Historical Tsunamis at the Seal Cove and Victoria Canadian Coast Guard Stations, British Columbia

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V8L 4B2

2018

Canadian Technical Report of

Hydrography and Ocean Sciences 325

Fisheries and Oceans Canada Pêches et Océans Canada

Canadian Technical Report of Hydrography and Ocean Sciences

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HISTORICAL TSUNAMIS AT THE SEAL COVE AND VICTORIA CANADIAN COAST GUARD STATIONS, BRITISH COLUMBIA

by

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Cat. No. Fs97-18/325E-PDF ISBN 978-0-660-25797-6 ISSN 1488-5417

Correct citation for this publication:

Alexander B. Rabinovich, Richard E. Thomson, Lauren M. Lupton and Stephen Mundschutz, 2018. Historical Tsunamis at the Seal Cove and Victoria Canadian Coast Guard Stations, British Columbia. Can. Tech. Rep. Hydrogr. Ocean Sci. 325: ix + 44p.

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ABSTRACT

Historical Tsunamis at the Seal Cove and Victoria Canadian Coast Guard Stations, British Columbia.

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Tsunamis generated by subduction zone earthquakes are a major threat to coastal installations around the Pacific Rim of Fire. Here, several tsunami generation regions are considered, with emphasis on two major source regions impacting directly the west coast of British Columbia: an Alaska 1964-type rupture and a Cascadia Subduction Zone (CSZ) failure. Meteorological events are also found to be a source for tsunami-like events.

Tide gauge records from Prince Rupert and Victoria are used to define the threat to the Seal Cove and Victoria Coast Guard Stations. Victoria is at risk from most Pacific tsunamis, however, at Prince Rupert only eight tsunamis, mainly associated with earthquakes of magnitude 8.6 or greater, have been observed. Observations suggest that, prior to reaching Prince Rupert, high frequency waves are dampened or filtered out by the shallow water topography as they propagate through Dixon Entrance and across the shelf. Paleotsunami evidence suggests that both sites are at risk from CSZ-generated tsunamis.

Estimation of the tsunami risk to the British Columbia west coast is of vital importance for areas of new construction or renovation and requires accurate modelling using high resolution bathymetry.

RESUME

Tsunamis historiques aux stations de la Garde côtière canadienne de Seal Cove et de Victoria, en Colombie-Britannique.

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Les tsunamis générés par les séismes dans les zones de subduction constituent des menaces majeures pour les installations côtières autour de la ceinture de feu du Pacifique. À cet endroit, plusieurs régions de production de tsunamis sont prises en compte, et on met surtout l’accent sur les deux principales régions sources qui ont des effets directs sur la côte ouest de la Colombie-Britannique : une rupture de type Alaska 1964 et une faille de la zone de

subduction Cascadia. Les événements météorologiques sont également une source de tsunamis.

Les dossiers de marégraphes de Prince Rupert et de Victoria sont utilisés pour définir la menace pour les stations de Seal Cove et de Victoria de la Garde côtière. Victoria est à risque de la plupart des tsunamis du Pacifique. Toutefois, à Prince Rupert, seulement huit tsunamis associés à des séismes de magnitude 8.6 ou plus ont été observés. Les observations laissent supposer que, avant d'atteindre Prince Rupert, les vagues à haute fréquence sont amorties ou filtrées par la topographie des eaux peu profondes à mesure qu'elles se propagent dans l'entrée Dixon et le long du plateau continental. Des preuves de paléotsunamis semblent indiquer que les deux sites sont à risque de tsunamis générés par la zone de subduction Cascadia.

L'estimation des risques soulevés par les tsunamis pour la côte ouest de la Colombie-Britannique est de première importance pour les zones de nouvelles constructions ou de rénovation et nécessite une modélisation précise à l'aide de données bathymétriques à haute résolution.

PREFACE

Large segments of the British Columbia coastline are susceptible to tsunamis generated within the Pacific Ocean. The catastrophic events of the last two decades, in particular the 2004 Sumatra and 2011 Tohoku tsunamis, have once again demonstrated the threat of major tsunamis to coastal installations and human life.

The purpose of this report is to investigate historical tsunami wave heights at two Canadian Coast Guard (CCG) stations on the west coast of British Columbia: Seal Cove and Victoria. Century-long tide gauge records for Prince Rupert and Victoria have been used to estimate the tsunami risk to both these stations.

This study has demonstrated high tsunami risk for these two regions and that this risk is mainly associated with earthquakes generated at the Alaskan rupture and Cascadia Subduction Zone (CSZ). Tsunami waves of greater than 1.0 m are considered to pose a risk at both sites. The research has enabled us to specify the requirement for reliable modelling of maximum tsunami wave heights and associated currents for both regions and for both source areas. This has been undertaken as a series of four reports by Fine et al. (2018a-d).

The main findings of the present report are the following:

Prince Rupert/ Seal Cove

- Eight tsunamis have been identified in the Prince Rupert tide gauge records, the gauge site most representative of the Seal Cove Coast Guard Station region. Five of these events, consisting of four major seismically generated Pacific tsunamis of the 20th century (1952, 1957, 1960 and 1964) plus one tsunami of unknown origin, were recorded by a pen-and-paper analogue tide gauge. The three others (all occurring during the period 2010-2012), were recorded by high-quality digital instruments with 1-minute sampling rates.
- A consistent feature of all seven distal tsunami events recorded by the Prince Rupert tide gauge is the long wave periods of 100-120 minutes, which are much longer than tsunami waves at other sites on the British Columbia coast.
- Of the recorded tsunami events, the tsunami from the $M_w = 9.2$ Alaska earthquake of 28 March 1964 had the greatest impact on the Prince Rupert region. The first wave arrived at Prince Rupert 2 hours and 54 minutes after the main earthquake shock. The initial wave had an amplitude of 62 cm, while the second, and highest wave of the entire event, had an amplitude of 132 cm and had a trough-to-crest wave height of 271 cm.

- The high frequency (short period) components of seismically generated tsunamis arriving at the outer north coast of British Columbia are strongly attenuated as they propagate toward the Prince Rupert region through Dixon Entrance. As a consequence, only major earthquakes, such at the 1964 Alaska earthquake, with large spatial source regions, that are capable of generating low frequency tsunami waves (periods of around 100 minutes) can significantly affect the Prince Rupert region. It is the spatial extent of the earthquake, in addition to its magnitude, that determines the tsunami threat to the Prince Rupert region.
- A major M_w~9.0 earthquake along the CSZ could generate significant (> 100 cm) tsunami waves at Prince Rupert and Seal Cove and may also pose a serious risk to this region.

Victoria

- Thirty-two tsunamis have been recorded by the Victoria tide gauge, which is located in the Inner Harbour, roughly one km from the Victoria CCG station. Nine of these events, consisting of five major Pacific tsunamis of the 20th century (1946, 1952, 1957, 1960 and 1964) and four moderate tsunamis from 1994-1996, were recorded by a pen-and-paper analogue tide gauge. Twenty-three others occurring during the period 2000-2016, were recorded by high-quality digital instruments with 1-minute sampling; five of these were tsunamis of meteorological origin while all others were seismically generated tsunamis.
- Recorded tsunamis had a consistent, regular character with dominant periods of 20-25 minutes and 50-55 minutes, which appear to be related to resonant features of the inner and outer basins of the harbour.
- Of the 27 seismic tsunamis, only seven tsunamis had maximum trough-to-crest wave heights of >20 cm; these tsunamis were associated with the seven greatest earthquakes (M_w 8.6-9.5) that occurred in the Pacific Ocean during the observation period: 1946 Aleutian (M_w 8.6), 1952 Kamchatka (M_w 9.0), 1957 Andreanof Islands (M_w 8.6), 1960 Chile (M_w 9.5), 1964 Alaska (M_w 9.2), 2010 Chile (M_w 8.8) and 2011 Tohoku (M_w 9.0). The highest tsunamis with maximum wave height, h_{max} > 50 cm were associated with the 1960 (73 cm), 1964 (147 cm) and 2011 (52 cm) events.
- Of the recorded tsunami events, the tsunami generated by the M_w = 9.2 Alaska earthquake of 28 March 1964 had the greatest impact on the Victoria region and the entire outer coast of British Columbia. Great Alaska earthquakes with M_w = 9.0-9.3 are a major threat to the Victoria area.

Tsunamis generated along the CSZ pose another major threat to the entire coast of British Columbia. Recent paleotsunami studies for the coast of Vancouver Island and the west coast of the USA, as well as preliminary numerical modelling of CSZ tsunamis for coastal North America, demonstrate the high risk of CSZ tsunamis for British Columbia and, in particular, for the area of Victoria. The Great CSZ earthquake of 26 January 1700 (M_w 9.0) generated a major trans-oceanic tsunami that caused significant destruction in Japan and strongly affected the outer coast of British Columbia: research indicates that tsunami waves with amplitudes of 15-20 m likely struck the west coast of Vancouver Island at the time of this event. Numerous seismotectonic studies indicate that great megathrust earthquakes in the CSZ region have occurred on a regular basis in the past and can be expected to occur with an average return period of about 500 years in the foreseeable future.

1 INTRODUCTION

Large segments of the British Columbia coastline are susceptible to tsunamis generated within the Pacific Ocean. Destructive tsunamis have occurred on this coast in the past and will occur again in the future [cf. Clague, 2001; Clague et al., 2003]. Catastrophic events in the last two decades, in particular, the 2004 Sumatra and 2011 Tohoku tsunamis, once again demonstrated the threat of seismically generated tsunamis to coastal installations and human life. Estimation of the potential tsunami risk to the British Columbia coast is vitally important, especially for areas being considered for new construction or major renovations [Leonard et al., 2014].

The purpose of this project is to investigate historical tsunami wave heights at the Victoria and Seal Cove Canadian Coast Guard (CCG) stations on the west coast of British Columbia. Basic information on the risk to these stations from major tsunami source regions in the Pacific Ocean is needed by Fisheries and Oceans Canada to inform the CCG how to optimally upgrade or redesign the stations in light of the risk from major tsunamis arriving on the British Columbia coast. Although there now exits a reasonable body of research on tsunamis in the northeast Pacific, there has been no specific tsunami research related to these particular sites.

This study examines historical observations of major Pacific tsunamis along the coast of British Columbia and provides estimates of the possible tsunami wave heights at the two CCG stations. These estimates will help to identify the potential sources of tsunami waves that are a major threat for these two specific sites and to provide background information in support of the numerical modelling of tsunami waves to be provided by separate project elements.

2 SEAL COVE AND PRINCE RUPERT

Seal Cove is located adjacent to Prince Rupert, British Columbia, Canada. The Seal Cove Water Airport is actively used by Inland Air, Vancouver Island Helicopters and White River Helicopters. It is classified as an airport of entry by Nav. Canada and is controlled by the Canada Border Services Agency.

Prince Rupert has a population of roughly 12,500 and this port is the land, air, and water transportation hub for British Columbia's North Coast. Situated on Kaien Island, the city lies just north of the mouth of the Skeena River and is linked by a short bridge to the mainland. The city is located along the island's northwestern shore, fronting on Prince Rupert Harbour.

Although detailed tsunami zoning for Seal Cove and Prince Rupert areas is only possible through numerical modelling of the entire region (which is the topic of a separate project [Fine et al., 2018a,b]), some preliminary estimates can be obtained based on historical data and the information on tsunamis and earthquakes observed in this region.

There are three main sources of information on historical tsunamis in this region:

- Paleotsunami studies
- Archived material, local newspapers, magazines, and existing tsunami catalogues
- Tide gauge records and other instrumental data.

Paleo-examination of tsunami waves is an effective method for identifying historical tsunamis and for estimating actual onshore run-up heights [cf. Clague et al., 2000, 2003; Wang et al., 2013]. Unfortunately, detailed paleotsunami studies in the vicinity of Prince Rupert and in northern British Columbia began only recently [Peter Bobrovsky, 2017; Pers. Comm.], and no results are yet available.

Tsunami catalogues give crucial information about historical tsunamis. In this study, we have used catalogues by Lander [1996] and Stephenson et al., [2007] and also recent papers on tsunami occurrences along the coast of British Columbia [Stephenson and Rabinovich, 2009; Rabinovich et al., 2013; Fine et al., 2015]. We have also examined local newspapers for major tsunami events that occurred in the Pacific Ocean, in particular for information on the 1946 Aleutian, 1952 Kamchatka, 1957 Andreanof Islands, 1960 Chile and 1964 Alaska tsunamis. The only information in newspapers for these events in the Prince Rupert region is for the 1964 tsunami, the strongest tsunami recorded at Prince Rupert [Prince Rupert Daily News, 1964].

The most useful information on historical tsunamis is obtained from the analysis of tide gauge records. Although there is no tide gauge at Seal Cove, there is an instrument at Prince Rupert, located only a few kilometres north of Seal Cove. This gauge can be used effectively to obtain preliminary estimates of tsunami occurrence in this region.

2.1 OBSERVATIONS

The Prince Rupert tide gauge has been operational since 1909 and has one of the longest records for the Pacific coast of Canada. Tsunami observations at this station for the period of 1909-2006 were examined by Stephenson et al., [2007]. For this report, we re-examined several analogue tsunami records for major historical events of 1909-1998 measured at Prince Rupert, digitizing record segments containing these events and also analyzed the last twenty years of digital records at this site.

Although the total length of the Prince Rupert tide gauge record is >100 years, only five tsunamis were measured at this site during the pre-digital period (Table 1). Four of them were associated with the most powerful earthquakes of the 20th century, with momentum magnitude $M_w \geq 8.6$: 1952 Kamchatka, 1957 Andreanof Islands, 1960 Chile, and 1964 Alaska. One other tsunami listed by Stephenson et al., [2007] for this site was an "event of unknown origin" (1963), but was likely due to atmospheric processes. Additionally, we examined the Prince Rupert tide gauge records for one more major historical event (the 1946 Aleutian tsunami), which is listed by Lander [1996] as among the strongest in the Pacific Ocean. However, we could not detect any tsunami signatures in the Prince Rupert record related to this event.

It is important to note that the tides at Prince Rupert are quite large (> 6 m) [Thomson, 1981], making the detection of relatively weak tsunamis from analogue records almost impossible. Moreover, this makes difficult the reliable direct estimation of tsunami parameters even for the greatest tsunamis as, for example, the 1952 Kamchatka, 1957 Andreanof Islands, 1960 Chile and 1964 Alaska tsunamis. For this reason, we used digitized records for these events to subtract the tides, enabling accurate estimation of the wave heights, periods and other parameters of the observed tsunami waves.

In 1998, the Canadian Hydrographic Service (CHS) initiated a major upgrade of the existing Tsunami Warning Stations (TWS) and Permanent Water Level Network (PWLN) on the British Columbia coast. The new digital instruments were designed to continuously measure sea level variations with much higher precision than the earlier analogue gauges and to store sea level data at one-minute sampling increments [Rabinovich and Stephenson, 2004]. These new data enabled CHS to identify and examine not only major events, but also many weak tsunamis and to significantly improve the general statistics of tsunamis for the British Columbia coast. Altogether these new instruments have recorded more than 25 tsunamis since 1998. This includes waves from the Great Sumatra tsunami of 26 December 2004 in the Indian Ocean [Rabinovich et al., 2006b], a number of trans-Pacific tsunamis and local tsunamis generated off the west coast of Canada [Stephenson et al., 2007; Stephenson and Rabinovich, 2009].

From the 25 tsunamis digitally measured for the British Columbia coast since 1998, only three tsunamis have been identified in the Prince Rupert tide gauge records. Two of these tsunamis, the 2010 Chile tsunami and 2011 Tohoku tsunami, were generated by the two strongest Pacific Ocean earthquakes in the 21st century, with magnitudes $M_w = 8.8$ and $M_w = 9.0$, respectively. The one additional tsunami in this list was generated by the $M_w = 7.7$ Haida Gwaii earthquake of 28 October 2012. This corresponds to the second strongest, instrumentally recorded, local earthquake in Canadian history and the largest thrust fault earthquake ever recorded along a predominantly strike-slip margin associated with the Queen Charlotte Fault [Cassidy et al., 2013; Leonard, 2014]. The epicenter of this earthquake was located westward from Moresby Island, Haida Gwaii (former Queen Charlotte Islands, see Thomson [1981]), relatively close to Prince Rupert (Figure 2.1).

Figure 2.1 Location of the Prince Rupert tide gauge (red circle) and other modern CHS tide gauges located on the outer coast of British Columbia (white circles). The yellow circles indicate stations Alert Bay, Bella Coola and Fulford Harbour that are not presently working but recorded several historical events. The Alert Bay tide gauge on the northeastern coast of Vancouver Island recorded the 1952, 1957, 1960 and 1964 tsunamis; the Fulford Harbour gauge recorded the 1957, 1960 and 1964 tsunamis, while a temporary tide gauge at Bella Coola recorded the 1957 tsunami. The epicenter of the Haida Gwaii earthquake (M_w = 7.7) 28 October 2012 is indicated by a red star.

Including all measurements, the tide gauge at Prince Rupert has recorded a total of eight tsunamis. Five of the tsunamis (major Pacific tsunamis of the 20th century and one tsunami of unknown origin) were recorded by a pen-and-paper analogue tide gauge; the three others, all during 2010-2012, were recorded by high-quality digital instruments with a 1-minute sampling interval. The epicenters of seven tsunamigenic earthquakes are shown in Figure 2.2; they all are situated in the major seismically active zone of the Pacific Ocean known as the “Ring of Fire”. Our analyses of tsunamis observed at Prince Rupert show that six were generated by earthquakes with $M_w \geq 8.6$ and correspond to the strongest tsunamis instrumentally recorded in the Pacific Ocean. The only exceptions are the 2012 Haida Gwaii tsunami, which was produced by a $M_w \geq 7.7$ earthquake within the thrust fault rupture zone near Moresby Island (i.e., close to Prince Rupert), and the 1963 event of “unknown origin”.

