Deformation of the Quaternary sediments occurs on either side of the fault with significant folding south of the fault. Offsets are at least 20 m. North of this fault, between 300 to 900 m, a second vertical to north-dipping fault (greater than 45 degrees) displaces stratified Quaternary sediments through to the seabed surface. The fault pair continues toward the southwest beyond the geophysical survey data, but the faults are identifiable in the MBES bathymetry data. The surficial expression, as seen in the MBES bathymetry, suggests that these paired faults end at Constance Bank (Fig. 1), though until further geophysical data are collected the western extent of the faults remains unknown.

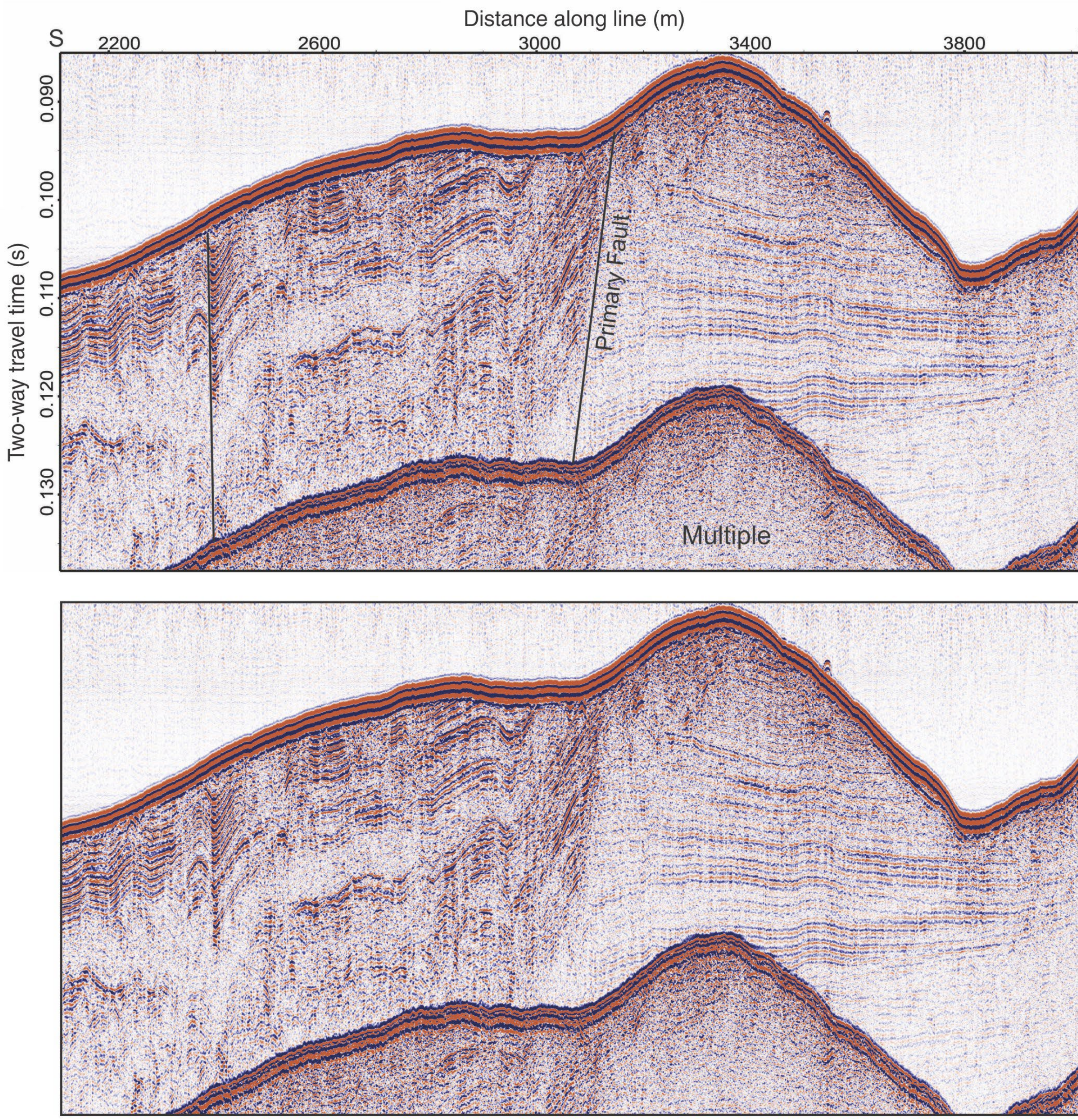

Figure 3. Annotated and original Huntec DTS sparker sub-bottom profile of the primary fault of the DMFZ and one conjugate fault. Notice the deformed, folded strata on the southern side of the primary fault. Vertical exaggeration is 11 X. Location of the profile is shown in Figure 1.

