The Seismic and Tsunami Threat to Ships, Personnel, and Defence Infrastructure on Canada's West Coast

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DRDC CORA TM 2013-185
October 2013

Defence R&D Canada
Centre for Operational Research & Analysis

National Defence / Défense nationale

Canada

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Technical Memorandum

DRDC CORA TM 2013-185

October 2013

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Abstract

The west coast of Canada is a high risk region for earthquakes and possible associated tsunamis. The commander of Maritime Forces Pacific/Joint Task Force (Pacific) requested an assessment of these threats, particularly the tsunami threat, to Royal Canadian Navy (RCN) vessels, personnel, and defence infrastructure on the west coast. This report brings together the extant geophysical science on the topic. The 'offshore' threat from tsunamis generated elsewhere around the Pacific Basin is characterized, as is the primary tsunami threat to coastal British Columbia – the Cascadia subduction zone. Probabilistic theory is developed to model subduction zone rupture events.

The results confirm a likelihood of about one chance in ten of a major tsunami event happening on the west coast in the next 50 years. The severity of the tsunami in Esquimalt Harbour will be more modest if the 500-year event happens, with a predicted rise and fall of plus or minus three meters in water levels, but could be double that if the (unlikely but possible) 5,000-year event occurs. The tsunami amplitude will be doubled on exposed coastlines of Vancouver Island, and doubled again when focused in longer inlets (like Alberni Inlet). Warning times are estimated at 60 to 90 minutes in the Victoria area, but only 25 minutes on the outer coast. An assessment of the impact of changing water levels on docked RCN vessels and the effect of water inundation on defence infrastructure is provided.

Résumé

La côte Ouest du Canada est une région où le risque de tremblements de terre, et des tsunamis qu'ils pourraient provoquer, est élevé. Le commandant des Forces maritimes du Pacifique/de la Force opérationnelle interarmées du Pacifique a demandé que ces risques soient évalués, particulièrement le risque de tsunami qui menace les navires, le personnel et l'infrastructure de défense de la Marine royale du Canada (MRC), sur la côte ouest. Ce rapport réunit les connaissances scientifiques existantes en géophysique à ce sujet. La menace « au large » que représentent les tsunamis dont la source serait ailleurs dans le bassin du Pacifique y est caractérisée, de même que la plus grande menace de tsunami pour la côte de la Colombie-Britannique – la zone de subduction de Cascadia. De plus, une théorie probabiliste est élaborée pour modéliser les ruptures dans la zone de subduction.

Les résultats confirment que la probabilité d'un important tsunami sur la côte ouest est d'environ une chance sur dix au cours des 50 prochaines années. La gravité d'un tsunami déferlant sur le port d'Esquimalt sera plus modérée si le tsunami à récurrence de 500 ans survient, avec une hausse et une baisse prévues du niveau de l'eau de ±3 mètres. Ces chiffres pourraient doubler si le tsunami à récurrence de 5 000 ans (peu probable, mais possible) se produit. L'amplitude du tsunami sera deux fois plus élevé sur les côtes exposées de l'île de Vancouver et quatre fois plus élevé dans les longs bras de mer (comme le bras Alberni). On estime que les préavis dont on disposera seront de 60 à 90 minutes pour la région de Victoria, mais de 25 minutes seulement sur la côte extérieure. Une évaluation de l'impact de la variation des niveaux de l'eau sur les navires de la MRC à quai et des effets de l'inondation sur l'infrastructure de défense est fournie.

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Executive Summary

The Seismic and Tsunami Threat to Ships, Personnel, and Defence Infrastructure on Canada's West Coast, D.W. Mason & A. Zegers, DRDC CORA TM 2013-185; Defence R&D Canada, Centre for Operational Research & Analysis, October 2013.

Introduction

ES-1. The objective of this study was to bring together the extant science on earthquakes and tsunamis, add to that science if possible, and focus it as directly and clearly as possible in support of decisions within the Department of National Defence in general, and within the Maritime Forces Pacific/Joint Task Force (Pacific) (MARPAC/JTFP) command in particular, on strategies to mitigate the earthquake and tsunami threats to Royal Canadian Navy ships, personnel, and defence infrastructure on the west coast of Canada.

ES-2. There has been a wealth of scientific research produced over the past couple of decades to advance our understanding of the seismological nature of the west coast of North America. The authors have relied heavily on the expertise and research programs run by established Canadian experts at the Institute of Ocean Sciences in Sidney, BC, specifically Dr. Garry Rogers of Natural Resources Canada and Dr. Josef Cherniawsky of Fisheries and Oceans Canada. We have also consulted some of the top paleoseismic researchers in the USA, including Dr. Brian Atwater of the University of Washington and Dr. Chris Goldfinger of Oregon State University.

Geophysics 101

ES-3. The earth's surface is composed of a mosaic of tectonic plates. Pressures under the earth's mantle cause them to move in relation to each other at about the rate one's fingernails grow. At convergent interfaces one plate will be moving underneath the other, called a subduction zone, which is often marked by an undersea trench. The earth's surface is cool so the plates will stick on each other. Pressure builds up over time, causing the upper plate to compress and buckle upwards. This pressure may get relieved at random intervals via local earthquakes in the buckling region.

ES-4. However, the largest ("megathrust") earthquakes result when all or part of the subduction zone finally gives way under the built up pressure and ruptures. When this occurs, the lateral shift of the land underwater pushes up a mass of water, resulting in a tsunami. Examples include the Great Chilean Earthquake (1960), the Great Alaskan Earthquake (1964), the Indian Ocean earthquake (Boxing Day 2004), and the recent Tohoku earthquake in Japan (2011).

ES-5. The biggest tsunami threat to the west coast of Canada sits about 100 km off the coast. It is the Cascadia subduction zone, where the Juan de Fuca plate subducts under the North American plate along a 1,100 km fault stretching from Vancouver Island to northern California. Cascadia last ruptured in the year 1700.

ES-6. The three big questions concerning the tsunami threat are simply stated: how likely is a tsunami on the west coast, how severe would it be, and how much warning time will we have?

The Offshore Tsunami Threat

ES-7. But before dealing with Cascadia, we should get a firm handle on the threat posed by tsunamis generated by subduction zone ruptures elsewhere in the Pacific basin ('offshore'). We have a reasonably recent example in the 1964 Great Alaskan Earthquake, spawned by the next closest subduction zone to Canada's Pacific coast. Its close proximity and large magnitude (at M9.2, the second largest earthquake in recorded history), suggest that it should represent very close to the maximum threat from a tsunami generated elsewhere in the Pacific basin. Statistics from this earthquake and tsunami form the basis for the following estimates.

ES-8. **How likely?** Expect perhaps one or two notable offshore tsunamis per century.

ES-9. **How severe?** Expect a 2.5 metre wave height (total swing, peak to trough) on the exposed outer coastline of BC, perhaps 2 to 2.5 times more than that at the head of long inlets open to the ocean (e.g. Port Alberni), but reducing to 1.5 metres at locations along the Strait of Juan de Fuca (e.g. Victoria).

ES-10. **How much warning time?** Travel time from the Alaskan subduction zones is about two hours to Haida Gwaii, three hours to the northern coast and outer Vancouver Island and 4 hours into the Victoria area.

The Cascadia Subduction Zone Tsunami Threat

ES-11. **How Likely?** Paleoseismic research led by Atwater looking at tsunami deposits in coastal marshes, and led by Goldfinger looking at underwater landslides caused by earth shaking events, has uncovered evidence of up to 19 past Cascadia subduction zone ruptures in the past 10,000 years. This gives a mean rupture interval of about 500 years. The authors recommend a mathematical model that reflects an increasing propensity to re-rupture as time passes and pressure accumulates, which is described precisely by the Weibull distribution. Using this distribution, a mean rupture interval of 500 years, and the fact that the last rupture occurred 313 years ago, the probability of Cascadia subduction zone rupture is estimated at about *1 chance in 10 in the next 50 years*.

ES-12. In the Strait of Juan de Fuca there is paleoseismic research that suggests local earthquakes may also have produced tsunamis. Indeed, this happened during the 1946 Vancouver Island earthquake. Taking into account this additional source, the estimated probability of a tsunami striking a given locale near the Strait of Juan de Fuca increases to about *1 chance in 7 in the next 50 years*.

ES-13. **How Severe?** Cherniawsky's tsunami modelling efforts have produced estimates of wave heights for a Cascadia rupture releasing 500 years of built-up strain, The modelling predicts a maximum 8 metre wave height in the Victoria area (±4 metres from the current tide level), double that on the outer coast of Vancouver Island (eg. Tofino or Ucluelet), and double that again at the end of any long focussing inlets facing the ocean (e.g. Port Alberni). *For the Esquimalt Dockyard area the models estimate a* *maximum 6 metre wave height (±3 metres from current tide level) for this '500-year event'.*

ES-14. Although these 500-year tsunami heights are recommended for planning purposes, there remains the very remote risk of a 'giant' tsunami. Notably, the 2011 Tohoku tsunami contained a water height spike that considerably exceeded what historical observations over the past thousand years had led the Japanese to believe was possible. Goldfinger postulates that not all the built up strain gets released every time the subduction zone ruptures, and that two of the 19 ruptures of the past 10,000 years show evidence of being about double the size of the '500 year' event. Although models of built-up strain in Cascadia show only average levels currently, planners should be cognizant of the possibility of this '5,000 year event' (two occurred in 10,000 years). The likelihood of the 5,000-year event is estimated using the Weibull model as 1 *chance in 54 in the next 50 years*. For this event, the modelling estimates of tsunami heights in the previous paragraph should be doubled.

ES-15. The Gulf Islands provide a sufficient physical barrier that the Strait of Georgia region, including Vancouver, Comox, and Nanoose, is not at risk from a Cascadia-induced tsunami.

ES-16. **How much warning time?** The earthquake itself is the alarm bell. A subduction zone earthquake will last several minutes or more and will induce long-period ground motion that may make it difficult to even stand up. If one should experience an earthquake with these characteristics, assume a tsunami will follow. Cherniawsky's modelling predicts the first waves will strike the west coast of Vancouver Island within 25 minutes. Victoria area will see the first drop in water levels at about 60 minutes, and *the first wave will crest about 90 minutes after the earthquake*. The models predict that several waves will arrive over the next six hours or so, and the second or third wave may be the largest.

The General Earthquake Threat

ES-17. Using a research technique similar to that employed by Dr. Goldfinger, Dr. Rogers has investigated the record of past earthquakes off Vancouver Island (Saanich Inlet). Eighteen major incidents were recorded over the past 4,500 years, of which about half can be correlated with a Cascadia rupture. This offers a useful rule of thumb: any earthquake that produces 'strong shaking' in the southern Vancouver Island region has about a 50 percent chance of being a local earthquake in the M7 range, and a 50 percent chance of being a Cascadia subduction zone event (M9 range). The former may generate a local tsunami. The latter will almost certainly generate a widespread tsunami.

ES-18. With an average return rate of 220 years, *the probability of a 'strong shaking' event being experienced in any location on southern Vancouver Island is about 1 in 5 over the next 50 years.*

Impact on Ships, Personnel, and Defence Infrastructure

ES-19. **Vessels in open water.** The impact of the long period waves of a tsunami on vessels in open water is negligible. However, Cherniawsky's modelling suggests that vessels under way in the entrance to Esquimalt Harbour will have to negotiate currents in excess of 10 knots as the tsunami surges ebb and flow.

ES-20. **Docked frigates, destroyers, submarines, and replenishment ships.** The threat is much greater for vessels tied up in port. The larger naval vessels alongside in the Esquimalt Dockyard, including Colwood, should suffer minimal damage from the 500-year tsunami (±3 metres). At some jetty positions a ship's sonar dome may ground at low water, or the replenishment ship or submarine hulls may ground. At high water, the jetties will be inundated and all ships will be pushed landward, but the water height should still be low enough to enable the large ships to maintain contact with the jetties. This assumes that fender systems, bollards, and hawsers continue to function as designed. However, the 5,000-year tsunami would be devastating. All ships alongside will ground at low water, and lose contact with the jetties at high water.

ES-21. **Coastal defence vessels and smaller boats.** Past tsunami experience has indicated that smaller vessels tend to suffer more damage than larger ships. The shallower water at 'Y' Jetty will probably see the coastal defence vessels ground at low water during a 500-year tsunami. Appropriate fender and mooring systems should ensure they maintain contact with the jetty at high water. It is unclear what effect having one vessel 'rafting off' another (as they tend to do) might have on damage. The Orca class training vessels should be able to ride out the tsunami at the (deeper) 'B' Jetty. The height of the piles holding the floating docks for smaller vessels should be just sufficient to withstand a 3 metre rise at high tide, but this assumes the tsunami's lateral forces do not break the piles. Some grounding of vessels at the floating docks may occur at low water. And, as with the larger ships, the 5,000-year tsunami is devastating to all the smaller vessels.

ES-22. **Esquimalt Dockyard inundation.** The tops of the jetties would be inundated at high water. Experience has shown that wooden pile jetties can be severely battered by ships. Dock structures can get buoyed off their piles, and the piles can even be floated out of their sockets. It is noted that existing wood pile jetties 'A' and 'B' in the Dockyard are scheduled for replacement in the department's site development plan.

ES-23. Expect the base drydock, as well as the commercial Esquimalt Graving Dock across the harbour, to be inundated.

ES-24. Fuel is lighter than water. Past tsunami experience has shown that fuel tanks will float off, puncture, and catch fire during a tsunami. Expect the older fuel tanks (to the west of the drydock entrance) to be inundated.

ES-25. The 500-year tsunami will inundate the ground levels of all Fleet Maintenance Facility (FMF) buildings, the operational headquarters building (Bldg 100), and several others in the Dockyard, as well as the dockside buildings at Colwood. The nature of the high rocky land on the Dockyard peninsula will not expose that many more buildings during a 5,000-year tsunami, but the isthmus may get temporarily flooded, turning the peninsula into an island during high water.

Recommendations

ES-26. In the event of another tsunami from an offshore source, like that generated by the 1964 Alaska earthquake, the Navy should be prepared to respond to inundation crises in communities at the end of long inlets facing the ocean on Vancouver Island, like Port Alberni and other smaller communities up the coast (Tahsis, Zeballos, Port Alice).

ES-27. For a Cascadia event (1 chance in 10 in the next 50 years), planners should employ a 6 metre tsunami wave height estimate (±3 metres from current tide level) for defence installations in Esquimalt Harbour and an 8 metre height for the general Victoria area. However, planners should be cognizant of the more remote threat of a giant, 5,000-year Cascadia event (1 chance in 50 in the next 50 years), which would result in doubled wave heights.

ES-28. Ships are much safer in open water than in port when a tsunami strikes. Canadian Fleet Pacific should examine the possibility of putting procedures in place to get as many Navy vessels to sea as possible within the 60 to 90 minute window before the arrival of the tsunami. The benefit of having ships in open water during the tsunami would need to be weighed against the risk of moving the ships on short notice in a potentially chaotic situation.

ES-29. Engineering studies should be initiated to determine the best fender and mooring solutions to enable both ships and jetties to survive the forces and water level changes associated with a tsunami.

ES-30. Buildings and facilities for operational command and ship maintenance will be impacted by tsunami inundation in the Dockyard. Studies should be initiated to identify how the operational impact of tsunami inundation of defence infrastructure can be minimized.

ES-31. All fuel storage tanks should be elevated to above 6 meters above maximum high tide. Footings should be strengthened to prevent them from floating off if submerged.

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Sommaire

The Seismic and Tsunami Threat to Ships, Personnel, and Defence Infrastructure on Canada's West Coast, D.W. Mason & A. Zegers, DRDC CARO TM 2013-185; R&D pour la défense Canada - Centre d'analyse et de recherche opérationnelle, octobre 2013.

Introduction

S-1. La présente étude visait à réunir les connaissances scientifiques sur les tremblements de terre et les tsunamis, à les approfondir si possible, et à les orienter de façon claire et directe pour appuyer les décisions prises au sein du ministère de la Défense nationale en général et du commandement des Forces maritimes du Pacifique/de la Force opérationnelle interarmées du Pacifique (FMAR[P]/FOIP) en particulier, en ce qui concerne les stratégies d'atténuation des menaces que représentent les tremblements de terre et les tsunamis pour les navires, le personnel et l'infrastructure de défense de la Marine royale du Canada, sur la côte Ouest du Canada.

S-2. De nombreuses études scientifiques ont été réalisées, au cours des dernières décennies, en vue de mieux comprendre les caractéristiques sismologiques de la côte ouest de l'Amérique du Nord. Les auteurs ont eu largement recours à l'expertise et aux programmes de recherche de spécialistes canadiens reconnus de l'Institut des sciences de la mer à Sidney (Colombie-Britannique), plus précisément M. Garry Rogers (Ph. D.) de Ressources naturelles Canada et M. Josef Cherniawsky (Ph. D.) de Pêches et Océans Canada. Plusieurs chercheurs de premier ordre en paléosismologie aux États-Unis, notamment M. Brian Atwater (Ph. D.) de la University of Washington et M. Chris Goldfinger (Ph. D.) de la Oregon State University ont également été consultés.

Géophysique 101

S-3. Une mosaïque de plaques tectoniques couvre la surface de la Terre. La pression régnant sous le manteau de la Terre entraîne le mouvement des plaques l'une par rapport à l'autre, à peu près à la vitesse de croissance des ongles. À la frontière de plaques convergentes, une plaque se glisse en dessous de l'autre. Cet endroit est appelé une zone de subduction et est souvent marqué par une fosse océanique. La surface de la Terre est froide, de sorte que les plaques adhèrent entre elles. La pression s'accumule au fil du temps, ce qui provoque la compression et la déformation vers le haut de la plaque supérieure. La pression peut être libérée à intervalles aléatoires par des tremblements de terre locaux dans la zone de déformation.

S-4. Cependant, les plus grands séismes (« méga-séismes ») sont déclenchés lorsque la zone de subduction finit par céder en partie, ou au complet, sous la pression accumulée et qu'il y a rupture. Lorsque cela se produit, le déplacement latéral du plancher océanique pousse une masse d'eau vers le haut, provoquant un tsunami. Voici quelques exemples de méga-séismes : le séisme de 1960 au Chili, le séisme de 1964 en Alaska, le séisme de 2004 dans l'océan Indien (le lendemain de Noël) et le récent séisme du Tohoku au Japon (2011).

S-5. La plus grande menace de tsunami pour la côte Ouest du Canada se situe environ 100 km au large de la côte. Il s'agit de la zone de subduction de Cascadia, où la plaque Juan de Fuca se glisse sous la plaque nord-américaine le long d'une faille de 1 100 km s’étendant de l’île de Vancouver jusqu’au nord de la Californie. La dernière rupture de la zone de subduction de Cascadia s’est produite en 1700.

S-6. Les trois principales questions relatives à la menace de tsunami s’énoncent clairement : Quelle est la probabilité qu’un tsunami déferle sur la côte Ouest? Quelle en sera la gravité? Quel sera le préavis dont nous disposerons?

Menace de tsunamis au large

S-7. Avant d’aborder la zone de subduction de Cascadia, il faut bien comprendre la menace que représentent les tsunamis engendrés par les ruptures dans une zone de subduction située ailleurs dans le bassin du Pacifique (en mer). Le grand séisme de 1964 en Alaska, causé par la zone de subduction voisine la plus proche de la côte canadienne du Pacifique, en est un exemple assez récent. La grande proximité et la forte magnitude de ce séisme (M9,2; c’est le deuxième plus grand séisme jamais enregistré) portent à croire que ce genre d’événement constitue, à peu de chose près, la plus importante menace de tsunami dont la source est ailleurs dans le bassin du Pacifique. Les statistiques établies en fonction de ce séisme et du tsunami qu’il a provoqué constituent le fondement des estimations ci-dessous.

S-8. **Quelle est la probabilité qu’un tsunami survienne?** Il faudrait s’attendre à un ou deux tsunamis d’envergure au cours d’un siècle.

S-9. **Quelle en sera la gravité?** Il faut s’attendre à une hauteur de vague de 2,5 mètres (distance verticale totale entre le creux et la crête d’une vague) dans les zones côtières extérieures et exposées de la Colombie-Britannique et à une hauteur de vague peut-être 2 à 2,5 fois plus grande à l’entrée des longs bras de mer ouverts à l’océan (p. ex. à Port Alberni). La hauteur de vague serait, cependant, de 1,5 mètre dans les endroits le long du détroit de Juan de Fuca (p. ex. à Victoria).

S-10. **Quel sera le préavis dont nous disposerons?** Le temps de propagation, à partir des zones de subduction de l’Alaska, est d’environ deux heures jusqu’à Haida Gwaii, d’environ trois heures jusqu’à la côte septentrionale et à la côte extérieure de l’île de Vancouver et d’environ quatre heures jusqu’à la région de Victoria.

Menace de tsunami dans la zone de subduction de Cascadia

S-11. **Quelle est la probabilité qu’un tsunami survienne?** Les recherches paléosismologiques, d’une part, celles dirigées par M. Atwater portant sur les dépôts de tsunamis dans les marais côtiers et, d’autre part, celles dirigées par M. Goldfinger portant sur les glissements de terrain sous-marins causés par les séismes, ont permis de découvrir des preuves selon lesquelles 19 ruptures se seraient produites dans la zone de subduction de Cascadia au cours des dix derniers millénaires. L’intervalle moyen entre ruptures serait donc d’environ 500 ans. Les auteurs recommandent un modèle mathématique reflétant le risque de plus en plus grand de nouvelles ruptures à mesure que le temps passe et que la pression s’accumule, ce que la distribution de Weibull décrit précisément. Compte tenu de cette distribution, d’un intervalle moyen entre ruptures de 500 ans et du fait que la dernière rupture a eu lieu il y a 313 ans, la probabilité d’une rupture dans la zone de subduction de Cascadia serait d’environ *1 chance sur 10 au cours des 50 prochaines années*.