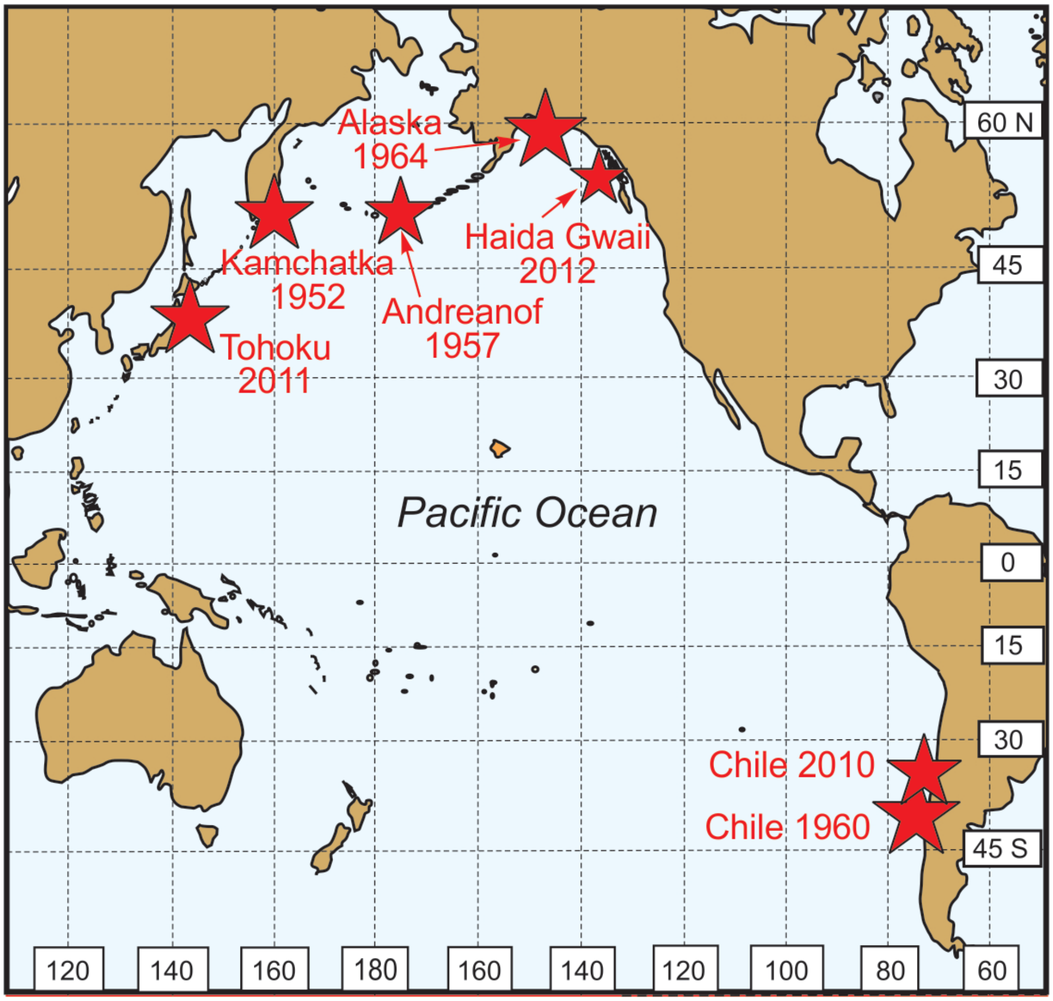

Figure 2.2. Epicenters of the seven distal earthquakes (red stars) that produced tsunamis recorded at Prince Rupert, British Columbia.

To estimate parameters of the tsunamis measured at Prince Rupert by analogue tide gauges, the 1952 Kamchatka, 1957 Andreanof Islands, 1960 Chile and 1964 Alaska tsunami records were digitized and resampled to 1-minute sampling. The astronomical tides were calculated for all records and subtracted from the original records; the resulting “residual records” were statistically analysed. The estimated wave parameters for these historical tsunamis were found to be slightly different from those presented by Wigen [1960], Wigen and White [1964] and Stephenson et al., [2007], which were based on direct examination of the paper records.

An important feature of all tsunami waves recorded at Prince Rupert is their long ’ringing” (duration of substantial oscillations). This feature is consistent among all observed tsunamis. A visual inspection of the wave forms for all seven seismically generated events yields periods of 100-120 minutes, which is much longer than at other sites on the British Columbia coast [cf. Stephenson et al., 2007; Stephenson and Rabinovich, 2009]. Specific information on the individual events is given below.

2.1.1 The Kamchatka Tsunami of 4 November 1952

The 1952 tsunami was generated by a M_w = 9.0 earthquake with the source area located near the southern end of the Kamchatka Peninsula, Russia. The tsunami had wave heights >18 m and killed about 10,000 people in Severo-Kurilsk (Paramushir Island, Northern Kuril Islands) and southern Kamchatka. It was the most devastating tsunami in Russian history [Gusiakov, 2013]. After six hours, 6-8 m waves struck the Hawaiian Islands, with a maximum wave height of 9.1 m on the easternmost coast of Oahu Island. However, no fatalities were reported from the far-field areas affected by this tsunami.

The Kamchatka tsunami was clearly recorded on the coast of British Columbia. According to Weeks and Studds [1953], Wigen [1983] and Stephenson et al., [2007], the maximum wave height at Prince Rupert was 28 cm; waves were also recorded at Tofino (58 cm), Victoria (~40 cm), Alert Bay (~40 cm) and Kitimat (noticeable, but small). The de-tided and high-pass filtered tsunami records are shown in Figure 2.3.

The maximum estimated wave height from the digitized record for Prince Rupert was 28 cm, which is the same as previously estimated by Weeks and Studds [1953] and Stephenson et al., [2007] directly from the analogue tide gauge records. However, other parameters significantly correct the earlier studies. In particular, the tsunami arrival time at Prince Rupert is now estimated to have been 00:43 UTC (November 5) instead of 02:20 UTC [Stephenson et al., 2007]. This means that the tsunami waves propagated from the 1952 source to Prince Rupert in 7h 45min, in good agreement with the calculated travel time [Weeks and Studds, 1953]. A particular property of all records (Figure 2.3) is the very long “ringing” of the tsunami waves for more than three days. An important feature of the tsunami waves observed at Prince Rupert compared to three other sites is the dominant period of 2 hours in the waves; at the other CHS tide gauge stations, the dominant periods were much shorter, 20-64 minutes. This prevalence for low frequency oscillations at Prince Rupert is clearly evident in the records presented in Figure 2.3.

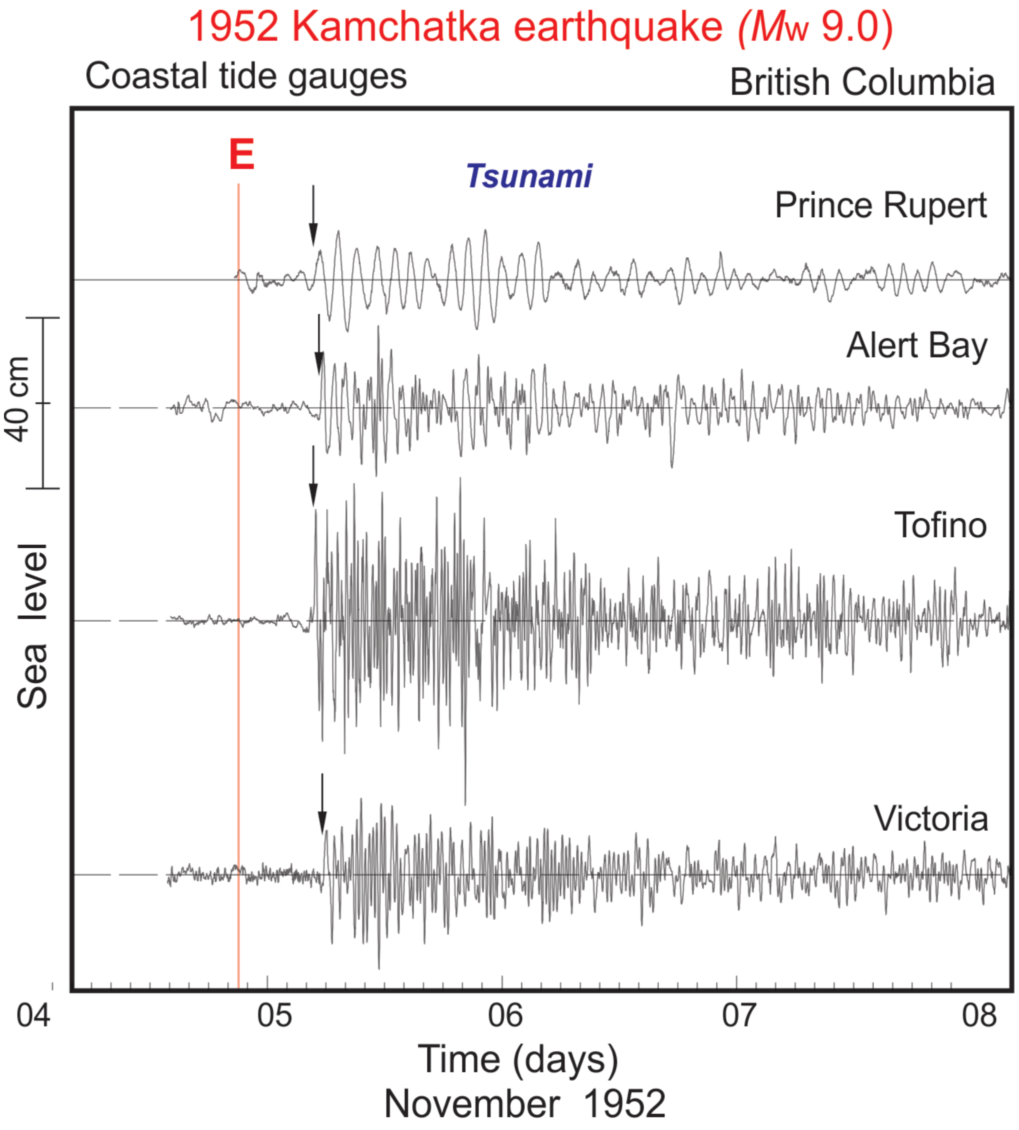

Figure 2.3. The 4 November 1952 Kamchatka tsunami recorded at Prince Rupert, Alert Bay, Tofino and Victoria on the coast of British Columbia. The solid vertical red line labelled “E” denotes the time of the earthquake; the arrows indicate the tsunami arrival.

2.1.2 The Andreanof Islands (Aleutian) Tsunami of 9 March 1957

The tsunami of 9 March 1957 was generated by a M_w = 8.6 earthquake whose source area was located south of the Andreanof Islands group, which are part of the Aleutian Islands (Figure 2.2). Based on the aftershock distribution, the source area of the earthquake was one of the longest of any earthquakes instrumentally recorded, stretching almost 1200 km along the Aleutian Trench [Johnson et al., 1994]. The earthquake generated a major tsunami that was recorded by tide gauges throughout the entire Pacific Ocean [Salsman, 1959]. The estimated tsunami wave heights on the coasts of some unpopulated Aleutian Islands were more than 20 m; the maximum wave height recorded was 3.6 m at

Kahului on the Island of Maui in Hawaii. The Hawaiian Islands suffered greatest, with infrastructure damages of approximately $5 million (in 1957 US dollars). Timely tsunami warnings prevented any direct fatalities, even in the furthest-field areas affected.

The effects of the 1957 event were poorly documented for the coast of British Columbia. An analysis of the analogue records by Wigen [1983] indicated that the maximum wave height at Tofino was 52 cm, but he did not examine any other records, probably because the tsunami signal was weak and not readily extracted from the tidal records. For this report, we digitized all available analogue records of this event, excepting Port San Juan (Port Renfrew), which was too noisy. We found that the tsunami was recorded at six stations: Fulford Harbour, Victoria, Tofino, Alert Bay, Bella Coola and Prince Rupert (see Figure 2.1 for the location of these stations). The 1957 de-tided and high-pass filtered tsunami records for the three northern stations, including Prince Rupert, are shown in Figure 2.4.

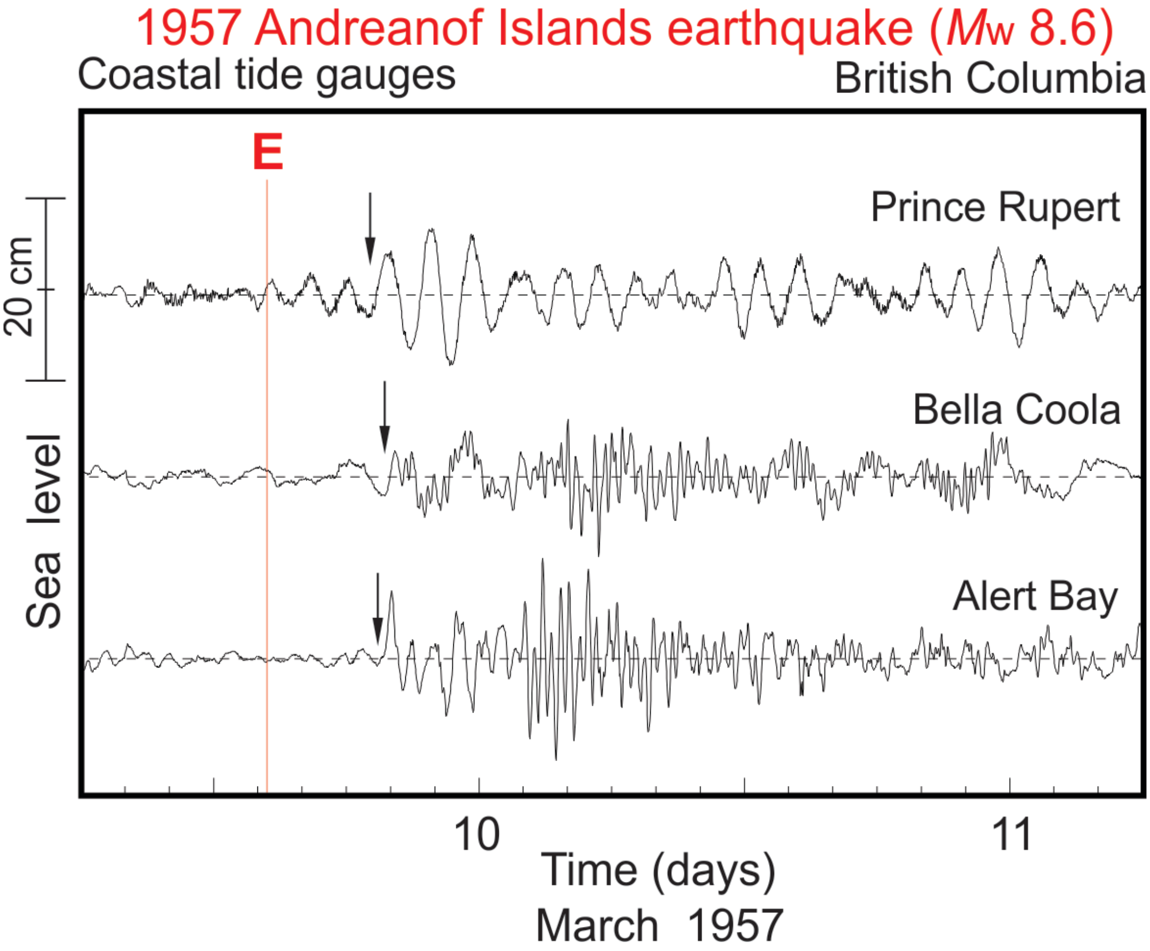

Figure 2.4. The 9 March 1957 Andreanof Islands tsunami recorded at Prince Rupert, Bella Coola and Alert Bay on the coast of British Columbia. The solid vertical red line labelled "E" denotes the time of the earthquake; the arrows indicate the tsunami arrival.

The maximum wave height of 48 cm was observed at Tofino, which is slightly less than the 52 cm height estimated by Wigen [1983] based on the original paper record of this event. The maximum estimated wave height at Prince Rupert was 15 cm and the tsunami arrived at 19:07 UTC (March 9), i.e., 4 hours 47 minutes after the main shock (14:22:27 UTC). The latter values indicate that the tsunami waves propagated from the 1957 source to Prince Rupert in 7 hours 45 minutes, in good agreement with the calculated travel time [Salsman, 1959]. A particular property of all records, which is similar to the 1952 tsunami (Figure 2.3), was the very long "ringing" of the tsunami waves for more than three days. A major feature of the tsunami waves observed at Prince Rupert (Figure 2.4) was the dominant period of 110 minutes. At all of the other stations, the dominant period was 22-25 minutes.

2.1.3 The Chilean Tsunami of 22 May 1960

The Chilean tsunami of 22 May 1960 was generated by the M_w = 9.5 Great Chile Earthquake, the strongest earthquake ever instrumentally recorded in the World Ocean. The tsunami from this event was the largest of the 20th century. In southern Chile, about 1,655 people were killed, 3,000 injured and 2,000,000 displaced; 61 people lost their lives on the coasts of the Hawaiian Islands, 142 in Japan, and 32 in the Philippines. The high degree of destruction and loss of life in a number of the Pacific countries located far from the source area was the impetus for international cooperation in tsunami research and mitigation, and resulted in the establishment of the International Tsunami Warning System in the Pacific (ITSU) and the Pacific Tsunami Warning Center (PTWC) in Honolulu, Hawaii [Pacific, 2015].