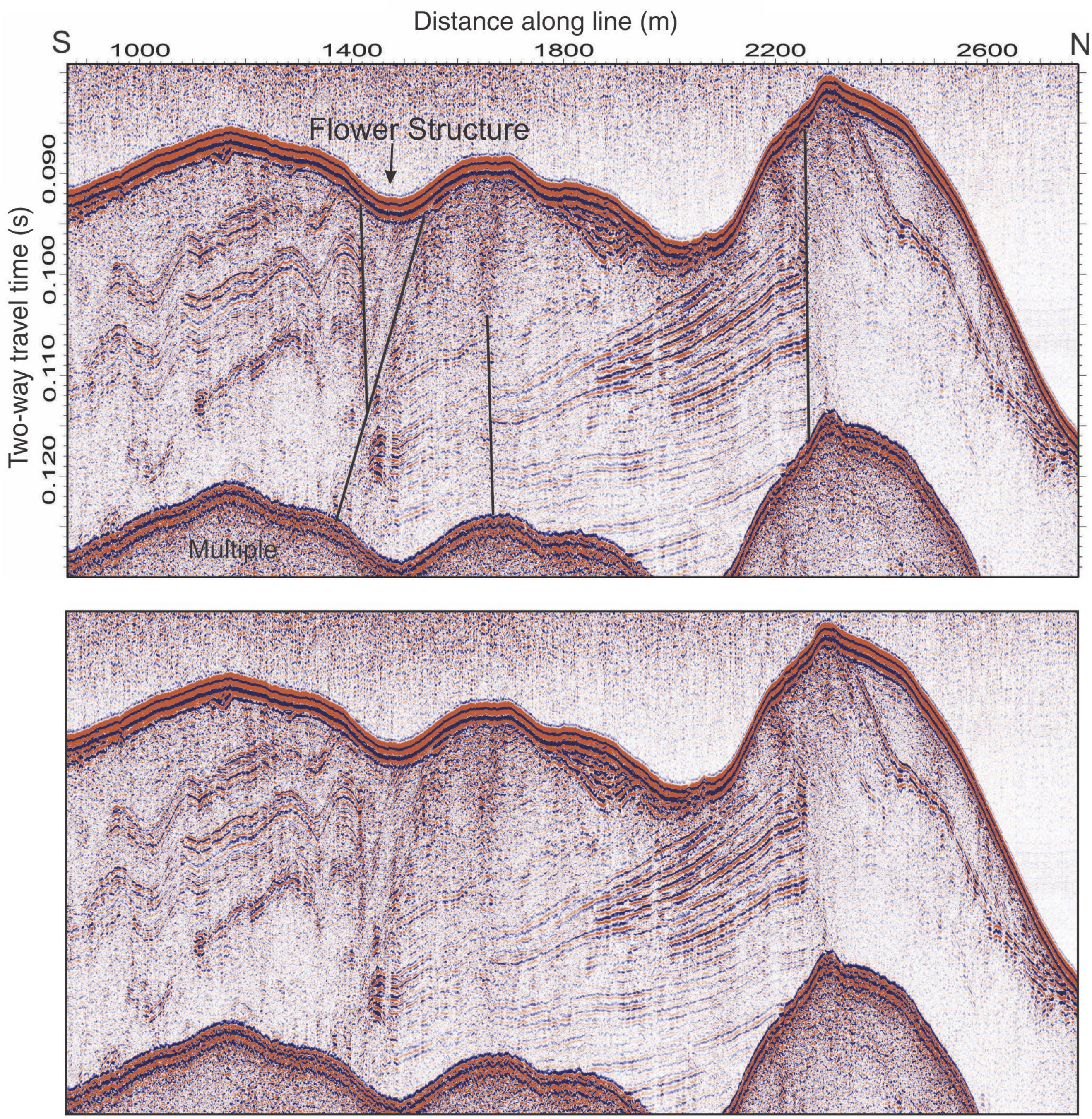

Figure 4. Annotated and original Huntec DTS sparker sub-bottom profile of the southwest trending conjugate fault pair. Notice the deformed, folded strata south of the fault pair. Vertical exaggeration is 11 X. Location of the profile is shown in Figure 1.