S-12. Des recherches paléosismologiques dans le détroit de Juan de Fuca semblent indiquer que des séismes locaux auraient pu produire des tsunamis. Effectivement, cela s'est réellement produit pendant le séisme de 1946 survenu sur l'île de Vancouver. Compte tenu de cette information supplémentaire, on estime que la probabilité de voir un tsunami déferlant sur un endroit donné proche du détroit de Juan de Fuca augmente à environ *1 chance sur 7 au cours des 50 prochaines années*.

S-13. **Quelle en sera la gravité?** Les travaux de modélisation de tsunamis de M. Cherniawsky ont produit des estimations des hauteurs de vague résultant d'une rupture dans la zone de subduction de Cascadia, qui libérerait 500 ans de tension accumulée. La modélisation prédit une hauteur de vague maximale de 8 mètres dans la région de Victoria (±4 mètres par rapport au niveau de marée actuel), le double de cette hauteur sur la côte extérieure de l'île de Vancouver (p. ex. à Tofino ou à Ucluelet), et le quadruple de cette hauteur à l'extrémité des longs bras de mer convergents faisant face à l'océan (p. ex. à Port Alberni). *Pour la zone du chantier naval d'Esquimalt, les modèles estiment une hauteur de vague maximale de 6 mètres (±3 mètres par rapport au niveau de marée actuel) si un événement à récurrence de 500 ans se produit.*

S-14. Même si on recommande d'utiliser ces hauteurs de vague pour les événements à récurrence de 500 ans dans la planification, il existe un très faible risque qu'un tsunami « géant » soit déclenché. Le tsunami du Tohoku en 2011 a produit une crête d'une hauteur dépassant considérablement les prévisions maximales établies par les Japonais en fonction des observations historiques du dernier millénaire. M. Goldfinger émet l'hypothèse selon laquelle la tension accumulée n'est pas libérée complètement à chaque rupture dans la zone de subduction et que deux des 19 ruptures des dix derniers millénaires auraient laissé des preuves indiquant qu'elles auraient été deux fois plus fortes qu'un événement à récurrence de 500 ans. Même si les modèles de tension accumulée dans la zone de subduction de Cascadia ne montrent actuellement que des niveaux moyens, les planificateurs doivent être conscients de la possibilité qu'un événement à « récurrence de 5 000 ans » survienne (deux se sont produits au cours de dix millénaires). La probabilité d'un tel événement estimée à l'aide du modèle de Weibull est de *1 chance sur 54 au cours des 50 prochaines années*. Pour cet événement, il faut doubler les hauteurs de vague de tsunami estimées à l'aide de modèles, fournies dans le paragraphe précédent.

S-15. Les îles Gulf formant une barrière physique suffisante, la région du détroit de Georgia, y compris Vancouver, Comox et Nanoose, est protégée contre un tsunami qui pourrait être causé par la zone de subduction de Cascadia.

S-16. **Quel sera le préavis dont nous disposerons?** Le tremblement de terre lui-même donnerait l'alarme. Un séisme dans une zone de subduction dure plusieurs minutes, voire plus longtemps, et provoque des mouvements du sol de longue période, pendant lesquels il peut être difficile de rester debout. Si un tremblement de terre correspondant à ces caractéristiques venait à se produire, on peut supposer qu'un tsunami suivra. Selon la modélisation de M. Cherniawsky, les premières vagues déferleront sur la côte ouest de l'île de Vancouver moins de 25 minutes plus tard. Une première baisse des niveaux de l'eau se produira dans la région de Victoria environ 60 minutes plus tard, et *la première crête de vague se formera environ 90 minutes après le tremblement de terre*. Les modèles prédisent que plusieurs vagues déferleront durant les six heures suivantes environ et que la deuxième ou troisième vague sera probablement la plus grande.

Menace générale de tremblement de terre

S-17. En appliquant une technique de recherche semblable à celle utilisée par M. Goldfinger, M. Rogers a étudié les données historiques sur les séismes au large de l'île de Vancouver (bras de mer Saanich). Dix-huit événements majeurs ont été enregistrés au cours des dernières 4 500 années, dont environ la moitié peuvent être corrélés avec une rupture dans la zone de subduction de Cascadia. On peut en dégager une règle empirique utile : tout séisme produisant de « fortes secousses » dans la région du sud de l'île de Vancouver peut être, avec une probabilité de 50 %, un tremblement de terre local dans la plage de magnitude M7 et, avec une probabilité de 50 %, un événement lié à la zone de subduction de Cascadia (plage de magnitude M9). Le premier événement peut déclencher un tsunami local. Le deuxième événement provoquera presque certainement un tsunami étendu.

S-18. Avec une récurrence moyenne de 220 ans, *il y a environ 1 chance sur 20 qu'un événement de « fortes secousses » soit ressenti à un endroit, quel qu'il soit, sur le sud de l'île de Vancouver au cours des 50 prochaines années*.

Impact sur les navires, le personnel et l'infrastructure de défense

S-19. **Navires en mer.** L'impact des vagues de longue période d'un tsunami sur les navires en mer est négligeable. Cependant, la modélisation de M. Cherniawsky indique que les navires faisant route à l'entrée du port d'Esquimalt devront faire face à des courants de plus de 10 nœuds avec les mouvements de flux et de reflux du tsunami.

S-20. **Frégates, destroyers, sous-marins et navires ravitailleurs à quai.** La menace est beaucoup plus grande pour les navires ancrés au port. Les plus grands navires de guerre à quai dans le chantier naval d'Esquimalt, y compris à Colwood, ne devraient subir que très peu de dommages si un tsunami à récurrence de 500 ans (±3 mètres) survient. Selon la position des navires sur la jetée, leur dôme sonar pourrait toucher le fond lorsque le niveau de l'eau baissera. La coque des navires ravitailleurs ou des sous-marins pourrait aussi toucher le fond. En revanche, lorsque le niveau de l'eau montera, les jetées seront submergées, et tous les navires seront poussés vers la terre, mais le niveau de l'eau devrait demeurer suffisamment bas pour permettre aux grands navires de rester amarrés aux jetées. Cela suppose que les systèmes de défense, les bollards et les aussières continueront à fonctionner comme prévu. Cependant, un tsunami à récurrence de 5 000 ans serait dévastateur. S'il se produit, tous les navires à quai toucheront le fond lorsque le niveau de l'eau baissera et ne resteront pas accostés à la jetée lorsque le niveau de l'eau montera.

S-21. **Navires de défense côtière et embarcations plus petites.** Si on se fie aux tsunamis qui se sont produits dans le passé, les plus petites embarcations ont tendance à subir plus de dommages que les grands navires. En eaux moins profondes à la jetée Y, les navires de défense côtière toucheront le fond lorsque le niveau de l'eau baissera, pendant un tsunami à récurrence de 500 ans. Grâce à des systèmes de défense et d'amarrage appropriés, on devrait pouvoir s'assurer que ces navires restent accostés à la jetée lorsque le niveau de l'eau monte. Les dommages que les navires pourraient se causer l'un l'autre (« *rafting off* ») ne sont pas clairs. Les navires-écoles de la classe Orca à la jetée B (en eaux plus profondes) devraient résister au tsunami. La hauteur des pieux supportant les pontons pour les plus petites embarcations devrait suffire tout juste pour résister à une hausse de 3 mètres lorsque le niveau de l'eau montera, mais cela suppose que les forces latérales du tsunami ne brisent pas les pieux. Certaines embarcations accostées aux pontons pourraient toucher le fond lorsque le niveau de l'eau baissera. Tout comme pour les grands navires, un tsunami à récurrence de 5 000 ans serait dévastateur pour les petites embarcations.

S-22. **Inondation du chantier naval d'Esquimalt.** La partie supérieure des jetées sera submergée lorsque le niveau de l'eau montera. Les expériences passées ont montré que les jetées avec des pieux en bois peuvent être gravement endommagées par les navires. Les structures de quai peuvent se détacher de leurs pieux, et les pieux, se détacher de leurs bases. Il convient de noter que le remplacement des jetées avec pieux en bois, A et B, du chantier naval est prévu dans le plan d'aménagement du site du ministère.

S-23. Il faut s'attendre à ce que la cale sèche de la base, de même que le bassin de radoub commercial d'Esquimalt de l'autre côté du port, soient inondés.

S-24. Le carburant est plus léger que l'eau. Lors de tsunamis survenus dans le passé, les réservoirs de carburant ont dérivé, subi des perforations et se sont enflammés. Il faut s'attendre à ce que les plus anciens réservoirs de carburant (à l'ouest de l'entrée de la cale sèche) soient submergés.

S-25. Le tsunami à récurrence de 500 ans inondera les rez-de-chaussée de tous les bâtiments des installations de maintenance de la flotte (IMF), du quartier général opérationnel (bâtiment 100) et de plusieurs autres bâtiments dans le chantier naval, ainsi que les bâtiments du quai à Colwood. À cause de la nature du terrain montagneux et rocheux sur la péninsule où se trouve le chantier naval, à peu près le même nombre de bâtiments seront exposés si un tsunami à récurrence de 5 000 ans survient, mais l'isthme pourrait être inondé temporairement, auquel cas la péninsule deviendra une île lorsque le niveau de l'eau sera élevé.

Recommandations

S-26. Au cas où un autre tsunami serait déclenché par une source au large, comme celui engendré par le séisme de 1964 en Alaska, la Marine doit être préparée à intervenir aux inondations de collectivités se trouvant à l'extrémité des longs bras de mer faisant face à l'océan, sur l'île de Vancouver, comme c'est le cas de Port Alberni et d'autres petites collectivités qu'on rencontre en remontant la côte (Tahsis, Zeballos, Port Alice).

S-27. En ce qui concerne un tsunami qui serait provoqué par la zone de subduction de Cascadia (1 chance sur 10 au cours des 50 prochaines années), les planificateurs devraient tenir compte d'une hauteur de vague estimée à 6 mètres (±3 mètres par rapport au niveau de marée actuel) pour les installations de défense du port d'Esquimalt et à 8 mètres pour l'ensemble de la région de Victoria. Cependant, les planificateurs doivent être conscients de l'éventualité peu probable d'un tsunami géant à récurrence de 5 000 ans, qui pourrait aussi être causé par la zone de subduction de Cascadia (1 chance sur 50 au cours des 50 prochaines années) et qui produirait des hauteurs de vague deux fois plus grandes.

S-28. Les navires sont beaucoup plus en sécurité en mer qu'ils ne le sont dans un port, lorsqu'un tsunami survient. La Flotte canadienne du Pacifique devrait envisager la mise en place de procédures pour envoyer en mer autant de navires que possible dans l'intervalle de 60 à 90 minutes précédant l'arrivée du tsunami. L'avantage que procure le fait d’avoir les navires en mer pendant un tsunami doit être soupesé par rapport au risque que représente leur déplacement avec un court préavis dans une situation potentiellement chaotique.

S-29. Il faudrait entreprendre des études d’ingénierie afin de trouver les meilleures solutions de défense et d’amarrage pour que les navires et les quais puissent résister aux forces et aux changements de niveau de l’eau engendrés par un tsunami.

S-30. Les bâtiments et installations du commandement opérationnel et de l’entretien des navires seraient touchés en cas d’inondation provoquée par un tsunami dans le chantier naval. Il faudrait entreprendre des études pour déterminer de quelle façon on pourrait réduire l’impact opérationnel d’une telle inondation sur l’infrastructure de défense.

S-31. Tous les réservoirs de carburant devraient être surélevés de manière à dépasser de plus de six mètres le niveau maximal de la marée haute. Les surfaces d’appui devraient être renforcées afin d’empêcher qu’elles partent à la dérive si elles sont submergées.

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1. Introduction

1. The west coast of North America is an acknowledged zone of seismic activity. Tectonic plate movement – specifically the relative motion of the larger Pacific and North American plates, as well as the smaller Juan de Fuca plate – create the potential for west coast earthquakes of all magnitudes. The threat of 'the big one' always looms.

2. Occasionally, an earthquake can also generate a tsunami. The memories of tsunamis caused by the Great Chilean Earthquake (Magnitude 9.5) of 1960 and the Great Alaskan Earthquake (M 9.2) of 1964 – the latter which extensively damaged Port Alberni, BC - have faded in the public mind. However, the Indian Ocean Earthquake of Boxing Day 2004 (M 9.1), another big Chile earthquake in 2010 (M 8.8), and the most recent Tohoku Earthquake and tsunami off Japan in March 2011 (M 9.0) have refocused the world on this infrequent but serious threat to human life and infrastructure. Tsunami awareness and preparation has been in the Japanese mindset for centuries (see Figure 1), yet the Tohoku tsunami, a 1,000-year event, showed their preparations as insufficient.

3. Acknowledging the local earthquake and tsunami threat, the Pacific Fleet Commander asked the Operational Research Team to conduct an assessment of these threats to defence ships, personnel, and infrastructure on the west coast. This report presents the results of that assessment.

Figure 1. *The Great Wave off Kanagawa, by Katsushika Hokusai, 1820s*
(public domain image courtesy of the US Library of Congress)

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2. Study Approach

2.1 Aims and Objectives

4. In early 2011 the Pacific Fleet Commander asked the J5 planning staff a range of questions on the impact a tsunami might have on the Esquimalt dockyard, specifically:

a. Will ships tied to jetties at CFB Esquimalt touch ground during a tsunami?
b. Will they lift the jetty off (will bollards fail, will hawsers part)?
c. Will the cranes fall onto ships?
d. Will the drydock gate fail?
e. Will communications be knocked out?
f. Will MARPAC headquarters be unable to function and be isolated?
g. What will the residual operational capability be?

5. Acknowledging the local earthquake and tsunami threat, the Pacific Fleet Commander asked the Operational Research Team to conduct an assessment of these threats to defence ships, personnel, and infrastructure on the west coast. The J5 staff approached the J02OR staff on 20 January 2011 to see if analytical resources could usefully be applied to address these questions, individually or collectively.

6. Other than the first question, 4 a., the questions listed above identify issues that are strictly engineering or organizational in nature, and are beyond the scope of a typical Operational Research study. But it was quickly determined that no assessments of any type could be made without first having as strong a characterization of the tsunami threat as possible. How *often* can a tsunami be expected to strike the west coast of Canada? How *severe* will the inundation be in the various locations of concern to coastal British Columbia residents and the Department of National Defence's ships, personnel, and infrastructure? And how much *warning time* can be expected?

7. Because of the duality of earthquakes and tsunamis – the latter, if it arises, will always be generated by the former – it was decided to include a general assessment of the earthquake threat as well.

8. The *aim* of this study, therefore, is threefold:

a. Firstly, it is information discovery; to research, comprehend, and describe the geophysical phenomena of earthquakes and tsunamis.

b. Secondly, it is to characterize the expected frequency and intensity of these threats to the west coast of Canada as accurately as possible, summarizing the extant science and, if possible, adding to that science.

c. Thirdly, it is to further interpret the identified tsunami threat parameters in terms of the impact on vulnerable DND assets, including Royal Canadian Navy ships, department personnel, and coastal infrastructure.

2.2 Information Sources

2.2.1 Previous Research

9. This issue was visited initially in 2007 when raised by a previous Maritime Forces Pacific (MARPAC) commander. The thrust at that time was to provide an assessment of the threat posed by earthquakes and tsunamis to civilian populations and infrastructure. This work was done to support the development of plans for possible disaster scenarios. An understanding of the broader nature of the earthquake and tsunami threat was researched and prepared for this more general application.

10. The results were delivered in the form of a briefing note produced for COMD Canada COM [1], authored by Mr. A. Zegers, one of the co-authors of this report. A copy of this briefing note is included as Annex B to this report.

11. The background research material compiled for the 2007 study was comprehensive and formed a solid starting point for this study. This included a breadth of internet sources, many of which are still current.

2.2.2 Primary References

12. Mr. Zegers interviewed two key subject matter experts in 2007, whom the authors interviewed again for this study [2, 3].

13. Dr. Josef Cherniawsky of Fisheries and Oceans Canada was interviewed at his Institute of Ocean Sciences offices in Sidney, BC, on 01 June 2011 and 07 March 2012 [2]. Dr. Cherniawsky led the significant tsunami modelling efforts that were undertaken in the 2004 time frame. These results form the foundation of our assessment of the severity of potential tsunami scenarios [4, 5]. These results are discussed in detail in Chapter 5.

14. Dr. Garry Rogers of the Geological Survey of Canada was interviewed at his offices at Natural Resources Canada in Sidney, BC, on 23 September 2011 and 07 March 2012 [3]. Dr. Rogers is an acknowledged Canadian seismologist. He reviewed our preliminary research and provided clarity on historical information. He is also the co-author of the primary paper that we reference concerning the seismic threat [6]. These results are discussed in detail in Chapter 6.

15. The open literature contained a wealth of supporting information. A full engineering level analysis of the Great Alaska Earthquake of 1964 [7] was published by the US National Research Council some years after the event and, combined with tide station recordings published at [8], provided much of the key information needed to scope the threat of a tsunami originating elsewhere around the Pacific Ocean.

16. The two most useful authors for predicting the expected frequency of a tsunami generated by earthquakes in the immediate area of the Canadian west coast were Dr. Brian Atwater [9-12] and Dr. Chris Goldfinger [13-15]. Dr. Atwater has led research that examines the layers of soil in tidal marshes off the coast of Washington and Oregon that contained evidence of layering caused by past earthquake and tsunami activity. Dr.

Goldfinger has led research employing drilled cores at the base of steep slopes off the continental shelf, where strong earthquake activity caused material to landslide down and accumulate in layers (called 'turbidites'). Both of these paleoseismic approaches used radiocarbon dating of organic materials in the various layers to create a relatively clear and very consistent historical record of tsunami-producing earthquakes going back thousands of years. This material will be presented in Chapter 5.

17. The authors also communicated via email and/or telephone with Drs. Atwater [12] and Goldfinger [15] to clarify points concerning their research and to get their confirmation of our interpretations of their data.

2.2.3 The Internet

18. As always, the internet is an invaluable research resource. As well as helping to identify and download copies of specific references, it was a rich source for illustrative graphics. A number of such graphics have been reproduced in this report to enhance clarity and understanding of concepts and results. The web source of each is attributed.

2.3 Document Outline

19. The reader will require some geophysical background to fully comprehend the threat and to place the conclusions and recommendations in their proper context. Chapter 3 provides that 'Geophysics 101' background.

20. Tsunamis striking the west coast of British Columbia can originate in the immediate area, or can travel across the Pacific Ocean having originated in Alaska, Japan, Chile, or other Pacific basin locales. Chapter 4 characterizes the tsunami threat from these more remote sources. What is their frequency, how severe an inundation can be expected, and how much warning time will be provided?

21. Chapter 5 then examines the most severe tsunami threat faced by coastal communities: the Cascadia subduction zone. This is the major seismic fault that resides off the west coast of North America. What is the likelihood of its rupture in the next 10, 50, or 100 years, how severe an inundation can be expected from that source, and how much warning time will we have? There is also the possibility of a tsunami of limited scope being generated during a local earthquake, and we will try to quantify this threat as well.

22. Tsunamis are a by-product of earthquakes. Chapter 6 moves on to characterize the broader earthquake threat to regions of coastal British Columbia.

23. Chapter 7 examines the impact a tsunami would have on navy ships, personnel, and defence infrastructure on the British Columbia coast. The impact of water level swings on docked vessels and the anticipated amount of water inundation of land and infrastructure are investigated.

24. Finally, Chapter 8 presents the conclusions and recommendations emanating from this study. For reference, Annex A contains the 'Study Request Form' that was generated to initiate this analysis.

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3. Geophysics 101: Earthquakes and Tsunamis

25. The science explaining the occurrence of earthquakes and tsunamis is fairly well understood. It is based on the theory of plate tectonics which became generally accepted by the scientific community in the second half of the 20th century. The movement of tectonic plates relative to each other results in areas of convergence, divergence or shear. These relative motions cause various types of seismic and volcanic activity, as the tectonic plates do not simply slide smoothly past one another, but stick together, building up pressure that must be released from time to time in seismic events.

3.1 Cascadia Subduction Zone

26. Off the west coast of Canada, There is a zone of converging tectonic plates called the Cascadia Subduction Zone. In this region, the Juan de Fuca plate, under the ocean floor, is moving toward shore converging with the North American plate. It is a 1,100 km fault that runs about 100 km offshore from Vancouver Island in the north to northern California in the south. In this convergent plate boundary, the Juan de Fuca plate gets pushed underneath the North American plate, forming what is called a subduction zone. A schematic representation of the Cascadia Subduction Zone is shown in Figure 2.

27. Although the Juan de Fuca plate is moving towards the North American plate in a geological sense, they are actually stuck together at their interface; thus, there is in fact no slippage between them for the majority of time. This apparent inaction causes a build-up of stress and strain in the surrounding rock as the plates compress. The relative movement of the plates occurs at the rate of about 4 cm per year, adding up to tens of meters if the plates remain stuck together for a few centuries [3].

28. The built up stress at the plate junction can be released in a number of ways. The most obvious is when the boundary between the plates ruptures releasing part or all the accumulated stress. This is called a megathrust earthquake. The accumulation of strain creates deformations in the North American and Juan de Fuca plates which can also cause earthquakes from time to time as the rock structures compress and shift position. If this happens in the North American plate, it is called a crustal earthquake (since it occurs near the surface), and if it happens in the underlying Juan de Fuca plate, it is called a deep earthquake.