The 1960 tsunami was recorded by about 250 tide gauges in the Pacific Ocean [Berkman and Symons, 1960; Miller et al., 1962]. The maximum measured far-field wave height was 8.1 m at Sanriku, Japan. Strong oscillations with trough-to-crest wave heights of more than 3-5 m were recorded at a number of stations on the coast of Alaska [Lander, 1996], at sites relatively close to Prince Rupert.

The 1960 Prince Rupert tsunami record was digitized and examined; the de-tided and high-pass filtered record is shown in Figure 2.5. The first arrival of tsunami waves was indicated as "indefinite" by Wigen [1960] and Berkman and Symons [1960] based on analysis of the paper record. However, in the newly digitized and de-tided record, the tsunami arrival is very clearly observed.

The tsunami waves arrived at Prince Rupert 19 hours 46 minutes after the earthquake, in good agreement with the theoretical travel time[1]. The record was characterized by very long ringing (~2.8 days) and slow energy decay. The maximum trough-to-crest wave height recorded at Prince Rupert was 31 cm. In comparison, Wigen [1960] and Berkman and Symons [1960] estimated this height as 12 cm from the

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[1] Theoretically, tsunami waves propagate with the speed $c = \sqrt{gh}$, where g is the gravity acceleration and h is the water depth. For example, if h = 4 km, then c=200 m/s = 720 km/h. Estimated tsunami travel times to particular coastal locations from likely earthquake sources may be found on the following site: https://www.arcgis.com/home/item.html?id=effffe4b4b4e4e7c9d6a2954aafe9d78.

paper record. This maximum wave height was observed 26 hours after the first arrival denoted by the arrow in Figure 2.5. This demonstrates the prolonged threat of tsunami waves and associated strong tsunami-induced currents for coastal communities and infrastructure; the leading wave is not always the highest. Similar to what was observed during the 1952 and 1957 events, the 1960 tsunami waves at Prince Rupert had very long periods of about 100 minutes.

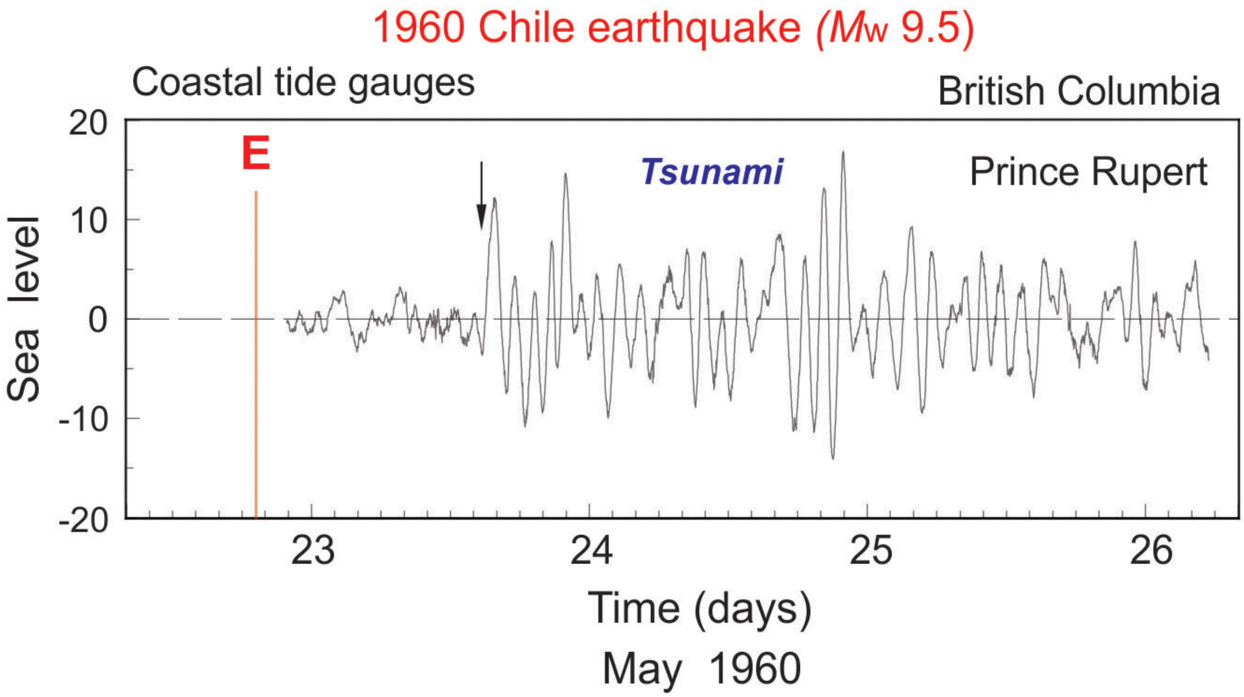

Figure 2.5. The 22 May 1960 Chilean tsunami recorded at Prince Rupert. The solid vertical red line labelled "E" denotes the time of the earthquake; the arrow indicates the tsunami arrival.

2.1.4 The 1963 Graham Island Event

On 28 March 1963, an anomalous "tidal wave" occurred on the northern and eastern coasts of Graham Island. Because the wave coincided with unusually high tide, an extraordinary high tide of 7.5 m occurred at Prince Rupert. This tide was 0.52 m above the predicted high tide. At Wiah Point (north coast of Graham Island), the wave, or waves, washed over a high-water rock and dislodged two big oil tanks and washed them onto the shore. A wave on the western coast of the island reached 10.7 m high, tore oil tanks from a concrete base and apparently took the life of one man. The wave caused extensive damage at Wiah Point and at the village of Masset [Stephenson et al., 2007].

An oceanic disturbance was reported from the Dixon Entrance region to the Queen Charlotte Islands (Haida Gwaii) during the night of 30-31 March 1963. Wave heights reached 3.7 to 5.5 m above high tide and caused minor damage at Langara Island, Wiah Point and Port Simpson. The disturbance was probably due to atmospheric activity and wind-generated storm waves, but was not recorded by any tide gauge and was not reported in any other area [Stephenson et al., 2007]. No correlation between this event and any seismic or atmospheric activity was found [Cloud, 1963]. Nevertheless, some features, in particular very low pressure in Hecate Strait, are evidence of a meteorological origin for this "tsunami". It is likely that the event was caused by the superposition of several correlated factors, including low atmospheric pressure, strong winds, and wind-wave set-up.

2.1.5 The 1964 Alaska "Good Friday" Tsunami

The Alaska earthquake of 28 March 1964 with magnitude M_w = 9.2 produced a catastrophic tsunami, the second strongest in the 20th century (after the 1960 Chilean tsunami). The maximum water rise was 20 m at the source. The earthquake also initiated a great number of landslides and submarine landslides that generated local tsunamis with a runup up to 70 m [Lander, 1996]. The earthquake, which was the strongest instrumentally recorded earthquake in the North Pacific Ocean and one of the strongest earthquakes ever recorded, occurred in the region of Prince William Sound, leading to widely used name of the "Prince William Sound Earthquake" [Spaeth and Berkman, 1967; Johnson et al., 1996]. Because of the date (28 March 1964), this earthquake and associated tsunami are also called the "Good Friday Earthquake and Tsunami". This event generated the strongest tsunami response ever recorded at Prince Rupert.

The 1964 earthquake occurred within the Alaska-Aleutian megathrust zone where the Pacific Plate subducts under the North American Plate (Figure 2.6). This zone has the greatest potential to generate destructive tsunamis and is one of the most seismically active fault zones in the North Pacific. The 1964 megathrust Alaska earthquake caused the most destructive tsunami in Alaskan history and, further south, strongly impacted the west coasts of the USA and Canada [Johnson et al., 1996; Myers and Baptista, 2001; Suleimani et al., 2013; Fine et al., 2018a,c]. In addition to the major tectonically-generated tsunami, the earthquake triggered several landslides in the coastal fjords of Alaska, resulting in more than 20 local tsunamis. Waves from some of these events were as high as 60-70 m [Rabinovich et al., 2003]. Of 132 fatalities associated with the 1964 earthquake, 122 were caused by tsunamis [Lander, 1996]. The tsunami spread over the entire Pacific Ocean and was recorded by a number of coastal tide gauges.

The tsunami swept southward from the source area in Prince William Sound along the British Columbia coast, causing about $10 million in damage (1964-dollar values). If such an earthquake and tsunami were to occur today, the cost of the damage would be a factor of 10 to 100 times greater. The

1964 tsunami was the strongest tsunami ever observed on the Pacific coast of Canada. According to [Spaeth and Berkman, 1967], the tsunami struck the coast of British Columbia near the time of high tide (see Figures 25 and 26 in [Stephenson et al., 2007]). The earliest recorded arrival was at 05:33 UTC at Tasu Sound on the west coast of Haida Gwaii. The highest wave reported in Canada was at Shields Bay on the west coast of Graham Island where the crest wave was reported to be ~5.5 m above the spring high water; the wave damaged a logging camp located in this region. The main damage occurred at the twin towns of Alberni and Port Alberni, with the maximum tsunami run-up at Port Alberni reaching more than 8 m [Stephenson et al., 2007].

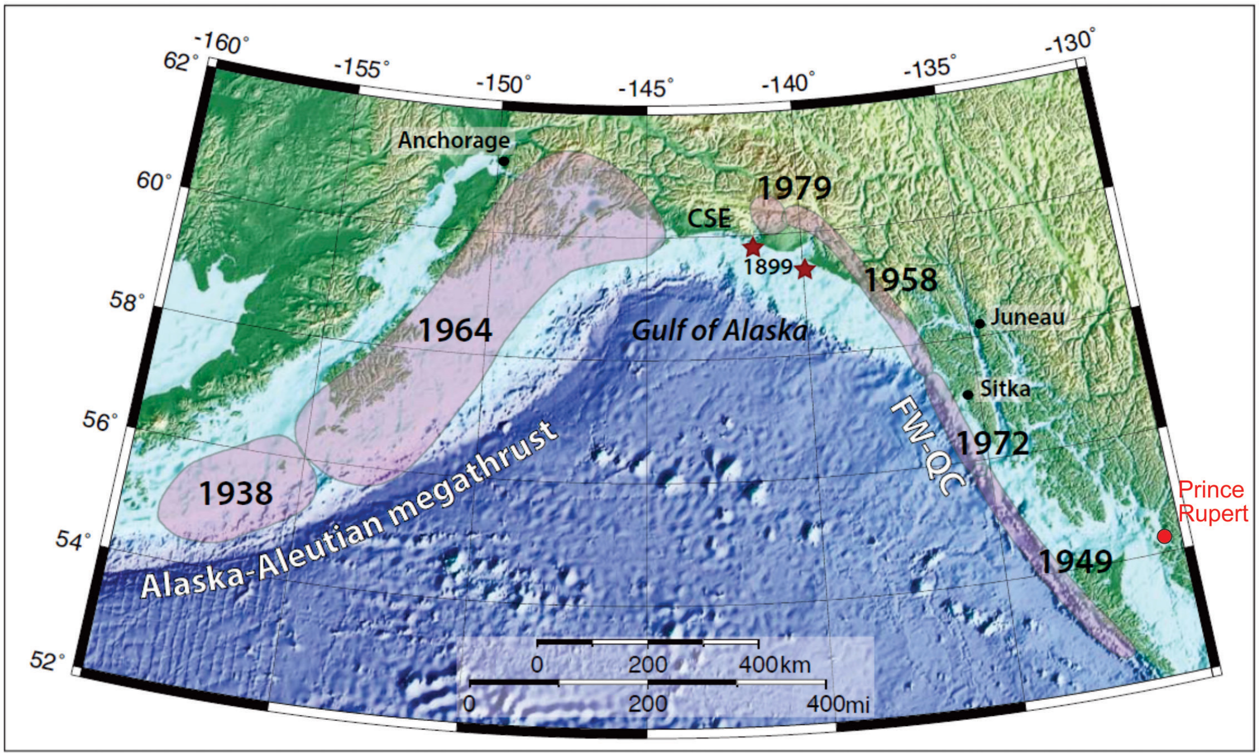

Figure 2.6. Map of south-central and southeastern Alaska with the rupture zones of major historical earthquakes (shaded). Red stars indicate epicenters of two September 1899 earthquakes. CSE=Chugach-St. Elias fold and thrust belt; FW-QC=Fairweather-Queen Charlotte fault system. Tide gauges at Sitka, Juneau and Anchorage are indicated by solid black circles (from Suleimani et al., [2013]). The red circle denotes the tide gauge at Prince Rupert.

Tsunami waves created severe damage at Prince Rupert. The details of the tsunami effects in Prince Rupert are described by local newspapers. Specifically:

- The vessel *Yaloa* sank at her Digby Island moorings;
- Eight to nine million feet of logs in Metlakatla Pass and Casey Cove were cut loose;

- The float and pierhead at Metlakatla were torn out;
- There was extensive breakwater damage at Fairway Bay;
- The submarine cable providing telephone service and main power supply to Digby Island was put out of action, causing Digby Island airport and homes to go on emergency power.

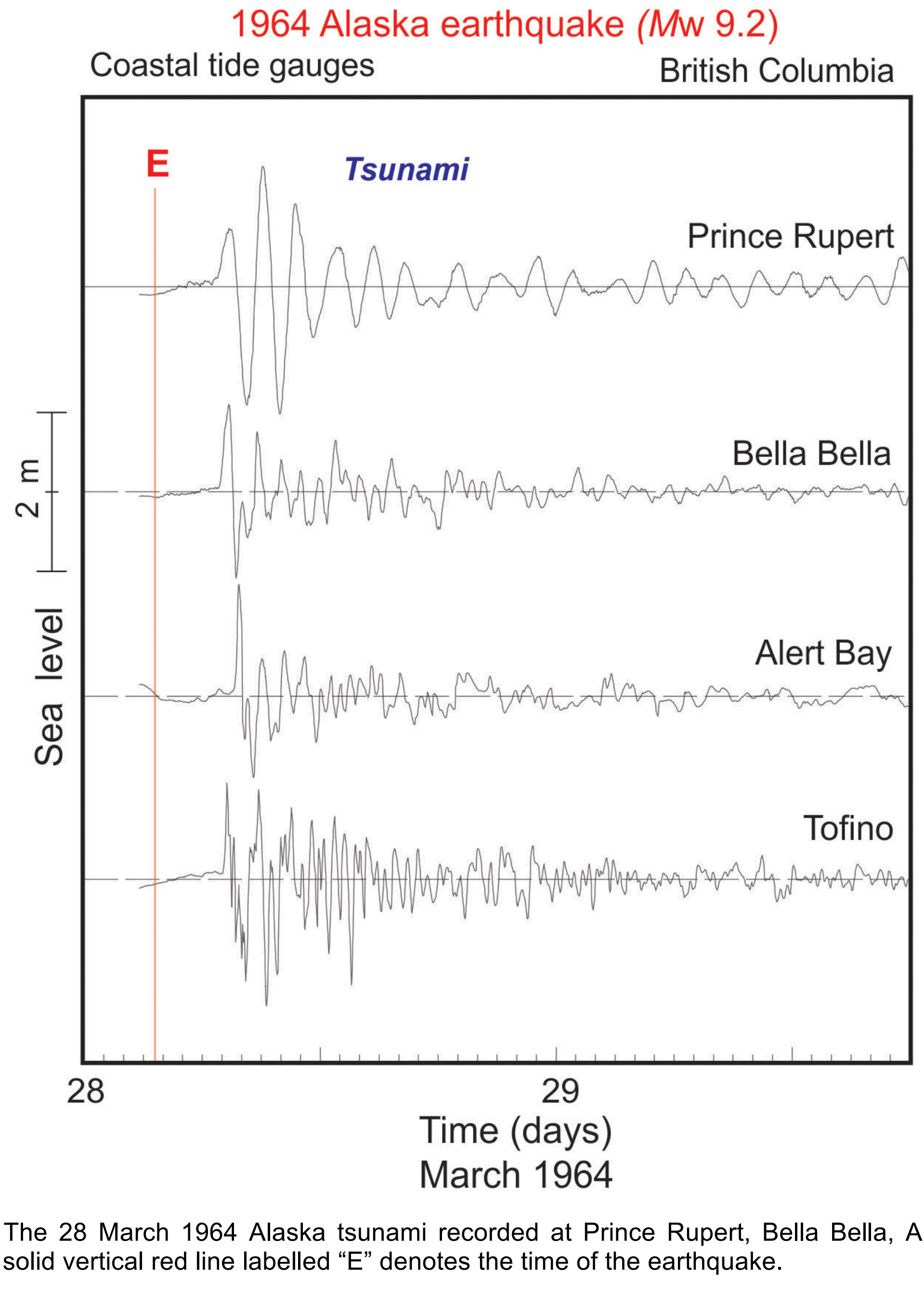

Figure 2.7. The 28 March 1964 Alaska tsunami recorded at Prince Rupert, Bella Bella, Alert Bay and Tofino. The solid vertical red line labelled “E” denotes the time of the earthquake.