The acoustic stratigraphy in the high-resolution sub-bottom profiles is characterized by one dominant seismic facies. Discontinuous to semi-continuous reflections progressively become more coherent, higher amplitude, and closely spaced toward the seabed. Within the mapped area the unit is between 20 and 50 m thick. Reflections within the fault zone are extensively folded and faulted. This stratified unit is unconformably overlain in some areas by a very thin unstratified facies. Where this unit thickens, extensive sand and gravel wave fields are found (Fig. 1), including dunes that reach a maximum height of 25 m, with 500 m wavelengths (Mosher and Thomson, 2000)

Cores collected within the fault zone vary from only a few cm to 3.0 m in total length. For those cores that had reasonable penetration the stratigraphy is very similar. A surficial shelly-muddy-sand unit of less than 40 cm (average of 20 cm) in thickness is the uppermost unit in all cores. This unit contains fine gravel and the occasional large cobble. The base of the unit is bounded by an erosional unconformity. Underlying the unconformity are dark grey, stiff muds with minor gravel and cobbles throughout. The unit has silt laminations that vary in concentration throughout the cores. For the cores (e.g. Core 2013002–37; *see* Fig. 2 and 5) taken at the surface exposure of the fault, deformed laminations are apparent. There is little evidence of shell or foramanifers within this lower unit. However, core 2013002-42 (Fig. 2) has a sub-unit of 70 cm of thick grey laminated mud with burrows below the unconformity, which then changes to laminated, dark grey, stiff mud, as in the other cores.

Except for the upper few centimetres of all the cores, there is a lack of datable material. The surficial sandy gravel unit is considered to be mobile and therefore any dates from the upper part of this unit would be of no value. One conventional radiocarbon date (9,630 ^{14}C y BP) was obtained just below the unconformable boundary between the two units in core 2013002PGC-38 (Fig. 5).

Photographs obtained from the two camera stations along the faults (Fig. 2) show a sandy gravel seabed with abundant cobbles and shell fragments. Many areas contain large angular to sub-rounded boulders. Sponges, anemones and urchins are the most common species identified in the photographs.

DISCUSSION

The thrust and fold belt associated with the Devil's Mountain fault zone (DMFZ) near Victoria is very apparent in the high-resolution sub-bottom profiles, as seen in the deformation of a thick stratified acoustic sequence. This sedimentary sequence is interpreted by Hewitt and Mosher (2001) to be a glaciomarine deposit that extends over much of the eastern Juan de Fuca Strait. Cores collected within this unit (Fig. 5) are typical of ice-proximal glaciomarine sedimentation (Hewitt and Mosher, 2001; Barrie and Conway, 2002). The sediments were likely deposited near or just under a retreating and degrading ice sheet, subsequent to the end of the Fraser Glaciation between 13 690 and 10 270 ^{14}C yr BP (Hewitt and Mosher, 2001). The fine-grained sediments of this unit (Fig. 5) are very stiff and, consequently, deform in a similar fashion to bedrock. The upper bioturbated unit of core 2013002-42 (Fig. 2) may represent a transition to ice distal sedimentation. The radiocarbon date of 9630 ^{14}C yr BP, just below the surficial sand unit in 2013002PGC-38 (Fig. 5), may represent early postglacial sedimentation soon after ice had left the region (Hewitt and Mosher, 2001; Barrie and Conway, 2002).

Faults observed in the seismic-reflection profiles along the southern San Juan Islands and Vancouver Island associated with the DMFZ are either reverse faults or thrust faults with a distinct component of thrust motion and the overriding plate being highly fractured with many conjugate faults. Within the area of our study, transpression appears to be occurring along the DMFZ expressed as wrench-fault-like deformation. The deformation off Victoria appears to be right-lateral, based on the conjugate faulting. Transpression is a result of north-south shortening (Mazzotti et al., 2002).