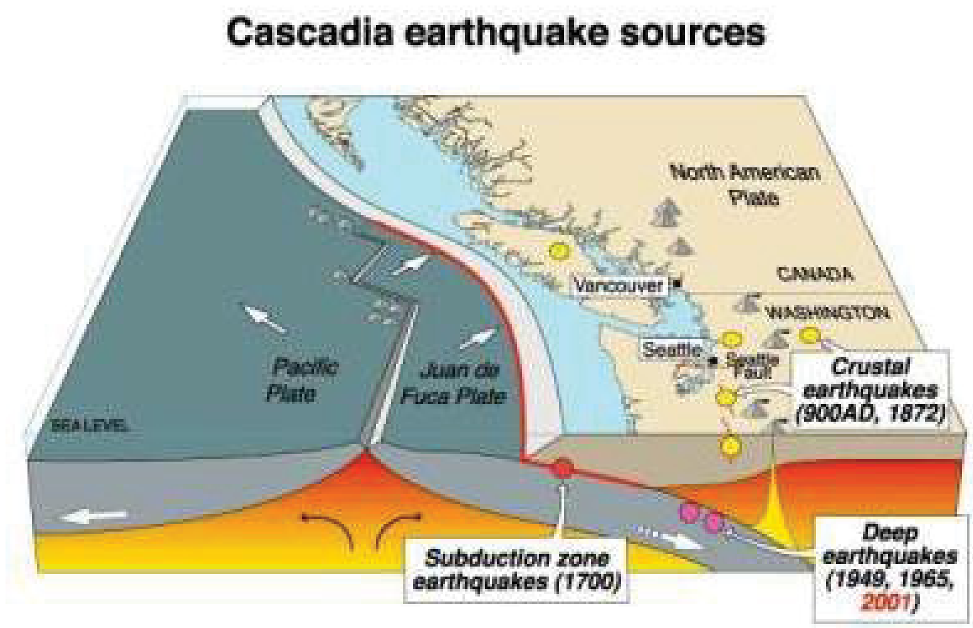

Figure 2. *The Cascadia Subduction Zone (public domain image courtesy of USGS)*

3.2 Cascadia Megathrust Earthquakes

29. An interesting feature of megathrust earthquakes is that they are somewhat predictable [29]. Although it is not currently possible to predict exactly when one will occur, it is certain that one will occur at some point. We are also able to estimate the probability that it will occur within specified time periods, based on analyses of geologic patterns of occurrence. In the case of the Cascadia Subduction Zone, megathrust earthquakes take place every 200 to 1,200 years [13]. Paleoseismic research has determined that the last one occurred in the year 1700 [19].

30. It is also possible to describe, with a fair degree of confidence, certain characteristics of such an event, such as its magnitude, location, and the triggering of a tsunami. The potential magnitude of the earthquake will increase as the time between earthquakes increases, and based on the strain accumulated, a megathrust earthquake is currently expected to have a magnitude of nine or more. The Cascadia megathrust is also expected to affect a large geographic area along the subduction zone, stretching from north of Vancouver Island to the coast of northern California [19].

31. A very important feature of a megathrust earthquake is that it is certain to produce a tsunami. The fault lies underwater about 100 kilometres off the coast. As the tectonic plates shift, they will displace water in the ocean over a very large area, as the ocean floor lowers or raises. This displaced water will then shift to re-establish equilibrium in a pattern of radiating long-period waves. From the perspective of an observer on shore, the tsunami behaves somewhat similarly to a rapid tide, with a peak-to-peak period of about one hour. Although the tsunami is generated relatively far from population centres, the impact can be quite severe depending on configuration and exposure of the coastal area. Areas of increased risk are along exposed outer coasts, and certain deep inlets that can funnel and amplify the tsunami's impact.

32. The largest earthquakes in recorded history have all been subduction zone ruptures (magnitude 9.0 or greater) and they all tended to generate tsunamis. This includes the Great Chilean Earthquake (1960), the Great Alaskan Earthquake (1964), the Indian Ocean earthquake (Boxing Day 2004), and the recent Tohoku earthquake (2011). A list of selected megathrust earthquakes from the past century, and the most recent Cascadia megathrust earthquake, is presented in Table I.

Table I. *Megathrust Earthquakes in the Past Century*
(Ref: http://en.wikipedia.org/wiki/Megathrust_earthquake)

Location	Year	Slip Length (km)	Magnitude
Tohoku, Japan	2011	500	9.0
Maule, Chile	2010	500	8.8
Sumatra, Indonesia	2004	1600	9.1 - 9.3
Great Alaskan	1964	800	9.2
Great Chilean	1960	1000	9.5
Andreanof Is., Alaska	1957	700	8.8
Kamchatka, Russia	1952	600	9.0
Nankaido, Japan	1946	Unk.	8.1
Cascadia, N. America	1700	1000	8.7 – 9.2

3.3 Crustal and Deep Earthquakes

33. Crustal and deep earthquakes have quite different characteristics than megathrust earthquakes. They occur due to the deformation in the earth's crust caused by the accumulation of strain which builds up over the centuries, as the rocks shift to accommodate this strain. They can occur in any local area where the local strain causes the rock shifts, and will thus affect a smaller geographic area than a megathrust earthquake. But exactly where they may occur is not predictable. They will release less energy than a megathrust earthquake, and their effects will be more localized. They can take place in remote locations, in which case the impacts may not be severe, however they also have the possibility of occurring closer to population centres than a Cascadia megathrust, in which case the effects could be devastating.

34. As the epicentres of deep earthquakes are located deep in the earth, damage tends to be minimal. Crustal earthquakes occur near the Earth's surface, potentially near population centres, and thus there is potential for severe impact. Examples of crustal earthquakes include the Los Angeles earthquake of 1994 and the Kobe earthquake of 1995. The most severe earthquake recorded in Canadian history was a 'crustal' earthquake, which occurred in Courtenay, BC, in 1946. Deep and crustal earthquakes cannot be predicted, and occur randomly with a probability that varies by region. The probability of a deep or crustal earthquake with severe impact occurring within the next 10 years has been calculated at 4.5% for the Victoria area and 2.5% for the Vancouver area [20]. The probability of a deep or crustal earthquake occurring reduces as the distance from Cascadia Subduction Zone increases. Chapter 6 presents a detailed assessment of the earthquake threat to British Columbia.

3.4 Measuring Earthquakes

35. Many people are familiar with the term "Richter scale" as a way of describing the strength of Earthquakes. The Richter scale is no longer commonly used by professional seismologists, having been replaced with the Moment Magnitude Scale. Although these two scales have technical differences, they are similar in that they are both magnitude scales, which means they seek to measure the total energy released by an earthquake. An alternative to a magnitude scale is an intensity scale. An intensity scale seeks to measure the local effects of an earthquake in a particular area.

36. The advantage of using intensity scales is that it is more useful for planners to consider the risk based on the effects of the earthquake in a particular area. These effects can vary based on the magnitude of the earthquake, the distance from the earthquake, and local soil composition. The most commonly used intensity scale is called the Modified Mercalli Intensity scale. It uses standard verbal descriptions of typical effects corresponding to numerical intensities ranging from I to XII, and is presented in Table II.

Table II. *The Modified Mercalli Intensity Scale (Source: US Geographical Survey)*

I.	Not felt except by a very few under especially favorable conditions.
II.	Felt only by a few persons at rest, especially on upper floors of buildings.
III.	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV.	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V.	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI.	Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII.	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII.	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX.	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X.	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI.	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
XII.	Damage total. Lines of sight and level are distorted. Objects thrown into the air.

4. The Tsunami Threat from Earthquakes Elsewhere Around the Pacific Basin

37. A map of tectonic plate interfaces in the Pacific Ocean basin [1] shows tens of thousand of kilometres of convergent subduction zones around the Pacific Ocean 'Ring of Fire'. Some segments converge at a higher speed than others, and may rupture more frequently. For example the zones off Chile and northeast Japan converge at 10-11 cm/year, whereas Cascadia only converges at about 4 cm/year. Dr. Goldfinger indicated [15] that there is no evidence that speed of convergence correlates with the potential size of megathrust earthquakes, but it does influence the interval between such earthquakes.

38. The Great Chilean Earthquake of 1960 was the largest in recorded history. This subduction zone rupture generated a tsunami that caused extensive loss of life and property damage thousands of miles away in Hawaii. And it was observed at all locations around the Pacific Ocean.

39. Indeed, any location in the Pacific basin will record a steady sequence of tsunamis from different corners of the ocean. For example, over the 70 year period from 1906 to 1976, Reference [28] lists 34 tsunamis that were recorded at Tofino on the outer coast of Vancouver Island. These are listed in Table III below.

Table III. *Tsunamis Recorded at Tofino, BC, 1906 to 1976*
with Peak-to-Trough Wave Height Exceeding 10 cm (from Reference [28])

Date	Source	Height (m)
01 Nov 1915	Sanriku, Japan	0.12
01 May 1917	Kermadec Is., New Zealand	0.12
18 Jul 1918	Sulawesi, Indonesia	0.16
07 Sep 1918	S. Kuril Is., Russia	0.16
30 Apr 1919	Tonga Is.	0.15
11 Nov 1922	Vallenar, Chile	0.27
03 Feb 1923	Kamchatka, Russia	0.27
13 Apr 1923	Kamchatka, Russia	0.15
07 Mar 1929	Fox Is., Alaska	0.11
02 Mar 1933	Sanriku, Japan	0.23
30 Nov 1934	Jalisko, Mexico	0.22
10 Nov 1938	Aleutian Is.	0.27
07 Dec 1944	Tonankai, Japan	0.12
27 Dec 1944	Vanuatu Is.	0.12
01 Apr 1946	Aleutian Is., Alaska	0.58
04 Mar 1952	Hokkaido, Japan	0.12
04 Nov 1952	Kamchatka, Russia	0.58
09 Mar 1957	Aleutian Is., Alaska	0.52
11 Mar 1957	Aleutian Is., Alaska	0.18
06 Nov 1958	Kuril Is., Russia	0.10
22 May 1960	**Valdivia, Chile**	**1.26**
13 Oct 1963	Kuril Is., Russia	0.16
28 Mar 1964	**Prince Wm. Sound, Alaska**	**2.40**
16 May 1968	Aomori, Japan	0.13

40. Note that only the 24 events with a peak-to-trough height of more than 10 cm are shown in the table. Two earthquakes in this 70-year interval – the Great Chilean Earthquake of 1960 and the Great Alaskan Earthquake of 1964 – produced a tsunami reading exceeding 1 metre in height.

41. The largest number in Table III, 2.40 metres, represents the Great Alaskan Earthquake of 1964. This represents the ultimate (or very close to it) offshore threat from the Pacific Ocean 'Ring of Fire' if we exclude the Cascadia Subduction Zone. It was spawned by the next closest subduction zone to Canada's Pacific coast, and at magnitude 9.2 was the second largest earthquake recorded in the past century.

4.1 Offshore Threat: How Likely?

42. It is difficult on such a tiny sample to predict when some segment of the Alaskan subduction zones might rupture again, but the authors conclude that it should not be unreasonable to expect maybe one or two per century.

4.2 Offshore Threat: How Severe?

43. The wave heights produced in 1964 are well established. Figure 3 presents plots from the tide gauges at various Canadian locations, copied directly from the original source [8]. The exposed outer coastline of British Columbia should see a 2.5 metre wave height, peak to trough (±1.25 metres from current tide level). The heads of long inlets facing the ocean will likely see waves 2 to 2.5 times larger than that. Although the Port Alberni tide gauge was knocked out by the tsunami in 1964 (hence the discontinuity in the plot in Figure 3), Reference [28] estimated a wave height of 5-6 metres in that location, which caused extensive damage to 60 buildings and some damage to an additional 200 buildings [28]. The heights in Victoria were about half those experienced on the outer coast: about 1.5 metres, peak to trough. There was no indication of any tsunami whatsoever on Vancouver tide gauges.

44. It can be concluded that only locations at the head of long inlets facing the ocean - like Port Alberni - will face substantial damage from a tsunami originating from an offshore source. The tsunami will be definitely noticeable and may cause isolated damage to communities along the outer coast. The 1964 tsunami struck near high tide and damaged some boats, log booms, and wharfs at Ucluelet and Tofino, and swept some buildings off their foundations at Zeballos and Hot Springs Cove [28]. In the Victoria area the tsunami will be no more noticeable than a winter storm surge.

4.3 Offshore Threat: How Much Warning Time?

45. The Great Alaska Earthquake struck at 03:36 GMT on 28 March 1964. The tide gauge records from that event [8], some shown in Figure 3, show that the tsunami took about 2 hours to reach Haida Gwaii, about three hours to reach the northern BC coast and the outer coast of Vancouver Island, and about four hours to reach the Victoria area. The earthquake event itself will likely not be felt in Canada, so coastal communities like Port Alberni, Ucluelet, Tofino, and others will have to rely on public tsunami warning systems.

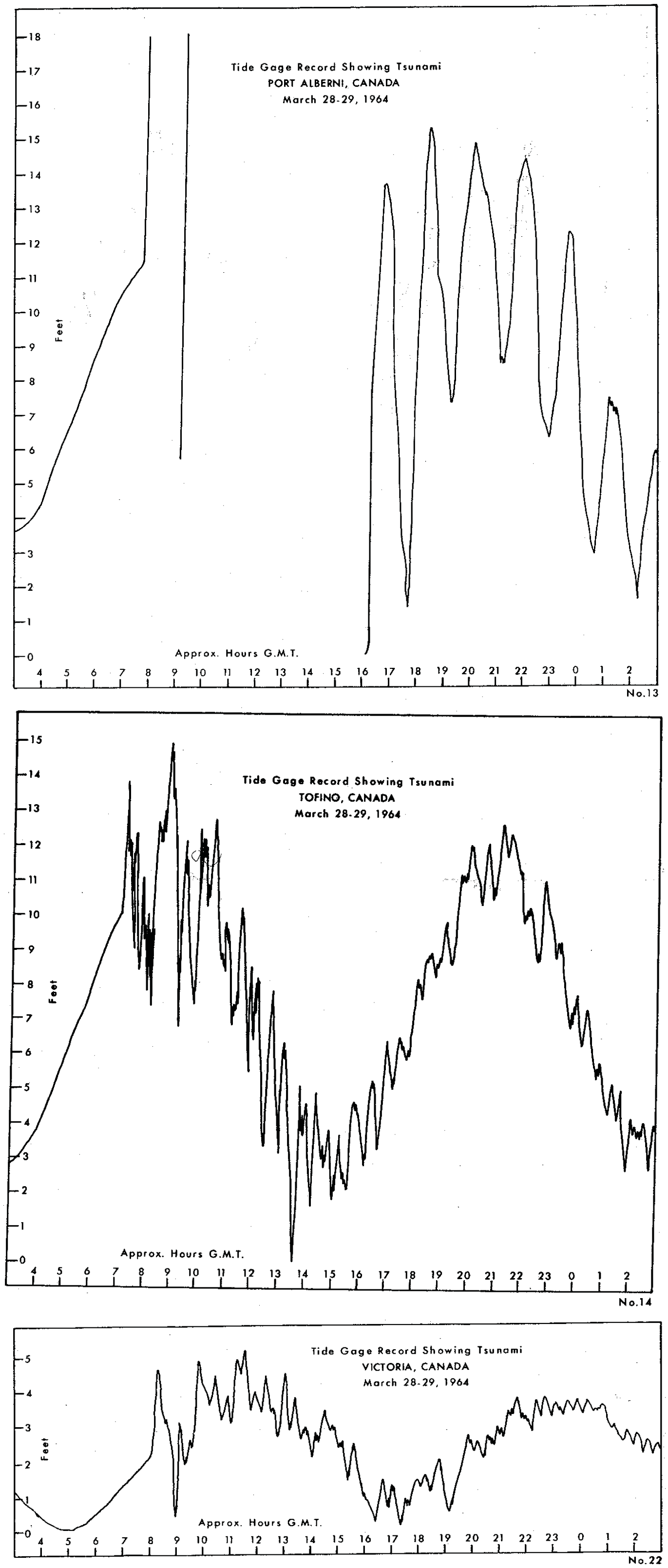

Figure 3. *Tide Gauge Records Showing the Tsunami from the Great Alaska Earthquake at Port Alberni, Tofino, and Victoria, BC, March 28-29, 1964. Graphics extracted from [8]*

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5. The Tsunami Threat from the Cascadia Subduction Zone

46. As presented in Chapter 3, we know that the relentless movement of the tectonic plates means that the plate interface will rupture periodically to relieve the built up stress. The Cascadia subduction zone last ruptured around 9pm on the 26th of January, 1700.

47. This degree of precision may seem incredulous, considering that this event predates recorded history of the region, but there is convincing evidence that it is correct. Atwater's research, [9] and [10], included the ring dating of trees that were killed by salt water inundation centuries ago, assumed to be the result of earthquake co-subsidence of the coastal marshes of Washington State. The last growth rings in those dead trees were dated to 1699. But the key resource was reliable records of past tsunamis kept in Japan [11]. An 'orphan tsunami' – a tsunami that arrived without any earthquake preceding it – struck the coast of Japan on January 26th, 1700, and the time of day was noted. Through computer modelling, the propagation time for the tsunami across the Pacific Ocean can be accurately estimated (about 10 hours), permitting the time of the earthquake at Cascadia to be pinpointed to about 9pm in the evening. Various corroborating legends among the native nations speak of a sudden rise of the ocean that happened many generations in the past, which occurred at night and in the winter [28].

48. A Consensus Statement from the Penrose Conference of the Geological Society of America, held in 2000 [19] is clear:

> "The Cascadia subduction zone produces great earthquakes, the most recent of which occurred in 1700 and was of moment magnitude (M_w) 9."

49. So if the most recent rupture of Cascadia was 313 years ago, the logical question to ask is "When can we expect the next one?" What can be done to estimate the likelihood of its next rupture? Paleoseismic research - investigating the history of past great earthquakes – holds some answers.

5.1 Cascadia Threat: How Likely?

5.1.1 Estimating the Mean Rupture Interval

50. Regardless of the probability model employed, a key determinant of probability of rupture (within a given time period into the future) will be the mean rupture interval value that is assumed. A pair of paleoseismic research efforts has contributed significantly to the understanding of the natural frequency of Cascadia subduction zone (CSZ) ruptures. They rely on quite different sources for obtaining dating evidence, and together form a very solid foundation for the probabilistic calculations that will follow.

51. Dr. Brian Atwater of the University of Washington has led research into exploring the records contained in the soils of tidal marshes in Washington and Oregon [9], [10]. When a subduction zone ruptures, the land within a few hundred kilometres of the zone will subside (lower) slightly – around a meter, more or less. This causes plant materials

that are now sitting continuously in salt water to die. A layer of sand or other tsunami wash materials may overlay it as well. Over the following centuries the land rises above the water level again due to both the uplifting of the crust as tension builds again and the deposits of new plant growth. The cycle then repeats, leaving the soil with a stratified historical record of this activity. Figure 4 (from [9]) depicts these types of deposits.

Figure 4. *Stratified Coastal Marsh Soils (with permission from Dr. Atwater [9])*

52. Employing radiocarbon dating methods on the organic material in the layers, Atwater discovered seven unique layers, which he attributes to co-subsidence associated with CSZ rupture events going back 3,500 years. These are presented in the first column of Table IV along with the single letter label assigned to each soil layer. The age uncertainty ranges, which they calculated using standard statistical procedures applied to the radiocarbon dates, are depicted graphically in Figure 6 as well. Taking the mean dated age of soil layer 'J' as 3408 years, the Atwater data gives an average interval between CSZ ruptures of (3408-310) / 6 = 516 years. The data was normalized as years before the year 2010, hence the use of 310 as the time since last eruption.

53. Dr. Chris Goldfinger at Oregon State University has led research into another possible source of evidence of past Cascadia events [13], [14]. When the subduction zone ruptures the earth will shake considerably, especially near the fault. They have discovered evidence of underwater landslides, called 'turbidites', occurring in the past down the slopes of the continental shelf. Goldfinger's group drilled cores into these areas (see Figure 5) and, like Atwater, used radiocarbon dating methods to identify the ages of organic material found in the different layers. This environment, perhaps being more protected underwater, has permitted layers to be identified going back in time almost three times further to about 10,000 years ago. The value of these data hinge greatly on establishing the source of the deposits. Were they caused by earthquakes, or other natural phenomena (storms, etc.)? In [14], Goldfinger outlines the elaborate battery of tests that were conducted to confirm the origin of these turbidites as seismic. The turbidite dating results are presented in the second column of Table IV, and are depicted graphically in Figure 6 as well.