Because the 1964 Alaska tsunami was the highest and the most important tsunami to impact the coast of British Columbia, all available paper records of the event (see Wigen and White [1964] – WW64 in the following text; White [1966]; Spaeth and Berkman [1967]; Stephenson et al., [2007]) were carefully digitized and examined. The de-tided (but unfiltered) tsunami records from four tide gauges, including Prince Rupert, are shown in Figure 2.7. According to our estimates, the first wave arrived at Prince Rupert at 06:30 UTC, 2 hours and 54 minutes after the main shock (previous estimates by WW64 show an arrival time of 06:52). This wave had an amplitude of 62 cm (43 cm according to WW64). The second wave was the highest (Figure 2.7), with a trough-to-crest wave height of 271 cm. These estimates are in good agreement with the results of numerical modelling by Fine et al., [2018a]. It follows from the results of WW64 (see also Wigen [1983]) and from the results presented in this report, that wave heights along the entire outer coast of British Columbia were higher than 2 m or close to this value (Figure 2.7). The dominant period of observed waves at Prince Rupert was about 100 minutes.

2.1.6 The 2010 Chilean (Maule) Tsunami

During the 46 years after the 1964 Alaska earthquake, the Pacific region was relatively quiet. However, on 27 February 2010, a magnitude M_w = 8.8 thrust-fault earthquake occurred near the coast of Central Chile, offshore of the Maule region. The source area of the 2010 Chilean earthquake, which was about 550 km long and more than 100 km wide, was located immediately to the north of the rupture zone of the M_w = 9.5 Great Chilean Earthquake of 22 May 1960. The 2010 earthquake was one of the most powerful earthquakes in recent human history and the largest in the Southern Hemisphere since 1960. The 2010 Chilean earthquake generated a trans-oceanic tsunami that caused major damage and loss of life along 800 km of the Central Chilean coastline. Tsunami alerts (Warnings and Advisories) were declared in 54 Pacific countries, including Canada, the United States, Russia, and Japan. Although tsunami waves were observed throughout the entire Pacific Ocean, the only noticeable damage and casualties, except Chile, were reported for California. The 2010 tsunami was recorded by more than 200 high-precision digital coastal tide gauges and by a large number of Deep-ocean Assessment and Reporting of Tsunamis (DART) bottom pressure stations operated by NOAA.

The 2010 Chilean tsunami was clearly recorded by Ocean Network Canada's (ONC) North-East Pacific Underwater Networked Experiment (NEPTUNE-Canada), a cabled bottom geophysical observatory array deployed to the west of Vancouver Island, and by many tide gauges along the British Columbia coast. Detailed analysis of these data is provided by Rabinovich et al., [2013]. Tsunami waves recorded at Prince Rupert had a maximum trough-to-crest wave height of 33.6 cm. The tsunami waves arrived at this station at 01:18 UTC on 28 February 2010, 18 hours and 44 minutes after the earthquake. As with other tsunami events, the waves at Prince Rupert had a dominant period of around 100 minutes. Figure 2.8 shows the tsunami record at this station; for comparison we also include the records of this tsunami for Henslung and Winter Harbour (locations of the stations are shown in Figure 2.1). The tsunami waves at Prince Rupert had much longer observed periods than at the two other stations. Comparison of the Prince Rupert and Winter Harbour records show that the main trains of tsunami waves at these stations are similar but wave heights at the latter station are much higher, probably because of high-frequency components.

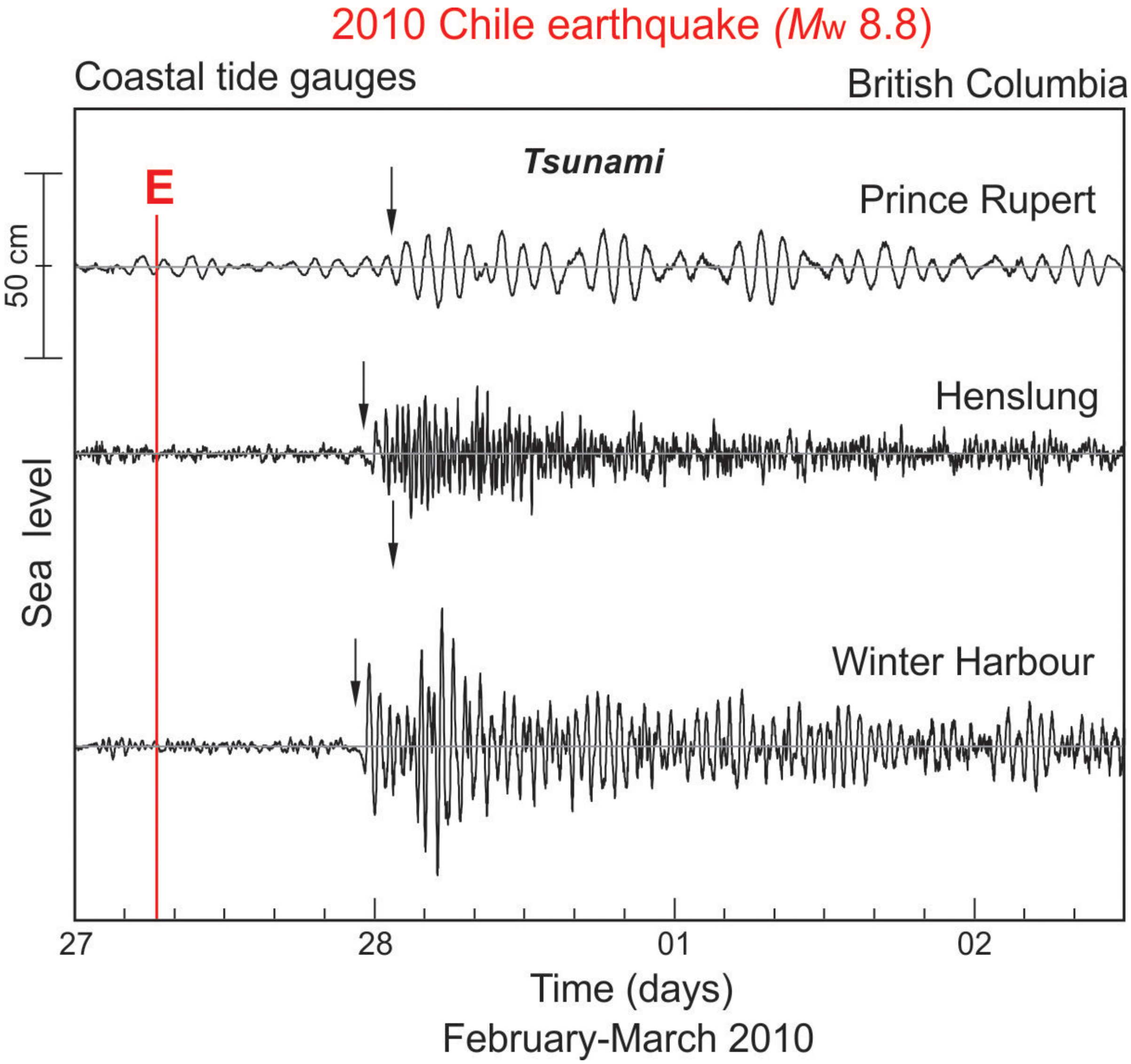

Figure 2.8. The 27 February 2010 Chilean tsunami recorded by tide gauges at Prince Rupert, Henslung and Winter Harbour on the coast of British Columbia. The solid vertical red line labelled “E” denotes the time of the earthquake.

2.1.7 The 2011 Tohoku Tsunami

At 05:46 UTC on 11 March 2011, a giant thrust fault earthquake of magnitude M_w = 9.0 occurred off the coast of Tohoku District, northeastern Honshu, Japan. The earthquake was the strongest in Japan's history and one of the strongest ever instrumentally recorded. Waves from the tsunami reached run-up heights of up to 41 m along the coast of Japan. The tsunami was responsible for almost 20,000 deaths and caused enormous structural damage, including the serious accident at the Fukushima Dai-ichi nuclear power station. The 2011 tsunami was recorded by approximately 250 coastal tide gauges throughout the Pacific Ocean and by numerous bottom pressure gauges at autonomous and cabled observatories.

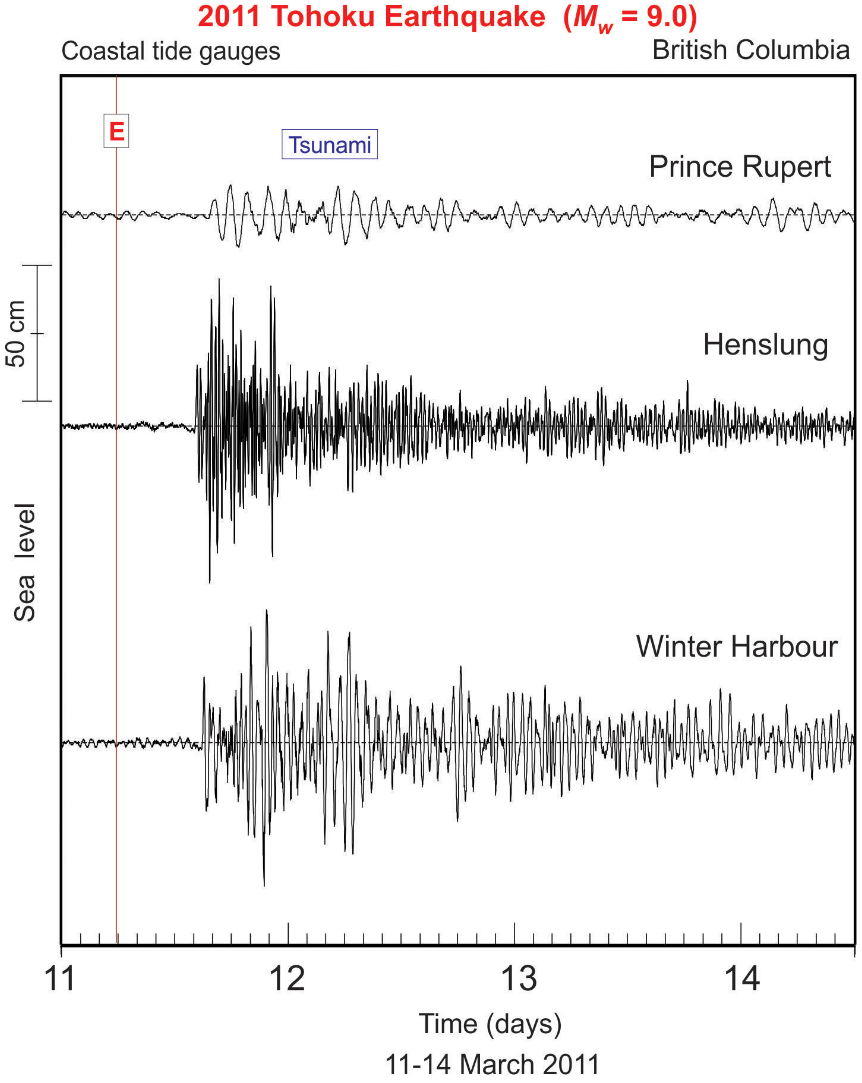

Figure 2.9. The 11 March 2011 Tohoku tsunami recorded by tide gauges at Prince Rupert, Henslung and Winter Harbour on the coast of British Columbia. Data are the residual sea levels obtained by removing the calculated tides from the original time series and then high-pass filtering the resulting de-tided time series with a 4-hour Kaiser-Bessel window. The solid vertical red line labelled "E" denotes the time of the earthquake.

The 2011 Tohoku tsunami waves were recorded by 15 CHS permanent tide gauges along the coast of British Columbia. This included those located inside the Strait of Georgia, five temporary tide gauges in Victoria Harbour and adjacent waterways and numerous NEPTUNE-Canada and VENUS bottom observatories, in particular those located in the southern part of the Strait of Georgia and in Saanich Inlet and Patricia Bay. Tsunami waves that reached Prince Rupert were strongly attenuated and only attained a maximum trough-to-crest wave height at this station of 26 cm. Tsunami waves recorded at these stations, together with the waves recorded at Henslung and Winter Harbour, are shown in Figure 2.9. Similarly to the 2010 Chilean tsunami observations, the waves at Prince Rupert had much lower frequencies (longer periods) than at Henslung or Winter Harbour. At the same time, there is visual similarity between the tsunami records for Henslung and Prince Rupert (the entire group structure of these two records is similar; see Figure 2.8). The Henslung station is located near the entry to Dixon Entrance, while Prince Rupert is deep inside the entrance. Comparison of these two records suggests that low frequency motions are penetrating along Dixon Entrance to Prince Rupert, whereas high frequency tsunami waves are effectively suppressed. Tsunami waves reached Prince Rupert at 15:31 UTC on 11 March 2011, exactly 9 hours and 45 minutes after the main shock.

2.1.8 The 2012 Haida Gwaii Tsunami

At 03:04 UTC on 28 October 2012, a major M_w = 7.7 earthquake occurred off the west coast of Moresby Island, the southern part of Haida Gwaii. The earthquake caused several local landslides on Moresby Island and minor damage in and near Queen Charlotte City on the eastern side of the island.

The 2012 Haida Gwaii earthquake was the second strongest instrumentally recorded earthquake in Canadian history and the largest thrust earthquake ever recorded along this predominantly strike-slip margin [Cassidy et al., 2013]. The 2012 Haida Gwaii earthquake generated a tsunami that propagated throughout the Pacific Ocean where it was recorded by many tide gauges on the coasts of the USA, Canada, Japan, New Zealand and at various Pacific islands, resulting in more than 110 records of this event according to the NOAA database. The event was also recorded by a large number of open-ocean DART stations off Alaska, the US West Coast and in other regions of the Pacific Ocean. The West Coast/Alaska Tsunami Warning Center issued a warning for the area extending from the north coast of Vancouver Island to the Alaska-British Columbia border. The warning was cancelled three hours after the earthquake when it became clear that there was no threat to local settlements in the area.

The 2012 Haida Gwaii tsunami strongly affected the nearby coast of Moresby Island [cf. Leonard and Bednarski, 2013] and was measured along the British Columbia coast by a number of CHS digital coastal tide gauges and by offshore bottom pressure recorders at NEPTUNE to the west of Vancouver Island. Altogether, the 2012 Haida Gwaii tsunami was recorded by 11 CHS coastal tide gauges, including two temporary stations at Hartley Bay and Kitimat. The tsunami was observed at Prince Rupert but the maximum wave height at this station was only 13.9 cm. The tsunami record at Prince Rupert along with the records for Henslung and Winter Harbour are shown in Figure 2.10. The tsunami signal at Prince Rupert was much weaker than in the two latter stations and, once again, had much longer periods. As with previous events, the observational data suggest that low frequency wave motions propagated along Dixon Entrance to Prince Rupert, whereas high frequency tsunami waves were effectively filtered out. The tsunami arrived at Prince Rupert at 05:01 UTC on 28 October, 1 hour and 57 minutes after the main earthquake.

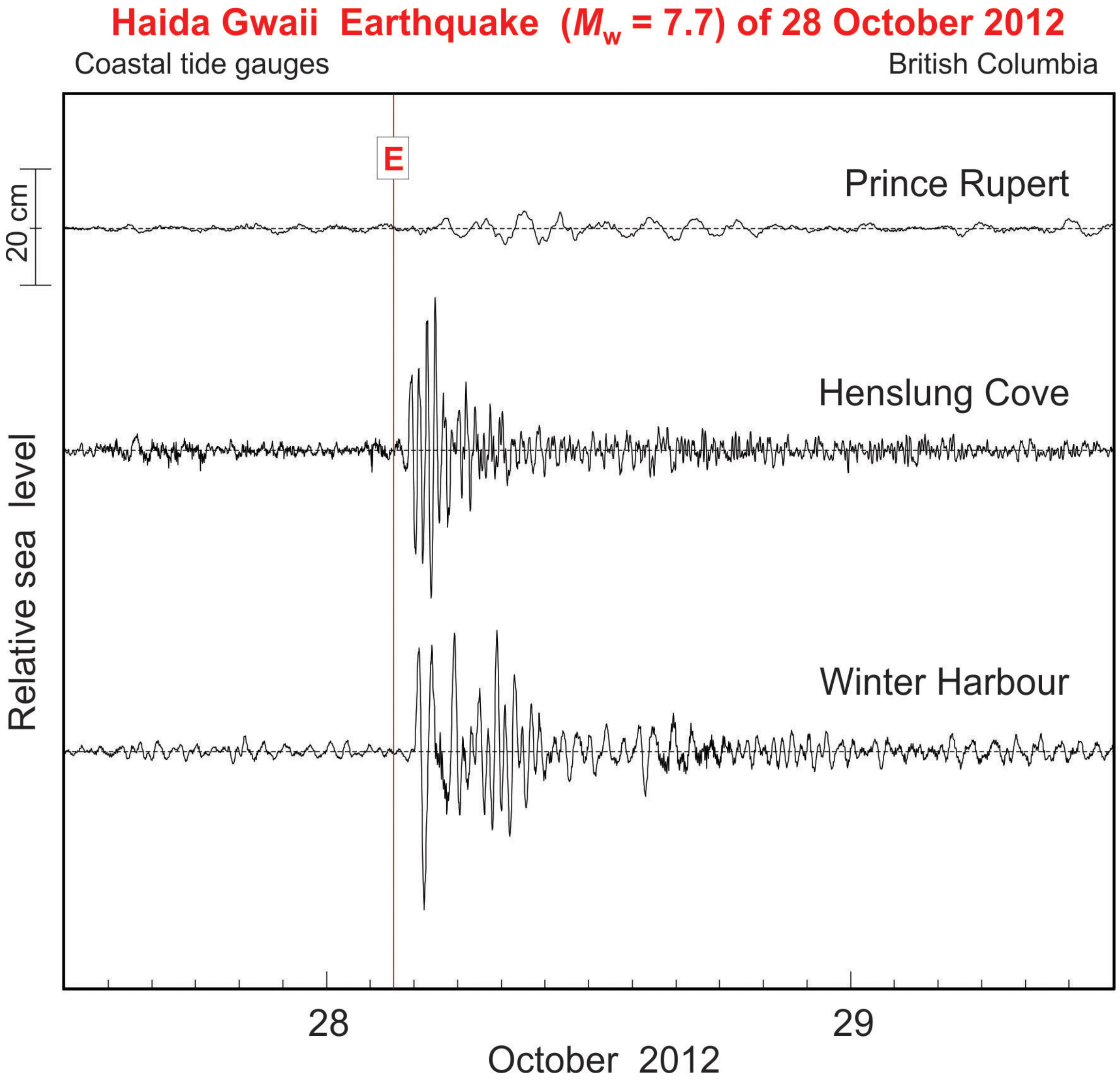

Figure 2.10. The 28 October 2012 Haida Gwaii tsunami recorded by tide gauges at Prince Rupert, Henslung and Winter Harbour on the coast of British Columbia. The solid vertical red line labelled “E” denotes the time of the earthquake.