Although the dip of the DMFZ is not precisely constrained by our data, we infer a moderate to steep northerly dip, which is similar to the steep northerly dip interpreted for the DMFZ on Whidbey Island and steeper than the northerly dips mapped by deep seismic surveys for the Leech River and Survey Mountain faults at the southeast tip of Vancouver Island. Evidence for Quaternary movement on the DMFZ includes 1) offset and disrupted upper Quaternary strata through to the seabed imaged on seismic-reflection profiles; 2) sediment core data that suggests deformation; 3) several metres of displacement along exposed faults in upper Quaternary sediments; and 4) late Quaternary folds with limb dips of as much as approximately 10°. Using the relationship between rupture length and moment magnitude refined by Wells and Coppersmith (1994) and assuming that the entire mapped length of the DMFZ from inside Washington state to offshore Victoria (~125 km) could rupture in one event, an earthquake of magnitude of 7.5 could be generated on this structure within 5 km of Victoria. Because of the many fault strands, the documented paleoseismic behaviour in Washington state, and the left-lateral movement in Washington and right-lateral movement offshore Victoria, a single rupture of the entire fault seems unlikely, but cannot be ruled out.

Recent movement (Holocene) on the fault is inferred from the surface seafloor expressions of the primary thrust fault set and many of the conjugate faults in the seismic-reflection profiles. Much of the seafloor along the western end of the DMFZ, in Canadian waters, is being eroded, so dating younger sediments in order to determine frequency of movement and timing of the last earthquake event is difficult. However, younger sediments do occur along the central portion of the DMFZ south of the San Juan Islands. Further examination of cores obtained as part of this same field program from sediments juxtaposed by the faults along the central and eastern fault zone, on the U.S.A. side of the