Table IV. *Comparison of Earthquake Event Dates (years before 2010AD)*

Soil Layer Ages Atwater et al. [10]	**Offshore Turbidite Ages (Northern Margin)** Goldfinger et al. [14]	**Saanich Inlet Debris-Flow Deposit Ages** Blais-Stevens et al. [6]
Y: 310 (assumed)	T1: 139-371	
		D1: 410-435
	T2: 384-573	D2: 493-582
		D3: 767-887
W: 820-1230	T3: 679-906	D4: 874-950
		D5: 1001-1133
		D6: 1163-1292
U: 1289-1324	T4: 1119-1348	D7: 1238-1349
S: 1600-1670	T5: 1383-1730	D8: 1546-1741
		D9: 1694-1811
		D10: 1859-2104
		D11: 2197-2509
		D12: 2296-2483
N: 2480-2680	T6: 2390-2674	D13: 2525-2844
L: 2905-2985	T7: 2865-3162	D14: 2987-3298
J: 3365-3450	T8: 3287-3596	D15: 3164-3392
(no older data)		D16: 3654-4569
	T9: 3918-4278	D17: 3989-4284
	T10: 4579-4940	(no older data)
	T11: 5824-6100	
	T12: 6334-6613	
	T13: 7062-7303	
	T14: 7488-7763	
	T15: 8038-8356	
	T16: 8761-9066	
	T17: 8810-9360	
	T17A: 8989-9429	
	T18: 9563-9979	

Figure 5. *Stratified Underwater Turbidites (with permission from Dr. Goldfinger [14])*

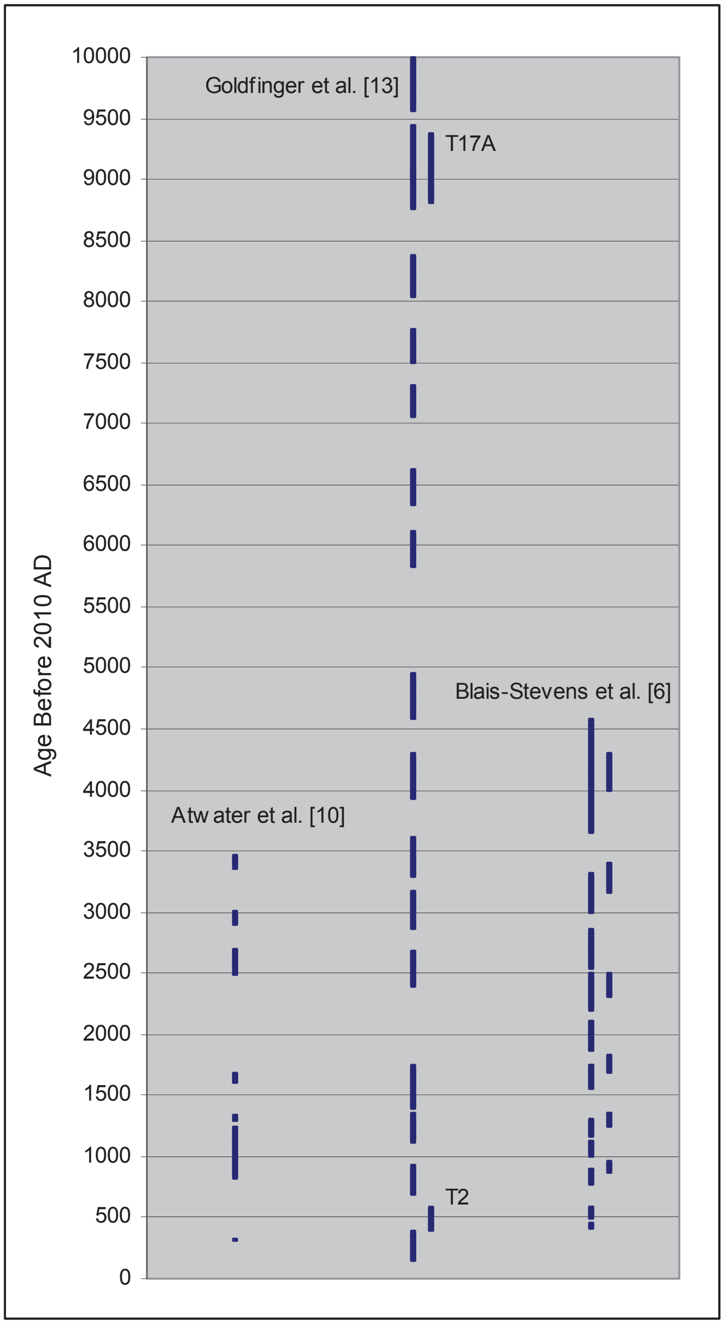

Figure 6. *Plot of Earthquake Event Dates with Uncertainty Ranges*

54. Comparing the Atwater and Goldfinger columns in Table IV and Figure 6, it can be seen that the event date ranges, although centuries wide in some cases, do appear to be compatible with each other over the past 4,000 years, giving strong confidence on these date ranges for previous CSZ ruptures. The only difference is that Goldfinger's 'T2'

turbidite has no match in Atwater's data set. However, T2 is correlated with data collected at other land sites in central and northern Cascadia [14].

55. The reader will note a third data set from Blais-Stevens et al. [6] is presented in Table IV and Figure 6. That data set will be discussed in Chapter 6. Note that all three data sets are normalized to 'years before 2010 AD'. Hence a value of 310 is employed as the time since Cascadia last erupted (in year 1700).

56. The Goldfinger data over the same period - up to T8 which has a mean age of 3,443 years ago – yields a mean CSZ rupture interval of (3,443-310) / 7 = 448 years. Taking all of the Goldfinger data out to T18 (mean age of 9,795 years ago) yields a rupture interval a bit longer, at (9,795-310) / 18 = 525 years. Paleoseismic research generates an upper bound on the mean rupture interval, as there may be seismic events that, for whatever reason, have not been captured in the paleoseismic record. Such unrecorded events can only reduce the average rupture interval. Goldfinger confirmed at [15] that 430 to 530 years is the range current paleoseismic research generally supports for the mean Cascadia rupture interval.

57. Therefore, it would seem reasonable to conclude that: *the mean interval between Cascadia subduction zone ruptures is in the range of 430 to 530 years.*

58. The mean rupture interval is a key determinant of probability of rupture. We have concluded that the CSZ ruptures, on average, every 430 to 530 years, and that the last rupture was 313 years ago. As the results of the paleoseismic research in the previous section clearly show, these ruptures will not occur in a 'regular' fashion (ie. like clockwork every 430 to 530 years), but are rather much more of a variable phenomenon. We will consider two types of models in this analysis: a 'time-independent' model and a 'time-dependent' model.

5.1.2 The Time-Independent (Poisson) Model

59. The time-independent model is straight-forward. If rupture was equally likely at any point in time then a simple Poisson process is engaged [21]. Reliable prediction of earthquakes of all types has certainly evaded scientists to date, so the Poisson model would appear to be a 'not unreasonable' assumption at worst. It is certainly a better assumption for crustal earthquakes where predictability is most difficult, but we will declare it as not unreasonable for subduction zone earthquakes as well, and will include the Poisson model as the time-independent comparison in this analysis.

5.1.3 The Time-Dependent (Weibull) Model

60. However, a time-dependent model would appear to be a more natural fit for subduction zone ruptures. As the converging tectonic plates compress and uplift, strain builds up and eventually rupture occurs. How strain gets relieved in the upper mantle of the earth is quite variable and difficult to assess, so when the subduction zone ruptures it may not be the entire length of the fault (1,100 km in the case of Cascadia), and it may not relieve the full amount of built up strain. None-the-less, a model in which the instantaneous probability of rupture (or 'hazard rate') increases over time would seem to be a reasonable approach.

61. The literature has looked at the distribution of inter-earthquake time intervals along a given seismic fault, notably References [24], [25], [26], and [27]. The most relevant distributions were found in these references to be the lognormal and Weibull [22], [14], [35]. Not only does each have a reasonable visual fit to the (limited) data that is available, but each has a natural explanation that can be appealing.

62. The lognormal distribution, a generic distribution investigated in [23], is often used to describe the rate at which fatigue cracks in materials grow over time. This seems to be certainly a relevant, if not exactly parallel issue to the build up in stresses in tectonic plates until massive failure occurs.

63. The Weibull distribution, employed in [14], [35], and [24], describes the time between failures of mechanical components if the hazard rate increases geometrically over time, that is, as a function of some power of time passed. The application of the Weibull model to subduction zone ruptures is very appealing. The movement of the tectonic plates is very linear (moving consistently at about the rate one's fingernails grow) [19], and this builds up strain over time, so it seems reasonable that the hazard rate (instantaneous probability of re-rupture) should increase correspondingly, perhaps linearly as well. Following this argument, the authors decided to go with the Weibull probability distribution as the time-dependent model. Note that others, including Hagiwara [24], Ellsworth [35], and Goldfinger [14], have also employed this distribution.

64. Annex C presents the mathematics of the Weibull distribution, drawn largely from Reference [22]. This distribution has two parameters: a shape parameter k and a scale parameter α. The shape parameter reflects the rate at which the hazard rate for re-rupture increases with passing time. The value of k is the exponent for the hazard rate increase function with time, plus 1. Hence a value of $k = 2$ represents a linear relationship. A value between 1 and 2 is less than linear increase in hazard rate with time and a value greater than 2 represents a growth that is more rapid than linear.

65. In Annex C we also present the results of a simple fitting exercise, using a least squares method to best fit the historical recurrence interval data for the Cascadia subduction zone researched by Goldfinger [14] to a Weibull distribution for a range of values for k. The analysis shows a value of $k = 2.14$ is the optimum using a least squares fit to the observed cumulative distribution, which gives a hazard rate that increases just slightly more than linearly with time. Since this value has only a slightly better (by 8%) sum of squares over the pure linear case, we can make the general conclusion that a value of $k = 2$ provides an excellent fit. This exercise also demonstrated the superiority of a time-dependent model over the time-independent model.

66. Figure 7 graphically supports these conclusions. It presents a visual comparison of the historical intervals to both the time-dependent (pink line) and time-independent (yellow line) models.

67. The historical interval histogram (dark blue) is what the distributions are attempting to fit, and it is compiled from Goldfinger's data [14], the middle column of Table IV. The mid-points of the 19 historical rupture date ranges yield 18 estimated rupture intervals. The mean interval in this data set is 528 years.

68. The light blue line presents how the time-dependent Weibull distribution (yellow line) would be adjusted for the fact that the Cascadia subduction zone has not ruptured in

the past 313 years. The probability of rupture in the next x years is calculated by integrating the light blue curve from year 313 to year 313 + x. The solid area under the light blue curve in Figure 7 graphically represents the probability of eruption in the next x = 50 years.

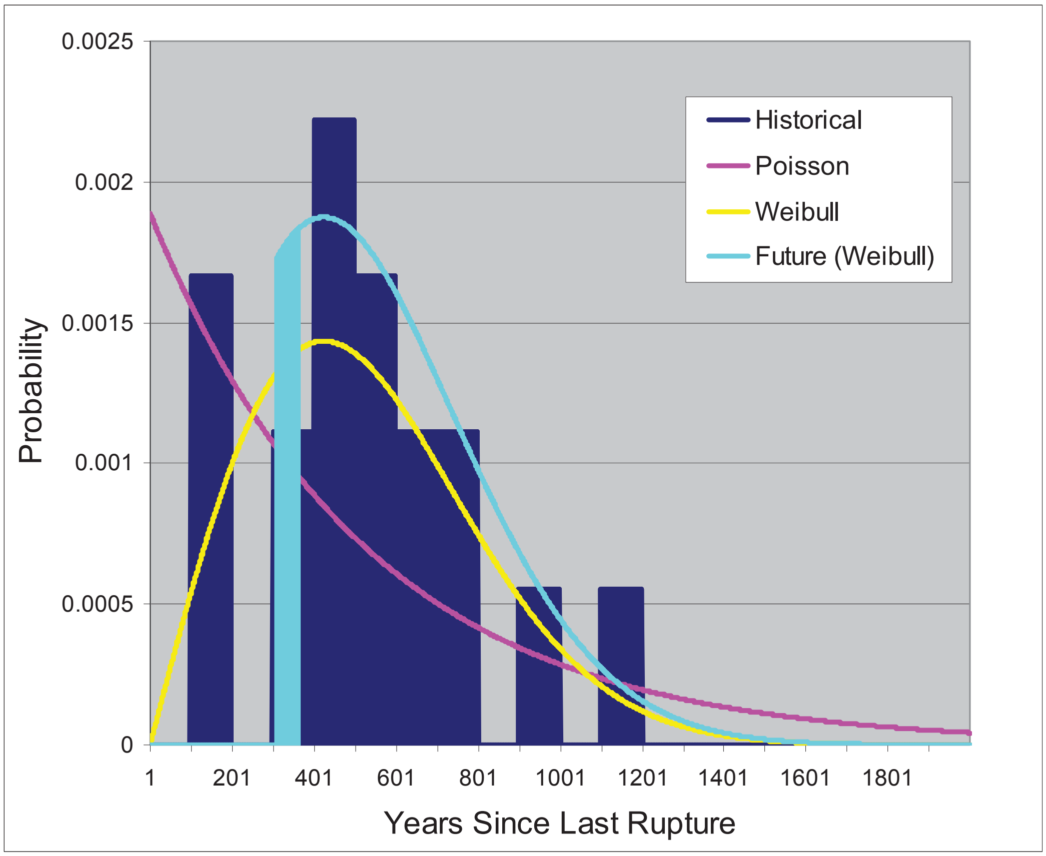

***Figure 7.** Theoretical Probability Distribution of Cascadia Subduction Zone Rupture Intervals Compared to Historical Intervals (Goldfinger [14])*

5.1.4 Probability Calculations

69. The time until the next event in a Poisson process is exponentially distributed [21]. If the rate of rupture occurrence is λ (where we assuming λ is in the range of 1/450 to 1/590 per year), then the probability that the time of the next rupture, R, will occur before future time T is given by:

$$P(R < T) = 1 - \exp(-\lambda T) \quad (1)$$

70. The time-dependent Weibull calculation is only slightly more complicated. If we have observed a time T_0 since the last rupture without a re-rupture (currently T_0 = 313 years), then the probability of observing a rupture in the next T years is derived in Annex C as the following:

$$P(R < T) = 1 - \exp((T_0 / \alpha)^2 - ((T_0 + T) / \alpha)^2) \qquad (2)$$

71. The scale parameter α is related to the mean rupture interval $E(R)$, which we have estimated as being somewhere between 450 and 590 years, by the relationship:

$$\alpha = 2 \cdot E(R) / \sqrt{\pi} \qquad (3)$$

72. Substituting the minimum and maximum values determined for λ, and using 10, 50, and 100 year values for T we calculate, using Equations (1) and (2), the values shown in Table V for the probability of Cascadia subduction zone rupture.

Table V. *Probability of Cascadia Subduction Zone Rupture (with Tsunami) in the Next 10, 50, or 100 Years*

Model	Rupture in Next	Mean Rupture Interval	
		Min 430 yrs	Max 530 yrs
Time-Independent (Poisson)	10 years	2.3%	1.9%
	50 years	**11.0%**	**9.0%**
	100 years	20.7%	17.2%
Time-Dependent (Weibull)	10 years	2.7%	1.8%
	50 years	**13.3%**	**9.0%**
	100 years	26.5%	18.4%

73. These numbers agree very closely with other independently calculated mathematical estimates produced by Petersen et al. [26], Mazzotti and Adams [27], and Goldfinger et al. [14].

74. In general, then, we can conclude that *the Cascadia subduction zone has about a 1 in 10 chance of rupturing in the next 50 years*.

5.2 Tsunamis in the Strait of Juan de Fuca Region from all Sources: How Likely?

75. Dr. Atwater pointed out to the authors [12] the research done on sites on the Juan de Fuca Strait by Williams et al. [16], where layers of sand have been uncovered in tidal bays. They discovered up to 9 sand deposit layers in a tidal peat bay that date back about 3,000 years (see Figure 8). They also attempted to date organic materials in those sand deposits using radiocarbon methods. These deposits are hypothesized to have been deposited by tsunamis from either subduction zone earthquakes, other northern margin plate ruptures off Vancouver Island [3], or by local crustal earthquakes. Radiocarbon dating uncertainties and source uncertainties mean the results are less conclusive than those based on coastal subsidence and underwater turbidite research of Atwater and Goldfinger. However, they raise uncertainty to a sufficiently high level that perhaps the Juan de Fuca Strait is vulnerable to tsunamis produced by crustal earthquakes along the known crustal faults in the region.

Figure 8. *Sand Layers Deposited at Discovery Bay, Washington (photo permission of Dr. Atwater [12])*

76. The one data point on the historical record is the 1946 Vancouver Island earthquake [23]. It was a crustal earthquake of magnitude 7.3 striking with epicentre near Courtenay, BC. The Lions' Gate Bridge in Vancouver reportedly "swayed like a leaf" and damage was noted as far away as Seattle [28]. Land movement underwater caused a 2 metre tsunami to strike the west coast of Texada Island in the Strait of Georgia [28].

77. In acknowledging this tsunami threat, we have taken the best mean tsunami inundation interval as estimated by Williams et al. [16], which they peg at 330 years, and present the Poisson calculations for a seeing a tsunami in the Juan de Fuca Strait region from all potential sources in the next 10, 50, or 100 years. The results are presented in Table V. *The probability of seeing a tsunami in the Juan de Fuca Strait region over the next 50 years rises from the 10 percent range to about 14%.*

Table V. *Probability of a Tsunami from All Sources Being Observed in the Juan de Fuca Strait Region in the Next 10, 50, or 100 Years*

Model	Rupture in Next	Mean Rupture Interval 330 years
Time-Independent (Poisson)	10 years	3.0%
	50 years	**14.1%**
	100 years	26.1%

78. Note that crustal earthquakes are considered a more random phenomenon than subduction zone ruptures, so only the Poisson calculation is applied here. A hybrid calculation combining both Poisson and Weibull distributed sources yields a similar value of 13.3% over the next 50 years.

5.3 Cascadia Threat: How Severe?

5.3.1 The 500-Year Event

79. In 2003, Dr. Cherniawsky's group at the Institute of Ocean Sciences, Fisheries and Oceans Canada, in Sidney, BC, did some extensive modelling of the tsunami that would result from a rupture of the Cascadia subduction zone. This was a one-time research project, where a suitable computer model was acquired, bathymetric and other data was developed, and a range of scenarios were run. Reference [4] documents this research, and the results also are available online at [5].

80. The group researched available tools and decided to employ the MOST-3 (Method of Splitting Tsunamis, version 3) simulation. Reference [4] describes MOST-3 as a finite-difference numerical model employing nested grids. Bathymetric detail for harbours and coastlines can be specified on a fine (10 metre) grid, whereas open ocean bathymetry can be specified on a much coarser (1 kilometre) grid. MOST-3 solves the non-linear shallow water equations numerically.

81. MOST-3 explicitly models the land and water displacements associated with a subduction zone rupture. When the Cascadia subduction zone ruptures, the land on the North American plate along the 1,100 km fault will be shifted some distance laterally, assumed in this case to be 20 metres, which is the accumulation of 500 years worth of strain at 4 cm per year. Simultaneously with the rupture, co-subsidence will occur in regions of the North American plate just east of the subduction zone.

82. As in all modelling exercises, assumptions will be made. A typical bottom friction coefficient was applied to all areas (bottom friction is only important in quite shallow water). And although MOST-3 is capable of modelling on-shore run up, this required high resolution digital topographic (elevation) data to be provided, and this data was not readily available for the project. Hence, the shorelines were modelled as reflective vertical walls.

83. The effect of these assumptions on the predicted tsunami wave heights was discussed with Dr. Cherniawsky. One could argue on very general scientific principles that water flowing over land will absorb energy and will be partially removed from the main basins, which could have an effect of lessening the wave heights further east along Juan de Fuca Strait from those levels predicted under the assumption of vertical walls at the shoreline. But as Dr. Cherniawsky pointed out, it is not clear, due to the back and forth ebb and flow of the tsunami waters over many hours and numerous high/low cycles, that these assumptions would suggest a real tsunami would be either higher or lower than the model predictions. So we will assume that this assumption has minimal effect on the model's predictions.

84. Overall, the high scientific quality of the MOST-3 simulation warrants giving the output predictions our fullest confidence. MOST-3 has been shown to 'work well when tested against actual observations of tsunami inundation' [4].

85. Figure 9 graphically presents the results from MOST-3 for the southern Vancouver Island region. The model simulated a 20 metre lateral movement westward of a 1,100 km long by about 100 km wide portion of the stressed North American plate, together

with a co-subsidence (vertical drop) of land east of that region up to 2 metres. The top left graphics box in the figure displays these initial conditions, as modelled in MOST-3. The initial conditions show a rise of a section of seabed across an area where the North American plate has slipped westward some 20 metres. Higher (than current tide level) water levels are shown in red, and lower water levels in blue (both in centimetres).

86. The remaining graphics boxes in Figure 9 show the progression of the tsunami wave over the first two hours at 15 minute intervals. The reader can see how two initial waves are generated, one heading westward across the Pacific Ocean, and the other heading eastward towards the coast. Note how the first high water arrives in about 30 minutes at the outer coastline, but slows down once entering the shallower Juan de Fuca Strait, inundating the Victoria region about 90 minutes after the earthquake.

87. Cherniawsky's group modelled Esquimalt and Victoria harbours in high (10 metre) resolution. Figure 10, spread over two pages, presents the images of the high and low water points for the first six cycles. The reader will note that the highest high is predicted to be the first high at about 1:35 hours after the earthquake, with the second and fifth highs at 2:28 and 4:02 hours being almost as high. The deepest lows are predicted to be the fourth and fifth lows, at 2:55 and 3:26 hours after the earthquake.

88. The MOST-3 model predicts a cycle time average in the Victoria region of about 30 minutes, high to high, with the longest interval being between the first and second highs (53 minutes) and the shortest interval being between the fourth and fifth highs (21 minutes). A similar cycle time was observed in Victoria during the 1964 tsunami from the Great Alaskan Earthquake [8]. These periods are a function of the harmonics of the water basins in the area. For example, in 1964 the first three highs were about 85 minutes apart in Port Alberni, which is at the end of a very long channel.