2.2 SUMMARY OF TSUNAMI OBSERVATIONS AT PRINCE RUPERT

Table 1 presents a summary of the eight tsunami-events observed at Prince Rupert. Very similar events, with similar maximum wave heights, likely occurred at nearby Seal Cove. All recorded seismic tsunamis, except the 1964 Alaska tsunami, had relatively small maximum trough-to-crest wave heights of $h_{tsu} < 35$ cm; these events would not produce any noticeable damage at this site and did not attract any public or media attention. The 1964 Alaska "Good Friday" tsunami was exceptional. The maximum recorded wave height from this event at Prince Rupert was 271 cm and the tsunami caused significant damage in and around the vicinity of the city [Prince Rupert Daily News, 1964].

The 1963 event observed off Graham Island appears to have had an atmospheric origin. The extensive region of shallow water along the northern part of Hecate Strait creates favourable conditions for storm surge, meteorological tsunamis and other types of sea level oscillations related to atmospheric activity. However, during the entire observational period of 1909-2017 at Prince Rupert, no non-seismic event with a wave height greater than 1 m above the tidal level has been observed. This height is much smaller than the tsunami wave heights at this site from the 1964 Alaska earthquake. Consequently, the threat of atmospherically generated waves at Seal Cove may be ignored relative to the tsunami threat.

Table 1. Parameters of the earthquake-generated tsunamis recorded at Prince Rupert, British Columbia and statistical parameters of the tsunamis derived from the tide gauge observations at Prince Rupert*.

Region	**Year**	**Date (dd-mm)**	**Momentum magnitude (M_w)**	**Type of record**	**Travel time (hh:min)**	**Maximum amplitude (cm)**	**Maximum wave height (cm)**	**Wave period (min)**
Kamchatka	1952	04-11	9.0	Analogue	7:45	12	24	110
Andreanof	1957	09-03	8.6	Analogue	4:44	7	15	110
Chile	1960	22-05	9.5	Analogue	19:10	26	40	100
Graham	1963	28-03	-	Analogue	-	?	52?	?
Alaska	1964	28-03	9.2	Analogue	2:54	132	271	100
Chile	2010	28-02	8.8	Digital	18:44	17.0	33.6	110
Tohoku	2011	11-03	9.0	Digital	9:45	13.0	26.0	120
Haida Gwaii	2012	28-10	7.7	Digital	1:57	8.6	13.9	105

* A recent thorough examination of historical tide gauge records at Prince Rupert indicated that one more tsunami event was measured at this station, generated by the 10 November 1938 Shumagin Islands (Alaska) earthquake with $M_w = 8.2$ ($M_s = 8.7$). The maximum wave height at Prince Rupert was 15 cm.

2.3 DISCUSSION AND TSUNAMI RECORDS

The modern CHS network of digital high-precision coastal tide gauges has enabled scientists to measure and examine even quite weak tsunamis on the British Columbia coast. In addition, ONC's NEPTUNE array provides precise measurements over the southwestern shelf of Vancouver Island. As a result for the period 1999-2017 there are good records of a large number of tsunamis from source areas located all around the Pacific Ocean, including the Sumatra tsunami from its source area in the Indian Ocean [Rabinovich and Stephenson, 2004; Rabinovich et al., 2006b, 2013; Stephenson and Rabinovich, 2009].

Despite the large numbers of tsunamigenic events, only three tsunamis (the 2010 Chile, 2011 Tohoku and 2012 Haida Gwaii tsunamis) were digitally recorded at Prince Rupert (Table 1). A list of the other 21 Pacific Ocean tsunamis that were recorded from 1999 to 2017 at sites on the coast of British Columbia, but not at Prince Rupert, is presented in Table 2. Why these 21 tsunamis were not recorded at Prince Rupert is an important applied and scientific question. Certainly, one of the principal reasons is that all of these tsunamis were relatively weak. Nevertheless, they were recorded and identified at other British Columbia stations. A possible explanation is that occurrences of tsunami waves at Prince Rupert are related not only to the strength of the earthquake event, but also to the geographical and bathymetric properties of the regions surrounding Prince Rupert which filter out high-frequency tsunami waves.

Figure 2.11 shows frequency-time (*f-t*) diagrams for three records of the 2010 Chilean tsunami presented in Figure 2.8. These diagrams, which show the temporal variation in the tsunami signal as a function of frequency (wave period), clearly demonstrate the difference in spectral properties of the three stations. At Henslung and Winter Harbour, tsunami waves occupy a broad frequency band, with the main spectral energy at periods from 15 to 80 minutes. In contrast, Prince Rupert shows no tsunami energy in this particular frequency band, but considerable energy at the dominant tsunami wave periods of 100-120 minutes. Approximately the same result is observed for other tsunamis (for example, for the 2011 Tohoku and 2012 Haida Gwaii tsunamis). Thus, tsunami wave energy at Prince Rupert is negligible at high frequencies (frequencies > 0.01 cpm; periods less than 100 minutes) but relatively high at low frequencies (with peak frequencies at 0.008-0.010 cpm; periods of 100 to 125 minutes). In contrast, the main spectral energy of tsunami waves at other British Columbia stations (e.g. at Henslung, Winter Harbour, Tofino, Bamfield and Bella Bella) is mainly concentrated at much higher frequencies.

Table 2. Tsunamis for the period 1999-2014 that were recorded on the coast of British Columbia but which were not recorded at Prince Rupert.

Source region	**Year**	**Momentum magnitude (M_w)**	**Number of BC coastal + offshore (if available) stations recording tsunamis**	**Maximum observed wave height (cm)**
Peru	2001	8.4	8	15.1
Queen Charlotte Is.	2001	6.1	4	22.7
Colima, Mexico Alberni	2003	7.4	3	10.5
Hokkaido, Japan	2003	8.3	5	10.0
Vancouver Island Hardy	2004	6.6	2	10.8
Sumatra, Indian Ocean	2004	9.2	6	21.0
Northern California	2005	7.2	4	4.3
Tonga	2006	8.0	6	10.8
Kuril Islands	2006	8.3	10	38.5
Kuril Islands	2007	8.1	8	17.1
Solomon Islands	2007	8.1	5+	>12
Southern Peru	2007	8.0	10	28.0
Irian Jaya, Indonesia	2009	7.6	5+	>10
Tonga	2009	7.6	5+	>10
Samoa	2009	8.1	9+6	14.5
Vanuatu Is	2009	7.7	5+6	4.3
Bonin Is. Japan	2010	7.4	4+4	1.0
Craig, SE Alaska	2013	7.5	1	12.0
Solomon Islands	2013	8.0	10+4	13.0
Chile (Iquique)	2014	8.2	11+4	14.0
Chile (Illapel)	2015	8.3	16+4	31.3

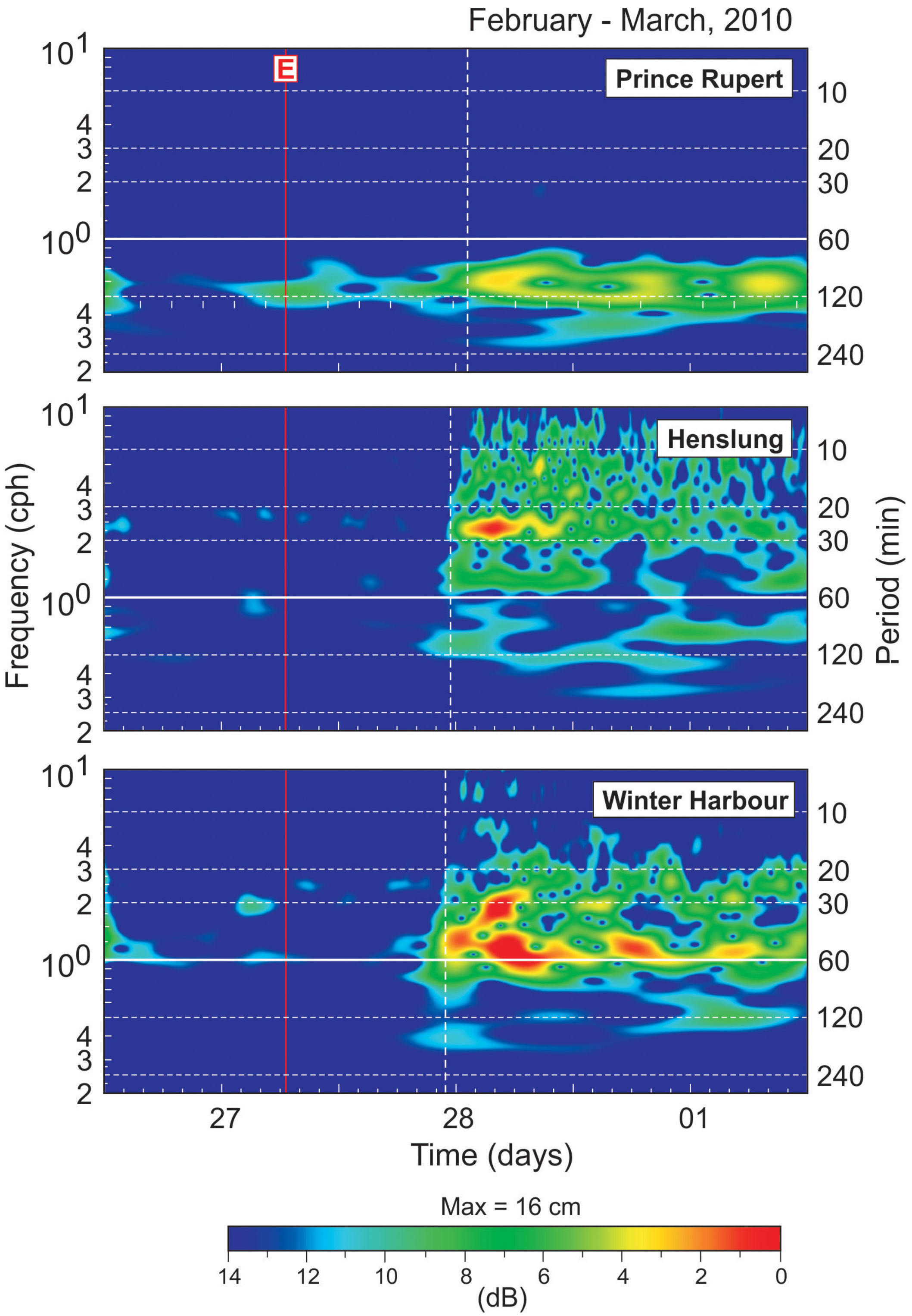

Figure 2.11. Frequency-versus-time plots (*f-t* diagrams) for the 2010 Chilean tsunami recorded at coastal tide gauges at Prince Rupert, Henslung and Winter Harbour (the respective tsunami records are shown in Figure 2.8). The solid vertical red line labelled "E" denotes the time of the earthquake; the dashed vertical white line indicates the tsunami arrival time.

This high frequency feature is not specifically related to tsunami waves but reflects the general frequency properties of the British Columbia coast. Rabinovich and Stephenson [2004] used long records of background long wave noise to estimate the topographic response properties for CHS tide gauge stations along the coast of British Columbia. These plots (Figure 2.12) show that, while long waves resonantly amplify at certain high frequencies at most coastal stations, the signal arriving at Prince Rupert is strongly attenuated at high frequencies. It appears that Dixon Entrance and the shelf adjacent to Prince Rupert act as a very effective low-pass filter that strongly suppresses high frequency waves incoming to this region.

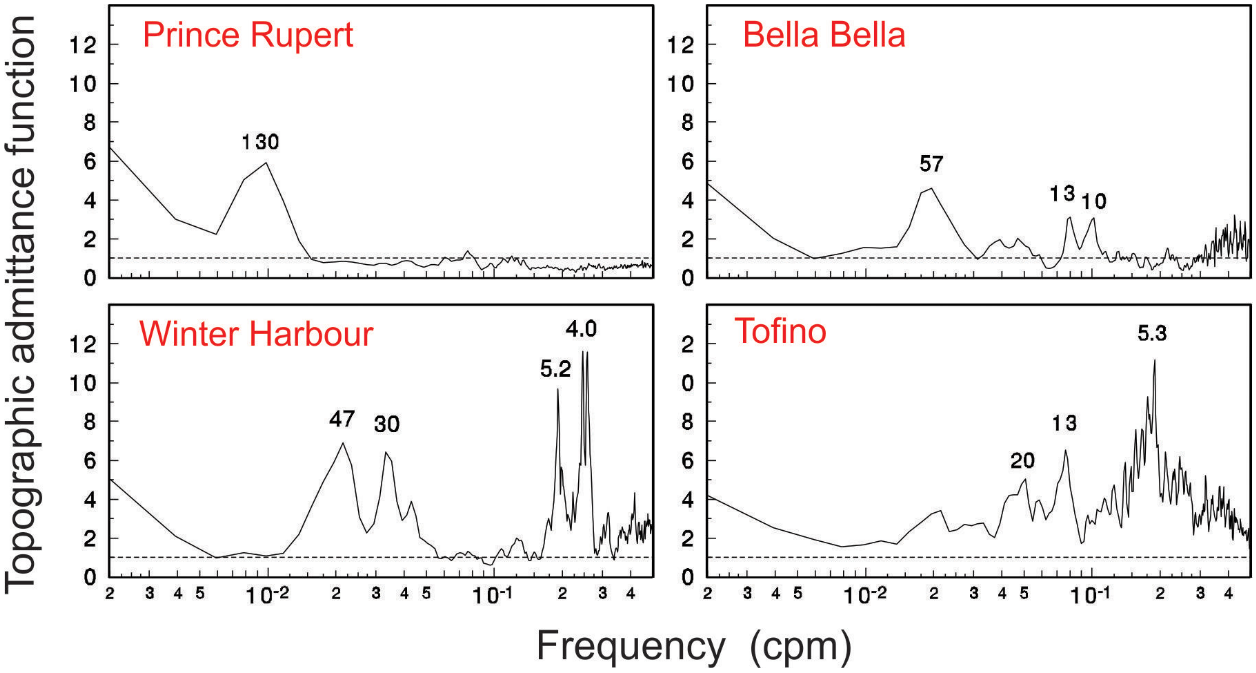

Figure 2.12. Topographic transfer (admittance) characteristics for four tide gauge stations on the British Columbia coast. Periods of the main peaks (in minutes) are indicated (from Rabinovich and Stephenson, 2004).

This wave attenuation feature explains why the seven earthquake related tsunamis listed in Table 1 have been recorded at Prince Rupert, while 21 tsunamis in Table 2 have not. The reason is not only that these six recorded tsunamis were considerably stronger in the vicinity of Prince Rupert than those listed in Table 2, but also because six of the seven were related to intense earthquakes with $M_w \geq 8.6$ that had huge extension source areas and, consequently, produced tsunami waves with much lower frequencies (i.e., longer wavelengths) than those with $M_w \leq 8.3$. This aspect of the Prince Rupert region indicates that only tsunamis with very long wavelengths associated with the largest earthquakes can present a major threat to this region.

2.4 EXPECTED TSUNAMI WAVE HEIGHTS

The data and information we have collected and summarized indicate that of the Pacific tsunamis that occurred over the observational period of more than 100 years, only seven seismically generated tsunamis have been observed in the Prince Rupert region. The existing information cannot give an unequivocal long-term forecast of possible tsunami heights in this region. However, based on our best estimates, we can provide several preliminary conclusions regarding the tsunami risk for the Chatham Sound-Portland Inlet-Prince Rupert region.

We find that there are only two potential sources of high tsunami risk for the Prince Rupert region:

Alaska*:* The 1964 Alaska tsunami generated by the M_w = 9.2 megathrust earthquake inflicted considerable damage in the Prince Rupert area. If such a tsunami were to occur today, the damage would be much greater given the new construction and infrastructure in this area. Such strong earthquakes have occurred in the past and are likely to occur in the future. Moreover, we cannot exclude the possibility that a future Alaska earthquake could be somewhat stronger (for example, M_w = 9.3). The exact positions and orientations of any future Alaska earthquake and tsunami source region must also be taken into account. Estimations of tsunami run-up and inundation require the use of numerical tsunami modelling for worst-case earthquake scenarios. It is evident that tsunami waves associated with a future Alaska tsunami can be several metres high. High-resolution seafloor and coastal bathymetry for this region is necessary to derive precise estimates of possible tsunami wave heights for Prince Rupert and Seal Cove.