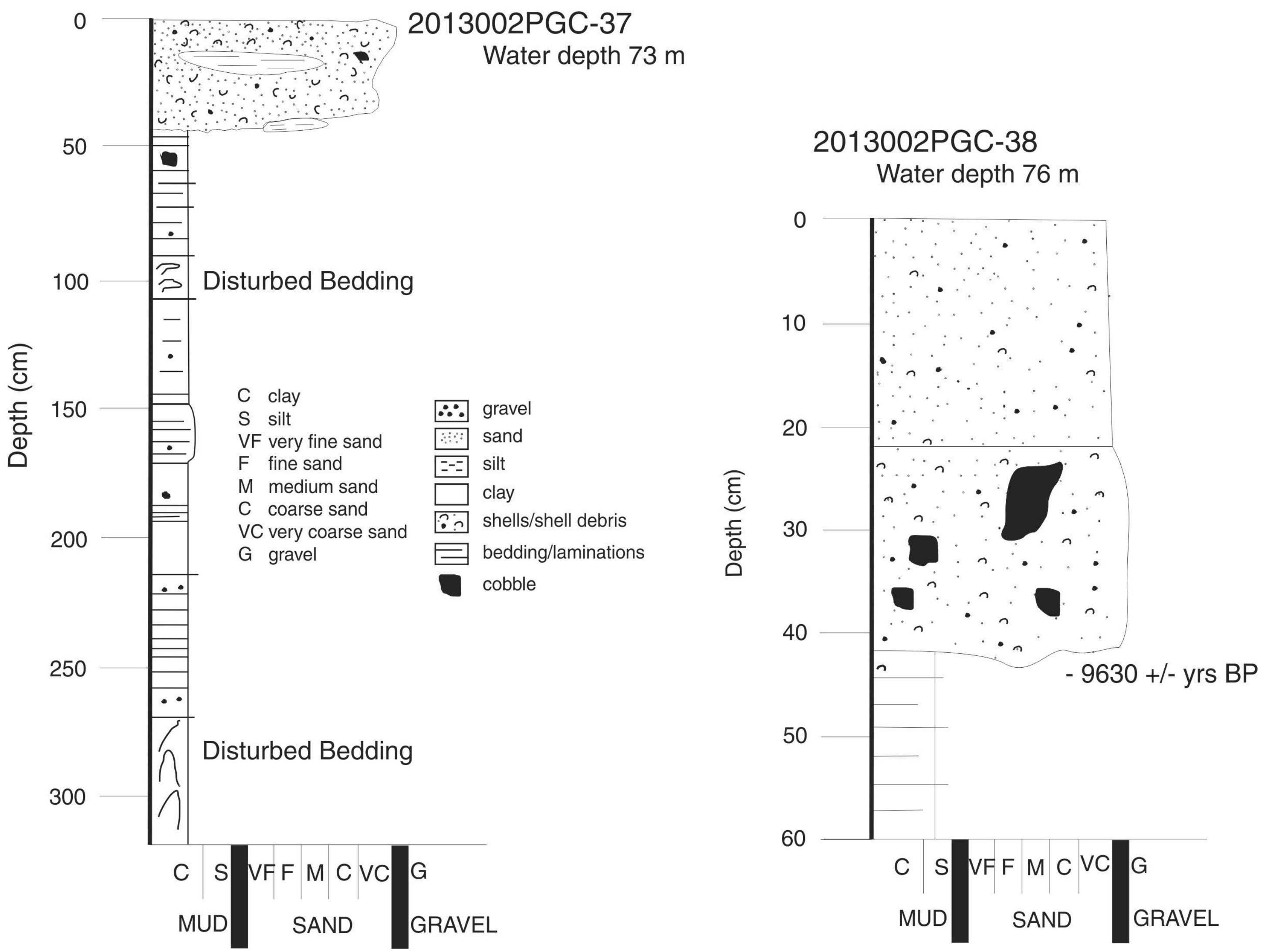

Figure 5. Schematic diagrams of representative cores within the DMFZ (cores locations in Figure 1). Core 2013002PGC-37, located within the southern fault of the conjugate pair, has a thin sandy-gravel mobile unit that unconformably overlies a very stiff, laminated silty-clay that contains ice-rafted debris. Notice the disturbed bedding within the core. Core 2013002PGC-38, located between the southwest trending conjugate fault pair, consists of a 42 cm sandy-gravel unit that overlies unconformably on a laminated silt unit. This unit may represent early post-glacial deposition, dated to 9,630 14C yr BP. The radiocarbon date was analyzed by Beta Analytic and the sample number is Beta 367871.

International boundary, should provide a chronology of displacement through the Holocene for that region of the DMFZ.

Although the DMFZ has not been traced onto Vancouver Island, MBES data suggests that it projects into the region just south of Victoria where the northeast shallow-dipping Leech River and Survey Mountain faults are less than 2 km apart and continue offshore. The data here does not suggest any connection between these faults, though they are separated by only 5 km. Further data are required to the west of our survey data set examined here to determine any relationship between these fault zones.

One analogy to understand risk for Victoria is to evaluate the impact of the 2010 and 2011 earthquakes that occurred near Christchurch, New Zealand. The September 2010 magnitude 7.1 earthquake occurred west of the city along an active fault that broke through to the surface and approached to about 25 km from the city. It involved a complex thrusting and strike-slip rupture sequence. The earthquake resulted in about $ 4 billion NZ dollars in damage and fortunately no deaths, largely due to the time of its occurrence at 4:35 a.m. However, the deadly 2011 earthquake happened in the noon hour when city centre buildings were occupied and resulted in the loss of 185 lives with damage of approximately $40 billion NZ dollars. It had an effective magnitude of 6.7 and was approximately 5 km from central Christchurch at its closest approach, a result of movement along a previously unknown crustal reverse fault tilting toward Christchurch. The DMFZ is less than 5 km from central Victoria and is likely capable of similar sized earthquakes.

SUMMARY

Based on recently collected geophysical and sediment core data, the western extent of the active DMFZ has been mapped for the first time, offshore the city of Victoria. The occurrence of this active fault poses the real possibility of an earthquake, similar to the devastating 2011 Christchurch, New Zealand earthquake, occurring near the city of Victoria. The data set used to provide this preliminary interpretation is part of a larger data set collected in 2013 along the greater length of the marine extension of the DMFZ in the northern Juan de Fuca Strait. Once fully analyzed, a better understanding of fault geometry and activity will be determined, including displacements, ages of deformation and tsunami potential. In addition, further survey data are required to map the western extent of the DMFZ directly offshore Victoria and Esquimalt, British Columbia.

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