89. The colour of each cell in Figure 10 shows water height, as per the scale attached to each graphic, but there is also a line drawn in each cell that shows the direction (orientation of the line) and magnitude (length of the line) of the water flow at that instant. The reader will note substantial eddies and whirlpools induced by the underwater topography and the various headlands.

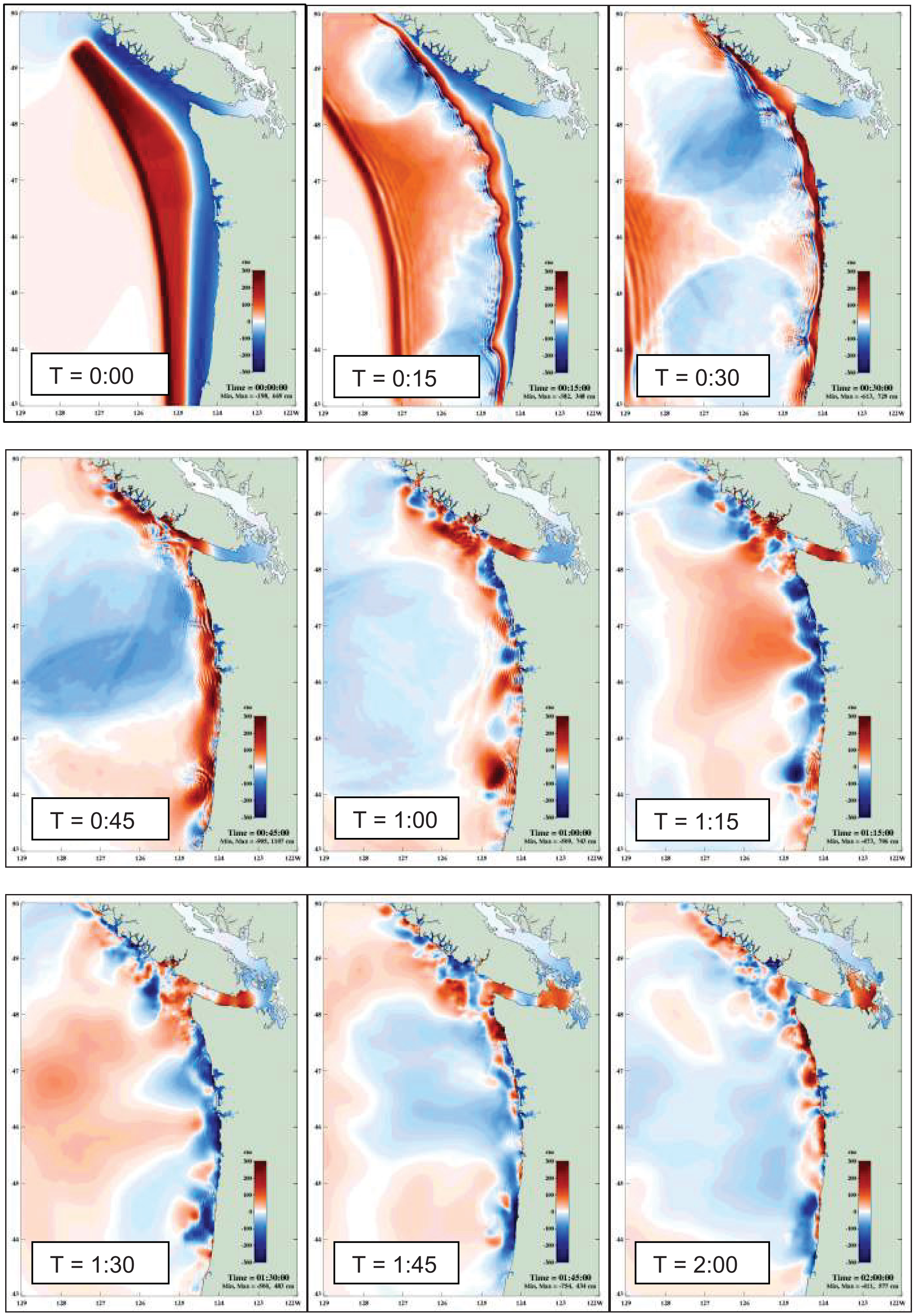

***Figure 9**. Computer Modelling Results for 500-Year, Cascadia-Induced Tsunami*
(20 metre lateral rupture of subduction zone)
Graphics printed with permission from [5]
Note: water height scale ranges from -300 cm (dark blue) to +300 cm (dark red)

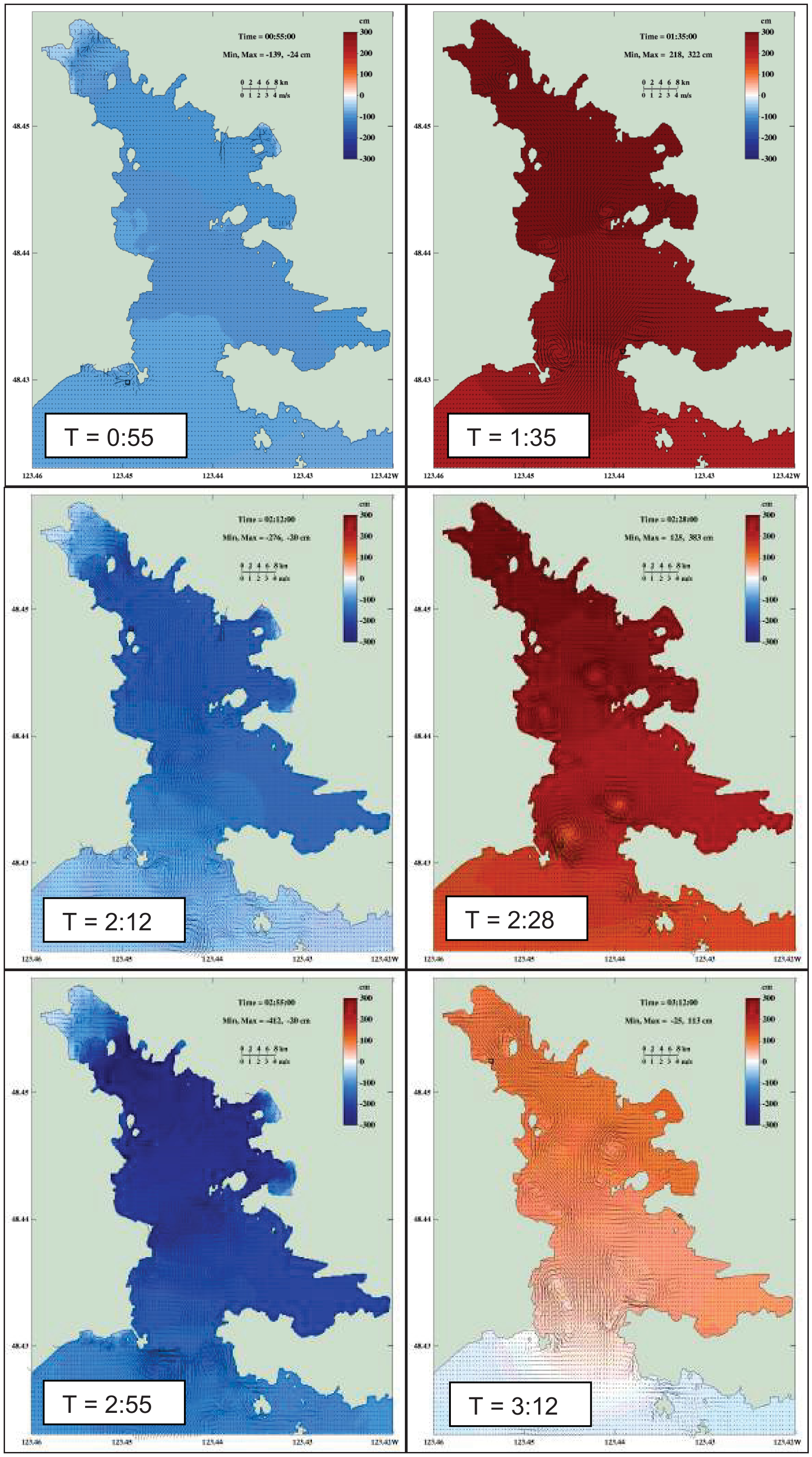

***Figure 10**. Lows and Highs Predicted for Esquimalt Harbour*
500-Year, Cascadia-Induced Tsunami (graphics printed with permission from [5])
Note: water height scale ranges from -300 cm (dark blue) to +300 cm (dark red)

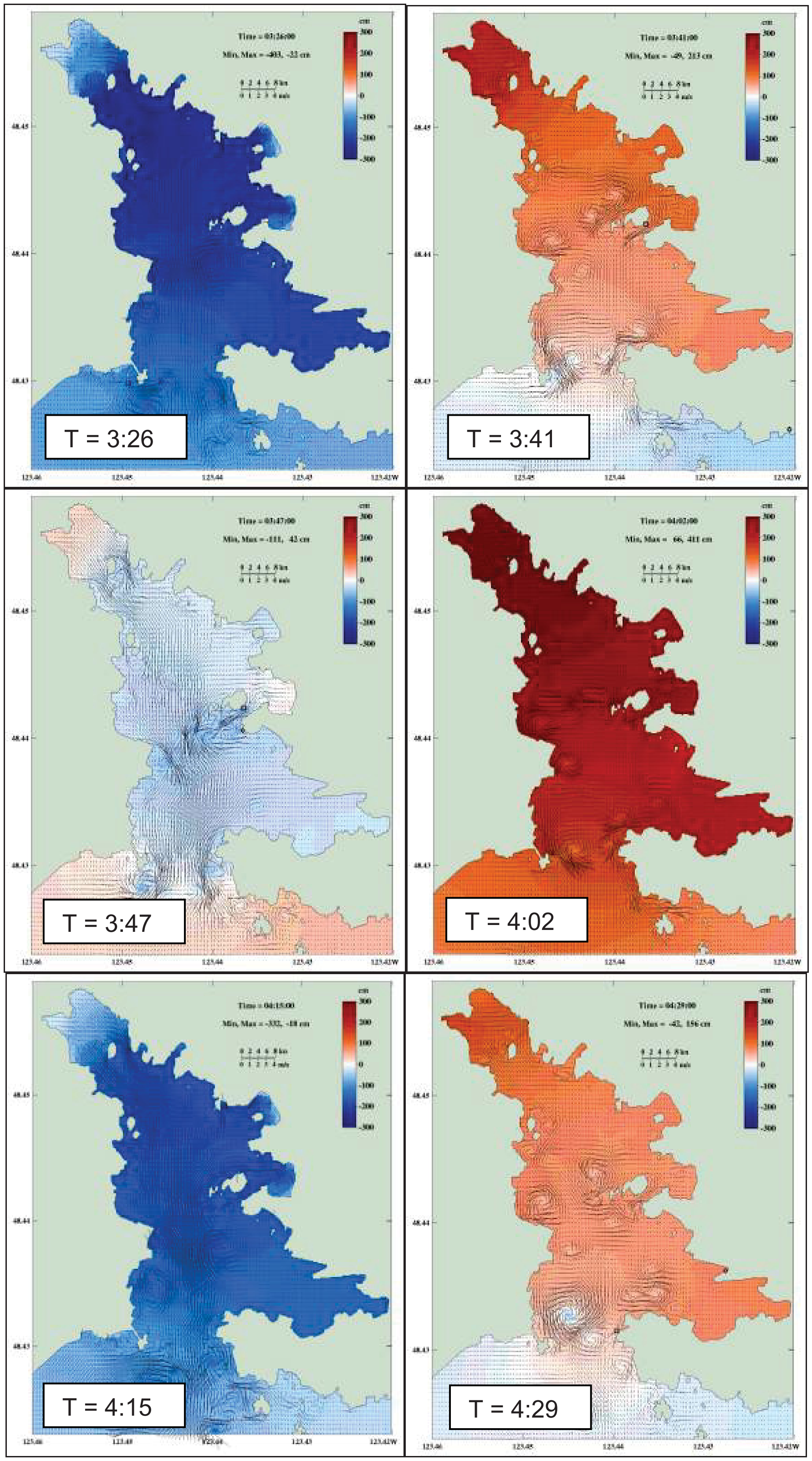

***Figure 10 (cont'd)**. Lows and Highs Predicted for Esquimalt Harbour*
500-Year Cascadia-Induced Tsunami (graphics printed with permission from [5])
Note: water height scale ranges from -300 cm (dark blue) to +300 cm (dark red)

90. Figure 11 below, extracted directly from [5], summarizes the previous graphics to show the maximum high water attained (above current tide level) for the Esquimalt and Victoria Harbour area over the 12 hour period immediately following the earthquake. These MOST-3 model predictions are for the 500-year tsunami.

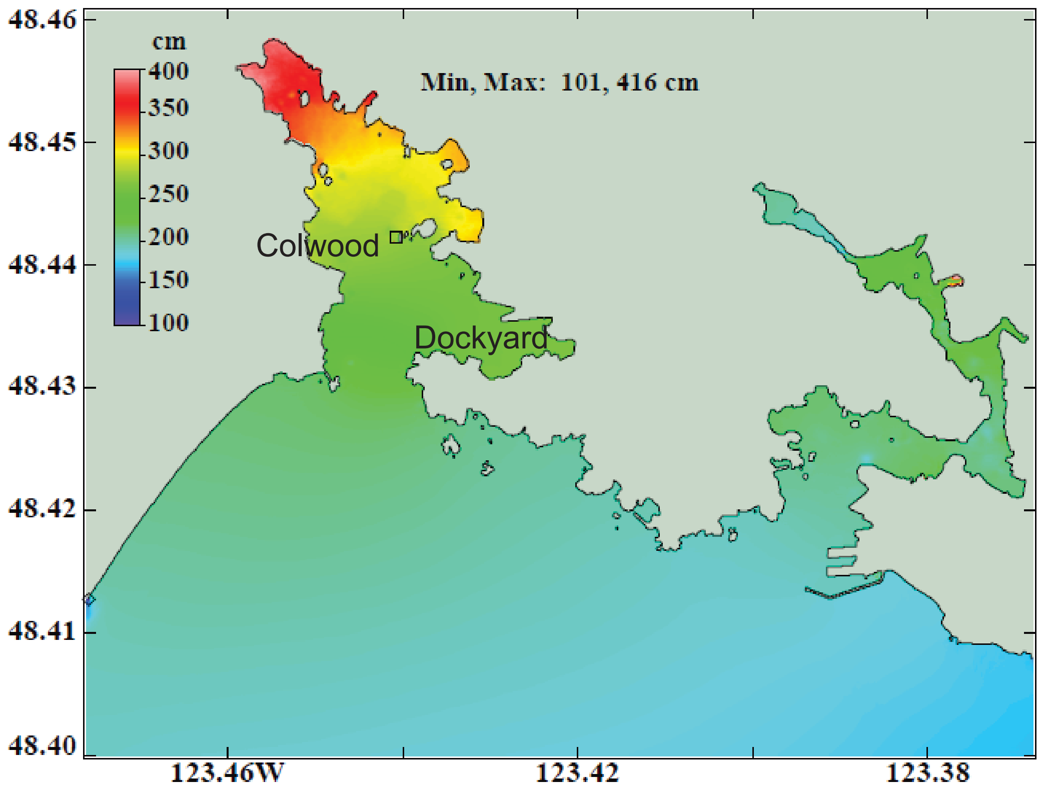

***Figure 11**. Maximum High Water (Above Current Tide Level) Predicted by Computer Modelling of a 500-Year, Cascadia-Induced Tsunami (Graphic printed with permission from [5])*

91. The model predicts about a 8 metre maximum wave height (±4 metres from current tide level) across the greater Victoria area, and about a *6 metre wave height (±3 metres from current tide level) specifically for the Esquimalt Dockyard and Colwood area*.

92. It has been only 313 years since the last Cascadia rupture, so it would seem that an assumption that the next Cascadia rupture will release 500 years of built-up strain should contain a reasonable safety margin for any earthquake that might be spawned by Cascadia in the next few decades. Indeed, the City of Victoria [31] has employed this 8 metre wave height prediction into their emergency planning documentation. The authors also recommend that these 500-year modelling predictions be used for planning purposes for the Esquimalt Dockyard, Colwood, and other Department of National Defence properties at risk in the Victoria area.

93. The Gulf Islands provide a sufficient physical barrier that the Strait of Georgia region, including Vancouver, Comox, and Nanoose, is not at risk from a Cascadia tsunami. Clague et al. [28] note that, in paleoseismic terms "No deposits of the 1700 event or, for that matter, any other tsunami, have yet been found in the Strait of Georgia, suggesting that waves were probably no more than 1 m high in this area.". Goldfinger [15] cautions, however, that strong currents are likely in these more protected areas and can cause damage.

5.3.2 The 5,000-Year Event

94. A word of caution, however. The Japanese are the most prepared nation in the world when it comes to tsunamis, and yet the Tohoku tsunami on 11 March 2011 contained a water height spike [17] that considerably exceeded what their historical observations over the previous one thousand years had led them to believe was possible. It is critical that we also consider the maximum size of possible earthquakes and tsunamis generated by Cascadia, not just a typical size.

95. Dr. Goldfinger has produced a model of the accumulated strain in Cascadia over the past 10,000 years. His 'sawtooth' chart, reproduced from [15], is presented with permission as Figure 12 below. The inclined lines in the chart show the (linear) build up of strain over time between ruptures. The vertical drops show the release in strain, where the mass of materiel found in the turbidites (calculated from the thickness of layers in drilled cores) is used as a proxy for the size of the earthquake and hence the amount of strain released. The two are calibrated by assuming that the amount of strain built up and released over the past 10,000 years is equal. One substantial unknown, of course, is the absolute level of energy (strain) at the beginning of this time window, so we cannot be sure of the absolute level of strain at the present time either, but the figure should give us insight into the relative strain levels that existed when past ruptures occurred.

96. The chart shows that the current strain level is about average (shown as the central horizontal line in the chart). The chart also shows two earthquakes, at 5,900 and 8.800 years before present (YPB), were 'giants'. Also noteworthy are the three fairly large quakes that occurred 3,000, 3,500, and 4,200 YBP. All five of these events occurred at strain levels that were relatively higher than the average over this 10,000 year period.

97. So despite the indications that current strain levels are not suggesting a 'giant' is imminent, we still must acknowledge the possibility of this kind of '5,000-year event' (2 occurrences in 10,000 years). Running the Weibull model for giants, using 5,000 years as the mean rupture interval and 5,900 years ago as the time since last rupture, we calculate about a *1.8% chance (or 1 chance in 54) of a giant tsunami in the next 50 years*. Note that the long time since the last event (5,900 years ago with a 5,000 year mean) means that this rising hazard rate model will yield a much higher probability prediction than the time-independent Poisson model, which estimates a 1.0 percent in the next 50 years.

98. Indeed, Dr. Goldfinger has been working with Oregon coastal communities in their emergency preparations and is recommending they assume a release of 1,000 years of built up strain, or a 40 metre (vice 20 metre) lateral rupture of the subduction zone, to simulate such a giant [15].

99. In the case of giants, Dr. Cherniawsky agrees [2] that the estimates emerging from the computer modelling work at [4] and [5] should, to a first order approximation, be doubled. So the 5,000-year event can entail a 16 metre wave height in the Victoria area (±8 metres from the current tide level), double that on the outer coast of Vancouver Island, and double that again at the end of any long focussing inlets facing the ocean. *For the Esquimalt dockyard area a 12 metre wave height (±6 metres from current tide level) represents the 5,000-year threat.*

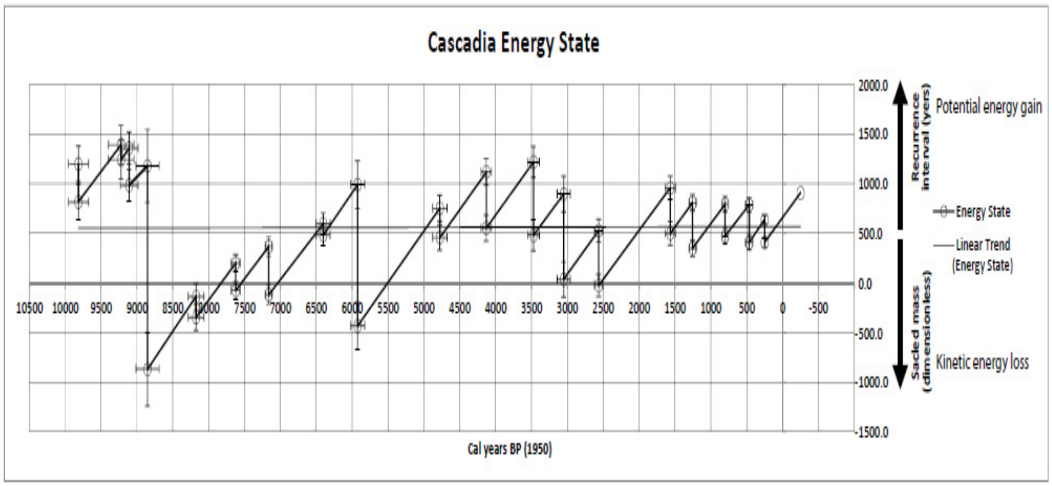

***Figure 12**. Cascadia Energy State over the Past 10,000 Years (chart copied from [14] with permission from Dr. Goldfinger [15])*

5.4 Cascadia Threat: How Much Warning Time?

100. The earthquake itself is the alarm bell. A subduction zone earthquake will last several minutes or longer and will have long-period ground motions that may make it difficult to even stand up. If one experiences an earthquake with these characteristics, assume a tsunami will follow.

101. Dr. Cherniawsky's modelling [4] predicts the first waves will strike the west coast of Vancouver Island within 25 minutes. The Victoria area will see the first drop in water levels at about 60 minutes, and *the first wave will peak at about 90 minutes*.