Cascadia Subduction Zone (CSZ): There is no reliable information or data concerning historical tsunami heights in the region of Prince Rupert associated with a CSZ earthquake. However, paleotsunami findings on the coast of Vancouver Island [Clague, 2001; Clague et al., 2000, 2003] show that tsunami waves of ~15-20 m likely struck the coast of the island at the time of the 1700 CSZ earthquake, and during other such events in the past. Cascadia earthquakes and tsunamis are a serious risk for the Prince Rupert region. The estimated recurrence period of major CSZ earthquakes is approximately 500 years (cf. Atwater et al., 2005; Wang et al., 2013). Paleotsunami field surveys in the Prince Rupert area would be helpful for estimating historical CSZ tsunami heights for the region and for predicting possible tsunami run-up in the future. At the same time, CSZ tsunami modelling for the Prince Rupert region would be valuable. There are tsunami models for a possible CSZ tsunami but the models do not include Prince Rupert and Seal Cove [Cherniawsky et al., 2007; Cheung et al., 2011] or were undertaken using very coarse grids spanning the entire northeast Pacific [Whitmore, 1993; Myers et al., 1999]. That is why, in the frame of the general examination of tsunami risk for Prince Rupert and Seal Cove, Fine et al., [2018b] created a high-resolution numerical model of the this specific region.

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3 VICTORIA TSUNAMI RECORDS AND OBSERVATIONS

Victoria, the capital city of British Columbia, is located on the southeastern tip of Vancouver Island on Canada's Pacific coast. The city is situated close to the head of Juan de Fuca Strait, which connects the Strait of Georgia and Puget Sound with the Pacific Ocean. Juan de Fuca Strait is the conduit for tsunamis arriving at the city from the open ocean. The Victoria Canadian Coast Guard (CCG) Station is located on the southeastern coast of Upper Victoria Harbour, close to the main port for large cruise ships. The Outer Harbour is linked to the Inner Harbour through a narrow entrance, where a CHS permanent tide gauge is located. Although detailed tsunami zoning for the area around the CCG station requires numerical modelling of the entire adjacent region (the topic of a separate project), preliminary estimates can be obtained based on historical data for tsunamis from the Victoria tide gauge, combined with paleotsunami studies in this region and from various seismological information.

3.1 TIDE GAUGE OBSERVATIONS

The continuous tide gauge record at Victoria spans approximately 115 years and is one of the longest sea level records in Canada and in North America. During this century-long period, the tide gauge recorded numerous tsunamis arriving from the Pacific Ocean. Despite the proximity of the Victoria station to the tide gauge site, there are differences in tsunami waves at the two sites worth noting. Tsunami waves arriving from the Pacific Ocean at Victoria generate significant natural (seiche) oscillations within the Inner Harbour with typical periods (T) ranging from ~25 to 6 minutes [cf. Rabinovich and Stephenson, 2004], which are unimportant in the Upper Harbour. The transfer (response) function from the Outer Harbour to the Inner Harbour has a specific shape, transforming incoming tsunami waves with different periods in a substantially different way:

- Long-period waves (with periods, $T > 30$ minutes) arriving at the entrance to the Inner Harbour penetrate into the Inner Harbour with minor changes;
- Short-period waves (with $T < 6$ minutes) are strongly dampened by the entrance, which plays the role of an effective low-pass filter;
- Incoming waves with intermediate periods of $30 < T < 6$ minutes can be significantly amplified in the Inner Harbour due to harbour resonance effects.

The frequency response properties of the Inner Harbour determine the spectral features of tsunami waves at the Victoria tide gauge and their differences from those at the Victoria CCG station. Although the two sites are located close to each other (about 1 km apart), the differences in the tsunami wave response can be significant. Such local effects can be estimated based only on comprehensive numerical modelling experiments [cf. Cherniawsky et al., 2007]. However, high-frequency tsunami waves are typically associated with small source-area earthquakes that do not have great magnitudes and are not a major threat to the Victoria region. For the two other types of tsunami waves (low-frequency and intermediate), recorded tsunami waves at the tide gauge site are expected to be the same or higher than waves at the CCG site. This means that estimates of maximum possible tsunami wave heights at the CCG area based on the records from the Victoria tide are overestimates.

Up to the end of the 1990s, analogue instruments were used for sea level measurements at Victoria. The accuracy of these instruments was a few centimetres. For this reason, only five major events - the 1946 Aleutian, 1952 Kamchatka, 1957 Andreanof, 1960 Chile and 1964 Alaska tsunamis (the most destructive of the 20th century) - could be easily extracted from the Victoria tide gauge records [Stephenson et al., 2007]. Thorough digitization of the tide gauge records and the subsequent subtraction of the calculated tides, makes it possible to estimate statistical parameters for these tsunamis at Victoria. Much higher precision is achieved than initially possible directly from the paper records [Shepard et al., 1950; Weeks and Studds, 1953; Wigen, 1960; Wigen and White, 1964]. The maximum estimated trough-to-crest wave height of 147 cm was associated with the 1964 Alaska tsunami; the wave heights of four other tsunamis were: 27 cm (1946 Aleutian), 19 cm (1952 Kamchatka), 26 cm (1957 Andreanof), and 73 cm (1960 Chile) (Table 3).

Stephenson and Rabinovich [2009] digitized and examined several analogue records related to moderate events from the mid-1990s and identified four more recorded tsunami events on the British Columbia coast. For Victoria these are: the 1994 South Kuril Islands (Shikotan), 1995 North Chile, 1995 Kuril Islands and 1996 Irian Jaya events. The maximum trough-to-crest wave heights for all these tsunami waves at Victoria were below 10 cm, i.e., much smaller than those of the five major events. Statistical parameters for all nine 20th century events (from the “pre-digital era”) are included into Table 3 (indicated in italics); the epicenters of the respective earthquakes are shown in Figure 3.1.

Table 3. Statistical parameters of the tsunami waves recorded at the Victoria tide gauge.

Earthquake				**Tide gauge record**				
Region	**Year**	**Date (dd-mm)**	**Momentum magnitude (M_w)**	**Type of record**	**Travel time (hh:min)**	**Max amplitude (cm)**	**Max wave height (cm)**	**Wave period (min)**
Aleutian	*1946*	*01-04*	*8.6*	*Analogue*	*5:19*	*16*	*27*	*21*
Kamchatka	*1952*	*04-11*	*9.0*	*Analogue*	*8:42*	*18*	*39*	*25*
Andreanof Is.	*1957*	*09-03*	*8.6*	*Analogue*	*5:42*	*12*	*26*	*22*
Chile	*1960*	*22-05*	*9.5*	*Analogue*	*17:46*	*41*	*73*	*22, 55*
Alaska	*1964*	*28-03*	*9.2*	*Analogue*	*4:32*	*70*	*147*	*25, 90*
South Kuril Is.	*1994*	*04-10*	*8.3*	*Analogue*	*9:30*	*4*	*8.7*	*25, 29*
North Chile	*1995a*	*30-07*	*8.1*	*Analogue*	*13:42*	*4*	*8.2*	*22*
Kuril Is.	*1995b*	*03-12*	*7.9*	*Analogue*	*9:02*	*3*	*6.4*	*14*
Irian Jaya	*1996*	*17-02*	*8.2*	*Analogue*	*15:44*	*5*	*9.1*	*25*
South Peru	2001	23-06	8.4	Digital	15:11	4	7.4	22
Hokkaido,	2003	25-09	8.3	Digital	?	3.4	6.7	23, 55
Sumatra, Ind.	2004	26-12	9.3	Digital	32:38	6	10.6	55
BC coast	2005	09-12	Meteo	Digital	-	8.0	13.9	23
Tonga Is.	2006a	03-05	7.9	Digital	13:41	4.0	9.0	23, 55
Central Kuril Is.	2006b	15-11	8.3	Digital	?	8	17.5	18
Central Kuril Is.	2007a	13-01	8.1	Digital	8:51	4	7.4	21
Solomon Is	2007b	01-04	8.1	Digital	14:22	3.8	6.7	50
BC, Gulf Is.,	2007c	13-07	Meteo	Digital	-	10.3	17.7	20
South Peru	2007d	15-08	8.1	Digital	12:15	5.4	10.2	15, 20
BC, Gulf Is.,	2008	26-02	Meteo	Digital	-	8.2	14.8	15, 22
Irian, Jaya	2009a	03-01	7.6	Digital	16:05	5.3	9.3	22
Tonga Is.	2009b	19-03	7.6	Digital	14:21	6.1	11.4	18, 50
BC, Gulf Is,	2009c	16-08	Meteo	Digital	-	9.3	16.2	15
Samoa	2009d	29-09	8.1	Digital	13:10	4	7.5	23
Vanuatu Is.	2009e	07-10	7.8	Digital	14:03	3.8	7.7	24, 50
Central Chile	2010a	28-02	8.8	Digital	16:44	11	23.2	25
BC, Gulf Is,	2010b	01-11	Meteo	Digital	-	9	17.4	20
Tohoku, Japan	2011	11-03	9.0	Digital	10:31	26	52.0	24
Solomon Is.	2013	06-02	8.0	Digital	13:19	3.8	6.5	24, 50
North Chile	2014a	01-04	8.2	Digital	16:54	3.6	5.7	22
Rat Is.,Aleutian	2014b	23-06	7.9	Digitial	7:54	1.9	2.7	20
Central Chile	2015	16-09	8.3	Digital	16:45	5.6	10.7	25.50

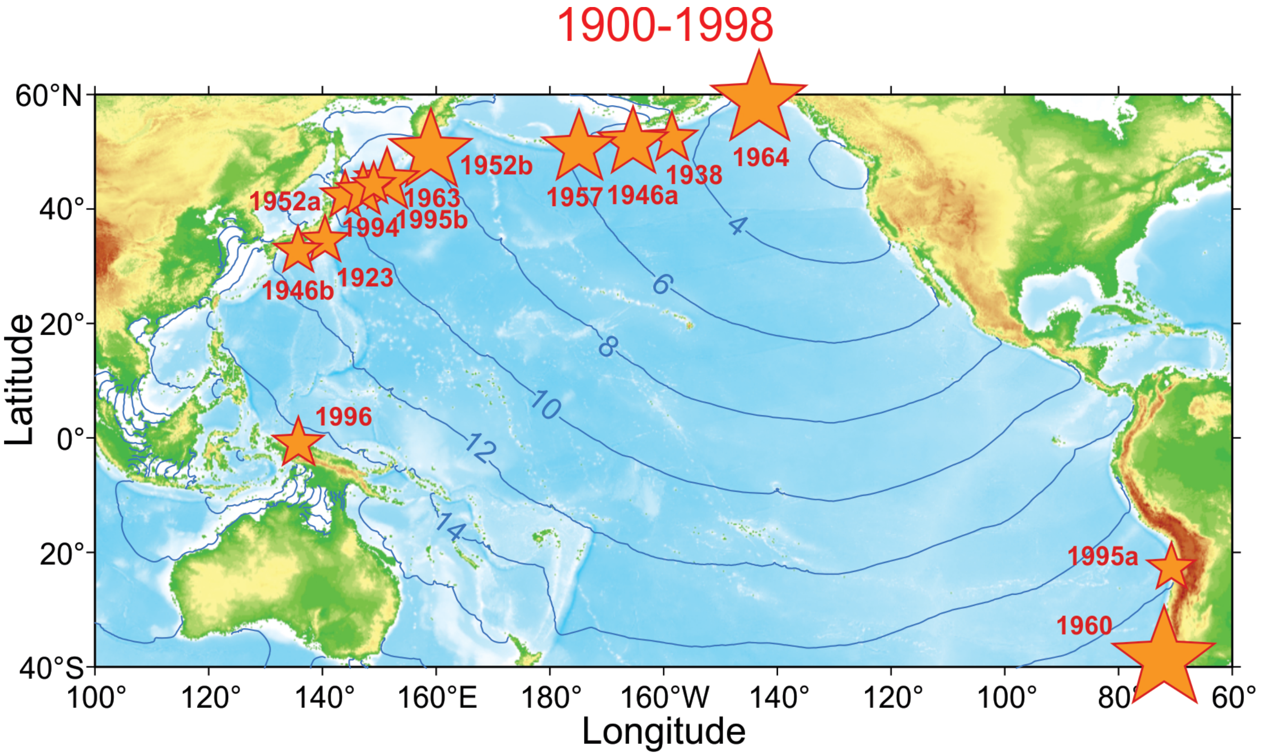

Figure 3.1. Epicenters of earthquakes in the 20th century (orange stars) that produced tsunamis recorded at the analogue tide gauge in Victoria Harbour, British Columbia. The star size is proportional to the momentum magnitude (M_w) of the earthquake.

The new digital instruments deployed by CHS in 1998 [cf. Rabinovich and Stephenson, 2004] enabled CHS to accurately record even weak tsunami events. As a result, 23 tsunamis were recorded at Victoria during the last 17 years [Rabinovich et al., 2006a; Stephenson and Rabinovich, 2009]. This is in strong contrast with Prince Rupert, where only three tsunamis were recorded during this period (Section 2, Table 1). The main reason is the very different frequency response properties of these two sites [Rabinovich and Stephenson, 2004]: only extra low-frequency tsunamis were recorded at Prince Rupert, while almost all tsunamis arriving at the British Columbia coast are recorded at Victoria[2]. From the 23 events of 2000-2016, five were of the meteorological origin, while 18 others were seismically generated. The epicenters of the respective earthquakes were located along the entire Ring of Fire of the Pacific Ocean, with the exception of the subduction zones off the coasts of North and Central America (Figure 3.2). The statistical parameters for all 23 tsunamis are presented in Table 3.

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[2] During the Haida Gwaii tsunami of 28 October 2012 the Victoria tide gauge was not operative.

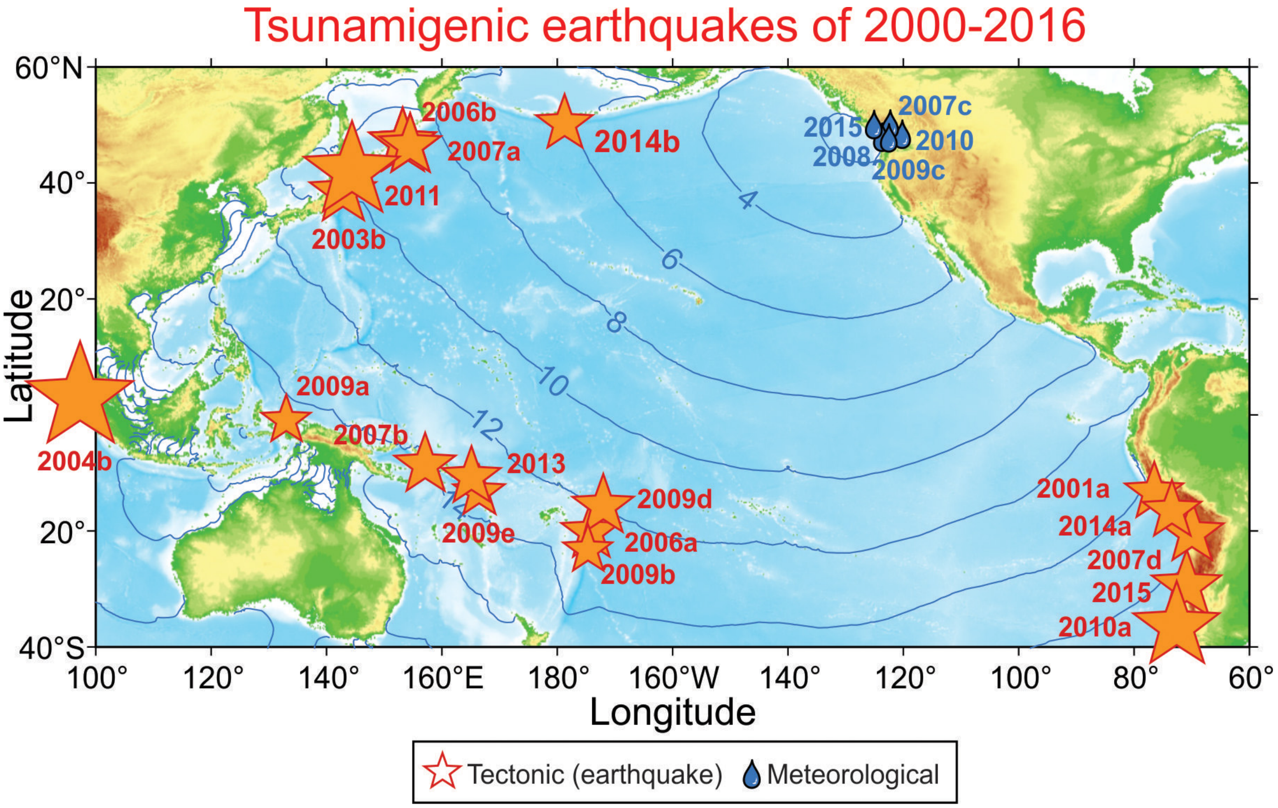

Figure 3.2. Epicenters of earthquakes in the 21st century (orange stars) that produced tsunamis digitally recorded at Victoria, British Columbia. The star size is proportional to the momentum magnitude (M_w) of the earthquake.

3.2 INDIVIDUAL TSUNAMI EVENTS RECORDED AT VICTORIA

The list of tsunamis instrumentally recorded at Victoria includes 32 events: 9 events recorded in the 20th century by analogue instruments and 23 events recorded from 2000 to 2016 by digital tide gauges. However, if we exclude tsunamis of meteorological origin (which are out of scope for the present study), there have been only seven events that produced tsunamis with maximum wave heights at Victoria >15 cm. All of these are major events, including five of the strongest events of the 20th century (1946, 1952, 1957, 1960 and 1964) and two very intense events that occurred in the Pacific Ocean during the present century (2010 and 2011). The momentum magnitudes (M_w) of the corresponding earthquakes were from M_w = 8.6 (1946) to M_w = 9.5 (1960), the largest magnitude earthquake ever recorded during the entire observational period. These seven particular events are examined in more detail. Six of them (except

1946) generated tsunamis that were also recorded at Prince Rupert; descriptions of these events are given in Section 2. For these six events, this Section briefly describes the tsunami waves in the Victoria region. For the 1946 event, additional details are presented to help characterize this important tsunami.

3.2.1 The Aleutian Tsunami of 1 April 1946

The 1946 Aleutian tsunami was generated by an M_w = 8.6 earthquake with the epicenter located 150 km from Unimak Island in the eastern Aleutian Islands. The earthquake generated one of the largest trans-Pacific tsunamis ever instrumentally recorded, with maximum runup heights on the coasts of Alaska and the Aleutian Islands of up to 40 m. Within 48 minutes after the earthquake, the tsunami struck the area of Scotch Cap, Alaska and completely destroyed a newly built US Coast Guard Lighthouse, surging over the coastal cliff to a height of 42 m above mean sea level. Then, 4.5 hours after the main shock, the destructive waves reached the coast of the Hawaiian Islands, where it was totally unexpected. The maximum runup in the area of Hilo, Big Island, was 17 m; on the islands of Oahu and Maui, the maximum run-up was 11 m and 10 m, respectively. The tsunami was also recorded along the entire west coast of the United States, and crossed the Pacific Ocean to produce 9-m waves at some locations in the Marquesas Islands and extended southeastwards, damaging boats in Chile. Altogether, the tsunami killed 167 people, most of them in Hawaii (158), but also in the Scotch Cap lighthouse, Alaska (5), Marquesas (2) Peru (1) and California (1).

The tsunami was unusually powerful for the size of the earthquake. Due to the large discrepancy between the tsunami magnitude, M_t = 9.3 [Abe, 1979], and the surface wave magnitude, M_s = 7.4, this earthquake was identified as a ‘tsunami earthquake’ [Kanamori, 1972; Abe, 1973], i.e., as an earthquake generating a tsunami that is much larger than it should be based on the earthquake magnitude. The severe destructions and large number of casualties in the Hawaiian Islands prompted the United States to create, in Honolulu, Hawaii, the Seismic Sea Wave System, which was then converted in 1949 into the Pacific Tsunami Warning Center (PTWC).

The 1946 tsunami was clearly recorded at the Tofino and Victoria tide gauges, both being in operation at the time of the event (Figure 3.3). The tsunami waves arrived at the Victoria tide gauge 5 hours 19 minutes after the earthquake, in good agreement with the theoretical travel time and with earlier estimates of arrival times [cf. Stephenson et al., 2007]. The maximum wave height recorded was 27 cm; this is approximately one half of the maximum wave height at Tofino (55 cm). Based on a paper trace record, Sheppard et al., [1950] estimated the height at Victoria to be 20 cm. The observed waves were monochromatic, with a very consistent period of ~21 minutes (Figure 3.3).

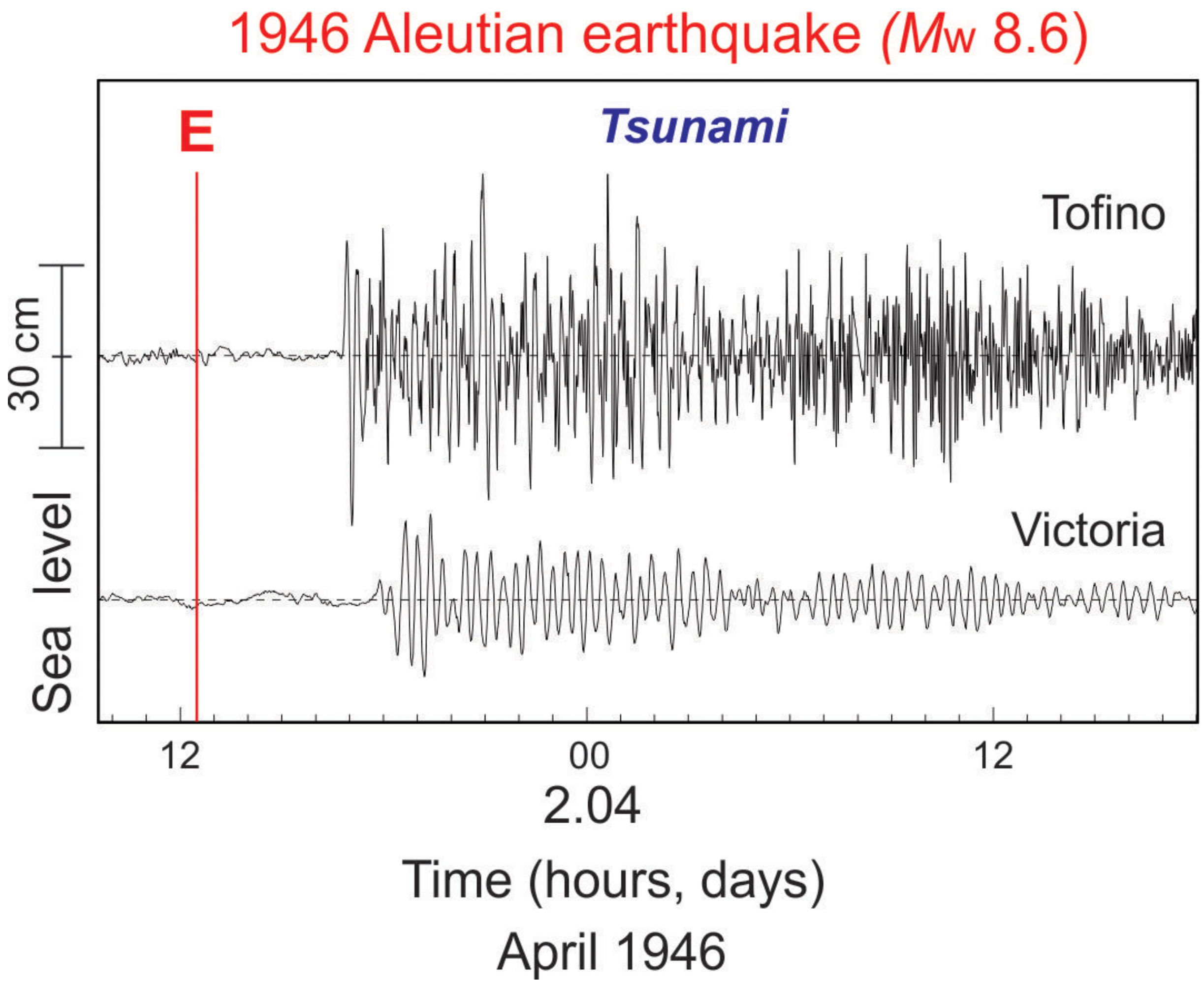

Figure 3.3. The 1 April 1946 Aleutian tsunami recorded at Tofino and Victoria. The solid vertical red line labelled “E” denotes the time of the earthquake.

3.2.2 The Kamchatka Tsunami of 4 November 1952

A description of this event is given in Section 2.1.1; the digitized and de-tided records at four tide gauges, including Victoria, are shown in Figure 2.3. Tsunami waves were noticed by shipping in Victoria Harbour but there was no damage [Stephenson et al., 2007]. The District Engineer (CHS, Victoria) reported “This wave was of somewhat greater amplitude on our coast than the one of 1946 and continued to oscillate for a considerably longer time…” [Weeks and Studds, 1953]. The maximum tsunami wave height at Victoria estimated from the de-tided record (Figure 2.4) was 39 cm; in agreement with the historical estimate by Weeks and Studds [1953] who reported a maximum wave height of 40 cm. Tsunami travel time was also substantially corrected from 8 hours 12 minutes to 8 hours 42 minutes.

3.2.3 The Andreanof Islands Tsunami of 9 March 1957

A description of this event is given in Section 2.1.2. The tsunami was recorded at six tide gauges; the digitized and de-tided records at three southern gauges, including Victoria, are shown in Figure 3.4. There is some conflicting information on the observation of this tsunami in Victoria Harbour and Gorge Waterway according to articles published in local newspapers. Our analysis of the digitized Victoria tide gauge record (Figure 3.4) shows that the tsunami arrived at Victoria at 20:05 UTC, i.e., 5 hours 42 minutes after the main shock. The maximum tsunami wave height at Victoria estimated from the record was 26 cm. This height is approximately one half of the wave height at Tofino, but larger than for any other tide gauge. The period of the observed tsunami waves was 22 minutes, which is typical for Victoria Harbour and in good agreement with periods observed during this event at all other stations, except Prince Rupert.

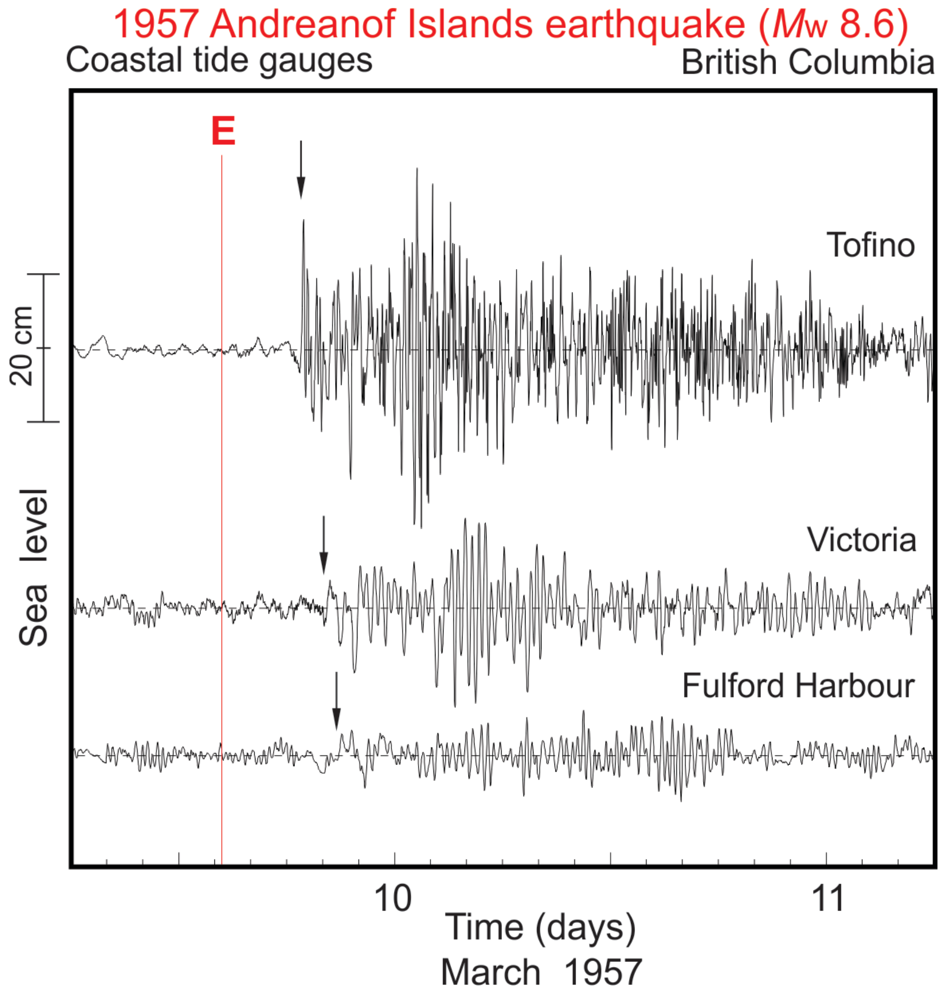

Figure 3.4. The 9 March 1957 Andreanof Islands tsunami recorded at Tofino, Victoria and Fulford Harbour on the coast of British Columbia. The solid vertical red line labelled "E" denotes the time of the earthquake; the arrows indicate the tsunami arrival.

3.2.4 The Great Chile Tsunami of 22 May 1960

The May 1960 tsunami, the strongest tsunami ever instrumentally recorded in the Pacific Ocean, is described in Section 2.1.3. All available tide gauge records for this event were carefully digitized and de-tided. The residual 1-minute records make it possible for us to examine this event along the British Columbia coast and, in particular in the area of Victoria, with much higher precision than was possible using paper records [Wigen and White, 1964; Stephenson et al., 2007].

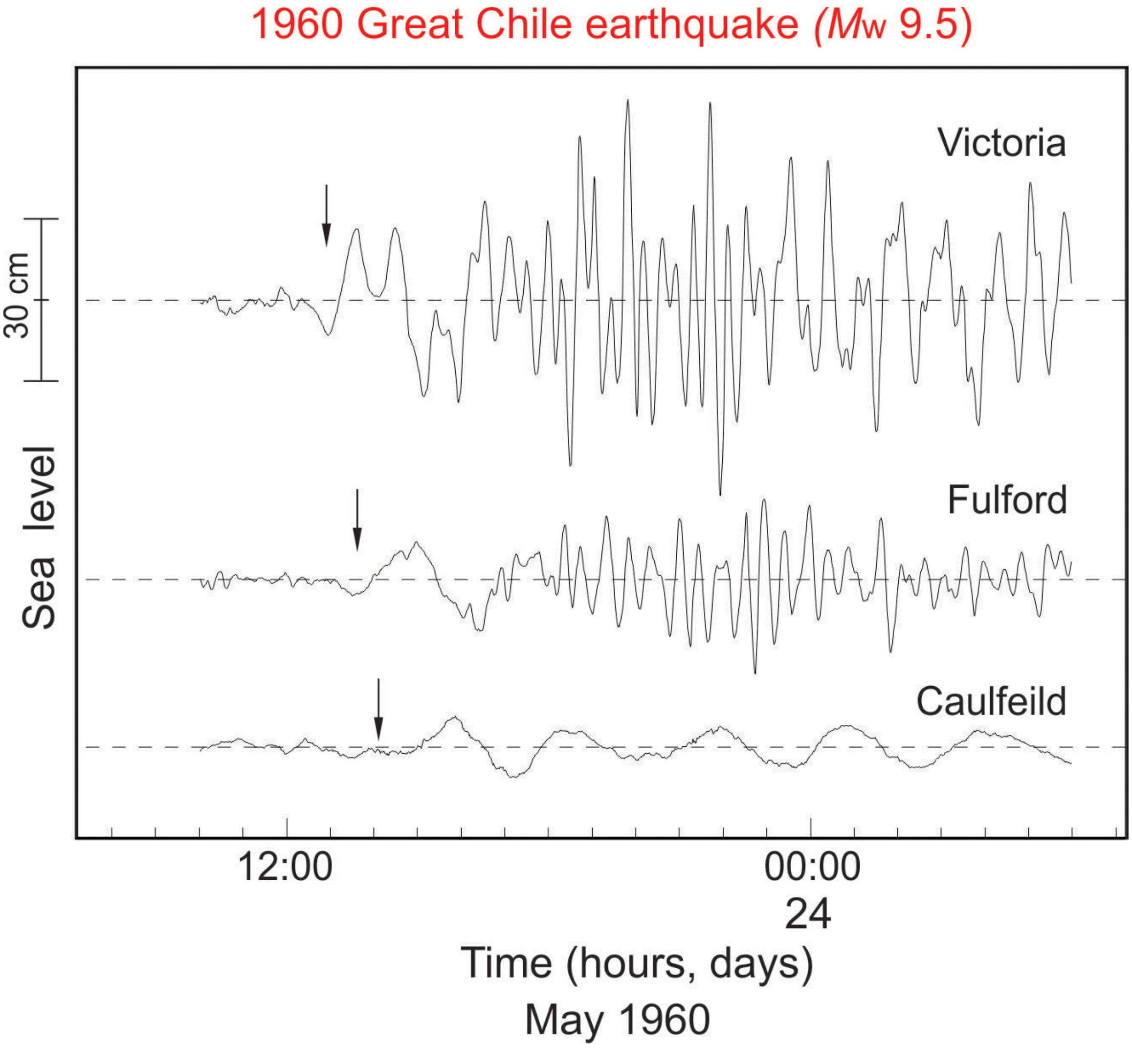

Figure 3.5. The 22 May 1960 Chile tsunami recorded at Victoria, Fulford (Salt Spring Island) and Caulfeild (Point Atkinson). The arrow indicates the tsunami arrival time.

The tsunami arrived at Victoria at 12:57 UTC on 23 May 1960, or 17 hours 46 minutes after the main earthquake shock and 34 minutes later than at Tofino (12:23 UTC) on the west coast of Vancouver Island. The wave propagated into the Strait in Georgia and, at 13:31 UTC, it reached Fulford Harbour and then, at 14:02, reached Caulfeild in West Vancouver (Figure 3.5). The tsunami observed at Victoria, Fulford and Caulfeild consisted of very long-period waves with T ~ 150-160 minutes. However, after reflection within Victoria Harbour, waves with shorter periods were induced (T ~ 55 minutes). The effect of wave dispersion is clearly present in the tsunami record for Victoria; roughly four hours after the first wave arrival, a train of prominent waves with much shorter periods (T ~ 22 minutes) arrived; the maximum trough-to-crest tsunami wave of 73 cm was associated with this train of waves. This maximum wave occurred at 21:41 UTC, more than 8.5 hours after the leading wave arrival. In general the record at the Victoria tide gauge was characterized by very long ringing (> 3 days) and slow energy decay.