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6. General Earthquake Threat

102. The overall threat from earthquakes on Canada's west coast can be considered as a combination of threats from three different types of seismic events: megathrust, deep, and crustal earthquakes. Within each of these earthquake types, the threat can also be subdivided into likelihood of occurrence, and consequences.

6.1 Likelihood of Earthquake Occurrence

103. All types of earthquake are similar in the fact that their occurrence cannot be predicted definitively, their potential for occurring must be looked at in terms of a probability or likelihood. Where the types of earthquakes do differ, however, is how these likelihoods of occurrence vary by location. In the case of the megathrust earthquake, it will be one large event that covers a large geographic region. Thus, while the impact will vary by location, the likelihood of occurrence can be considered as a single probability which is the same at any location.

104. Crustal and deep earthquakes, on the other hand, will have different likelihoods of occurring depending on location. It is simple to understand why this should be so. Crustal and deep earthquakes are caused by the buckling and deformation in the North American tectonic plate, and the underlying subducting Juan de Fuca plate respectively. The buckling and deformation in these plates will release strain in occasional rock movements, which are experienced as shaking and shifting on the earth's surface. Although these seismic events occur in unpredictable locations, it would be expected that where there is more strain building up over time, these earthquakes would be more likely to occur. And since the buildup of strain is greatest near the subduction zone, we would expect the likelihood of crustal and deep earthquakes to be greatest near the subduction zone, with diminishing odds the farther on gets from the subduction zone. For the west coast of Canada, this means that the likelihood of crustal or deep earthquakes is greatest near the coast, with diminishing risk as one moves inland.

105. It should also be noted that earthquake intensity and likelihood are interrelated. Every day there are hundreds of very small earthquakes in the region, but they are so small that they are not noticeable without sensitive detection equipment. When we speak of likelihood of occurrence, we are talking about earthquakes over a certain threshold where the effects become significant. For this purpose, it is useful to use the Modified Mercalli Intensity scale which categorises earthquakes based on the effects they have at the earth's surface (see Table II).

6.1.1 Likelihood of Earthquakes in Southern Vancouver Island

106. In order to understand the likelihoods of earthquakes at a certain location, a good approach is to study the history of earthquakes in that specific area. Luckily for the Southern Vancouver Island / Victoria area, studies of this nature have been undertaken by Dr. Garry Rogers and his group at Natural Resources Canada. Using a similar research approach to that employed by Dr. Goldfinger's group, Dr. Rogers has led research into underwater landslides that have occurred in the Saanich Inlet near the southern end of Vancouver Island [6].

107. Due to the specific geography of the Saanich Inlet, it as an anoxic fjord with underwater sediments consisting of annual layers of mud called varves. These varves are, at some layers, interrupted by coarser sedimentary debris from underwater landslides, called debris flow deposits. These debris flow deposits have been correlated to earthquake events, whose strong shaking causes the underwater landslides. By taking core samples of the sedimentary layers, the researchers were able to construct a historical record of strong shaking events in the region. These data are presented alongside the Atwater and Goldfinger results in Table IV and Figure 6 in Section 5.1.1.

108. The study and interpretation of these debris flows is very complicated, with many potential uncertainties. In order to achieve a reasonable degree of confidence in their findings, the researchers had to compare the Saanich Inlet debris flows with other similar studies and known seismic events. The paleoseismic evidence was compared with several similar studies in the Washington State, near Whidbey Island, and from the Cascadia Subduction Zone. In this way, they were able to establish that the debris flows corresponded to known seismic events.

109. Rogers' group has also used comparison with similar studies to estimate the level of shaking that would be necessary to trigger debris flow deposits. Based on similar flows correlated to known earthquakes, it was determined that almost all the landslides were triggered by 'strong shaking', classified as level VII on the Modified Mercalli Intensity (MMI) scale. This intensity scale is used to describe the amount of shaking experienced at a particular location. It describes the effects of an earthquake, rather than the energy released described in the usual earthquake magnitude scale (often referred to as the 'Richter scale'). The MMI is more appropriate for our purposes since we are concerned with the effects of an earthquake at our location.

110. Eighteen incidents of 'strong shaking', deemed to be equivalent to that of the 1946 Vancouver Island crustal earthquake (M 7.3) or the more distant 1700 Cascadia subduction zone earthquake (M 9.0), were recorded over the past 4,500 years, of which about half can be correlated with a Cascadia event. This data [6] suggests to the authors (and Dr. Rogers at [3] concurs) that a useful rule of thumb has emerged: any earthquake that produces 'strong shaking' in the southern Vancouver Island region has about a 50 percent chance of being a local crustal or deep earthquake in the M7 range, and a 50 percent chance of being a Cascadia subduction zone event. The former may generate a local tsunami. The latter will almost certainly generate a widespread tsunami.

111. With an average return rate of 220 years, one can employ a simple Poisson calculation to show *the probability of a 'strong shaking' event being experienced in any location on southern Vancouver Island is about 1 in 5 over the next 50 years, or 1 in 20 over the next 10 years [20], [3].*

6.1.2 Likelihood of Earthquakes in the Wider Region

112. A study to quantify the earthquake risk at various locations in British Columbia was conducted by Onur and Seeman in 2004 [20]. This study used a probabilistic approach to incorporate the various types of earthquakes, their likelihoods and intensities based on location. These probabilistic models were used to generate likelihoods of occurrence for various earthquake intensities, locations and time periods. A map showing the results for likelihood of an event causing strong shaking over the next ten years is shown in Figure 13.

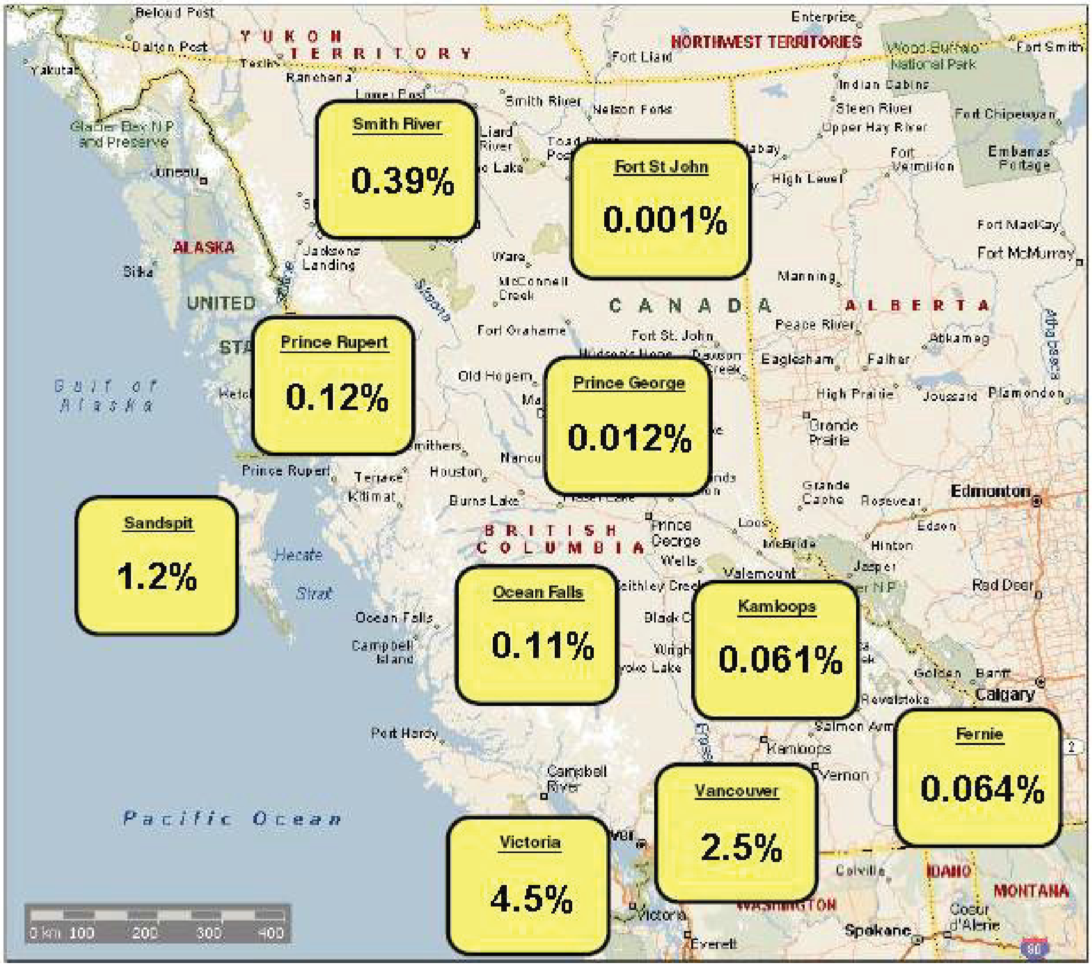

Figure 13. *Probabilities of Strong Shaking (Level VII) the Next 10 Years [20]*

6.2 Impact from an Earthquake

113. When considering the potential impact from an earthquake, it is important to distinguish the characteristics of a megathrust event and deep or crustal earthquakes. One major difference is the geographical extent of the impacts. For a megathrust earthquake, the impact would extend over a very large area, all the way from north of Vancouver Island to Northern California. Crustal and deep earthquakes, by contrast, would have much more localized effects.

114. Although a megathrust earthquake would release huge amounts of energy, and measure a moment magnitude of 9 or more, the direct effects in population centres will not be as severe as the most devastating earthquakes can be, but will likely produce significant damage. The earthquake would last a long time, with large long-period motion. It would cause general alarm in the population, and damage to older unreinforced masonry structures, but minimal damage to modern buildings (anything built from the 1960s onward). An important characteristic to note about the megathrust event is that while the damage may not be as acute as other earthquakes, it will be spread over a large geographic area, which could pose challenges for the response. As well, the long cycle

time will be more likely to induce liquefaction of in-fill areas [15]. The impact of a Cascadia megathrust earthquake has been described as follows:

> "Strong ground shaking from a M_w 9 plate-boundary earthquake will last three minutes or more and will be dominated by long-period ground motions. Damaging ground shaking will probably occur as far inland as Vancouver, Portland, and Seattle. … Although the shaking at these locations will be less than that of a nearby large $M_w \geq 7$ crustal earthquake, the shaking will last much longer and the long-period waves could damage many tall or long engineered structures." [19]

115. Crustal earthquakes, compared to a megathrust earthquake, would release much less energy, and would likely register a lower moment magnitude than a megathrust event, however, as they are local events they have the potential to occur very near population centres. This means that they can potentially have very severe impacts, and cause heavy damage. Because their location, timing, and intensity are unpredictable, it is not possible to estimate the effects in advance. The most useful approach is to look at the experience of previous crustal earthquakes to get a sense of the possible effects.

116. One of the most severe crustal earthquakes in recent years was the Great Hanshin Earthquake which occurred in Kobe, Japan, in 1995. This was an earthquake of moment magnitude 7.2, located 16 km underground, and 20 km from Kobe, a city of 1.5 million. The earthquake struck at 5:46 AM and lasted for about 20 seconds. The effects were severe, over 5,000 people died as a result, and over 200,000 were injured. Property damage was estimated at 10 trillion Yen, the equivalent of $100 billion Canadian.

117. An important feature to note from the Kobe experience was the significance of secondary effects. The shaking itself was fairly brief, and most modern buildings were undamaged. Damage to infrastructure, however, sparked fires that did more damage than the earthquake did directly, shown in Figure 14. Congestion and chaos hampered rescue efforts, businesses closed, and many people were homeless. Most of the deaths and damages were caused by these secondary effects [3].

***Figure 14**. Fires following the Great Hanshin Earthquake (Kobe 1995)*

118. Another example of a crustal earthquake occurred in Courtenay, British Columbia, in 1946. It had a moment magnitude of 7.3 making it the strongest on-land earthquake in Canadian history. It was felt as far away as Portland Oregon, and Prince Rupert BC. Many chimneys were damaged, as well as few masonry structures. Two deaths were attributed to the earthquake, one a drowning when boat capsized from the resulting wave, and one man in Seattle who died of a heart attack.

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7. Tsunami Impact on Defence Ships and Infrastructure

119. This section will assess the general impact of a tsunami on defence vessels and infrastructure in the Victoria area. No impact is predicted for other defence locations on Vancouver Island, such as Nanoose and Comox, as they are located along the protected shores of the Strait of Georgia.

120. The official coastal engineering report on the Great Alaska Earthquake of 1964, Reference [7], contains a wealth of observations and lessons learned from that and previous tsunami events. Despite that event having occurred over 50 years ago, many of these points are well worth repeating. This section will be sprinkled with supporting quotations from this comprehensive report.

7.1 Impact on Vessels

121. When it comes to the survival of vessels during a tsunami, size matters. As Reference [7] concluded:

> "Large ships survived the tsunami … whereas the small boats there were either badly damaged or destroyed."

7.1.1 Vessels in Open Water

122. In open seas, well away from harbours or shorelines, vessels face no real threat from a tsunami. They will rise and fall with the long period waves and personnel onboard may not even notice that a tsunami has passed under them.

> "It has been proved many times that the safest place for ships and boats of all types during the rampage of a tsunami is in the open sea." [7]

123. As the vessels get closer to the shore and enter a zone of relatively shallow water, the slowing speed of the incoming tsunami will cause the water to build up in a more defined, wave-like form. This can carry vessels into each other and onto land and result in substantial damage or even total destruction. The reader will have seen numerous images from the recent Tohoku tsunami that testify to the risk faced by vessels caught in near-shore locations. Vessels anchored or moored to buoys can be dragged considerably by the water forces, or at worst floated off their moorings completely and become battering rams for onshore infrastructure.

124. Even vessels that are under way will face severe challenges in near-shore situations. The tsunami surge can move at speeds in excess of what a manoeuvring vessel can counter. And the topography (above water and under water) of the area can result in severe currents and eddies, even whirlpools, being generated. Indeed, during the Great Chilean Earthquake of 1960:

"… large ships (had) not fared so well, largely as a result of being caught in narrow waterways where the whip action of violent surge currents carried them out of control" [7]

125. Dr. Cherniawsky's modelling suggests that vessels under way in the entrance to Esquimalt Harbour will have to negotiate currents in excess of 10 knots as the (500-year) tsunami ebbs and flows into and out of the harbour. Figure 15 presents the maximum current predictions from the model for Esquimalt Harbour [4], [5].

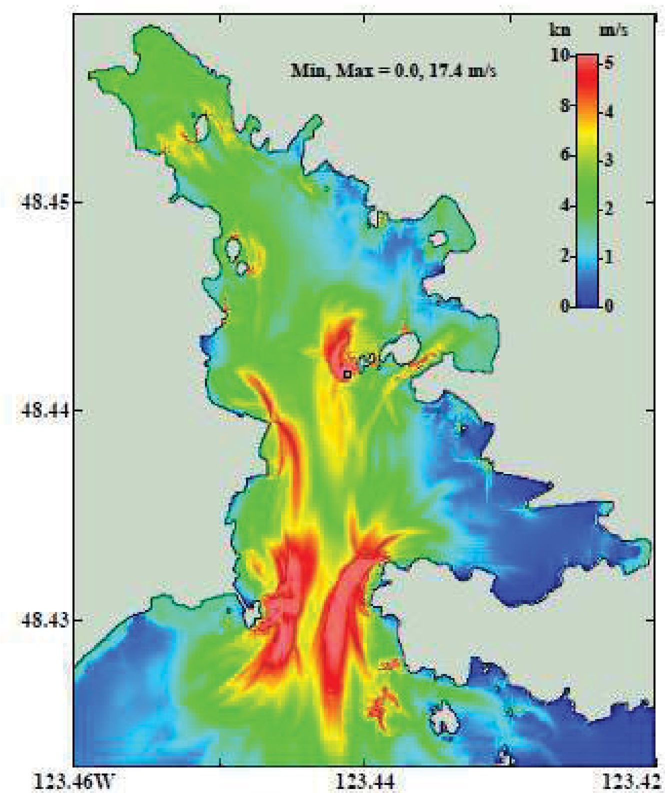


Figure 15. *Maximum Currents Predicted by Computer Modelling for Esquimalt Harbour (500-year tsunami) (printed with permission from [5])*

126. With only 60 to 90 minutes maximum to respond, the decision to put ships to sea must acknowledge the risk of being caught in severe currents within Esquimalt Harbour or at its entrance. They may be better off riding it out alongside.

"The extent of advance warning of the approach of a tsunami might even be insufficient to warrant risking the lives of crews in attempts to undock ships and head for open sea." [7]

7.1.2 Docked Larger Ships

127. This study examines the effect of a rise and drop of water on the ships alongside jetties in Esquimalt Harbour. Incoming and outgoing tsunami waves will exert forces to push the ships towards its jetty or pull them back, respectively. However, an engineering assessment of these more detailed considerations was beyond the scope of this study.

128. The two important numbers here are straightforward: the depth of water each class of ship draws, and the depth of water that exists beneath the surface at each jetty position. Tables VI and VII, respectively, present these details, drawing from current charts.

129. The draught values (from Wikipedia) assume a fully loaded vessel, which is a conservative assumption as they are seldom fully loaded when alongside. Note that the Halifax class frigates and Iroquois class destroyers have a sonar dome extending below the keel an additional 2.5 metres.

Table VI. *Draught of Major Royal Canadian Navy Vessels Based at Esquimalt (Source: Wikipedia)*

Ship Class	Draught
Halifax class frigate (FFH)	4.9 m*
Iroquois class destroyer (DDH)	4.7 m*
Victoria class submarine (SSK)	7.6 m
Protecteur class replenishment oiler (AOR)	10.1 m
Kingston class coastal defence vessel (MM)	3.4 m
Orca class training/patrol vessel (PCT)	2.6 m

* Plus an additional 2.5 m depth for the sonar dome

Table VII. *Water Depths off Jetties at Esquimalt Dockyard and Colwood (Source: Canadian Hydrographic Service chart #3419)*

Esquimalt Harbour Jetty (Position)	Water Depth Below Low Normal Tide
‘A’	8.7 – 10.9 m
‘B’ (West side)	7.4 – 11.3 m
‘B’ (East)	5.8 – 11.3 m
‘C1’ (West pier, outside)	10.9 – 11.8 m
‘C2’ (West, inside)	8.2 – 11.0 m
‘C3’ (East pier, inside)	9.7 – 11.0 m
‘C4’ (East, outside)	9.1 – 10.4 m
‘F’ (North)	10.4 – 13.5 m
‘F’ (South)	7.4 - 10.4 m
‘Y’ (Northeast)	5.7 – 5.8 m
‘Y’ (Southwest)	5.0 – 5.8 m
Floating Docks	2.9 – 8.1 m

130. The water depth values off each jetty have been extracted from spot readings shown on Canadian Hydrographic Service chart #3419 'Esquimalt Harbour'. These values indicate the depth of water below 'low normal tide' (LNT). As this phrase suggests, LNT represents close to the lowest low tide one can expect in the area.

131. Tidal statistics for Victoria were compiled for a full year (2010). Due to its location, Victoria generally experiences one low and one high tide daily, and the tidal swing is relatively low at about three metres or less. The daily low tide varies between 0.0 and 2.0 metres above LNT, with the 5th percentile being 0.2 meters. The daily high tide varies between 2.2 and 3.5 metres above LNT, with the 95th percentile being 3.2 metres.

132. Figure 16 graphically summarizes the normal jetty-side situation. It shows the tidal range described above, and the heights of the jetties, which are all consistently at about 5 metres above LNT. To promote clarity, only the Halifax class frigate cross-section is illustrated. The water depths under each jetty position are shown as curves, which vary from left to right. This corresponds to how water depths vary from left to right along that jetty position as viewed looking seaward from that position. Hopefully, superimposing these curves with an end-on view of the ship and jetty is not confusing for the reader. Jetties 'A', 'C' (inside berths only), and 'F' have fixed cylindrical fenders, as illustrated in the figure. Other jetty positions employ floating fenders.

133. All jetties are assumed to experience the tides and tsunami effects to the same degree. As a look back at Figure 11 will confirm, the computer model predicts essentially the same maximum water rise at all naval jetties in Esquimalt Harbour, including 'Y' Jetty at the end of Lang Cove and 'F' Jetty on the Colwood side.

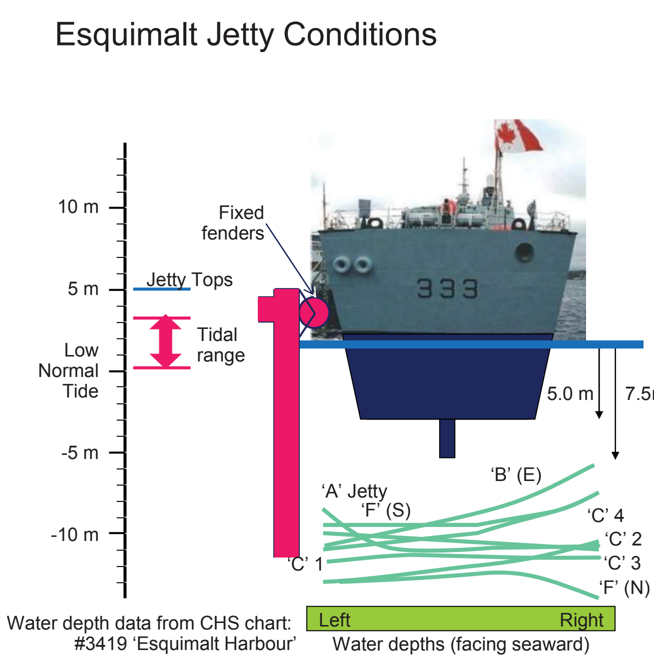


***Figure 16**. Normal Water Conditions at CFB Esquimalt Jetties*

134. Figure 17 illustrates the extreme low or high water situations under the conditions of a 500-year tsunami, with water levels shown at three meters below the 5th percentile daily low tide and three metres above the 95th percentile high tide.