3.2.5 The Alaska Tsunami of 28 March 1964

The 1964 Alaska ("Good Friday") tsunami was the strongest seismically generated tsunami ever observed on the coast of British Columbia. The event itself is described in Section 2.1.5. The tsunami waves propagated from the source area (Prince William Sound, Alaska; see Figure 2.6) in the southeast direction along the outer coast of Haida Gwaii and then along the outer coast of Vancouver Island. The leading wave arrived at Tofino at 07:01 UTC on 28 March and then propagated through Juan de Fuca Strait, arriving at Victoria at 08:08 UTC (4 hours 32 minutes after the main shock). The waves then entered the Strait of Georgia and propagated into narrow inlets on the mainland coast and into the Fraser River delta. Waves were observed at Fulford Harbour, Point Atkinson, Vancouver, Stevenson, the North Arm of the Fraser River, New Westminster and even Pitt Lake.

A prominent feature of the 1964 Alaska tsunami in Victoria Harbour is that the leading wave was the highest (Figure 3.6). The wave arrived as a pronounced wave crest of 70 cm, followed by an abrupt trough of 77 cm; the period of this wave was about 100 minutes. Although the same wave is evident in the Fulford Harbour record (Figure 3.6), the highest wave was the third wave, not the first, apparently as the result of amplification of the waves by local harbour resonant effects. In contrast to other major tsunamis (1946, 1960, 2010 and 2011), the 1964 tsunami at Victoria and Fulford, as well as at other stations of the British Columbia coast (see Figure 2.7 in Section 2.1.5), decayed relatively quickly. The reason for this decay appears to be the closeness of the 1964 source region to the observation area: as shown by Rabinovich et al., [2011] for the global 2004 Sumatra tsunami, near-field tsunami oscillations decay much faster than more distant far-field oscillations. A high-resolution numerical model of the 1964 tsunami for Victoria Harbour and the vicinity was constructed by Fine et al., [2018c].

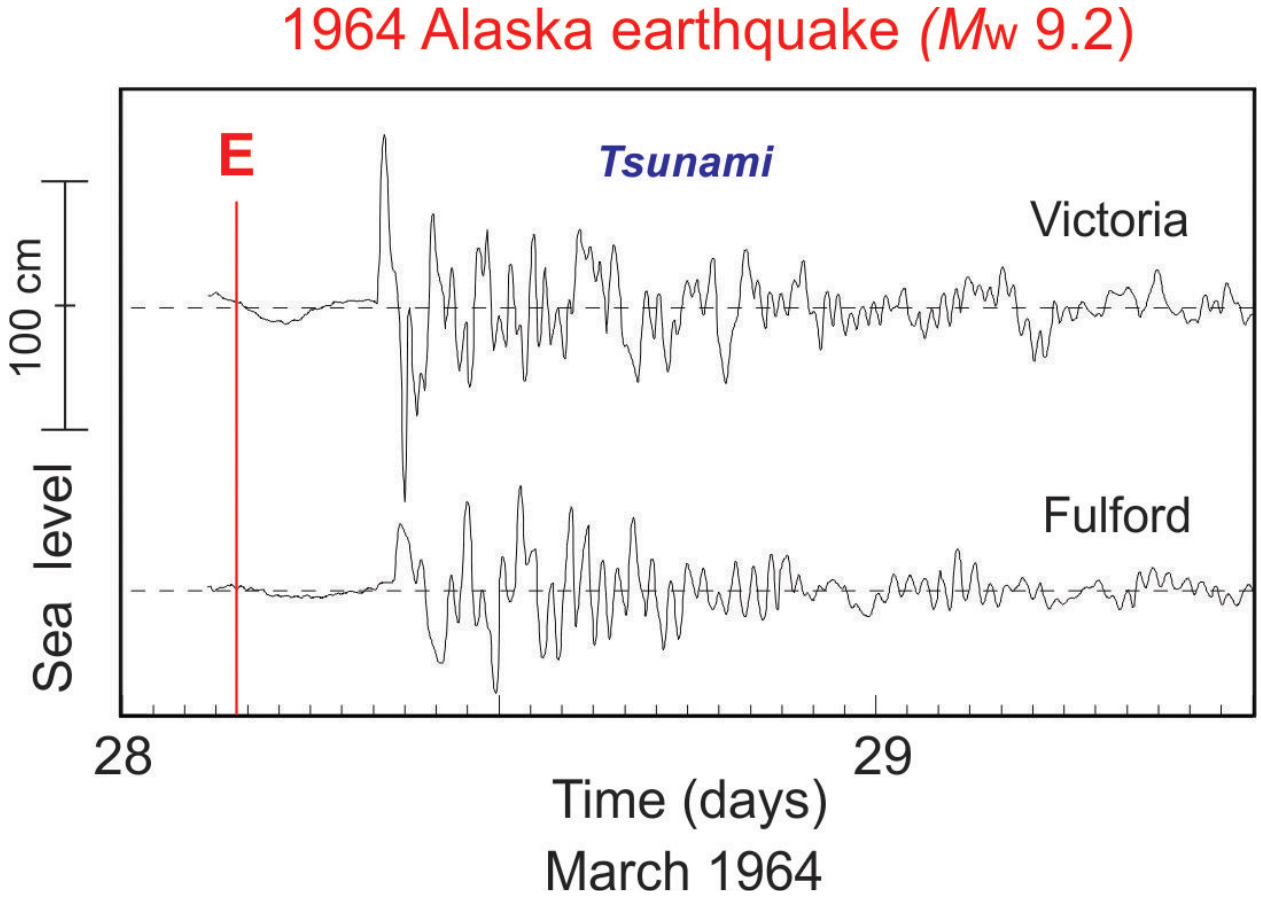

Figure 3.6. The 28 March 1964 Alaska tsunami recorded at Victoria and Fulford Harbour (Salt Spring Island). The solid vertical red line labelled "E" denotes the time of the earthquake.

3.2.6 The Chile (Maule) Tsunami of 27 February 2010

The 2010 Chilean (Maule) tsunami was the first major tsunami in 46 years to affect the coast of British Columbia after the 1964 Alaska tsunami. The main properties of this tsunami near the coast of British Columbia were examined by Rabinovich et al., [2013]. Some general features of this event are described in Section 2.1.6 of this report. The tsunami arrived at Victoria at 23:18 UTC on 27 February, roughly 16 hours 44 minutes after the earthquake. The maximum wave height of 23 cm was associated with the second train of waves that came to the site approximately four hours after the first train (Figure 3.7). The oscillations at Victoria and at other British Columbia stations were characterized by long ringing and slow energy decay.

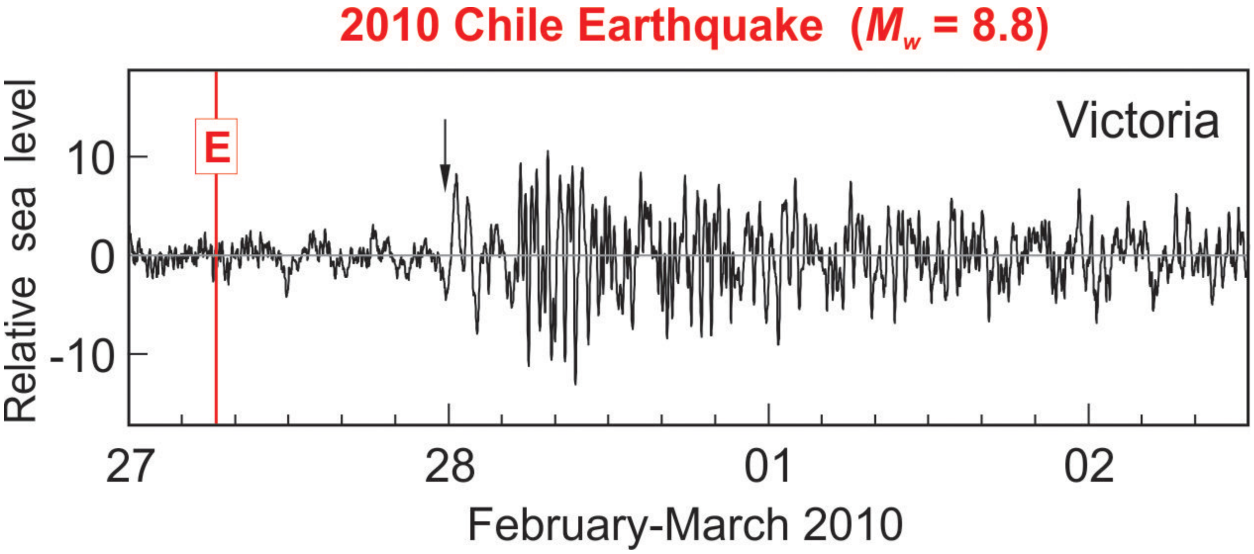

Figure 3.7. The 27 February 2010 Chilean tsunami recorded at Victoria. The solid vertical red line labelled "E" denotes the time of the earthquake; the arrow indicates the tsunami arrival time.

3.2.7 The Tohoku (East Japan) Tsunami of 11 March 2011

The 2011 Tohoku tsunami is described in Section 2.1.7. The tsunami was recorded by the Victoria tide gauge, five CHS permanent tide gauges in the Strait of Georgia (Patricia Bay, Point Atkinson, West Vancouver, Vancouver and Campbell River) and four ONC VENUS instruments in the Strait of Georgia and Saanich Inlet. What is especially important is that the event was recorded by five temporary tide gauges which were working in the adjacent Gorge Waterway. The data from the waterway and the Strait of Georgia make it possible to examine the character and evolution of the 2011 Tohoku tsunami in great detail.

Figure 3.8 shows the 2011 tsunami waves recorded at the Victoria tide gauges and at two temporary tide gauges located in the Gorge Waterway. The maximum wave height at Victoria (in the Inner Harbour) was 52 cm; the waves were amplified in the waterway up to 67 cm at Selkirk Water and 94 cm at Aaron Point. Associated currents were very strong, reaching several knots. The first wave arrived at Victoria at 16:17 UTC on 11 March, or 10 hours 31 minutes after the main earthquake shock. This is 54 minutes later than at Tofino. A typical feature of the Victoria record, as well as all other 2011 tsunami records on the British Columbia coast, is the very long ringing (4 to 5 days) and very slow energy decay.

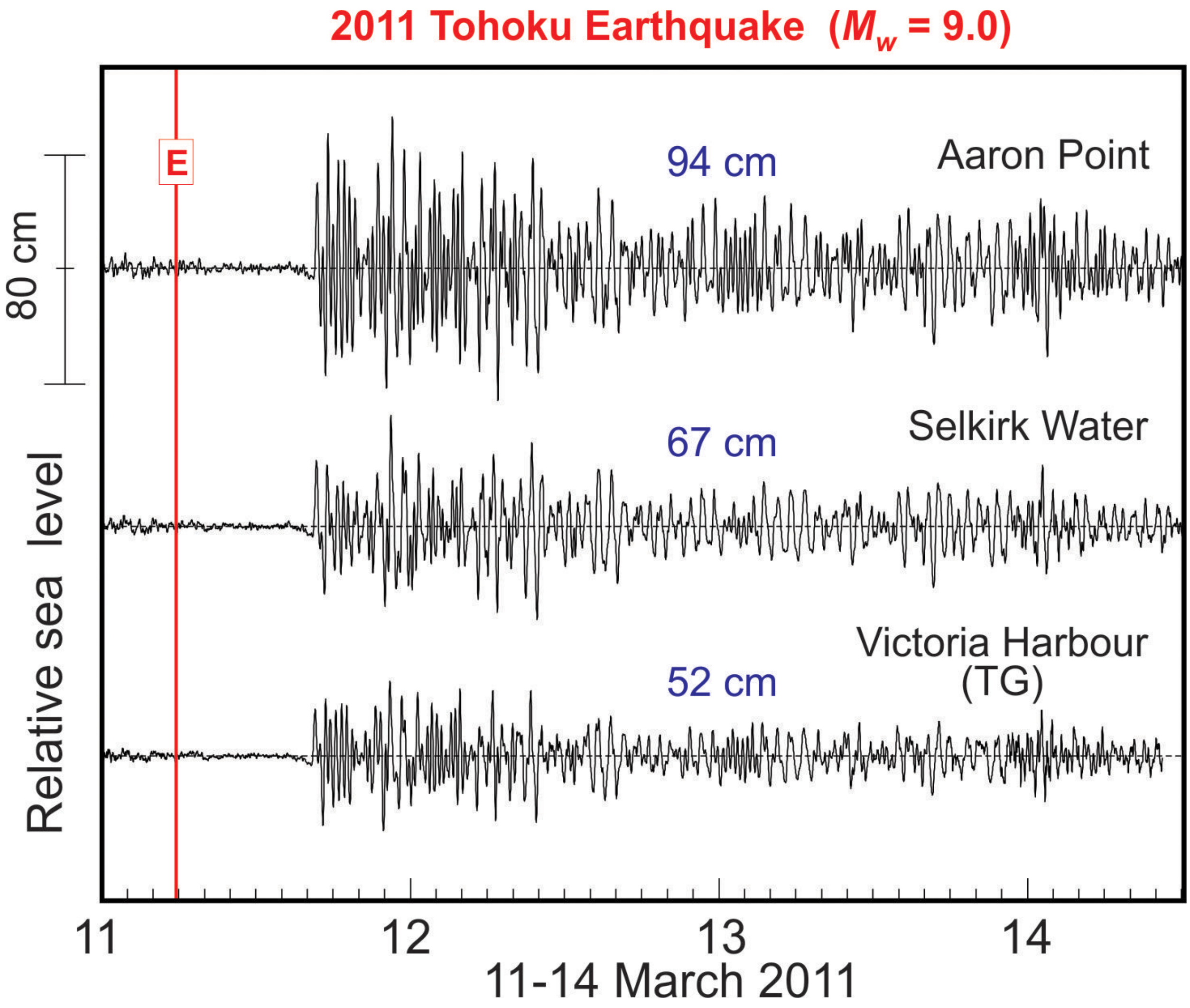

Figure 3.8. The 11 March 2011 Tohoku (East Japan) tsunami recorded at Victoria Harbour and at two stations - Selkirk Water and Aaron Point – in the Gorge Waterway. The solid vertical red line labelled "E" denotes the time of the earthquake.

3.3 SUMMARY OF TSUNAMI OBSERVATIONS AT VICTORIA

Table 3 presents a summary of the 32 tsunami events observed at Victoria; 27 of them are due to seismically generated tsunamis. Thus, tsunami statistics for Victoria station are quite extensive. Tsunami waves recorded at the Victoria tide gauge had a very regular, consistent character. Two periods were strongly predominant: 20-25 minutes and 50-55 minutes. The same periods were found by Rabinovich and Stephenson [2004] in the topographic response function of the Victoria tide gauge based on analysis of 9-day long, pre-tsunami background records at this station. It is likely that the former period is determined by the fundamental seiche mode of the Inner Harbour, while the latter period is associated with the resonant properties of the outer basin and Juan de Fuca Strait.

Of the 27 seismically-generated tsunamis that arrived at Victoria, only seven had maximum trough-to-crest wave heights $h_{tsu} > 20$ cm. All seven tsunamis were related to major events in the Pacific Ocean, being associated with the great Pacific earthquakes of 1946, 1952, 1957, 1960, 1964, 2010 and 2011 that had $M_w = 8.6$-9.5. Moreover, of these seven events, only three (all with $M_w \geq 9.0$) – 1960, 1964 and 2011 – produced tsunamis with wave heights at Victoria of $h_{tsu} > 50$ cm.

Of all recorded events, only the 1964 event generated tsunami waves that were hazardous to Victoria Harbour and, in particular, to the CCG site. The 1964 Alaska “Good Friday” tsunami was exceptional. This tsunami destructively affected the twin cities of Alberni and Port Alberni, and created significant damage in and around the vicinity of Prince Rupert. At Victoria, the first wave had a height $h_{tsu} = 147$ cm. It should be noted that any tsunami of wave height $h_{tsu} > 100$ cm (1 m) is considered to be potentially destructive. It is evident that great Alaska earthquakes with $M_w = 9.0$-9.3 are a major threat to the Victoria area. A slightly different location or orientation of the Alaska tsunami source region could create tsunami waves substantially larger than those originating from 1964 event. Precise estimates of possible tsunami wave heights in the area of the CCG station associated with various Alaska earthquake scenarios can be only obtained from comprehensive numerical studies.

Another, and even more important tsunami threat for the coast of British Columbia, is the Cascadia Subduction Zone (CSZ) [Wang et al., 2003; Clague et al., 2003; Leonard et al., 2014]. The Great CSZ earthquake of 26 January 1700, which had an estimated magnitude $M_w = 9.0$, generated a major trans-oceanic tsunami that caused significant destruction in Japan, on the opposite side of the Pacific Ocean [cf. Atwater et al., 2005], and strongly affected the outer coast of British Columbia.

Recent paleotsunami studies for the coast of Vancouver Island and the west coast of the USA [cf. Clague et al., 2000, Clague, 2001], as well as preliminary numerical modelling of CSZ tsunamis for coastal North America [cf. Cherniawsky et al., 2007; Fine et al., 2008; Cheung et al., 2011], demonstrate the high risk of CSZ tsunamis for British Columbia and, in particular, for the area of Victoria. Numerous seismotectonic studies indicate that great megathrust earthquakes in the CSZ region have occurred on a regular basis in the past and can be expected to occur with an average return period of about 500 years, with an uncertainty of approximately 200 years [Witter et al., 2013; Wang et al., 2013; Wang and Tréhu, 2016]. The only way to accurately determine the risk of CSZ tsunamis and the maximum expected tsunami wave heights for Victoria is through a series of numerical experiments that apply various scenarios for the source region of a CSZ earthquake. Detailed high-resolution modelling of a possible CSZ tsunami for Victoria Harbour and adjacent regions was carried out by Fine et al., [2018d].

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