135. Figure 18 illustrates these extremes under the assumption of a 5,000-year tsunami, and an associated six metre rise or fall of water levels.

136. Although the first wave of a tsunami may fortuitously arrive at a favourable tide condition, there will be numerous waves to follow over the next 6 to 8 hours which may be just as severe and may strike very close to the daily low or high tide points. Therefore, the high and low extremes illustrated in Figure 17 (or Figure 18) would both likely occur over that course of time.

137. For the 500-year tsunami (Figure 17), the low water may see the sonar domes of the frigates or destroyers ground. The hulls of the replenishment ship and submarines may also ground slightly. High water will see the jetties inundated and the incoming water will attempt to push the ships onto them. However, well-positioned, fixed fenders should just suffice to keep the ships in place. This assessment is based only on a comparison of water heights, and does not take into account the forces placed on both the ships and jetties by the incoming water and the particular mooring system (hawsers, bollards, fenders) in place. A full engineering assessment would be required to determine effects on ships, jetties, and mooring systems under these conditions.

138. For the 5,000-year tsunami (Figure 18), the effects will be extreme. At low water the sonar domes of the frigates and destroyers will definitely ground, as will the replenishment ship and submarines. The frigate and destroyer hulls will likely ground. At high water all ships will lose contact with the jetties and be pushed landward.

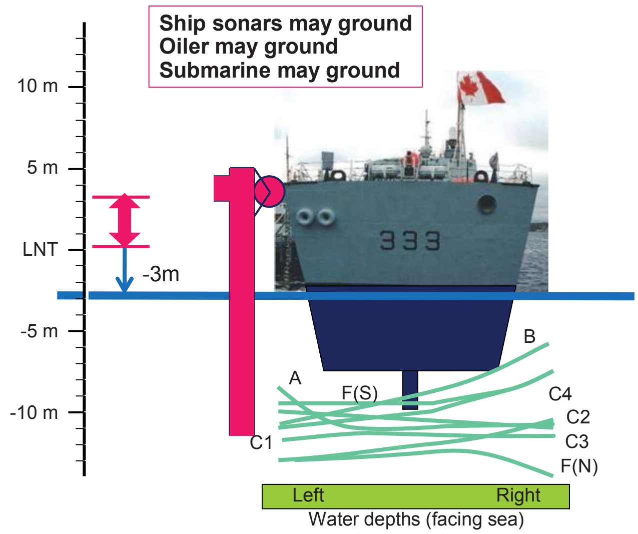
7.1.3 Docked Smaller Vessels

139. The Kingston class coastal defence vessels are located at ‘Y’ Jetty in Lang Cove, with floating fenders. They will often ‘raft off’ each other. The water depths at ‘Y’ Jetty run about 5-6 metres below LNT and the vessels draw 3.4 metres.

140. All the remaining vessels that are alongside in the dockyard are smaller than the frontline ships and the coastal defence vessels. The larger of these remaining vessels, which include the Orca class training/patrol vessels, are usually located at ‘B’ Jetty, which has a greater water depth than ‘Y’ Jetty, ranging from 6 to 11 meters below LNT. The remainder of the smaller vessels are tied up at the floating docks between ‘C’ and ‘Y’ Jetties, where the water depths range from 3 to 8 metres.

141. With the 500-year tsunami expect the coastal defence vessels at ‘Y’ Jetty to partially ground at low water. The Orcas and other vessels at ‘B’ Jetty, which has greater water depth, will not ground. Depending on draught and dock position, some vessels moored at the floating docks may ground.

Three Metre Drop at Low Tide



Three Metre Rise at High Tide

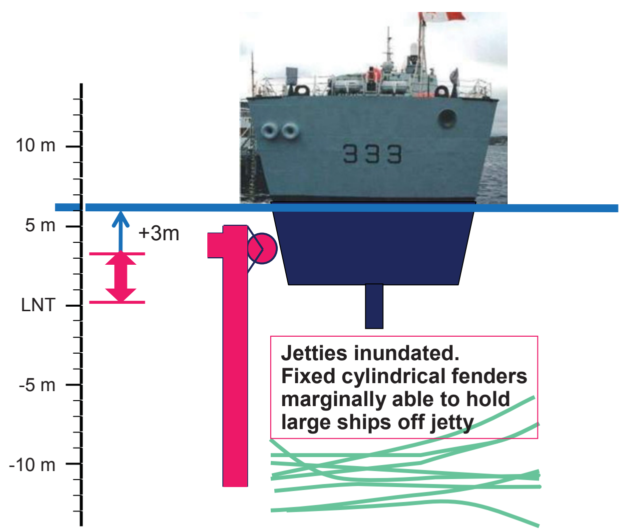
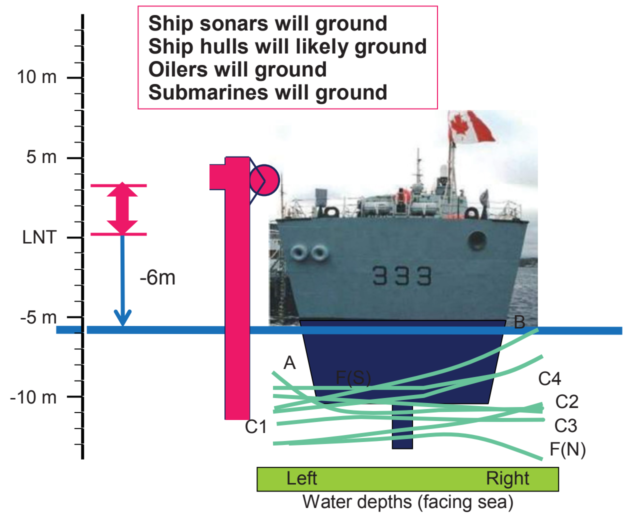


***Figure 17**. Impact on Halifax Class Ships of a Three Metre Rise or Fall in Water Levels (500-Year Tsunami)*

Six Metre Drop at Low Tide



Six Metre Rise at High Tide

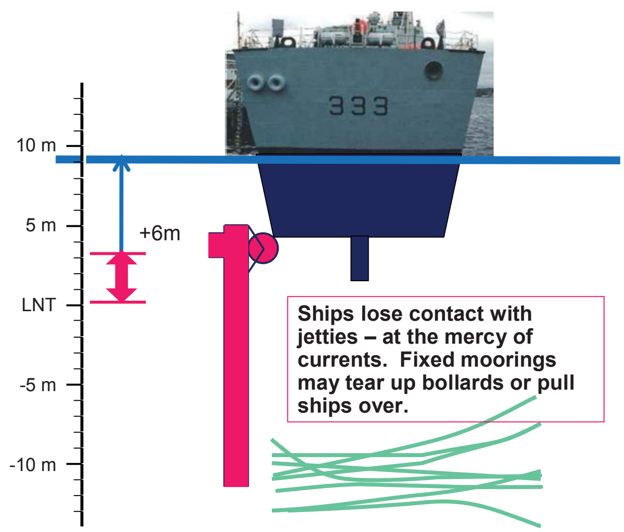


Figure 18*. Impact on Halifax Class Ships of a Six Metre Rise or Fall in Water Levels (5,000-Year Tsunami)*

142. At high water the tops of 'Y' and 'B' Jetties, which are less than 2 metres above the 95th percentile high tide, will be inundated. Floating fenders may not function in this situation, which may result in damage to the vessels (and the jetty). It is unclear whether 'rafting off' (or 'nesting') vessels would improve or aggravate the prospects of damage for the coastal defence vessels during these high water events.

143. The floating docks are on piles that have just sufficient height to weather a 3 meter water rise at high tide. However, this assumes that the lateral forces from the surging water do not unseat these key piles.

144. With the 5,000 year tsunami the coastal defence vessels will ground at low water, as will most vessels at the floating docks. Only the smaller vessels at 'B' Jetty have a chance of avoiding grounding at low water. At high water the coastal defence vessels and all other smaller vessels will lose contact with their jetties/docks, and damage will be extensive as they float into each other and onto the jetties and shore infrastructure.

7.2 Impact of Water Inundation

145. Due to data availability limitations at the time, Dr. Cherniawsky's tsunami modelling efforts did not include modelling the run up of water onto land. The shape of the land will dictate where run ups are higher than the nominal height of the incoming water surge. But to a first order approximation, tracing elevation contours will provide a reasonable estimate of water inundation levels during the high water periods of a tsunami [2, 3].

146. Figure 19 presents a map of the Dockyard area showing the major buildings on the property. Estimates of the contours at three and six metres above high tide are depicted. A more detailed, large scale inundation map of Esquimalt Harbour is being prepared separately.

7.2.1 Jetties and Floating Docks

147. At only 5 meters above LNT (less than 2 meters above the 95th percentile high tide), expect the tops of the jetties to be inundated at high water. Typically, wooden pile jetties, such as 'A' and 'B' Jetties, suffer the most damage. In fact, during the 1964 tsunami

> "The docks in the areas that suffered substantial tsunami damage were all of timber construction." [7]

Wooden deck structures can get buoyed off their piles, and the piles can even be floated out of their sockets [7].

148. Well-constructed jetties made of reinforced concrete, such as 'C' and 'F' Jetty, should survive the forces of a tsunami well. It is noted that 'B' and 'A' Jetties (in that order) are scheduled for replacement in the departmental Site Development Plan (SDP) for CFB Esquimalt [34].

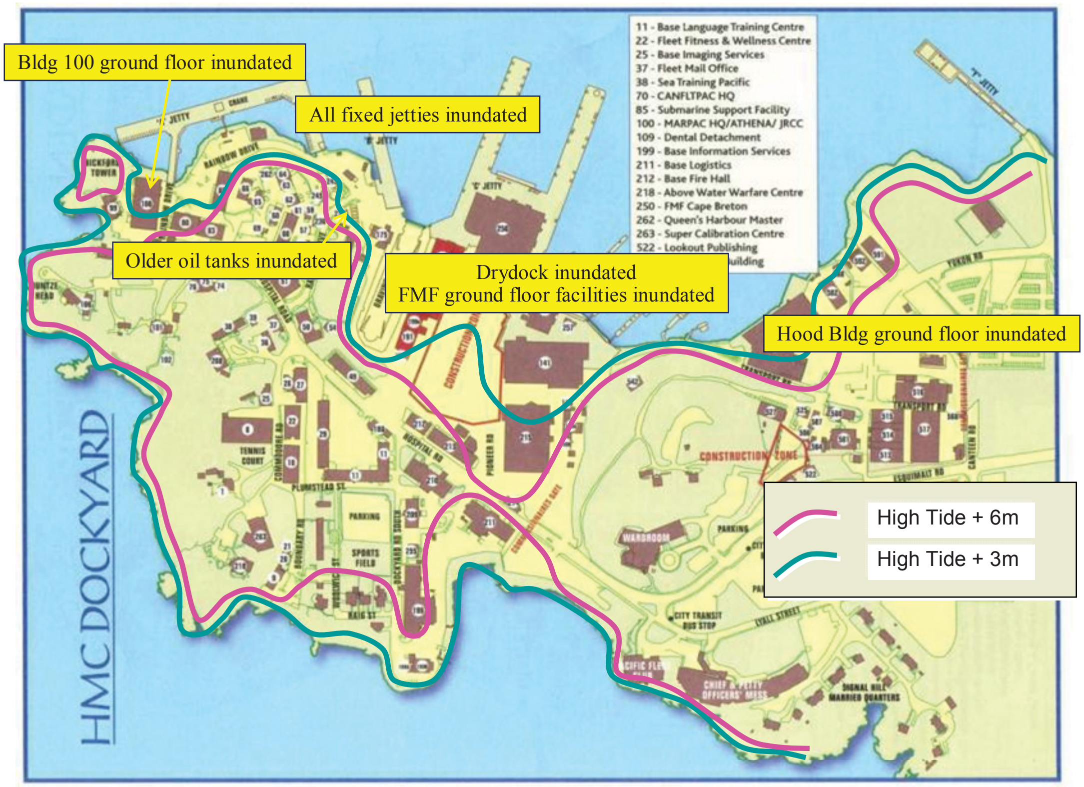


Figure 19. *Esquimalt Dockyard Inundation Map (Contours Estimated)*

149. The timber floating docks, while having just sufficient height in their guide piles to accommodate a 3 metre rise at high tide, also need to withstand the lateral forces associated with the tsunami waves. Notably, in the 1964 Alaska tsunami:

> "All the boat floats in Kodiak Harbor were completely demolished when the piles to which they were attached broke as a result of the heavy lateral forces caused by the tsunami." [7]

And their engineering recommendation is worth repeating:

> "Guide piles for small-craft floating landing decks should preferably be cross-braced above the water to develop adequate truss strength against water loading." [7]

150. The connections between ship and jetty are critical during a tsunami, and there is a wide range of engineering solutions for fenders, bollards, and hawsers. These devices need to manage and withstand the forces associated with a tsunami. It is recommended that an engineering study be initiated to determine the best solutions for having both the ships and the jetties survive a 500-year tsunami.

151. And, again, it may be worth repeating a couple of engineering recommendations that emerged from the 1964 Alaska experience:

> "Docks catering to seagoing vessels should be provided with specially designed shock-absorbing fenders."
>
> "Large ships should be required to carry constant-tensioning winches as standard equipment."

7.2.2 Drydock

152. The top of the caisson (gate) of the older CFB Esquimalt Drydock is only 4.4 metres above LNT. Unless the 500-year tsunami peaks fortuitously at low tide, expect the drydock to be inundated. The newer, commercial Esquimalt Graving Dock across the harbour was not measured, but will be in a similar position. The 5,000-year tsunami will inundate both docks with certainty.

7.2.3 Buildings

153. A number of waterside defence buildings at the Dockyard and Colwood sites are at risk of inundation during the 500-year tsunami event.

154. Most of the Fleet Maintenance Facility (FMF) structures are located behind 'C' Jetty in the Dockyard, with ground floors at roughly the elevation of the jetties themselves. Like the drydock, unless high water strikes at low tide, one should expect the ground floors of the FMF buildings to be inundated with up to one metre of water.

155. Three other Dockyard buildings are also at the same elevation. Building DY100, which contains elements of the MARPAC/JTFP headquarters, DY85 housing the Submarine Support Facility, and DY575 (Hood Building) which holds the staff of the Base Construction Engineering Officer (BCEO). Expect the ground floors of these buildings to be inundated with up to one metre of seawater during the 500-year tsunami as well.

156. On the Colwood side, all of the buildings at the level of 'F' Jetty and can also be expected to have their ground levels inundated with the 500-year tsunami. It appears that all of the buildings on the Naden side are safely above the 3 metre level.

157. The 5,000-year tsunami will cause the above-mentioned buildings to be inundated to the second storey as well. It will reach the ground levels of several other Dockyard buildings such as DY211 (Base Logistics), and the houses on Haig St. Also, it may flood the road near the entrance gate to the Dockyard turning the peninsula into a temporary island. However, the majority of the buildings in the Dockyard are safely perched on higher rocky ground well above the 6 metre level.

158. It is recommended that an assessment be made of the impact of these potential inundations on MARPAC operations, with an eye to developing organizational or engineering changes that would minimize the effects of water inundation into the ground levels of these buildings.

159. Buildings at or below the 6 metre elevation should be engineered to withstand tsunami forces. One of the notable conclusions from Reference [7] is:

> "In general, the type of land structure that can best survive a tsunami inundation is one of sound reinforced concrete construction with deeply embedded foundations … Wood-frame structures, however, should be strongly braced both vertically and horizontally at floor and ceiling levels."

7.2.4 Fuel Storage Tanks

160. Fuels are generally lighter than water. When waterfront fuel tanks are inundated they will float off their positions and are very likely to end up punctured. Widespread fires and contamination will result. This happened graphically in the recent Tohoku tsunami, and Reference [7] noted that in 1964:

> "Waterfront oil storage tanks, devastated by the tsunami waves, burned at Seward, Valdez, Whittier, and Crescent City (California); these oil fires were spread by water and burned uncontrolled, resulting in considerable oil contamination from spillage and spreading by the waves."

161. For this reason, it is important to have all fuel storage tanks on National Defence property above the 3 meters above high tide level. A quick visual inspection of the Dockyard facilities shows that environmental water processing facility (at the foot of 'B' Jetty) is a good three meters above high tide and has its own containment walls. However, the older fuel storage tanks just below them (just west of the drydock caisson) appear to be at risk of inundation with a 500-year tsunami.

162. Although a very remote risk, if fuel storage tanks are being repositioned they might as well be elevated above the 6 metres above high tide level, placing them safely above the 5,000 year tsunami threat as well.

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8. Conclusions and Recommendations

8.1 Conclusions

163. **Earthquakes on Southern Vancouver Island.** There is about *1 chance in 5* that an earthquake involving 'substantial shaking' will strike southern Vancouver Island in the next 50 years. In the Vancouver area the probability is about half of that, or *1 chance in 10* in the next 50 years. When such an earthquake happens there will be about a 50-50 chance of it being a rupture of the Cascadia subduction zone, which will almost certainly produce a widespread tsunami. The other possibility is a local crustal earthquake, which also has the potential to trigger a local tsunami (but likelihood unpredictable).

164. **Tsunamis Generated from Offshore Subduction Zones.** For coastal British Columbia the tsunami threat from the rupture of subduction zones elsewhere around the Pacific basin is only significant for communities at the end of long inlets facing the ocean, such as Port Alberni. Such events may happen a few times per century (the Great Alaska Earthquake of 1964, for example) and may result in up to a 5 metre rise in water levels in these endangered locations. A minimum of two (Haida Gwaii) to four (Vancouver Island) hours warning time can be expected. The tsunami from these offshore events in the Victoria area will be small, no more than that of a winter storm surge.

165. **Tsunamis Generated by the Cascadia Subduction Zone (500-year event).** Paleoseismic research indicates that Cascadia has ruptured 19 times in the past 10,000 years, yielding a mean interval of just over 500 years. It last ruptured 313 years ago. Probability calculations under various mathematical assumptions all predict that there is about *1 chance in 10 that Cascadia will rupture in the next 50 years*. This event will almost certainly generate a substantial tsunami. Computer models predict that it will rise up to 4 metres high above tide levels in the Victoria area (3 metres at the Esquimalt Dockyard and Colwood locations in Esquimalt Harbour), double that on the outer coast of Vancouver Island, and double that again at the end of long inlets facing the ocean, such as Port Alberni. The first wave can be expected on the outer coast of Vancouver Island within 25 minutes of the earthquake striking and within 60 to 90 minutes in the Victoria area.

166. **The Possibility of a 5,000-Year Tsunami.** Paleoseismic research has identified two Cascadia ruptures in the past 10,000 years that were giants. The authors estimate a probability of *1 chance in 54 of a giant tsunami occurring in the next 50 years*. If such an event were to arise, expect double the tsunami wave heights.

167. **Tsunami Effect on Royal Canadian Navy Vessels.** Ships in open water are relatively unaffected by a tsunami. However, currents can be severe around headlands and in harbours, so shallow water areas will be dangerous even for vessels under way. The computer models predict currents in excess of 10 knots for the entrance to Esquimalt Harbour. Larger ships, such as the front line warships of the Royal Canadian Navy, will survive a tsunami better than smaller vessels. For vessels alongside in Esquimalt Harbour, the (500-year) tsunami will cause some ships' sonars to possibly ground at low water and the jetties to be inundated at high water. Most docked vessels should be able to successfully ride out the high water periods, providing the fender and mooring systems

withstand the water forces associated with the tsunami. High water during a 5,000-year tsunami will be catastrophic for all vessels.

168. **Tsunami Effect on Infrastructure.** The drydock and the ground level of the Fleet Maintenance Facility buildings will likely be inundated. The operational headquarters (DY 100), Submarine Support Facility (DY85), Base Construction Engineering (DY575) buildings, and jetty level buildings in Colwood will all have their ground floors inundated as well. Expect the older fuel storage tanks just west of the drydock to be inundated, with a significant chance of initiating a fire. The 5,000 year tsunami will only impact a few more dockyard buildings due to the height of land in the area.

8.2 Recommendations

169. In the event of another tsunami from an offshore source, like that generated by the Great Alaska Earthquake of 1964, the Department of National Defence should be prepared to respond to inundation crises in communities at the end of long inlets facing the ocean on Vancouver Island, such as Port Alberni, Tahsis, Zeballos, and Port Alice.

170. For a Cascadia event, planners should employ a 6 metre tsunami wave height estimate (±3 metres from current tide level) for Esquimalt Harbour and an 8 metre height for the general Victoria area. However, planners should be cognizant of the more remote threat of a giant, 5,000 year Cascadia event, which would result in doubled wave heights.

171. Ships are much safer in open water than in port when a tsunami strikes. Canadian Fleet Pacific should examine the possibility of putting procedures in force to get as many Navy vessels to sea as possible within the 60 to 90 minute window before the arrival of the tsunami. The benefit of having ships in open water during the tsunami would need to be weighed against the risk of moving the ships on short notice in a potentially chaotic situation.

172. Engineering studies should be initiated to determine the best fender and mooring solutions to enable both ships and jetties to survive the forces and water level changes associated with a tsunami.

173. Buildings and facilities for operational command and ship maintenance will be impacted by tsunami inundation in the Dockyard. Studies should be initiated to identify how the operational impact of tsunami inundation of defence infrastructure can be minimized.

174. All fuel storage tanks should be elevated to above 6 meters above maximum high tide. Footings should be strengthened to ensure that tanks will not float off if submerged.

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Annex A
Study Request Form

Study Title*: "Impact of a Tsunami on West Coast Navy Assets and Operations"*

Background

175. The Pacific Fleet Commander, Cmdre Ellis, recently asked some questions of the JTFP J5 cell that concerned the impact of a tsunami on west coast Navy assets and operations:

a. Will ships tied to jetties at CFB Esquimalt touch ground during a tsunami?
b. Will they lift the jetty off (will bollards fail, will hawsers part)?
c. Will the cranes fall onto ships?
d. Will the drydock gate fail?
e. Will comms be all knocked out?
f. Will MARPAC HQ fail and be isolate
g. What will the residual operational capability be?

176. Tsunamis are a real threat to infrastructure, assets, and persons working or residing in coastal areas of the west coast of North America. LCdr Bannister approached the J02OR team to see if analytical resources could usefully be applied to this issue. The client met with J02OR staff on 20 January 2011 to discuss the possibilities. This form summarizes and documents the results of these discussions.

Study Objective

177. To assess the impact of a potential tsunami on the ships, land assets, and personnel of the west coast Navy, with particular emphasis on the Esquimalt harbour and base.

178. Also, to assess what residual operational capability might be, and to identify possible avenues for future study to possibly mitigate the impact of a tsunami.

Methodology

179. **Phase One – Information Discovery.** This is viewed as a multi-phase study, where the first phase will bring together existing knowledge, data, and expertise to give as clear a picture as possible of the threat, addressing questions such as:

a. What is the likelihood of a tsunami in west coast waters?
b. What water heights (and depths) would be expected?
c. How much warning time can be expected?
d. What are the physical dynamics of a tsunami in a harbour (particularly Esquimalt Harbour) setting?
e. What land areas can be expected to be inundated?

180. **Follow-On Phases.** By bringing together this existing knowledge, recommendations will be issued on further studies that might be required. Perhaps there are engineering solutions to mitigate the effects of a tsunami on docked vessels (more robust jetty or tie down system designs). Perhaps harbour dredging would be a worthwhile action. Perhaps warning times will permit evacuation of primary ships to open waters, and perhaps drills of such evacuations are worth considering. Perhaps tsunami warning documentation to potentially affected base personnel should be developed and promulgated. Perhaps relocation of key command units to infrastructure at higher locations will make sense. However, all such directions are speculative until the first 'information discovery' phase is completed.

Timelines

181. Phase One to be completed by 30 June 2011. Completion of follow-on phases is to be determined (depends on the complexity of recommended follow-on efforts), but total completion anticipated by December 2012.

Personnel

Client OPI: LCdr Grant Bannister, JTFP J5, SSO Future Ops Plans

DRDC CORA OPI: Mr. Antony Zegers, J02OR

Other DRDC Centre Resources Required: Advice from DRDC Atlantic marine engineering experts to be arranged.

Annex B
January 2007 Briefing Note to COMD Canada COM

EARTHQUAKE AND TSUNAMI THREAT TO CANADA'S WEST COAST

ISSUE

182. Earthquakes and tsunamis represent a tangible threat to civilian and CF installations and assets within the JTFP area of responsibility (AOR). In order to produce plans for possible disaster scenarios, the threat posed by earthquakes and tsunamis must be understood.

BACKGROUND

183. JTFP J02OR was approached by JTFP J5 to assist with analyzing and quantifying the threat posed by earthquakes and tsunamis in the JTFP AOR, and the impact that these phenomena could have on population centres and vital installations.

DISCUSSION

184. The JTFP AOR includes the most seismically active region in Canada; as such, earthquakes are a credible threat to population centres and CF assets in this region.

185. The primary geological feature of interest on the coast of BC is known as the Cascadia Subduction Zone, which is shown at Annex A. This zone consists of a tectonic plate, under the ocean floor, called the Juan de Fuca plate. This plate is moving towards North America and is being pushed under the North American plate, which causes a build-up of strain that is released periodically in the form of earthquakes.

186. There are three types of earthquakes that occur in the Cascadia Subduction Zone: crustal, deep, and megathrust. Although the Juan de Fuca plate is moving towards the North American plate in a geological sense, they are actually stuck together at their interface; thus, there is in fact no slippage between them for the majority of time. This apparent inaction causes a build-up of stress and strain in the surrounding rock as the plates compress. This stress causes shifting in the rocks from time to time, which produces earthquakes. When these earthquakes occur in the North American plate, which is plate at the surface of the earth, they are called 'crustal' earthquakes. When these earthquakes occur in the lower Juan de Fuca plate, they are called 'deep' earthquakes. When sufficient stress accumulates to cause the interface between the Juan de Fuca and North American plates to rupture, a 'megathrust' earthquake occurs.

187. 'Deep' earthquakes with a magnitude of seven or more on the Richter scale occur every 30 to 50 years. As the epicentres of these 'deep' earthquakes are located deep in the earth, damage tends to be minimal. 'Crustal' earthquakes with a magnitude seven or more occur every few hundred years. As these earthquakes can occur close to population centres, there is potential for severe impact. Examples of 'crustal' earthquakes include

the Los Angeles earthquake of 1994 and the Kobe earthquake of 1995. The most severe earthquake in Canadian history was a ‘crustal’ earthquake and occurred in Courtenay, BC in 1946. Deep and crustal earthquakes cannot be predicted, and occur randomly with a probability that varies by region. The probability of a ‘deep’ or ‘crustal’ earthquake with severe impact occurring within the next 10 years has been calculated at 4.5% for the Victoria area and 2.5% for the Vancouver area. The probability of a deep or crustal earthquake occurring reduces as the distance from Cascadia Subduction Zone increases.

188. Cascadia ‘megathrust’ earthquakes differ from the other types of earthquakes, as it is certain that one will occur along the Cascadia Subduction Zone at some point, it is just a matter of time. The characteristics of this type of earthquake, such as magnitude and location, are also predictable. Megathrust earthquakes take place every 300 to 900 years. The last one occurred in 1700; thus, it can be surmised that BC is about to enter a “window” of potential occurrence. The magnitude of the earthquake will increase as the time between earthquakes increases. When a ‘megathrust’ earthquake occurs, it will have a magnitude of nine or more, and it will affect an area stretching from north of Vancouver Island to the coast of North California. It will also create a tsunami wave. One factor that will mitigate the impact, however, is that it will occur relatively far away from population centres. The earthquake near Sumatra on 26 December 2004 that created the tsunami was a ‘megathrust’ earthquake.

189. The probability of occurrence of a Cascadia ‘megathrust’ earthquake gradually increases with time. Depending on the modelling assumptions used, the probability of a Cascadia ‘megathrust’ earthquake occurring within the next 10 years has been calculated to be anywhere from less than 1% to up to 15%, giving a “best guess” mid-point estimate of 7.5%. This probability estimate increases to 11% over the next 50 years, and 17% over the next 100 years. The effect of this type of earthquake is predictable; however, the local effect is dependant upon many factors primary of which is the type of terrain. Data and maps that show the vulnerability of specific locations and that provide predictions of the severity of damage are available.

190. Any underwater earthquake can create a tsunami, and the tsunami often results in more damage that the earthquake itself. The characteristics of a tsunami created by a Cascadia ‘megathrust’ earthquake have been modelled, and planning levels for the height of the tsunami varies from 10 metres on the outer coast of Vancouver Island, to two metres in areas sheltered by Vancouver Island. The planning level for the Victoria area is four metres. Again, local conditions will affect the height of the wave. Data and maps are available that predict the height and speed of the wave in specific locations.

CONCLUSION

191. Earthquakes and tsunamis pose a credible threat to JTFP AOR, and Victoria is the area at highest risk of a major earthquake in Canada. The risk of earthquake is less in Vancouver, and the risk decreases as the distance from the Cascadia Subduction Zone increases. The effects of earthquakes and tsunamis vary depending upon a large number of factors; however, modelling has produced very good predictions upon which planning can commence.

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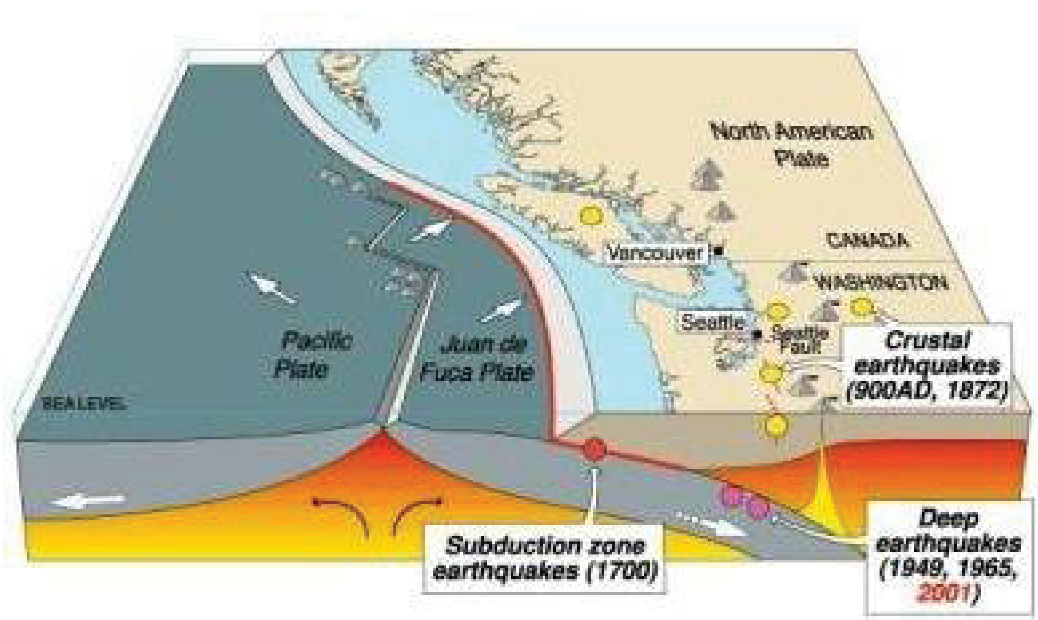
Date prepared: 24 January 2007

Attachment:

Appendix 1 The Cascadia Subduction Zone

Appendix 1
Earthquake and Tsunami Threat To Canada's West Coast
24 January 2007

CASCADIA SUBDUCTION ZONE



Source: US Geological Survey

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Annex C
The Time-Dependent Weibull Model

192. We assume that the instantaneous probability of Cascadia subduction zone re-rupture (or 'hazard rate') is zero immediately following a rupture, and increases into the future in some manner. If it is further assumed that this hazard rate increases geometrically – that is, as a function of time to some power – then it is well known that the resulting probability distribution can be solved in closed form and is the Weibull distribution. The mathematical details on the Weibull distribution have been extracted from Reference [22].

193. The generalized Weibull distribution has two parameters: a shape parameter k, and a scale parameter α. The probability density function and cumulative distribution function are defined, respectively, for any time $t \geq 0$ as

$$\begin{aligned} f(t;\alpha,k) &= (k/\alpha)(t/\alpha)^{k-1}\exp(-(t/\alpha)^k) \\ F(t;\alpha,k) &= 1-\exp(-(t/\alpha)^k) \end{aligned} \quad \text{(C1)}$$

194. As one might expect, the scale parameter α has a direct relationship to the mean of the Weibull distribution. The mean is given by [22] as follows, where Γ represents the gamma function.

$$E(t) = \alpha \cdot \Gamma(1+1/k) \quad \text{(C2)}$$

195. The shape parameter k represents the power with which the hazard rate increases, plus 1. As [22] describes, a value of $k = 2$ represents a linearly increasing hazard rate over time. A value of $k = 1$ results in a constant rate over time, which is identically the Poisson distribution. A value of $k = 1.5$ represents a rate of increase as the square root of time (which is less than a linear rate), and a value of $k = 3$ represents a rate that increases as the square of time (which is more than linear).

196. What would be a good value to use for the shape parameter k? The logical approach would be to try to fit the Weibull distribution to historical recurrence interval data.

197. Goldfinger [14] estimated 19 past rupture data points for the Cascadia subduction zone over the past 10,000 years, producing 18 calculated intervals. Table C-I presents these data, extracted from his Table 9 of Reference [14]. Note that we have used the accepted value of 313 years before present (BP) as the firm time of the last rupture, rather than use the mean of his turbidite T1 data which is closer to 250 years BP. The mean interval for this data set is 528 years between ruptures.

198. Figure C-1 presents a graphical comparison of the cumulative distribution based on the historical data (the dark blue step function) with the cumulative Weibull distribution calculated using Equation C1 for five different values of k ranging from $k = 1$ (which is identically the Poisson distribution) to $k = 3$. Parameter α is estimated by substituting the mean of 528 years into Equation (C2).

Table C-I. *Historical Cascadia Subduction Zone Rupture Intervals (Source: Table 9 of Goldfinger [14])*

Mean age (years BP)	Interval (years) Mean: 528 yrs
T1: (313)	
T2: 481	169
T3: 796	316
T4: 1,243	446
T5: 1,553	311
T6: 2,537	984
T7: 3,028	491
T8: 3,443	415
T9: 4,108	665
T10: 4,770	661
T11: 5,959	1,189
T12: 6,466	508
T13: 7,182	715
T14: 7,625	443
T15: 8,173	548
T16: 8,906	733
T17: 9,101	195
T17A: 9,218	117
T18: 9,795	577

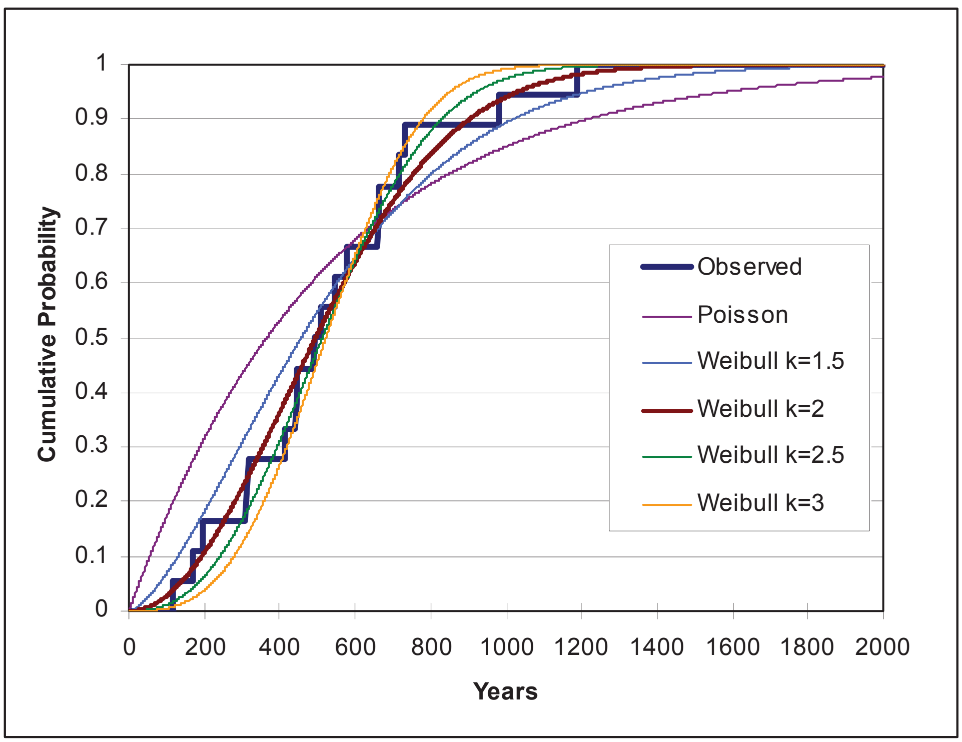

Figure C1. *Cumulative Recurrence Interval Distributions – Observed and Fit*

199. It can be seen visually that a value near $k = 2$ (the dark red curve in Figure C-1) best fits the observed data set. The Poisson distribution (purple curve) is visibly a much poorer fit than the other Weibull distributions.

200. A sum of squares calculation was conducted to see which precise value of k minimized the integral of the square of the differences between the cumulative Weibull for a given value of k and the cumulative observed distribution. A value of $k = 2.14$ was determined as being the best fit value, with just a marginally better (by 8%) sum of squares than with $k = 2$.

201. Therefore, we have confidence that the observed historical data exhibits behaviour that is consistent with the assumption that the instantaneous probability of Cascadia subduction zone re-rupture increases more-or-less linearly with time after the most recent rupture, and hence is reasonably represented by a Weibull distribution with shape parameter $k = 2$.

202. Substituting k = 2 into equation C1 yields simplified formulae for the probability density and the cumulative probability functions:

$$\begin{aligned} f(t,\alpha) &= (2t/\alpha^2)\exp(-(t/\alpha)^2) \\ F(t,\alpha) &= 1-\exp(-(t/\alpha)^2) \end{aligned} \tag{C3}$$

203. Substituting $k = 2$ into Equation C2 yields:

$$E(t) = \alpha \cdot \Gamma(1+1/k) = \alpha \cdot \Gamma(1.5) = \alpha \cdot 0.5 \cdot \Gamma(0.5) = \alpha\sqrt{\pi}/2 \tag{C4}$$

Note that the gamma function maps to the factorial function on the integers (see [22]), and hence has the property that $\Gamma(1+x) = x\,\Gamma(x)$. It is known [22] that $\Gamma(1/2) = \sqrt{\pi}$.

204. Returning to our real-world problem, we have estimates of the mean Cascadia subduction zone rupture interval that range from 430 years to 530 years. Substituting these values for $E(t)$ in (C3) and solving for α yields the two bracketed estimates for the scale parameter α

$$\begin{aligned} \alpha_{430} &= 430 \cdot 2/\sqrt{\pi} = 485.2 \\ \alpha_{530} &= 530 \cdot 2/\sqrt{\pi} = 598.0 \end{aligned} \tag{C5}$$

205. In the case of the Cascadia subduction zone, we assume that we have been observing a Weibull-distributed phenomenon for $T_0 = 313$ years and have observed no ruptures. The remaining probability under the curve is $1 - F(T_0, \alpha)$ so we will have to normalize the remainder of our Weibull distribution now by that value. The probability of observing a rupture event, R, in the next T years is then given by

$$P(R \le T) = \frac{F(T_0+T,\alpha) - F(T_0,\alpha)}{1-F(T_0,\alpha)} \tag{C6}$$

206. Substituting (C3) into (C6) and simplifying yields the final formula:

$$P(R \leq T) = 1 - \exp((T_0/\alpha)^2 - ((T_0 + T)/\alpha)^2) \qquad \text{(C8)}$$

where T_0 = 313 years and α is bracketed by the values in (C5). We will use three values for T when presenting results: the next 10, 50, and 100 years.

List of Abbreviations

AOR	Area of responsibility
BCEO	Base Construction Engineering Officer
Canada COM	Canada Command
CF	Canadian Forces
CFB	Canadian Forces Base
CORA	Centre for Operational Research & Analysis
CSZ	Cascadia subduction zone
DND	Department of National Defence
DRDC	Defence Research & Development Canada
JTFP	Joint Task Force (Pacific)
LNT	Low normal tide
M	Magnitude (earthquakes, measured on the moment magnitude scale)
MARPAC	Maritime Forces Pacific
MOST-3	Method of Splitting Tsunamis, Version 3
RCN	Royal Canadian Navy
SDP	Site development plan

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The Seismic and Tsunami Threat to Ships, Personnel, and Defence Infrastructure on Canada's West Coast

4. AUTHORS (last name, first name, middle initial)

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5. DATE OF PUBLICATION (month Year of Publication of document) October 2013	6a. NO OF PAGES (total containing information. Include Annexes, Appendices, etc.) 68	6b. NO OF REFS (total cited in document) 37

7. DESCRIPTIVE NOTES (the category of document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

DRDC CORA Technical Memorandum

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address).

N/A

9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.) N/A	9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written.) N/A
10a. ORIGINATOR's document number (the official document number by which the document is identified by the originating activity. This number must be unique to this document.) DRDC CORA TM 2012-185	10b. OTHER DOCUMENT NOS. (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

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The west coast of Canada is a high risk region for earthquakes and possible associated tsunamis. The commander of Maritime Forces Pacific/Joint Task Force (Pacific) requested an assessment of these threats, particularly the tsunami threat, to Royal Canadian Navy (RCN) vessels, personnel, and defence infrastructure on the west coast. This report brings together the extant geophysical science on the topic. The ‘offshore’ threat from tsunamis generated elsewhere around the Pacific Basin is characterized, as is the primary tsunami threat to coastal British Columbia – the Cascadia subduction zone. Probabilistic theory is developed to model subduction zone rupture events.

The results confirm a likelihood of about one chance in ten of a major tsunami event happening on the west coast in the next 50 years. The severity of the tsunami in Esquimalt Harbour will be more modest if the 500-year event happens, with a predicted rise and fall of plus or minus three meters in water levels, but could be double that if the (unlikely but possible) 5,000-year event occurs. Water levels will be doubled on exposed coastlines of Vancouver Island, and doubled again when focused in longer inlets (like Alberni Inlet). Warning times are estimated at 60 to 90 minutes in the Victoria area, but only 25 minutes on the outer coast. An assessment of the impact of changing water levels on docked RCN vessels and the effect of water inundation on defence infrastructure is provided.

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Earthquake
Cascadia subduction zone
Royal Canadian Navy
Esquimalt
Likelihood
Inundation
Infrastucture
Warning time
Weibull distribution

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